NGNP-CTF MTECH-TDRM
Revision 0

December 2008

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

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**NGNP-CTF MTECH-TDRM-000** **December 2008**
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# Section 0: Executive Summary Report

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| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| ALWR | Advanced Light Water Reactors |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Electrolyzer System |
| EM | Evaluation Model |
| EMB | Electromagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| Acronym | Definition |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| GIF | Generation IV International Forum |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| Acronym | Definition |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |

| Acronym | Definition |
|---|---|
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VHTR | Very High Temperature Reactors |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# 0 EXECUTIVE SUMMARY REPORT

## 0.1 NGNP Background

Several countries across the world are involved in the development of advanced nuclear systems that are envisioned to follow the Advanced Light Water Reactor (ALWR) systems that are now leading the resurgence of nuclear power. These advanced non-ALWR systems have been coined "Generation IV" (Gen IV) concepts. An international forum of these countries and a framework for cooperation have been established – the Generation IV International Forum (GIF).

The GIF model envisions that individual countries will take the lead for developing and demonstrating Gen IV nuclear systems in which they have particular interest, and that other countries will provide support through implementing agreements. The first of such implementing agreements has been recently signed. Early in the process, the US took the lead for developing the High Temperature Gas-Cooled Reactor (HTGR) – also referred to as the Very High Temperature Reactor (VHTR) within the GIF forum.

The HTGR technology offers enhanced safety features based on inherent material properties and passive design features, plus improved reliability, proliferation resistance, security and waste management capabilities. Furthermore, the HTGR is evaluated to be competitive for a broad range of applications, including small-to-medium high efficiency power generation that is well suited for dry cooling, cogeneration and water desalination, plus unique high temperature process heat applications such as bulk hydrogen production. High pressure steam, well beyond the temperatures available with water reactor systems, can also be provided to displace natural gas for enhanced oil recovery and tar sands production - all without greenhouse gas emissions.

Within the US, the Department of Energy (DOE) has focused the development of the HTGR technology through the Next Generation Nuclear Plant (NGNP) Project which is the dominant part of the US Gen IV Program. From the start, the NGNP Project was centered at the Idaho National Laboratory (INL). Initially, the goals were set for 1000ºC core outlet temperatures to drive Brayton cycle gas turbines and/or water splitting processes for the production of hydrogen.

The NGNP Project was subjected to a critical review by a group of experts known as the Independent Technology Review Group (ITRG) over the period November 2003 through April 2004. The objective was to provide a critical review of the proposed NGNP Project and to identify areas of R&D that needed attention. In the report, the ITRG observations and recommendations focused on overall design features and important technology uncertainties. A key recommendation was to reduce the core outlet temperature to the range of 900°C to 950ºC.

High temperature process heat from the HTGR has been an attractive concept from inception. To date, the leading application and the focus of the work herein has been for hydrogen production from various water splitting based technologies, which require core outlet temperatures in the range of 900ºC to 950ºC. However, there are broad process steam and other process heat applications, e.g. steam methane reforming, that are accessible with lower core outlet temperatures that will be the subject of follow-on work.

## 0.2 NGNP Demonstration Plant Description

The PBMR NGNP Demonstration Plant described herein, as initially conceived and developed per the NGNP and Hydrogen Production Pre-conceptual Design Report (PCDR) [0-1] consists of various Systems, Structures and Components (SSCs) integrated into a functional plant capable of producing process heat for hydrogen production as well as electricity (used notably for the hydrogen plant, but also for export). The PBMR NGNP Demonstration Plant, consists of a 500 MWt pebble bed reactor with primary and secondary helium loops coupling to a 50 MWt process coupling heat exchanger for the demonstration of hydrogen production and a 470 MWt steam generator for a Rankine cycle power generation plant.

The process flow diagram of the NGNP Demonstration Plant for Hydrogen Production is given in Figure 0-1.

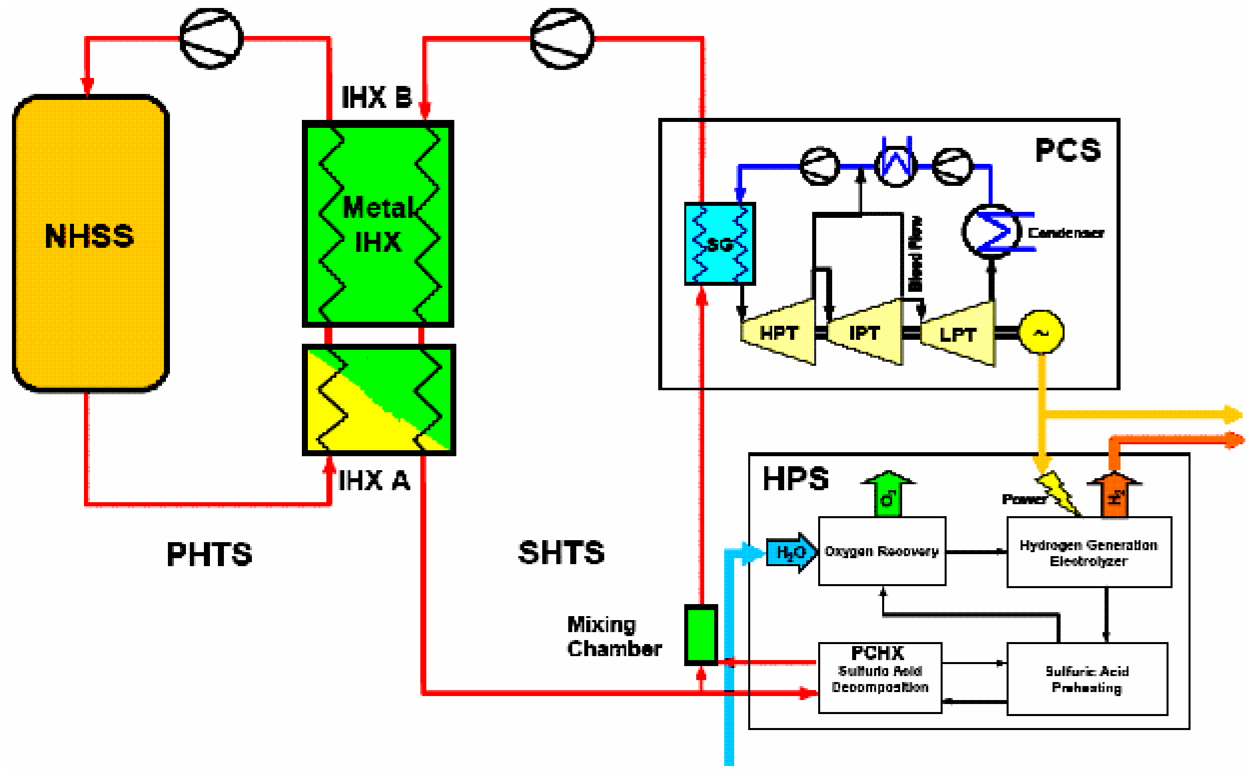


**Figure 0-1: PBMR NGNP Demonstration Plant Process Flow Diagram – $H_2$ Production (950°C)**

The NGNP Preconceptual Design and conceptual design studies to date have focused on a 950°C reactor outlet temperature for hydrogen production. Figure 0-2 shows the Steady State Conditions for that application.

The NGNP may also be used for process heat applications. Figure 0-3 presents one option for a steam production plant, and this option will be used as the 750°C reference for the purposes of this study. In this option, the Process Coupling Heat Exchanger (PCHX) is removed from the Secondary Heat Transport System (SHTS) and a single Intermediated Heat Exchanger (IHX) is retained. The steam could be used for electricity production, process steam or cogeneration. This configuration represents the minimum departure from the PBMR NGNP Preconceptual Design and would provide enveloping development requirements for 750°C applications. It is potentially representative of applications, such as oil sands, in which extreme water quality requirements or other considerations (e.g., tritium migration) would dictate the use of an IHX. In other applications, it may be possible to eliminate the IHX and relocate the SG to the Primary Heat Transport System (PHTS). The actual configuration of a 750°C application remains subject to trade studies that would be done when functions and requirements are identified.

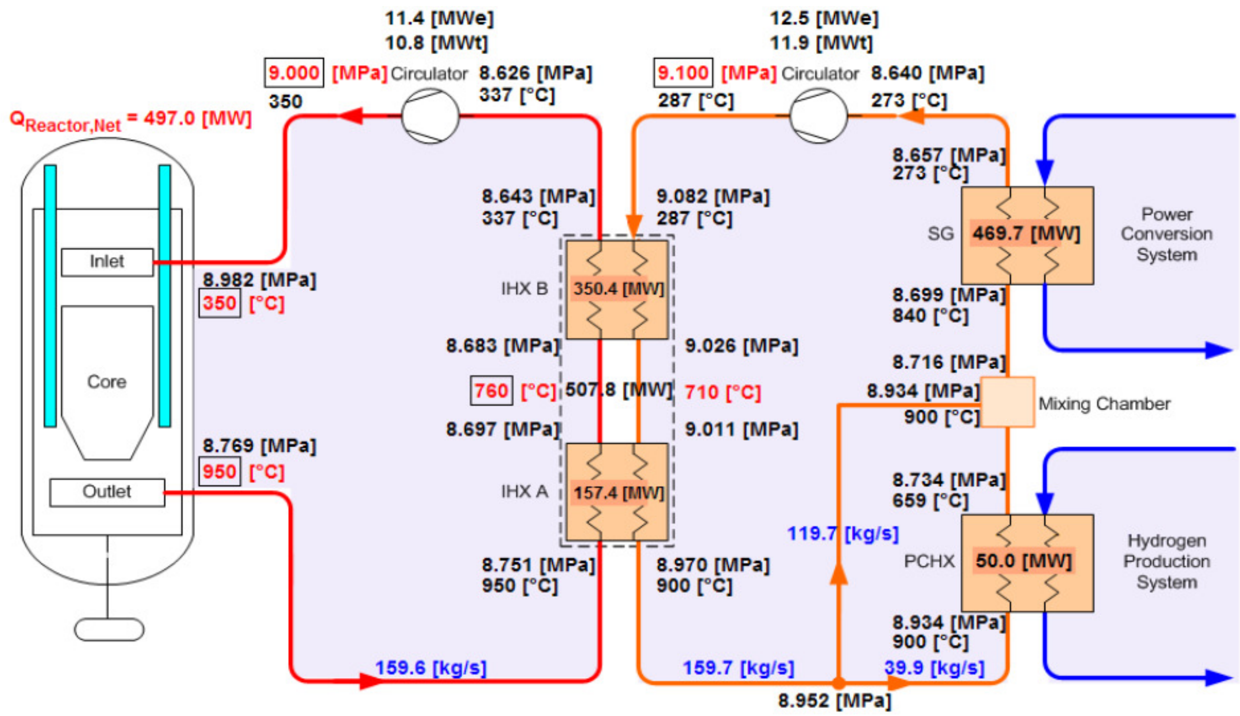


**Figure 0-2: Nominal Process Conditions for a NGNP Demonstration Plant ($H_2$, 950°C)**

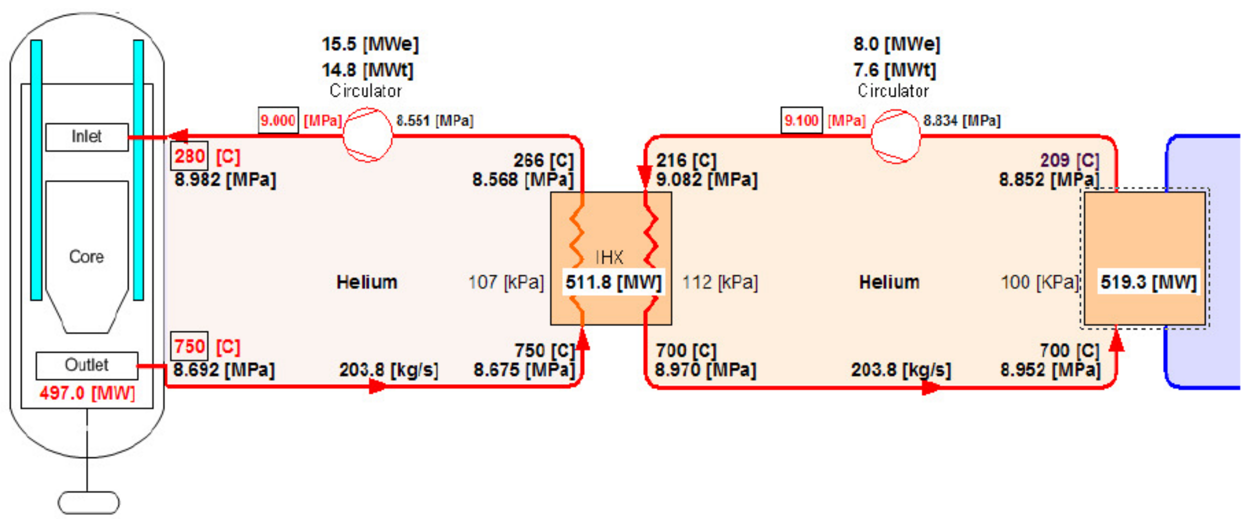


**Figure 0-3: Process Conditions for a NGNP Steam Plant (750 °C)**

The modes and states of the NGNP demonstration plant as currently anticipated are indicated in Figure 0-4. These states are subject to change as the design and the operational requirements of the plant are further analyzed. Note that the 750°C steam production plant will probably not have states 7 & 8.

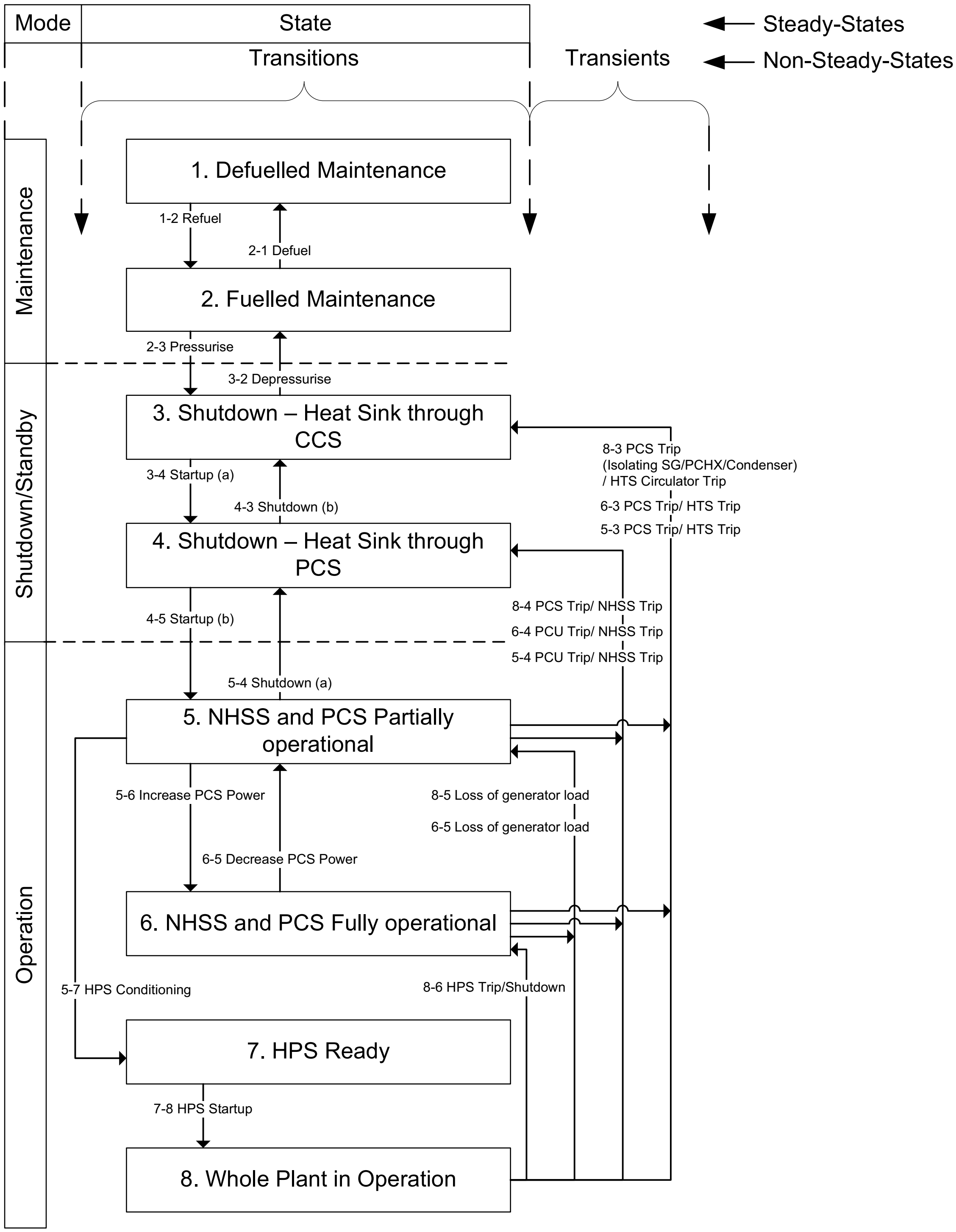


**Figure 0-4: NGNP Plant Modes and States of Operation**

## 0.3 The Basis for the NGNP Technology Development Road Mapping

In order to minimize the safety and economic risk of the NGNP Demonstration Plant, the intent is that all the SSC's should have demonstrated the ability of the applied technologies to function according to specification within their intended operational environment, prior to nuclear start-up of the NGNP Demonstration Plant. This would then leave the ability of these technologies to perform according to specification when integrated into their final NGNP Demonstration Plant configuration as the remaining risk to be addressed.

The NGNP TDRM Process is detailed in NGNP-CTF MTECH-TDRM-002, Technology Development Road Mapping Process, Section 02 [0-4] of this report.

### 0.3.1 The Technology Development Road Mapping Process

Obviously the advancement of the readiness of technology for application within the NGNP needs to be addressed at the level of the SSCs within which the technology is being applied. There are SSCs which use technology that is either commercially unavailable or lacks proven industry experience for the specific application, thus further technology development needs to be done for these SSCs to achieve acceptable Technology Readiness Levels (TRLs) prior to installation in the NGNP. These SSCs are referred to as critical SSCs.

Design Data Needs (DDNs) are identified shortcomings in information regarding materials, technologies and manufacturing processes that follow from design and trade studies in specific technologies. Thus, given the current design maturity of the NGNP Demonstration Plant, it is recognized that not all the DDNs have been identified at this stage and it is highlighted that the technology development needs will be supplemented as the integrated design progresses.

For the NGNP, levels of readiness of needed technologies have been assessed. However, these levels vary significantly for the various SSCs. The overall technology readiness assessment process is referred to as Technology Development Roadmapping (TDRM) and is illustrated in Figure 0-5. The TDRM process is used to assess, map, plan and visualize the needed technology development activities to advance the technology readiness of a particular SSC to a state that will reduce commercial risk and support plant operation. The TDRM process determines what is needed *firstly* to verify performance and safety of the SSC and *secondly* to minimize the risk associated with operating the SSC. The latter is achieved through a series of scale test programs, up to and including tests at full-scale NGNP plant temperatures, pressures and flow rates. These test programs are documented in Test Specifications which specify the needed maturation tasks to advance the relevant technologies. The results from the maturations tasks serve as input to the various SSC's design, manufacturing and operation. Only critical SSC's to be utilized in the 950℃ NGNP demonstration plant were considered for the road mapping process herein

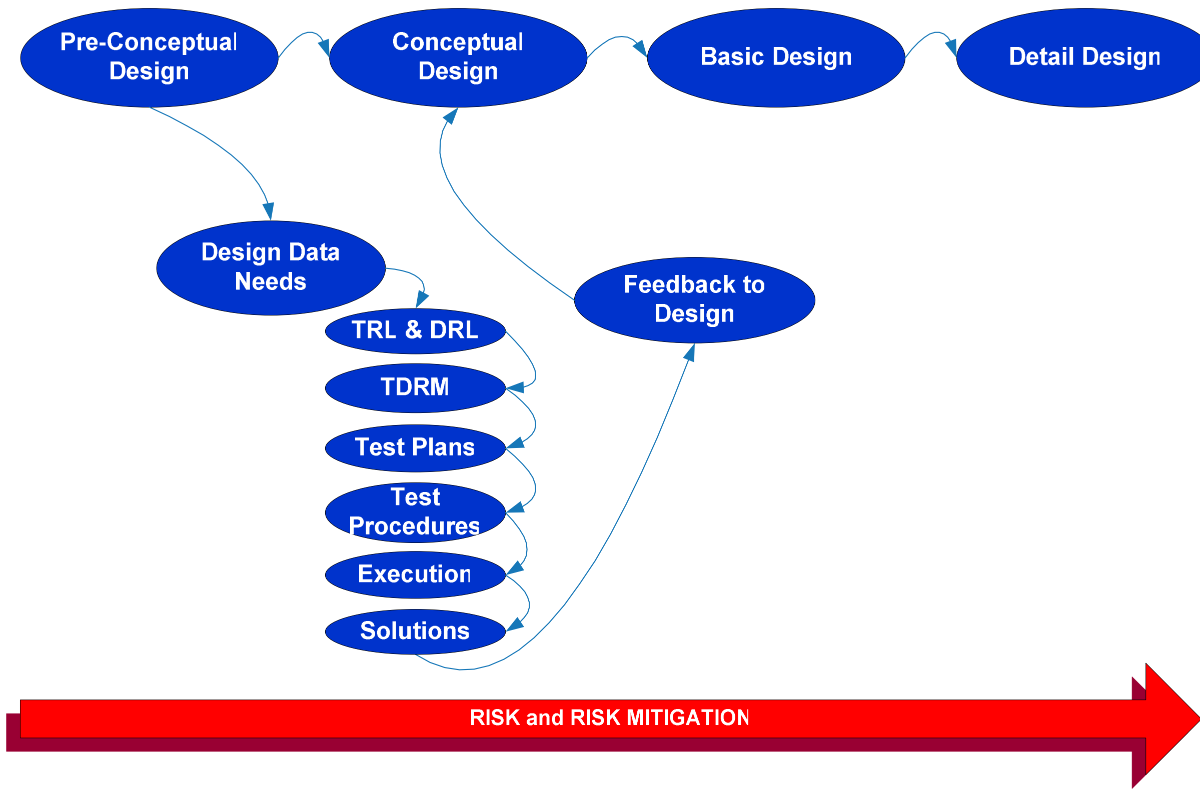


**Figure 0-5: The TDRM process and Related Outputs**

Critical SSCs are defined as Systems, Structures and Components that utilize technologies that are not commercially available or do not have proven industry experience in the intended application.

The following deliverables are relevant in the TDRM process for these SSCs:

- Technology Readiness Level Rating Sheets, which supply the current readiness of a particular SSC to serve as input into the NGNP.
- Technology Development Roadmaps, which set out the high level vision for maturing certain technologies up to a point where the technology can be utilized in the NGNP.
- Technology Maturation Plans and Test Specifications, which specify the more detailed plans/actions required to mature technologies for utilization in the NGNP.

### 0.3.2 Technology Development Roadmap

In Figure 0-6:, a template for a Technology Development Roadmap is shown. The roadmap is typically populated with items relating to down selection of technologies (shown on the left side of the roadmap), TRL of the technology (yellow blocks) and technology maturation tasks needed for advancement (shown on the right side of the roadmap).

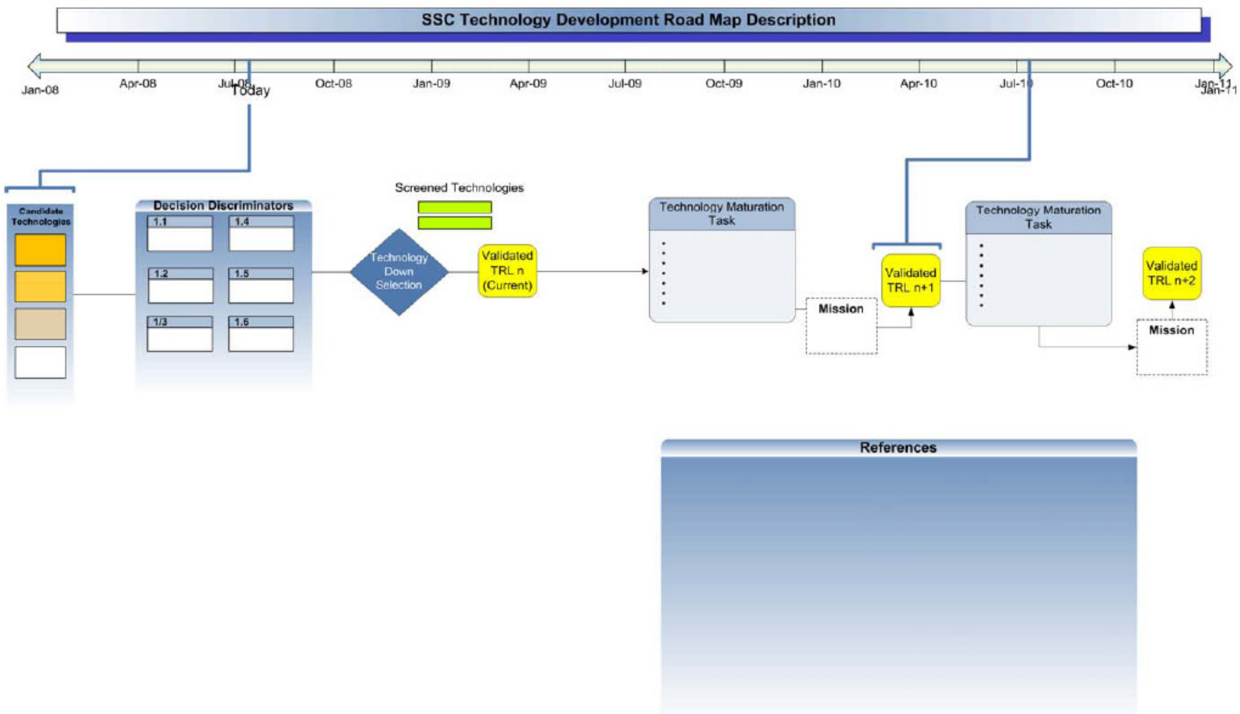


**Figure 0-6: Technology Development Roadmap Template**

On the left side of the roadmap, all candidate technologies that are in contention to be utilized in the SSC for the NGNP are shown. The decision discriminators shown just to the right of the technology candidates on the roadmap are used to guide a down selection of the available technologies. Typical decision discriminators may entail *inter alia service experience of technologies*, *available data* and *maturity of respective technologies*. Upon the screening of the candidate technologies against the decision discriminators, a down selection can be made.

On the right side of the roadmap, the current TRL rating together with the Maturation Tasks necessary to achieve progressively higher levels of validated TRLs up to a TRL 8 are shown. At each validated TRL level, a mission statement gives an indication against which environmental parameters the qualification has been conducted. All the maturation tasks shown in the roadmap are also linked to a schedule in the form of the timeline. References that serve as input into the roadmap at this stage involve Design Data Needs, Pre-conceptual Design Documents and Special Studies.

### 0.3.3 TRL Rating Sheet

Technology Readiness Levels are ratings between 1 and 10 are assigned by Subject Matter Experts to a certain SSC or where applicable to a facility or technology, which gives an indication of the maturity of the SSC involved. Various definitions are assigned to the existing TRL ratings and are shown in Table 0-1:.

**Table 0-1: The Technology Rating Level definitions**

| Rating Level | Technology Readiness Level Definition | TRL Abbreviated Definition |
|---|---|---|
| 1 | **Basic principles observed** and reported in white papers, industry literature, lab reports, etc. Scientific research without well defined application. | Basic principles observed |
| 2 | **Technology concept and application formulated.** Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation. | Application formulated |
| 3 | **Proof-of concept:** Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service. | Proof of Concept |
| 4 | **Technology or component is tested at bench scale to** demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties. | Bench scale testing |
| 5 | **Component demonstrated at experimental scale in relevant environment**. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection. | Component Verified at Experimental Scale |
| 6 | **Components have been integrated into a subsystem** and demonstrated at a pilot scale in a relevant environment. | Subsystem Verified at Pilot scale |
| 7 | **Subsystem integrated into a system** for integrated engineering scale demonstration in a relevant environment. | System demonstration at Engineering Scale |
| 8 | **Integrated prototype of the system is demonstrated** in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup | Integrated Prototype Tested and Qualified |
| 9 | **The project is in final configuration** tested and demonstrated in operational environment. | Plant Operational. |
| 10 | **Commercial-scale demonstration** is achieved. Technological risks minimized by multiple units built and running through several years of service cycles. | Commercial Scale – Multiple Units |

The purpose for developing the TRL's is to:

- Provide a semi-quantitative measure of the readiness of the technology of critical SSC's for commercialization.
- Provide a qualitative measure of the readiness of the design of critical systems. The term "qualitative" is used because the TRL ratings are partially subjective, and not based on a numerical score. The fact that the levels are numbered is only a method to categorize the levels, and they could have been assigned letters instead of numbers.
- Provide the ability to compare the design and technology readiness of any SSC relative to another SSC to assist in programmatic decisions.
- Provide input to the path forward for the Technology Development Roadmap.
- Provide design "hold points" that reflect and coordinate technology development with the design process that trigger a dramatic increase in project risk if not adhered to or mitigated.
- Establish a rational framework and criteria in which to communicate the current state and advancement of the design and technology development among the NGNP project team and stakeholders.

The TRL rating goes hand in hand with the Design Readiness Level (DRL) rating as the design of the plant and the SSCs also need to be matured. A rating system similar to the TRL system exists for DRL. DRL ratings were however not included in this study but will be in future updates as the design of the NGNP also matures.

### 0.3.4 Technology Maturation Plans

In the TDRM process, the associated details for each action/test required to advance an SSC to progressively higher TRL levels are captured in Technology Maturation Plans (TMPs) and subsequent Test Specifications.(TSs) These TMPs incorporate details ranging from material qualification specifics to prototypical SSC testing details. The TMP content can reflect the following details:

- Test Objectives
- Test Conditions
  - Test Configuration / Setup
  - Test Duration
  - Test Location / Facility
- Measured Parameters
- Data Requirements
- Test Evaluation Criteria
- Test Deliverables
- Cost, Schedule & Risk

## 0.4 Summary of the SSC's

In order to minimize the safety and economic risk of the NGNP Demonstration Plant, the intent is that all the NGNP SSC's should have demonstrated the ability of the applied technologies to function according to specification within their intended operational environment, prior to nuclear start-up of the NGNP Demonstration Plant. This would then leave the ability of these technologies to perform according to specification when integrated into their final NGNP Demonstration Plant configuration as the remaining risk to be addressed.

The various critical SSC's are listed in Table 0-2 with their associated TRL ratings. A brief summary of the respective critical SSC's TRL status follow hereafter. The maturation plans for the various technologies are also briefly outlined. The maturation plans may change as the design of the NGNP plant progresses and as new DDN's are identified. The detailed TRL ratings of all SSC's, including the critical SSC's, are outlined in Appendix A of this document.

**Table 0-2: List of the Critical SSCs**

| Section Number | SSC | SSC TRL |
|---|---|---|
| NGNP-CTF MTECH-TDRM-003 | PHTS Circulator | 6 |
| NGNP-CTF MTECH-TDRM-004 | Intermediate Heat Exchanger A | 2 (Metallic/Ceramic) |
| NGNP-CTF MTECH-TDRM-005 | Intermediate Heat Exchanger B | 3 |
| NGNP-CTF MTECH-TDRM-006 | HTS Piping | 4 |
| NGNP-CTF MTECH-TDRM-007 | SHTS Flow Mixing Chamber | 6 |
| NGNP-CTF MTECH-TDRM-008 | Hydrogen Production System | Refer to Appendix A |
| NGNP-CTF MTECH-TDRM-009 | Power Conversion System Steam Generator | 6 |
| NGNP-CTF MTECH-TDRM-010 | Software Codes Verification and Validation | N/A |
| NGNP-CTF MTECH-TDRM-011 | Fuel Elements | 6 |
| NGNP-CTF MTECH-TDRM-012 | Core Structure Ceramics | 6(Graphite)/4(Ceramics) |
| NGNP-CTF MTECH-TDRM-013 | Reserve Shutdown System | 6 |
| NGNP-CTF MTECH-TDRM-014 | Reactivity Control System | 6 |
| NGNP-CTF MTECH-TDRM-015 | Core Conditioning System | 6 |
| NGNP-CTF MTECH-TDRM-016 | Reactor Cavity Cooling System | 6 |

### 0.4.1 PHTS Circulator

The PHTS circulator is a critical component of the NGNP with its main function being to circulate the primary coolant helium within the PHTS. Discriminators have been identified to assist in the selection of an optimum design for the PHTS circulator. These discriminators address the required technology development, the availability of a manufacturing base, the circulator operation and maintenance, the safety and investment implications and the lifecycle costs.

Several arrangements and design options are available for the PHTS helium circulator that satisfy the pre-conceptual functions and design requirements, as detailed in NGNP-CTF MTECH-TDRM-003 PHTS Circulator, Section 03 [0-5] of this report. Several design selections remain to be made. Trade studies are recommended to select the design option that is best suited for the NGNP plant (at component, system and component/system level). The only key design selection provided is the use of an electric drive for the circulator.

Based on engineering judgement, two design options are proposed to which sound TRL ratings are assigned. The first design option is a submerged circulator with magnetic bearings while the second design option is a circulator in which the electric drive is located outside the pressure boundary, oil lubricated bearings are utilized for support and rotating seals are incorporated as part of the pressure boundary.

All the circulator sub-components have a TRL of 8 (except for the EMB's and primary pressure boundary rotating seals if included in the design), while the integrated assembly of these components as a subsystem has a TRL of 6 because it has not been demonstrated in a loop similar to the PHTS within a relevant environment. Following the selection of a reference circulator design, the circulator components that require technology development will be validated with supporting single effect tests. After that, the circulator subsystem will be validated with a partial scale or full-scale integrated test, subsequently qualifying the subsystem at a TRL of 7. Advancement to a validated TRL 8 will comprise the final integrated tests of the PHTS circulator prototype to take place in the first NGNP nuclear power plant.

Based on current pressure loss estimates, the PHTS pressure losses are expected to be larger than the SHTS pressure losses. Since the PHTS pressure losses are larger than the SHTS pressure losses and as the PHTS operates at a higher temperature, the PHTS circulator is expected to envelope the SHTS circulator and, hence, only the PHTS circulator is discussed. It is assumed that the PHTS circulator testing can be applied to the SHTS circulator also and, hence, does not warrant a separate discussion.

The PHTS check valve functionally forms an integral part of the circulator and therefore will be tested as part of the circulator. It is recognized that design development will be required to qualify the valve. At this stage no technology development is envisioned to the point where advance testing is required. However, as the design evolves unique tests might be identified which will be included at the appropriate time.

### 0.4.2 IHX A

The IHX is a critical high-temperature component of the NGNP and its main function is to transfer thermal energy from the Primary Heat Transport System (PHTS) to the Secondary Heat Transport System (SHTS). Previous studies related to the NGNP Heat Transport System (HTS) have shown the advisability of splitting the IHX into two units, IHX A operating at up to 950°C and IHX B operating at up to ~760°C – particularly when metallic materials are employed in the high-temperature heat transfer section. Uncertainties related to achieving full service life at 950°C using metallic materials argue for parallel development of metallic and ceramic heat exchangers.

Decision Discriminators were established and exercised in decisions taken relative to heat exchanger designs and materials. Cost/performance, state-of-the-art, robustness, environmental compatibility, Reliability and Integrity Management (RIM), IHX integration, and design/ licensing basis were considered in the down select of potential designs. A wide range of heat exchanger designs were evaluated and the result was the selection of a compact printed circuit or plate-fin heat exchanger (PCHE or PFHE) design for a metallic heat exchanger. A down select has not been made for a ceramic IHX design and awaits the completion of future Trade Studies.

Decision discriminators applied to the selection of a metallic material for IHX A were the availability of a materials database (e.g., maturity of data and service experience), materials lifetime (e.g., creep lifetime and corrosion behavior), and fabrication related factors. The choice based on the above was Ni-base Alloy 617. As for the ceramic heat exchanger design, selection of specific ceramic materials awaits completion of future trade studies.

Evaluations of the status of technology for high temperature metallic and ceramic heat exchangers were made and resulted in the determination of TRL 2 for IHX A. The underlying bases for these selections are described in the TRL rating sheets in NGNP-CTF MTECH-TDRM-004 [0-6] provided for both metallic and ceramic heat exchanger versions.

The IHX A is detailed in NGNP-CTF MTECH-TDRM-004, Intermediate Heat Exchanger A, Section 04 [0-6] of this report.

### 0.4.3 IHX B

Just as for IHX A, Decision Discriminators were established and exercised in decisions taken relative to heat exchanger designs and materials for IHX B. Cost/performance, state-of-the-art, robustness, environmental compatibility, RIM, IHX integration, and design/licensing basis were considered in the down select of designs. A wide range of heat exchanger designs were evaluated and the result was the selection of a compact design (PCHE or PFHE) heat exchanger design using metallic materials. Decision discriminators applied to the selection of a material for IHX B were materials database (e.g., maturity of data and service experience), materials lifetime (e.g., creep lifetime and corrosion behavior), and fabrication related factors. The choice based on the above was Fe/Ni-base Alloy 800H.

The status of technology for metallic heat exchangers was evaluated, and resulted in the determination of a level of TRL 3 for IHX B. The underlying bases for this selection are described in the TRL rating sheet for IHX B.

TDRMs are provided to summarize down select tasks, TRL status, and maturations tasks necessary to increase the maturity of the technology of IHX B to a level of TRL 8. These tasks include consideration of materials properties and performance, material and design codes, model development for thermal and mechanical performance, and testing of IHX modules progressing from unit cells to full-size IHX units. Details of the tasks necessary for technology advancement between TRL levels are presented as a series of Technology Maturation Plans that include information on objectives, test conditions, measured parameters, data requirements, test evaluation criteria, test deliverables, and cost/schedule/risk. It is noted that the technology roadmap and maturation plans will need to be adjusted as new DDNs evolve as part of the conceptual and detail designs.

IHX B is detailed in NGNP-CTF MTECH-TDRM-005, Intermediate Heat Exchanger B, Section 05 [0-7] of this report.

### 0.4.4 HTS Piping

The HTS involves pipes of varying temperature capabilities in both the PHTS and SHTS. High-temperature piping is utilized within the PHTS to direct helium flow from the reactor to IHX A and from IHX A to IHX B. Lower temperature portions of the PHTS piping circuit transport the helium flow from the exit of IHX B to the circulator and thereafter from the circulator to the reactor. High-temperature piping is utilized within the SHTS to direct helium flow from the high-temperature exit of IHX A to the mixing chamber and the PCHX and from the mixing chamber to the SG. Also, high-temperature portions of the SHTS piping circuit transport the helium from IHX B to IHX A and from the PCHX to the mixing chamber.

Low-temperature sections of the SHTS piping direct helium from the SG to the circulator and from the circulator to IHX B. Very preliminary design selections for the various piping sections were made on the basis of pre-conceptual design studies (these selections remain to be revisited during conceptual design):

- The high-temperature portion of the PHTS piping is to combine both active cooling and insulation.
- The low-temperature section of the PHTS piping and all SHTS piping is to be passively cooled (insulation only).

An evaluation of the status of technology for the HTS piping was made and resulted in the determination of a level of TRL 4. Maturation tasks address the effects of Helium environment and possible rapid depressurization transients on the integrity and thermal conductivity of insulation materials. There are further tasks to quantify environmental and operational effects on prototypic piping section performance.

The HTS Piping is detailed in NGNP-CTF MTECH-TDRM-006, HTS Piping, Section 06 [0-8] of this report.

### 0.4.5 SHTS Flow Mixing Chamber

The secondary heat transport system (SHTS) flow mixing chamber's main function is to minimize the thermal effects associated with the mixing of two helium streams that are joined together at significantly different temperatures. At 100% nominal steady-state operation, the higher temperature stream enters the chamber at 900°C, while the other lower temperature stream enters at 659°C. At this stage of the design, only a very high level concept of the SHTS flow mixing chamber is available.

Discriminators have been identified to assist in the selection of an optimum design for the SHTS flow mixing chamber. These discriminators address the required technology development, the availability of a manufacturing base, the SHTS flow mixing chamber operation and maintenance, the safety and investment implications and the lifecycle costs.

Several arrangements and design options are available for the SHTS flow mixing chamber that satisfy the pre-conceptual functions and design requirements. The simplest SHTS flow mixing chamber design option comprises of a single chamber (plenum) with two inlets (for hotter helium and for cooler helium) and one outlet. Additionally, mixing and acoustic or/and flow induced vibration damping devices can be added within the SHTS flow mixing chambers' plenum to enhance the mixing process, reduce size of the chamber and prevent fatigue damages. Alternative designs of the SHTS flow mixing chamber could replace single inlets with multiple inlets to reduce the pressure drop and the streams inlet velocities.

A number of design selections remains to be made. Trade studies that will use computational modeling and analysis, previous experience, similar designs and engineering judgment will determine the advantages and disadvantages of each option with the help of the decision discriminators. The only key design selection provided is the use of suitable high temperature materials for the walls of the SHTS flow mixing chamber.

All the SHTS flow mixing chamber components are at TRL 8, while the integrated assembly of these components as a subsystem is at TRL 6 because it has not been demonstrated in a loop similar to the SHTS within a relevant environment. Following the selection of a reference SHTS flow mixing chamber design, the components that require technology development will be validated with supporting single effect tests. After that, the SHTS flow mixing chamber subsystem will be validated with a partial scale or full-scale integrated test, subsequently qualifying the subsystem at TRL 7. Advancement to a validated TRL 8 will comprise the final integrated tests of the SHTS flow mixing chamber to take place in the first NGNP nuclear power plant.

The SHTS Flow Mixing Chamber is detailed in NGNP-CTF MTECH-TDRM-007, SHTS Flow Mixing Chamber, Section 07 [0-9] of this report.

### 0.4.6 Hydrogen Production System

The hydrogen production development is organized into four separate process technology areas, which are:

1. Sulfuric Acid Decomposition (common to both Sulfur-Iodine and Hybrid Sulfur hydrogen production systems).
2. Sulfur Dioxide Electrolysis (principal step in Hybrid Sulfur thermo- electro-chemical water splitting).
3. Bunsen Reaction and HI Decomposition (steps in Sulfur-Iodine thermo-chemical water splitting).
4. High Temperature Steam Electrolysis.

The technology areas of the Hydrogen Production System (HPS) were further divided into subsystems. TRL ranks were assigned to these subsystems. Section 8, NGNP-CTF MTECH-TDRM-008 [0-10] of this report documents the subsystem ranking and outlines technology maturation steps.

Specific hydrogen outputs, heat or power inputs, scale factors and scale-up steps are quantified and were used as input to the road mapping report. These are all estimates based on the TDRM's developed here and on the present plans of the technology developers in the US DOE Nuclear Hydrogen Initiative (NHI) who have been consulted. Far more progress in development and work on specific designs of commercial scale components is required before these numbers can be confirmed. Several of the anticipated tests may be avoided by alternative designs and other tests may be suggested as designs progress. Test scale-up steps selected thus far have been somewhat arbitrary. Final scale for each test will depend upon the specific purpose for that test and the needs of the designer of the commercial-scale equipment. Therefore, these estimates should be used only for general planning purposes and not as bases for design or for detailed planning.

For each process concept, the Hydrogen Production Facility is made up of the Hydrogen Production System (HPS) and the Hydrogen Production Buildings and Structures. For discussion of technology development, the buildings and structures are assumed to be entirely commercially available or having proven industry experience. Therefore, the following technology assessment relates only to the Hydrogen Production System.

Testing of any major components of the thermo-chemical or hybrid cycles will require importing, handling and disposing of at least a ton or more of hazardous chemicals such as sulfuric acid, sulfur dioxide, iodine and hydroiodic acid. Provisions for the safe and environmentally responsible handling and disposal of these materials are a prerequisite for the testing of these components in the CTF.

Testing of components for any of the technologies will require handling of high temperature and high pressure oxygen and hydrogen either as pure streams or mixed with other gases. Provisions for safe handling and disposal of these materials are necessary. Handling of hydrogen requires specially designed electrical equipment and controls. If hydrogen production technology testing is to be done at the CTF, these requirements must be met.

It may be more convenient to carry out large-scale testing of water splitting technology at a facility that is specially designed for handling the process streams described above, rather than design the CTF to envelope those requirements.

The Hydrogen Production System is detailed in NGNP-CTF MTECH-TDRM-008, Hydrogen Production System, Section 08 [0-10] of this report.

### 0.4.7 Power Conversion System Steam Generator

The Steam Generator (SG) is a major component of the Power Conversion System (PCS) and interfaces with the Secondary Heat Transport System (SHTS). Location of the SG in the SHTS is a significant departure from prior High-Temperature Gas-Cooled Reactor (HTGR) applications in which the SG was located in the Primary Heat Transport System (PHTS).

In the context of the NGNP PCS, the Steam Generator is a developmental component that is based on proven technologies. These technologies must be re-established, adapted and extrapolated for the NGNP. Based on prior applications such as Fort St. Vrain and the Thorium High-Temperature Reactor (THTR), the SG has been rated at a technology readiness level of TRL 6.

Advancement from TRL 6 to TRL 7 will involve performing as down selection trade study to determine the preferred conceptual arrangement of the SG. The requirements and the design details of the SG will need to be defined. The design will then have to undergo development tests as well as prototype testing at the CTF. Further maturation of technology to TRL 8 will require completion of the SG design and delivery of a prototype to the NGNP site. The SG will then undergo through integrated tests as part of the PCS.

The Power Conversion System Steam Generator is detailed in NGNP-CTF MTECH-TDRM-009, Power Conversion System Steam Generator, Section 09 [0-11] of this report.

### 0.4.8 Software Codes Verification & Validation

The PBMR DPP software codes are expected to envelope the NGNP Software Code Validation requirements for the NHSS, recognizing that the PBMR DPP commissioning itself forms an integral part of the V&V program. However, only once the NGNP plant level conceptual design analyses have been done will it be possible to confirm this statement and quantify specific further testing needs (i.e. beyond the DPP V&V which is up to 900°C reactor outlet operating at 400 MWt). It is noted that all NGNP evaluation models, once established, will remain subject to verification and validation (V&V).

The NGNP core design for the reference case (950°C reactor outlet operating at 500 MWt) with its higher gas outlet temperature and power density relative to the PBMR DPP may increase the risk that the best estimate analysis plus uncertainties are too close to the safety margins. In certain cases, this may imply more advanced methods, software and models to be required. It is noted that the lower temperature NGNP option reduces the need for software V&V.

It is noted that the software V&V employed for the Rankine Power Conversion System (PCS) and Hydrogen Production System (HPS) remain to be considered, as it has not been covered by the PBMR DPP V&V process.

In order to analyze various aspects of the integrated NGNP Plant, the software currently used for the PBMR DPP design is proposed to be further enhanced and extended to include an integrated core neutronic/thermal hydraulic analysis tool coupled to the Power Conversion and Hydrogen Production Systems models for simulating normal and off-design conditions. This tool will allow for steady-state and transient analyses of the integrated NGNP plant and will enable operational and control studies. Such a tool remains to be developed, verified and validated.

The Software Code Verification and Validation is detailed in NGNP-CTF MTECH-TDRM-010, Software Code Verification and Validation, Section 10 [0-12] of this report.

### 0.4.9 Fuel Elements

The PBMR Demonstration Power Plant (DPP) is rated at 400 MWt and has a reactor outlet temperature of 900°C. The DPP fuel qualification consists of irradiating fuel spheres up to a temperature of 1250°C and to a burn-up value of approximately 111,900 MWD/tU[1]. The fast neutron dose for these irradiation tests is specified at $2.7 \times 10^{21}$ $cm^{-2}$. Post-irradiation heat-up tests will be performed at 1600°C and 1800°C to determine delayed radionuclide releases, thereby simulating Loss of Forced Cooling (LOFC) events. The maximum design fuel temperature for the DPP during normal operation is 1130°C and for the depressurized LOFC (DLOFC) is 1593°C. Irradiation tests for the PBMR DPP fuel qualification program will be performed at INM in Russia and HFR Petten in the Netherlands and will be used to achieve an equivalent fuel TRL of 8 for the PBMR DPP.

[1] All of the fuel and reactor qualification envelope values are still subject to change as the analysis is refined with actual design & manufacturing feedback regarding the fuel and reactor.

Initial analyses of the NGNP NHSS predicted a peak fuel temperature of 1168°C during normal operation and 1750°C during a DLOFC event. Based on the results, the NGNP and Hydrogen Production Pre-conceptual Design Report [0-1] states that the fuel should have a capability to achieve a maximum temperature of at least 1300°C and a burn-up value of 109,000 MWD/tU. The fast neutron dose is specified at 2.7 x $10^{21}$ $cm^{-2}$. The recent Reactor Parametric NGNP Conceptual Design Study refined the maximum fuel temperature to 1235°C during normal operation and the peak maximum temperature to 1703°C during a DLOFC event.

The anticipated operational profile of the fuel in the NGNP is outside the PBMR DPP fuel envelope with regards to temperature while the fast neutron flux and burnup are the same and within the DPP envelope. Note that if the NGNP program focuses on lower temperature applications (<800°C ROT), it is expected that the PBMR DPP qualification envelope would suffice.

The Fuel Elements are detailed in NGNP-CTF MTECH-TDRM-011, Fuel Elements, Section 11 [0-13] of this report.

### 0.4.10 Core Structures Ceramics

The NGNP is envisaged to utilize core internals similar to those of the PBMR DPP. These core internals consists of the core barrel assembly and the Core Structures Ceramics (CSC) of which the latter is identified as a critical SSC. The CSC can further be broken down into the graphite, composites, ceramic and metallic components. The graphite components are mostly made up of the reflector blocks, while the composites are comprised of the Lateral Restraint Straps and Tie Rod assemblies. The CSC also includes ceramic components utilized as insulation material at the bottom of the reactor and a number of metallic parts, notably in the metallic links of the Lateral Restraint Straps.

A study was conducted to determine the TRL ratings of the different proposed technologies. During this study, the CSC were subdivided into two sections, namely the graphite components and the ceramics, composites etc. The graphite components were given a TRL 6 rating while the other components were rated at TRL 4. Advancement of the CSC to a TRL 7 is achieved by a complete PBMR qualification process, which ends with operational testing in the PBMR DPP.

The additional activities needed to advance this system to the required TRL 8 are mainly due to the fact that the NGNP operates at a lower inlet temperature as well as a higher outlet temperature. These activities have been captured in Design Data Needs (DDN) from the NGNP Pre-Concept Design Report and related Special Studies

The Core Structure Ceramics are detailed in NGNP-CTF MTECH-TDRM-012, Core Structure Ceramics, Section 12 [0-14] of this report.

### 0.4.11 Reserve Shutdown System

The RSS forms part of the Reactivity Control and Shutdown System and is a totally diverse reactor shutdown system. The RSS is used to keep the reactor sub-critical and below an average core temperature not exceeding 100°C during shutdown. The NGNP WEC-team envisages utilizing a RSS similar to that of the PBMR DPP.

The RSS development for the PBMR DPP is currently in its basic design phase, with a number of development tests being performed, resulting in a TRL rating of 6. A number of development and qualification tests will be performed in the Helium Test Facility (HTF) in South Africa before the RSS will be commissioned in the PBMR DPP. Upon the completion of these tests, the DPP RSS will have a TRL status of 7. Subsequent completion of PBMR DPP tests will advance the DPP RSS TRL status to an 8. If the NGNP Requirements are enveloped by the PBMR DPP, these development and qualification tests will be sufficient to advance the NGNP RSS to a TRL of 8.

If the NGNP requirements are not enveloped by the DPP, then the RSS will be re-qualified in the HTF to progress the NGNP RSS to TRL 7, in which case it will obtain TRL 8 status in the NGNP itself. The need for potential further qualification can, however, only be defined once more analyses have been performed to determine what the exact requirements would be for application in the NGNP.

The Reserve Shutdown System is detailed in NGNP-CTF MTECH-TDRM-013, Reserve Shutdown System, Section 13 [0-15] of this report.

### 0.4.12 Reactivity Control System

The RCS forms part of the Reactivity Control and Shutdown System, and serves the purpose of controlling the reactivity in the core, and shutting the reactor down quickly. The NGNP WEC-team envisages utilizing a RCS similar to that of the PBMR DPP. Operating experience exists with reactivity control systems similar to that of the RCS in other gas cooled reactors. The RCS development for the PBMR Demonstration Power Plant is nearing basic design completion, with a number of development tests being performed, resulting in a TRL rating of 6.

A number of development and qualification tests will be performed in the Helium Test Facility (HTF) in South Africa before the RCS can be commissioned in the PBMR DPP. Upon the completion of these tests, the RCS will have a TRL status of 7. It has been identified however, that the environment in which the RCS must operate in the NGNP may be at a higher temperature than that of the PBMR DPP. For this reason, it is possible that alternative materials may need to be investigated for certain components of the RCS. More analyses need to be done on these alternative materials, such as carbon composite materials, to determine their current TRL status.

In section 14, NGNP-CTF MTECH-TDRM-014 [0-16], a TDRM outlines the process to be followed for the RCS to obtain a TRL status of 8. Experience obtained in the development of the RCS for the PBMR DPP can be fed back into the development of the RCS that may need to be done for application in the NGNP. Any additional qualification tests for temperature effects that may need to be performed for the NGNP RCS can be conducted at the HTF, depending on the details of the test requirements. Testing required in a radiation environment will have to be performed outside the HTF. The NGNP RCS is expected to be operated at slightly different conditions than the PBMR DPP and, hence, detailed system level analyses are required to confirm the DDN's and operating envelope.

The Reactivity Control System is detailed in NGNP-CTF MTECH-TDRM-014, Reactivity Control System, Section 14 [0-16] of this report.

### 0.4.13 Core Conditioning System

It is envisaged that the Core Conditioning System (CCS) to be used in the NGNP will be of a similar design to that of the PBMR DPP. The CCS consists of a dual redundant system, each having a gas circulating blower, a high temperature water-cooled heat exchanger, isolation and blower control valves, hot gas ducts, pressure boundary piping and control instrumentation.

A study was conducted in which the TRL ratings of the different proposed technologies were determined. During this study the CCS components were given a TRL 6 rating. The TRL maturation process has been divided into two main activities, namely a maturation from the current TRL rating up to TRL 7 and then from TRL 7 to TRL 8. To reach a TRL 7, various tests will be done on the individual components of the CCS. The tests will qualify the technology to be used in the final designs of the CCS components. The final components will be integrated as a subsystem into the DPP and will be tested as an integrated unit. When the CCS subsystem tests are complete, it will have progressed to a TRL 8.

The NGNP CCS is expected to operate at slightly different conditions than the DPP CCS. Hence detailed system level analyses are required to confirm the DDN's and the operating envelope.

The Core Conditioning System is detailed in NGNP-CTF MTECH-TDRM-015, Core Conditioning System, Section 15 [0-17] of this report.

### 0.4.14 Reactor Cavity Cooling System

The Reactor Cavity Cooling System (RCCS) system is envisaged by the WEC NGNP Team to be utilized in a similar operational environment to that of the PBMR DPP. The RCCS is required to maintain the reactor citadel concrete structure within allowable temperatures through heat removal and shielding of the concrete from direct thermal radiation during normal and abnormal conditions. The DPP RCCS design is expected to be employed 'as is' for the PBMR NGNP, with possibly only minor changes to water reservoir requirements.

The PBMR DPP RCCS is currently rated at TRL 6. Progression from TRL 6 to TRL 7 will be achieved through analysis, while progression to TRL 8 will be through the commissioning and operation of the PBMR DPP. The current DPP RCCS strategy is to utilize two independent internationally recognized software codes RELAP5™ and SPECTRA™ to evaluate the passive operation of the RCCS. To date, both software codes have indicated that the RCCS will adequately satisfy its requirements. However, the benefits of testing to reduce risk are acknowledged and, therefore, PBMR is investigating further means for validating RCCS software code models. The definition of these validation tests has not yet been fully developed – although it is favored to use representative part-scale testing.

Even though PBMR is investigating supplementary testing, additional testing by others will be welcomed by PBMR through a CRADA-type arrangement if;

1) the tests are representative of the PBMR RCCS design (with PBMR providing test specification inputs),
2) the tests can be conducted by the 2010 timeframe, and
3) if PBMR is involved with the test definitions and execution of such tests.

The Reactor Cavity Cooling System is detailed in NGNP-CTF MTECH-TDRM-016, Reactor Cavity Cooling System, Section 16 [0-18] of this report.

## 0.5 Integrated Schedule and Cost Estimate

The cost and schedule of the NGNP evolves continuously as the project progresses due to high uncertainties associated with technology advancements, evolving test plans and schedules, timely availability of resources, etc. There is an integrated Test Schedule which includes the NGNP schedule, the original SSC TDRM schedules and the CTF high level schedule (summarized version shown in Figure 0-7) [0-19]. The SSC TDRM schedules were modified to relieve pressure on the overall schedule, as it initially assumed that all work would start in October 2008 (FY 2009). In the modified schedule the less critical SSC's were moved to a later starting date, but still within the constraints of the CTF and NGNP start-up dates.

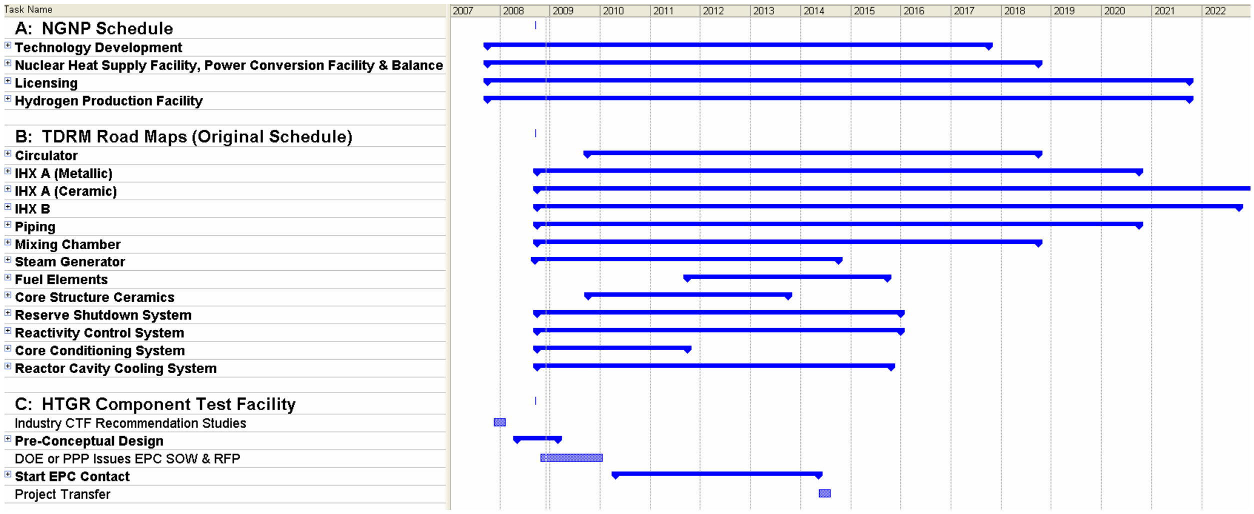


**Figure 0-7: CTF Integrated Schedule**

Cost estimates are provided for certain critical SSCs. Estimates have been provided only up to a TRL rating of 5. Estimates for higher TRL advancements can only be provided when additional design information (preliminary or final) of the NGNP and components are available. For some of the SSCs, more design information is required in order to develop reliable cost estimates. For some, trade studies (or various trade studies) need to be done to verify and determine the specific combinations of sub-components that will be used. There is enough time in the modified schedule to perform the trade studies before the advancement of the TRLs and before possible testing in the CTF will be performed. The summary costs needed for the original TDRMs as stated in [0-19] are shown in Figure 0-8.

**Summary costs: Original TDRMs**

| SSC [1], [2] | FY2009 | FY2010 | FY2011 | FY2012 | FY2013 | FY2014 | FY 2015 |
|---|---|---|---|---|---|---|---|
| Circulator [3] | $450,000 | $0 | $0 | $0 | $0 | $0 | $0 |
| IHX A (Metallic) | $4,205,030 | $4,464,905 | $3,300,971 | $1,007,072 | $225,225 | $100,000 | $100,000 |
| IHX A (Ceramic) | $5,482,274 | $4,488,666 | $3,896,338 | $0 | $0 | $0 | $0 |
| IHX B | $3,107,690 | $2,851,809 | $1,689,406 | $0 | $0 | $100,000 | $100,000 |
| Piping | $1,481,867 | $283,333 | $0 | $0 | $0 | $0 | $0 |
| Mixing Chamber [3] | $0 | $0 | $1,124,000 | $1,124,000 | $0 | $0 | $0 |
| Steam Generator | $0 | $4,092,000 | $7,274,000 | $7,741,000 | $2,814,000 | $0 | $0 |
| HPS [4] | $3,500,000 | $5,300,000 | $12,670,000 | $15,610,000 | $15,610,000 | $23,110,000 | $30,670,000 |
| Fuel | $4,500,000 | $6,500,000 | $6,500,000 | $6,500,000 | $5,500,000 | $3,500,000 | $3,500,000 |
| CSC | $500,000 | $600,000 | $800,000 | $800,000 | $700,000 | $900,000 | $700,000 |
| RSS | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| RCS | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| CCS | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| RCCS | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| TOTAL ($) | $23,226,861 | $28,580,714 | $37,254,714 | $32,782,072 | $24,849,225 | $27,710,000 | $35,070,000 |

[1] Estimates noted for some SSC's are those given in NGNP-16-RPT-001 (notably Mixing Chamber, Steam Generator, Fuel, CSC) due to limited design information

[2] Costing of RSS, RCS, CCS and RCCS make part of PBMR DPP and are not included

[3] For the Circulator, Mixing Chamber as well as the Steam Generator, concept design needs to be progressed further before sensible estimations can be made

[4] Sum total of HPS reflects totals of sulfuric acid decomposition technology development as well as sulfur dioxide electrolysis technology development [NGNP-CTF MTECH-TDRM-008]. For the purposes of this estimation, estimations reflect costs needed to etablish Hybrid Sulphur hydrogen production system (even though the reference design still has to be selected).

**Summary costs: Original TDRMs**

| SSC [1], [2] | FY 2016 | FY 2017 | FY 2018 | FY 2019 | FY 2020 | FY 2021 | Total |
|---|---|---|---|---|---|---|---|
| Circulator [3] | $0 | $0 | $0 | $0 | $0 | $0 | **$450,000** |
| IHX A (Metallic) | $0 | $0 | $0 | $0 | $0 | $0 | **$13,403,203** |
| IHX A (Ceramic) | $0 | $705,925 | $705,925 | $705,925 | $380,325 | $400,000 | **$16,765,378** |
| IHX B | $0 | $0 | $0 | $0 | $0 | $0 | **$7,848,905** |
| Piping | $0 | $0 | $0 | $0 | $0 | $0 | **$1,765,200** |
| Mixing Chamber [3] | $0 | $0 | $0 | $0 | $0 | $0 | **$2,248,000** |
| Steam Generator | $0 | $0 | $0 | $0 | $0 | $0 | **$21,921,000** |
| HPS [4] | $30,670,000 | $24,500,000 | $24,500,000 | $7,800,000 | $0 | $0 | **$193,940,000** |
| Fuel | $3,500,000 | $4,500,000 | $0 | $0 | $0 | $0 | **$44,500,000** |
| CSC | $0 | $0 | $0 | $0 | $0 | $0 | **$5,000,000** |
| RSS | n/a | n/a | n/a | n/a | n/a | n/a | **n/a** |
| RCS | n/a | n/a | n/a | n/a | n/a | n/a | **n/a** |
| CCS | n/a | n/a | n/a | n/a | n/a | n/a | **n/a** |
| RCCS | n/a | n/a | n/a | n/a | n/a | n/a | **n/a** |
| TOTAL ($) | $34,170,000 | $29,705,925 | $25,205,925 | $8,505,925 | $380,325 | $400,000 | $113,901,686 |

[1] Estimates noted for some SSC's are those given in NGNP-16-RPT-001 (notably Mixing Chamber, Steam Generator, Fuel, CSC) due to limited design information

[2] Costing of RSS, RCS, CCS and RCCS make part of PBMR DPP and are not included

[3] For the Circulator, Mixing Chamber as well as the Steam Generator, concept design needs to be progressed further before sensible estimations can be made

[4] Sum total of HPS reflects totals of sulfuric acid decomposition technology development as well as sulfur dioxide electrolysis technology development [NGNP-CTF MTECH-TDRM-008]. For the purposes of this estimation, estimations reflect costs needed to etablish Hybrid Sulphur hydrogen production system (even though the reference design still has to be selected).

**Figure 0-8: CTF Cost Estimate**

The Integrated Schedule and Cost is detailed in NGNP-CTF MTECH-TDRM-017, Integrated Schedule and Cost, Section 17 [0-19] of this report.

## 0.6 Input to CTF

It is expected that some of the maturation plans will be carried out at the CTF. However, some of the SSCs are either still in the early developmental stages or have progressed much further and other facilities in which the technologies can be advanced may have to be sourced around the world. Table 0-3 lists the SSC's which have expected inputs to the CTF.

**Table 0-3:** Input of various SSC's to the CTF

| SSC | TRL 5 → TRL 6 | TRL 6 → TRL 7 | TRL 7 → TRL 8 | Input to CTF |
|---|---|---|---|---|
| Circulator | - | ▪ Development of sub-components<br>▪ Supporting single effect tests<br>▪ Prototype testing | ▪ Circulator integrated tests | Components and prototype to be tested at the CTF |
| IHX A & B | ▪ Testing of a Compact Heat Exchanger (CHE) module | ▪ Shell side flow distribution and bypass leakage testing<br>▪ Multi-module heat transfer testing | ▪ Testing of full size IHX at the NGNP | Metallic and ceramic modules to be tested at CTF |
| Piping | ▪ Effects of He infiltration on thermal conductivity of insulation material<br>▪ The effects of fluid impurities on insulation properties | ▪ Prototype performance & environment testing (high & low temp piping, insulation material). | ▪ Full scale installation at the NGNP | TRL 6 – TRL 7 will be tested at the CTF. But other facilities will be required for TRL 5 – TRL 6 |
| SHTS Flow Mixing Chamber | - | ▪ Supporting single effect tests (Enhanced mixing devices testing, Vibration dumping device testing)<br>▪ Test mixing chamber | ▪ Perform mixing chamber integrated tests at the NGNP to validate flow coupling and mixer performance and verify its interaction with other subsystems | Full scale mixing chamber will be tested at the CTF |
| Hydrogen Production System | See NGNP-CTF MTECH-TDRM-008 [0-10] | See NGNP-CTF MTECH-TDRM-008 [0-10] | See NGNP-CTF MTECH-TDRM-008 [0-10] | To be determined |
| Steam Generator | - | ▪ Perform supporting tests as per DDN's<br>▪ Perform prototype tests, including instrumentation demonstration tests, tube in-service inspection methods demonstration tests, feed water orifice performance tests and seals performance demonstration tests | ▪ Perform SG integrated tests, including nuclear and non-nuclear pre-operational tests<br>▪ Tune the SG during initial operation | Scale prototype testing at the CTF |

# APPENDIX A: NOMENCLATURE

**Bench Scale** – A technology to be tested that will provide the data or demonstration intended but is not necessarily like the design of the final SSC. (~1:3600 scale)

**Experimental Scale** – A component to be tested that will provide the data or prove function intended but is not necessarily like the design of the final SSC. (~1:1000 scale)

**Pilot Scale** – A model or facsimile of the subsystem used as a basis or standard for proof of principle testing and/or operation. The model or facsimile may progress through several evolutions, but is not necessarily in form or fit a final version. (~1:100 scale)

**Engineering Scale** – A model or facsimile of the system used as a basis or standard for proof of principle testing and/or operation. The model or facsimile may progress through several evolutions, but is not necessarily in form or fit a final version. (~1:20 scale)

**Prototype** – Subsequent to Pilot/Engineering Scale model or facsimile of the SSC, a version that is intended to be the final version or is an evolutionary step toward the final version. (~1:4 scale)

**Lab Environment** – Refers to a controlled environment where effects can be quantified with appropriate accuracy.

**Relevant Environment** – Refers to an environment that does not necessarily have the same temperatures and pressures, but is close. Not necessarily the same fluids, but chemically similar insofar as thermo-fluid and corrosion/reaction.

**Operational Environment** – For SSCs normally operating when the plant is running, the operational environment consists of the normal operating fluids, and anticipated temperatures (static and transient) and pressures (static and transient). For SSCs not normally operating, the operational environments are the design basis operating fluids, temperatures and pressures.

# APPENDIX B: LIST OF DDNs

**Table B.0-1 List of DDNs for Critical SSCs**

| DDN Number | Mission Need |
|---|---|
| **1. Nuclear Heat Supply System (NHSS)** | |
| ***Fuel Irradiation*** | |
| NHSS-01-01 | Fuel irradiation test for normal operational conditions |
| NHSS-01-02 | Fuel heating tests for accident conditions |
| NHSS-01-03 | Fuel Graphite irradiation tests |
| ***Graphite*** | |
| NHSS-02-01 | Extended Properties of Irradiated Graphite at Low Temperatures |
| NHSS-02-02 | Extended Properties of Irradiated Graphite at High Temperatures |
| **2. Heat Transport System (HTS)** | |
| ***Intermediate Heat Exchanger - Metallic*** | |
| HTS-01-01 | Establish Reference Specifications for Alloy 617 |
| HTS-01-02 | Thermal/Physical and Mechanical Properties of Alloy 617 |
| HTS-01-03 | Welding and As-Welded Properties of Materials of Alloy 617for Compact Heat Exchangers |
| HTS-01-04 | Aging Effects of Alloy 617 |
| HTS-01-05 | Environmental Effects of Impure Helium on Alloy 617 |
| HTS-01-06 | Influence of Grain Size on Materials Properties on Alloy 617 |
| HTS-01-13 | Methods for Thermal/Fluid Modeling of Plate-Type Compact Heat Exchangers |
| HTS-01-14 | Methods for Stress/Strain Modeling of Plate-Type Compact Heat Exchangers |
| HTS-01-15 | Criteria for Structural Adequacy of Plate-Type Compact Heat Exchangers at Very High Temperatures |
| HTS-01-16 | Methods for Performance Modeling of Plate-Type Compact Heat Exchangers |
| HTS-01-17 | Metallic: IHX Performance Verification |
| HTS-01-18 | Data Supporting Materials Code Case |
| HTS-01-19 | Data Supporting Design Code Case |
| HTS-01-20 | Influence of Section Thickness on Materials Properties of Alloy 617 |
| HTS-01-21 | Corrosion Allowances for Alloy 617 |
| HTS-01-22 | Establish Reference Specification for Alloy 800H |
| HTS-01-23 | Supplemental High-Temperature Mechanical Properties of Alloy 800H |
| HTS-01-24 | Effects of Joining Techniques on the Properties of Alloy 800H |

| DDN Number | Mission Need |
|---|---|
| HTS-01-25 | Effects of Aging on the Properties of Alloy 800H |
| HTS-01-26 | Effects of Exposure in Impure Helium on Alloy 800H Properties |
| HTS-01-27 | Influence of Grain Size on Materials Properties of Alloy 800H |
| HTS-01-28 | Influence of Section Thickness on Materials Properties of Ally 800H |
| HTS-01-29 | Corrosion Allowances for Alloy 800H |
| HTS-01-30 | Brazing and Diffusion Bonding Processes for Alloy 617 and Alloy 800H |
| HTS-01-31 | Readiness Assessment for Hastelloy XR as an IHX Material |
| ***Intermediate Heat Exchanger - Ceramic*** | |
| HTS-02-01 | Review Existing Technology |
| HTS-02-02 | Materials Property Database |
| HTS-02-03 | Design Methods |
| HTS-02-04 | Ceramic: IHX Performance Verification |
| HTS-02-05 | Manufacturing Technology |
| HTS-02-06 | Codes and Standards |
| ***SHTS Helium Mixing Chamber*** | |
| HTS-03-01 | Mixing Chamber Performance Test |
| ***High Temperature Ducts and Insulation*** | |
| HTS-04-01 | Evaluation of High Temperature Ducts and Insulation Systems |
| **3. Hydrogen Production System (HPS)** | |
| ***Sulfuric Acid Decomposition (SAD)*** | |
| HPS-SAD-01 | Confirm Thermodynamic Data for the Sulfuric Acid Decomposition Process |
| HPS-SAD-02 | Develop a Commercial Sulfuric Acid Decomposition Catalyst |
| HPS-SAD-03 | Gather Decomposition Reaction Kinetics Data |
| HPS-SAD-04 | Test Silicon Carbide and other Ceramic Material in Decomposition Service |
| HPS-SAD-05 | Test Alloy 230 and Alloy 617 in a High Temperature Sulfuric Acid, Sulfur Dioxide, and Oxygen Atmosphere. |
| HPS-SAD-06 | Develop a Method to Bond Alloy 230 or Alloy 617 or Similar Materials to Silicon Carbide and other Ceramics. |

| DDN Number | Mission Need |
|---|---|
| HPS-SAD-07 | Develop Materials to Seal the Joints between Ceramic Decomposer Elements and the Metallic Tube Sheet or Vessel. |
| HPS-SAD-08 | Test a Pilot-Scale Decomposer. |
| HPS-SAD-09 | Provide Data  Supporting a Design Code Case |
| HPS-SAD-10 | Develop Gasket Materials and Design |
| HPS-SAD-11 | Develop Seal Materials and Design |
| HPS-SAD-12 | Develop Welding Materials |
| HPS-SAD-13 | Develop Cladding and Coating Materials |
| HPS-SAD-14 | Develop Piping Materials and Design Methods |
| HPS-SAD-15 | Measure the Height Equivalent to a Theoretical Plate (HETP) for the Concentrator (Vacuum Tower) |
| HPS-SAD-16 | Measure the Height Equivalent to a Theoretical Plate (HETP) for the SO2 Absorber |
| HPS-SAD-DT-02 | Develop additional alternatives for the decomposition reactor |
| HPS-SAD-DT-03 | Complete thermal and hydraulic analyses of the alternatives using equilibrium data only |
| HPS-SAD-DT-04 | Complete a conceptual mechanical design of each of the alternative concepts |
| HPS-SAD-DT-05 | Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing |
| HPS-SAD-DT-06 | Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing |
| HPS-SAD-DT-07 | Develop a preliminary piping spec and materials selections for equipment |
| HPS-SAD-DT-08 | Size conceptual equipment and track economics as technology develops |
| ***Feed Purification (FUS)*** | |
| HPS-FUS-01 | Identify Critical Impurities and Determine Critical Component Tolerance |
| HPS-FUS-02 | Develop Feed Water Purification Methods |
| HPS-FUS-03 | Develop Process Fluid Purification Methods |
| HPS-FUS-DT-09 | Design a feed water purification system including equipment sizing and economics |
| HPS-FUS-DT-10 | Design a process fluid purification system including equipment sizing and economics |
| HPS-FUS-DT-01 | Design a feed water purification system including equipment sizing and economics |

| DDN Number | Mission Need |
|---|---|
| HPS-FUS-DT-02 | Design a process fluid purification system including equipment sizing and economics |
| ***Electrolyzers (ELE)*** | |
| HPS-ELE-01 | Develop a Cell Membrane |
| HPS-ELE-02 | Optimize Catalyst Loading in the Electrodes |
| HPS-ELE-03 | Develop a Cell Configuration and Materials |
| HPS-ELE-04 | Build and Test a Prototype Cell |
| HPS-ELE-05 | Build and Test a Pilot-scale Cell |
| HPS-ELE-06 | Build and Test a Stack of Cells in a Pilot Plant |
| HPS-ELE-07 | Test Alloy 230 and Alloy 617 in High Temperature Helium and Air/Oxygen and Steam/Hydrogen Mixtures |
| HPS-ELE-08 | Test a Pilot-Scale PCHX |
| HPS-ELE-09 | Provide Data Supporting a Design Code Case |
| HPS-ELE-10 | Develop Gasket Materials and Design |
| HPS-ELE-11 | Develop Seal Materials and Design |
| HPS-ELE-12 | Develop Welding Materials |
| HPS-ELE-13 | Develop Piping Materials and Design Methods |
| HPS-ELE-DT-03 | Design a cell stack suitable for operation at high temperature in a high pressure, oxygen-rich environment |
| HPS-ELE-DT-04 | Design an economical stack enclosure that minimizes heat loss, sealing and stack handling and maximizes safety |
| HPS-ELE-DT-05 | Design a conceptual plant layout and piping arrangement that accommodates expected thermal expansion |
| HPS-ELE-DT-06 | Design and rate conceptual PCHXs |
| HPS-ELE-DT-11 | Design an electrolysis system based on the electrolyzer design and track economics |
| ***Product Purification (PPU)*** | |
| HPS-PPU-01 | Identify Product Impurities |
| HPS-PPU-02 | Test Product Purification Methods |
| HPS-PPU-DT-27 | Develop a pre-conceptual design for a product purification system |
| ***Instrument and Controls (PCN)*** | |
| HPS-PCN-01 | Test Sensors in the Pilot Plant |
| HPS-PCN-02 | Develop Valves for High-Temperature Acid and/or Helium Service |
| HPS-PCN-03 | Test Valves in the Pilot Plant |
| HPS-PCN-04 | Develop and Test High Temperature Helium Control Valves |
| HPS-PCN-DT-12 | Identify appropriate valve materials and sensing devices for the aggressive environments of the process technology |
| ***Hybrid Sulfur*** | |
| HPS-HYS-DT-01 | Analyze Data and Improve Process Simulation |

| DDN Number | Mission Need |
|---|---|
| HPS-HYS-DT-13 | Develop P&IDs and operating outline including normal and abnormal transients |
| HPS-HYS-DT-14 | Perform appropriate hazard and operability reviews at designated stages in process development |
| ***Bunsen Reaction (BUN)*** | |
| HPS-BUN-01 | Confirm Thermodynamic Data for the Bunsen Reaction Process including Phase Equilibria |
| HPS-BUN-02 | Gather Kinetic and Mass Transfer Data for the Bunsen Reaction in the proposed reactor configuration |
| HPS-BUN-03 | Develop Gasket Materials and Design for Bunsen Reaction Environment |
| HPS-BUN-04 | Develop Seal Materials and Design for Bunsen Reaction Environment |
| HPS-BUN-05 | Develop Welding Materials for Bunsen Reaction Environment |
| HPS-BUN-06 | Develop Cladding and Coating Materials for Bunsen Reaction Environment |
| HPS-BUN-07 | Develop Piping Materials and Design Methods for Bunsen Reaction Environment |
| HPS-BUN-DT-15 | Design Alternative Bunsen Reactors |
| HPS-BUN-DT-16 | Complete thermal and hydraulic analyses of the alternatives using equilibrium data only |
| HPS-BUN-DT-17 | Complete a conceptual mechanical design of each of the alternative concepts |
| HPS-BUN-DT-18 | Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing |
| HPS-BUN-DT-19 | Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing |
| HPS-BUN-DT-20 | Develop a preliminary piping spec and materials selections for BUN equipment |
| ***Hydroiodic Acid Decomposition (HID)*** | |
| HPS-HID-01 | Demonstrate Hydroiodic Acid Reactive Distillation Decomposition in Principle |
| HPS-HID-02 | Confirm Thermodynamic Data for the Hydroiodic Acid Decomposition Process including Phase Equilibria |
| HPS-HID-03 | Develop commercial HI Decomposition Catalyst |

| DDN Number | Mission Need |
|---|---|
| HPS-HID-04 | Gather Kinetic and Mass Transfer Data for the Hydroiodic Acid Decomposition in the proposed reactor configuration based on the commercial catalyst |
| HPS-HID-05 | Develop Gasket Materials and Design for Hydroiodic Acid Decomposition Environment |
| HPS-HID -06 | Develop Seal Materials and Design for Hydroiodic Acid Decomposition Environment |
| HPS-HID -07 | Develop Welding Materials for Hydroiodic Acid Decomposition Environment |
| HPS-HID -08 | Develop Cladding and Coating Materials for Hydroiodic Acid Decomposition Environment |
| HPS-HID-09 | Develop Piping Materials and Design Methods for Hydroiodic Acid Decomposition Environment |
| HPS-HID-DT-21 | Design Alternative HI Decomposition Reactors |
| HPS-HID-DT-22 | Complete thermal and hydraulic analyses of the alternatives using equilibrium data only |
| HPS-HID-DT-23 | Complete a conceptual mechanical design of each of the alternative concepts |
| HPS-HID-DT-24 | Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing |
| HPS-HID-DT-25 | Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing |
| HPS-HID-DT-26 | Develop a preliminary piping spec and materials selections for HID equipment |
| ***Sulfur Iodine*** | |
| HPS-SI-DT-01 | Analyze Data and Improve Process Simulation |
| HPS-SI-DT-08 | Track equipment size and cost as development progresses |
| HPS-SI-DT-13 | Develop P&IDs and operating outline including normal and abnormal transients |
| HPS-SI-DT-14 | Perform appropriate hazard and operability reviews at designated stages in process development |
| **4. Power Conversion System (PCS)** | |
| ***Steam Generator*** | |
| SG-01-01 | Secondary side Corrosion Characteristics 800H & 2-1/4Cr-1Mo and Weldments |
| SG-01-02 | Helium Environment Effects on 2-1/4 Cr-1Mo |
| SG-01-03 | Helium Environment Effects on 800H |
| SG-01-04 | Acoustic Response of Helical Bundle |
| SG-01-05 | Large Helical Coil Fabrication Methods |

| DDN Number | Mission Need |
|---|---|
| SG-01-06 | Inlet Flow Distribution |
| SG-01-07 | Insulation Verification Test |
| SG-01-08 | Fretting & Sliding Wear Protection Tests |
| SG-01-09 | Tube Wear Protection Device Testing |
| SG-01-10 | Shroud Seal Test |
| SG-01-11 | Lead-in/Lead-out/Transition/Expansion Loop Mock-ups |
| SG-01-12 | Flow Induced Vibration Testing of Helical Bundle |
| SG-01-13 | Orifice Qualification Test |
| SG-01-14 | Instrumentation Attachment Test |
| SG-01-15 | Bi-Metallic Weld Structural Integrity |
| SG-01-16 | Helical Bundle and Transition Region Heat Transfer Test |
| SG-01-17 | Tubing Inspection Methods and Equipment |
| SG-01-18 | Review and re-assemble existing SG development data |
| ***DDN from Composite Study*** | |
| COMP-01-01 | Characterize Race Track Strap and Tie Rod Materials |
| COMP-01-02 | RCS Materials Characterization |
| COMP-01-03 | Core Outlet Connection or Hot Gas Duct Liner |
| COMP-01-04 | Insulation Materials |

# APPENDIX B: REFERENCES

[0-1] NGNP-01-RPT-001 – NGNP and Hydrogen Production Pre-conceptual Design Report

[0-2] NGNP-CTF MTECH-TDRM-000 – Executive Summary

[0-3] NGNP-CTF MTECH-TDRM-001 – NGNP Systems and operation description

[0-4] NGNP-CTF MTECH-TDRM-002 – Technology Road Mapping Process

[0-5] NGNP-CTF MTECH-TDRM-003 – PHTS Circulator

[0-6] NGNP-CTF MTECH-TDRM-004 – Intermediate Heat Exchanger A

[0-7] NGNP-CTF MTECH-TDRM-005 – Intermediate Heat Exchanger B

[0-8] NGNP-CTF MTECH-TDRM-006 – HTS Piping

[0-9] NGNP-CTF MTECH-TDRM-007 – SHTS Flow Mixing Chamber

[0-10] NGNP-CTF MTECH-TDRM-008 – Hydrogen Production System

[0-11] NGNP-CTF MTECH-TDRM-009 – Power Conversion System Steam Generator

[0-12] NGNP-CTF MTECH-TDRM-010 – Software Code Verification and Validation

[0-13] NGNP-CTF MTECH-TDRM-011 – Fuel Elements

[0-14] NGNP-CTF MTECH-TDRM-012 – Core Structure Ceramics

[0-15] NGNP-CTF MTECH-TDRM-013 – Reserve Shutdown System

[0-16] NGNP-CTF MTECH-TDRM-014 – Reactivity Control System

[0-17] NGNP-CTF MTECH-TDRM-015 – Core Conditioning System

[0-18] NGNP-CTF MTECH-TDRM-016 – Reactor Cavity Cooling System

[0-19] NGNP-CTF MTECH-TDRM-017- Integrated Schedule and Cost (And Facility Info)

[0-20] NGNP-CTF MTECH-TDRM-00A – SSC list and current Technology Readiness Levels and 750 °C Comments

NGNP-CTF MTECH-TDRM-00A
Revision 0

November 2008

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Appendix A: SSC List with current Technology Readiness Levels and 750°C Comments

**APPROVALS**

| Function | Printed Name and Signature | | | Date |
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# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | | |

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# ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |

| Acronym | Definition |
|---|---|
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |

| Acronym | Definition |
|---|---|
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |

| Acronym | Definition |
|---|---|
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1. Nuclear Heat Supply System (NHSS)** | | | | | | | | | | | |
| | **1.1 Reactor Unit System** | | | | | | | | | | |
| | | **1.1.1 Fuel Elements (Spheres)** | | The PBMR DPP Tests will progress fuel to TRL 7. Additional testing will progress SSC to TRL 8 prior to installation in NGNP. | ✓ | | ✓ | 6 | 6 | No additional testing beyond PBMR DPP is required. (PBMR DPP to progress Fuel to TRL 8. No Unique NGNP test required) | NHSS-01-01* NHSS-01-02* NHSS-01-03* |
| | | | 1.1.1.1 Graphite Matrix | Previous experience applicable but not sufficient | ✓ | | | not incl. | 6 | Previous experience will now be sufficient for TRL 8 | NHSS-01-03* |
| | | | 1.1.1.2 Fuel Particles | Previous experience applicable but not sufficient | ✓ | | | not incl. | 6 | The PBMR DPP Tests will progress fuel to TRL8. No unique NGNP test required. | NHSS-01-03* |
| | | **1.1.2 Core Internal Structure (Graphite)** | | PBMR DPP experience applicable, but additional testing required for low (NHSS-02-01) and high temperature irradiation (NHSS-02-02) | ✓ | | ✓ (Combined in one TDRM) | 6 | 6 | Comments/testing under 950°C column apply; however, testing of insulation materials driven by transient events and economic considerations vs. high temperatures. For the CSC, at 500 MWt, three (NHSS-02-01, NHSS-02-02, COMP-01-01) of the four tests will remain relevant – noting that the insulation testing is not needed. If the power level were lowered, only the Irradiated Graphite testing at lower temperatures will remain relevant (test NHSS-02-01). | NHSS-02-01 NHSS-02-02* COMP-01-01* COMP-01-04* |
| | | **1.1.3 Core Internal Structure (Ceramics)** | | PBMR DPP experience applicable, but additional irradiation testing of strap and rod materials (COMP-01-01) may be required if scoping fluence estimates at 500MWt are significantly exceeded. Incremental testing of reference and/or alternate insulation materials (COMP-01-04) will be required. | ✓ | | | 4 | 4 | | |
| | | **1.1.4 Reserve Shutdown System (RSS)** | | The current HTF facility will progress the PBMR DPP RSS to a TRL of 7. If the PBMR DPP envelopes the NGNP requirements, then the PBMR DPP demonstration will progress the NGNP RSS to TRL 8. If not, the NGNP RSS can be installed in adapted/revised HTF to envelope NGNP requirements which will progress NGNP RSS to TRL 7 prior to installation in NGNP. | ✓ | | ✓ | not incl . | 6 | DPP testing & operation will take the RSS to TRL 8 - No additional testing required. | |
| | | **1.1.5 Reactivity Control System (RCS)** | | The current HTF facility will progress the PBMR DPP RCS to a TRL of 7. If the PBMR DPP envelopes the NGNP requirements, then the PBMR DPP demonstration will progress the NGNP RCS to TRL 8. If not, the NGNP RCS can be installed in adapted/revised HTF to envelope NGNP requirements which will progress NGNP RCS to TRL 7 prior to installation in NGNP. | ✓ | | ✓ | 6 | 6 | DPP testing & operation will take the RCS to TRL 8 - No additional testing required. | |
| | | **1.1.6 Reactor Pressure Vessel** | | Commercially available<br>See ASME Code Case N-499-2 | | ✓ | | 6 | 7 | No Change | |
| | | **1.1.7 Neutron Source System** | | Commercially available | | ✓ | | 8 | 8 | No Change | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1.1.8 RU Instrumentation** | | Commercially available | | ✓ | | not incl . | 8 | No Change | |
| | | **1.1.9 Reactor Unit Insulation** | | Part of Composite Study<br>Design needs to be done first – Then DDNs developed.<br>Left hand side Road Map | | ✓ | | not incl . | 8 | No Change | |
| | **1.2 Core Conditioning System (CCS)** | | | HTF and associated testing will progress blower and valves to TRL 7 prior to installation in PBMR DPP. PBMR DPP testing and operation will progress CCS to TRL 8 prior to installation in NGNP. | ✓ | | ✓ | 6 | 6 | Comments/testing under 950°C column applies. | |
| | | **1.2.1 CCS Blower** | | Commercially available | ✓ | | | not incl . | 8 | No Change | |
| | | **1.2.2 CCS Heat Exchanger** | | | | ✓ | | not incl . | 6 | No Change | |
| | | | 1.2.2.1 CCS HX Core | Applicable experience provided by HTTR PPWC | | ✓ | | not incl. | 8 | No Change | |
| | | | 1.2.2.2 CCS Vessel, Including External Supports | Commercially available | | ✓ | | not incl. | 8 | No Change | |
| | | | 1.2.2.3 CCS HX Vessel Insulation | Previous experience applicable but not sufficient | | ✓ | | not incl. | 6 | No Change | HTS-04-01 |
| | | **1.2.3 CCS Valves** | | Previous experience sufficient | | ✓ | | not incl . | 6 | No Change | |
| | | **1.2.4 CCS Piping** | | Commercially available | | ✓ | | not incl . | 6 | No Change | |
| | | **1.2.5 Internal Ducts, Supports and Insulation** | | Previous experience applicable but not sufficient | ✓ | | | not incl . | 6 | No Change | HTS-04-01 |
| | **1.3 Reactor Cavity Cooling System (RCCS)** | | | Codes / Analyses to progress RCCS to TRL 7 with PBMR DPP progressing it to TRL-8. | ✓ | | ✓ | 6 | 6 | Comments/testing under 950°C column applies. | |
| | **1.4 Fuel Handling and Storage System** | | | Previous experience sufficient | | ✓ | | 6 | 6 | No Change | |
| | | **1.4.1 Core Loading Subsystem** | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | **1.4.2 Sphere Storage Subsystem** | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | **1.4.3 Sphere Circulation Subsystem** | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | **1.4.4 Sphere Replenishment Subsystem** | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | **1.4.5 Fuel Handling Control Subsystem** | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1.4.6 Circulating Gas Subsystems | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.4.7 Sphere Decommissioning Subsystem | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.4.8 Auxiliary Gas Subsystem | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.4.9 High-level Waste Handling Subsystem | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.4.10 Burn Up Measurement System | | Previous experience sufficient | | ✓ | | not incl . | 6 | No Change | |
| | 1.5 Helium Service System | | | | | ✓ | | 6 | 8 | No Change | |
| | | 1.5.1 PHTS Inventory Control System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.5.2 SHTS Inventory Control System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.5.3 PHTS Helium Purification System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.5.4 SHTS Helium Purification System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.5.5 Helium Make-Up System | | Commercially available | | ✓ | | not incl . | 8 | No Change | |
| | 1.6 NHSS Control & Instrumentation System | | | | | ✓ | | not incl. | 8 | No Change | |
| | | 1.6.1 Operational Control System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.6.2 Reactor Protection System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.6.3 Equipment Protection System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | | 1.6.4 Post-event Monitoring and Recovery System | | Previous experience sufficient | | ✓ | | not incl . | 8 | No Change | |
| | 1.7 Pressure Boundary Support Systems | | | | | ✓ | | not incl. | not incl. | No Change | |
| | | 1.7.1 De-fuel Chute Cooling System | | Previous experience sufficient | | ✓ | | not incl. | not incl. | No Change | |
| | | 1.7.2 Vessel Over-Pressure System | | Previous experience sufficient | | ✓ | | not incl. | not incl. | No Change | |
| | | 1.7.3 Inertial Dust Filter | | Previous experience sufficient | | ✓ | | not incl. | not incl. | No Change | |
| | 1.8 NHSS Cooling Water System | | | Previous experience sufficient | | ✓ | | | 8 | No Change | |
| | | 1.8.1 Auxiliary Component Cooling Water System | | Previous experience sufficient | | ✓ | | not incl. | 8 | No Change | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1.8.2 Equipment Protection Cooling Circuit (incl. Backup Heat Sink)** | | Previous experience sufficient | | ✓ | | not incl. | 8 | No Change | |
| | **1.9 NHSS Electrical Distribution System** | | | Commercially available | | ✓ | | not incl. | 8 | No Change | |
| | **1.10 Reactor Building HVAC** | | | Commercially available | | ✓ | | not incl. | 8 | No Change | |
| | **1.11 Primary Loop Initial Cleanup System** | | | Previous experience sufficient | | ✓ | | not incl. | 8 | No Change | |
| **Nuclear Heat Supply Buildings and Structures** | | | | | | | | | | | |
| | **1.12 Nuclear Heat Supply Buildings** | | | Commercially available | | ✓ | | not incl. | 8 | No Change | |
| **2. Heat Transport System (HTS)** | | | | | | | | | | | |
| | **2.1 Primary Heat Transport System (PHTS)** | | | | ✓ | | | 2 | 2 | No Change | |
| | | **2.1.1 PHTS Circulator** | | Previous experience applicable but not sufficient.<br>The PHTS circulator(s) is classified as "Critical Component" because the previous applicable commercial experience (THTR) used submerged circulators in parallel similar to the NGNP preconceptual design but at lower power (roughly half) and with oil bearings. Part-scale testing as proposed is envisioned to progress the circulator to TRL 7 prior to installation in NGNP. | ✓ | | ✓ | 6 | 6 | Although the 750°C application has lower temperatures at the circulator inlet/outlet than the 950°C application, the uncertainty as to the integration of the circulator components still exists. | |
| | | | 2.1.1.1 Impeller and Shaft | Commercially available.<br>The helium inlet temperature (approximately 340 ºC) is not a problem for the impeller and the shape of the blades for a helium environment has been optimized before. | | ✓ | | not incl. | 8 | No Change | |
| | | | 2.1.1.2 Electromagnetic Bearings (EMB) and Support | Previous experience sufficient. Siemens has recently built large electrical motors (~ 26MW) with EMBs for the gas pipeline compressors in the Netherlands. The dielectric strength of the helium should not be a problem at the relative low voltage required by the EMBs. | | ✓ | | not incl. | 8 | No Change | |
| | | | 2.1.1.3 Seals (stationary and rotating) | Commercially available.<br>Rotating seals between the impeller/primary coolant and the motor cavity have been successfully built before and static seals between the vessel and the circulator assembly have been used in the nuclear industry successfully. | | ✓ | | not incl. | 8 | No Change | |
| | | | 2.1.1.4 Electric Motor, Cooling System and Support | Previous experience sufficient. Siemens has recently built large electrical motors (~ 26MW) with EMBs for the gas pipeline compressors in the Netherlands. The dielectric strength of the helium should not be a problem at the relative low voltage required by the EMBs. | | ✓ | | not incl. | 8 | No Change | |
| | | | 2.1.1.5 Instrumentation & Control (Motor and EMB) | Commercially available.<br>Electric motors are routinely instrumented and controlled. The more sophisticated control system required by the EMBs is industrially available. | | ✓ | | not incl. | 6 | No Change | |
| | | | 2.1.1.6 PHTS Circulator Check Valve | Check valve is recommended in PHTS TDRM. Pressure balanced check valves at these temperatures are commercially available. | ✓ | | Included in Circulator TDRM | 6 | 6 | No Change | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **2.1.2 Intermediate Heat Exchanger (IHX A) Metallic (950°C)** | | No previous operating experience for compact designs at 950C. Note that the HTTR in Japan has operating experience for tube design. | ✓ | | ✓ | 2 | 2 | IHX A (Metallic) will not be required at 750°C | |
| | | | 2.1.2.1 IHX Core | No previous operating experience at 950C | ✓ | | | 4 | 2 | | HTS-01-01*<br>HTS-01-02*<br>HTS-01-03*<br>HTS-01-04*<br>HTS-01-05*<br>HTS-01-06*<br>HTS-01-13*<br>HTS-01-14*<br>HTS-01-15*<br>HTS-01-16*<br>HTS-01-17*<br>HTS-01-18*<br>HTS-01-19*<br>HTS-01-20*<br>HTS-01-21*<br>HTS-01-22*<br>HTS-01-23*<br>HTS-01-24*<br>HTS-01-25*<br>HTS-01-26*<br>HTS-01-25*<br>HTS-01-27*<br>HTS-01-28*<br>HTS-01-29*<br>HTS-01-30*<br>HTS-01-31* |
| | | | 2.1.2.2 IHX Internal Ducts, Supports and Insulation | Previous experience applicable but not sufficient | ✓ | | | 2 | 3 | | HTS-04-01 |
| | | | 2.1.2.3 IHX Vessel Subsystem | Previous experience applicable but not sufficient | ✓ | | | 6 | 3 | | |
| | | | 2.1.2.3.1 IHX Vessel, Including External Supports | Commercially available | | ✓ | | not incl. | 8 | | |
| | | | 2.1.2.3.2 IHX Vessel Insulation | Previous experience applicable but not sufficient | ✓ | | | not incl. | 3 | | HTS-04-01 |
| | | **2.1.3 Intermediate Heat Exchanger (IHX B) Metallic (760°C)** | | Previous experience applicable but not sufficient | ✓ | | ✓ | not incl. | 3 | IHX B will be required for the 750°C application | HTS-01-22<br>HTS-01-23<br>HTS-01-24<br>HTS-01-25<br>HTS-01-26<br>HTS-01-27<br>HTS-01-28<br>HTS-01-29<br>HTS-01-30 |
| | | | 2.1.3.1 IHX Core | No previous experience with compact design 760°C | ✓ | | | not incl. | 4 | | |
| | | | 2.1.3.2 IHX Internal Ducts, Supports and Insulation | Previous experience applicable but not sufficient | ✓ | | | not incl. | 4 | | HTS-04-01 |
| | | | 2.1.3.3 IHX Vessel Subsystem | Materials Commercially available, See ASME Section III NB | ✓ | | | not incl. | 7 | | |
| | | | 2.1.3.3.1 IHX Vessel, Including External Supports | Commercially available, See ASME Code Case N-499-2 | | ✓ | | not incl. | 8 | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2.1.3.3.2 IHX Vessel Insulation | Previous experience applicable but not sufficient | | ✓ | | not incl. | 70 | | HTS-04-01 |
| | | **2.1.4 Intermediate Heat Exchanger (IHX A) Ceramic (950°C)** | | See ASME Code Case N-499-2 | ✓ | | Combined with Metallic IHX A TDRM | 2 | 2 | IHX A (Ceramic) will not be required for the 750°C application | |
| | | | 2.1.4.1 IHX Core | No previous relevant experience at 950°C | ✓ | | | 3 | 3 | | HTS-02-01*<br>HTS-02-02*<br>HTS-02-03*<br>HTS-02-04*<br>HTS-02-06* |
| | | | 2.1.4.2 IHX Internal Ducts, Supports and Insulation | No previous experience with metal to ceramic transitions | ✓ | | | 2 | 2 | | HTS-04-01*<br>HTS-02-05* |
| | | | 2.1.4.3 IHX Vessel Subsystem | Previous experience applicable but not sufficient | ✓ | | | 6 | 3 | | |
| | | | 2.1.4.3.1 IHX Vessel, Including External Supports | Commercially available | | ✓ | | not incl. | 8 | | |
| | | | 2.1.4.3.1 IHX Vessel Insulation | Previous experience applicable but not sufficient | ✓ | | | not incl. | 3 | | HTS-04-01* |
| | | **2.1.5 Piping (primary circuit from Reactor to IHX and between IHX vessels -both hot and cold legs)** | | Previous experience applicable but not sufficient | ✓ | | ✓ | 5 | 4 | No Piping required between IHX vessels | HTS-04-01 |
| | | | 2.1.5.1 Pressure boundary piping, including external supports and insulation | Commercially available<br>Still need to be designed as part of CD | | ✓ | | 5 | 7 | PBMR DPP testing and operation will take pressure boundary to TRL 8 | |
| | | | 2.1.5.2 Piping Internal Ducts, Supports and Insulation (Hot Gas Duct) | Previous experience applicable but not sufficient.<br>Alternate insulation concept may mitigate loss of heat removal transient and offer improved economics | ✓ | | | 6 | 4 | DPP testing and operations take the Hot Gas Ducts internals to TRL 8, however, potential incentives for alternate insulation concept remain. | HTS-04-01 |
| | **2.2 Secondary Heat Transport System (SHTS)** | | | | ✓ | | | 2 | 4 | | |
| | | **2.2.1 SHTS Circulator** | | The SHTS circulator(s) is classified as "Critical Component" because the previous applicable commercial experience (THTR) used submerged circulators in parallel similar to the NGNP preconceptual design but at lower power (roughly half) and with oil bearings. | ✓ | | ✓ (Included in PHTS Circulator TDRM) | 6 | 6 | Although the 750°C application has lower temperatures at the circulator inlet/outlet than the 950°C application, the uncertainty as to the integration of the circulator components still exists. | |
| | | | 2.2.1.1 Impeller and Shaft | Commercially available.<br>The helium inlet temperature (approximately 275 °C) is not a problem for the impeller and the shape of the blades for a helium environment has been optimized before. | | ✓ | | not incl. | 8 | | |
| | | | 2.2.1.2 Electromagnetic Bearings (EMB) and Support | Previous experience sufficient. Siemens has recently built large electrical motors (~ 26MW) with EMBs for the gas pipeline compressors in the Netherlands. The dielectric strength of the helium should not be a problem at the relative low voltage required by the EMBs. | | ✓ | | not incl. | 8 | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2.2.1.3 Seals (stationary and rotating) | Commercially available.<br>Rotating seals between the impeller/primary coolant and the motor cavity have been successfully built before and static seals between the vessel and the circulator assembly have been used in the nuclear industry successfully. | | ✓ | | not incl. | 8 | | |
| | | | 2.2.1.4 Electric Motor, Cooling System and Support | Previous experience sufficient. Siemens has recently built large electrical motors (~ 26MW) with EMBs for the gas pipeline compressors in the Netherlands. The dielectric strength of the helium should not be a problem at the relative low voltage required by the EMBs. | | ✓ | | not incl. | 8 | | |
| | | | 2.2.1.5 Instrumentation & Control (Motor and EMB) | Commercially available.<br>Electric motors are routinely instrumented and controlled. The more sophisticated control system required by the EMBs is industrially available. | | ✓ | | not incl. | 6 | | |
| | | **2.2.2 Piping (secondary circuit, hot and cold legs, plus PCHX to SG)** | | Previous experience applicable but not sufficient | ✓ | | | 6 | 4 | Lower Temperature will benefit the Piping Design | |
| | | | 2.2.2.1 Piping Internal Ducts, Supports and Insulation (Hot Gas Duct) | Commercially available | | ✓ | | 6 | 7 | | |
| | | | 2.2.2.2 Piping Internal Ducts, Supports and Insulation (Hot Gas Duct) | Previous experience applicable but not sufficient. Passive insulation identified as the reference for the NGNP not utilized in PBMR DPP | ✓ | | | 6 | 4 | | HTS-04-01 |
| | | **2.2.3 SHTS Flow Mixing Chamber** | | No previous experience<br>The SHTS flow mixing chamber is classified as "Critical Component" because of the high velocities and temperatures (900 °C and 660 °C) of the flows to be mixed and lack of a credible design. | ✓ | | | 2 | 6 | Flow Mixing Chamber is not required for 750°C | HTS-03-01 HTS-04-01 |
| | | | 2.2.3.1 Mixing Chamber | Previous experience sufficient.<br>Gasses at different temperatures are routinely mixed in industry. | | ✓ | | not incl. | 8 | | |
| | | | 2.2.3.2 Vibrations Damping Devices | Previous experience applicable but not sufficient. Flow and acoustic induced vibrations can damage structures within the flow and along the inner walls. The vibrations are effected by the mixing chamber geometry and the velocities/densities of the mixing gasses. | ✓ | | | not incl. | 6 | | |
| | | | 2.2.3.3 Chamber Inner Walls Insulation | Previous experience applicable but not sufficient. Because of the high temperatures and potential for flow and acoustic induced vibrations the design of the inner walls insulation requires same development. | ✓ | | | not incl. | 6 | | HTS-04-01 |
| **3. Hydrogen Production System (HPS), Process Technology #1 – Sulfuric Acid Decomposition** | | | | | | | | | | | |
| | **3.1 Sulfuric Acid Decomposition** | | | | | | | 2 | 3 | | HPS-SAD-DT-08 |
| | | 3.1.1 Process flow scheme | | Further development of the process flow scheme and confirmation of basic data needed; kinetic, heat transfer, mass and momentum transfer data and analyses to be incorporated; flow scheme depends upon cycle selected (SI or HyS). | | | | | | Basic flow scheme stays the same; flows in recycle loop increase dramatically | HPS-HYS-DT-01 |
| | | 3.1.2 Integration and operation | | Previous experience applicable but not sufficient | | | | | | Integration and process transients may be less challenging due to lower peak operating temperature | HPS-HYS-DT-13 |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3.1.3 Hazards and operability | | Previous experience applicable but not sufficient | | | | | | Hazards may be somewhat mitigated by lower peak temperature | HPS-HYS-DT-14 |
| | **3.2 Acid Decomposer (decomposition reactor) [H3SO4 → ½O3 + SO3 + H3O]** | | | Basic data; catalyst; materials of construction; seals; hydraulic, kinetic, and thermal design and analysis needed | ✓ | | | | 3 | Reactor gets larger as temperature decreases; materials selection is less challenging | HPS-SAD-01<br>HPS-SAD-04<br>HPS-SAD-05<br>HPS-SAD-06<br>HPS-SAD-07<br>HPS-SAD-08<br>HPS-SAD-09<br>HPS-SAD-DT-02<br>HPS-SAD-DT-04<br>HPS-SAD-DT-05<br>HPS-SAD-DT-06<br>HPS-SAD-DT-08 |
| | | 3.3.1 Commercial catalyst | | Effective; 20,000hr life, minimum, Resistant to expected poisons | ✓ | | | | 3 | Lower temperature will have an effect on catalyst. Higher temperature favours kinetics and impacts life negatively | HPS-SAD-02 |
| | | 3.3.3 Kinetic data | | Based on commercial catalyst | | | | | | (This is not a SSC, but line item kept for tracking DDN applicability) Lower temperature slows reaction | HPS-SAD-03 |
| | | 3.3.3 Decomposer tube | | Design and analysis based on kinetic data | ✓ | | | | 4 | Lower temperature may allow a wider range of materials choices. It will also be a very significant factor in bayonet tube thermal design | HPS-SAD-DT-03<br>HPS-SAD-DT-05<br>HPS-SAD-DT-06 |
| | | 3.3.4 Seals | | Transition between SiC tubes and metallic vessel; reliable seal or design that is tolerant of feed/effluent leakage, but not He/ acid leakage | ✓ | | | | 4 | Lower temperature may allow a wider range of materials choices. | HPS-SAD-11<br>HPS-SAD-10 |
| | | 3.3.5 Vessel | | Materials of construction; arrangement of tubes; | ✓ | | | | 4 | Lower temperature may allow a wider range of materials choices. | HPS-SAD-12<br>HPS-SAD-13<br>HPS-SAD-DT-04 |
| | **3.3 Reactor product handling equipment** | | | Basic data for phase separation, materials of construction, seals needed | ✓ | | | | 6 | Only liquid handling equipment gets larger as temperature decreases; materials issues remain the same | HPS-SAD-01<br>HPS-SAD-12<br>HPS-SAD-13<br>HPS-SAD-14<br>HPS-SAD-DT-07 |
| | **3.4 Acid concentration vacuum column** | | | HETP confirmation needed. Previous experience applicable but not sufficient; also included in feed acid handling and concentrating equipment | ✓ | | | | 6 | Only liquid handling equipment gets larger as temperature decreases; materials issues remain the same | HPS-SAD-15 |
| | **3.5 Feed acid handling and concentrating equipment** | | | Materials of construction and seals confirmation needed | ✓ | | | | 6 | Only liquid handling equipment in the recycle loop gets larger as temperature decreases; materials issues remain the same | HPS-SAD-01<br>HPS-SAD-10<br>HPS-SAD-11<br>HPS-SAD-12<br>HPS-SAD-13<br>HPS-SAD-14<br>HPS-SAD-DT-07 |
| | **3.6 Steam ejectors and vacuum pump** | | | | | ✓ 2 | | | 6 | | |
| | **3.7 Helium Control Valves** | | | | ✓ | | | | 4 | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **3.8 SO2 Absorber** | | | HETP confirmation needed | ✓ | | | | 6 | | HPS-SAD-16 |
| | [2] "Non-Critical " SSCs are those which although they require design data, this data-gathering is normally carried out in the design of plants and is not considered technology development or research and development. | | | | | | | | | | |
| **4 Hydrogen Production System (HPS), Process Technology #2 – Hybrid Sulfur Electrolysis** | | | | | | | | | | | |
| | **4.1 Hybrid Sulfur Electrolysis** | | | | | | | 4 | 2 | | |
| | **4.2 Feed Purification** | | | Feed purification is critical to all water splitting technologies. Preliminary work on critical component tolerance has not yet been done. Commercially available feed water purification may not be adequate; process fluid purification may be required. TRL for this cannot be assigned until the requirements are known. The DDN changes somewhat depending upon the main process technology. | ✓ | | | | U | No change | HPS-FUS-01<br>HPS-FUS-02<br>HPS-FUS-03<br>HPS-FUS-DT-09<br>HPS-FUS-DT-10 |
| | **4.3 SO2 Electrolyzer** | | | Previous experience applicable but not sufficient. Scale-up, manufacturability, and cost are key issues | ✓ | | | | 2 | No change | HPS-ELE-01<br>HPS-ELE-02<br>HPS-ELE-03<br>HPS-ELE-04<br>HPS-ELE-05<br>HPS-ELE-06<br>HPS-ELE-DT-11 |
| | **4.4 Product Purification** | | | Commercially available | | ✓ | | | 8 | No change | HPS-PPU-01<br>HPS-PPU-02 |
| | **4.5 Instrumentation and Controls** | | | Chief concern in this sub-system is valves and sensors in aggressive environments. Previous experience applicable but not sufficient. The DDN changes somewhat depending upon the main process technology. | ✓ | | | | 6 | No change | HPS-PCN-01<br>HPS-PCN-02<br>HPS-PCN-03<br>HPS-PCN-DT-12 |
| **5 Hydrogen Production System (HPS), Process Technology #3 – Bunsen Reaction and HI Decomposition** | | | | | | | | | | | |
| | **5.1 Bunsen Reaction and HI Decomposition** | | | A robust and stable simulation of the process using either measured or reasonably estimated physical property, phase and reaction equilibria data is required. | ✓ | | ✓ | Not Incl. | 2 | No change | HPS-SI-DT-13 |
| | | 5.1.1 Process flow scheme | | Further development of the process flow scheme and confirmation of basic data needed for both sections; kinetic, heat transfer, mass and momentum transfer data and analyses to be incorporated. | | | | | | (This is not a SSC, but line item kept for tracking DDN applicability)<br>No change | HPS-SI -DT-01 |
| | | 5.1.2 Integration and operation | | Previous experience applicable but not sufficient. Very large flows of hazardous material required for a reasonably sized hydrogen plant is beyond the experience of the chemical industry. | | | | | | No change | HPS-SI -DT-13 |
| | | 5.1.3 Hazards and operability | | Previous experience applicable but not sufficient. Possibility of very large iodine spills must be considered. Reactive distillation takes place at relatively elevated temperatures | | | | | | No change | HPS-SI –DT-14 |
| | **5.2 Bunsen Reactor [ I2 + SO2 + 2H2O → H2SO5 + 2HI ]** | | | No previous commercial experience. ILS experience is applicable, but not sufficient. Basic thermodynamic data; materials of construction; seals; hydraulic, kinetic, and thermal design and analysis needed | ✓ | | ✓ | | 3 | No change | HPS-BUN-01 |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5.2.1 Kinetic and mass transfer data | | Bubbling gas through two liquid phases as is done in the ILS is not an optimal solution for good mass transfer. Alternative designs and data consistent with those designs are required | | | | | | (This is not a SSC, but line item kept for tracking DDN applicability) No change | HPS-BUN-02 |
| | | 5.2.2 Reactor surface and gas/liquid contact device | | Design and analysis based on kinetic and mass transfer data | | | | | | No change | HPS-BUN-DT-15<br>HPS-BUN-DT-16<br>HPS-BUN-DT-18<br>HPS-BUN-DT-19 |
| | | 5.2.3 Seals | | Economic seals and gaskets for use in the highly corrosive, acidic and halogen-rich environment | ✓ | | | | 3 | No change | HPS-BUN-03<br>HPS-BUN-04 |
| | | 5.2.5 Vessel | | Materials of construction; arrangement of internals; attachment of corrosion resistant internals to a TFE lined vessel are some possible issues. | ✓ | | | | 3 | No change | HPS-BUN-05<br>HPS-BUN-06 |
| | **5.3 Reactive Still [2HI → I2 + H2]** | | | No previous experience. Reactive distillation must be demonstrated in principle. Thermodynamic data must be confirmed and kinetic and mass transfer data gathered | ✓ | | ✓ | | 2 | No change | HPS-HID-01<br>HPS-HID-02<br>HPS-BUN-DT-17 |
| | | 5.3.1 Commercial catalyst | | A commercial catalyst with adequate life (20,000 hours) must be developed. | ✓ | | | | 2 | | HPS-HID-03 |
| | | 5.3.2 Kinetic and mass transfer data | | Kinetic and mass transfer characteristics of the commercial catalyst must be determined | | | | | | (This is not a SSC, but line item kept for tracking DDN applicability) No change | HPS-HID-04 |
| | | 5.3.3 Reactor surface and gas/liquid contact device | | Reaction surface and the form of the catalyst and mass transfer devices must be determined based on the kinetic and mass transfer characteristics of the commercial catalyst | ✓ | | | | 2 | No change | HPS-HID-DT-21<br>HPS-HID-DT-22<br>HPS-HID-DT-24<br>HPS-HID-DT-25 |
| | | 5.3.4 Seals | | See 2.3 above | ✓ | | | | 2 | No change | HPS-HID-05<br>HPS-HID-06 |
| | | 5.3.5 Vessel | | See 2.5 above | ✓ | | | | 2 | No change | HPS-HID-07<br>HPS-HID-08<br>HPS-HID-DT-23 |
| | **5.5 Reactor product handling equipment (both Bunsen and HI Decomp)** | | | Basic data for phase separation, materials of construction, seals needed. Pumping and handling very large streams of iodine and hydroiodic acid is a problem that has not been dealt with commercially. The large flows required are beyond the experience of chemical plants. The possibility of very large spills has to be considered. Economic solutions need to be found. | ✓ | | | | 6 | No change | HPS-BUN-07<br>HPS-BUN-DT-20<br>HPS-HID-09<br>HPS-HID-DT-26 |
| | **5.6 Feed Purification** | | | Previous experience applicable but not sufficient. See HyS electrolysis #1 | ✓ | | | | U | No change | HPS-FUS-01<br>HPS-FUS-02<br>HPS-FUS-03<br>HPS-FUS-DT-09<br>HPS-FUS-DT-10 |
| | **5.7 Product Purification** | | | Previous experience applicable but not sufficient. Trace iodine removal is essential | ✓ | | | | U | No change | HPS-PPU-01<br>HPS-PPU-02<br>HPS-PPU-DT-27 |
| | **5.8 Helium Control Valves** | | | | ✓ | | | | 4 | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **5.9 Instrumentation and Controls** | | | Previous experience applicable but not sufficient. See comments on HyS electrolysis #5 | ✓ | | | | 6 | No change | HPS-ELE-10<br>HPS-ELE-11<br>HPS-PCN-DT-12 |
| **6. Hydrogen Production System (HPS), Process Technology #4 – High Temperature Steam Electrolysis** | | | | | | | | | | | |
| | **6.1 High Temperature Steam Electrolysis** | | | | ✓ | | ✓ | | 3 | Lower temperature will reduce thermal efficiency. As an off-setting factor; it will reduce the cost of vessels and piping substantially. | |
| | **6.2 Solid Oxide Electrolyzer** | | | | ✓ | | | | 3 | Lower temperature will reduce thermal efficiency. As an off-setting factor; it will reduce the cost of vessels and piping substantially. | |
| | | 6.2.1 Cells | | Cells must be shown to be capable of being manufactured and successfully operated at a size approaching 0.25 $m^2$. Cause of rapid cell degradation must be identified and a solution found. | ✓ | | | | 3 | | HPS-ELE-01<br>HPS-ELE-02<br>HPS-ELE-03<br>HPS-ELE-04<br>HPS-ELE-05 |
| | | 6.2.2 Stacks | | Stacks of approximately 2500 cells must be shown to operate successfully and with adequate flow distribution. Seals must be high-integrity and extremely reliable. Failure will cause a hydrogen fire or explosion | ✓ | | | | 3 | Lower temperatures make fabrication, thermal stress, creep and sealing requirements slightly less difficult | HPS-ELE-06<br>HPS-ELE-DT-03 |
| | | 6.2.3 Internals and Enclosure | | Stacks are currently sealed using tension bars. In the enclosure at 800°C the bars will eventually creep causing loss of pressure on the cells and possible seal leakage. Electrical cables must pass through the pressure boundary from ambient conditions to the oxygen-rich high-temperature environment. Electrical connections must be made in this atmosphere. Either these issues must be solved or a successful enclosure design must be developed to avoid these and the danger of hydrogen fires. | ✓ | | | | 5 | | HPS-ELE-06<br>HPS-ELE-10<br>HPS-ELE-11<br>HPS-ELE-DT-04 |
| | **6.3 Piping to enclosures from nuclear reactor.** | | | Previous experience applicable but not sufficient. Piping very high temperature gas to several dozen cell modules will be an extremely difficult problem. Thermal expansion of the pipe is expected to be from 1 ½ to 2 %. Pipe runs will be on the order of 100+ meters. The growth that must be accommodated is therefore about 2m. Absorbing this amount of expansion in very high temperature piping has not been done commercially. | ✓ | | | | U | | HPS-ELE-10<br>HPS-ELE-11<br>HPS-ELE-12<br>HPS-ELE-13<br>HPS-ELE-DT-05 |
| | **6.4 He-to-Process Heat Exchanger(s)** | | | No previous experience; issues with high-temperature service, relatively large pressure differential between helium and process side and leakage of helium to process side | ✓ | | | | 5 | Lower temperatures allow use of a significantly less expensive material with better mechanical properties; should reduce development time significantly | HPS-ELE-07<br>HPS-ELE-08<br>HPS-ELE-09<br>HPS-ELE-DT-06 |
| | **6.5 Electrolysis Heat Recuperation – H2** | | | | | | | | | | |
| | | 6.5.1 Superheater | | No previous experience; high temperature service | ✓ | | | | 5 | Lower temperatures allow use of a significantly less expensive material with better mechanical properties; should reduce development time significantly | HPS-ELE-07<br>HPS-ELE-08<br>HPS-ELE-09 |
| | | 6.5.2 BFW preheater and boiler | | Commercially available | | ✓ | | | 8 | | |
| | **6.6 Electrolysis Heat Recuperation – O2** | | | | | | | | | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6.5.1 Superheater | | No previous experience; high temperature service | ✓ | | | | 5 | Lower temperatures allow use of a significantly less expensive material with better mechanical properties; should reduce development time significantly | HPS-ELE-07<br>HPS-ELE-08<br>HPS-ELE-09 |
| | | 6.5.2 BFW preheater and boiler | | Commercially available | | ✓ | | | 8 | | |
| | **6.7 Sweep Gas Turbine** | | | Commercially available | ✓ | | | | 7 | | |
| | **6.8 H2 Recirculator** | | | Commercially available | | ✓ | | | 8 | | |
| | **6.9 Feed Purification** | | | Previous experience applicable but not sufficient. See HyS electrolysis #1 | ✓ | | | | U | | HPS-FUS-01<br>HPS-FUS-02<br>HPS-FUS-03<br>HPS-FUS-DT-01<br>HPS-FUS-DT-02 |
| | **6.10 Product Purification** | | | Commercially available | | ✓ | | | 8 | | |
| | **6.11 Helium Control Valves** | | | | ✓ | | | | 4 | | |
| | **6.12 Instrumentation and Controls** | | | Previous experience applicable but not sufficient. See comments on HyS electrolysis #5 | ✓ | | | | 6 | | |
| **7. Power Conversion System (PCS)** | | | | | | | | | | | |
| | **Main Steam System** | | | | | | | | | | |
| | **7.1 Turbine Generator System** | | | | | | | not incl. | 8 | | |
| | | 7.1.1 High-Pressure Turbine | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.2 Intermediate- Pressure Turbine | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.3 Low-Pressure Turbines | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.4 Low-Pressure Turbines | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.5 Generator and Auxiliaries (incl. H2 and CO2) | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.6 Lube Oil System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.7 Vacuum System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.1.8 Air-cooled Condenser | | | | ✓ | | | | | |
| | **7.2 Main Steam System** | | | | ✓ | | | 6 | 6 | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7.2.1 Steam Generator | | Previous experience is applicable; the main concern is the helium inlet temperature is a design challenge. First-of-a-kind configuration depending on thermal rating, design parameters and specific design selections | ✓ | | ✓ | Not Incl. | 6 | The 750°C application should simplify the Steam Generator Design as the Steam Generator helium inlet temperature will be lowered. TRL is rated as 6 and a down select study on tube bundle configuration is recommended regardless of helium inlet temperature. The development needs are somewhat configuration and design condition dependent. | PCS-01-01<br>PCS-01-02<br>PCS-01-02<br>PCS-01-03<br>PCS-01-04<br>PCS-01-05<br>PCS-01-06<br>PCS-01-07<br>PCS-01-08<br>PCS-01-09<br>PCS-01-10<br>PCS-01-11<br>PCS-01-12<br>PCS-01-13<br>PCS-01-14<br>PCS-01-15<br>PCS-01-16<br>PCS-01-17<br>PCS-01-18 |
| | | | 7.2.1.1 Steam Generator Vessel | Commercially available technology, but first- of- a-kind configuration and system integration for the NGNP application. Transportation versus field fabrication is an issue | | ✓ | | Not Incl. | 7 | Reduce helium-side temperature will reduce design challenges. | |
| | | | 7.2.1.2 SG Superheater tube bundle and supports | Previous experience is applicable; the main concern is the helium inlet temperature is a design challenge. First-of-a-kind configuration depending on thermal rating and design parameters. | ✓ | | | not incl. | 6 | | |
| | | | 7.2.1.3 SG Evaporator tube bundle and supports | Previous experience is applicable. First-of-a-kind configuration depending on thermal rating and design parameters. | ✓ | | | | 6 | | |
| | | | 7.2.1.4 SG Internal Ducts, Supports and Insulation | Previous experience is applicable, but not sufficient. | ✓ | | | | | Reduced helium-side temperature will reduce design challenges. | HTS-04-01?? |
| | | | 7.2.1.5 SG internal flow baffles and bypass seals | Minimal experience; the configuration is dependent on thermal rating. Performance to be determined. | ✓ | | | | | | |
| | | | 7.2.1.6 SG vessel penetrations for feedwater tubesheet and superheater tubesheet, and instrumentation | Previous experience is applicable; configuration is dependent on system design. | | ✓ | | | 7 | | |
| | | | 7.2.1.7 SG Vessel External Supports | Commercially available, but custom design for the application. | | ✓ | | not incl. | 8 | | |
| | | | 7.2.1.8 SG Vessel External Insulation | Previous experience is applicable. Assume vessel operating temperature <799°F ( 371°C) | ✓ | ✓ | | not incl. | 8 | | HTS-04-01?? |
| | | 7.2.2 Startup/Shutdwn Steam System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.2.3 Extraction and Auxiliary Steam System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.2.4 Steam Bypass/Dump System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.2.5 Seal Water System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.2.6 Gland Steam System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.2.7 Steam Vents and Drains | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.2.8 Steam Pressure Relief System | | Commercially available | | ✓ | | not incl. | 8 | | |

| Area | System | Structure | Component | 950°C Comments | Critical SSC | Non Critical | Road Map | TRL 07-Sep | TRL 08-Jul | 750°C Comments | DDN # [1] * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **7.3 Feedwater and Condensate System** | | | | ✓ | | | not incl. | 8 | | |
| | | 7.3.1 Heater Drains System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.3.2 Feedwater Heater System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.3.3 High-Pressure Feedwater Pump | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.3.4 Condensate Pumps | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.4 PCS Control and Instrumentation System** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.5 PCS Electrical Distribution System** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.6 PCS Water Supply and Treatment System** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.6.1 Condensate Polishing System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.6.2 Turbine Plant Sampling System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | | 7.6.3 Chemical Feed System | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.7 PCS Component Cling Water System** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.8 Turbine Building HVAC** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| **8. Power Conversion Buildings and Structures** | | | | | | | | | | | |
| | **7.9 Steam Generator Building** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.10 PCS (Turbine Building) Building** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.11 Aux Steam Boiler Room** | | | Commercially available | | ✓ | | not incl. | 8 | | |
| | **7.12 Condenser Area** | | | Commercially available | | ✓ | | not incl. | 8 | | |

* DDNs no longer applicable for 750°C application
[1] Identifying numbers for the DDNs from the WEC PCDR have been changed to reflect the application to Sulfuric Acid Decomposition technology. The letter designation “SAD” has been added after the system designator “HPS”

**NGNP-CTF MTECH-TDRM-001** **November 2008**
**Revision 1**

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 1: NGNP Systems and Operational Description

**APPROVALS**

| Function | Printed Name and Signature | Date |
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| Author | Name: Herman van Antwerpen<br>Company: M-Tech Industrial (Pty.) Ltd. | November 18, 2008 |
| Reviewer | Name: Renee Greyvenstein<br>Company: Pebble Bed Modular Reactor (Pty) Ltd. | November 19, 2008 |
| Reviewer | Name: Roger Young<br>Company: Pebble Bed Modular Reactor (Pty) Ltd. | November 19, 2008 |
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| Roger Young, Pebble Bed Modular Reactor (Pty) Ltd | October 24, 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
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# RECORD OF CHANGES

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| NGNP and Hydrogen Production Preconceptual Design Report | NGNP-01-RPT-001 | 0 |

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## ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |

| Acronym | Definition |
|---|---|
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |

| Acronym | Definition |
|---|---|
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |

| Acronym | Definition |
|---|---|
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

This document summarizes the plant-level operation of the Pebble Bed Modular Reactor (PBMR)-based Next Generation Nuclear Plant (NGNP) Demonstration Plant concept and presents the nominal operating conditions as defined in the Preconceptual Design Report (PCDR) and modified in subsequent Conceptual Design Studies.

The modes diagram from *PCDR Section 11 – Overall NGNP Operation* [1-1] was re-arranged into a more systematic arrangement in order to provide a qualitative overview of the plant operating envelopes.

To date, no plant-level NGNP transient simulations have been done. The transient analyses will form part of the conceptual design process and falls outside of the scope of this study. None of the operating Modes, States, Transients and Transitions, nor the SSC dimensions can be confirmed as of yet. Therefore, the conceptual design of the Component Test Facility (CTF) is based on the steady-state PCDR [1-2] and Intermediate Heat Exchanger (IHX) Conceptual Design Study [1-3] as reference.

It is further noted that the technology roadmaps and maturation plans will need to be adjusted as new design data needs (DDNs) evolve as part of the conceptual and preliminary design effort. Therefore requirements influencing the CTF will continue to emerge during the NGNP Conceptual Phase.

# 1 NGNP SYSTEMS AND OPERATIONAL DESCRIPTION

The NGNP Demonstration Plant consists of various Systems, Structures and Components (SSCs) integrated into a functional plant capable of producing process heat for hydrogen production as well as electricity (used notably for hydrogen plant but also for export). The Westinghouse Team NGNP Demonstration Plant consists of a 500 MW pebble bed reactor with primary and secondary helium loops coupling a 470 MW steam generator and a 50 MW process coupling heat exchanger for the hydrogen production system.

In order to minimize the safety and economic risk of the NGNP Demonstration Plant, the intent is that all the SSC's should have demonstrated the ability of the applied technologies to function according to specification within their intended operational environment, prior to nuclear start-up of the NGNP Demonstration Plant. This would then leave the ability of these technologies to perform according to specification when integrated into their final NGNP Demonstration Plant configuration as the remaining risk to be addressed.

Obviously the advancement of the readiness of technology for application within the NGNP needs to be addressed at the level of the SSC within which the technology is being applied. There are SSCs which use technology that is either commercially unavailable or lacks proven industry experience, thus further technology development needs to be done for these SSC's to achieve acceptable Technology Readiness Levels (TRL) prior to installation in the NGNP.

In addition, given the current design maturity of the NGNP Demonstration Plant, it is recognized that not all the DDNs are identified at this stage and it is highlighted that the technology development needs will be supplemented as the integrated design progresses.

This section will describe the overall NGNP system and provide an operational description of two NGNP applications (at different temperatures) under consideration. There are a number of systems that are similar between the two applications, however at different operating conditions.

## 1.1 Steady State Conditions (Hydrogen Production at 950°C)

The overall operation and control of the NGNP is described in detail in *PCDR Section 11 - Overall NGNP Operation* [1-1] and will not be repeated here, other than to present the steady state conditions which have evolved through the NGNP Conceptual Design Studies completed subsequent to the definition of the PCDR baseline.

The process flow diagram of the NGNP Demonstration Plant for Hydrogen Production is given in Figure 1-1.

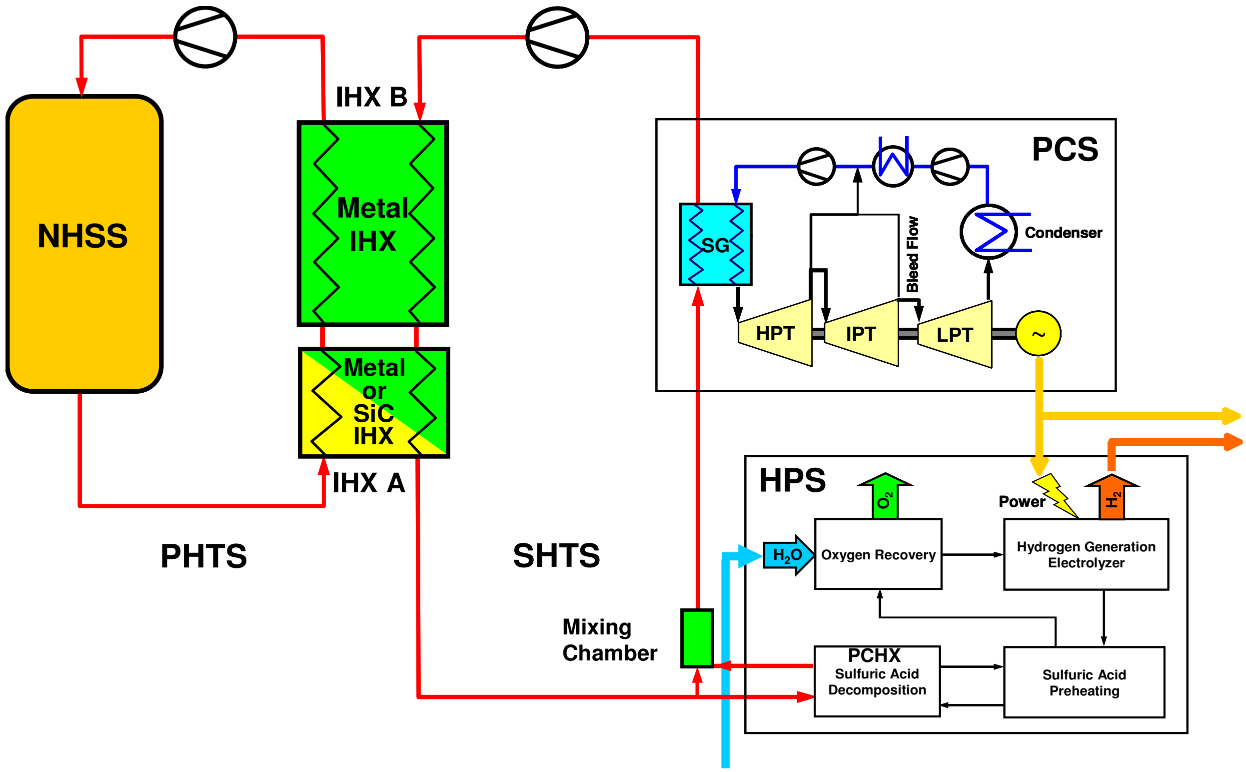


**Figure 1-1: NGNP Demonstration Plant Process Flow Diagram – Hydrogen Production (950°C)**

The latest reference schematic of the NGNP at 950°C was documented in the *NGNP Conceptual Design Study: IHX and HTS* [1-3]. The Heat Transport System (HTS) is comprised of the primary HTS and the secondary HTS as described in *PCDR Section 6 - Heat Transport System* [1-4]. The reference steady state operating conditions are presented in Figure 1-2 of [1-3] and repeated below in Figure 1-2. below.

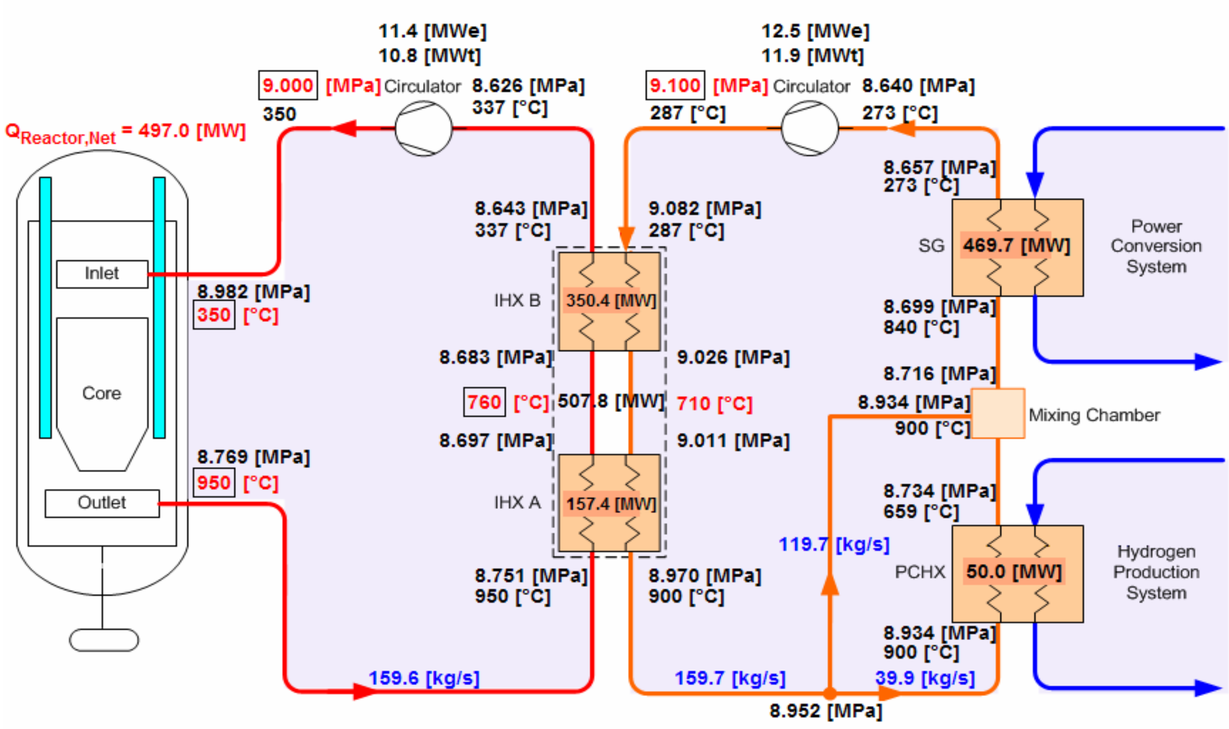


**Figure 1-2: Nominal Process Conditions for the NGNP Demonstration Plant (Hydrogen Production, 950°C)**

## 1.2 Steady State Conditions (Steam Production at 750°C)

The NGNP Preconceptual Design and conceptual design studies to date have focused on a 950°C reactor outlet temperature for hydrogen production. Depending on the process application, various alternatives to the reference preconceptual design are possible. The schematic in Figure 1-3 presents one option for a steam production plant, and this option will be used as the 750°C reference for the purposes of this study. In this option, the Process Coupling Heat Exchanger (PCHX) is removed from the Secondary Heat Transport System (SHTS) and a single Intermediated Heat Exchanger (IHX) is retained. The steam could be used for electricity production, process steam or cogeneration. This configuration represents the minimum departure from the PBMR NGNP Preconceptual Design and would provide enveloping development requirements for 750°C applications. It is potentially representative of applications, such as oil sands, in which extreme water quality requirements or other considerations (e.g., tritium migration) would dictate the use of an IHX. In other applications, it may be possible to eliminate the IHX and relocate the SG to the Primary Heat Transport System (PHTS). The actual configuration of a 750°C application remains subject to trade studies that would be done when functions and requirements are identified.

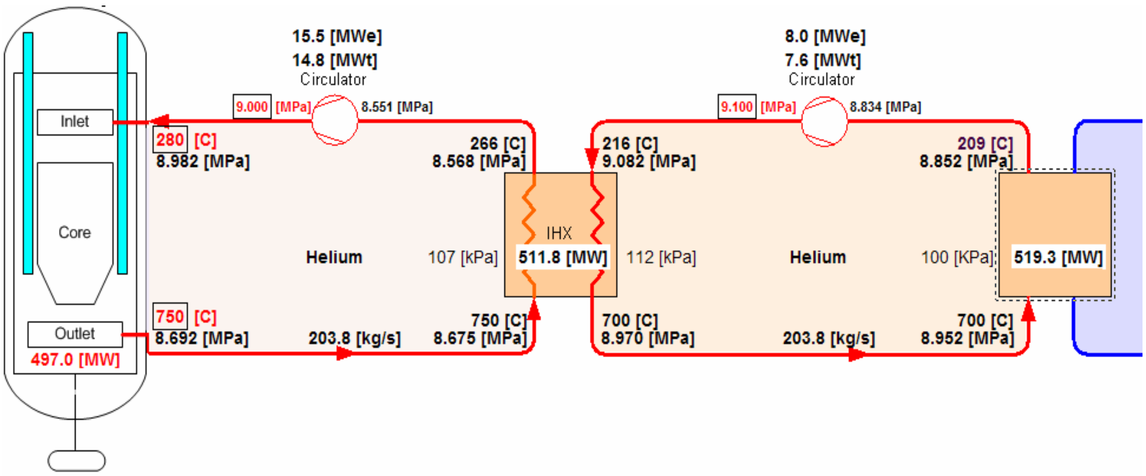


**Figure 1-3: Nominal Process Conditions for a NGNP Steam Production Plant (750°C)**

## 1.3 High-Level Operating Envelope (Hydrogen Production at 950°C)

In order to have a clear link between component testing and the plant design, it is necessary to derive the test requirements from the intended operating range of each component in the NGNP. It is recognized that it is not sufficient to simply use nominal operating conditions to determine the test parameters for an SSC, as the design would notably need to accommodate various transitions such as startup or shut-down and transient events such as loss of heat sink. The risk of missing such a condition can only be avoided by explicitly determining the complete operating envelope of the plant and consequently each SSC. This is done by calculating the component conditions during each state and event in the Modes and States. However, at this stage, the conceptual design of the integrated NGNP system has not been done and, consequently, detailed transient constraints have not been analyzed or quantified for each SSC. Hence, at this point in time, the test plans of the CTF are mostly based on steady state requirements.

The Modes and States for the NGNP, as described in Figure 11.2-2 *PCDR Section 11: Overall NGNP Operation* [1-1], has been rearranged as shown in Figure 1-4, where the states are numbered in order to create a consistent numbering system for the Transitions and Transients. Transitions and Transients are numbered according to the start state and the end state between which it takes place.

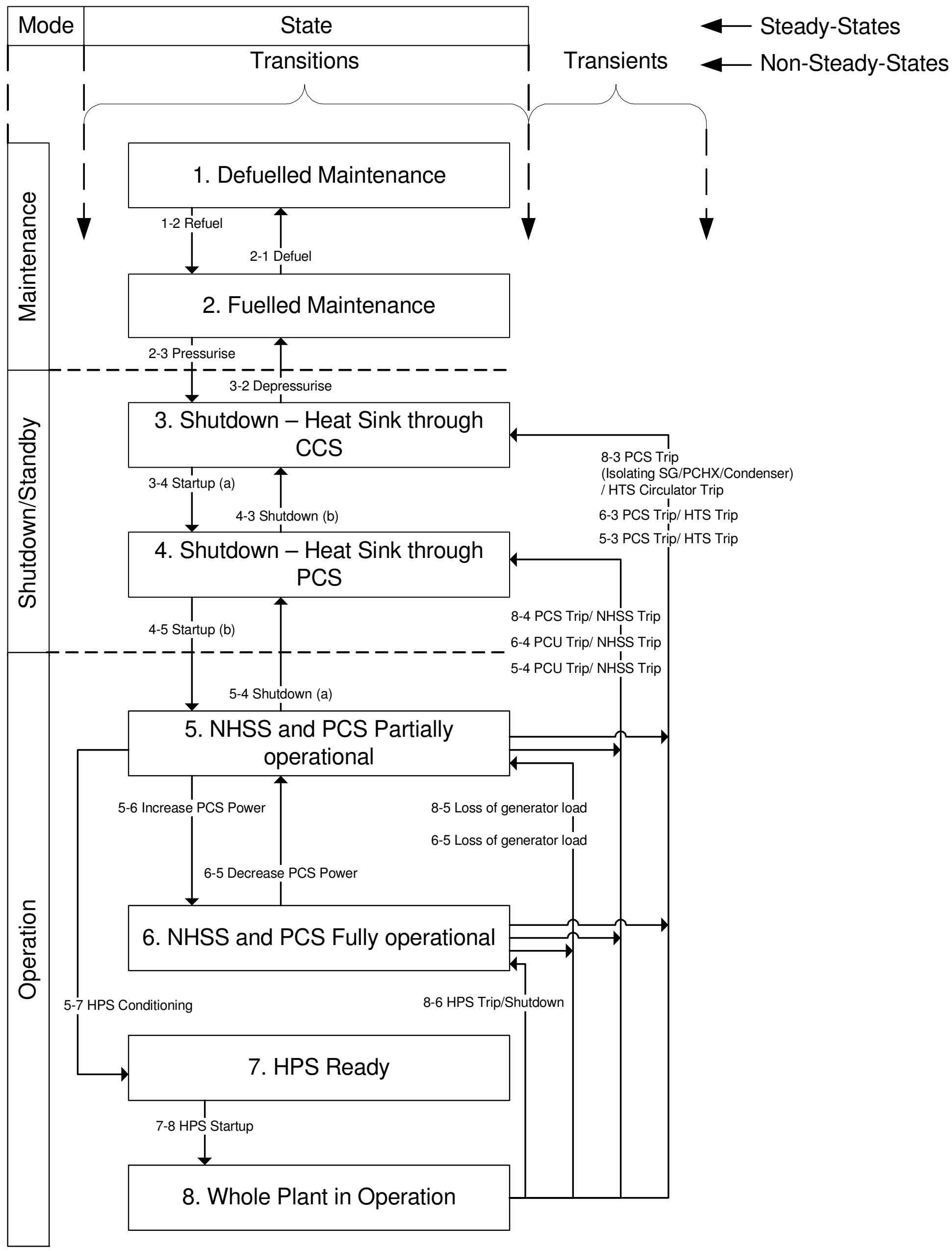


**Figure 1-4: Modes, States, Transitions and Transients for the NGNP.**

**<u>NOTE:</u>** These modes, states, transitions and transients are all subject to revision during conceptual and preliminary design when a more thorough and intensive functional analysis is done to a level where the specific SSC Failure Modes, Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA) can identify the expected plant- and SSC level responses to component failures or responses to external events.

At this stage it is useful to distinguish between modes, states, transitions and transients. Modes are high-level groupings of steady-state conditions or “States”, as shown in Figure 1-4.

"Transitions" are events that the plant is designed to undergo as a matter of day-to-day operation, while "Transients" are undesirable events which the plant has to be able to withstand.

Given that transitions are controlled changes between modes and states, all transitions will be specified, designed and performed to ensure that the SSCs remain within their nominal operating parameters where possible.

Considering that transients are essentially plant and SSC responses to anticipated operational occurrences (AOOs) and the plant operational control system will be responding to these changes of conditions and a full analysis of the plant response has not been performed, an assumption is required at this stage regarding the ability of the operational control system to manage these events. For the purposes of determining a bounding set of conditions for all the SSCs it is thus assumed that the plant operating control system will be able to respond to all anticipated operational occurrences such that the operational parameters being measured will not exceed the nominal full power values by more than 10% (assumption to be confirmed during conceptual design).

It must be kept in mind that currently, only the nominal operating state is well defined. For other operating conditions, the power levels, detail control strategy and temperature levels still have to be clarified in more detail than described by *PCDR Section 11 - Overall NGNP Operation* [1-1] if component envelopes are to be properly defined.

For determining the transient requirements to SSC`s, it is necessary to do full transient simulations of the applicable systems. To date, no plant-level NGNP transient simulations have been done. The transient analyses will form part of the system-level conceptual design and falls outside of the scope of this study. Therefore, this section will not cover transient simulations.

# REFERENCES

[1-1] NGNP and Hydrogen Production Preconceptual Design Report, NGNP-11-RPT-001, Section 11 – Overall NGNP Operation

[1-2] NGNP and Hydrogen Production Preconceptual Design Report, NGNP-03-RPT-001, Section 3 – Plant Level Design and Integration

[1-3] NGNP Conceptual Design Study: IHX and HTS, NGNP-HTS-RPT-TI001

[1-4] NGNP and Hydrogen Production Preconceptual Design Report, NGNP-06-RPT-001, Section 6 – Heat Transport System

**NGNP-CTF MTECH-TDRM-002** **November 2008**
**Revision 1**

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 2: Technology Development Road Mapping Process

**APPROVALS**

| Function | Printed Name and Signature | Date |
|---|---|---|
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| Reviewer | Name: Renée Greyvenstein<br>Company: Pebble Bed Modular Reactor | November 20, 2008 |
| Approval | Name: Jan van Ravenswaay<br>Company: M-Tech Industrial | November 21, 2008 |

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| Jan van Ravenswaay (M-Tech Industrial) | October 17, 2008 |

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## ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |

| Acronym | Definition |
|---|---|
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
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| PPM | Parts per million |
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| RIT | Reactor Inlet Temperature |
| RM | Road Map |
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| RPS | Reactor Protection System |

| Acronym | Definition |
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| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
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| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
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| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# 2 TECHNOLOGY DEVELOPMENT ROADMAPPING PROCESS

## 2.1 Introduction to NGNP TDRM Process

For the NGNP, levels of readiness of needed technologies have been assessed. However, these levels vary significantly for the various Systems, Structures and Components (SSCs). The overall technology readiness assessment process is referred to as Technology Development Roadmapping (TDRM). The TDRM process is used to assess, map, plan and visualize the needed technology development activities to advance the technology readiness of a particular System, Structure or Component (SSC) to a state that will reduce commercial risk and support plant operation. The TDRM process determines what is needed *firstly* to verify the performance and safety of the SSC and *secondly* to minimize the risk associated with operating the SSC. The latter is achieved through a series of scale test programs, up to and including tests at full-scale NGNP plant temperatures, pressures and flow rates. These test programs are documented in Test Plans which specifies the needed maturation tasks to advance the relevant technologies (Refer to Figure 2.1).

For the purpose of this document, only critical SSCs to be utilized in the 950℃ NGNP demonstration plant have been considered. Critical SSCs are defined as Systems, Structures and Components that are not commercially available or do not have proven industry experience. The following deliverables are relevant in the TDRM process for these SSCs:

- Technology Development Roadmaps, which sets out the high level vision for maturing certain technologies up to a point where the technology can be utilized in the NGNP
- Technology Readiness Level Rating Sheets, which supplies the current readiness of a particular SSC to serve as input into the NGNP
- Technology Maturation Plans, which specifies the more detailed plans/actions required to mature technologies for utilization in the NGNP
- Test Specification, which provide a requirement for specific testing

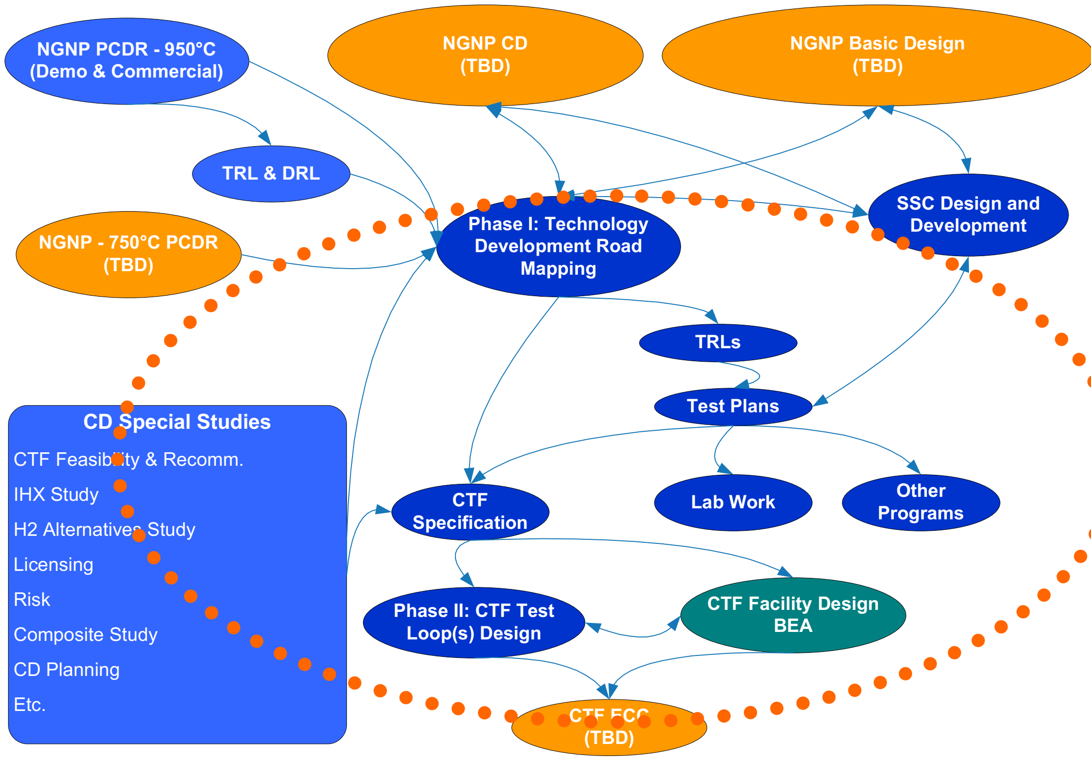


**Figure 2-1: TDRM Process with Associated Outputs**

## 2.2 Technology Development Roadmap

Shown in Figure 2.2 is a typical Technology Development Roadmap. The roadmap is typically populated with items relating to down selection of technologies (shown on the left side of the roadmap), TRL of the technology (yellow blocks) and technology maturation tasks needed for advancement (shown on the right side of the roadmap).

Items shown on the left of the roadmap involve the following aspects:

- Candidate Technologies
- Decision Discriminators
- Down Selection Task

Items shown on the right of the roadmap involve the following aspects

- Appropriate TRL Levels
- Technology Maturation Tasks

Additional information reflected in the roadmap involves:

- Timeframe for completion of maturation of technology
- Mission at reaching validated TRL levels
- All applicable references/input into the roadmap

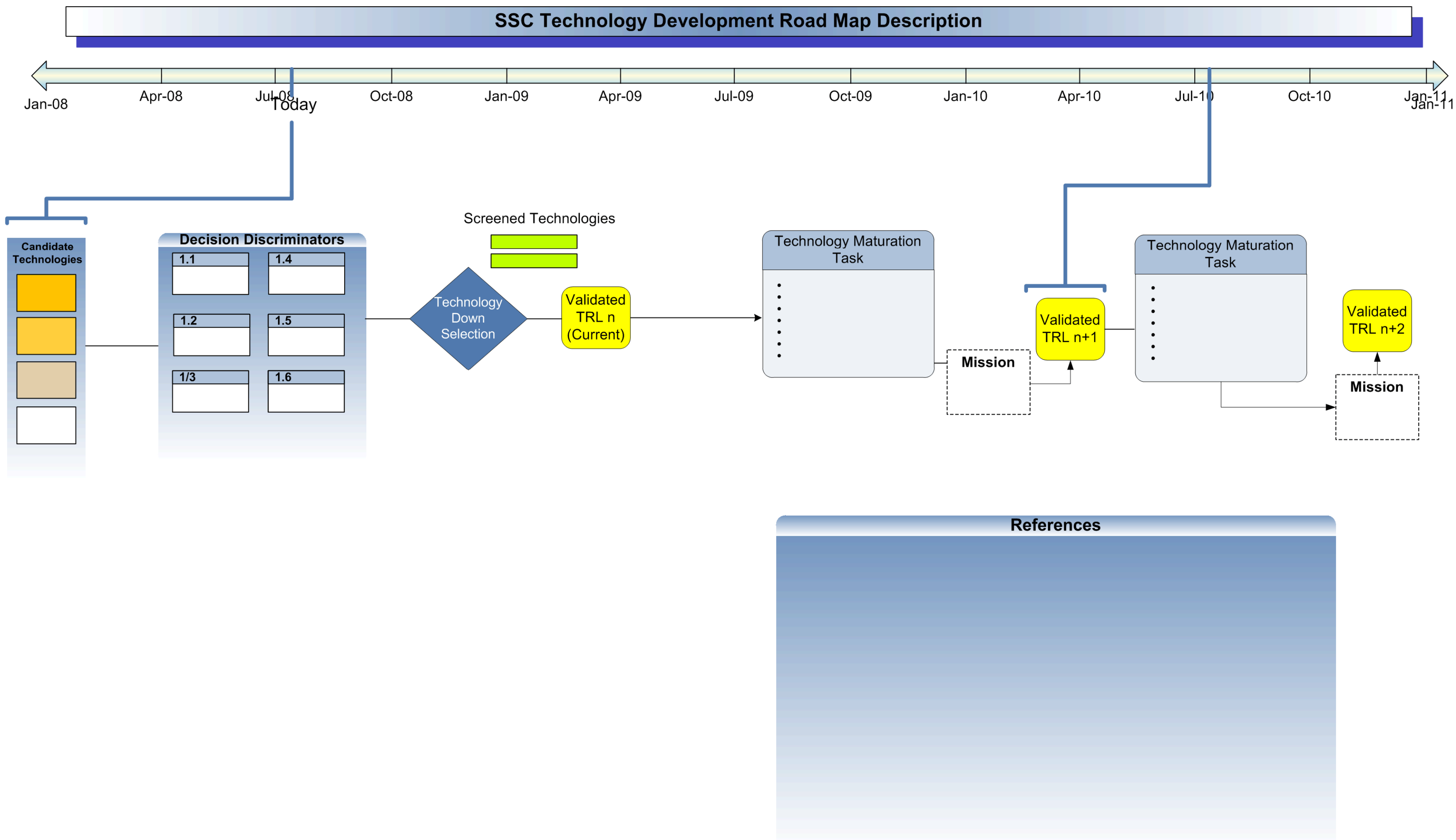


**Figure 2-2: TDRM Example**

On the left side of the roadmap, all candidate technologies that are in contention to be utilized for the NGNP are shown. The Decision Discriminators shown just to the right of the technology candidates on the roadmap are used to guide a down selection of the available technologies. Typical decision discriminators may entail *inter alia service experience of technologies*, *available data* and *maturity of respective technologies*. Upon the screening of the candidate technologies against the decision discriminators, a down selection can be made.

On the right side of the roadmap, the current TRL rating together with the Maturation Tasks necessary to achieve progressively higher levels of Validated TRLs up to a TRL 8 are shown. At each validated TRL level, a mission statement is stated which gives an indication at which environmental parameters the qualification has been conducted. All the maturation tasks shown in the roadmap are also linked to a schedule in the form of the timeline shown in Figure 2-2. References that serve as input into the roadmap at this stage involve *Design Data Needs, Preconceptual Design Documents* and *Special Studies*.

## 2.3 Technology Readiness Levels

Technology Readiness Levels are ratings between 1 and 10 assigned by Subject Matter Experts to a certain Island/System/Structure/Component/Technology (ISSCT) which gives an indication of the maturity of the ISSCT involved. Various definitions are assigned to the existing TRL ratings and are shown in Table 2.1. For explanation of relevant terminology referred to in Table 2-1, please refer to Appendix B.

As an aid to understanding the context under which TRL ratings are applied, Figure 2-3 depicts the interrelationship among the TRL ratings, their abbreviated definition, the increasing amount of integration and testing.

### Table 2-1: TRL Definitions and Abbreviations [2-1]

| Rating Level | Technology Readiness Level Definition | TRL Abbreviated Definition |
|---|---|---|
| 1 | **Basic principles observed** and reported in white papers, industry literature, lab reports, etc. Scientific research without well defined application. | Basic principles observed |
| 2 | **Technology concept and application formulated.** Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation. | Application formulated |
| 3 | **Proof-of concept:** Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service. | Proof of Concept |
| 4 | **Technology or Component is tested at bench scale to** demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties. | Bench scale testing |
| 5 | **Component demonstrated at experimental scale in relevant environment**. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection. | Component Verified at Experimental Scale |
| 6 | **Components have been integrated into a subsystem** and demonstrated at a pilot scale in a relevant environment. | Subsystem Verified at Pilot scale |
| 7 | **Subsystem integrated into a system** for integrated engineering scale demonstration in a relevant environment. | System demonstration at Engineering Scale |
| 8 | **Integrated prototype of the system is demonstrated** in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup | Integrated Prototype Tested and Qualified |
| 9 | **The project is in final configuration** tested and demonstrated in operational environment. | Plant Operational. |
| 10 | **Commercial-scale demonstration** is achieved. Technological risks minimized by multiple units built and running through several years of service cycles. | Commercial Scale – Multiple Units |

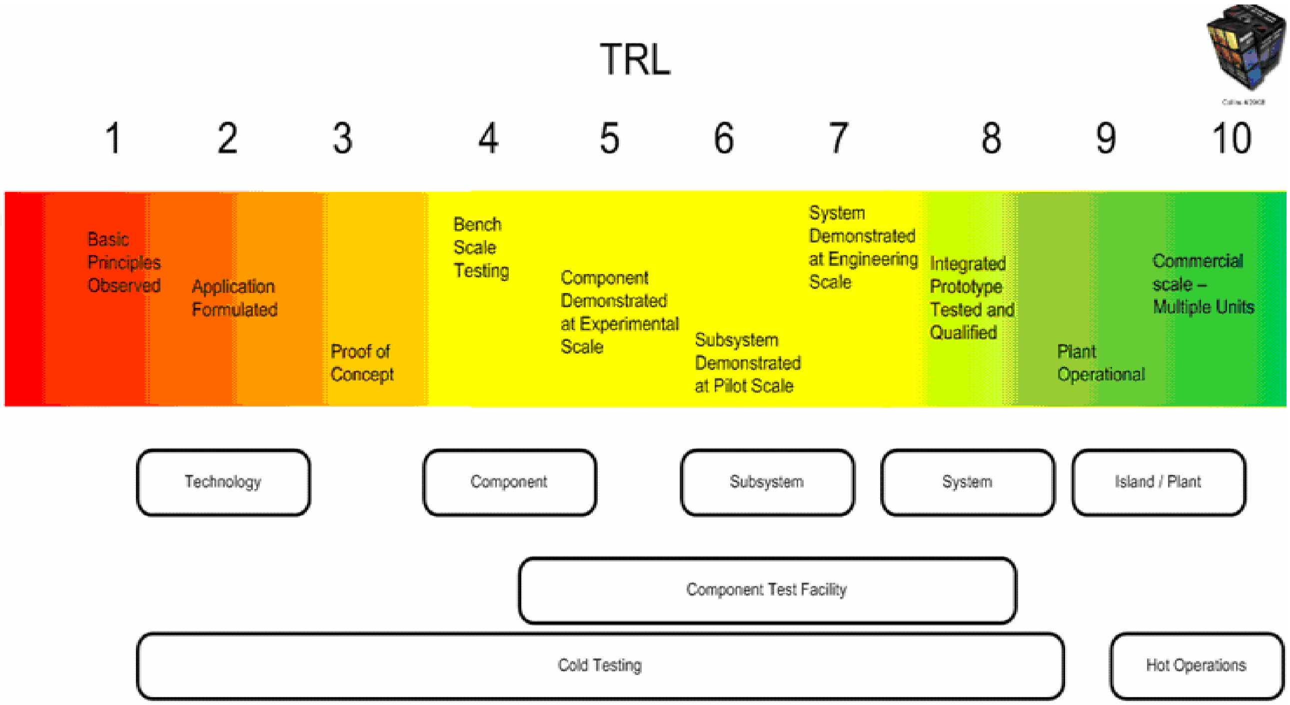


**Figure 2-3**: **TDRM Process with Associated Outputs**

The TRL ratings for the associated SSCs are captured in the TRL Rating Sheets as displayed in Table 2-2. These sheets reflect the following information:

- The current TRL Rating of the SSC
- Basis of rating: Justification for the calculated readiness, which can include one of the following:
    - Trade studies completed
    - Tests and actions completed
    - Reference documentation
- Outline of actions/tests needed to advance to higher TRL ratings
- Cost and schedule associated with advancement to a successively higher TRL level
- All DDN's supported / resolved through the action plans to advance the TRL rating

**Table 2-2: TRL Rating Sheet Example**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: | Document Number: | | Revision: |
| ☐ Island ☐ System ☐Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: | | | |
| Description: | | | |
| | | | |
| Island(s): ☐ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP | | | |
| ISSCTBS: | Parent: | WBS: | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | | | |
| **TRL** | # | **#** | # |
| Basis for Rating (Attach additional sheets as needed) | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (K$) | |
| | | | |
| DDN(s) supported: | Technology Case File: | | |
| Subject Matter Expert Making Determination: | | | |
| Date: | Originating Organization: | | |

## 2.4 Test Specifications

In the TDRM process, the associated details for each action/test required to advance an SSC to progressively higher TRL levels are captured in test plans. These test plans incorporate details ranging from material qualification specifics to prototypical SSC testing details. The test plan content can reflect the following details:

- Function of test
- Duration of test
- Scale of test article
- Proposed Location
- Test Items
- Scope of testing (i.e. features to be tested)
- Approach/Method
- Evaluation Criteria
- Test Deliverables
- Planning Risks & Contingencies

## 2.5 Principles followed in the TDRM Process

Although the NGNP requires a critical SSC to be at a minimum of TRL 7 before utilization in the NGNP, the preferred option is to have an SSC qualified at a TRL 8 before being installed into the NGNP. Some critical SSC's are envisioned to be supplied to the NGNP at a validated TRL 7, primarily because qualification of the applicable full scale SSC in its operational environment is deemed uneconomical or unpractical outside the NGNP. Other SSC's that propose envisioned qualification testing in other locations (notably the CTF, PBMR HTF and the PBMR DPP) are advanced to TRL 8 levels independently from the NGNP if the operating conditions of these facilities envelope the NGNP requirements in the relevant fields (*fields may involve temperature, pressure, mass flows, etc).* Consequently, no additional testing will then be required. However, if the NGNP operating envelope is not covered by these alternate testing facilities, testing in these facilities will only advance and supply the applicable SSC's to the NGNP at a TRL 7.

It must be recognized that once the down select of technology has been made and the SSC is at TRL 6, all subsequent tasks are in fact design maturity advancement tasks of the SSC, as it is no longer only the technology and the manner in which it is being applied within the SSC that is under scrutiny, but now the manner in which the SSC is being applied within its operational environment. For this reason it is believed pertinent to include a description of the PBMR (DPP) Qualification Process (Appendix A) which describes how the SSCs are individually brought to a status where the risk involved in starting up the plant is adequately addressed. In addition it covers the activities to ensure that the plant can operate within its design parameters for the intended life cycle.

## 2.6 References

[2-1] INLÆXT-08-14251, Rev 0: Technology Readiness Level Plan

# APPENDIX A: PBMR QUALIFICATION PROCESS

# A THE PBMR QUALIFICATION PROCESS

## A1 INTRODUCTION

The PBMR Qualification Process is a formal and logical process aimed at the generation and maintenance of evidence to ensure that all safety classified systems and its equipment will operate reliably within design requirements under all operating and accident conditions.
All SSCs within the PMBR plant are subjected to the same qualification approach graded according to its contribution to safety.

## A2 THE QUALIFICATION PROCESS

The integrated qualification programme for the Structures, Systems and Components (SSC) is divided into logical stages to facilitate a process of progressive confidence building and risk reduction.

The SSC that uses software to implement operational functions needs that software to be completed according to the applicable Software Life Cycle Process before the SSC Equipment Qualification (EQ) can be finalised. The Software Lifecycle Process includes all the software verification and validation tasks that are needed to satisfy the requirements.

The quality assurance requirements for software used in SSC for the PBMR are as per ASME NQA-1-2004.

The major stages of EQ as indicated in Figure A1-1 are the following:

### A2.1 Equipment Qualification

Equipment Qualification (EQ) ensures that the individual SSC designs are robust and comply with their design specifications, including safety and functional requirements.

The initial phase of EQ is conducted prior to installation in the plant (i.e. off-site). Termed the **EQ Verification Phase**, it includes functional, environmental and seismic assessment. The SSCs capability to perform its safety functions under anticipated operational and environmental stresses associated with Design Basis Accidents and postulated seismic events is deterministically verified during this phase. Seismic response is by analysis except for some systems that are physically tested. Some repetitive or cyclic testing may be done during this stage to provide supportive probabilistic data.

Only in exceptional cases, typically where infrastructure or interface restrictions have been identified, are functional verification tests conducted on site on installed SSC during commissioning of the plant.

After installation on the plant (site-based) the **EQ Validation Phase** starts, validating the performance of the individual SSC within their installed environment. No environmental or seismic qualification activities are conducted during this phase.

During the commercial operation of the plant, the operating utility must ensure that all SSC of high and medium safety significance retain their qualification status. This **EQ Preservation Phase** shall be achieved through technical specification In-service Surveillance Testing, In-service Inspections, Surveillance Testing and Continuous Plant Health and Condition Monitoring, and Operational Performance Monitoring. This will tie in with the Technical Surveillance Programme.

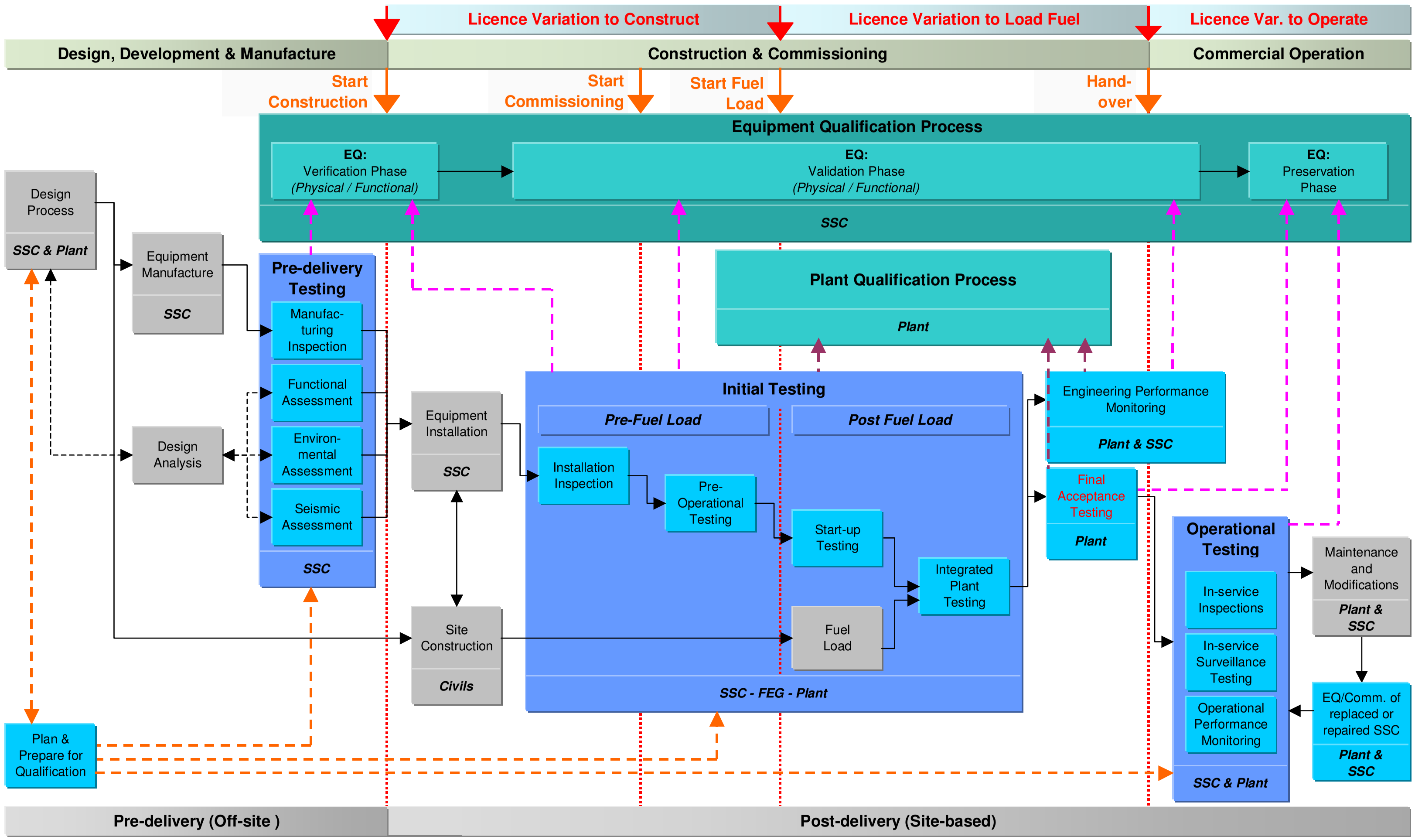


**Figure A1-1: PBMR Integrated Qualification Process**

Where SSC of high and medium safety significance have become obsolete and are replaced by new SSC, EQ tests shall be conducted before installation to verify the design of the new equipment. Commissioning testing shall be conducted after installation of the new equipment, or where major maintenance activities have been conducted on equipment, to verify the installation and integrated functioning of such equipment.

Probabilistic data shall also be captured during this phase to support the Reliability Growth Programme and Product Improvement Programmes.

## A2.2 Installation Inspection (Site-based)

Installation Inspections are physical inspections that are conducted after SSC have been installed and integrated into the plant, to confirm correct installation before the equipment is commissioned. This phase will include the seismic qualification reconciliation process.

## A2.3 Initial Testing (Site-based)

Initial Testing is divided into pre-fuel-load testing and post-fuel-load testing. The pre-fuel-load testing is carried out before fuel may be brought on site. The pre-fuel-load inspection and testing verifies that installed equipment, functional equipment groups, control systems and safety features are functional before fuel is loaded into the reactor. This phase also confirms that operational staff is suitably trained, and that required operating and maintenance procedures are in place.

Once the pre-fuel-load testing is completed successfully and the license to load fuel is approved by the Nuclear Regulator, the stepwise loading of fuel and start-up testing commences. This phase ends with the Integrated Plant Testing. All integrated functions of the plant, including start-up, reactivity control, power ascension, reactor shutdown, load following and load rejection are verified during this phase. The first electrical generation to the grid shall occur during this stage.

## A2.4 Final Acceptance Testing (Site-based)

On successful completion of the post-fuel-load testing, the client verifies that the plant complies with contractual requirements, prior to handover. This is called the Plant Acceptance Testing.

## A2.5 Performance Monitoring (Site-based)

Performance Monitoring is an engineering activity concerned with the validation of the performance of the plant and its individual SSC against their development specifications. Engineering data is gathered by design engineers from operational tests and inspections.

Instrumentation monitoring confirms and where necessary addresses variations in the plant and SSC performance and design data packs, software and computer models. This monitoring takes place throughout the pre-fuel-load, post-fuel-load, plant acceptance testing and operational phases.

### A2.6 Operational Testing (Site-based)

On successful completion of the plant acceptance testing and demonstration of the safe operation of the plant, the client can apply for the license to operate the plant. During the operational phase and throughout the service life in-service testing, in-service inspection and monitoring of the plant and individual SSC performance will continue. Together with the maintenance programme Operational Testing will ensure that all systems are functioning to specification, and that the qualification status is retained.

## A3. EQUIPMENT QUALIFICATION VS PLANT QUALIFICATION

Figure A1-2 emphasizes the difference as well as the interfacing between the Equipment Qualification process and the Plant Qualification process. This process is initiated prior to plant installation and is monitored and maintained throughout the service life of the plant by using data obtained from the plant qualification process and from operational testing conducted during commercial operations.

The qualification of the plant comprises a progressive process to build confidence in the plant's ability to operate as required. It starts with the verification of individual SSC performance during the EQ verification phase, followed by installation inspection of installed equipment, and then the initial testing on individual SSC, functional equipment groups, and the integrated plant during commissioning. The Plant Qualification process is more concerned with the functioning of the integrated plant when subjected to Anticipated Operational Occurrence and plant trips.

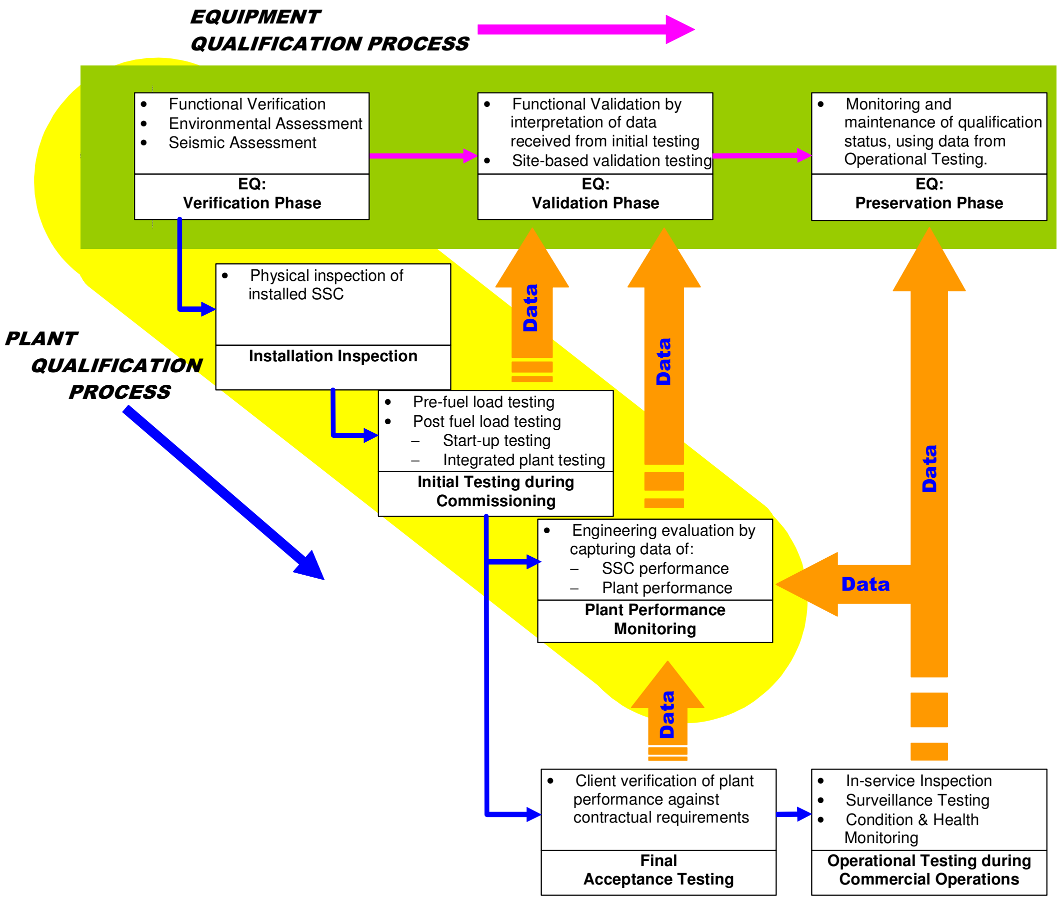


**Figure A1-2: Equipment Qualification vs. Plant Qualification**

# A4 MANAGEMENT OF THE QUALIFICATION PROGRAMME

## A4.1 Roles and Responsibilities in the PBMR Qualification Process

Due to the turnkey nature of the PBMR development, PBMR (Pty) Ltd is responsible for providing a qualified plant to the client. The plant is qualified to meet all regulatory safety requirements as well as the relevant contractual requirements. Off-site qualification activities are conducted by the SSC suppliers under PBMR supervision, while PBMR (Pty) Ltd and the client conduct most site-based activities. The qualification programme is compiled, executed and managed in accordance with a formal, well-documented and transparent process. Figure 3 illustrates the roles and responsibilities of the various parties involved in the Qualification process, and the detail is discussed in the remainder of this section.

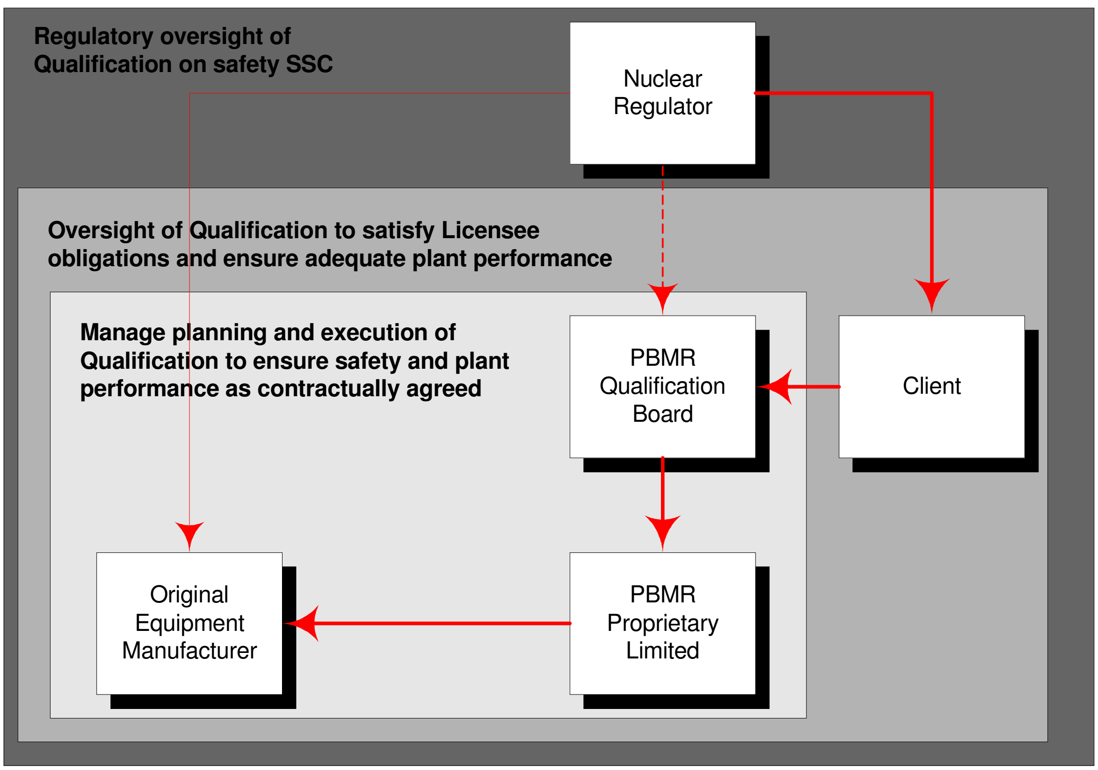


**Figure A1-3: Illustration of Roles and Responsibilities in the Qualification Process**

## A4.2 PBMR Plant Qualification Manager

The PBMR Plant Qualification Manager has the primary responsibility for the planning, documentation, execution and management of all qualification activities within PBMR (Pty) Ltd. The PBMR Plant Qualification Manager controls the qualification of SSC, manages the qualification tests at off-site locations, and provides supervision of any site-based qualification tests executed during commissioning of the integrated plant. All site-based tests executed during commissioning of the integrated plant are executed under the overall supervision of the Client Commissioning Manager. The responsibilities of the PBMR (Pty) Ltd personnel involved in qualification are detailed in the PBMR Qualification Management Plan. The Plant Qualification Manager is also the chairman of the PBMR Qualification Board.

## A4.3 The Client

The client as the licensee ensures that the PBMR qualification programme sufficiently addresses all contractual performance and nuclear safety requirements in support of the various licensing stages. Interaction with the PBMR Plant Qualification group is done through the PBMR Qualification Board (PQB) on which the Client serves as a standing member. The client ensures the distribution of all qualification information pertaining to nuclear safety to the Nuclear Regulator.

## A4.4 Nuclear Regulator

The Nuclear Regulator as the licensor ensures that the PBMR qualification programme complies with national nuclear safety requirements and international nuclear safety guidelines and participates in the PQB as an observer to ensure independent oversight. The Nuclear Regulator may request any qualification information and may conduct qualification audits at PBMR (Pty) Ltd and any of its suppliers.

## A4.5 PBMR Qualification Board

The PQB is responsible for approving all SSC and plant qualification and commissioning programmes, as well as the associated qualification results. The Plant Qualification Board has the authority to certify, or refuse certification of, an SSC to meet its qualification requirements. In order to promote efficient handling and consideration of issues before the Plant Qualification Board, the NGNP client is a standing member of this board, and the Nuclear Regulator will be co-opted by the NGNP client as required.

## A4.6 Qualification Management Structure

The qualification management structure internal to PBMR (Pty) Ltd varies depending on the project phase. Each of the following requires a different qualification management structure:

- Management of planning for qualification.
- Management of off-site qualification.
- Management of site-based qualification.
- Management of site-based commissioning.

The management structure for each phase given above is described in the Qualification Management Plan.

## A4.7 Qualification Management Activities

Qualification Management activities include the following:

- Approval of the qualification programmes and reports
- SSC Certification process
- Scheduling of qualification tasks
- Qualification risk/hazard and operability assessment
- Safety assessment of qualification activities
- Manage the communication within PBMR and to the subcontractors
- Propose regulatory hold and witness points for approval by the Nuclear Regulator
- Manage the execution of the approved hold and witness points with involvement of the Nuclear Regulator
- Manage the configuration of documents and qualification data during qualification
- Execute qualification audits and design reviews during the qualification programme
- Manage the handling of failures during tests
- Manage the handling of deviations from test and analysis specifications
- Manage the reporting of the occurrence of unusual incidents during the qualification program.

## A4.8 Qualification Documentation

The documents relating to the qualification programme is divided into the following six categories:

- Qualification planning documentation
- Qualification execution documentation
- Qualification output documentation
- Qualification control documentation
- Qualification process documentation
- Qualification guidelines

## A4.9 Management of Facilities and Equipment

Existing test facilities are utilized as far as possible for development and qualification testing, however dedicated facilities may be constructed for specific SSC tests. All test facilities are subjected to a formal PBMR authorization process prior to initiation of any test programmes. The test facilities are evaluated for their suitability to fulfil identified test requirements.

# APPENDIX B: TERMINOLOGY OF TRL DEFINITIONS

# Nomenclature

**Bench Scale** – A technology to be tested that will provide the data or demonstration intended but is not necessarily like the design of the final SSC. (~1:3600 scale)[1]

**Experimental Scale** – A component to be tested that will provide the data or prove function intended but is not necessarily like the design of the final SSC. (~1:1000 scale)

**Pilot Scale** – A model or facsimile of the subsystem used as a basis or standard for proof of principle testing and/or operation. The model or facsimile may progress through several evolutions, but is not necessarily in form or fit a final version. (~1:100 scale)

**Engineering Scale** – A model or facsimile of the system used as a basis or standard for proof of principle testing and/or operation. The model or facsimile may progress through several evolutions, but is not necessarily in form or fit a final version. (~1:20 scale)

**Prototype** – Subsequent to Pilot/Engineering Scale model or facsimile of the SSC, a version that is intended to be the final version or is an evolutionary step toward the final version. (~1:4 scale)

**Lab Environment** – Refers to a controlled environment where effects can be quantified with appropriate accuracy.

**Relevant Environment** – Refers to an environment that does not necessarily have the same temperatures and pressures, but is close. Not necessarily the same fluids, but chemically similar insofar as thermo-fluid and corrosion/reaction. This would apply, for example, to AGR and AGC testing in ATR.

**Operational Environment** – For SSCs normally operating when the plant is running, the operational environment consists of the normal operating fluids, and anticipated temperatures (static and transient) and pressures (static and transient). For SSCs not normally operating, the operational environments are the design basis operating fluids, temperatures and pressures.

[1] Scale provided for illustrative purposes only. The applicable scale will be determined by the specific SSC development plan based on the SSC size and the ability to generate acceptable test results at a specific scale.

NGNP-CTF MTECH-TDRM-003 November 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 3: PHTS Circulator

**APPROVALS**

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**Section** **Title** **Page**

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## LIST OF FIGURES

## ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |

| | |
|---|---|
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |

| | |
|---|---|
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |

| | |
|---|---|
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# SUMMARY AND CONCLUSIONS

The PHTS circulator is a critical component of the NGNP with its main function being to circulate the primary coolant helium within the PHTS. The PHTS circulator primarily needs to overcome the pressure losses associated with the PHTS flow path (notably including the PBMR, the hot gas ducting and IHX). After leaving the circulator, helium flows through the reactor core where it removes approximately 500 MWt energy. From there the helium flows to the IHX where the energy removed from the core, along with the compression energy added by the circulator, is transferred to the SHTS.

Discriminators have been identified to assist in the selection of an optimum design for the PHTS circulator. These discriminators address the required technology development, the availability of a manufacturing base, the circulator operation and maintenance, the safety and investment implications and the lifecycle costs.

Several arrangements and design options are available for the PHTS helium circulator that satisfy the preconceptual functions and design requirements. The large PHTS circulator can be replaced by a number of smaller circulators arranged in parallel. The trade-offs of one versus multiple circulators also have system-level trade-offs (controllability, reliability, size, etc.), as documented in NGNP-HTS-RPT-TI001 Section 3.5.3. Hence, the decision of single versus multiple circulators will be influenced by a combination of system-level and circulator-specific trade-offs.

The compressor drive can be located inside or outside of the helium pressure boundary and the bearings can be conventional oil lubricated or electromagnetic. The type of bearings selected imposes additional requirements for dedicated service systems for support. Additionally, the compressor design can be of the radial, axial type or mixed flow (axial/radial), depending upon the economics, required efficiency, available space within the primary pressure boundary, and the maintenance intervals. For axial and mixed flow compressors, there is the further option of selecting a single versus multiple stage configuration.

Hence, several design selections remain to be made. It is not clear at this point if the drive should be submerged or located outside the primary pressure boundary. The same applies for the use of magnetic versus oil lubricated bearings and the selection of more than one circulator in parallel for the PHTS loop. Trade studies are recommended to select the design option that is best suited for the NGNP plant (at component, system and component/system level). The only key design selection provided by reference documentation [3-1] is an electric drive for the circulator.

Based on engineering judgment, two design options are proposed to which sound TRL ratings are assigned in Appendix A. The first design option is a submerged circulator with magnetic bearings and the second design option is a circulator located outside the pressure boundary with oil lubricated bearing and rotating seals at pressure boundary. It should be noted that these design options as well as all work in this TDRM are based on current knowledge, engineering judgment and experience and remains to be supported by trade studies.

All the circulator sub-components have a TRL of 8 (except for the EMBs and primary pressure boundary rotating seals if included in the design), while the integrated assembly of these components as a subsystem has a TRL of 6 because it has not been demonstrated in a loop similar to the PHTS within a relevant environment. Following the selection of a reference circulator design, the circulator components that require technology development will be validated with supporting single effect tests. After that, the circulator subsystem will be validated with a partial scale or full-scale integrated test, subsequently qualifying the subsystem at a TRL of 7. Advancement to a validated TRL 8 will comprise the final integrated tests of the PHTS circulator prototype to take place in the first NGNP nuclear power plant.

Based on current pressure loss estimates, the PHTS pressure losses are expected to be larger than the SHTS pressure losses. Since the PHTS pressure losses are larger than the SHTS pressure losses and since the PHTS operates at a higher temperature, the PHTS circulator is expected to envelope the SHTS circulator and hence only the PHTS circulator will be discussed. It is assumed that the PHTS circulator testing can be applied to the SHTS circulator also and hence do not warrant a separate discussion.

The PHTS check valve functionally forms an integral part of the circulator and therefore will be tested as part of the circulator. It is recognized that design development will be required qualify the valve. At this stage no technology development is envisioned to the point where advance testing is required. However, as the design evolves unique tests might be identified which will be included at the appropriate time.

# 3 PRIMARY HEAT TRANSPORT SYSTEM (PHTS) CIRCULATOR

## 3.1 Function and Operating Requirements

During the NGNP preconceptual design phase [3-1] an electric-driven circulator was selected as the reference design to circulate the primary coolant helium within the PHTS. The PHTS circulator primarily needs to overcome the pressure losses associated with the PHTS flow path (notably including the PBMR, the hot gas ducting and IHX). After leaving the circulator, helium flows through the reactor core where it removes approximately 500 MWt energy. From there the helium flows to the IHX where the energy removed from the core, along with the compression energy added by the circulator, is transferred to the SHTS.

The circulator nominal operating conditions are summarized in Table 3-1. Under these conditions the required pumping power is 10.8 MWt. The circulator is located in the cold leg of the PHTS at the IHX exit and its piping and support structure could allow for a vertical or horizontal configuration. A self-acting check valve will be integrated with the circulator assembly or elsewhere in the PHTS cold-leg piping to limit backflow through the PHTS loop. The location of the circulator in the Nuclear Heat Supply building will allow for periodic maintenance and/or replacement during the life of the plant.

**Table 3-1: NGNP PHTS Circulator Design Requirement**

| Parameters | PHTS Loop |
|---|---|
| | |
| **Performance Requirements** | |
| Core power, MWt | 500 |
| Rotor shaft power, MWt | 10.8 |
| He flow rate, kg/s | 159.6 |
| Inlet He temp., C | 337 |
| Inlet He press, MPa | 8.626 |
| Outlet He temp., C | 350 |
| Outlet He pressure, Mpa | 9.0 |
| Circ press rise, kPa | 374 |
| Compression ratio | 1.043 |
| Inlet density, Kg/$m^3$ | 6.81 |

## 3.2 Design Selection Status

### 3.2.1 Candidate Circulators

Several arrangements and design options are available for the PHTS helium circulator that satisfy the preconceptual functions and design requirements. The large PHTS circulator can be replaced by a number of smaller circulators arranged in parallel. The compressor drive can be located inside or outside of the helium pressure boundary and the bearings can be conventional oil lubricated or electromagnetic. The type of bearings selected imposes additional requirements for dedicated service systems to support them. Additionally, the compressor design can be of the radial, axial type or mixed flow (axial/radial), depending upon the economics, required efficiency, available space within the primary pressure boundary, and the maintenance intervals. For axial and mixed flow compressors, there is the further option of selecting a single versus multiple stage configuration.

Figure 3-1 shows a schematic that illustrates how all the design options of the PHTS circulator are interconnected. The map has been color-coded to identify in green the design options that, at least at this pre conceptual design level, appear to require less design and technology development. This first assessment needs to be confirmed by furthering the design of the circulator and by trade studies that compare the advantages and disadvantages of the various design options using the decision discriminators specified in Section 3.2.2.

The left side of Figure 3-1 relates to the selection of the drive for the circulator impeller. An electric motor drive was recommended in [3-1] that is likely to be a synchronous with variable speed. This motor can be either located inside the primary pressure boundary (submerged) or outside this boundary (as shown in Figure 3-1).

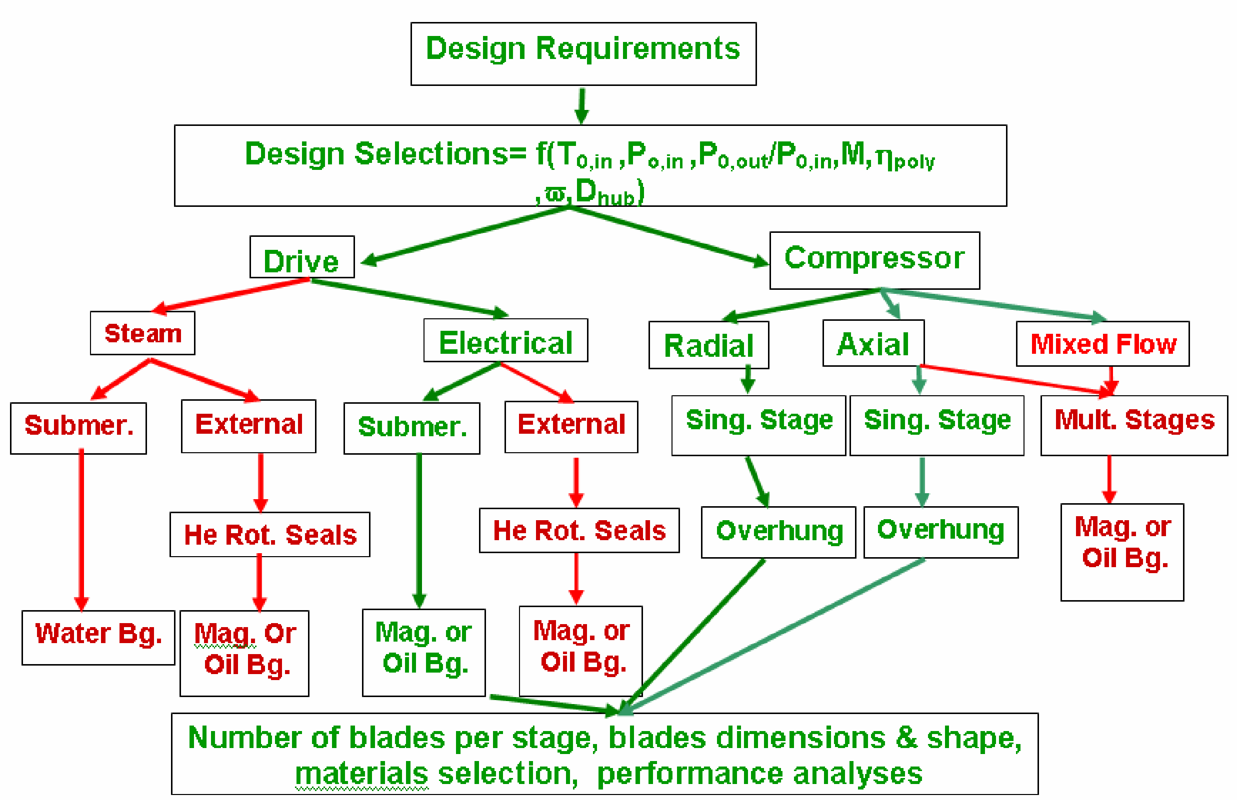



**Figure 3-1 Design Options of the PHTS Circulator**

For the case in which the circulator motor is located inside the primary pressure boundary, either oil lubricated or magnetic bearings can be used. The former have been used with submerged circulators in the early British gas-cooled reactors and in the German THTR. The drawbacks of oil lubricated bearings are the potential for oil ingress into the reactor cooling loop, the flammability of oil, and the need for dedicated oil service modules which must be kept in an inert atmosphere in order to avoid potential fires. On the other hand, magnetic bearings require some technology development to understand their response during design transients (e.g. seismic events) and during the shaft run down on catcher bearings following a loss of the magnetic field. Recent progress in the magnetic bearing design and the advantage of not having to deal with oil inside the primary pressure boundary has made this option more appealing. At the moment, magnetic bearings are the preferred choice because of the progress made in recent years in sensing and controlling the shaft position, their proliferation in several industrial applications and because of the advantage of not having to deal with oil. On the other hand, considering the substantial operating experience that has been accumulated with submerged oil bearings in previous gas cooled reactors, oil lubricated bearings should not be excluded. In Section 3.5 down selection tasks are recommended to address these design options.

Locating the circulator's electric motor outside the primary pressure boundary alleviates the concern with oil ingress in the reactor core, but introduces the complication of external rotating seals along the compressor shaft. These seals must be highly reliable to prevent leakage of pressurized helium from the PHTS during steady state and transient operations. It is conceivable that these seals will require the use of purified buffer helium to separate the primary coolant from the air outside the pressure boundary and a helium recovery system to separate and recover the helium from the exhaust buffer stream. It should be noted that the experience gained in this area from the PBMR Demonstration Power Plant (DPP) turbo machinery could be a valuable support for using these external rotating seals. The arrangement with the motor outside can use either oil lubricated or magnetic bearings. Oil lubricated bearings seem in this case to be the preferred choice in view of the large experience with this type of bearings and in view of the fact that oil ingress in the reactor is not a concern. On the other hand, magnetic bearings cannot be excluded because of the advantages of removing the need for a dedicated oil supply and purification modules, plus related fire hazards. In Section 3.5 down selection tasks are recommended to address these design options.

The right side of Figure 3-1 relates to the selection of the type of the circulator impeller. Two types of compressors are available for this application: radial and axial. The selection of one versus the other depends upon several factors, including rotational speed and consequently diameter of the compressor disk, number of stages, and required efficiency – and notably also the economics. The selection of the type of impeller for the PHTS circulator is not further discussed because it is part of the design process and does not require technology development.

The integration of the PHTS circulator into the NHSS influences the design selection. A few considerations are applicable:

- The circulator should be located in the cold leg of the PHTS loop, because of the sensitivity of their electric components and blade material to high temperatures, plus impacts on efficiency and power requirements.
- For multiple parallel circulators, a check valve or other means must be included in conjunction with each circulator to prevent backflow during reactor core shutdown cooling with the Core Conditioning System and/or to isolate a circulator if more than one is arranged in parallel.
- Care must be taken to locate the circulator impeller away from large surfaces that could be affected by acoustic loads. Strengthening of the surrounding PBMR around the circulator is needed to prevent PB rupture as a result of impeller failure. As an alternative to strengthening the reactor vessel, the design could also consider positioning the circulator rotors to minimize the possibility of missiles impinging the reactor vessel, or include missile shields to absorb any possible debris. This may be a factor that favors radial compressors over axial compressors.
- For a design selection that locates the circulator drive within the primary pressure boundary (submerged), consideration must be given to supply and remove purified

helium to and from the driver cavity in order to prevent radionuclide contamination that will complicate maintenance.

- If oil bearings are used, provisions must be made to locate the dedicated oil bearing modules in a safe inert atmosphere environment to prevent fire.
- The failure probability and consequences must be used when determining the number and type of circulators to be employed in the PHTS.

An additional factor that could influence the integration of the circulators within the plant is the number of circulators per loop. The large pumping power required for the PHTS circulator could dictate a design option with two or more circulators in parallel to reduce the size of the electric motor. It should also be noted that the use of multiple circulators would provide redundancy, which may improve reliability / operability. The trade-offs of one versus multiple circulators also have system-level trade-offs (controllability, reliability, size, etc.), as documented in NGNP-HTS-RPT-TI001 Section 3.5.3. Hence, the decision of single versus multiple circulators will be influenced by a combination of system-level and circulator-specific trade-offs. Multiple parallel circulators have been used in several gas cooled reactors, including the Magnesium Non-Oxidizing (MAGNOX), Arbeitsgemeinschaft Versuchs Reaktor (AVR), Advanced Gas-Cooled Reactors (AGRs), Thorium Hoch Temperature Reaktor (THTR) and Fort St. Vrain (FSV).

Based on engineering judgment, two design options are proposed for the purpose of assigning TRL ratings - see Appendix A. The first design option is a submerged circulator with magnetic bearings and the second design option is a circulator located outside the pressure boundary with oil lubricated bearing and rotating seals at pressure boundary. It should be noted that these design options as well as all work in this TDRM are based on current knowledge, engineering judgment and experience. Trade studies remain to be completed relating to various design options in order to conduct a down selection for a reference circulator design, which may not necessarily entail one of the proposed design options.

## 3.2.2 Decision Discriminators

### 3.2.2.1 Introduction

Discriminators have been identified to help in the selection of an optimum design for the PHTS circulator. These discriminators address the required technology development, the availability of a manufacturing base, the circulator operation and maintenance, the safety and investment implications and the lifecycle costs.

A Kepner-Tregoe (K-T)-based comparative analysis will be used to facilitate the selection of the reference PHTS circulator design. The discriminating factors will be rated based on the relative success with which each design meets them. Each discriminating factor will be further weighted proportionally to its perceived importance.

A summary of the K-T process was outlined in the IHX Conceptual Design Study (NGNP-HTS-RPT-TI001) in Section 3.5.3 – a similar rating and weighting scheme could be employed as basis for a circulator K-T.

#### 3.2.2.2 Design / Technology Development

Gas circulators have been built and operated successfully in high temperature gas cooled reactors for several years. Most of these circulators have been operated in a carbon dioxide environment and some in helium. Nevertheless, due to the large pumping power required for the NGNP PHTS circulator, some new technology development could be required (alternatively multiple parallel circulator units can be employed). The following discriminating factors will aid to assist in identifying an optimal design from a developmental requirement perspective:

- What is the relevant experience base?
- Can the new technology be validated from similar proven technologies using only analytical methods?
- What testing is required? (single effects bench scale tests, integrated scaled tests, integrated full-scale prototype circulator tests)

#### 3.2.2.3 Manufacturing and Transportability

The type of gas circulator to be used in the NGNP has not been built for several years. There are several companies capable of developing the design, validating the required technology and building this component for nuclear applications. Nevertheless it is expected that a lot of the specialized manufacturing experience has been lost, including experienced personnel. The discriminating factors to be used in this case are:

- What are the manufacturing constraints and what effort is required to overcome them?
- What are the unique manufacturing considerations?
- Have circulators with a similar design been built recently?
- What is the highest pumping power of these circulators?
- Does the manufacturing process require integration among several suppliers?
- Is a specific technology to be used for a circulator design available from several suppliers or can it only be provided by a few specialized suppliers?
- Can the circulator be transported as a single unit or must it be assembled at the site?

#### 3.2.2.4 Operation and Maintenance

Operation and maintenance of the NGNP PHTS circulator will strongly affect ~~by the~~ its design selection. For example, maintenance of an electric motor located outside the primary helium pressure boundary is simpler than that of a submerged motor. On the other hand, the presence of a shaft rotating seal for the motor located outside the pressure boundary requires additional maintenance. The discriminating factors to be used in this case are:

- Does the design require specialized maintenance tools?
- Does the design require remote handling for maintenance?
- How often must the entire circulator assembly be replaced for maintenance?
- Can periodic maintenance be performed in place (without removing the circulator)?
- Does the design require the development of specialized instrumentation and control software?
- What is the operational performance (efficiency, transients, surge, etc.)?

#### 3.2.2.5 Safety and Investment Protection

For the design selection in which the circulator motor is located outside the primary pressure boundary the key safety and investment risk for the NGNP PHTS circulator is the potential leakage of contaminated primary helium through the shaft rotating seal during normal operations and accident conditions. For the design selection with a submerged circulator and oil bearings, the key investment risk is oil ingress into the primary cooling loop. Plant level analyses will be done to determine design basis transients that cover all these scenarios and evaluate their probability of occurrence and their consequences to the plant personnel and the public and the impact on the plant investment. If necessary, the PHTS circulator design will be modified to satisfy the plant safety and investment goals.

#### 3.2.2.6 Lifecycle Cost

Cost and impact on the plant schedule (indirect cost) will be evaluated for each of the PHTS circulator designs. The discriminating factors to be used in this case are:

- Design development cost (non-recurring)
- Capital cost (recurring) of circulator integrated into PHTS
- Operating and Maintenance costs (recurring)
- Impact on the plant schedule (non-recurring)

### 3.2.3 Reference Design

The present reference design for the PHTS circulator is described in Section 6.2.1.2.3 of the PCDR [3-1]. The only key design selection provided by this high level description is an electric drive for the circulator.

### 3.2.4 Alternatives for Further Evaluation

There are several design selections that are still to be made, as described in Section 3.2.1. It is not clear at this point if the drive should be submerged or located outside the primary pressure boundary. The same applies for the use of magnetic versus oil lubricated bearings and the selection of more than one circulator in parallel for the PHTS loop.

The degree to which the circulator options respond to the plant-level and NHSS functions and requirements will be analyzed and compared with each other on the basis of similar operating experience, recent applicable circulators designs, and engineering judgment. Decision discriminators will be used to facilitate this selection. The proposed trade studies will form a basis for the selection of a reference design. These studies should be done with the support of qualified gas circulator vendors.

### 3.2.5 Down Selection Task

Several design candidates have been identified for the PHTS circulator in Section 3.4.1. Trade studies are recommended to select the design option that is best suited for the NGNP plant. Some of these trade studies will be done at the system design level in order to provide clear requirements to the designers of the circulators. Other trade studies will be done at the component level to select a circulator design that best optimizes often conflicting requirements. A third type of trade study requires the close collaboration and interfacing between the system and component designers.

Table 3-2 lists the recommended trade studies.

Trade studies identified as "System Level" are presumed to be done by the PHTS systems designers, trade studies identified as "Component Level" are presumed to be done by the circulators suppliers and, trade studies identified as "System/Component Level" are presumed to be done in close collaboration between the system and component designers.

**Table 3-2: Trade Studies Recommended for the PHTS Helium Circulators**

| Recommended Trade Studies | System Level | Component Level | System/Component Level |
|---|---|---|---|
| a) Number of circulators per loop | | | X |
| b) Location of the circulators in each loop | X | | |
| c) Horizontal versus vertical orientation | | | X |
| d) Selection of circulators' drive. | X | | |
| e) Type of motor cooling (water versus helium) | | | X |
| f) Submerged versus external circulators' drive | | | X |
| g) Oil lubricated versus magnetic bearings | | | X |
| h) Radial versus axial compressors | | X | |
| i) Single versus multistage compressors | | X | |
| j) Overhung versus supported compressor shaft | | X | |
| k) Number of blades per stage, blades dimensions & shape, materials selection | | X | |

Each of these trade studies will evaluate the technical maturity of each subsystem design, establish the availability of the suppliers, perform a Reliability, Availability, Maintainability and Inspectability (RAMI) analysis and supporting plant level analyses to develop a mature reference circulator design with the best relative costs and impact on the plant schedule.

## 3.3 TRL Status of PHTS Circulator

The reference design of the PHTS circulator subsystem (see Section 3.2.3) has been classified at a TRL of 6. This classification was based on the fact that similar helium circulators have been successfully used in other relevant applications in a nuclear environment. The six THTR submerged helium circulators used oil bearings with a pumping power of 2.3 MW (each). The higher power submerged AGRs circulators (up to 5.4 MW) used also oil bearings in a in

CO2 environment. A relevant application of externally located gas circulators in a nuclear environment is provided by the 10.9 MW variable speed motors for the AGR at Windscale. For this application rotating shaft dry gas seals were used at the primary pressure boundaries.

Table 3.3 summarizes nominal operating conditions for key gas circulators previously used in the nuclear industry.

**Table 3.3 Prior Experience with Gas Circulator in the Nuclear Industry**

| | | AVR<br>He | PB<br>He | THTR<br>He | FSV<br>He | AGR<br>CO2 |
|---|---|---|---|---|---|---|
| Reactor Power | MWt | 46 | 115 | 750 | 850 | 1500 |
| Core inlet temp. | C | 260 | 344 | 250 | 405 | 286 |
| Core outlet temp. | C | 960 | 728 | 750 | 775 | 675 |
| Blower inlet temp | C | **251** | **331** | **250** | **395** | **282** |
| Blower inlet pressure | MPa | 1.00 | 2.34 | 3.8 | 4.73 | 3.81 |
| Mass flow per circ. | kg/s | **6.4** | **30** | **51** | **126** | **476** |
| Pressure ratio | | 1.01 | 1.03 | 1.03 | 1.02 | 1.09 |
| Blower inlet density | $kg/m^3$ | 0.9 | 1.85 | 3.49 | 3.41 | 36.9 |
| Number of circ. | | 2 | 2 | 6 | 4 | 8 |
| Type | | **radial** | **radial** | **radial** | **axial** | **radial** |
| Motor configuration | | **submerged** | **submerged** | **submerged** | **submerged** | **submerged** |
| Blower speed | rpm | 4,000 | 3,460 | 5,600 | 9,550 | 2770 |
| Blower motor power | MWe | **0.16** | **1.5** | **2.3** | **3.95** | **5.37** |

Applicable industrial experience in electro magnetic bearings is provided by Siemens that built 26 MW motors for the gas pipeline compressors in the Netherlands that operate on Waukesha EMBs. On the other hand, none of the previous applications is an exact match of what could become the new PHTS circulator reference design after the trade studies, because of the demand for a high pumping power in a helium environment and the possibility of using EMBs.

Section 0 provides a detailed explanation of the design and technology readiness levels of the PHTS circulator subsystem and its components. The Table shows that, although all the circulator components have a TRL of 8 (except for the EMBs and primary pressure boundary rotating seals if included in the design), and the integrated assembly of these components as a subsystem has a TRL of 6 because it has not been demonstrated in a loop similar to the PHTS within a relevant environment.

The applicable TRL Sheets are attached in Appendix A.

## 3.4 Technology Development Road Map Summary

### 3.4.1 Overview

The PHTS circulator design is only at a preconceptual level. The TDRM identifies several design options that have to be addressed during the plant conceptual design phase and trade studies that will justify a selection of a more mature reference design. In addition the TDRM proposes selection criteria that will support this design selection.

Once a mature reference design is selected, the technologies of this design will be validated in two major areas.

The first area includes the validation of technologies not previously used in similar circulators or used in non-nuclear relevant applications. Typical examples of these technologies are the EMBs with their catcher bearings and the shaft external rotating seals if the electric motor is located outside the pressure boundary. It is conceivable that single effects tests can address this first area of development.

The second area in which some technology development is required is the validation of a partial or a full-scale circulator model in a relevant environment. This validation will verify that each component of the circulator subsystem performs within its specifications.

The PHTS Circulator Technology Development Road can be seen in Appendix B while the maturation tasks are described below.

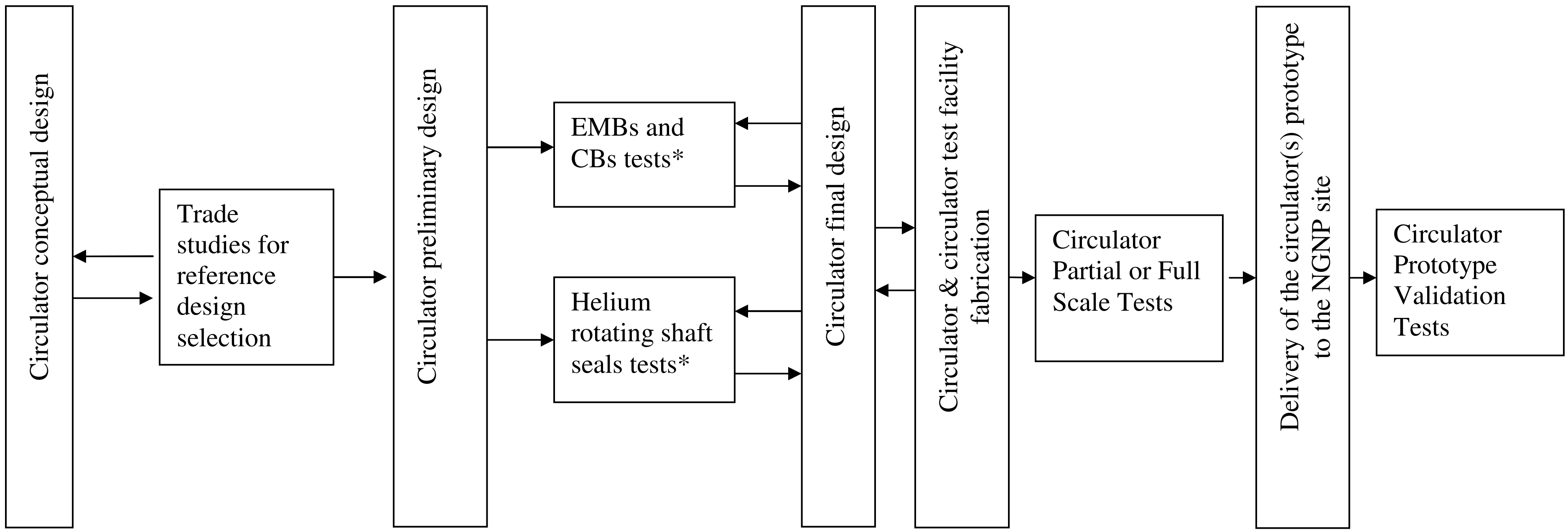
## 3.5 Technology Maturation Plan Summary

The Technology Maturation Plan required to mature this technology to a TRL of 8 is attached in Appendix C.

The section below describes the maturation tasks needed to advance the technology of the PHTS Circulator from a validated TRL 6 to a validated TRL 8.

Advancement to a validated TRL 7 will require parallel execution of firstly the design and fabrication of the PHTS circulator with the circulator test facility and secondly the development of the required sub-component technologies (EMB's, CB tests, Helium external rotating shaft seals tests). During the conceptual design phase, trade studies will support the down selection from various design options and a mature reference design will be established (see Figure 3-2). The components tests will be done during preliminary design to validate the selected technologies. The test facility (either partial of full-scale) will be constructed in parallel with the circulator construction as part of detail design.

Advancement to a validated TRL 8 will comprise the final integrated tests of the PHTS circulator to take place in the first NGNP nuclear power plant.




* Indicates activity only required if these technologies form part of the design

**Figure 3-2 PHTS Circulator Development Logic**

## 3.6 SHTS Circulator and PHTS Check Valve Technology Development

### 3.6.1 SHTS Circulator

Based on current pressure loss estimates, the PHTS pressure losses are expected to be larger than the SHTS pressure losses. Since the PHTS pressure losses are larger than the SHTS pressure losses and since the PHTS operates at a higher temperature, the PHTS circulator is expected to envelope the SHTS circulator and hence only the PHTS circulator will be discussed. It is assumed that the PHTS circulator testing can be applied to the SHTS circulator also and hence do not warrant a separate discussion.

### 3.6.2 PHTS Check Valve

The PHTS check valve functionally forms an integral part of the circulator and therefore will be tested as part of the circulator. It is recognized that design development will be required to qualify the valve. At this stage no technology development is envisioned to the point where advance testing is required. However, as the design evolves unique tests might be identified which will be included at the appropriate time.

## 3.7 Inputs into CTF

The PHTS circulator may be tested in the CTF for qualification of a TRL 7.

## 3.8 References

[3-1] NGNP-06-RPT-003, Rev0, April 2007 – NGNP and Hydrogen Production Preconceptual Design Report

# Appendix A: TRL Rating Sheets

**Table A-3: Technology Readiness Levels for the Reference PHTS Circulator**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: | Document Number: | Revision: | |
| ☐ Island ☐ System ☑ Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: PHTS Circulator Subsystem | | | |
| Description: | | | |
| A circulator driven by an electric-motor was selected to move the primary coolant helium within the PHTS. For the purpose of defining its readiness level, the circulator is classified as a subsystem within the PHTS. The circulator subsystem comprises of five components: the impeller and the rotating shaft, the bearings with their supports, stationary and rotating seals (external or internal), the electric motor with its cooling system and the required instrumentation and controls. | | | |
| Island(s): ☐ NHSS ☑HTS ☐ HPS ☐ PCS ☐ BOP | | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Component Verified at Experimental Scale | Subsystem Verified at Pilot scale | System demonstration at Engineering Scale |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>There is relevant operating experience with gas circulators in several gas-cooled reactors that have been built and tested. There is experience with similar helium circulators in THTR and HTTR. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed)<br>Following the selection of a reference circulator design, the circulator components that require technology development will be validated with supporting single effect tests. After that, the circulator subsystem will be validated with a partial scale or full-scale integrated test. | | | |
| Actions (list all) | Schedule | Cost (K$) | |

| | | |
|---|---|---|
| • Validation of EMBs, if they are selected over oil bearings.<br>• Validation of primary boundary external rotating seals, if the electric motor is located outside<br>• Integrated test of a partial or full-scale model of the circulator subsystem | August 2010<br><br>August 2010<br><br>August 2013 | Refer to Section C3 |
| DDN(s) supported: None | | |
| Subject Matter Expert Making Determination: G. Baccaglini | Originating Organization: Technology Insights | |
| Date: 3 September 08 | | |

**Table A-4: Technology Readiness Levels for the Reference PHTS Circulator**

**TRL Rating Sheet**

Vendor Name: Document Number: Revision:

☐ Island ☐ System ☑ Subsystem/Structure ☐ Component ☐ Technology

Title: PHTS Circulator Components – Impeller and Shaft/ Oil Bearings and Bearing Supports/ Seals (rotating & stationary)/ Electric Motor/ Instrumentation & Control

Description:

The impeller and shaft assembly comprises of the entire rotating section of the circulator that is supported by the bearings assembly.

This bearings and bearing support comprise of the bearings housing, its supports, the bearings auxiliary systems and the required control and instrumentation. The TRL rating of this sheet applies only if the mature circulator conceptual design uses oil bearings and a submerged motor (non rotating seals at the primary boundary). Specific TRL sheets have been develop (see Tables A-4 and A-5) for a conceptual design with EMBs and the motor outside the primary boundary. The use of electromagnetic versus oil bearings will be determined by the scheduled trade studies.

The assembly of the rotating and stationary seals comprises of the stationary seals if this motor is submerged (at the primary pressure boundary flange) and the internal rotating seals required to isolate the submerged motor cavity for maintenance access (between the impeller and the electric motor cavity).

The electric motor assembly comprises of the electric motor itself, the motor supports and the cooling system.

The instrumentation and control assembly comprises of the hardware and software required to control the entire circulator subsystem while interfacing with local bearings and electric motor controls.

Island(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: N/A | Parent: N/A | WBS: N/A |
|---|---|---|

| | Technology Readiness Level | | |
|---|---|---|---|
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | System demonstration at Engineering Scale | Integrated Prototype Tested and Qualified | Plant Operational. |
| **TRL** | 7 | **8** | 9 |

| Basis for Rating (Attach additional sheets as needed) | | |
|---|---|---|
| There is operating experience with gas circulators with similar components in several industrial applications and in gas-cooled reactors. There is experience with similar helium circulators in THTR and HTTR. | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed)<br>The PHTS circulator components, integrated in the circulator prototype, will be verified in the NGNP when the performance of the circulator in its final configuration is verified during preoperational testing in hot operational environment. Successful completion of the NGNP preoperational tests will qualify the circulator assembly as TRL 9. | | |
| Actions (list all) | Schedule | Cost (K$) |
| • Test the circulator prototype, while mounted in the PHTS loop, to verify its interaction with the other loop subsystems<br><br>It is noted that the circulator will likely also be tested in helium, and air or a mixture of gases. | August 2016 | Refer to Section 17 |
| DDN(s) supported: None | Technology Case File: | |
| Subject Matter Expert Making Determination: G. Baccaglini | | |
| Date: 6 August 08 | Originating Organization: Technology Insights | |

**Table A-5: Technology Readiness Levels for the Reference PHTS Circulator**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: | Document Number: | Revision: | |
| ☐ Island ☐ System ☑ Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: PHTS Circulator EMBs and Their Support | | | |
| Description: | | | |
| The EMBs comprise of the radial and axial bearings, the CBs, their supports, the bearings auxiliary systems and the required control and instrumentation. The TRL rating of this sheet applies only if the mature circulator conceptual design selects EMBs to support the circulator shaft. | | | |
| Island(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP | | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Component Verified at Experimental Scale | Subsystem Verified at Pilot scale | System demonstration at Engineering Scale |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>There is operating experience with EMBs in several industrial applications, but not in gas-cooled reactors. Applicable industrial experience is provided by Siemens that built 26 MW motors for the gas pipeline compressors in the Netherlands that operate on Waukesha EMBs and several other Waukesha industrial applications.. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed)<br>Following the selection of a reference circulator design, the EMBs performance will be validated with engineering scale tests After that, they will be included in the circulator subsystem that will be validated with a partial or full-scale integrated test. | | | |
| Actions (list all) | Schedule | Cost (K$) | |

| | | |
|---|---|---|
| • Validation of EMBs, if they are selected over oil bearings. | August 2010 | Refer to Section 17 |
| DDN(s) supported: None | Technology Case File: | |
| Subject Matter Expert Making Determination: G. Baccaglini | | |
| Date: 6 November 08 | Originating Organization: Technology Insights | |

**Table 3-6: Technology Readiness Levels for the Reference PHTS Circulator**

<table>
<tr><td colspan="4">TRL Rating Sheet</td></tr>
<tr><td colspan="4">Vendor Name: Document Number: Revision:</td></tr>
<tr><td colspan="4">☐ Island ☐ System ☑ Subsystem/Structure ☐ Component ☐ Technology</td></tr>
<tr><td colspan="4">Title: PHTS Circulator Primary Boundary Rotating Seals</td></tr>
<tr><td colspan="4">Description:</td></tr>
<tr><td colspan="4">The primary boundary rotating seals comprise of the seals housing, the buffer gas supply system and the buffer helium recovery system. The TRL rating of this sheet applies only if the mature circulator conceptual design selects a circulator motor located outside the primary boundary.</td></tr>
<tr><td colspan="4">Island(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP</td></tr>
<tr><td>ISSCTBS: N/A</td><td>Parent: N/A</td><td colspan="2">WBS: N/A</td></tr>
<tr><td></td><td colspan="3">Technology Readiness Level</td></tr>
<tr><td></td><td>Next Lower Rating Level</td><td>Calculated Rating</td><td>Next Higher Rating Level</td></tr>
<tr><td>Generic Definitions (abbreviated)</td><td>Component Verified at Experimental Scale</td><td>Subsystem Verified at Pilot scale</td><td>System demonstration at Engineering Scale</td></tr>
<tr><td>TRL</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td colspan="4">Basis for Rating (Attach additional sheets as needed)<br>There is operating experience with primary boundary rotating seals in several industrial applications, but not in gas-cooled reactors. Applicable industrial experience is provided for example by the John Crane company with their single, tandem, or triple seal cartridge designs.</td></tr>
<tr><td colspan="4">Outline of a plan to get from current level to next level (Attach additional sheets as needed)<br>Following the selection of a reference circulator design, the primary boundary rotating seals performance will be validated with engineering scale tests After that, they will be included in the circulator subsystem that will be validated with a partial or full-scale integrated test.</td></tr>
<tr><td colspan="2">Actions (list all)</td><td>Schedule</td><td>Cost (K$)</td></tr>
<tr><td colspan="2">• Validation of primary boundary external rotating seals, if the electric motor is located outside</td><td>August 2010</td><td>Refer to Section 17</td></tr>
</table>

| | | |
|---|---|---|
| DDN(s) supported: None | | Technology Case File: |
| Subject Matter Expert Making Determination: G. Baccaglini | | |
| Date: 6 November 08 | Originating Organization: Technology Insights | |

# Appendix B: Technology Development Road Map

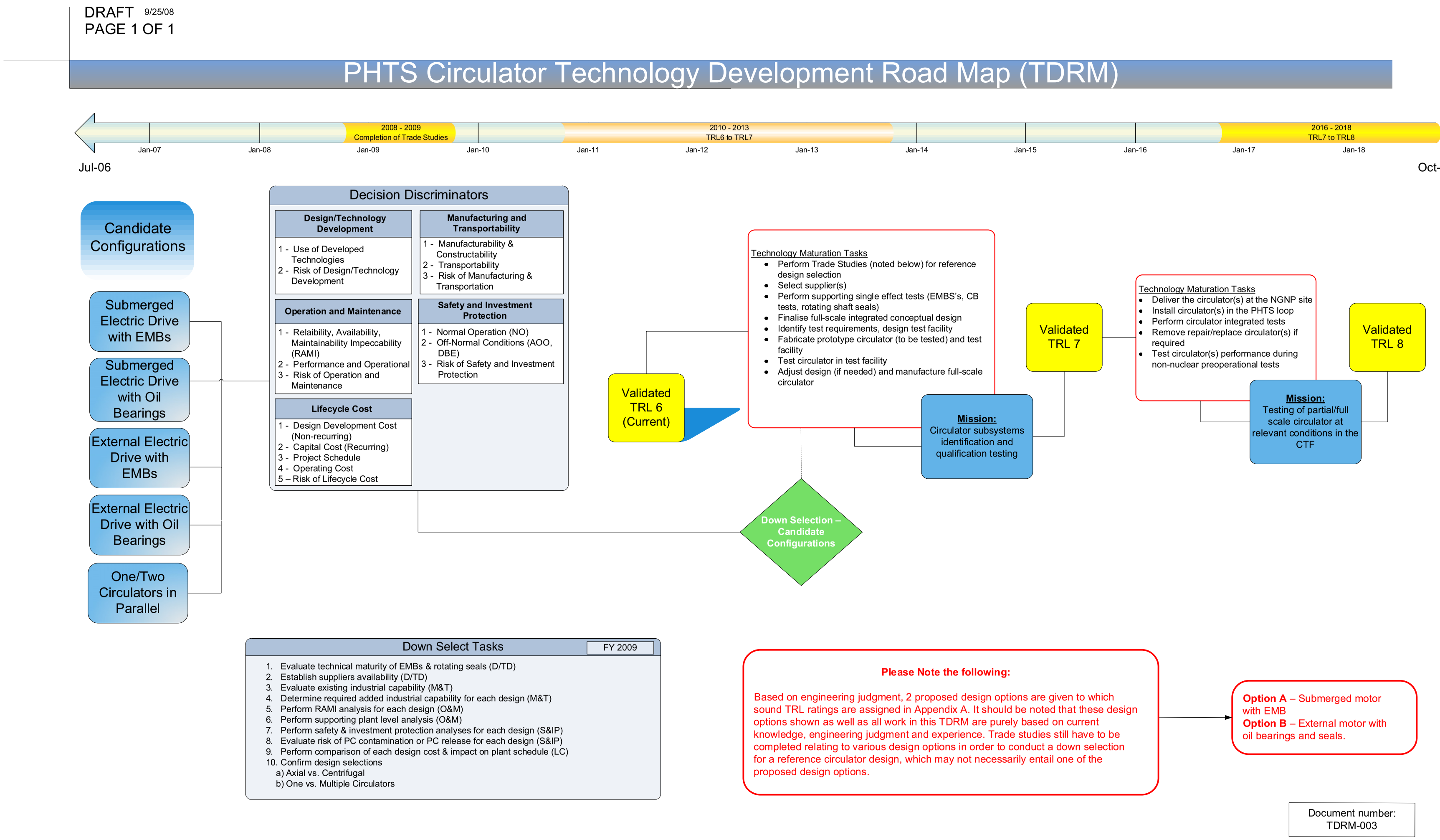



**Figure B-3: Technology Development Road Map – Circulator**

# Appendix C: Technology Maturation Plan

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## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

**TRL 6 to TRL 7:**

- Specification 1: Electro Magnetic Bearings (EMBs), and Catcher Bearings Test Specification
- Specification 2: Helium Rotating Seals Test Specification
- Specification 3: Partial or Full Scale Circulator Model Test Specification

**TRL 7 to TRL 8:**

- Specification 1: Prototype Circulator Test Specification

# C1 TECHNOLOGY MATURATION PLAN - TRL 6 TO TRL 7

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the PHTS circulator from a TRL of 6 to a TRL of 7. Some of the maturations tasks required to achieve this goal involve the validation of the performance of the EMBs, if they are selected over oil bearings, in helium and in a nuclear environment and the validation of primary boundary external rotating seals, if the circulator electric motor is located outside the pressure boundary. A verification of the external rotating seals technology is required because of the safety implications of accidental leaks of contaminated primary coolant through the external rotating seals dictates a more rigorous verification of the technology maturity. These tasks will be followed by an integrated test of a partial or full-scale model of the circulator subsystem that will complete its maturation to a TRL of 7. This integrated test is required because some of the operating conditions and design features to be used in the NGNP (depending on which PHTS circulator reference design will be selected) do not match the experience with similar circulators used in previous gas cooled reactors.

Planning for full scale testing introduces severe risk in terms of time scales before definitive results are achieved. Scaled testing is expected to provide adequately addressed technical issues. However, it needs to be recognised that the step from scaled to full-scale could possibly introduce unexpected risks.

The technology maturation tasks from TRL 6 to 7 will be done in parallel with the design and fabrication of the circulator itself. A mature circulator reference design will be developed from the various design options by the end of the conceptual design phase with the support of trade studies. Once a mature reference design is achieved, ad hoc tests will validate some of the technologies used in the circulator assembly, followed by the integrated test.

A Test Specification is provided to cover each of the maturation tasks as shown in Section C1.2.

### C1.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the PHTS circulator from TRL 6 to TRL 7 are as shown below.

- Validation of the use of EMBs, if they are selected over oil bearings, for use in helium and in a nuclear environment.
- Validation of primary boundary external rotating seals if the electric motor is located outside.
- Integrated test of a partial or full-scale model of the circulator subsystem.

The tasks above will be described fully in individual Test Specifications provided in sections to follow.

### C1.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY2010 through FY2013. Work described in the Test Specifications to validate the performance of individual portions on the circulator assembly can be done in parallel.

### C1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C1.2 Test Specifications

### C1.2.1 Electro Magnetic Bearings (EMBs), and Catcher Bearings Test Specification

#### C1.2.1.1 Objectives

If electromagnetic bearings are selected by the trade studies over oil bearings for the circulator reference design, some technology development may be required since EMBs of this size have not been previously used in helium and in a nuclear environment.

The EMB subsystem comprises of the EMB rotor and stator, the rotor position sensors, the EMB control system and the associated power supplies, cabling, etc. Catcher Bearings (CB) are included to provide auxiliary and backup support for the PHTS circulator rotor when either the primary support from the EMB subsystem is not available, or when transient loads exceed its capabilities.

The objective of this task is to address, through validation tests, the following technical issues for the EMBs and CBs:

- Static and dynamic EMBs load response

- Control of shaft rotordynamic
- Modeling of EMBs redundancy features to increase reliability and verification of on-line maintenance
- Adequacy of the CB for the assigned plant duty cycle
- Validation of techniques for assessing the condition of the CBs following actuation without circulator assembly removal.

**C1.2.1.2 Test Conditions**

*C1.2.1.2.1 Test Configuration/Set-up*

A full scale model of the radial and axial EMBs with their CBs will be used to support a full scale rotor with a simulated impeller. The shaft will be rotated by an electric motor.

*C1.2.1.2.2 Test Duration*

The duration of this activity could be up to 12 months.

*C1.2.1.2.3 Proposed Test Location*

The work should likely be performed at the EMBs supplier test facility.

**C1.2.1.3 Measured Parameters**

The supplier is to determine the measured parameters, which may include the following:

- Rotor rotordynamic stability as a function of bearings stiffness and location during simulated startups and shutdowns.
- Loads and rotordynamic stability during rundown on CBs.
- Electric currents, temperatures, loads, shaft displacements, rotor mode shapes and amplitudes, vibration frequencies, and unbalances.

**C1.2.1.4 Data Requirements**

Measured parameters will be determined using recognized techniques, codes, standards, and QA that will be developed, identified, and/or agreed to as part of the test program.

**C1.2.1.5 Test Evaluation Criteria**

The EMBs and CBs must perform according to specifications during simulated steady state plant operating conditions and Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA).

#### C1.2.1.6 Test Deliverables

Deliverables are as follows.

- Validated EMBs and CBs specifications
- Procurement requirements and specifications for EMBs and CBs
- Specifications and design of the test facility
- Test Procedure
- Report confirming that the EMBs and CBs meet all specifications and requirements

#### C1.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the PHTS circulator technology for TRL 6 to TRL 7 is addressed in Sections C1.1.3 and C1.1.4. There is no or only minimal risk associated with Section C1.2.1.

### C1.2.2 Helium Rotating Seals Test Specification

#### C1.2.2.1 Objectives

Trade studies will determine whether the PHTS circulator electric motor is submerged (inside the primary pressure boundary) or outside this boundary. If the circulator motor is submerged, internal rotating shaft seals are required to keep the motor cavity from being contaminated by the primary coolant and allow for periodic maintenance without remote handling. If the circulator motor is located outside the primary boundary, external rotating shaft seals are required to keep the primary coolant from leaking and affecting the plant personnel and eventually the public. Rotating shaft seals are industrially available, and in the case of a submerged motor do not require technology development. For an external motor, the safety implications of accidental leaks of contaminated primary coolant dictate a more rigorous verification of the external seals technology.

The objective of this task is to address, through validation tests, the following technical issues for the helium external rotating seals:

- Leakage control during normal and off-normal operations
- Need for buffer purified helium and helium recovery
- Leakages during plant pressurized shutdowns (external motor)
- Safety related leakage monitoring system.

#### C1.2.2.2 Test Conditions

*C1.2.2.2.1 Test Configuration/Set-up*

A full scale model of the primary boundary rotating seal will be used with a simulated full scale shaft. The shaft will be rotated by an electric motor and supported by oil bearings.

*C1.2.2.2.2 Test Duration*

The duration of this activity could be up to 12 months.

*C1.2.2.2.3 Proposed Test Location*

The work should likely be performed at the test facility of the rotating seal supplier.

#### C1.2.2.3 Measured Parameters

The supplier is to determine the measured parameters, which may include the following: Leakages across the rotating seal as a function of pressure differential, shaft rotating speed, buffer gas flow rates, and gas pressures and temperatures.

#### C1.2.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA that will be developed, identified, and/or agreed to as part of the test program.

#### C1.2.2.5 Test Evaluation Criteria

The primary boundary external rotating seals must perform according to specifications during simulated steady state plant operating conditions and Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA).

#### C1.2.2.6 Test Deliverables

Deliverables are as follows.

- Validated rotating seal specifications
- Report confirming that the rotating seal meets all specifications and requirements.

#### C1.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the PHTS circulator technology for TRL 6 to TRL 7 is addressed in C1.1.3 and C1.1.4. There is no or only minimal risk associated with Section C1.2.2.

### C1.2.3 Partial or Full Scale Circulator Model Test Specification

#### C1.2.3.1 Objectives

The PHTS circulator comprises of a rotating impeller/shaft assembly supported by EMBs or oil bearings that transmits static and dynamic loads between the stationary and rotating portions of the circulator. A water or helium cooled variable speed electric motor rotates the shaft. Rotating internal shaft seals keep the motor cavity accessible for maintenance for a design with a submerged motor or prevent primary coolant helium for escaping if the motor is located outside.

A partial or full-scale model of the circulator must be tested to verify the performance of each of its components in an integrated representative environment. This integrated test is desirable because some of the operating conditions and design features to be used in the NGNP (depending on which PHTS circulator reference design will be selected) do not match the experience with similar circulators used in previous gas cooled reactors.

At this early stage of the design, a full rather than a partial scale model of the circulator is preferred (if schedule and budget allows) because of the different scaling requirements of its various components and their complex interaction (to be confirmed at appropriate time). The test environment and the scale of the circulator model will be better defined later on when the reference design is selected. Air, nitrogen or combination of other gases will be considered for the individual circulator components and for the entire circulator tests.

The objective of this task is to address, through validation tests, technical issues for the integrated partial or full-scale circulator model which may include the following (suppliers to ultimately define tests):

- Compressor gas dynamic performance under steady state, full and part load conditions, and during design transients
- Shaft stability as it passes through its critical speeds
- Thermal performance of the motor and bearings cooling systems
- Strength of the circulator acoustic source under key operating conditions
- Verification of the clearances between the rotor and the EMBs and catcher bearings while turning the circulator on EMB system suspension
- Transition from EMBs full suspension to operation on catcher bearings under loss of power simulation
- Rotating shaft seal performance when operating from 0 rpm to the circulator maximum speed
- Verification of maintenance and handling techniques.

#### C1.2.3.2 Test Conditions

*C1.2.3.2.1 Test Configuration/Set-up*

A full or partial scale model of the circulator will be tested.

*C1.2.3.2.2 Test Duration*

The duration of this activity could be up to 18 months.

*C1.2.3.2.3 Proposed Test Location*

The circulator integrated tests are likely to be done at the CTF site.

**C1.2.3.3 Measured Parameters**

Supplier to provide measured parameters which may include the following:

- Circulator performance under steady state and transient conditions.
- Gas temperatures and pressures at the circulator inlet and outlet, circulator assembly temperatures, loads and frequency/amplitudes of vibrations.
- Acoustic intensity and frequencies at the inlet and outlet of the impeller and flow induced vibrations at the outlet.
- Rotational speed and shaft mode shapes and amplitudes.

**C1.2.3.4 Data Requirements**

Measured parameters will be determined using recognized techniques, codes, standards, and QA that will be developed, identified, and/or agreed to as part of the test program.

**C1.2.3.5 Test Evaluation Criteria**

The full or partial scale circulator must perform according to specifications during simulated steady state plant operating conditions and Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA).

**C1.2.3.5 Test Deliverables**

Deliverables are as follows.

- Validated circulator model design specifications
- Report confirming that the circulator model meets all specifications and requirements

**C1.2.3.7 Cost, Schedule, and Risk**

Cost and schedule for the overall Technology Maturation Plan for advancing the PHTS circulator technology for TRL 6 to TRL 7 is addressed in Sections C1.1.3 and C1.1.4. There is only minimal risk associated with Section C1.2.3.

# C2 TECHNOLOGY MATURATION PLAN FOR PHTS CIRCULATOR (TRL 7 TO TRL 8)

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C.2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the PHTS circulator from a TRL of 7 to a TRL of 8. The final integrated tests of the PHTS circulator will take place in the first NGNP nuclear power plant.

In the first phase, the testing will take place without a heat source and the PHTS circulator will be used to move the coolant around the primary loop and provide heat of compression. The main objective of these tests is to verify the integrated performance of all the PHTS subsystems operating as a system in the first NGNP plant. More specifically, the scope for the circulator tests will be similar to that of the integrated partial or full-scale model tests done to progress it from a TRL of 6 to 7, with the difference that the remaining PHTS and SHTS subsystems will be also involved. Since the reactor core has not yet gone critical, there will still be access during and after these tests for inspection and possible design improvements of PHTS circulator(s), if necessary.

### C2.1.2 Scope

The maturation task and associated testing necessary to advance the maturity of the technology of the PHTS circulator from TRL 7 to TRL 8 involves the non-nuclear testing of the circulator prototype integrated within the NGNP PHTS loop

The task above will be described fully in a test specification provided in the following section.

### C2.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY2016 through FY2018.

### C2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C2.2 Test Specifications

### C2.2.2 Prototype Circulator Test Specification

#### C2.2.2.1 Objectives

The objective of testing the circulator in helium without nuclear heat, while mounted in the PHTS loop, is too verify its interaction with the other loop subsystems in an environment that is as close as possible with the NGNP operating conditions. The heat to bring the helium to temperatures representative of the NGNP nuclear operation is provided by the circulator compression. The IHX and the bearing and motor cooling subsystems will be acting as heat sinks. The absence of nuclear heating allows access for inspections and adjustments.

The technical issues to be addressed by the prototype circulator test in helium are:

- Compressor gas dynamic performance under steady state, full and part load conditions, and during design transients
- Shaft stability as it passes through its critical speeds
- Thermal performance of the motor and bearings cooling systems
- Presence of flow induce phenomena upstream and downstream of the circulator
- Strength of the circulator acoustic source under key operating conditions and its propagation throughout the PHTS loop
- Verification of clearances between the rotor and the EMBs and catcher bearings while turning the circulator on EMB system suspension
- Transition from EMBs full suspension to operation on catcher bearings under loss of power simulation
- Rotating shaft seal performance when operating from 0 rpm to the circulator maximum speed
- Maintenance and handling techniques

It is anticipated that testing will likely be conducted in air also. This will be specified at a later stage.

#### C2.2.2.2 Test Conditions

*C2.2.2.2.1 Test Configuration/Set-up*

The circulator prototype will be tested in the PHTS loop mounted with all the other subsystems in helium under pressures and temperatures selected to represent as close as possible the NGNP operating environment.

*C2.2.2.2.2 Test Duration*

The duration of this activity is expected to be in the range of 3 months but could be as long as 12 months.

*C2.2.2.2.3 Proposed Test Location*

The circulator integrated tests in helium will be done at the NGNP site.

**C2.2.2.3 Measured Parameters**

The supplier is to determine the measured parameters, which may include the following:

- Circulator performance under steady state and transient conditions.
- Gas temperatures and pressures at the circulator inlet and outlet, circulator assembly temperatures, loads and frequency/amplitudes of vibrations.
- Acoustic intensity and frequencies at the inlet and outlet of the impeller and in key locations around the PHTS loop and flow induced disturbances at the inlet and outlet of the circulator assembly.
- Rotational speed and shaft mode shapes and amplitudes.

**C2.2.2.4 Data Requirements**

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

**C2.2.2.5 Test Evaluation Criteria**

The prototype circulator must perform according to specifications during simulated steady state plant operating conditions and Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA).

**C2.2.2.6 Test Deliverables**

Deliverables are as follows.

- Validated Circulator performance specifications in helium
- Report confirming that the circulator prototype meets all specifications and requirements.

#### C2.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the PHTS circulator technology for TRL 7 to TRL 8 is addressed in Sections C2.1.3 and C2.1.4. There is only minimal risk associated with Section C2.2.2.

NGNP-CTF MTECH-TDRM-004 November 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 4: Intermediate Heat Exchanger A

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
| Author | Name:<br>Company: | Phil Rittenhouse<br>Technology Insights | November 18, 2008 |
| Reviewer | Name:<br>Company: | Johan Markgraaff<br>M-Tech Industrial | November 19, 2008 |
| Reviewer | Name:<br>Company: | Werner Koekemoer<br>M-Tech Industrial | November 19, 2008 |
| Reviewer | Name:<br>Company: | Renée Greyvenstein<br>Pebble Bed Modular Reactor | November 19, 2008 |
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| George Hayner (Technology Insights) | November 2008 |
| Roger Young (PBMR) | November 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
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| NGNP and Hydrogen Production Preconceptual Design Report | NGNP-01-RPT-001 | 0 |

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# ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |

| Acronym | Definition |
|---|---|
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |

| Acronym | Definition |
|---|---|
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |

| Acronym | Definition |
|---|---|
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

The IHX is a critical high-temperature component of the NGNP and its main function is to transfer thermal energy from the Primary Heat Transport System (PHTS) to the Secondary Heat Transport System (SHTS). Previous studies related to the NGNP Heat Transport System (HTS) have shown the advisability of splitting the IHX into two units, IHX A operating at up to 950°C and IHX B operating at up to ~760°C – particularly when metallic are employed. Uncertainties related to achieving full service life at 950°C using metallic materials argue for parallel development of metallic and ceramic heat exchangers. This portion of the document deals only with ceramic and metallic versions of IHX A. The lower temperature heat exchanger, IHX B, will be addressed in a later section.

Decision Discriminators were established and exercised in decisions taken relative to heat exchanger designs and materials. Cost/performance, state-of-the-art, robustness, environmental compatibility, RIM, IHX integration, and design/licensing basis were considered in the down select of potential designs. A wide range of heat exchanger designs were evaluated and the result was the selection of a compact design (PCHE or PFHE) for a metallic heat exchanger. A down select has not been made for a ceramic IHX design and awaits the completion of future Trade Studies as proposed in this document.

Decision discriminators applied to the selection of a metallic material for IHX A were materials database (e.g., maturity of data and service experience), materials lifetime (e.g., creep lifetime and corrosion behavior), and fabrication related factors. The choice based on the above was Ni-base Alloy 617. As for the ceramic heat exchanger design, selection of specific ceramic materials awaits completion of future Trade Studies.

Evaluations of the status of technology for metallic and ceramic heat exchangers were made and resulted in the determination of TRL 2 for both. The underlying bases for these selections are described in the TRL rating sheets provided for both metallic and ceramic heat exchanger versions.

TDRMs are provided to summarize down select tasks, TRL status, and maturations tasks necessary to increase the maturity of technology for metallic and ceramic IHX designs to a level of TRL 8. These tasks include consideration of materials properties and performance, material and design codes, model development for thermal and mechanical performance, and testing of IHX modules progressing from unit cells to full-size IHX units. Details of the tasks necessary for technology advancement between TRL levels are presented as a series of Technology Maturation Plans that include information on objectives, test conditions, measured parameters, data requirements, test evaluation criteria, test deliverables, and cost/schedule/risk. It is noted that the technology roadmap and maturation plans will need to be adjusted as new DDNs evolve as part of the conceptual and detail designs.

# 4 INTERMEDIATE HEAT EXCHANGER A

## 4.1 Function and Operating Requirements

The IHX is a critical high-temperature component of the NGNP. Because of cost and performance goals for the NGNP and related commercial process heat plants, compact heat exchangers have been selected as the reference design. The IHX has been separated into two regions, a high-temperature IHX A and a lower temperature IHX B, because it is unlikely that the corrosion resistance of the candidate metallic materials can provide for full service life (60 years) at the higher temperatures. Therefore, one or more replacements of a metallic based IHX A are anticipated and planned. A parallel development of an IHX based on ceramics is to be pursued because a ceramic IHX A should be able to provide for the full desired life. The alloy selected for IHX B should provide for the entire life of the plant without replacement.

The IHX transfers thermal energy between the Primary Heat Transport System (PHTS) and the Secondary Heat Transport System (SHTS). The PHTS is comprised of the primary piping, primary circulator, and primary helium working fluid. By current definition, the IHX is considered part of the PHTS. Its main functions are to contain the primary and secondary helium coolants and to transport thermal energy from the reactor to the SHTS working fluid. The SHTS is comprised of the secondary piping, secondary circulator and secondary helium working fluid. Its main function is to transport thermal energy from the IHX to the Process Coupling Heat Exchanger and Steam Generator.

The Intermediate Heat Exchanger (IHX) is comprised of:

- Heat exchanger cores and/or modules containing the heat transfer surface
- The IHX vessel
- Headers and/or piping that provide a transition between the heat exchanger cores and/or modules and the PHTS/SHTS piping
- Internal structures that provide for support (steady state, transients and seismic loading) of the IHX and related internal components within the IHX vessel
- Thermal baffles and/or insulation that is attached to the above IHX components

The IHX Vessel is part of the helium pressure boundary and includes internal support features, incorporated within the vessel structure, that interface with the IHX internal supports. It also includes thermal baffles and/or insulation that are directly attached to the vessel. The allocation of the IHX vessel (or parts thereof) as being part of the PHTS or SHTS will depend upon which fluids (PHTS or SHTS) are contained within the shell-side of the heat exchanger. This, in turn will be subject to the further selection of which circuit (PHTS or SHTS) will be coupled to the “shell” side of the heat exchanger.

The specified service conditions and other key requirements for IHX A are as given below.

- The nominal helium temperature at the primary side entrance to IHX A is 950°C.
- The nominal helium temperature at the secondary side entrance to IHX A is 710°C.
- The nominal helium temperature at the secondary side exit from IHX A is 900°C.
- The nominal helium temperature at the primary side exit from IHX A is 760°C.
- IHX A will provide for transfer of ~160 MWt.
- Helium in both the PHTS and SHTS will have controlled levels of impurities.
- Primary loop pressure will be nominally 9 MPa and essentially pressure balanced with the secondary loop pressure.
- The forced outage allocation is <1 %.
- Required operating life is >10 years for a metallic IHX A and 60 years for a ceramic version.
- The pressure loss across the entire IHX (IHX A + IHX B) primary side and also across secondary side of IHX shall be smaller than 1.23 % of its respective inlet pressures.

Further, there are a substantial number of fixed and preferred requirements in the areas of:

- Interfaces (e.g., IHX internal structures and fluid flow shall ensure that the vessel temperature be limited to 371°C during normal operation).
- System Configuration (e.g., the size ratio of IHX B to IHX A shall be as large as possible and overall capacity shall be 510 MW).
- Operation (e.g., the components of IHX A shall be able to accommodate 600 start-up and shut-down cycles).
- Tritium Migration Allowance (Tritium migration is s NHSS-level issue taking into account production and mitigation provided by various barriers and the He purification system. The specific IHX requirement is TBD.)
- Structure - the IHX vessel diameter shall be smaller than 6 m.
- Environment - all subject to further review
- Instrumentation & Control – to be determined
- Availability and Reliability – inherent availability of the IHX shall be >99.98%.
- Maintenance (e.g., the IHX shall not require preventive maintenance)
- Transport – design features shall be included to allow for transportation of subassemblies with final assembly on-site.
- Testing, Qualification, Commissioning – the entire PHTS, including the IHX, shall be pressure tested in accordance to ASME requirements.

All of the above are discussed in more detail in the *IHX and Heat Transport System (NGNP-HTS-RPT-TI001)* report.

# 4.2 IHX Down Selection Status

## 4.2.1 Candidate Designs and Materials

Various designs and materials for IHX A were proposed and evaluated in a series of recent studies. These studies were described and discussed in the following reports:

- Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007 [4-1]
- PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007 [4-2]
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008 [4-3].

The first of these studies considered both helical shell and tube and compact designs, primarily the Heatric based PCHE for the latter, and evaluated a broad range of Ni- and Fe/Ni base alloys for their construction. Based on this study, it was recommended that the compact heat exchanger design should be pursued with separate high-temperature (IHX A) and lower temperature (IHX B originally specified at <850°C and subsequently at <760°C) sections. It was also noted that a full life (60 year) IHX A was, because of corrosion limitations, almost certainly unobtainable with existing metallic materials. This implies one or more replacements during life, and argues that a compact IHX concept with a ceramic core should be pursued in parallel to achieve a 60 year version of IHX A. Alloy 617 was proposed as the reference material for the metallic version of IHX A with Alloy 230 as a backup; no specific ceramic material was proposed.

The second study confirmed the conclusions above (i.e., IHX A and IHX B sections, a PCHE compact design, Alloy 617 and Alloy 230 metallics, and parallel development of a ceramic based IHX) and further recommended that the IHX A/IHX B split be set at <760°C to take advantage of the ASME Section III qualification of Alloy 800H (760°C max).

The third study above was by far the most comprehensive in its evaluation of designs, performance, and materials. It also included two additional designs, a Capillary Heat Exchanger (small-diameter tube shell-and-tube) and a novel Involute (small-diameter tubes in an involute configuration) design. Also, an extensive study and evaluation of a plate-fin version of a compact heat exchanger was performed. No new recommendations were made relative to materials of construction for IHX A but data needs and concerns were covered in detail.

### 4.2.2 Decision Discriminators

This section provides discussion of the decision discriminators that were used in the *IHX and Heat Transport* study *(NGNP-HTS-RPT-TI001)* to evaluate various IHX designs and candidate materials. The five designs considered are as shown below.

- Conventional helical coil shell & tube
- Capillary tube
- PCHE
- Plate-fin
- Involute

Candidate materials evaluated were Alloy 230, Alloy 617, Alloy 800H, Hastelloy X, and ceramics (undefined). The metallic materials above were selected based on analyses of a much wider range of Alloys (Ref. 1).

The qualitative comparisons of the heat exchanger concepts were based on the following parameters.

- Cost/Performance Indicators
    - *Compactness in terms of heat transfer density ($MWt/m^3$)*
    - *Materials utilization (t/MWt)*
    - *Manufacturing cost*
- State-of –the-Art
    - *Experience base*
    - *Design & manufacturing*
- Robustness
    - *Normal operation*
    - *Transients*
- Environmental Compatibility
    - *Corrosion effects*
    - *Erosion effects*
    - *Tritium transport*
- Reliability & Integrity Management
    - *Detection of leaks/degradation during operation*
    - *Detection of leaks/degradation during outages*
    - *Leak location/isolation/repair/replacement*
- IHX Integration
    - *Integration with vessels and piping*
    - *Compatibility with multi-stage designs*
    - *Compatibility with multi-module designs*
    - *Compatibility with alternate heat transfer fluids*
- Design & Licensing Basis
    - *Code basis for design*

The Decision Discriminators applied for the materials were those shown below.

- Thermal Conductivity

- Materials Database
    - *Maturity of data*
    - *Specifications and standards status*
    - *ASME Code qualification requirement*
    - *Service experience*
    - *R&D status*
- Materials Lifetime
    - *Maximum operating temperature*
    - *Thermal and mechanical fatigue*
    - *Creep and creep-rupture*
    - *Erosion*
    - *Loss-of-secondary-pressure (LOSP) effects*
    - *Transient behavior*
    - *Corrosion*
- Fabrication Related Factors
    - *Product availability*
    - *Workability*
    - *Joining technology maturity and effects*
    - *Cost*

The application of the factors above to both the design and materials down select process is given and discussed below.

The following was indicated for design concepts based on the Decision Discriminators for design:

Cost/Performance Indicators

- The shell & tube design is poor except for established manufacturing processes.
- The capillary concept appears to be very expensive and labor intensive in terms of manufacturing.
- The PCHE is relatively good in all aspects.
- The plate-fin is good overall and best in terms of materials utilization
- PCHE and PFHE are best in terms of compactness ($MWt/m^3$).
- Materials costs for all are high, but least for the plate-fin assuming the same metallic materials.

State-of-the Art

- There is a reasonable and applicable experience base with design, manufacturing, and operation of metallic IHXs of shell & tube, PCHE, and plate-fin designs, although at somewhat lower temperatures.
- The experience base and technology for the capillary and involute designs are essentially nonexistent.
- There is no metallic material currently proven for any design for 10-year operation at 950°C. Further, no specific ceramic candidates have been identified.

Robustness

- Shell & tube designs are by far the most robust under normal operating conditions.
- The integrity of the braze joints in the plate-fin design offers some concern or uncertainty but the design appears good under normal operation and transients.
- The PCHE should be good under both normal operation and transients.
- Assessment of the capillary and involute designs is at best speculative at this time.
- There is concern relative to corrosion in the compact designs because of the use of very thin sections; the shell & tube design is of less concern because of the use of greater material thicknesses.

Environmental Compatibility

- As noted above, the shell & tube design would provide the maximum resistance to corrosion and erosion effects and tritium transport because of its heavier section thicknesses.
- The compact PCHE and plate-fin concepts are inferior to the shell & tube design because of associated thin sections and small fluid passages.
- The capillary and involute designs are intermediate in all of these factors.
- Corrosion allowances to be applied to the thin metallic sections of the PCHE and plate-fin designs are not currently quantitative and are somewhat worrisome.

Reliability & Integrity Management

- Detection of leaks during operation is possible and equivalent for all concepts.
- Easiest inspection for leaks during outages is for the shell & tube design but is possible for all concepts.
- Shell & tube, capillary, and involute designs permit plugging of individual tubes but the number of tubes to be accessed for the latter two is very large.
- Leaks in the PCHE and plate-fin designs can be identified and isolated at the module level.

HX Integration

- Integration with vessels and piping has been demonstrated for the shell & tube concept and appears acceptable for the PCHE and plate-fin designs; further evaluation would be needed for the capillary and involute designs.
- The PCHE and plate-fin designs are superior with respect to multi-stage and multi-module concepts.

Code Basis for Design

- There is an existing ASME Section VIII Code for design of shell & tube heat exchangers. This would likely also apply to the tubes for the capillary and involute designs but their headers have no precedent in the ASME Code.
- There is no existing ASME Code basis for either the PCHE or plate-fin designs.
- There are no existing ASME Code bases for either ceramic materials or a ceramic IHX design.

Application of the materials Decision Discriminators resulted in the following observations and decisions:

Materials Database

- All of the metallic candidates have significant databases but those for Alloy 800H and Hastelloy X are the most complete.
- All of the metallic candidates are recognized by the ASTM and the ASME but only Alloy 800H has ASME Section III approval and only to a maximum temperature of 760°C.
- All metallic candidates have substantial elevated temperature service in non-nuclear environments; Alloy 800H and Hastelloy X have seen some application in nuclear plants.
- Little if any R&D is ongoing on any of the metallic candidates.
- Little can be said about the database for a ceramic until specific selections have been made.

Materials Lifetime

- Potential lifetime of the metallic candidates at 950°C based on high-temperature creep strength increases from Alloy 800H, to Hastelloy X, to Alloy 230, and to Alloy 617.
- The fatigue resistance of all of the metallic candidates is likely sufficient for IHX operation.
- There is no current basis for down select of the metallic materials candidates based on transient behavior or erosion.
- The time before creep-rupture or creep-collapse under 950°C LOSP conditions is almost ten times greater for Alloy 617 than for Alloy 230. This was a significant factor in the selection of Alloy 617 for IHX A.
- The corrosion performance of any of the candidate metallics in NGNP He is suspect and possibly life-limiting at 950°C.

Fabrication Related Factors

- Product forms necessary for the fabrication of the compact heat exchanger designs are available for all of the metallic material candidates.
- Brazing and diffusion bonding processes for all of the alloys remain to be proven but all can likely be achieved.
- Alloy 800H is the least expensive material but will not suffice for construction of IHX A; the costs for Hastelloy X, Alloy 230, and Alloy 617 are higher but comparable.
- Costs for ceramic materials will exceed those for the metallics and a number of fabrication problems will need to be resolved.

### 4.2.3 Reference Design

The single alternate relative to the metallic IHX A is a decision to be taken at TRL 5 on the PCHE versus plate-fin design.

No alternates currently exist for the ceramic IHX. However, alternates could emerge as a result of Trade Studies recommended in Technology Maturation Plan from TRL 1-2.

### 4.2.4 Summary of IHX A Down Selection Task

The IHX A down select evaluation conducted for the IHX and reported in the *NGNP Conceptual Design Study: IHX and Heat Transport System* resulted in the various conclusions and recommendations listed below.

- The earlier recommendation to utilize PCHE or plate-fin compact heat exchanger technology as the basis for the metallic IHX design has been confirmed. This is the current metallic reference design and both are to employ Alloy 617 in the high temperature sections.
- A compact IHX configuration (applicable to both PCHE and plate-fin heat exchangers) that potentially allows leak detection, location and isolation at the module-level has been identified.
- Due to potential life limitations associated with high-temperature corrosion, the acceptability of a compact metallic IHX at 950°C remains to be confirmed. The present database for thin section materials is inadequate to support a definitive assessment.
- The earlier recommendation to separate the IHX into IHX-A and IHX-B sections, based on temperature, is supported by the results of the present study. Alloy 617 will be used for IHX A and Alloy 800H for IHX B.

The earlier recommendation to undertake a parallel development of ceramic HX technology for IHX A is confirmed.

## 4.3 TRL Status

Evaluations of the status of technology for the metallic and ceramic heat exchangers were made and resulted in the determination of TRL 2 for both heat exchangers. The underlying bases for these selections are described in TRL rating sheets provided for both metallic and ceramic heat exchanger versions (refer to section 0).

## 4.4 Technology Development Road Map Summary

### 4.4.1 Overview

The TDRM for IHX A begins (left side) with a listing of candidate materials considered for the IHX core and a listing of candidate designs for both the metallic and ceramic versions of the IHX. The Decision Discriminators shown just to the right of the materials candidates on the

Road Map were used to guide a down select to Alloy 617 for the metallic IHX A. Decision Discriminators shown in association with candidate designs formed the basis for the selection of both PCHE and plate-fin designs as options. Similarly, a ceramic version of IHX A was selected, but with Trade Studies (shown as down select tasks) still needed to finalize ceramic materials selections and ceramic heat exchanger designs.

Further to the right on the Road Map are shown the Maturation Tasks necessary to achieve succeedingly higher levels of Validated TRLs up to a TRL 8. For the metallic IHX A the paths for materials and designs merge at TRL 4 and a final design concept is achieved at TRL 5. The ceramic IHX A paths merge at TRL 4 with a final design concept at TRL 5.

The IHX A Technology Development Road Map is attached in Appendix B while the maturation tasks are described below.

## 4.5 Technology Maturation Plan Summary

### 4.5.1 Summary of Maturation Tasks – Metallic IHX A

The section below describes maturation tasks needed to advance the technology of the metallic IHX A from a validated TRL 2 to a validated TRL 8. The materials tasks include studies of thermal/physical and mechanical properties of Alloy 617, joining and fabrication techniques applicable to the alloys use in compact heat exchangers, determination of corrosion allowances for Alloy 617, and the establishment of appropriate ASME Code qualification. Significant levels of effort will also be devoted to methods for thermal/fluid and stress/strain modeling and to establishment of structural integrity criteria. Methods for performance modeling of compact heat exchangers will also be developed. Small elements or modules containing the heat transfer surface of the IHX will be fabricated, tested, and evaluated. These maturation tasks will be keyed to the DDNs described in the *NGNP Conceptual Design Study: IHX and Heat Transport System* whenever possible.

At this point on the TDRM, IHX A will have achieved a level of validated TRL 5 and a PCHE versus plate-fin decision will have been made. Advancement to a validated TRL 6 will require manufacture of a nominally 1.2 MW single module of IHX A, its testing in a representative environment, and verification of its performance. It will also be necessary to establish an ASME Code Case design of compact heat exchangers.

Moving the technology of IHX A from TRL 6 to TRL 7 will require tests to assess shell-side flow distribution and bypass leakage and multi-module tests for confirmation of heat transfer and flow performance.

Advancement of IHX technology from TRL 7 to TRL 8 will be fulfilled by the manufacture of a full-size IHX A compact heat exchanger and its testing in the NGNP.

The costs and schedules associated with the DDNs given in the *NGNP Conceptual Design Study: IHX and Heat Transport System* report were first presented in *PCDR Section 6: Heat Transport System*. Subsequently, more extensive and detailed estimates of schedules and costs for IHX A design, development, testing, and manufacture were performed and can be examined in *Metallic Component Schedule Risk and Cost Uncertainty Assessment, NGNP_RPT_, 30 April, 2008*. Further, schedules and costs will be provided in each of the Maturation Plans.

The Technology Maturation Plan required to mature the technology for a metallic IHX A to a TRL of 8 is attached in Appendix C.

### 4.5.2 Summary of Maturation Tasks – Ceramic IHX A

It is generally recognized that the maturity of the technology for a ceramic IHX is no better than TRL 2 and is probably several years behind that of the metallic IHX. However, the importance of achieving a heat exchanger capable of full-life service at 950°C compels its development.

The maturation tasks listed in the ceramic technology maturation plans follow parallel in many ways those for the metallic IHX but do not have a parallel benefit of well defined DDNs. The *PCDR* report (Ref. 2) provided only 6 DDNs, and only as placeholders. They were as follows:

- HTS-02-01 – Review Existing Technology
- HTS-02-02 – Materials Property Database
- HTS-02-03 – Design Methods
- HTS-02-04 – Performance Verification
- HTS-02-05 – Manufacturing Technology
- HTS-02-06 – Codes & Standards

These DDNs can be used, however, as a rough guide to technology needs. Costs for ceramics materials and methods development were estimated in *PCDR Section 16* in 2007 to be at least 50% greater than those for similar activities for the metallic counterpart. Manufacturing costs have not been addressed.

The Technology Maturation Plan required to mature this technology for a ceramic IHX A to a TRL of 8 is attached in Appendix D.

## 4.6 Inputs into CTF

The metallic and ceramic versions of the IHX A will be tested in the CTF for qualification of a TRL5, TRL 6 as well as a TRL 7.

The following tasks noted in the Maturation Plans will be qualified in the CTF:

- Metallic IHX Unit Cell (In the Small Scale Development Test Facility)
- 1.2 MW Metallic IHX Module (In the Technology Development Loop)
- Testing of a Multiple Metallic IHX Modules (In the Component Qualification Loop).
- Ceramic IHX Unit Cell (In the Small Scale Development Test Facility)
- 1.2 MW Ceramic IHX Module (In the Technology Development Loop)
- Testing of a Multiple Ceramic IHX Modules (In the Component Qualification Loop).

## 4.7 References

[4-1] Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007

[4-2] PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007

[4-3] NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008

# APPENDIX A: TRL RATING SHEETS

**Table A-1: Technology Readiness Levels for the IHX A (Metallic)**

## TRL Rating Sheet

Vendor Name: Document Number: Revision:

☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology

Title: Intermediate Heat Exchanger (IHX A - Metallic) (950°C)

Description:

The Technology Readiness Level for a metallic intermediate heat exchanger operating in the NGNP at 950°C for up to 10 years has been assessed as TRL 2 based on studies noted below. The actions required to go to a level of TRL 3 are also shown below.

Area(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: N/A | Parent: N/A | WBS: N/A |
|---|---|---|

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Basic principles observed | Application formulated | Proof of concept |
| **TRL** | 1 | **2** | 3 |

Basis for Rating (Attach additional sheets as needed)

Various designs and metallic materials for an IHX operating at 950°C (IHX A) were proposed and evaluated in recent studies reported in:

- Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007
- PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008

The recommendation resulting from these studies was a compact heat exchanger design (PCHE or plate-fin) using Alloy 617 as the material for the heat exchanger core.

<table>
<tr><td colspan="3">Outline of a plan to get from current level to next level (Attach additional sheets as needed)</td></tr>
<tr><td>Actions (list all)</td><td>Schedule</td><td>Cost (K$)</td></tr>
<tr><td><ul><li>Alloy 617 Material Specifications and Procurement</li><li>Alloy 617 Joining Technology and Resultant Properties</li><li>Thermal/Physical and Mechanical Properties of Alloy 617</li><li>Effects of Thermal Aging and Environment on Alloy 617 Properties</li><li>Effects of Grain Size and Section Thickness on Alloy 617 Properties</li><li>Corrosion Allowances for Alloy 617</li></ul></td><td>FY 2009 – FY 2012</td><td>Refer to Section C6</td></tr>
<tr><td colspan="3">DDN(s) supported: HTS-01-01, HTS-01-02, HTS-01-03, HTS-01-04, HTS-01-05, HTS-01-06, HTS-01-20, HTS-01-21, HTS-01-30</td></tr>
<tr><td colspan="3">SME Making Determination: Phil Rittenhouse</td></tr>
<tr><td>Date: August 25, 2008</td><td colspan="2">Originating Organization: Technology Insights</td></tr>
</table>

**Table A-2: Technology Readiness Levels for the IHX A (Ceramic)**

## TRL Rating Sheet

Vendor Name: Document Number: Revision:

☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology

Title: Intermediate Heat Exchanger (IHX A - Ceramic) (950°C)

Description:

The Technology Readiness Level for a ceramic intermediate heat exchanger operating in the NGNP at 950°C for up to 60 years has been assessed as TRL 1 based on studies noted below. The actions required to go to a level of TRL 2 are also shown below.

Island(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: N/A | Parent: N/A | WBS: N/A |
|---|---|---|

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | | Basic principles observed | Application formulated |
| **TRL** | 1 | **2** | 3 |

Basis for Rating (Attach additional sheets as needed)

Various designs and materials for an IHX operating at 950°C (IHX A) were proposed and evaluated in recent studies reported in:

- Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007
- PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008

A recommendation resulting from these studies was to select and develop a ceramic heat exchanger.

Work on evaluation of ceramic heat exchanger materials, joining techniques, and heat exchanger performance was reported by Ceramatec in several venues (e.g., UNLV/DOE NHI Review and UNLVRF

| | | |
|---|---|---|
| HTHX Project Review) in 2006. The work supports a TRL level of 2. | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | |
| Actions (list all) | Schedule | Cost (K$) |
| • Trade Study to evaluate ceramic materials for heat exchangers with the goal of selecting a reference material or materials.<br>• Trade Study to evaluate candidate ceramic heat exchanger designs with the goal of selecting a reference design or designs. | FY 2009-2011 | Refer to Section D7 |
| DDN(s) supported: HTS-02-01, HTS-02-02, HTS-02-03 | | |
| SME Making Determination: Phil Rittenhouse | | |
| Date: August 25, 2008 | Originating Organization: Technology Insights | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

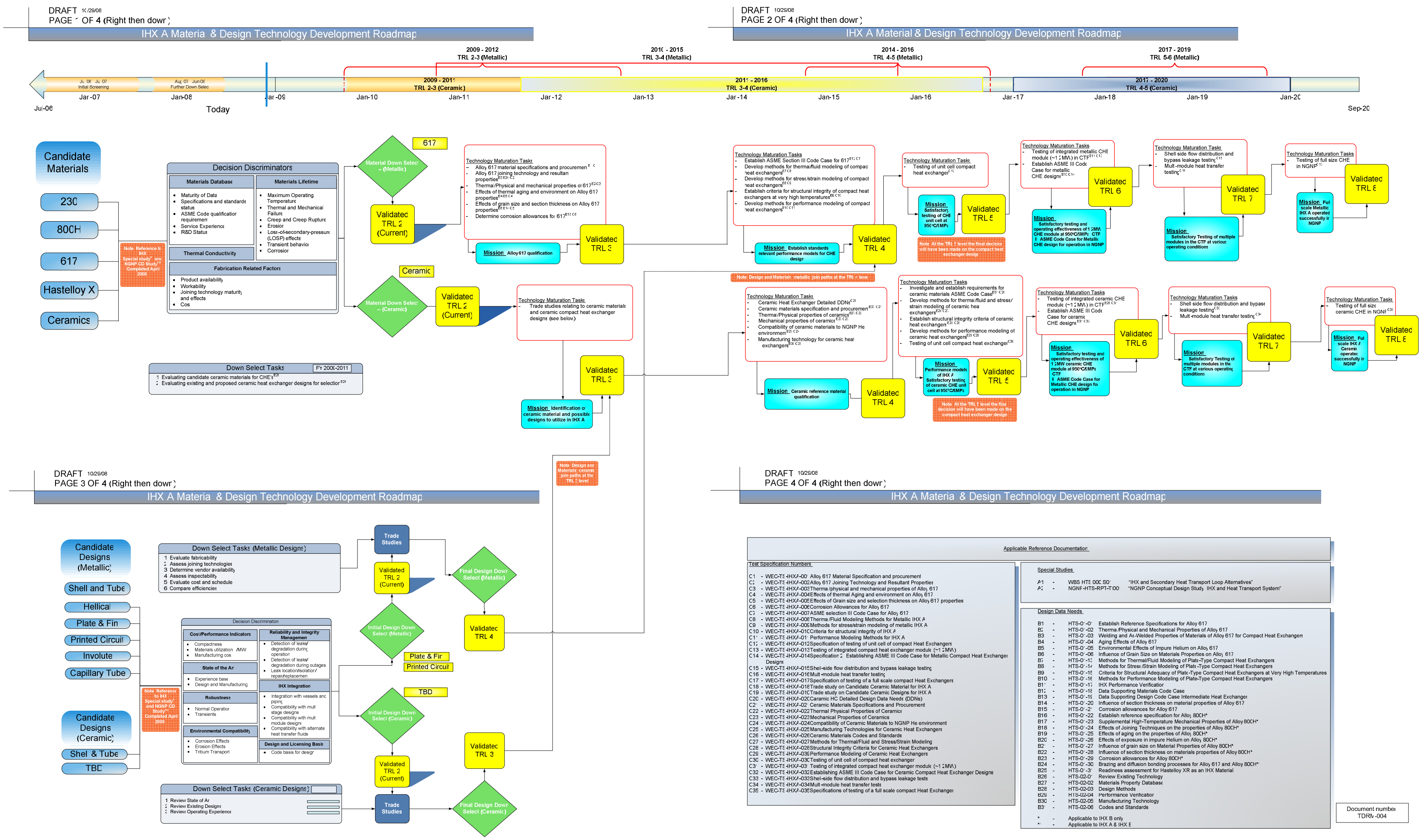


Figure B-1: TDRM for IHX A (Pages 1-4 to follow hereafter)

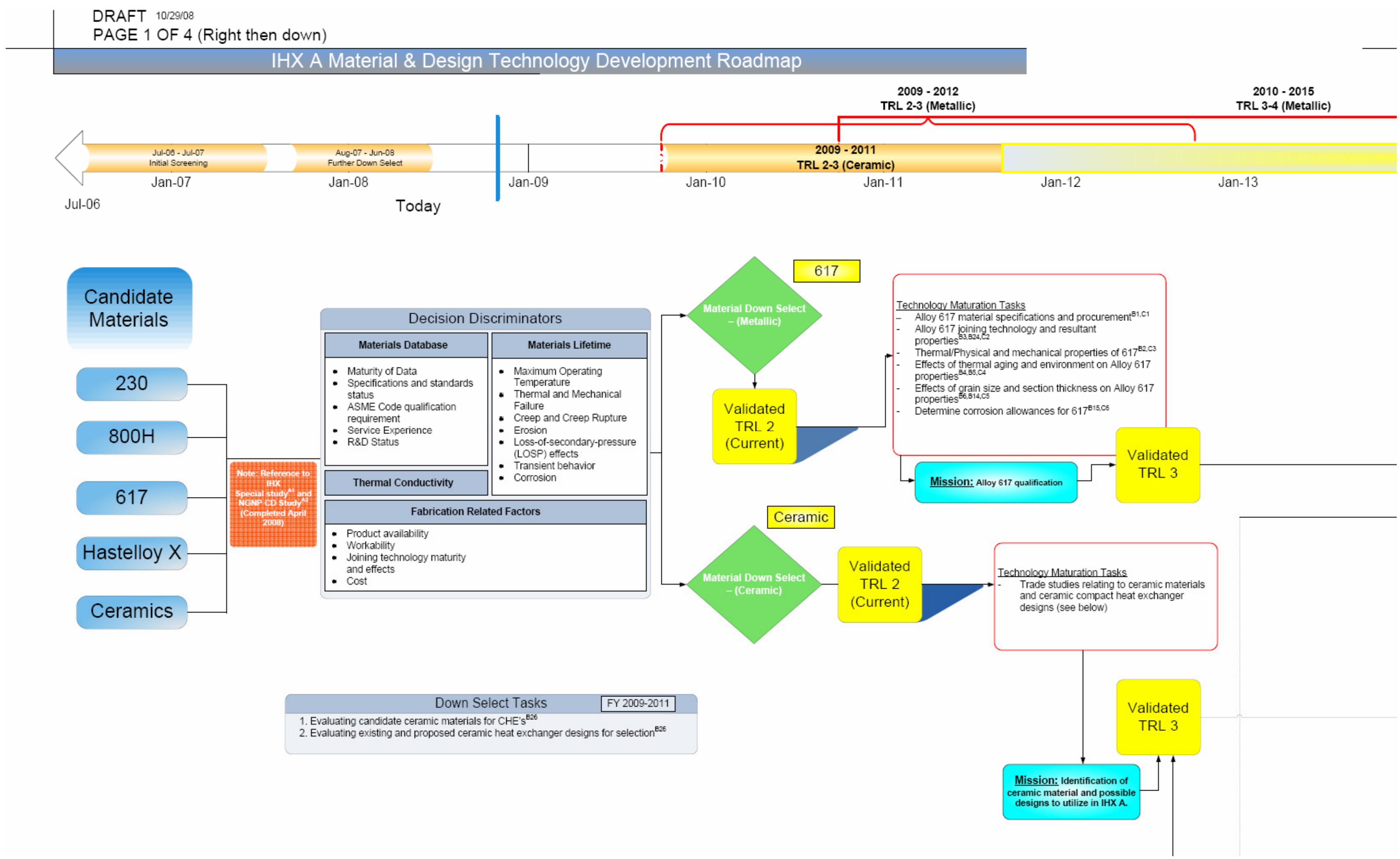


**Figure B-2: TDRM for IHX A (Page 1 of 4)**

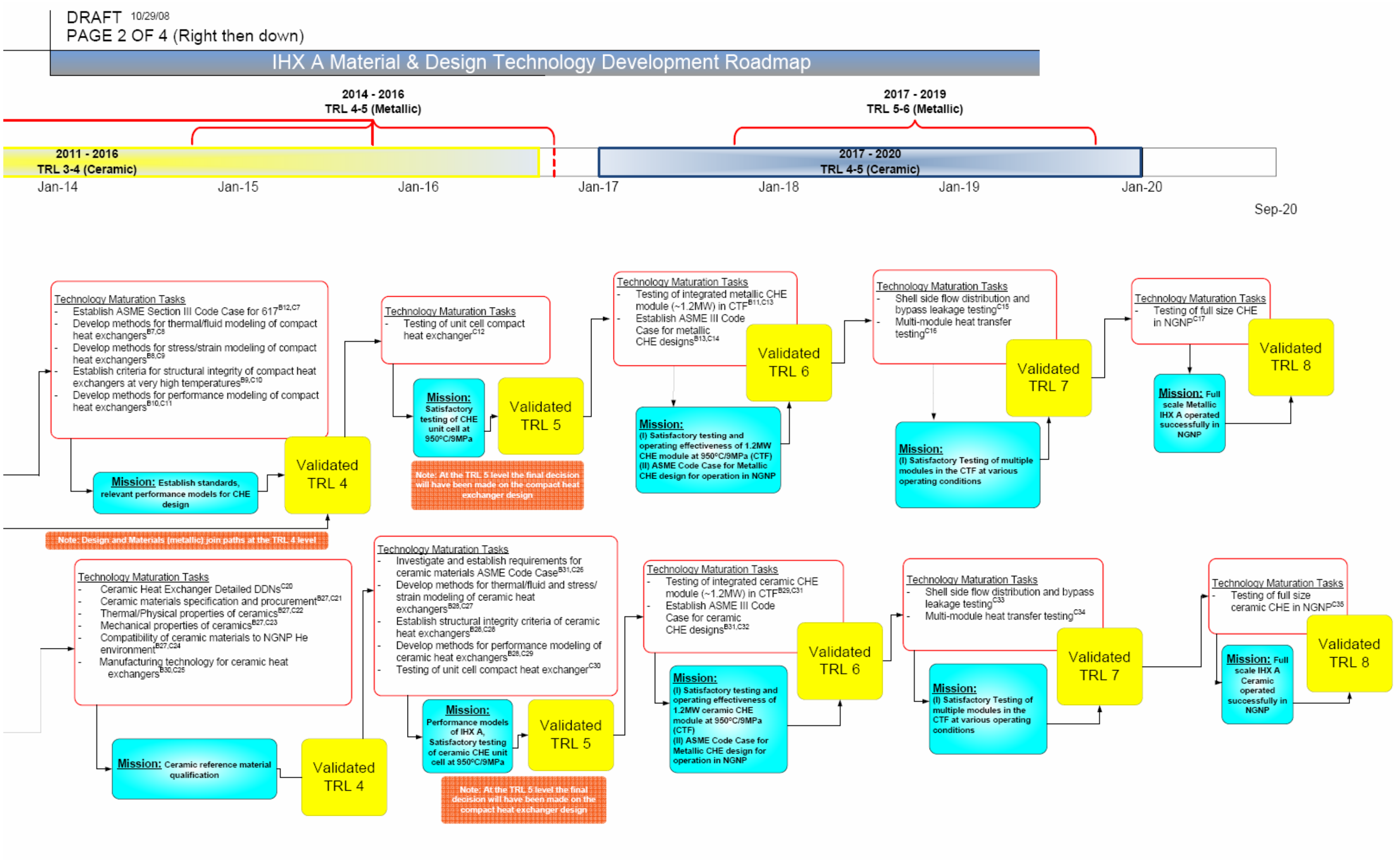


Figure B-3: TDRM for IHX A (Page 2 of 4)

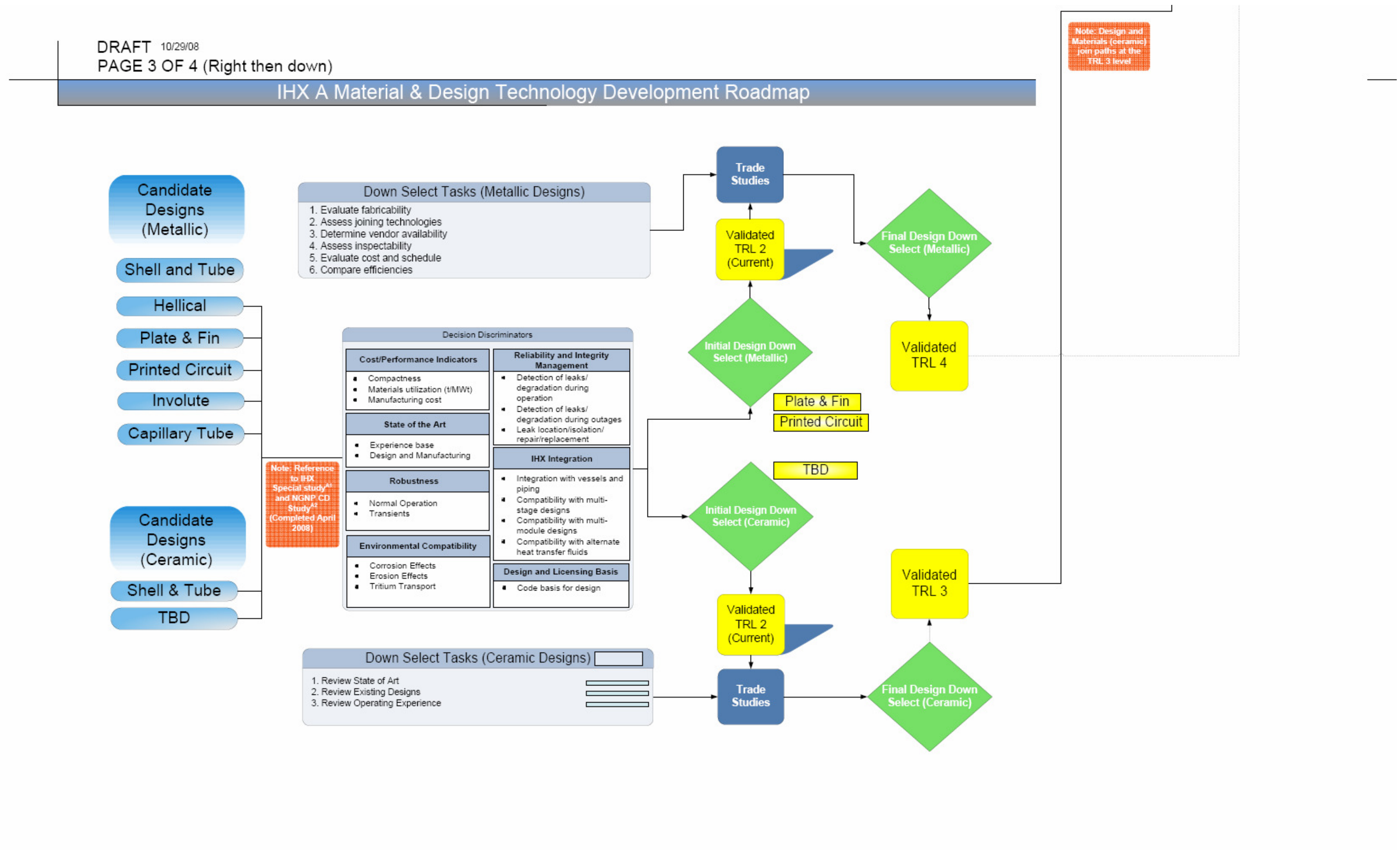


**Figure B-4: TDRM for IHX A (Page 3 of 4)**

DRAFT 10/29/08
PAGE 4 OF 4 (Right then down)

## IHX A Material & Design Technology Development Roadmap

Applicable Reference Documentation:

Test Specification Numbers:

C1 - WEC-TS-IHXA-001 Alloy 617 Material Specification and procurement
C2 - WEC-TS-IHXA-002 Alloy 617 Joining Technology and Resultant Properties
C3 - WEC-TS-IHXA-003 Thermal/physical and mechanical properties of Alloy 617
C4 - WEC-TS-IHXA-004 Effects of thermal Aging and environment on Alloy 617
C5 - WEC-TS-IHXA-005 Effects of Grain size and selection thickness on Alloy 617 properties
C6 - WEC-TS-IHXA-006 Corrosion Allowances for Alloy 617
C7 - WEC-TS-IHXA-007 ASME selection III Code Case for Alloy 617
C8 - WEC-TS-IHXA-008 Thermal/Fluid Modeling Methods for Metallic IHX A
C9 - WEC-TS-IHXA-009 Methods for stress/strain modeling of metallic IHX A
C10 - WEC-TS-IHXA-010 Criteria for structural integrity of IHX A
C11 - WEC-TS-IHXA-011 Performance Modeling Methods for IHX A
C12 - WEC-TS-IHXA-012 Specification of testing of unit cell of compact Heat Exchangers
C13 - WEC-TS-IHXA-013 Testing of integrated compact heat exchanger module (~1.2MW)
C14 - WEC-TS-IHXA-014 Specification 2: Establishing ASME III Code Case for Metallic Compact Heat Exchanger Designs
C15 - WEC-TS-IHXA-015 Shell-side flow distribution and bypass leakage testing
C16 - WEC-TS-IHXA-016 Multi-module heat transfer testing
C17 - WEC-TS-IHXA-017 Specification of testing of a full scale compact Heat Exchangers
C18 - WEC-TS-IHXA-018 Trade study on Candidate Ceramic Material for IHX A
C19 - WEC-TS-IHXA-010 Trade study on Candidate Ceramic Designs for IHX A
C20 - WEC-TS-IHXA-020 Caramic HC Detailed Design Data Needs (DDNs)
C21 - WEC-TS-IHXA-021 Ceramic Materials Specifications and Procurement
C22 - WEC-TS-IHXA-022 Thermal Physical Properties of Ceramics
C23 - WEC-TS-IHXA-023 Mechanical Properties of Ceramics
C24 - WEC-TS-IHXA-024 Compatibility of Ceramic Materials to NGNP He environment
C25 - WEC-TS-IHXA-025 Manufacturing Technologies for Ceramic Heat Exchangers
C26 - WEC-TS-IHXA-026 Ceramic Materials Codes and Standards
C27 - WEC-TS-IHXA-027 Methods for Thermal/Fluid and Stress/Strain Modeling
C28 - WEC-TS-IHXA-028 Structural Integrity Criteria for Ceramic Heat Exchangers
C29 - WEC-TS-IHXA-039 Performance Modeling of Ceramic Heat Exchangers
C30 - WEC-TS-IHXA-030 Testing of unit cell of compact heat exchanger
C31 - WEC-TS-IHXA-031 Testing of integrated compact heat exchanger module (~1.2MW)
C32 - WEC-TS-IHXA-032 Establishing ASME III Code Case for Ceramic Compact Heat Exchanger Designs
C33 - WEC-TS-IHXA-033 Shell-side flow distribution and bypass leakage tests.
C34 - WEC-TS-IHXA-034 Multi-module heat transfer tests.
C35 - WEC-TS-IHXA-035 Specifications of testing of a full scale compact Heat Exchanger

Special Studies:

A1 - WBS HTS.000.S01 "IHX and Secondary Heat Transport Loop Alternatives"
A2 - NGNP-HTS-RPT-TI001 "NGNP Conceptual Design Study: IHX and Heat Transport System"

Design Data Needs:

B1 - HTS-01-01 Establish Reference Specifications for Alloy 617
B2 - HTS-01-02 Thermal/Physical and Mechanical Properties of Alloy 617
B3 - HTS-01-03 Welding and As-Welded Properties of Materials of Alloy 617 for Compact Heat Exchangers
B4 - HTS-01-04 Aging Effects of Alloy 617
B5 - HTS-01-05 Environmental Effects of Impure Helium on Alloy 617
B6 - HTS-01-06 Influence of Grain Size on Materials Properties on Alloy 617
B7 - HTS-01-13 Methods for Thermal/Fluid Modeling of Plate-Type Compact Heat Exchangers
B8 - HTS-01-14 Methods for Stress/Strain Modeling of Plate-Type Compact Heat Exchangers
B9 - HTS-01-15 Criteria for Structural Adequacy of Plate-Type Compact Heat Exchangers at Very High Temperatures
B10 - HTS-01-16 Methods for Performance Modeling of Plate-Type Compact Heat Exchangers
B11 - HTS-01-17 IHX Performance Verification
B12 - HTS-01-18 Data Supporting Materials Code Case
B13 - HTS-01-19 Data Supporting Design Code Case Intermediate Heat Exchanger
B14 - HTS-01-20 Influence of section thickness on material properties of Alloy 617
B15 - HTS-01-21 Corrosion allowances for Alloy 617
B16 - HTS-01-22 Establish reference specification for Alloy 800H*
B17 - HTS-01-23 Supplemental High-Temperature Mechanical Properties of Alloy 800H*
B18 - HTS-01-24 Effects of Joining Techniques on the properties of Alloy 800H*
B19 - HTS-01-25 Effects of aging on the properties of Alloy 800H*
B20 - HTS-01-26 Effects of exposure in impure Helium on Alloy 800H*
B21 - HTS-01-27 Influence of grain size on Material Properties of Alloy 800H*
B22 - HTS-01-28 Influence of section thickness on materials properties of Alloy 800H*
B23 - HTS-01-29 Corrosion allowances for Alloy 800H*
B24 - HTS-01-30 Brazing and diffusion bonding processes for Alloy 617 and Alloy 800H**
B25 - HTS-01-31 Readiness assessment for Hastelloy XR as an IHX Material
B26 - HTS-02-01 Review Existing Technology
B27 - HTS-02-02 Materials Property Database
B28 - HTS-02-03 Design Methods
B29 - HTS-02-04 Performance Verification
B30 - HTS-02-05 Manufacturing Technology
B31 - HTS-02-06 Codes and Standards

* - Applicable to IHX B only
** - Applicable to IHX A & IHX B

**Figure B-5**: **TDRM for IHX A (Page 4 of 4)**

# APPENDIX C: TECHNOLOGY MATURATION PLAN – METALLIC IHX A

# TABLE OF CONTENTS

**Section** **Title** **Page**

## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

**TRL 2 to TRL 3:**

- Specification 1: Alloy 617 Material Specifications and Procurement *(WEC-TS-IHXA-001)*
- Specification 2: Alloy 617 Joining Technology and Resultant Properties *(WEC-TS-IHXA-002)*
- Specification 3: Thermal/Physical and Mechanical Properties of Alloy 617 *(WEC-TS-IHXA-003)*
- Specification 4: Effects of Thermal Aging and Environment on Alloy 617 Properties *(WEC-TS-IHXA-004)*
- Specification 5: Effects of Grain Size and Section Thickness on Alloy 617 Properties *(WEC-TS-IHXA-005)*
- Specification 6: Corrosion Allowances for Alloy 617 *(WEC-TS-IHXA-006)*

**TRL 3 to TRL 4:**

- Specification 1: ASME Section III Code Case for Alloy 617 *(WEC-TS-IHXA-007)*
- Specification 2: Thermal/Fluid Modeling Methods for Metallic IHX A *(WEC-TS-IHXA-008)*
- Specification 3: Methods for Stress/Strain Modeling of Metallic IHX A *(WEC-TS-IHXA-009)*
- Specification 4: Criteria for Structural Integrity of IHX A *(WEC-TS-IHXA-010)*
- Specification 5: Performance Modeling Methods for IHX A *(WEC-TS-IHXA-011)*

**TRL 4 to TRL 5:**

- Specification 1: Testing of unit cell compact heat exchanger *(WEC-TS-IHXA-012)*

**TRL 5 to TRL 6:**

- Specification 1: Testing of integrated compact heat exchanger module (~1.2MW) *(WEC-TS-IHXA-013)*
- Specification 2: Establishing ASME III Code Case for Metallic Compact Heat Exchanger Designs *(WEC-TS-IHXA-014)*

**TRL 6 to TRL 7**

- Specification 1: Shell-side flow distribution and bypass leakage testing *(WEC-TS-IHXA-015)*
- Specification 2: Multi-module heat transfer testing *(WEC-TS-IHXA-016)*

**TRL 7 to TRL 8:**

- Specification 1: Testing of full size compact heat exchanger *(Full scale NGNP IHX A)* (WEC-TS-IHXA-0017)

# C1 TECHNOLOGY MATURATION PLAN FOR IHX A (METALLIC) - TRL 2 TO TRL 3

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX A from a TRL level of 2 to a TRL level of 3. Several of the maturations tasks required to achieve this goal involve the mechanical and thermal/physical properties of Alloy 617 and how they are affected by material thickness, grain size, thermal aging, and environmental exposure. Joining processes (welding, brazing, and diffusion bonding) and their effects on properties are also addressed. Finally, one of the maturation tasks addresses the corrosion (scale formation, internal oxidation, etc.) of Alloy 617 in NGNP primary and secondary He atmospheres containing low levels of impurities. A Test Specification is provided to cover each of the maturation tasks. These are given in Section C1.2.

### C1.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the metallic version of IHX A from TRL 2 to TRL 3 are as shown below.

- Alloy 617 material specifications and procurement
- Alloy 617 joining technology and resultant properties
- Determine and/or confirm thermal/physical and mechanical properties of Alloy 617
- Confirm effects of thermal aging and environmental exposure on Alloy 617 properties
- Assess effects of grain size and section thickness on Alloy 617 properties
- Determine corrosion allowances for Alloy 617

The tasks above will be described fully in individual Test Specifications provided in the sections to follow.

### C1.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2009 through FY2012. No individual Test Specification describes work requiring more than 42 months and the work in most Test Specifications can be done in parallel.

#### C1.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

## C1.2 Test Specifications

### C1.2.1 Alloy 617 Material Specifications and Procurement (WEC-TS-IHXA-001)

#### C1.2.1.1 Objectives

Activities covered in this Test Specification are the finalization of the material specifications (alloy chemistry, fabrication processes etc.), development of procurement requirements for NGNP Alloy 617, and procurement of three heats of Alloy 617 for evaluation and testing. With respect to the former, it is expected that existing ASTM standards will encompass the NGNP specification. No actual physical testing will be performed. This Test Specification responds to DDN HTS-01-01.

#### C1.2.1.2 Test Conditions

*C1.2.1.2.1 Test Configuration/Set-up*

No test equipment/facility is needed except for existing conventional test machines (e.g., tensile test machine) for confirming that the procured Alloy 617 meets specifications.

*C1.2.1.2.2 Test Duration*

The duration of this activity could be up to 12 months.

*C1.2.1.2.3 Proposed Test Location*

The work could be performed at an appropriate National Laboratory.

#### C1.2.1.3 Measured Parameters

Properties, chemistry, grain size, etc. specified in the material specifications and requirements.

#### C1.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C1.2.1.5 Test Evaluation Criteria

Heats of Alloy 617 acquired shall meet all procurement requirements and material specifications.

#### C1.2.1.6 Test Deliverables

Deliverables are as follows.

- Alloy 617 material purchase specification
- Three heats of Alloy 617 acquired per the above
- Report confirming that the heats of Alloy 617 meet all specifications and requirements (e.g. Certified Materials Test Report, for each heat)

#### C1.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 2 to TRL 3 is addressed in Sections C1.1.3 and C1.1.4 Risks include that the material doesn't qualify and that the overall schedule will be delayed.

### C1.2.2 Alloy 617 Joining Technology and Resultant Properties (WEC-TS-IHXA-002)

#### C1.2.2.1 Objectives

Work conducted under this Test Specification will demonstrate that Alloy 617 can be welded, brazed, and diffusion bonded to produce structurally sound unit cells and modules of compact heat exchangers and that the properties of these joints will have properties appropriate to this use. This Test Specification responds to DDN HTS-01-03 and to DDN HTS-01-30.

#### C1.2.2.2 Test Conditions

##### *C1.2.2.2.1 Test Configuration/Set-up*

These activities require the following.

- Equipment and facilities for welding, brazing, and diffusion bonding
- Equipment for microscopic examination
- Equipment for mechanical property testing

*C1.2.2.2.2 Test Duration*

The duration of these joining and testing activities could be up to 30 months.

*C1.2.2.2.3 Proposed Test Location*

A National Laboratory or University could perform the work on microscopic examination and mechanical properties. Commercial organizations involved in compact heat exchanger manufacture would be appropriate for the joining studies, and to produce the bonded unit cells for test specimens.

### C1.2.2.3 Measured Parameters

Parameters to be measured include the following.

- Conditions and parameters applied in producing the joints
- Condition of the Alloy 617 joints as evidenced by metallography
- Chemistry profiles in the joints determined by SEM
- Tensile, creep, fatigue, and fracture toughness at temperatures up to 1000°C

### C1.2.2.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

### C1.2.2.5 Test Evaluation Criteria

This work or an accepted variation thereof will provide the basis for determination of the suitability of the three joining methods to the manufacture of compact heat exchangers. Criteria involved in the evaluation of each joint type will include:

- Structural integrity as evidenced by metallography and SEM
- Minimal or no reduction in strength or ductility of the Alloy 617 joints

### C1.2.2.6 Test Deliverables

Deliverables are as follows.

- Brazing procedure specifications
- Diffusion bonding procedure specifications
- Conventional welding procedure specifications
- Reports on structural integrity of joints formed by welding, brazing, and diffusion bonding
- Reports on mechanical properties of welded, brazed, and diffusion bonded joints

### C1.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 2 to TRL 3 is addressed in Sections C1.1.3 and

C1.1.4. The risks associated with Section C1.2.2 are small but include the possibility that one or more of the joining techniques may prove unsuitable for thin section of Alloy 617.

## C1.2.3 Thermal/Physical and Mechanical Properties of Alloy 617 (WEC-TS-IHXA-003)

### C1.2.3.1 Objectives

The objective of this work is to confirm that Alloy 617 materials procured to NGNP specifications will have thermal/physical and mechanical properties adequate for a compact IHX A. This Test Specification responds to DDN HTS-01-02.

### C1.2.3.2 Test Conditions

*C1.2.3.2.1 Test Configuration/Set-up*

Accomplishment of testing prescribed in DDN HTS-01-02 requires:

- Equipment for thermal/physical property testing
- Equipment for mechanical property testing up to 1000°C

*C1.2.3.2.2 Test Duration*

Thermal/physical and mechanical property testing could require up to 36 months.

*C1.2.3.2.3 Proposed Test Location*

Property tests on NGNP Alloy 617 could be conveniently performed at a National Laboratory or University.

### C1.2.3.3 Measured Parameters

Data to be determined include:

- Thermal conductivity to 1000°C
- Coefficients of thermal expansion to 1000°C
- Elastic properties to 1000°C
- Tensile properties (yield strength, tensile strength, elongation, and RA) to 1000°C
- Fatigue strength (LCF and HCF) to 1000°C
- Creep strength to 1000°C for 10,000 h
- Fracture toughness
-

### C1.2.3.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

#### C1.2.3.5 Test Evaluation Criteria

Mechanical property data from the three heats of NGNP Alloy 617 shall agree to within +/-15%; the data obtained shall also be representative of the existing database for Alloy 617.

#### C1.2.3.6 Test Deliverables

Deliverables are as follows.

- Reports of thermal/physical properties of Alloy 617 procured to NGNP specifications
- Reports on elastic, tensile, fatigue, creep, and fracture toughness of Alloy 617 procured to NGNP specifications

#### C1.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 2 to TRL 3 is addressed in Sections C1.1.3 and C1.1.4. The associated risk is high (since parameters are time and temperature dependant) and includes the possibility that one or more of the properties measured falls short of what is required for use of Alloy 617 in a high temperature compact heat exchanger.

### C1.2.4 Effects of Thermal Aging and Environment on Alloy 617 Properties (WEC-TS-IHXA-004)

#### C1.2.4.1 Objectives

The objective of the testing performed under this Test Specification is to demonstrate that Alloy 617 purchased to the NGNP specification and weld, braze, and diffusion bond joints prepared to accepted standards can be used at temperatures between 750°C and 950°C for up to at least 10 years without unacceptable degradation of mechanical properties or microstructure. Additionally, the work is to demonstrate that exposures conducted in NGNP He environment (low levels of CO, $CO_2$, $H_2$, $H_2O$, $O_2$ and $CH_4$) do not further degrade the properties of Alloy 617. This Test Specification responds to DDN HTS-01-03 and DDN HTS-01-04.

#### C1.2.4.2 Test Conditions

*C1.2.4.2.1 Test Configuration/Set-up*

Equipment/facilities must be available for:

- Thermal aging of Alloy 617 for up to 10,000 h at temperatures from 700°C to 1000°C.
- Exposure in representative NGNP He environment over the same time/temperature range

- Test equipment and facilities for measuring mechanical properties after thermal and environmental exposures
- Metallographic capability to determine structural changes

*C1.2.4.2.2 Test Duration*

Thermal aging and environmental exposures of Alloy 617 and subsequent testing will require about 42 months.

*C1.2.4.2.3 Proposed Test Location*

Thermal and environmental exposures of Alloy 617 and subsequent examinations are best suited to be conducted at a National Laboratory.

### C1.2.4.3 Measured Parameters

Data and exposure parameters to be measured/recorded include:

- Thermal exposure times and temperatures
- Environmental exposure times, temperatures, and He chemistry
- Tensile properties (yield strength, tensile strength, elongation, and RA) after exposures
- Fatigue strength (LCF and HCF) after exposures
- Creep strength after exposures
- Fracture toughness after exposures.

### C1.2.4.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

### C1.2.4.5 Test Evaluation Criteria

Mechanical property data from the three heats of NGNP Alloy 617 obtained after thermal and environmental exposures shall be in reasonable heat-to-heat agreement and shall be consistent with the existing database for Alloy 617.

### C1.2.4.6 Test Deliverables

Deliverables are as follows.

- Reports documenting details of the thermal and environmental exposures
- Reports describing the effects of thermal and environmental exposures on mechanical properties of base metal, welds, braze joints, and diffusion bonds
- Report describing the effects of thermal and environmental exposures on Alloy 617 structure of base metal, welds, braze joints, and diffusion bonds.

#### C1.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 2 to TRL 3 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with Section C1.2.4 is small but includes the possibility that one or more of the properties measured after exposure may fall short of what is required for use of Alloy 617 in a compact heat exchanger at up to 950°C for 10 years.

### C1.2.5 Effects of Grain Size and Section Thickness on Alloy 617 Properties (WEC-TS-IHXA-005)

#### C1.2.5.1 Objectives

The objective of the work prescribed in this Test Specification is to 1) demonstrate that the very thin as-fabricated material sections of Alloy 617 (significantly less than 1 mm) required in the IHX A compact heat exchanger will have creep and fatigue properties equivalent or only slightly degraded relative to those of products of more typical thickness and 2) that fatigue and creep properties of Alloy 617 with grain sizes smaller than those found in typical 617 products are acceptable for compact heat exchanger operation. Smaller grain sizes normally favor enhanced fatigue resistance at the expense of creep strength. This Test Specification responds to DDN HTS-01-06 and DDN HTS-01-20.

#### C1.2.5.2 Test Conditions

*C1.2.5.2.1 Test Configuration/Set-up*

Conduct of this work requires equipment/facilities for creep and fatigue measurement and for metallographic determination of grain size.

*C1.2.5.2.2 Test Duration*

The work relative to grain size and section thickness effects on Alloy 617 creep and fatigue properties should require about 24 months.

*C1.2.5.2.3 Proposed Test Location*

Study and measurements relative to grain size and section thickness effects on properties are best suited to be conducted at a National Laboratory.

#### C1.2.5.3 Measured Parameters

Data to be taken include:

- Creep properties (up to 1000°C) as a function of fabricated material thickness
- Creep properties (up to 1000°C) as a function of grain size
- Fatigue properties as a function of fabricated material thickness

- Fatigue properties as a function of grain size.

#### C1.2.5.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

#### C1.2.5.5 Test Evaluation Criteria

The creep and fatigue properties determined on thin section and small grain size Alloy 617 material must meet the requirements for fatigue and creep resistance in the IHX A compact heat exchanger.

#### C1.2.5.6 Test Deliverables

Deliverables for this Test Specification shall include:

- Report on the influence of section thickness on creep and fatigue properties of Alloy 617
- Report on the influence of grain size on creep and fatigue properties of Alloy 617.

#### C1.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 2 to TRL 3 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with Section C1.2.5 is small but includes the possibility that either thin sections or small grain size may result in creep or fatigue properties inconsistent with the use of Alloy 617 in the IHX A compact heat exchanger.

### C1.2.6 Corrosion Allowances for Alloy 617 (WEC-TS-IHXA-006)

#### C1.2.6.1 Objectives

The major objective of this activity is to ensure that exposure of Alloy 617 base metal, weldments, braze joints, and diffusion bonds at high temperatures (up to 950°C) for up to 10 years in NGNP He does not compromise the structural integrity of the material cross-section by oxide scale formation, internal oxidation, or other phenomena from either the primary or secondary side of the HTS. This Test Specification responds to DDN HTS-01-21.

#### C1.2.6.2 Test Conditions

*C1.2.6.2.1 Test Configuration/Set-up*

Determination of corrosion allowances for Alloy 617 will require the following.

- Facility for exposure in He (700°C to 1000°C) / 9MPa with low levels of CO, $CO_2$, $H_2$, $H_2O$, and $CH_4$ for up to 10,000 hours

- Provisions for introduction, control, and measurement of impurity levels
- Metallographic and SEM equipment for determination of thickness of the oxides, depths of internal oxidation, alloy element depletion, and carburization/decarburization

*C1.2.6.2.2 Test Duration*

Conduct of this work will require 36 months.

*C1.2.6.2.3 Proposed Test Location*

This work can most effectively be done by ASME members from industry, with supporting data from the test labs.

### C1.2.6.3 Measured Parameters

Parameters to be measured and data taken include:

- Impurity levels in primary side NGNP He as a function of time at all exposure temperatures
- Impurity levels in secondary side NGNP He as a function of time at all exposure temperatures
- Oxide scale thickness and composition
- Depth of internal oxidation
- Depth of depletion of alloy elements, primarily Cr
- Depth affected by carburization or decarburization.

### C1.2.6.4 Data Requirements

All data shall be acquired using best practice techniques and QA.

### C1.2.6.5 Test Evaluation Criteria

The corrosion allowances determined for Alloy 617 must not be of such magnitude that they degrade the structural integrity of the thin material sections (including welds, brazes, and diffusion bonds) required for the IHX A compact heat exchanger.

### C1.2.6.6 Test Deliverables C1.2.6.

The following will be provided to meet the objectives of this Test Specification.

- Reports providing details of all exposures in impure primary and secondary side NGNP He
- Oxide scale thickness as a function of time, temperature, and He chemistry
- Depth of internal oxidation as a function of time, temperature, and He chemistry
- Depth of alloy element depletion as a function of time, temperature, and He chemistry

- Depth of carburized or decarburized zone as a function of time, temperature, and He chemistry
- Analysis of all data above for prediction of corrosion allowances for Alloy 617 and Alloy 617 joints for all temperatures and times of interest

#### C1.2.6.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 2 to TRL 3 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with Section C1.2.6 is that the measured corrosion allowances may preclude the operation of IHX A at full life (~10 years) at full temperature (950°C).

# C2 TECHNOLOGY MATURATION PLAN FOR IHX A (METALLIC) - TRL 3 TO TRL 4

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX A from a TRL level of 3 to a TRL level of 4. The first of these maturation tasks is to develop and establish an ASME Section III Code Case for the use of Alloy 617 in the NGNP IHX. Four other maturation tasks involve the development of models to guide the design of high temperature compact heat exchangers and to form the predictive basis for their operation and performance. A Test Specification is provided to cover each of the maturation tasks. These are given in Section C2.2.

### C2.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the metallic version of IHX A from TRL 3 to TRL 4 are as shown below.

- Establish ASME Section III Code Case for Alloy 617
- Develop methods for thermal/fluid modeling of compact heat exchangers
- Develop methods for stress/strain modeling of compact heat exchangers
- Establish criteria for structural integrity of compact heat exchangers at very high temperature
- Develop methods for performance modeling of compact heat exchangers

The tasks above will be described fully in individual Test Specifications provided in the sections to follow.

#### C2.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2010 through FY2015.

#### C2.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

## C2.2 Test Specifications

### C2.2.1 ASME Section III Code Case for Alloy 617 (WEC-TS-IHXA-007)

#### C2.2.1.1 Objectives

This Test Specification has the overall objective of developing and establishing a Section III ASME Code Case for Alloy 617. It will involve the drafting of the code case, interactions with ASME during the approval process, and provision of any additional specific data/information requested by the ASME. This Test Specification responds to DDN HTS-01-18.

#### C2.2.1.2 Test Conditions

*C2.2.1.2.1 Test Configuration/Set-up*

No test equipment or facility is needed.

*C2.2.1.2.2 Test Duration*

The duration of this activity will be a minimum of 48 months.

*C2.2.1.2.3 Proposed Test Location*

The supplier / design authority may be best suited to perform the modeling work.

#### C2.2.1.3 Measured Parameters

Not applicable.

#### C2.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C2.2.1.5 Test Evaluation Criteria

Not applicable.

#### C2.2.1.6 Test Deliverables

The test deliverable is a Section III ASME Code case fully qualifying Alloy 617 for service in the NGNP IHX up to 950°C.

#### C2.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 3 to TRL 4 is addressed in Sections C2.1.3 and C2.1.4 There is minimal technical risk associated with C2.2.1. There is some risk that the Code Case will not be approved per the desired schedule; however, the schedule should be achievable with dedicated and directed efforts by a designer team.

### C2.2.2 Thermal/Fluid Modeling Methods for Metallic IHX A (WEC-TS-IHXA-008)

#### C2.2.2.1 Objectives

The work to be conducted under this Test Specification is the development of thermal structural models to provide a predictive basis for operation and performance characteristics of compact heat exchangers. This is required for both quasi-steady state and transient analyses. This Test Specification responds to DDN HTS-01-13.

#### C2.2.2.2 Test Conditions

*C2.2.2.2.1 Test Configuration/Set-up*

None currently identified but the models will likely be applied to the results obtained under Section C3.2.1 and DDN HTS-01-17. Relative to the latter, see Technology Maturation Plans for TRL 5 to TRL 7 and TRL 7 to TRL 8.

*C2.2.2.2.2 Test Duration*

Development of the thermal/fluid models would occur over a 36-month period.

*C2.2.2.2.3 Proposed Test Location*

The supplier / design authority may be best suited to perform the modeling work.

#### C2.2.2.3 Measured Parameters

The models to be developed will incorporate and combine the mechanical and thermal/physical property database for Alloy 617 with finite element analysis (FEA) techniques and known relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

#### C2.2.2.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

#### C2.2.2.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing described in Section C3.2.1 and in DDN HTS-01-17.

#### C2.2.2.6 Test Deliverables

The test deliverable is a model for predicting operation and performance characteristics of compact heat exchanger IHX A.

#### C2.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 3 to TRL 4 is addressed in Sections C2.1.3 and C2.1.4. There are no risks associated with Section C2.2.2.

### C2.2.3 Methods for Stress/Strain Modeling of Metallic IHX A (WEC-TS-IHXA-009)

#### C2.2.3.1 Objectives

The objective of this work is to develop structural modeling methods to provide a physical and mechanical design and predictive basis for operation and performance characteristics of compact heat exchanger IHX A. No physical testing is required to accomplish this task. This Test Specification responds to DDN HTS-01-14.

#### C2.2.3.2 Test Conditions

*C2.2.3.2.1 Test Configuration/Set-up*

None currently identified but the models will likely be applied to the results obtained under Section C3.2.1 and DDN HTS-01-17. Relative to the latter, see Technology Maturation Plans for TRL 5 to TRL 6, TRL 6 to TRL 7, and TRL 7 to TRL 8.

*C2.2.3.2.2 Test Duration*

Development of the thermal/fluid models would occur over a 36-month period

*C2.2.3.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

#### C2.2.3.3 Measured Parameters

The models to be developed will incorporate and combine the mechanical property database for Alloy 617 with finite element analysis (FEA) techniques and know relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

#### C2.2.3.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

#### C2.2.3.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing described in Section C3.2.1 and in DDN HTS-01-17. They will also form a part of an ASME design code (see DDN HTS-01-19 for TRL 5 to TRL 7).

#### C2.2.3.6 Test Deliverables

The test deliverable is a model for predicting operation and performance characteristics and to form a design basis for compact heat exchanger IHX A.

#### C2.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 3 to TRL 4 is addressed in Sections C2.1.3 and C2.1.4. There is no risk associated with Section C2.2.3.

### C2.2.4 Criteria for Structural Integrity of IHX A (WEC-TS-IHXA-010)

### C2.2.4.1 Objectives

The objective of this Test Specification is to establish criteria for the structural integrity of compact heat exchangers operating at very high temperature. This includes criteria for stresses and strains as well as development of safety factors needed in ASME Code development. These criteria will help to establish acceptable operational boundaries for compact heat exchangers. No physical testing is required to establish structural integrity criteria. This Test Specification responds to DDN HTS-01-15.

### C2.2.4.2 Test Conditions

*C2.2.4.2.1 Test Configuration/Set-up*

None currently identified.

*C2.2.4.2.2 Test Duration*

Establishment of structural integrity criteria will occur over a 36-month period.

*C2.2.4.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

### C2.2.4.3 Measured Parameters

Criteria for structural integrity will be developed from a review of appropriate ASME Code documentation, discussions with ASME Code personnel, and interactions during the development of stress/strain models (see activities associated with DDN HTS-01-14 under Section C2.2.3).

### C2.2.4.4 Data Requirements

Structural integrity criteria development activities will employ best standard practice and QA requirements.

### C2.2.4.5 Test Evaluation Criteria

The usefulness and predictive capability of the structural integrity models developed will be assessed based on its application to testing described in Section C3.2.1 and in DDN HTS-01-17. They will also form a part of an ASME design code (see DDN HTS-01-19 for TRL 5 to TRL 6).

### C2.2.4.6 Test Deliverables

Deliverables are as follows.

- Criteria for acceptable stresses and strains

- Safety factors for application to an ASME design code.

#### C2.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 3 to TRL 4 is addressed in Sections C2.1.3 and C2.1.4. There is no risk associated with Section C2.2.4.

### C2.2.5 Performance Modeling Methods for IHX A (WEC-TS-IHXA-011)

#### C2.2.5.1 Objectives

The objective of the work prescribed in this Test Specification is to provide performance modeling methods to adequately evaluate the results of performance testing of compact heat exchangers and to assist in the development of an ASME Code Case for design of compact heat exchangers. No physical testing is required for performance modeling. This Test Specification responds to DDN HTS-01-16.

#### C2.2.5.2 Test Conditions

*C2.2.5.2.1 Test Configuration/Set-up*

None, but the performance models will be applied to the results obtained under DDN HTS-01-17 (see Technology Maturation Plans for TRL 4 to TRL 5, TRL 5 to TRL 7 and TRL 7 to TRL 8.

*C2.2.5.2.2 Test Duration*

Establishment of structural integrity criteria will occur over a 48-month period.

*C2.2.5.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

#### C2.2.5.3 Measured Parameters

The performance models to be developed will incorporate all parameters necessary to predict the thermal and structural behavior of compact heat exchangers.

#### C2.2.5.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

#### C2.2.5.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing associated with DDN HTS-01-17 (see Technology Maturation Plans for IHX A from TRL 4 to TRL 5, TRL 5 to TRL 7 and TRL 7 to TRL 8).

#### C2.2.5.6 Test Deliverables

The deliverable for this Test Specification is a model to assess the thermal and structural performance of the compact heat exchanger modules to be tested in association with DDN HTS-01-17.

#### C2.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 3 to TRL 4 is addressed in Sections C2.1.3 and C2.1.4. There is no risk associated with Section C2.2.5.

# C3 TECHNOLOGY MATURATION PLAN FOR IHX A (METALLIC) - TRL 4 TO TRL 5

## C3.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C3.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX A from a TRL level of 4 to a TRL level of 5. The maturation task required to achieve this goal involve the testing of the compact heat exchanger unit cell (It is assumed that the compact heat exchanger unit cell will be provided by a compact heat exchanger vendor). A Test Specification is provided to cover the maturation task. This is given in Section C3.2.

### C3.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the metallic version of IHX A from TRL 4 to TRL 5 is as shown below.

- Specification 1: Testing of unit cell compact heat exchanger

The task above will be described fully in a Test Specification in the following section.

### C3.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY 2014 through FY 2016.

### C3.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

# C3.2 Test Specifications

## C3.2.1 Specification of testing of unit cell of compact heat exchanger (WEC-TS-IHXA-012)

### C3.2.1.1 Objectives

The objective of testing the compact heat exchanger unit cell is:

- To determine the joint integrity of the compact heat exchanger unit cell joints under tensile load at a typical pressure environment and elevated temperatures.

### C3.2.1.2 Test Conditions

#### *C3.2.1.2.1 Component Requirements*

Component requirements include the following:

- Size limitation: dependant on testing environment (e.g. furnace)
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Environment – Helium with controlled impurity levels

#### *C3.2.1.2.2 Interfacing Requirements*

n/a

#### *C3.2.1.2.3 Test Requirements*

Test requirements for the compact heat exchanger unit cell tests (not integrated) are as follows:

- Test environment which compact heat exchanger unit cell will be subjected to before post test evaluation:
  - Temperature = 950°C
  - Pressure = 9MPa
  - Cyclic loading (magnitude and cycles TBD)

- Proposed setup and relevant parameters (see following page):

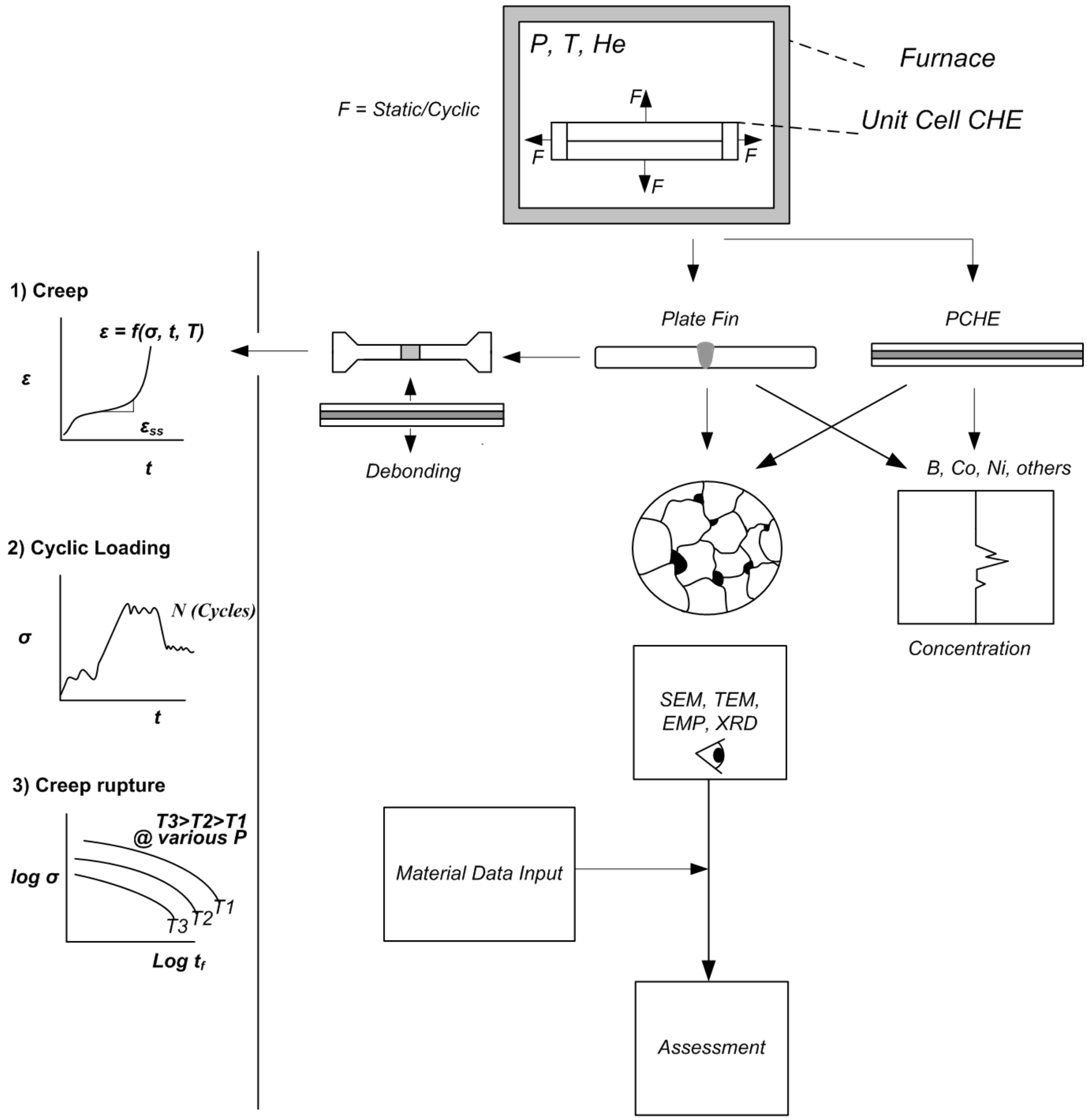


**Figure C-1: Proposed setup and relevant parameters in testing the unit cell**

*C3.2.1.2.4 Test Duration*

The duration of this activity will be a minimum of **24** months.

*C3.2.1.2.5 Facility Requirements*

1. Furnace suitable for test requirements
2. Facilities required for metallographic analysis of material and joints after testing

*C3.2.1.2.6 Proposed Test Location*

Manufacturers of metallic unit cells would most appropriately evaluate the joint integrities of the as-manufactured unit cells.

### C3.2.1.3 Measured Parameters

The following parameters will be measured:

- Temperature
- Pressure
- Post-test joint integrity inferred from SEM, microscopic/metallographic evaluations and tests
  - Creep and creep rupture data
  - 

### C3.2.1.4 Data Requirements

It is assumed that the compact heat exchanger unit cell will be produced by a vendor of metallic heat exchangers. The fabricated unit cell will require the following before progressing with testing:

- Materials certificates
- Weld certificates
- Inspection certificates
- All other quality assurance documents (bonding procedures, etc)

All new data shall be acquired using recognized techniques, codes, standards, and QA.

### C3.2.1.5 Test Evaluation Criteria

Satisfactory structural integrity of the compact heat exchanger unit cell joints as evidenced by post-testing examinations relating to metallographic procedures and tests.

### C3.2.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section C3.2.1.3.
- Documentation containing performance verification criteria and test results relating to the joint integrities of the CHE unit cell as observed through microscopic/metallographic evaluations and tests.

### C3.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 4 to TRL 5 is addressed in Sections C3.1.3 and C3.1.4.

The risk associated with Section C3.2 1 involves the non-satisfactory condition/integrity of the CHE unit cell joint, and may consequently require a re-evaluation of the unit cell design (or certain aspects thereof).

# C4 TECHNOLOGY MATURATION PLAN FOR IHX A (METALLIC) - TRL 5 TO TRL 6

## C4.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C4.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX A from a TRL level of 5 to a TRL level of 6. The maturation tasks required to achieve this goal involve the testing of the integrated compact heat exchanger module (~1.2MW) in the CTF (It is assumed that the compact heat exchanger module will be provided by a compact heat exchanger vendor) and the establishment of a Section III ASME Code case fully qualifying compact heat exchanger designs for service in the NGNP IHX. Test Specifications are provided to cover these maturation tasks (given in Section C4.2).

### C4.1.2 Scope

The maturation tasks necessary to advance the maturity of the technology of the metallic version of IHX A from TRL 5 to TRL 6 is as shown below.

- Specification 1: Testing of integrated compact heat exchanger module (~1.2MW)
- Specification 2: Establishing ASME Section III design code for compact heat exchanger designs

The tasks above will be described in the test specification provided hereafter.

### C4.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan will be accomplished during the period FY 2017 through FY 2019.

### C4.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

# C4.2 Test Specifications

## C4.2.1 Specification of testing of compact heat exchanger module (~1.2MW) (WEC-TS-IHXA-013)

### C4.2.1.1 Objectives

The objectives of testing the compact heat exchanger module (~1.2MW) are:

- To demonstrate the operating effectiveness of the compact heat exchanger module
- To demonstrate the fatigue life of the integrated compact heat exchanger module in terms of *thermal fatigue, joint integrity* and *corrosion & high temperature oxidation*
- 

### C4.2.1.2 Test Conditions

#### *C4.2.1.2.1 Compact Heat Exchanger Module (subsystem and system) Requirements*

Subsystem and system requirements include the following:

- Size limitation: TBD
- Certain interface design requirements and specifications (see interfacing requirements)
- Heat transfer fluid – Helium with controlled impurities
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Mass flow threshold – see test requirements
- Pressure drop threshold – see test requirements

#### *C4.2.1.2.2 Interfacing Requirements*

- TBD by Technology Development Loop and Subsystem Configuration / Design.
- Certain interface design requirements and specifications:
  - Appropriate surface finish of interfacing components
  - Gasket materials applicable
  - Flange torque values where applicable

#### *C4.2.1.2.3 Measurement Requirements*

- Measurement of strains
- Measurement of internal and external pressures
- Measurement of temperature
- Measurement of mass flow
- Measurement of fluid composition
- Measurement of leak rates from CHE module

*C4.2.1.2.4 Test Requirements*

Test requirements for the compact heat exchanger module tests (integrated) are as follows:

1) Test compact heat exchanger module operating effectiveness and behavior in typical steady state pressure, temperature and temperature/pressure drop environment (Helium)
   i. Temperature = 950°C
   ii. Pressure = 9MPa
   iii. Temperature Δ = 250°C
   iv. Pressure Δ = 500 – 600 kPa sustained (Primary to Secondary)
   v. Mass flow = tbd
   vi. He environment with varied composition

2) Test compact heat exchanger module behavior in typical pressure transient environment:
   i. Expose module to a high frequency, **normal** operating pressure transient, present with a startup / shutdown sequence
      1. Pressurizing transient (ambient to 9MPa in certain time frame)
      2. De-pressurizing transient (9MPa to ambient in certain time frame)
   ii. Number of cycles and temperature level TBD

3) Test compact heat exchanger module behavior in typical temperature transient environment:
   i. Expose module to a high frequency, normal operating temperature transient (ambient to 950°C) present with a startup / shutdown sequence
      1. Heat up transition
      2. Cool down transition
   ii. Number of cycles and pressure level TBD

4) Test compact heat exchanger module behavior at varying process parameters:
   i. Temperature = 950°C
   ii. Pressure = 9MPa primary (secondary TBD)
   iii. Pressure Δ = TBD (Rapid depressurization)
   iv. Mass flow = TBD

Proposed setup and parameters (see following page):

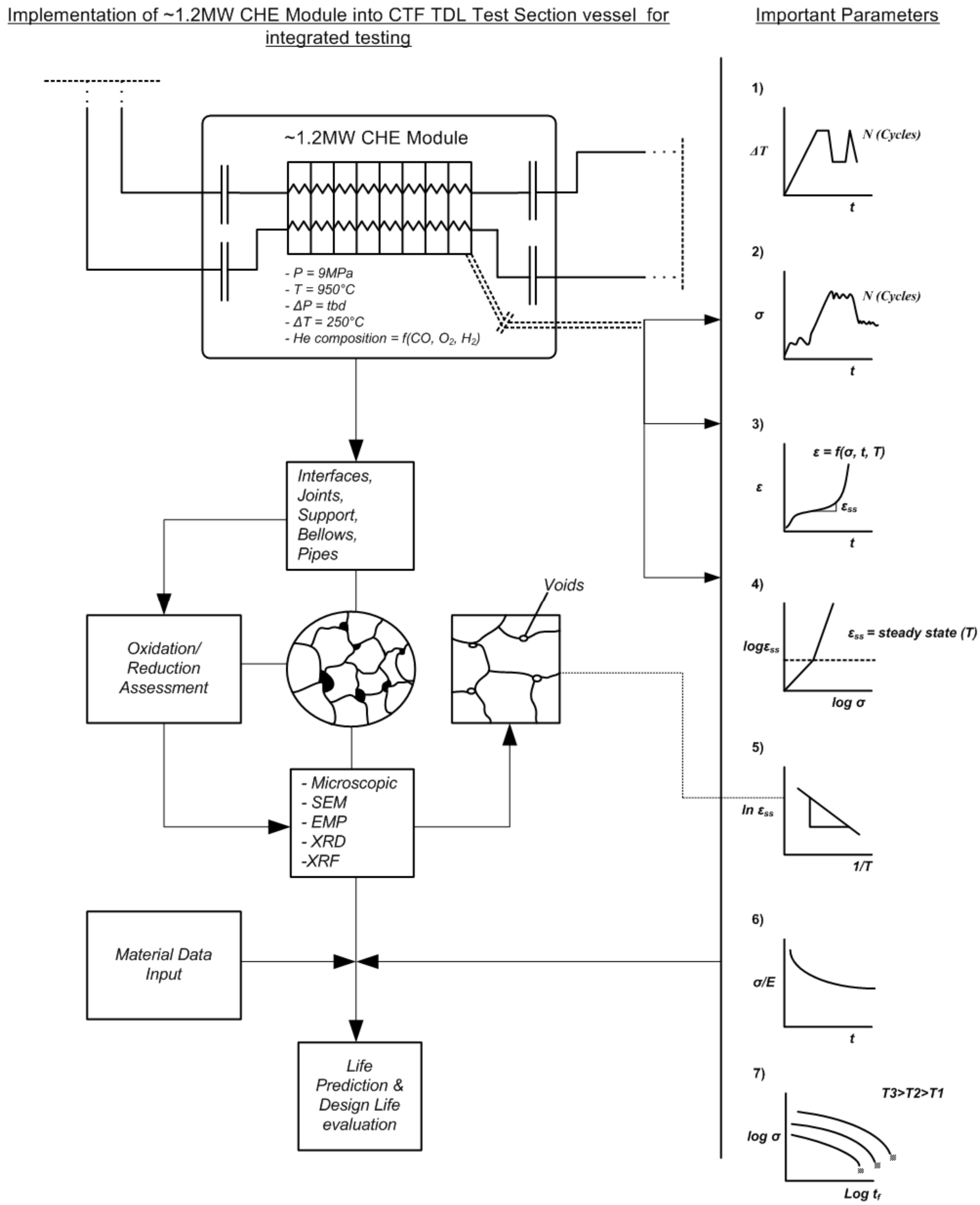


**Figure C-2 :Proposed setup and durability parameters in testing the CHE Module**

### *C4.2.1.2.5 Tests Duration*

The duration of this activity will be a minimum of **24** months.

*C4.2.1.2.6 Facility Requirements*

The following facilities will be required:

1. TDL facilities (TBD)
2. Gas analyzing facilities
3. Facilities required for metallographic analysis of material and joints after testing

*C4.2.1.2.7 Proposed Test Location*

Proposed tests will take place at the CTF or in a representative environment. This work can most effectively be done by ASME members from industry.

### C4.2.1.3 Measured Parameters

The following parameters will be measured:

- Temperatures
- Pressures
- Measurement of magnitude and number of temperature gradients and temperature gradient cycles respectively up to thermal fatigue failure
- Fluid composition
- Leak rates at varying process conditions
- Operating effectiveness of compact heat exchanger module
- Corrosion of module materials and joints over a predetermined time
- Oxidation of module materials and joints over a predetermined time
- Thermal fatigue observations through SEM, TEM and other analyses techniques, inclusive of Element Distribution Maps of selected joint samples
- Joint integrity(ies) – Tensile tests, SEM, microscopic/metallographic evaluations and testing of joint sections.

### C4.2.1.4 Data Requirements

It is assumed that the compact heat exchanger module will be produced by a vendor of metallic heat exchangers. The fabricated module of the compact heat exchanger will require the following before progressing with testing:

- Materials certificates
- Weld certificates
- Inspection certificates
- All other quality assurance documents (bonding procedures, etc)

All new data shall be acquired using recognized techniques, codes, standards, and QA.

#### C4.2.1.5 Test Evaluation Criteria

- Satisfactory number of transient cycles up to thermal fatigue of the module material/joints
- Structural integrity of the whole compact heat exchanger module assembly (system) as evidenced by
  - metallographic procedures and tests
  - analyses inclusive of remaining life assessments (if applicable)
  - comparison of data with assessment models, FEM's or other calculations
- An acceptable level of deformation of the compact heat exchanger module (subsystem) as evidenced by strain measurement measures
- The corrosion must not be of such magnitude as to degrade the structural integrity of the module material sections and joints.
- Limited oxidation formation thickness or no oxidation over a predetermined time
- An acceptable effectiveness of the compact heat exchanger module
- An acceptable rate of leakage of the compact heat exchanger module at varying process conditions.

#### C4.2.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section C4.2.1.3
- Documentation containing test requirements, performance verification criteria and test results verified against stress/strain models of the compact heat exchanger module and material properties.

#### C4.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 5 to TRL 7 is addressed in Sections C4.1.3 and C4.1.4.

The risk involved is the substantial difference that might be present between the generated test data and the predictions derived from the simulation models.

### C4.2.2 ASME Section III Code Case for Compact Heat Exchanger Designs (WEC-TS-IHXA-014)

#### C4.2.2.1 Objectives

This Test Specification has the overall objective of developing and establishing a Section III ASME Code Case for compact heat exchanger designs. It will involve the drafting of the code case, interactions with ASME during the approval process, and provision of any additional specific data/information requested by the ASME. This Test Specification responds to DDN HTS-01-19

### C4.2.2.2 Test Conditions

*C4.2.2.2.1 Test Configuration/Set-up*

No test equipment or facility is needed.

*C4.2.2.2.2 Test Duration*

The duration of this activity will be a minimum of 48 months.

*C4.2.2.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

### C4.2.2.3 Measured Parameters

Not applicable.

### C4.2.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

### C4.2.2.5 Test Evaluation Criteria

Not applicable.

### C4.2.2.6 Test Deliverables

The test deliverable is a Section III ASME Code case fully qualifying metallic compact heat exchanger designs for service in the NGNP IHX up to 950°C.

### C4.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX A from TRL 5 to TRL 6 is addressed in Sections C4.1.3 and C4.1.4.

The risk associated with Section C4.2.2 entails the failure to establish an ASME Code Case for compact heat exchanger designs.

# C5 TECHNOLOGY MATURATION PLAN FOR IHX A (MEALLIC) – TRL 6 TO TRL 7

## C5.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C5.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX A from a TRL level of 6 to a TRL level of 7. The maturation tasks required to achieve this goal involve the testing of models to determine shell-side flow distribution and bypass leakage and the heat transfer testing of multi-modules (e.g., 3 x ~1.2MW). Test Specifications are provided to cover the maturation tasks (given in section C5.2).

### C5.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the metallic version of IHX A from TRL 6 to TRL 7 is as shown below.

- Specification 1: Shell-side flow distribution and bypass leakage tests.
- Specification 2: Multi-module heat transfer tests.

These tasks will be described in C5.2.

### C5.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2018 through FY 2020.

### C5.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C5.2 Test Specifications

### C5.2.1 Shell-side Flow Distribution and Bypass Leakage Testing (WEC-TS-IHXA-015)

#### C5.2.1.1 Objectives

The objectives of testing are to

- Confirm shell-side flow distribution modeling
- Confirm that shell-side bypass leakage is acceptable
- Confirm shell-side pressure losses.

There is also the potential to use this test to characterize dust transport/dropout as a function of particulate size.

#### C5.2.1.2 Test Conditions

This likely would be an ambient temperature test with air as the working fluid. The test article would model inlet and outlet regions of the heat exchanger, features that promote good distribution to the core modules on the shell-side, and features that minimize bypass leakage. Details of the testing will be finalized at later stage.

### C5.2.2 Multi-module Heat Transfer Testing (WEC-TS-IHXA-016)

#### C5.2.2.1 Objectives

The objectives of this testing are to

- Investigate module-to-module interactions on both the tube- and shell-sides of the heat exchanger
- Confirm bypass leakage and effects.

#### C2.2.2.2 Test Conditions

The multi-module test would be a heated test in the CTF with 3 or more core modules (~4MWt would be required for 3 modules) representing a segment of the IHX. Details of the testing will be finalized at later stage.

# C6 TECHNOLOGY MATURATION PLAN FOR IHX A (METALLIC) - TRL 7 TO TRL 8

## C6.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C6.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX A from a TRL level of 7 to a TRL level of 8. The maturation task required to achieve this goal involve the testing of the full-scale compact heat exchanger. (It is assumed that the full-scale compact heat exchanger will be provided by a compact heat exchanger vendor and/or assembled by vendor staff on the NGNP site). The scope of this test on the full-scale compact heat exchanger will vary slightly from the scope of test noted to progress from a TRL 5 to TRL 6 and TRL 6 to TRL 7. A Test Specification is provided to cover the maturation task (given in section C6.2).

### C6.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the metallic version of IHX A from TRL 7 to TRL 8 is as shown below.

- Specification 1: Testing of full scale compact heat exchanger in the NGNP

This task will be described in the following test specification.

### C5.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2019 through FY 2020.

### C5.1.4 Overall Cost

Refer to Section C7 for the estimated costs regarding the development of metallic IHX A

## C5.2 Test Specifications

### C5.2.1 Specification of testing of a full scale compact heat exchanger (WEC-TS-IHXA-017)

#### C5.2.1.1 Objectives

The objectives of testing the full-scale compact heat exchanger are:

- To determine the leak rate of the compact heat exchanger (system) at various typical process parameters.
- To determine the operating effectiveness of the full-scale compact heat exchanger at various typical process parameters.

The metallic IHX A will be fully tested and commissioned in the NGNP. Details of the testing and commissioning will be finalized at later stage.

# APPENDIX D: TECHNOLOGY MATURATION PLAN – CERAMIC IHX A

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**REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL**

**TRL 2 to TRL 3:**

- Specification 1: Trade study on candidate ceramic materials for IHX A (WEC-TS-IHXA-018)
- Specification 2: Trade study on candidate ceramic designs for IHX A (WEC-TS-IHXA-018)

**TRL 3 to TRL 4:**

- Specification 1: Ceramic Heat Exchanger Detailed Design Data Needs (DDNs) (WEC-TS-IHXA-018)
- Specification 2: Ceramic Materials Specifications and Procurement (WEC-TS-IHXA-018)
- Specification 3: Thermal/Physical Properties of Ceramics (WEC-TS-IHXA-018)
- Specification 4: Mechanical Properties of Ceramics (WEC-TS-IHXA-018)
- Specification 5: Compatibility of ceramic Materials to NGNP He Environment (WEC-TS-IHXA-018)
- Specification 6: Manufacturing Technology for Ceramic Heat Exchangers (WEC-TS-IHXA-018)
- TRL 4 to TRL 5:
- Specification 1: Ceramic Materials Codes and Standards (WEC-TS-IHXA-018)
- Specification 2: Methods for Thermal/Fluid and Stress/Strain Modeling (WEC-TS-IHXA-018)
- Specification 3: Structural Integrity Criteria for Ceramic Heat Exchangers (WEC-TS-IHXA-018)
- Specification 4: Performance Modeling of Ceramic Heat Exchangers (WEC-TS-IHXA-018)
- Specification 5: Testing of unit cell of compact heat exchanger (WEC-TS-IHXA-018)
- TRL 5 to TRL 6:
- Specification 1: Testing of integrated compact heat exchanger module (~1.2MW) (WEC-TS-IHXA-018)
- Specification 2: Establishing ASME III Code Case for Ceramic Compact Heat Exchanger Designs (WEC-TS-IHXA-018)

**TRL 6 to TRL 7**

- Specification 1: Shell-side flow distribution and bypass leakage tests. (WEC-TS-IHXA-018)
- Specification 2: Multi-module heat transfer tests. (WEC-TS-IHXA-018)

**TRL 7 to TRL 8:**

- Specification 1: Testing of full size compact heat exchanger (Full scale NGNP IHX A) (WEC-TS-IHXA-018)

# D1. TECHNOLOGY MATURATION PLAN FOR IHX A (CERAMIC) - TRL 2 TO TRL 3

## D1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### D1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the ceramic IHX A from a TRL level of 2 to a TRL level of 3. Advancing the technology of a ceramic heat exchanger to a level higher than TRL 2 will require Trade Studies to guide selection of candidate ceramic materials and ceramic heat exchanger designs for the NGNP. Test Specifications are provided to cover both of these trade study maturation tasks. These are given in Section D1.2.

### D1.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the ceramic version of IHX A from TRL 2 to TRL 3 are as shown below.

- Specification 1: Trade study on candidate ceramic materials for IHX A
- Specification 2: Trade study on candidate ceramic designs for IHX A

The tasks above will be described fully in individual Test Specifications provided in sections to follow.

### D1.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during FY2009 to FY2010.

### D1.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

# D1.2 Test Specifications

## D1.2.1 Trade Study on Candidate Ceramic Materials for IHX A (WEC-TS-IHXA-018)

### D1.2.1.1 Objectives

The Trade Study prescribed by this Test Specification responds to DDN HTS-02-01. It will evaluate, assess, and select ceramic materials for application in ceramic heat exchangers under the demanding conditions required of IHX A.

### D1.2.1.2Test Conditions

*D1.2.1.2.1 Test Configuration/Set-up*

Not applicable

*D1.2.1.2.2 Test Duration*

The duration of the trade study could be up to 12 months.

*D1.2.1.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

### D1.2.1.3 Measured Parameters

Parameters to be considered include the following.

- Environmental compatibility of candidates at high temperatures
- Service temperature capability of candidates
- Product forms available and processing/forming potential of candidates
- Joining potential
- Thermal, physical and mechanical properties of candidates (including thermal shock resistance, thermal conductivity, CTE and creep properties)
- Chemical composition of candidate precursor materials/powders.

#### D1.2.1.3.1 Data Requirements

Personnel employed to conduct this Trade Study will be qualified by education and/or experience in the areas of heat exchanger design and materials.

#### D1.2.1.3.2 Test Evaluation Criteria

Ceramic materials identified as candidates for ceramic heat exchangers must have a reasonable expectation of achieving the goals and requirements for IHX A.

#### D1.2.1.3.3 Test Deliverables

Deliverables are as follows.

- Report on ceramics potentially capable of meeting IHX A service requirements
- Report on ceramics product form availability and potential forming/shaping methods
- Report on joining of candidates
- Summary of thermal, physical, and mechanical properties of ceramics
- Recommendation of candidate ceramic materials for further study with respect to IHX A
-

#### D1.2.1.3.4 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for ceramic IHX A from TRL 2 to TRL 3is addressed in Sections D1.1.3 and D1.1.4 The only risk associated with Section D1.2.1 would be the inability to identify suitable candidate ceramic material and this is extremely small.

## D1.2.2 Trade Study on Candidate Ceramic Designs for IHX A (WEC-TS-IHXA-019)

### D1.2.2.1 Objectives

The Trade Study prescribed by this Test Specification responds to DDN HTS-02-01. It will explore existing applications of ceramics heat exchangers and service experience with such heat exchangers. A major goal is to select candidate ceramic heat exchanger designs and potential heat exchanger vendors.

### D1.2.2.2 Test Conditions

*D1.2.2.2.1 Test Configuration/Set-up*

Not applicable

*D1.2.2.2.2 Test Duration*

The duration of the trade study could be up to 12 months.

*D1.2.2.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

### D1.2.2.3Measured Parameters

The following parameters will be considered.

- Existing and potentially viable ceramic heat exchanger designs
- Commercially available ceramic heat exchangers and vendors

- Experience with ceramic heat exchangers in service with special reference to feasibility of joining, joint integrity/debonding on thermal shock.

#### 1.2.2.3.1 Data Requirements

Personnel employed to conduct this Trade Study will be qualified by education and/or experience in the areas of heat exchanger design and materials.

#### 1.2.2.3.2 Test Evaluation Criteria

Designs identified must have a reasonable expectation of achieving the goals and requirements for IHX A.

#### 1.2.2.3.3 Test Deliverables

Deliverables are as follows.

- Report on integrated ceramic heat exchanger designs (notably including report on integrating ceramics with metallic piping/vessel)
- Report on service experience with ceramic heat exchangers
- Report on commercial availability of ceramic heat exchangers
- Recommendation for candidate ceramic heat exchanger designs for IHX A (inclusive of materials selection applicable to designs).
-

#### 1.2.2.3.4 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing ceramic heat exchanger technology for IHX A from TRL 2 to 3 is addressed in Sections D1.1.3 and D1.1.4. There is essentially no risk associated with Section D1.2.2.

# D2 TECHNOLOGY MATURATION PLAN FOR IHX A (CERAMIC) - TRL 3 TO TRL 4

## D2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### D2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the ceramic IHX A from a TRL level of 3 to a TRL level of 4. These tasks include the preparation of detailed DDNs, establishing specifications for candidate ceramic materials, materials acquisition, property determinations, and fabricability questions. A Test Specification is provided to cover each of the maturation tasks. These are given in Section D2.2.

### D2.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the ceramic version of IHX A from TRL 3 to TRL 4 are as shown below.

- Specification 1: Ceramic Heat Exchanger Detailed Design Data Needs (DDNs)
- Specification 2: Ceramic Materials Specifications and Procurement
- Specification 3: Thermal/Physical Properties of Ceramics
- Specification 4: Mechanical Properties of Ceramics
- Specification 5: Compatibility of ceramic Materials to NGNP He Environment
- Specification 6: Manufacturing Technology for Ceramic Heat Exchangers

The tasks above will be described in individual Test Specifications provided in sections to follow.

### D2.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2011 through FY2016. No individual Test Specification describes work requiring more than 48 months and the work in most Test Specifications can be done in parallel.

### D2.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

## D2.2 Test Specifications

### D2.2.1 Ceramic Heat Exchanger Detailed Design Data Needs (DDNs) (WEC-TS-IHXA-020)

#### D2.2.1.1 Objectives

The objective of this Test Specification is to develop detailed DDNs relative to materials, properties, modeling, and codes and standards for the ceramic IHX. Placeholder DDNs were provided in the *NGNP PCDR* but the more detailed DDNs to be provided here are necessary to define an efficient and effective path forward for ceramic IHX technology maturation.

#### D2.2.1.2 Test Conditions

*D2.2.1.2.1 Test Configuration/Set-up*

Not applicable.

*D2.2.1.2.2 Test Duration*

The duration of this activity could be up to 18 months.

*D2.2.1.2.3 Proposed Test Location*

TBD.

**D2.2.1.3 Measured Parameters**

Not applicable.

**D2.2.1.4 Data Requirements**

Knowledgeable personnel qualified by education and/or experience should do preparation of the DDNs.

**D2.2.1.5 Test Evaluation Criteria**

The DDNs produced must provide a quantitative description of the technology maturation work needed.

**D2.2.1.6 Test Deliverables**

Deliverables (DDNs) are, as a minimum, the following.

- Specifications for ceramic materials to be acquired for test
- Processing of ceramic materials
- Determination of thermal, physical, and mechanical properties of ceramic
- Aging and environmental effects on properties of ceramic materials
- Codes and Standards development for ceramic materials
- Methods for modeling of the thermal and structural performance of the ceramic IHX
- Performance testing of the ceramic IHX.

**D2.2.1.7 Cost, Schedule, and Risk**

Cost and schedule for the overall Technology Maturation Plan for advancing technology of ceramic IHX A from TRL 3 to TRL 4 is addressed in Sections D2.1.3 and D2.1.4. There is no risk associated with D2.2.1.

### D2.2.2 Ceramic Materials Specifications and Procurement (WEC-TS-IHXA-021)

### D2.2.2.1 Objectives

Work conducted under this Test Specification will define the specifications for the ceramic materials selected in Test Specification D1.2.1 and provide for their procurement with appropriate documentation and QA. This Test Specification responds in general to placeholder DDN HTS-02-02.

### D2.2.2.2 Test Conditions

*D2.2.2.2.1 Test Configuration/Set-up*

No testing will be required

*D2.2.2.2.2 Test Duration*

Preparation of ceramic material specifications and procurement of the ceramic materials will require up to 30 months.

*D2.2.2.2.3 Proposed Test Location*

N/A

### D2.2.2.3 Measured Parameters

Parameters to be measured include the following.

- Manufacturing/processing history of the ceramic material acquired
- Condition (dimensions, absence of defects, etc.) composition in terms of major, minor and trace elements of the ceramic materials
- 

### D2.2.2.4 Data Requirements

All materials shall be acquired/processed using best procurement practices, QA and certification.

### D2.2.2.5 Test Evaluation Criteria

- The ceramic material acquired must meet all requirements of the materials specification, procurement procedures, and QA.
- 

### D2.2.2.6 Test Deliverables

Deliverables are as follows.

- Material specifications for candidate ceramic materials
- Procurement requirements for candidate ceramic materials
- Representative lots of candidate ceramic materials

- Inspection reports and test certificates on the material procured.

**D2.2.2.7 Cost, Schedule, and Risk**

Cost and schedule for the overall Technology Maturation Plan for advancing technology for a ceramic IHX A from TRL 3 to TRL 4 is addressed in Sections D2.1.3 and D2.1.4. The risks associated with D2.2.2 are very small.

## D2.2.3 Thermal/Physical Properties of Ceramics (WEC-TS-IHXA-022)

**D2.2.3.1 Objectives**

The objective of this work is to confirm by testing that the ceramic materials procured to NGNP specifications will have thermal/physical adequate for a compact IHX A. This Test Specification responds in general to placeholder DDN HTS-02-02. However, a more detailed and directed DDN addressing thermal/physical properties will be prepared as part of the Test Specification in section D2.2.1 above.

**D2.2.3.2 Test Conditions**

*D2.2.3.2.1 Test Configuration/Set-up*

Conduct of thermal/physical property testing (principally thermal conductivity and coefficients of thermal expansion) of ceramics materials should involve only test rigs normally used for such work. However, testing will be required up to at least 1000°C.

*D2.2.3.2.2 Test Duration*

Thermal/physical property testing could require up to 18 months.

*D2.2.3.2.3 Proposed Test Location*

Property tests of ceramic materials could be conveniently performed at a National Laboratory or University.

**D2.2.3.3 Measured Parameters**

Data to be determined include:

- Thermal conductivity to at least 1000°C
- Coefficients of thermal expansion to at least 1000°C
- Thermal shock resistance
- Permeability to various gases (up to 1000°C)
-

#### D2.2.3.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

#### D2.2.3.5 Test Evaluation Criteria

All thermal/physical property data obtained shall be reasonably consistent with values in the literature.

.D2.2.3.6 Test Deliverables

Deliverables, at a minimum, are as follows.

- Reports of thermal conductivity measurements on ceramic materials procured to NGNP specifications
- Reports of coefficient of thermal expansion measurements on ceramic materials procured to NGNP specifications
- Reports on thermal shock resistance on ceramic materials procured to NGNP specifications.

#### D2.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of ceramic IHX A from TRL 3 to TRL 4 is addressed in Sections D2.1.3 and D2.1.4. The risk associated with D2.2.3 is very small but includes the possibility that one or more of the properties measured falls short of what is required for use in a high temperature compact heat exchanger.

### D2.2.4 Mechanical Properties of Ceramics (WEC-TS-IHXA-023)

#### D2.2.4.1 Objectives

The objective of the testing performed under this Test Specification is to demonstrate that the mechanical properties of ceramic materials purchased to the NGNP specification are appropriate for their use in a high temperature ceramic IHX. This Test Specification responds in general to placeholder DDN HTS-02-02.

#### D2.2.4.2 Test Conditions

##### *D2.2.4.2.1 Test Configuration/Set-up*

Equipment/facilities must be available for testing to determine the mechanical properties (strength, creep, fatigue, and toughness) of NGNP ceramics up to at least 1000°C and to provide for thermal aging and environmental exposures and post test evaluations.

*D2.2.4.2.2 Test Duration*

Mechanical property determinations and evaluations will require up to 36 months.

*D2.2.4.2.3 Proposed Test Location*

Property tests of ceramic materials could be conveniently performed at a National Laboratory or University.

### D2.2.4.3 Measured Parameters

Data and exposure parameters to be measured/recorded include:

- Test temperatures and test techniques
- Thermal and environmental exposure conditions
- Compression/tensile properties to 1000°C
- Fatigue strength to 1000°C
- Creep strength to 1000°C for 10,000 h
- Fracture toughness.

### D2.2.4.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

### D2.2.4.5 Test Evaluation Criteria

All mechanical property data obtained shall be reasonably consistent between lots and with values in the literature.

### D2.2.4.6 Test Deliverables

Deliverables are as follows.

- Reports on strength of candidate ceramic materials
- Reports on fatigue properties of candidate ceramic materials
- Reports on creep properties of candidate ceramic materials
- Reports on toughness of candidate ceramic materials
- Reports on any effects of aging or environmental exposures on the mechanical properties of candidate ceramic materials.

### D2.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 3 to TRL 4 is addressed in Sections D2.1.3 and D2.1.4. The risk associated with D2.2.4 is small but includes the possibility that one or more of the properties measured may fall short of what is required for use in a ceramic IHX.

## D2.2.5 Compatibility of Ceramic Materials to NGNP He Environment (WEC-TS-IHXA-024)

### D2.2.5.1 Objectives

The objective of the work prescribed in this Test Specification is to confirm that there are no adverse surface or internal structure effects when candidate ceramic IHX materials are exposed to NGNP He environment. No significant effects are expected but this work should to done to minimize risk A DDN has not previously been prepared for this work.

### D2.2.5.2 Test Conditions

*D2.2.5.2.1 Test Configuration/Set-up*

Conduct of this work requires equipment/facilities for exposure of ceramic materials in NGNP He for prolonged periods of time (duration to be determined). Equipment for post-exposure examination for surface and internal structure changes is also required.

*D2.2.5.2.2 Test Duration*

Work on NGNP He exposure and post-test examinations will require about 18 months.

*D2.2.5.2.3 Proposed Test Location*

Exposures and examinations of ceramic materials could be conveniently performed at a National Laboratory.

### D2.2.5.3 Measured Parameters

Parameters and data to be taken include:

- He exposure chemistry history
- Any observable surface changes on the ceramics
- Any exposure-related subsurface changes in the ceramics

### D2.2.5.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

### D2.2.5.5 Test Evaluation Criteria

Any observable effects on the surface condition or internal structure of the IHX ceramics must be insignificant relative the integrity of the ceramic cross-section.

#### D2.2.5.6 Test Deliverables

Deliverables for this Test Specification shall include:

- Reports on the exposure conditions and history of ceramic materials
- Reports on surface effects if observed
- Reports on sub-surface effects if observed.

#### D2.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 3 to TRL 4 is addressed in Sections D2.1.3 and D2.1.4. The risk associated with D2.2.5 is very small because no significant corrosion effects are expected.

### D2.2.6 Manufacturing Technology for Ceramic Heat Exchangers (WEC-TS-IHXA-025)

#### D2.2.6.1 Objectives

The major objective of this activity is to ensure that methods and techniques are available and effective for the manufacture of a ceramic IHX. This Test Specification responds to placeholder DDN HTS-02-02.

#### D2.2.6.2 Test Conditions

*D2.2.6.2.1 Test Configuration/Set-up*

Facilities, equipment, and fixing/joining must be available to develop ceramic-to-ceramic joints, C/C composite joints, ceramic-to-metal joints, and core/piping interfacing. Facilities must also be available to demonstrate that product forms needed for the IHX are fabricable.

*D2.2.6.2.2 Test Duration*

Conduct of this work will require 36 months.

*D2.2.6.2.3Proposed Test Location*

Conduct of the manufacturing technology tasks should be contracted to commercial organizations with expertise in ceramic materials, composites, ceramic heat exchangers, etc.

#### D2.2.6.3 Measured Parameters

Parameters and information to be measured and recorded include:

- Techniques and processes employed in producing ceramic-to-ceramic joints
- Techniques and processes employed in producing ceramic-to-metal joints
- Details of methods employed to investigate the integrity of the ceramic-to-ceramic and ceramic-to-metal joints
- Techniques and processes employed to produce required product forms

### D2.2.6.4 Data Requirements

All data shall be acquired using best practice techniques and QA.

### D2.2.6.5 Test Evaluation Criteria

The basis for evaluation of the results of the fabrication studies will be the success or failure of the processes employed to produce satisfactory joints and structures.

### D2.2.6.6 Test Deliverables

The following will be provided to meet the objectives of this Test Specification.

- Fabrication reports for all processes/materials used in producing ceramic-to-ceramic joints
- Fabrication reports for all processes/materials used in producing ceramic-to-metal joints
- Fabrication reports describing production of required product forms
- Reports providing characterization of all joints produced
- Reports describing structural integrity test methods and results.

### D2.2.6.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 3 to TRL 4 is addressed in Sections D2.1.3 and D2.1.4. The risk associated with D2.2.6 is that some of the procedures and techniques necessary for the fabrication of a ceramic heat exchanger may pose significant difficulties relative to cost and success.

# D3 TECHNOLOGY MATURATION PLAN FOR IHX A (CERAMIC) - TRL 4 TO TRL 5

## D3.1 TECHNOLOGY MATURATION PLAN SUMMARY

### D3.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the ceramic IHX A from a TRL level of 4 to a TRL level of 5. The tasks required to achieve this advancement include establishment of ASTM and ASME standards, modeling activities supporting ceramic heat exchanger design and performance evaluation, and testing of unit cells of ceramic IHX cores. A Test Specification is provided to cover each of the maturation tasks. These are given in Section D3.2.

### D3.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the ceramic version of IHX A from TRL 4 to TRL 5 are as shown below.

- Specification 1: Ceramic Materials Codes and Standards
- Specification 2: Methods for Thermal/Fluid and Stress/Strain Modeling
- Specification 3: Structural Integrity Criteria for Ceramic Heat Exchangers
- Specification 4: Performance Modeling of Ceramic Heat Exchangers
- Specification 5: Testing of unit cell of compact heat exchanger

The tasks above will be described fully in individual Test Specifications provided in the sections to follow.

### D3.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2017 through FY2020. No individual Test Specification describes work requiring more than 48 months and the work in most Test Specifications can be done in parallel.

### D3.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

# D3.2 Test Specifications

## D3.2.1 Ceramic Materials Codes and Standards (WEC-TS-IHXA-026)

### D3.2.1.1 Objectives

This Test Specification has the overall objective of developing and establishing of ASTM standards and an ASME Code Case for ceramic materials. It will involve the drafting of the code case, interactions with ASTM and ASME during the approval process, and provision of any additional specific data/information requested by the ASTM and/or ASME. This Test Specification responds to placeholder DDN HTS-02-06.

### D3.2.1.2 Test Conditions

*D3.2.1.2.1 Test Configuration/Set-up*

No test equipment or facility is needed.

*D3.2.1.2.2 Test Duration*

The duration of this activity will be a minimum of 48 months.

*D3.2.1.2.3 Proposed Test Location*

N/A

### D3.2.1.3 Measured Parameters

Not applicable.

### D3.2.1.4 Data Requirements

The ASME Section III Code case developed will meet all QA and ASME requirements; Similarly, ASTM ceramic materials standards will meet all QA and ASTM requirements.

### D3.2.1.5 Test Evaluation Criteria

N/A

### D3.2.1.6 Test Deliverables

Deliverables are as follows.

- A Section III ASME Code Case qualifying the use of specific ceramic materials for service in the NGNP IHX up to at least 1000°C
- An ASTM Standard specifying allowable commercial ceramic materials and their characteristics
- 

#### D3.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 4 to TRL 5 is addressed in Sections D3.1.3 and D3.1.4. The major risk associated with D3.2.1 is that the time required to obtain ASTM/ASME approvals could extend to 60 months.

### D3.2.2 Methods for Thermal/Fluid and Stress/Strain Modeling (WEC-TS-IHXA-027)

#### D3.2.2.1 Objectives

The work to be conducted under this Test Specification is development of thermal and mechanical structural models to provide a basis for design and predictive capability for operation and performance characteristics of compact heat exchangers. This is required for both quasi-steady state and transient analyses. This Test Specification responds to placeholder DDN HTS-02-03.

#### D3.2.2.2 Test Conditions

*D3.2.2.2.1 Test Configuration/Set-up*

None currently identified but the models will likely be applied to the results obtained under D3.2.5 and larger scale tests responding to placeholder DDN HTS-02-04.

*D3.2.2.2.2 Test Duration*

The duration of the modeling activities could be up to 48 months.

*D3.2.2.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

#### D3.2.2.3Measured Parameters

The models to be developed will incorporate and combine the mechanical and thermal/physical property database of ceramic materials with finite element analysis (FEA) techniques, and known relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

#### D3.2.2.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

#### D3.2.2.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing conducted in D3.2.5 and in later larger scale tests of ceramic heat exchanger modules.

#### D3.2.2.6 Test Deliverables

The test deliverable is a model for combining thermal/fluid and stress/strain parameters to guide the design of a ceramic heat exchanger IHX A and to predict its operation and performance characteristics.

#### D3.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 4 to TRL 5 is addressed in Sections D3.1.3 and D3.1.4. There are no risks associated with D3.2.2.

### D3.2.3 Structural Integrity Criteria for Ceramic Heat Exchangers (WEC-TS-IHXA-021)

#### D3.2.3.1 Objectives

The objective of this Test Specification is to establish criteria for the structural integrity of ceramic heat exchangers operating at very high temperature. This includes criteria for stresses and strains as well as development of safety factors needed in ASME Code development. These criteria will help to establish acceptable operational boundaries for ceramic heat exchangers. This Test Specification responds to the placeholder DDNs HTS-02-03, HTS-02-04, and HTS-02-06.

#### D3.2.3.2 Test Conditions

##### *D3.2.3.2.1 Test Configuration/Set-up*

None currently identified.

##### *D3.2.3.2.2 Test Duration*

Establish of structural integrity criteria for ceramic heat exchangers could require up to 48 months.

*D3.2.3.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

#### D3.2.3.3 Measured Parameters

Criteria for structural integrity will be developed from a review of appropriate ASME Code documentation, discussions with ASME Code personnel, and interactions during the development of stress/strain models (see activities associated D3.2.2).

#### D3.2.3.4 Data Requirements

Structural integrity criteria development activities will employ best standard practice and QA requirements.

#### D3.2.3.5 Test Evaluation Criteria

The usefulness and predictive capability of the structural integrity models developed will be assessed based on its application to testing described in D3.2.5 and in later larger scale tests responding to placeholder DDN HTS-02-04. They will also form a part of an ASME design code for moving from TRL 5 to TRL 7.

#### D3.2.3.6 Test Deliverables

Deliverables are as follows.

- Criteria for acceptable stresses and strains in ceramic heat exchangers
- Safety factors for application to an ASME design code.

#### D3.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 4 to TRL 5 is addressed in Sections D3.1.3 and D3.1.4. There is no risk associated with D3.2.3.

### D3.2.4 Performance Modeling of Ceramic Heat Exchangers (WEC-TS-IHXA-029)

#### D3.2.4.1 Objectives

The objective of the work prescribed in this Test Specification is to provide performance-modeling methods to adequately evaluate the results of performance testing of ceramic heat exchangers and to assist in the development of an ASME Code Case for their design. This Test Specification responds to placeholder DDN HTS-02-04.

### D3.2.4.2 Test Conditions

*D3.2.4.2.1 Test Configuration/Set-up*

None, but the performance models will be applied to the results obtained under DDN HTS-02-04 (see Technology Maturation Plans for TRL 4 to TRL 5, TRL 5 to TRL 6, and TRL 6 to TRL 7).

*D3.2.4.2.2 Test Duration*

Establishment of structural integrity criteria will occur over a 48-month period

*D3.2.4.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

### D3.2.4.3 Measured Parameters

The performance models to be developed will incorporate all parameters necessary to predict the thermal and structural behavior of compact heat exchangers.

### D3.2.4.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

### D3.2.4.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing associated with placeholder DDN HTS-02-04 (see Technology Maturation Plans for ceramic IHX A from TRL 4 to TRL 5, TRL 5 to TRL 6, and TRL 6 to TRL 7).

### D3.2.4.6 Test Deliverables

The deliverable for this Test Specification is a model to assess the thermal and structural performance of the compact heat exchanger modules to be tested in association with placeholder DDN HTS-02-04.

### D3.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for a ceramic IHX A from TRL 4 to TRL 5 is addressed in Sections D3.1.3 and D3.1.4. There is no risk associated with D3.2.4.

## D3.2.5 Testing of Unit Cell of Compact Heat Exchanger (WEC-TS-IHXA-030)

### D3.2.5.1 Objectives

The objective of testing the compact heat exchanger unit cell is:

- To determine the joint integrity of the compact heat exchanger unit cell joints under tensile load at a typical pressure environment and elevated temperatures.

### D3.2.5.2 Test Conditions

*D3.2.5.2.1 Component Requirements*

Component requirements include the following:

- Size limitation: dependant on testing environment (e.g. furnace)
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Environment - Helium

*D3.2.5.2.2 Interfacing Requirements*

n/a

*D3.2.5.2.3 Test Requirements*

Test requirements for the compact heat exchanger unit cell tests (not integrated) are as follows:

- Test environment which compact heat exchanger unit cell will be subjected to before post test evaluation:
  - Temperature = 1000°C (at least)
  - Pressure = 9MPa
  - Cyclic loading (magnitude and cycles TBD)

*D3.2.5.2.4 Test Duration*

The duration of this activity will be a minimum of **12**months.

*D3.2.5.2.5 Facility Requirements*

The following facilities will be required:

4. Furnace suitable for test requirements
5. Facilities required for metallographic analysis of material and joints after testing

*D3.2.5.2.6 Proposed Test Location*

Manufacturers of ceramic / metallic heat exchangers (depending on joint type) would most appropriately evaluate the joint integrities of the as manufactured unit cells.

### D3.2.5.3 Measured Parameters

The following parameters will be measured:

- Temperature
- Pressure
- Post-test joint integrity inferred from SEM, microscopic/metallographic evaluations and tests
  - Creep and creep rupture data

### D3.2.5.4 Data Requirements

It is assumed that the compact heat exchanger unit cell will be produced by a vendor of ceramic heat exchangers. The fabricated unit cell will require the following before progressing with testing:

- Materials certificates
- Joining certificates (if and when applicable)
- Inspection certificates
- All other quality assurance documents (bonding procedures, etc)

All new data shall be acquired using recognized techniques, codes, standards, and QA.

### D3.2.5.5 Test Evaluation Criteria

Satisfactory structural integrity of the compact heat exchanger unit cell joints as evidenced by post-testing examinations relating to metallographic procedures and tests.

### D3.2.5.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section D3.2.5.3
- Documentation containing performance verification criteria and test results relating to the joint integrities of the CHE unit cell as observed through microscopic/metallographic evaluations and tests.
- 

### D3.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing ceramic materials technology for IHX A from TRL 4 to TRL 5 is addressed in Sections D3.1.3 and D3.1.4.

The risk associated with Section D3.2.5 involves the non-satisfactory condition/integrity of the CHE unit cell joints, and may consequently require a reevaluation of the unit cell design (or certain aspects thereof).

# D4 TECHNOLOGY MATURATION PLAN FOR IHX A (CERAMIC) - TRL 5 TO TRL 6

## D4.1 TECHNOLOGY MATURATION PLAN SUMMARY

### D4.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the ceramic IHX A from a TRL level of 5 to a TRL level of 6. The maturation tasks required to achieve this goal involve the testing of the integrated compact heat exchanger module (~1.2MW) in the CTF (It is assumed that the compact heat exchanger module will be provided by a compact heat exchanger vendor) and the establishment of a Section III ASME Code case fully qualifying compact heat exchanger designs for service in the NGNP IHX. Test Specifications are provided to cover these maturation tasks.

### D4.1.2 Scope

The maturation tasks necessary to advance the maturity of the technology of the ceramic version of IHX A from TRL 5 to TRL 6 is as shown below.

- Specification 1: Testing of integrated compact heat exchanger module (~1.2MW)
- Specification 2: Establishing ASME Section III design code for compact heat exchanger designs

The tasks above will be described in the test specification provided hereafter.

### D4.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan will be accomplished during the period FY 2020 through FY 2022.

### D4.1.4 Overall Cost

Cost and schedule for the overall maturationplan with associated specifications are addressed in Section 17 of this document.

# D4.2 Test Specifications

## D4.2.1 Specification of testing of compact heat exchanger module (~1.2MW) (WEC-TS-IHXA-031)

### D4.2.1.1 Objectives

The objectives of testing the compact heat exchanger module (~1.2MW) are:

- To demonstrate the operating effectiveness of the compact heat exchanger module
- To demonstrate the fatigue life of the integrated compact heat exchanger module in terms of *thermal fatigue, joint integrity* and *corrosion & high temperature oxidation.*

### D4.2.1.2 Test Conditions

*D4.2.1.2.1 Compact Heat Exchanger Module (subsystem and system) Requirements*

Subsystem and system requirements include the following:

- Size limitation: dependant on test vessel size in Technology Development Loops 1 – 3 (TBD)
- Certain interface design requirements and specifications (see interfacing requirements)
- Heat transfer fluid – Helium with controlled impurities
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Mass flow threshold – see test requirements
- Pressure drop threshold– see test requirements

*D4.2.1.2.2 Interfacing Requirements*

- TBD by Technology Development Loop and Subsystem Configuration / Design.
- Certain interface design requirements and specifications:
  - Appropriate surface finish of interfacing components
  - Gasket materials applicable
  - Flange torque values where applicable

*D42.1.2.3 Measurement Requirements*

1. Measurement of internal and external pressures
2. Measurement of temperatures
3. Measurement of mass flows
4. Measurement of fluid composition
5. Measurement of leak rates from CHE module

*D4.2.1.2.4 Test Requirements*

Test requirements for the compact heat exchanger module tests (integrated) are as follows:

1) Test compact heat exchanger module operating effectiveness and behavior in typical steady state pressure, temperature and temperature/pressure drop environment (Helium)
   i. Temperature = 950°C
   ii. Pressure = 9MPa
   iii. Temperature Δ = 250°C
   iv. Pressure Δ = 500 – 600 kPa sustained (Primary to Secondary)
   v. Mass flow = tbd
   vi. He environment with varied composition

2) Test compact heat exchanger module behavior in typical pressure transient environment:
   i. Expose module to a high frequency, **normal** operating pressure transient, present with a startup / shutdown sequence
      1. Pressurizing transient (ambient to 9MPa in certain time frame)
      2. De-pressurizing transient (9MPa to ambient in certain time frame)
   ii. Number of cycles and temperature level TBD

3) Test compact heat exchanger module behavior in typical temperature transient environment:
   i. Expose module to a high frequency, **normal** operating temperature transient (ambient to 950°C), present with a startup / shutdown sequence
      1. Heat up transition
      2. Cool down transition
   ii. Number of cycles and pressure level TBD

4) Test compact heat exchanger module behavior at varying process parameters:
   i. Temperature = 950°C
   ii. Pressure = 9MPa primary (secondary TBD)
   iii. Pressure Δ = TBD (Primary to Secondary and Inlet to Outlet)
   iv. Mass flow = TBD

*D4.2.1.2.5 Tests Duration*

The duration of this activity will be a minimum of **12** months.

*D4.2.1.2.6 Facility Requirements*

The following facilities will be required:

1. TDL facilities 1-3 (TBD)
2. Gas analyzing facilities

3. Facilities required for metallographic analysis of material and joints after testing

*D4.2.1.2.7 Proposed Test Location*

Proposed tests will take place at the CTF.

### D4.2.1.3 Measured Parameters

The following parameters will be measured:

- Temperatures
- Pressures
- Measurement of magnitude and number of temperature gradients and temperature gradient cycles respectively up to thermal fatigue
- Fluid composition
- Leak rates at varying process conditions
- Operating effectiveness of compact heat exchanger module
- Corrosion of module materials and joints over a predetermined time
- Oxidation of module materials and joints over a predetermined time
- Thermal fatigue observations through SEM, TEM and other analyses techniques, inclusive of Element Distribution Maps of selected joint samples
- Joint integrity(ies) – Tensile tests, SEM, microscopic/metallographic evaluations and testing of joint sections.

### D4.2.1.4 Data Requirements

It is assumed that the compact heat exchanger module will be produced by a vendor of ceramic heat exchangers. The fabricated module of the compact heat exchanger will require the following before progressing with testing:

- Materials certificates specifying composition, sinter or compaction density, theoretical density
- Joining certificates
- Inspection certificates
- All other quality assurance documents

All new data shall be acquired using recognized techniques, codes, standards, and QA.

### D4.2.1.5 Test Evaluation Criteria

- Satisfactory number of transient cycles up to thermal fatigue of the module material/joints
- Structural integrity of the whole compact heat exchanger module assembly (system) as evidenced by
    - metallographic procedures and tests
    - analyses inclusive of remaining life assessments (if applicable)

   - comparison of data with assessment models, FEM's or other calculations
- The corrosion/oxidation over a predetermined time must not be of such magnitude as to degrade the structural integrity of the module material sections and joints.
- Limited reduction of oxide candidate materials. Limit value TBD.
- An acceptable effectiveness of the compact heat exchanger module
- An acceptable rate of leakage of the compact heat exchanger module at variable process conditions.

#### D4.2.1.6 Test Deliverables

Deliverables are as follows:

- Test Data for all areas as indicated in section D5.2.1.3
- Documentation containing performance verification criteria and test results verified against stress/strain models of the compact heat exchanger module and material properties.
-

#### D4.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing ceramic materials technology for IHX A from TRL 5 to TRL 7 is addressed in Sections D5.1.3 and D5.1.4.

Depending on the failure modes of the compact heat exchanger module, the design of relevant interfaces of the compact heat exchanger module will have to be reevaluated.

### D4.2.2 ASME Code Case for ceramic Compact Heat Exchanger Designs (WEC-TS-IHXA-032)

#### D4.2.2.1 Objectives

This Test Specification has the overall objective of developing and establishing an ASME Code Case for ceramic compact heat exchanger designs. It will involve the drafting of the code case, interactions with ASME during the approval process, and provision of any additional specific data/information requested by the ASME. This Test Specification responds to DDN HTS-01-19

#### D4.2.2.2 Test Conditions

*D4.2.2.2.1 Test Configuration/Set-up*

No test equipment or facility is needed.

*D4.2.2.2.2 Test Duration*

The duration of this activity will be a minimum of 48 months.

*D4.2.2.2.3 Proposed Test Location*

The supplier/design authority might be best suited for this task.

**D4.2.2.3 Measured Parameters**

Not applicable.

**D4.2.2.4 Data Requirements**

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

**D4.2.2.5 Test Evaluation Criteria**

Not applicable.

**D4.2.2.6 Test Deliverables**

The test deliverable is an ASME Code case (subsection to be determined) fully qualifying ceramic compact heat exchanger designs for service in the NGNP IHX up to 950°C.

**D4.2.2.7 Cost, Schedule, and Risk**

Cost and schedule for the overall Technology Maturation Plan for advancing ceramic materials technology for IHX A from TRL 5 to TRL 6 is addressed in Sections D4.1.3 and D4.1.4.

The associated risk entails the failure to establish an ASME Code Case for ceramic compact heat exchanger designs.

# D5 TECHNOLOGY MATURATION PLAN FOR IHX A (CERAMIC) – TRL 6 TO TRL 7

## D5.1 TECHNOLOGY MATURATION PLAN SUMMARY

### D5.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the ceramic IHX A from a TRL level of 6 to a TRL level of 7. The maturation tasks required to achieve this goal involve the testing of models to determine shell-side flow distribution and bypass leakage and the heat transfer testing of multi-modules (e.g., 3 x ~1.2MW). Test Specifications are provided to cover the maturation tasks (given in section D5.2).

### D5.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the ceramic version of IHX A from TRL 6 to TRL 7 is as shown below.

- Specification 1: Shell-side flow distribution and bypass leakage tests.
- Specification 2: Multi-module heat transfer tests.

These tasks will be described in D5.2.

### D5.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2022 through FY 2024.

### D5.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

# D5.2 Test Specifications

## D5.2.1 Shell-side Flow Distribution and Bypass Leakage Testing (WEC-TS-IHXA-033)

### D5.2.1.1 Objectives

The objectives of testing are to

- Confirm shell-side flow distribution modeling
- Confirm that shell-side bypass leakage is acceptable
- Confirm shell-side pressure losses.

There is also the potential to use this test to characterize dust transport/dropout as a function of particulate size.

### D5.2.1.2 Test Conditions

This likely would be an ambient temperature test with air as the working fluid. The test article would model inlet and outlet regions of the heat exchanger, features that promote good distribution to the core modules on the shell-side, and features that minimize bypass leakage. Details of the testing will be finalized at later stage.

## D5.2.2 Multi-module Heat Transfer Testing (WEC-TS-IHXA-034)

### D5.2.2.1 Objectives

The objectives of this testing are to

- Investigate module-to-module interactions on both the tube- and shell-sides of the heat exchanger
- Confirm bypass leakage and effects.

### D5.2.2.2 Test Conditions

The multi-module test would be a heated test in the CTF with 3 or more core modules (~4MWt would be required for 3 modules) representing a segment of the IHX. Details of the testing will be finalized at later stage.

# D6 TECHNOLOGY MATURATION PLAN FOR IHX A (CERAMIC) - TRL 7 TO TRL 8

## D6.1 TECHNOLOGY MATURATION PLAN SUMMARY

### D6.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the ceramic IHX A from a TRL level of 7 to a TRL level of 8. The maturation task required to achieve this goal involve the testing of the full scale ceramic compact heat exchanger. (It is assumed that the full-scale compact heat exchanger will be provided by a compact heat exchanger vendor and/or assembled by vendor staff on the NGNP site). The scope of this test on the full scale compact heat exchanger will vary slightly from the scope of test noted to progress from a TRL 5 to TRL 6 and from TRL 6 to TRL 7. A Test Specification is provided to cover the maturation task (given in section D6.2).

### D6.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the ceramic version of IHX A from TRL 7 to TRL 8 is as shown below.

- Specification 1: Testing of full scale ceramic compact heat exchanger in the NGNP

This task will be described in the following test specification.

### D6.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2024 through FY 2027.

### D6.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

# D6.2 Test Specifications

## D6.2.1 Specification of testing of a full scale compact heat exchanger (WEC-TS-IHXA-035)

### D6.2.1.1 Objectives

The objectives of testing the full-scale compact heat exchanger are:

- To determine the leak rate of the full scale compact heat exchanger (system) at various typical process parameters.
- To determine the operating effectiveness of the full scale compact heat exchanger at various typical process parameters.

The ceramic IHX A will be fully tested and commissioned in the NGNP. Details of the testing and commissioning will be finalized at later stage.

NGNP-CTF MTECH-TDRM-005 November 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 5: Intermediate Heat Exchanger B

**APPROVALS**

| Function | Printed Name and Signature | | Date |
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# ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| | |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| | |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |

| | |
|---|---|
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# SUMMARY AND CONCLUSIONS

The IHX is a critical high-temperature component of the NGNP and its bottom-line function is to transfer thermal energy from the Primary Heat Transport System (PHTS) to the Secondary Heat Transport System (SHTS). Previous studies related to the NGNP Heat Transport System (HTS) have shown the advisability of splitting the IHX into two units, IHX A operating at up to 950°C and IHX B operating at up to ~760°C. This portion of the document deals only with the lower temperature IHX B. Metallic and ceramic versions of the higher temperature heat exchanger, IHX A, are treated in an earlier section.

Decision Discriminators were established and exercised in decisions taken relative to heat exchanger designs and materials. Cost/performance, state-of-the-art, robustness, environmental compatibility, RIM, IHX integration, and design/licensing basis were considered in the down select of designs. A wide range of heat exchanger designs were evaluated and the result was the selection of a compact design (Printed Circuit Heat Exchanger (PCHE) or Plate Fin Heat Exchanger (PFHE)) for a metallic heat exchanger. Decision discriminators applied to the selection of a material for IHX B were materials database (e.g., maturity of data and service experience), materials lifetime (e.g., creep lifetime and corrosion behavior), and fabrication related factors. The choice based on the above was Fe/Ni-base Alloy 800H.

The status of technology for metallic heat exchangers was evaluated, and resulted in the determination of a level of TRL 3 for IHX B. The underlying bases for these selections are described in the TRL rating sheet for IHX B.

TDRMs are provided to summarize down select tasks, TRL status, and maturations tasks necessary to increase the maturity of the technology of IHX B to a level of TRL 8. These tasks include consideration of materials properties and performance, material and design codes, model development for thermal and mechanical performance, and testing of IHX modules progressing from unit cells to full-size IHX units. Details of the tasks necessary for technology advancement between TRL levels are presented as a series of Technology Maturation Plans that include information on objectives, test conditions, measured parameters, data requirements, test evaluation criteria, test deliverables, and cost/schedule/risk. It is noted that the technology roadmap and maturation plans will need to be adjusted as new DDNs evolve as part of the conceptual and detail designs.

# 5 INTERMEDIATE HEAT EXCHANGER B (IHX B)

## 5.1 Function and Operating Requirements

The IHX is a critical high-temperature component of the NGNP. Cost and performance goals for the NGNP and related commercial process heat plants have lead to the selection of compact heat exchangers as the reference design. Further, the IHX has been separated into two regions, a high-temperature IHX A and a lower temperature IHX B. This economically driven decision provides for the majority of heat exchange to be serviced by the IHX B, constructed from a lower cost alloy. This leaves a smaller portion for IHX A, constructed from a premium alloy, that will necessarily be replaced due to limitations of metals exposed to the high temperature gas issuing from the reactor (950°C temperature range under consideration).

The IHX transfers thermal energy between the Primary Heat Transport System (PHTS) and the Secondary Heat Transport System (SHTS). The PHTS is comprised of the primary piping, primary circulator, and primary helium working fluid. By current definition, the IHX is considered part of the PHTS. Its main functions are to contain the primary and secondary helium coolants and to transport thermal energy from the reactor to the SHTS working fluid. The SHTS is comprised of the secondary piping, secondary circulator and secondary helium working fluid. Its main function is to transport thermal energy from the IHX to the Process Coupling Heat Exchanger and Steam Generator.

The Intermediate Heat Exchanger (IHX) is comprised of:

- Heat transfer surface and/or modules containing the heat transfer surface
- The IHX vessel
- Headers and/or piping that provide a transition between the heat transfer surface and/or modules and the PHTS/SHTS piping
- Internal structures that provide for support (steady state, transients and seismic loading) of the IHX and related internal components within the IHX vessel
- Thermal baffles and/or insulation that is attached to the above IHX components

The IHX Vessel is part of the helium pressure boundary and includes internal support features, incorporated within the vessel structure, that interface with the IHX internal supports. It also includes thermal baffles and/or insulation that are directly attached to the vessel. The allocation of the IHX vessel (or parts thereof) as being part of the PHTS or SHTS will depend upon which fluids (PHTS or SHTS) are contained within the shell-side of the heat exchanger. This, in turn will be subject to the further selection of which circuit (PHTS or SHTS) will be coupled to the "shell" side of the heat exchanger.

The specified service conditions and other key requirements for IHX B are as given below.

- The nominal helium temperature at the primary side entrance to IHX B is 760°C.
- The nominal helium temperature at the secondary side entrance to IHX B is 287°C.

- The nominal helium temperature at the secondary side exit from IHX B is 710°C.
- The nominal helium temperature at the primary side exit from IHX B is 337°C.
- IHX B will provide for transfer of ~350 MW of heat.
- Helium in both the PHTS and SHTS will have controlled levels of impurities.
- Primary loop pressure is nominally 9 MPa and essentially pressure balanced with the secondary loop pressure.
- The forced outage allocation is <1 %.
- The required operating life is 60 years.
- The pressure loss across the entire IHX (IHX A + IHX B) primary side and also across secondary side of IHX shall be smaller than 1.23 % of its respective inlet pressures.

Further, there are a substantial number of fixed and preferred requirements in the areas of:

- Interfaces (e.g., IHX B internal structures and fluid flow shall ensure that the vessel temperature be limited to 371°C during normal operation)
- System Configuration (e.g., the size ratio of IHX B to IHX A shall be as large as possible and overall capacity shall be 510 MW)
- Operation (e.g., the components of IHX B shall be able to accommodate 600 start-up and shut-down cycles)
- Tritium Migration Allowance - Tritium migration is a NHSS-level issue taking into account production and mitigation provided by various barriers and the He purification system. The specific IHX requirement is TBD.
- Structure (e.g., the IHX B vessel diameter shall be smaller than 6 m)
- Environment (all subject to further review)
- Instrumentation & Control (to be determined)
- Availability and Reliability (e.g., inherent availability of the IHX B shall be >99.98%)
- Maintenance (e.g., IHX B shall not require preventive maintenance)
- Transport (e.g., design features shall be included to allow for transportation of subassemblies with final assembly on-site)
- Testing, Qualification, Commissioning (e.g., the entire PHTS, including IHX B, shall be pressure tested in accordance to ASME requirements)

All of the above are discussed in more detail in the *IHX and Heat Transport System* [5-3] report.

# 5.2 IHX B Down Select Status

## 5.2.1 Candidate Technologies

Various designs and materials for IHX B were proposed and evaluated in a series of recent studies. These studies were described and discussed in the following reports.

- Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007 [5-1]
- PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007 [5-2]
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008 [5-3]

The first of these studies considered both helical shell and tube and compact designs, primarily the Heatric based PCHE for the latter, and evaluated a broad range of Ni- and Fe/Ni base alloys for their construction. Based on this study, it was recommended that the compact heat exchanger design should be pursued with separate high-temperature (IHX A) and lower temperature (IHX B at <850°C) sections. Alloy 800H was designated as a leading candidate for IHX B.

The second study confirmed the conclusions above (i.e., IHX A and IHX B sections, a PCHE compact design, and further recommended that the IHX A/IHX B split be set at <760°C to take advantage of the ASME Section III qualification of Alloy 800H (760°C max).

The third study above was by far the most comprehensive in its evaluation of designs, performance, and materials. It also included two additional designs, a Capillary Heat Exchanger (small-diameter tube shell-and-tube) and a novel Involute (small-diameter tubes in an involute configuration) design. Also, an extensive study and evaluation of a plate-fin version of a compact heat exchanger was performed. Further consideration was given to materials alternate to Alloy 800H (e.g. Hastelloy X), but the recommendation remained to be Alloy 800H.

## 5.2.2 Decision Discriminators

This section provides a detailed listing of the decision discriminators that were used in the *IHX and Heat Transport* [5-3] study to evaluate various IHX designs. They were applied to the four designs below.

- Conventional helical coil shell & tube
- Capillary tube
- Printed Circuit Heat Exchanger
- Plate-fin
- Involute

The qualitative comparisons of these heat exchanger concepts were based on the following parameters.

- Cost/Performance Indicators
  - Compactness in terms of heat transfer density (MWt/$m^3$)
  - Materials utilization (t/MWt)
  - Manufacturing cost
- State-of –the-Art
  - Experience base
  - Design & manufacturing
- Robustness
  - Normal operation
  - Transients
- Environmental Compatibility
  - Corrosion effects
  - Erosion effects
  - Tritium transport
- Reliability & Integrity Management
  - Detection of leaks/degradation during operation
  - Detection of leaks/degradation during outages
  - Leak location/isolation/repair/replacement
- IHX Integration
  - Integration with vessels and piping
  - Compatibility with multi-stage designs
  - Compatibility with multi-module designs
  - Compatibility with alternate heat transfer fluids
- Design & Licensing Basis
  - Code basis for design

As for the higher temperature IHX A, metallic materials considered were Alloy 800H, Alloy 230, Alloy 617, and Hastelloy X. Also as for IHX A, materials database (maturity, status of codes and standards, and service experience), materials lifetime (high temperature properties and behavior and corrosion performance), and fabrication related factors (availability, joining, cost, etc.) were used as decision discriminators to select the preferred alloy.

The application of the materials decision discriminators as noted above to the down select process is given and discussed in Section 5.2.3 below (for the design decision discriminators, refer to Section 4 (IHX A)).

### 5.2.3 Application of the Decision Discriminators to the IHX B Down Select

Application of the materials decision discriminators to the four alloy candidates noted earlier, resulted in the identification of the following factors which overwhelmingly suggest the selection of Alloy 800H for IHX B.

- Alloy 800H has the most mature database and the greatest service experience.

- Alloy 800H is qualified under ASME Section III, Subsection NH for service in nuclear environments up to 760°C.
- The high-temperature mechanical properties (creep, fatigue, etc.) of Alloy 800H are more than adequate for use during normal operation and loss-of-secondary-pressure events.
- Corrosion performance of Alloy 800H in NGNP He at 760°C appears to be comparable to that for Alloy 617 and Alloy 230.
- Fabrication and joining technologies for Alloy 800H are the most mature of the candidate alloys. (However, work is still needed on brazing and diffusion bonding processes and effects.)
- Alloy 800H is the least expensive of the materials.

Reference Design

### 5.2.4 Reference Design

The single alternate relative to IHX B is a decision to be taken at TRL 5 on the PCHE versus plate-fin design.

### 5.2.5 Summary of the IHX B Down Selection Task

The IHX B down select evaluation conducted for the IHX and reported in the *NGNP Conceptual Design Study: IHX and Heat Transport System* [5-3] resulted in the various conclusions and recommendations listed below.

- The earlier recommendation to utilize PCHE or plate-fin compact heat exchanger technology as the basis for the metallic IHX B design has been confirmed. These are the current reference designs and both would employ Alloy 800H.
- A compact IHX configuration (applicable to both PCHE and plate-fin heat exchangers) that potentially allows leak detection, location and isolation at the module-level has been identified.
- The earlier recommendation to separate the IHX into IHX A and IHX B sections, based on temperature, is supported by the results of the present study.
- The recommendation to employ Alloy 800H for the heat exchanger core of IHX B was confirmed.

## 5.3 TRL Status

Evaluations of the status of the technology for IHX B were made and resulted in the determination of a level of TRL 3. (Note that this is higher than the TRL 2 assigned to the metallic IHX A. The major factor for this difference is the much lower temperatures associated with IHX B. This eases concerns with materials performance and is more consistent with temperatures in existing conventional and compact heat exchangers.) The bases for this selection are described in the TRL rating sheet provided in Appendix A.

## 5.4 Technology Development Road Map Summary

### 5.4.1 Overview

The TDRM lists the maturation tasks that are required to advance the maturity of the technology of IHX B from TRL 3 to TRL 8.

The IHX B Technology Development Road Map is attached in Appendix B and the maturation tasks in Appendix C.

## 5.5 Technology Maturation Plan Summary

This section describes the maturation tasks needed to advance the technology of IHX B from a validated TRL 3 to a validated TRL 8. Progress from a validated TRL 3 to a TRL 4 involves the completion of relevant material qualification tasks as well as the development of simulation models for the IHX B. The materials tasks include some consideration of thermal/physical and mechanical properties of Alloy 800H, joining and fabrication techniques applicable to Alloy 800H in compact heat exchangers, and determination of corrosion allowances for Alloy 800H. Significant levels of effort will also be devoted to methods for thermal/fluid and stress/strain modeling and to establishment of structural integrity criteria. Methods for performance modeling of compact heat exchangers will also be developed. Progress from a validated TRL 4 to TRL 5 involves the fabrication, testing and evaluation of small elements or modules containing the heat transfer surface of the IHX. These maturation tasks will be keyed to the DDNs described in the *NGNP Conceptual Design Study: IHX and Heat Transport System* [5-3] whenever possible.

At completion of the tasks above, IHX B will have achieved a level of validated TRL 5 and a PCHE versus PF design decision will have been made. Advancement to a validated TRL 6 requires manufacture of a nominally 1.2 MW module of IHX B, testing of the module in the CTF, and verification of its performance. It will also be necessary to establish an ASME Code Case the design of compact heat exchangers.

Moving the technology of IHX B from TRL 6 to TRL 7 will require tests to assess shell-side flow distribution and bypass leakage and multi-module tests for confirmation of heat transfer and flow performance.

Advancement of IHX B technology from TRL 7 to TRL 8 will be fulfilled by the manufacture of a full-size IHX B compact heat exchanger and its testing in the NGNP. The costs and schedules associated with the DDNs given in the *NGNP Conceptual Design Study: IHX and Heat Transport System* [5-3] report were first presented in *PCDR Section 6: Heat Transport System* [5-2]. Subsequently, more extensive and detailed estimates of schedules and costs for IHX B design, development, testing, and manufacture were performed and can be examined in the *Metallic Component Schedule Risk and Cost Uncertainty Assessment report*. Additionally, schedules and costs will be provided in each of the Technology Maturation Plans.

## 5.6 Inputs to CTF

IHX B modules will be tested in the CTF for qualification of a TRL 6 and a TRL 7.

## 5.7 References

[5-1] Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007 (Ref. 1)
[5-2] PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007 (Ref. 2)
[5-3] NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008 (Ref. 3)
[5-4] Metallic Component Schedule Risk and Cost Uncertainty Assessment report

# APPENDIX A: TRL RATING SHEETS

**Table A-1: Technology Readiness Levels for the IHX B**

**TRL Rating Sheet**

Vendor Name: Document Number: Revision:

☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology

Title: Intermediate Heat Exchanger (IHX B) (760°C)

Description:

The Technology Readiness Level for a metallic IHX operating in the NGNP at 760°C for 60 years has been assessed as TRL 3 based on studies shown below; actions needed to advance the level to TRL 4 are also given below.

Island(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: N/A | Parent: N/A | WBS: N/A |
|---|---|---|

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Application formulated | Proof of concept | Bench scale testing |
| **TRL** | 2 | **3** | 4 |

Basis for Rating (Attach additional sheets as needed)

Designs and materials for an IHX operating at 760°C were proposed and evaluated in recent studies reported in:

- Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007
- PCDR Section 6: Heat Transport System, NGNP-06-RPT-003, Rev 0, April 2007
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (K$) |
|---|---|---|

| | | |
|---|---|---|
| • Alloy 800H Material Specifications and Procurement<br>• Database for Brazed and Diffusion Bonded Alloy 800H<br>• Alloy 800H High Temperature Materials Properties<br>• Effects of Thermal Aging and Environment on Alloy 800H Properties<br>• Effects of Environmental Exposure on Alloy 800H Braze and Diffusion Bonded Joints<br>• Effects of Grain Size and Section Thickness on Alloy 800H Properties<br>• Corrosion Allowances for Alloy 800H<br>• Thermal/Fluid Modeling Methods for IHX B<br>• Methods for Stress/Strain Modeling of IHX B<br>• Criteria for Structural Integrity of IHX B<br>• Performance Modeling Methods for IHX B | FY 2009 – FY 2015 | Refer to Section 17 |
| DDN(s) supported:<br>HTS-01-22, HTS-01-23, HTS-01-24, HTS-01-25, HTS-01-26, HTS-01-27, HTS-01-28, HTS-01-29, HTS-01-30, HTS-01-13, HTS-01-14, HTS-01-15, HTS-01-16. | | |
| Subject Matter Expert Making Determination: Phil Rittenhouse | | |
| Date: September 16, 2008 | Originating Organization: Technology Insights | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

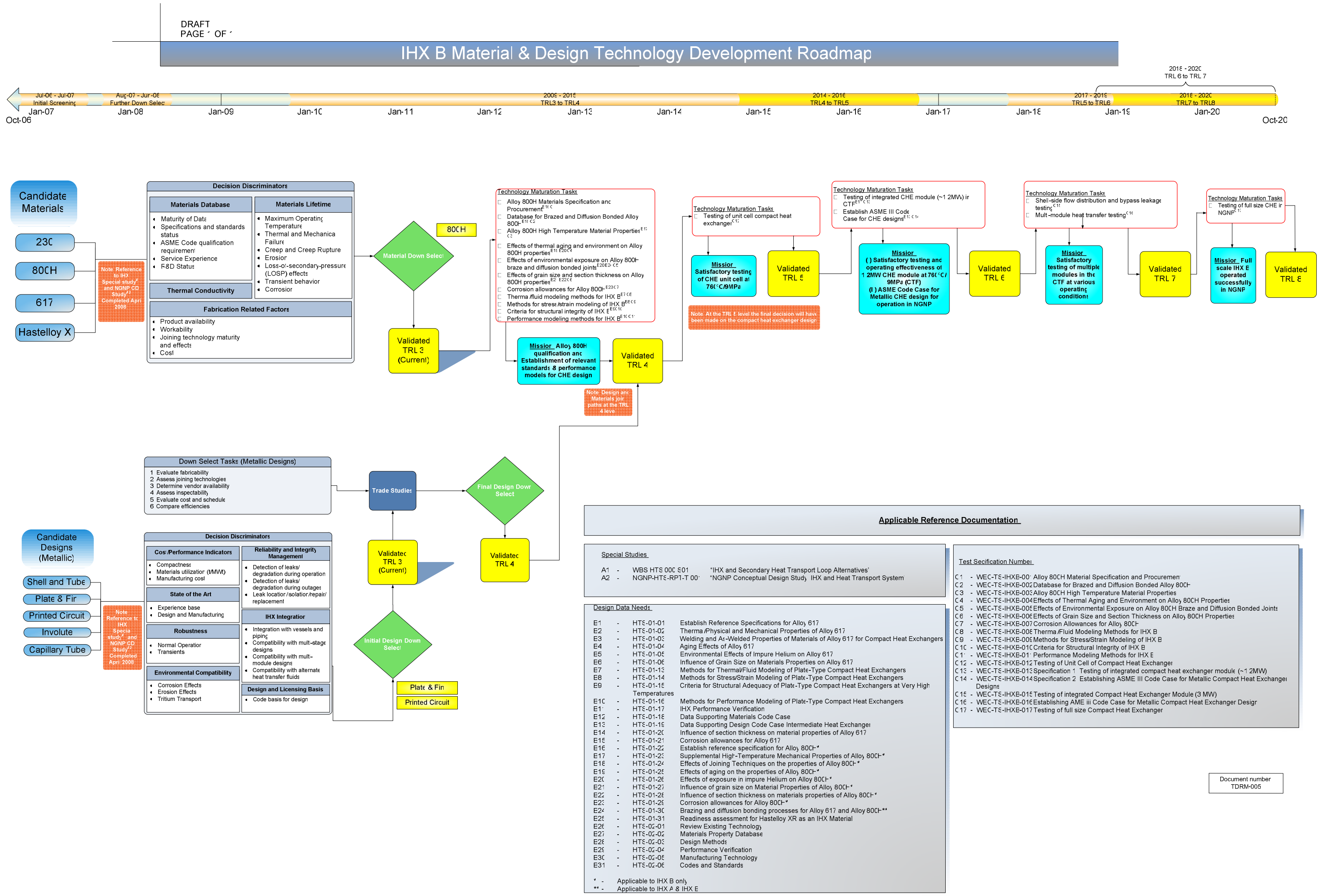


Figure B-1: TDRM for IHX B

# APPENDIX C: TECHNOLOGY MATURATION PLAN

## TABLE OF CONTENTS

## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

**TRL 3 to TRL 4:**

- Specification 1: Alloy 800H Material Specifications and Procurement *(WEC-TS-IHXB-001)*
- Specification 2: Database for Brazed and Diffusion Bonded Alloy 800H *(WEC-TS-IHXB-002)*
- Specification 3: Alloy 800H High Temperature Materials Properties *(WEC-TS-IHXB-003)*
- Specification 4: Effects of Thermal Aging and Environment on Alloy 800H Properties *(WEC-TS-IHXB-004)*
- Specification 5: Effects of Environmental Exposure on Alloy 800H Braze and Diffusion Bonded Joints *(WEC-TS-IHXB-005)*
- Specification 6: Effects of Grain Size and Section Thickness on Alloy 800H Properties *(WEC-TS-IHXB-006)*
- Specification 7: Corrosion Allowances for Alloy 800H *(WEC-TS-IHXB-007)*
- Specification 8: Thermal/Fluid Modeling Methods for IHX B *(WEC-TS-IHXB-008)*
- Specification 9: Methods for Stress/Strain Modeling of IHX B *(WEC-TS-IHXB-009)*
- Specification 10: Criteria for Structural Integrity of IHX B *(WEC-TS-IHXB-010)*
- Specification 11: Performance Modeling Methods for IHX B *(WEC-TS-IHXB-011)*

**TRL 4 to TRL 5:**

- Specification 1: Testing of unit cell of compact heat exchanger *(WEC-TS-IHXB-012)*

**TRL 5 to TRL 6:**

- Specification 1: Testing of integrated compact heat exchanger module (~1.2MW) *(WEC-TS-IHXB-013)*
- Specification 2: Establishing ASME III Code Case for Metallic Compact Heat Exchanger Designs *(WEC-TS-IHXB-014)*

**TRL 6 to TRL 7**

- Specification 1: Shell-side flow distribution and bypass leakage testing *(WEC-TS-IHXB-015)*
- Specification 2: Multi-module heat transfer testing *(WEC-TS-IHXB-016)*

**TRL 7 to TRL 8:**

- Specification 1: Testing of full size compact heat exchanger (IHX B) *(WEC-TS-IHXB-017)*

# C1 TECNOLOGY MATURATION PLAN FOR IHX B – TRL 3 TO TRL 4

## C1.1 Technology Maturation Plan Summary

### C1.1.1 Objectives

The objective of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for IHX B from a TRL level of 3 to a TRL level of 4. Several of the maturations tasks required to achieve this goal involve the mechanical and thermal/physical properties of Alloy 800H and how they are affected by material thickness, grain size, thermal aging, and environmental exposure. Joining processes (welding, brazing, and diffusion bonding) and their effects on properties are also addressed. Another of the maturation tasks addresses the corrosion (scale formation, internal oxidation, etc.) of Alloy 800H in NGNP primary and secondary He atmospheres containing low levels of impurities. Four maturation tasks discussed are involved with the development of models to guide the design of high temperature compact heat exchangers and to form the predictive basis for their operation and performance. A Test Specification is provided to cover each of the maturation tasks. These are given in Section C1.2.

### C1.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the metallic IHX B from TRL 3 to TRL 4 are as shown below.

- Alloy 800H material specifications and procurement
- Develop mechanical property database for brazed and diffusion bonded Alloy 800H.
- Accept existing high temperature properties database for Alloy 800H.
- Accept existing Alloy 800H database on effects of thermal aging and environment.
- Obtain environmental effects data for brazed and diffusion bonded joints of Alloy 800H.
- Assess effects of grain size and section thickness on Alloy 800H properties.
- Determine corrosion allowances for Alloy 800H.
- Develop methods for thermal/fluid modeling of compact heat exchangers.
- Develop methods for stress/strain modeling of compact heat exchangers.
- Establish criteria for structural integrity of compact heat exchangers at very high temperature.
- Develop methods for performance modeling of compact heat exchangers.

The tasks above will be described fully in individual Test Specifications in sections to follow.

### C1.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2009 through FY2015. No individual Test Specification describes work requiring more than 30 months and the work in most Test Specifications can be done in parallel.

### C1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C1.2Test Specifications

### C1.2.1 Alloy 800H Material Specifications and Procurement (WEC-TS-IHXB-001)

#### C1.2.1.1 Objectives

Activities covered in this Test Specification are the finalization of the material specifications (alloy chemistry, fabrication processes etc.), development of procurement requirements for NGNP Alloy 800H, and procurement of one or more heats of Alloy 800H as necessary. With respect to the former, it is expected that existing ASTM standards will be used. No actual physical testing will be performed. This Test Specification responds to DDN HTS-01-22.

#### C1.2.1.2 Test Conditions

*C1.2.1.2.1Test Configuration/Set-Up*

No test equipment/facility is needed except for existing conventional test machines (e.g., tensile test machine) for confirming that Alloy 800H procured meets specifications.

*C1.2.1.2.2Test Duration*

The duration of this activity could be up to 12 months.

*C1.2.1.2.3Proposed Test Location*

The work could be performed at an appropriate National Laboratory. Refer to Section 17 of the document .

#### C1.2.1.3 Measured Parameters

Properties, chemistry, grain size, etc. specified in the material specifications and requirements for the material procured.

#### C1.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C1.2.1.5 Test Evaluation Criteria

Heats of Alloy 800H acquired shall meet all procurement requirements and material specifications.

#### C1.2.1.6 Test Deliverables

Deliverables are as follows.

- Alloy 800H materials purchase specification
- One or more heats of Alloy 800H acquired per the above
- Report confirming that the heats of Alloy 800H meet all specifications and requirements (e.g. Certified Materials Test Report, for each heat).

#### C1.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. Risks include that the material doesn’t qualify and that the overall schedule will be delayed.

### C1.2.2 Database for Brazed and Diffusion Bonded Alloy 800H (WEC-TS-IHXB-002)

#### C1.2.2.1 Objectives

Work conducted under this Test Specification is intended to demonstrate that Alloy 800H brazed and diffusion-bonded joints will have mechanical properties appropriate to their use in compact heat exchangers. This Test Specification responds to DDN HTS-01-24 and to DDN HTS-01-30.

### C1.2.2.2 Test Conditions

*C1.2.2.2.1Test Configuration/Set-Up*

These activities require the following.

- Equipment and facilities for brazing and diffusion bonding
- Equipment for microscopic examination
- Equipment for mechanical property testing

*C1.2.2.2.2Test Duration*

The duration of these joining and testing activities could be up to 30 months.

*C1.2.2.2.3Proposed Test Location*

A National Laboratory or University could perform the work on microscopic examination and mechanical properties. Commercial organizations involved in compact heat exchanger manufacture would be appropriate for the joining studies, and to produce the bonded unit cells for test specimens. Refer to Section 17 of the document .

### C1.2.2.3 Measured Parameters

Parameters to be measured include the following.

- Conditions and parameters applied in producing the joints
- Condition of the Alloy 800H joints as evidenced by metallography
- Chemistry profiles in the joints determined by SEM
- Tensile, creep, fatigue, and fracture toughness at temperatures up to 850°C.

### C1.2.2.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

### C1.2.2.5 Test Evaluation Criteria

This work or an accepted variation thereof will provide the basis for determination of the suitability of brazing and diffusion bonding methods to the manufacture of compact heat exchangers. Criteria involved in the evaluation of each joint type will include:

- Structural integrity as evidenced by metallography and SEM
- Minimal or no reduction in strength or ductility of the Alloy 800H joints.

#### C1.2.2.6 Test Deliverables

Deliverables are as follows.

- Brazing procedure specifications
- Diffusion bonding procedure specifications
- Conventional welding procedure specifications
- Reports on structural integrity of joints formed by brazing and diffusion bonding
- Reports on mechanical properties of brazed and diffusion bonded joints.

#### C1.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. The risks associated with Section C1.2.2 are very small but include the possibility that one or both of the joining techniques may prove unsuitable for thin section of Alloy 800H.

### C1.2.3 Alloy 800H High Temperature Material Properties (WEC-TS-IHXB-003)

#### C1.2.3.1 Objectives

The objectives of this work are to agree to adopt the existing high temperature property database for Alloy 800H materials and to accept that these thermal/physical and mechanical properties are suitable for design and operation of compact heat exchanger IHX B. This Test Specification responds to DDN HTS-01-23.

#### C1.2.3.2 Test Conditions

*C1.2.3.2.1Test Configuration/Set-Up*

N/A.

*C1.2.3.2.2 Test Duration*

Agreement to the database and its collection should require no more than 3 months.

*C1.2.3.2.3 Proposed Test Location*

The database should be collected and archived by a National Laboratory. Most of this has been accomplished in a joint DOE-ASME program. Refer to Section 17 of the document .

### C1.2.3.3 Measured Parameters

Parameters to be recorded are:

- High temperature property data
- Source of the data.

### C1.2.3.4 Data Requirements

All data shall meet ASME standards and requirements.

### C1.2.3.5 Test Evaluation Criteria

N/A

### C1.2.3.6 Test Deliverables

The test deliverable is an achieved Alloy 800H high temperature property database.

### C1.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with Section C1.2.3. involves that the Alloy 800H high temperature property database does not provide for certain conditions and might consequently have to be revisited.

## C1.2.4 Effects of Thermal Aging and Environment on Alloy 800H Properties (WEC-TS-IHXB-004)

### C1.2.4.1 Objectives

The objective of this work is to agree to accept the existing database on the effects of thermal aging and environmental exposure on the thermal/physical and mechanical properties of Alloy 800H materials. This Test Specification responds to DDN HTS-01-25 and DDN HTS-01-26.

### C1.2.4.2 Test Conditions

*C1.2.4.2.1Test Configuration/Set-Up*

N/A.

*C1.2.4.2.2Test Duration*

Collection and archiving of information of the effects of thermal aging and environmental exposure on the properties of Alloy 800H should require no more than 6 months.

*C1.2.4.2.3Proposed Test Location*

The database should be collected and archived by a National Laboratory. Most of this has been accomplished in a joint DOE-ASME program. Refer to Section 17 of the document .

### C1.2.4.3 Measured Parameters

Parameters to be recorded are:

- Thermal aging and environmental exposure effects data
- Source of the data.

### C1.2.4.4 Data Requirements

All data shall meet NGNP standards and requirements for data.

### C1.2.4.5 Test Evaluation Criteria

N/A.

### C1.2.4.6 Test Deliverables

The test deliverable is an achieved database on the effects of thermal aging and environmental exposure on the properties of Alloy 800H.

#### C1.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with Section C1.2.4 involves that the relevant Alloy 800H property database does not provide for certain conditions and might consequently have to be revisited.

### C1.2.5 Effects of Environmental Exposure on Alloy 800H Braze and Diffusion Bonded Joints (WEC-TS-IHXB-005)

#### C1.2.5.1 Objectives

The objective of this task is to determine the response of the properties of welded, brazed, and diffusion bonded Alloy 800H to exposures in NGNP primary and secondary He environments (low levels of CO, $CO_2$, $H_2$, $O_2$, $H_2O$ and $CH_4$). This Test Specification responds to DDN HTS-02-26 and DDN HTS-02-30.

#### C1.2.5.2 Test Conditions

*C1.2.5.2.1Test Configuration/Set-Up*

The following are required relative determining the effects of NGNP He on the properties of Alloy 800H:

- Facility for exposure of specimens of welded, brazed, and diffusion bonded Alloy 800H to He environment representative of the NGNP for a predetermined time
- Equipment appropriate for conducting tensile, creep, fatigue, and fracture toughness tests
- Instruments for post-test characterization of structure of welds, brazes, and diffusion bonds

*C1.2.5.2.2 Duration*

Preparation, exposure, and testing of the weld, braze, and diffusion bonded specimens of Alloy 800H could require up to 36 months.

*C1.2.5.2.3 Proposed Test Location*

Preparation of the weld, braze, and diffusion bond specimens could be conducted at a National Laboratory or by commercial organizations experienced in these techniques. Refer to Section 17 of the document .

### C1.2.5.3 Measured Parameters

Parameters to be measured include the following.

- Conditions and parameters applied in producing the joints
- Environmental exposure conditions (times and temperatures) and He chemistry
- Condition of the Alloy 800H joints as evidenced by metallography
- Chemistry profiles in the joints determined by SEM
- Tensile, creep, fatigue, and fracture toughness at temperatures up to 850°C before and after He exposures
-

### C1.2.5.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA

### C1.2.5.5 Test Evaluation Criteria

Evaluation of the effects of environmental exposures on the properties of Alloy 800H welds, brazes, and diffusion bonds will be based on before and after values of tensile, creep, fatigue, and fracture toughness properties.

### C1.2.5.6 Test Deliverables

Deliverables are as follows.

- Reports documenting the details of preparation of the Alloy 800H joints
- Reports documenting details of the environmental exposures
- Reports describing the effects of environmental exposures on mechanical properties of welds, braze joints, and diffusion bonds
- Report describing the effects of environmental exposures of Alloy 800H on the structure of welds, braze joints, and diffusion bonds.

### C1.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with C1.2.5 is small but includes the possibility that one or more of the properties measured after exposure could fall short of what is required for use of Alloy 800H in a compact heat exchanger at up to 760℃ for 60 years.

## C1.2.6 Effects of Grain Size and Section Thickness on Alloy 800H Properties (WEC-TS-IHXB-006)

### C1.2.6.1 Objectives

The objective of the work prescribed in this Test Specification is to *firstly* demonstrate that the very thin as-fabricated sections of Alloy 800H (significantly less than 1 mm) required in the IHX B compact heat exchanger will have creep and fatigue properties equivalent or only slightly degraded relative to those of products of more typical thickness and *secondly* that fatigue and creep properties of Alloy 800H with typical grain sizes (ASTM 5) are acceptable for compact heat exchanger operation. This Test Specification responds to DDN HTS-01-27 and DDN HTS-01-28.

### C1.2.6.2 Test Conditions

*C1.2.6.2.1 Test Configuration/Set-Up*

Conduct of this work requires equipment/facilities for creep and fatigue measurement and for metallographic determination of grain size.

*C1.2.6.2.2 Test Duration*

The work relative to grain size and section thickness effects on Alloy 800H creep and fatigue properties should require about 24 months.

*C1.2.6.2.3 Proposed Test Location*

Study and measurements relative to grain size and section thickness effects on properties are best suited to be conducted at a National Laboratory. Refer to Section 17 of the document .

### C1.2.6.3 Measured Parameters

Data to be taken include:

- Creep properties (up to 850°C) as a function of fabricated material thickness
- Creep properties (up to 850°C) as a function of grain size, if required
- Fatigue properties as a function of fabricated material thickness
- Fatigue properties as a function of grain size, if required.

### C1.2.6.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

#### C1.2.6.5 Test Evaluation Criteria

The creep and fatigue properties determined on thin section and standard grain size Alloy 800H material must meet the requirements for fatigue and creep resistance in the IHX B compact heat exchanger.

#### C1.2.6.6 Test Deliverables

Deliverables for this Test Specification shall include:

- Report on the influence of section thickness on creep and fatigue properties of Alloy 800H
- Report on the influence of grain size on creep and fatigue properties of Alloy 800H with emphasis on ASTM 5.

#### C1.2.6.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with C1.2.6 is small but includes the possibility that either thin sections or small grain size could result in creep or fatigue properties inconsistent with the use of Alloy 800H in the IHX B compact heat exchanger.

### C1.2.7 Corrosion Allowances for Alloy 800H (WEC-TS-IHXB-007)

#### C1.2.7.1 Objectives

The major objective of this activity is to ensure that exposure of Alloy 800H at high temperatures (up to ~760°C) for up to 60 years in NGNP He does not compromise the structural integrity of the material cross-section by oxide scale formation, internal oxidation, or other phenomena from either the primary or secondary side of the HTS. This Test Specification responds to DDN HTS-01-29.

#### C1.2.7.2 Test Conditions

*C1.2.7.2.1 Test Configuration/Set-Up*

Determination of corrosion allowances for Alloy 800H will require the following.

- Facility for exposure in He (600°C to 850°C) / 9MPa with low levels of CO, $CO_2$, $H_2$, $H_2O$, and $CH_4$ for up to 10,000 hours

- Provisions for introduction, control, and measurement of impurity levels
- Metallographic and SEM equipment for determination of thickness of oxides and depths of internal oxidation, alloy element depletion, and carburization/decarburization

*C1.2.7.2.2 Test Duration*

Conduct of this work will require 36 months.

*C1.2.7.2.3 Proposed Test Location*

This work can most effectively be done by ASME members from industry, with supporting data from the test labs. Refer to Section 17 of the document.

### C1.2.7.3 Measured Parameters

Parameters to be measured and data taken include:

- Impurity levels in primary side NGNP He as a function of time at all exposure temperatures
- Impurity levels in secondary side NGNP He as a function of time at all exposure temperatures
- Oxide scale thickness and composition
- Depth of internal oxidation
- Depth of depletion of alloy elements, primarily Cr
- Depth affected by carburization or decarburization.

### C1.2.7.4 Data Requirements

All data shall be acquired using best practice techniques and QA.

### C1.2.7.5 Test Evaluation Criteria

The corrosion allowances determined for Alloy 800H must not be of such magnitude that they degrade the structural integrity of the thin material sections (including welds, brazes, and diffusion bonds) required for the IHX B compact heat exchanger.

### C1.2.7.6 Test Deliverables

The following will be provided to meet the objectives of this Test Specification.

- Reports providing details of all exposures in impure primary and secondary side NGNP He

- Oxide scale thickness as a function of time, temperature, and He chemistry
- Depth of internal oxidation as a function of time, temperature, and He chemistry
- Depth of alloy element depletion as a function of time, temperature, and He chemistry
- Depth of carburized or decarburized zone as a function of time, temperature, and He chemistry
- Analysis of all data above for prediction of corrosion allowances for Alloy 800H and Alloy 800H joints for all temperatures and times of interest.

#### C1.2.7.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. The risk associated with C1.2.7 is that the measured corrosion allowances may preclude the operation of IHX B for full life (~60 years) at full temperature (~760°C).

### C1.2.8 Thermal/Fluid Modeling Methods for IHX B (WEC-TS-IHXB-008)

#### C1.2.8.1 Objectives

The work to be conducted under this Test Specification is development of thermal structural models to provide a predictive basis for operation and performance characteristics of compact heat exchanger IHX B. This is required for both quasi-steady state and transient analyses. This Test Specification responds to DDN HTS-01-13.

#### C1.2.8.2 Test Conditions

*C1.2.8.2.1 Test Configuration/Set-Up*

None currently identified but the models will likely be applied to the results obtained under DDN HTS-01-17. Relative to the latter, see Technology Maturation Plans for TRL 5 to TRL 7 and TRL 7 to TRL 8.

*C1.2.8.2.2 Test Duration*

Development of the thermal/fluid models would occur over a 36-month period.

*C1.2.8.2.3 Proposed Test Location*

The supplier / design authority may be best suited to perform the modeling work. Refer to Section 17 of the document.

#### C1.2.8.3 Measured Parameters

The models to be developed will incorporate and combine the mechanical and thermal/physical property database for Alloy 800H with finite element analysis (FEA) techniques and known relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

#### C1.2.8.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

#### C1.2.8.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing described in DDN HTS-01-17.

#### C1.2.8.6 Test Deliverables

The test deliverable is a model for predicting operation and performance characteristics of compact heat exchanger IHX B relevant to thermal, structural and lifting analyses.

#### C1.2.8.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. There are no risks associated with C1.2.8.

### C1.2.9 Methods for Stress/Strain Modeling of IHX B (WEC-TS-IHXB-009)

#### C1.2.9.1 Objectives

The objective of this work is to develop structural modeling methods to provide a basis for prediction of stresses and strains under thermo-mechanical, mechanical and hydro-mechanical loading of compact heat exchanger IHX B. This Test Specification responds to DDN HTS-01-14.

### C1.2.9.2 Test Conditions

*C1.2.9.2.1 Test Configuration/Set-Up*

None currently identified but the models will likely be applied to the results obtained under DDN HTS-01-17. Relative to the latter, see Technology Maturation Plans for TRL 5 to TRL 7 and TRL 7 to TRL 8.

*C1.2.9.2.2 Test Duration*

Development of the stress/strain models would occur over a 36-month period

*C1.2.9.2.3 Proposed Test Location*

The supplier / design authority might be best suited for this task. Refer to Section 17 of the document.

### C1.2.9.3 Measured Parameters

The models to be developed will incorporate and combine the mechanical property database for Alloy 800H with finite element analysis (FEA) techniques and known relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

### C1.2.9.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

### C1.2.9.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing described in DDN HTS-01-17. They will also form a part of an ASME design code (see DDN HTS-01-19 for TRL 5 to TRL 7).

### C1.2.9.6 Test Deliverables

The test deliverable is a model for predicting operation and performance characteristics and to form a design basis for compact heat exchanger IHX B.

#### C1.2.9.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. There is no risk associated with C1.2.9.

## C1.2.10 Criteria for Structural Integrity of IHX B (WEC-TS-IHXB-010)

### C1.2.10.1 Objectives

The objective of this Test Specification is to establish criteria for the structural integrity of compact heat exchangers operating at high temperature. This includes criteria for stresses and strains as well as development of safety factors needed in ASME Code development. These criteria will help to establish acceptable operational boundaries for compact heat exchangers. This Test Specification responds to DDN HTS-01-15.

### C1.2.10.2 Test Conditions

#### *C1.2.10.2.1 Test Configuration/Set-Up*

None currently identified.

#### *C1.2.10.2.2 Test Duration*

Establishment of structural integrity criteria will occur over a 36-month period.

#### *C1.2.10.2.3 Proposed Test Location*

The supplier / design authority might be best suited for this task.

### C1.2.10.3 Measured Parameters

Criteria for structural integrity will be developed from a review of appropriate ASME Code documentation, discussions with ASME Code personnel, and interactions during the development of stress/strain models (see activities associated with DDN HTS-01-14).

### C1.2.10.4 Data Requirements

Structural integrity criteria development activities will employ best standard practice and QA requirements.

### C1.2.10.5 Test Evaluation Criteria

The usefulness and predictive capability of the structural integrity models developed will be assessed based on its application to testing described in DDN HTS-01-17. They will also form a part of an ASME design code (see DDN HTS-01-19 for TRL 5 to TRL 7).

### C1.2.10.6 Test Deliverables

Deliverables are as follows.

- Criteria for acceptable stresses and strains
- Safety factors for application to an ASME design code.

### C1.2.10.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. There is no risk associated with C1.2.10.

## C1.2.11 Performance Modeling Methods for IHX B (WEC-TS-IHXB-011)

### C1.2.11.1 Objectives

The objective of the work prescribed in this Test Specification is to provide performance-modeling methods to adequately evaluate the results of performance testing of compact heat exchangers and to assist in the development of an ASME Code Case for design of compact heat exchangers. This Test Specification responds to DDN HTS-01-16.

### C1.2.11.2 Test Conditions

#### *C1.2.11.2.1 Test Configuration/Set-Up*

None, but the performance models will be applied to the results obtained under DDN HTS-01-17 (see Technology Maturation Plans for TRL 4 to TRL 5, TRL 5 to TRL 7 and TRL 7 to TRL 8).

#### *C1.2.11.2.2 Test Duration*

Establishment of structural integrity criteria will occur over a 48-month period.

*C1.2.11.2.3 Proposed Test Location*

The supplier / design authority might be best suited for this task. Refer to Section 17 of the document.

### C1.2.11.3 Measured Parameters

The performance models to be developed will incorporate all parameters necessary to predict the thermal and structural behavior of compact heat exchangers.

### C1.2.11.4 Data Requirements

Model development activities will follow best standard practice and QA requirements.

### C1.2.11.5 Test Evaluation Criteria

The usefulness and predictive capability of the models developed will be assessed based on its application to testing associated with DDN HTS-01-17 (see Technology Maturation Plans for TRL 4 to TRL 5, TRL 5 to TRL 7 and TRL 7 to TRL 8).

### C1.2.11.6 Test Deliverables

The deliverable for this Test Specification is a model to assess the thermal and structural performance of the compact heat exchanger modules to be tested in association with DDN HTS-01-17

### C1.2.11.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for IHX B from TRL 3 to TRL 4 is addressed in Sections C1.1.3 and C1.1.4. There is no risk associated with C1.2.11.

# C2 TECHNOLOGY MATURATION PLAN FOR IHX B - TRL 4 TO TRL 5

## C2.1 Technology Maturation Plan Summary

### C2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the metallic IHX B from a TRL level of 4 to a TRL level of 5. The maturation task required to achieve this goal involve the testing of the compact heat exchanger unit cell. (It is assumed that a compact heat exchanger vendor will provide the compact heat exchanger unit cell.) A Test Specification is provided to cover the maturation task. This is given in Section C2.2.

### C2.1.2 Scope

The maturation task necessary to advance the maturity of the technology of IHX B from TRL 4 to TRL 5 is as shown below.

- Specification 1: Testing of unit cell compact heat exchanger

The task above will be described fully in a Test Specification in the following section.

### C2.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY 2014 through FY 2016.

### C2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

# C2.2Test Specifications

## C2.2.1 Specification of testing of unit cell of compact heat exchanger (WEC-TS-IHXB-012)

### C2.2.1.1 Objectives

The objective of testing the compact heat exchanger unit cell is:

- To determine the joint integrity of the compact heat exchanger unit cell joints under tensile load at a typical pressure environment and elevated temperatures.

### C2.2.1.2 Test Conditions

*C2.2.1.2.1 Component Requirements*

Component requirements include the following:

- Size limitation: dependant on testing environment (e.g. furnace)
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Environment – Helium with controlled impurity levels

*C2.2.1.2.2 2Interfacing Requirements*

n/a

*C2.2.1.2.3 Test Requirements*

Test requirements for the compact heat exchanger unit cell tests (not integrated) are as follows:

- Test environment which compact heat exchanger unit cell will be subjected to before post test evaluation:
  - Temperature = 760°C
  - Pressure = 9MPa
  - Cyclic loading (magnitude and cycles TBD)

- Proposed setup and relevant parameters (see following page):

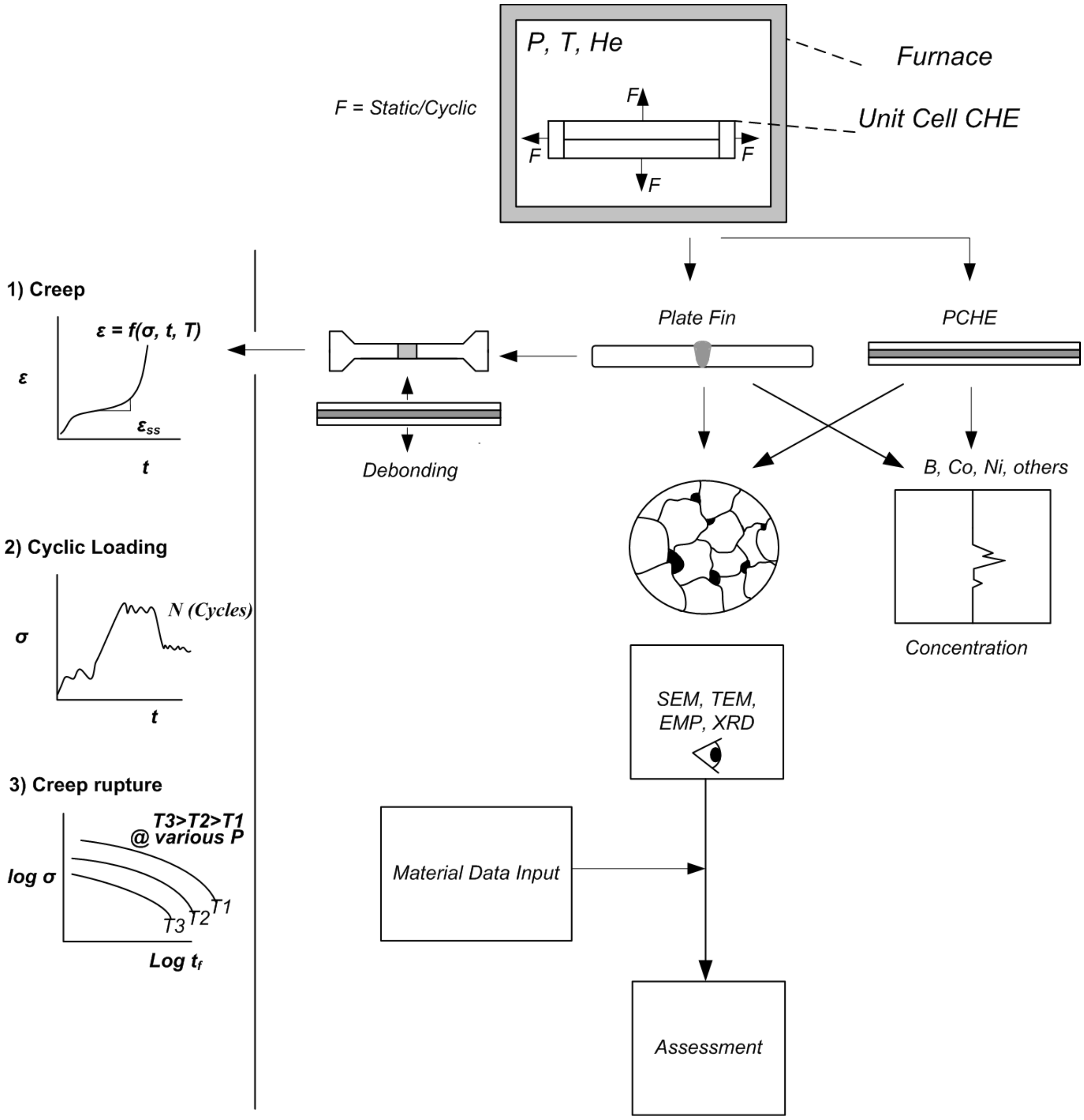


**Figure C-1: Proposed Setup and Relevant Parameters in Testing the Unit Cell**

*C2.2.1.2.4Test Duration*

The duration of this activity will be a minimum of **24** months.

*C2.2.1.2.5Facility Requirements*

1. Furnace suitable for test requirements
2. Facilities required for metallographic analysis of material and joints after testing

*C2.2.1.2.6Proposed Test Location*

Manufacturers of metallic unit cells would most appropriately evaluate the joint integrities of the as manufactured unit cells. Refer to Section 17 of the document.

### C2.2.1.3 Measured Parameters

The following parameters will be measured:

- Temperature
- Pressure
- Post-test joint integrity inferred from SEM, microscopic/metallographic evaluations and tests
  - Creep and creep rupture data.

### C2.2.1.4 Data Requirements

It is assumed that a vendor of metallic heat exchangers will produce the compact heat exchanger unit cell. The fabricated unit cell will require the following before progressing with testing:

- Materials certificates
- Weld certificates
- Inspection certificates
- All other quality assurance documents (bonding procedures, etc)

All new data shall be acquired using recognized techniques, codes, standards, and QA

### C2.2.1.5 Test Evaluation Criteria

Satisfactory structural integrity of the compact heat exchanger unit cell joints as evidenced by post-testing examinations relating to metallographic procedures and tests.

### C2.2.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section C2.2.1.3
- Documentation containing performance verification criteria and test results relating to the joint integrities of the CHE unit cell as observed through microscopic/metallographic evaluations and tests

#### C2.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX B from TRL 4 to TRL 5 is addressed in Sections C2.1.3 and C2.1.4.

The risk associated with Test Specification C2.2.1 involves the non-satisfactory condition/integrity of the CHE unit cell joint, and may consequently require a reevaluation of the unit cell design (or certain aspects thereof).

# C3 TECHNOLOGY MATURATION PLAN FOR IHX B - TRL 5 TO TRL 6

## C3.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C3.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for IHX B from a TRL level of 5 to a TRL level of 6. The maturation tasks required to achieve this goal involve the testing of the integrated compact heat exchanger module (~1.2MW) in the CTF (It is assumed that the compact heat exchanger module will be provided by a compact heat exchanger vendor) and the establishment of a Section III ASME Code case fully qualifying compact heat exchanger designs for service in the NGNP. Test Specifications are provided to cover these maturation tasks (given in Section C3.2).

### C3.1.2 Scope

The maturation tasks necessary to advance the maturity of the technology of IHX B from TRL 5 to TRL 6 are as shown below.

- Specification 1: Testing of integrated compact heat exchanger module (~1.2MW)
- Specification 2: Establishing ASME Section III design code for compact heat exchanger designs

The tasks above will be described in the test specifications provided hereafter.

### C3.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan will be accomplished during the period FY 2017 through FY 2019.

### C3.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C3.2Test Specifications

## C3.3

### C3.3.1 Specification of testing of compact heat exchanger module (~1.2MW) (WEC-TS-IHXB-013)

#### C3.3.1.1 Objectives

The objectives of testing the compact heat exchanger module (~1.2MW) are:

- To demonstrate the operating effectiveness of the compact heat exchanger module
- To demonstrate the fatigue life of the integrated compact heat exchanger module in terms of *thermal fatigue, joint integrity* and *corrosion & high temperature oxidation.*

#### C3.3.1.2 Test Conditions

*C3.3.1.2.1 Compact Heat Exchanger Module (subsystem and system) Requirements*

Subsystem and system requirements include the following:

- Size limitation: TBD
- Certain interface design requirements and specifications (see interfacing requirements)
- Heat transfer fluid – Helium with controlled impurities
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Mass flow threshold – see test requirements
- Pressure drop threshold – see test requirements

*C3.3.1.2.2 Interfacing Requirements*

- TBD by Technology Development Loop and Subsystem Configuration / Design

- Certain interface design requirements and specifications:
    - Appropriate surface finish of interfacing components
    - Gasket materials applicable
    - Flange torque values where applicable

*C3.3.1.2.3 Measurement Requirements*

- Measurement of strains
- Measurement of internal and external pressures
- Measurement of temperature
- Measurement of mass flow
- Measurement of fluid composition
- Measurement of leak rates from CHE module

*C3.3.1.2.4 Test Requirements*

Test requirements for the compact heat exchanger module tests (integrated) are as follows:

1. Test compact heat exchanger module operating effectiveness and behavior in typical steady state pressure, temperature and temperature/pressure drop environment (Helium)
    i. Temperature = 760°C
    ii. Pressure = 9MPa
    iii. Temperature Δ = 473°C
    iv. Pressure Δ = tbd
    v. Mass flow = tbd
    vi. He environment with varied composition

2. Test compact heat exchanger module behavior in typical pressure transient environment:
    i. Expose module to a high frequency, normal operating pressure transient, present with a startup / shutdown sequence
        1. Pressurizing transient (ambient to 9MPa in certain time frame)
        2. De-pressurizing transient (9MPa to ambient in certain time frame)
    ii. Number of cycles and temperature level TBD

3. Test compact heat exchanger module behavior in typical temperature transient environment:
    i. Expose module to a high frequency, normal operating temperature transient (ambient to 760°C), present with a startup / shutdown sequence
        1. Heat up transition
        2. Cool down transition
    ii. Number of cycles and pressure level TBD

4. Test compact heat exchanger module behavior at varying process parameters:
   i. Temperature = 760°C
   ii. Pressure = 9MPa primary (secondary TBD)
   iii. Pressure Δ = TBD (Primary to Secondary and Inlet to Outlet)
   iv. Mass flow = TBD

   Proposed setup and parameters (see following page):

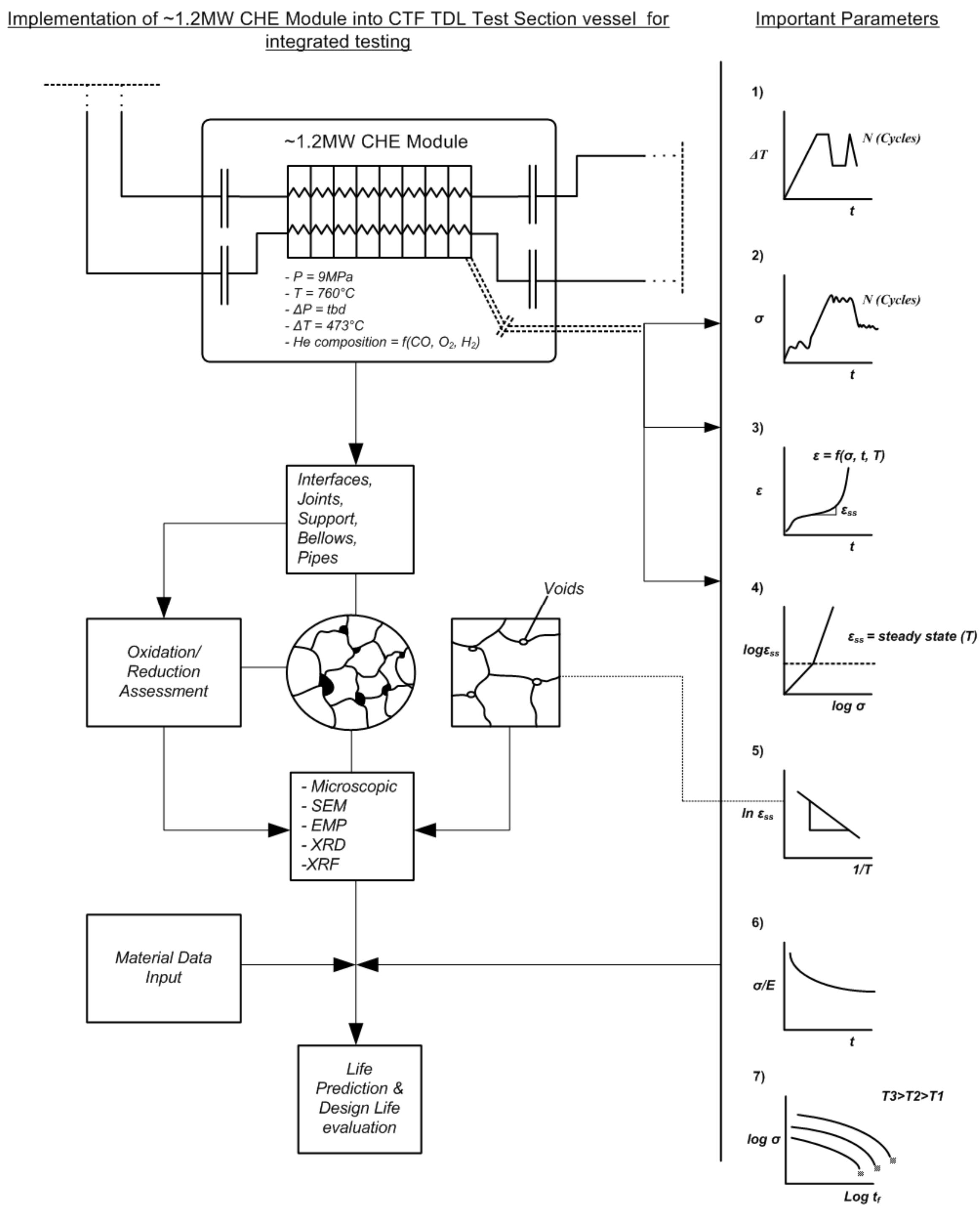


**Figure C-2: Proposed Setup and Durability Parameters in Testing the CHE Module**

*C3.3.1.2.5 Tests Duration*

The duration of this activity will be a minimum of **24** months.

*C3.3.1.2.6 Facility Requirements*

The following facilities will be required:

1. TDL facilities 1-3 (TBD)
2. Gas analyzing facilities
3. Facilities required for metallographic analysis of material and joints after testing

*C3.3.1.2.7 Proposed Test Location*

Proposed tests will take place at the CTF or in a representative environment. This work can most effectively be done by ASME members of industry. Refer to Section 17 of the document.

### C3.3.1.3 Measured Parameters

The following parameters will be measured:

- Temperatures
- Pressures
- Measurement of magnitude and number of temperature gradients and temperature gradient cycles respectively up to thermal fatigue failure
- Fluid composition
- Leak rates at varying process conditions
- Operating effectiveness of compact heat exchanger module
- Corrosion of module materials and joints over a predetermined time
- Oxidation of module materials and joints over a predetermined time
- Thermal fatigue observations through SEM, TEM and other analyses techniques, inclusive of Element Distribution Maps of selected joint samples
- Joint integrity(ies) – Tensile tests, SEM, microscopic/metallographic evaluations and testing of joint sections.

### C3.3.1.4 Data Requirements

It is assumed that a vendor of metallic heat exchangers will produce the compact heat exchanger module. The fabricated module of the compact heat exchanger will require the following before progressing with testing:

- Materials certificates
- Weld certificates
- Inspection certificates
- All other quality assurance documents (bonding procedures, etc)

All new data shall be acquired using recognized techniques, codes, standards, and QA

### C3.3.1.5 Test Evaluation Criteria

- Satisfactory number of transient cycles up to thermal fatigue of the module material/joints
- Satisfactory structural integrity of the whole compact heat exchanger module assembly (system) as evidenced by
  - metallographic procedures and tests
  - analyses inclusive of remaining life assessments (if applicable)
  - comparison of data with assessment models, FEM's or other calculations
- An acceptable level of deformation of the compact heat exchanger module (subsystem) as evidenced by strain measurement measures
- The corrosion must not be of such magnitude as to degrade the structural integrity of the module material sections and joints.
- Limited oxidation formation thickness or no oxidation over a predetermined time
- An acceptable effectiveness of the compact heat exchanger module
- An acceptable rate of leakage of the compact heat exchanger module at varying process conditions.

### C3.3.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section C3.2.1.3
- Documentation containing performance verification criteria and test results verified against stress/strain models of the compact heat exchanger module and material properties.

### C3.3.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of IHX B from TRL 5 to TRL 6 is addressed in Sections C3.1.3 and C3.1.4.

Depending on the failure modes of the compact heat exchanger module, the design of relevant interfaces of the compact heat exchanger module will have to be re-evaluated.

## C3.3.2 ASME Section III Code Case for Compact Heat Exchanger Designs (WEC-TS-IHXB-014)

### C3.3.2.1 Objectives

This Test Specification has the overall objective of developing and establishing a Section III ASME Code Case for compact heat exchanger designs. It will involve the drafting of the code case, interactions with ASME during the approval process, and provision of any additional specific data/information requested by the ASME. This Test Specification responds to DDN HTS-01-19.

### C3.3.2.2 Test Conditions

*C3.3.2.2.1 Test Configuration/Set-up*

No test equipment or facility is needed.

*C3.3.2.2.2 Test Duration*

The duration of this activity will be a minimum of 48 months.

*C3.3.2.2.3 Proposed Test Location*

The supplier / design authority might be best suited for this task. Refer to Section 17 of the document.

### C3.3.2.3 Measured Parameters

N/A

### C3.3.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

### C3.3.2.5 Test Evaluation Criteria

N/A.

#### C3.3.2.6 Test Deliverables

The test deliverable is a Section III ASME Code case fully qualifying metallic compact heat exchanger designs for service in the NGNP IHX up to 760°C.

#### C3.3.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing metallic materials technology for IHX B from TRL 5 to TRL 6 is addressed in Sections C3.1.3 and C3.1.4.

The risk associated with Test Specification C3.2.2 entails the failure to establish an ASME Code Case for compact heat exchanger designs.

# C4 TECHNOLOGY MATURATION PLAN FOR IHX B – TRL 6 TO TRL 7

## C4.1TECHNOLOGY MATURATION PLAN SUMMARY

### C4.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for IHX B from a TRL level of 6 to a TRL level of 7. The maturation tasks required to achieve this goal involve the testing of models to determine shell-side flow distribution and bypass leakage and the heat transfer testing of multi-modules (e.g., 3 x ~1.2MW). Test Specifications are provided to cover the maturation tasks (given in section C4.2).

### C4.1.2 Scope

The maturation tasks necessary to advance the maturity of the technology of IHX B from TRL 6 to TRL 7 are as shown below.

- Specification 1: Shell-side flow distribution and bypass leakage tests.
- Specification 2: Multi-module heat transfer tests.

These tasks will be described in D5.2.

### C4.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2018 through FY 2020.

### C4.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C4.2Test Specifications

### C4.2.1 Shell-side Flow Distribution and Bypass Leakage Testing (WEC-TS-IHXB-015)

#### C4.2.1.1 Objectives

The objectives of testing are to

- Confirm shell-side flow distribution modeling
- Confirm that shell-side bypass leakage is acceptable
- Confirm shell-side pressure losses.

There is also the potential to use this test to characterize dust transport/dropout as a function of particulate size.

#### C4.2.1.2 Test Conditions

This likely would be an ambient temperature test with air as the working fluid. The test article would model inlet and outlet regions of the heat exchanger, features that promote good distribution to the core modules on the shell-side, and features that minimize bypass leakage. Details of the testing will be finalized at later stage.

### C4.2.2 Multi-module Heat Transfer Testing (WEC-TS-IHXB-016)

#### C4.2.2.1 Objectives

The objectives of this testing are to

- Investigate module-to-module interactions on both the tube- and shell-sides of the heat exchanger
- Confirm bypass leakage and effects.

#### C4.2.2.2 Test Conditions

The multi-module test would be a heated test in the CTF with 3 or more core modules (~4MWt would be required for 3 modules) representing a segment of the IHX. Details of the testing will be finalized at later stage.

# C5 TECHNOLOGY MATURATION PLAN FOR IHX B (METALLIC) - TRL 7 TO TRL 8

## C5.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C5.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for IHX B from a TRL level of 7 to a TRL level of 8. The maturation task required to achieve this goal involve the testing of the full-scale compact heat exchanger. (It is assumed that a compact heat exchanger vendor will provide the full-scale compact heat exchanger and/or assembled by vendor staff on the NGNP site). The scope of this test on the full scale compact heat exchanger will vary slightly from the scope of test noted to progress from TRL 5 to TRL 6 a TRL 6 to TRL 7. A Test Specification is provided to cover the maturation task (given in section C5.2).

### C5.1.2 Scope

The maturation task necessary to advance the maturity of the technology of IHX B from TRL 7 to TRL 8 is as shown below.

- Specification 1: Testing of full scale compact heat exchanger in the NGNP

This task will be described in the following test specification.

### C5.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2020 through FY 2022.

### C5.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C5.2Test Specifications

### C5.2.1 Specification of testing of a full scale compact heat exchanger (WEC-TS-IHXB-017)

#### C5.2.1.1 Objectives

The objectives of testing the full-scale compact heat exchanger are:

- To determine the leak rate of the compact heat exchanger (system) at various typical process parameters
- To determine the operating effectiveness of the full-scale compact heat exchanger at various typical process parameters

IHX B will be fully tested and commissioned in the NGNP. Details of the testing and commissioning will be finalized at later stage.

NGNP-CTF MTECH-TDRM-006 November 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 6 – HTS Piping

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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| | |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| | |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |

| | |
|---|---|
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

The HTS involves pipes of varying temperature capabilities in both the PHTS and SHTS. High-temperature piping is utilized within the PHTS to direct He flow from the reactor to IHX A and from IHX A to IHX B. Lower temperature portions of the PHTS piping circuit transport the He flow from the exit of IHX B to the circulator and thereon from the circulator to the reactor. High-temperature piping is utilized within the SHTS to direct He flow from the high-temperature exit of IHX A to the mixing chamber and the PCHX and from the mixing chamber to the SG. Also, high-temperature portions of the SHTS piping circuit transport the He from IHX B to IHX A and from the PCHX to the mixing chamber. Low-temperature sections of the SHTS piping direct He from the SG to the circulator and from the circulator to IHX B. Very preliminary design selections for the various piping sections were made on the basis of pre-conceptual design studies (these selections remain to be revisited during conceptual design):

- The high-temperature portion of the PHTS piping is to combine both active cooling and insulation.
- The low-temperature section of the PHTS piping and all SHTS piping is to be passively cooled (insulation only).

An evaluation of the status of technology for the HTS piping was made and resulted in the determination of a level of TRL 4. The underlying bases for this selection are described in the TRL rating sheet (refer to Appendix A).

The TDRM provided for HTS piping summarizes TRL status and maturations tasks necessary to increase the maturity of HTS piping technology to a level of TRL 8. These tasks include five separate Trade Studies aimed at providing the basis for design selections for each of the PHTS and SHTS piping sections. Additional maturation tasks address the effects of He environment and possible rapid depressurization transients on the integrity and thermal conductivity of insulation materials. Finally, there are tasks to quantify environmental and operational effects on prototypic piping section performance. It is noted that the technology roadmap and maturation plans will need to be adjusted as new/different DDNs evolve as part of the conceptual and detail designs.

# 6 HTS PIPING

## 6.1 Description, Functions, and Operating Requirements

The HTS involves pipes of varying temperature capabilities in both the PHTS and SHTS. High-temperature piping and insulation are utilized within the PHTS to direct He flow from the reactor to IHX A and from IHX A to IHX B. Lower temperature portions of the PHTS piping circuit transport the He flow from the exit of IHX B to the circulator and further from the circulator to the reactor.

High-temperature piping and insulation are utilized within the SHTS to direct He flow from the high-temperature exit of IHX A to the mixing chamber and the PCHX and from the mixing chamber to the SG. Medium-temperature portions of the SHTS piping circuit transport the He from IHX B to IHX A and from the PCHX to the mixing chamber. Low-temperature sections of the SHTS piping direct He from the SG to the circulator and from the circulator to IHX B.

The nominal temperatures in each of the HTS piping sections are shown in Table 6-1 (see also Figure 6.1). The outer He pressure boundary (HPB) of the PHTS piping will be designed to meet ASME Section III Class 1 requirements; the SHTS HPB piping will be designed to meet either ASME Section III Class 2 or 3 requirements or ASME VIII (preferred).

**Table 6-1: Helium Temperatures in HTS Piping Sections**

| Piping Location | Temperature (°C) |
|---|---|
| **PHTS** | |
| RPV to IHX A | 950 |
| IHX A to IHX B | 760 |
| IHX B to Circulator | 337 |
| Circulator to RPV | 350 |
| **SHTS** | |
| IHX A to PCHX | 900 |
| IHX A to mixing chamber | 900 |
| Mixing chamber to SG | 840 |
| IHX B to IHX A | 700 |
| PCHX to mixing chamber | 659 |
| SG to circulator | 273 |
| Circulator to IHX B | 287 |

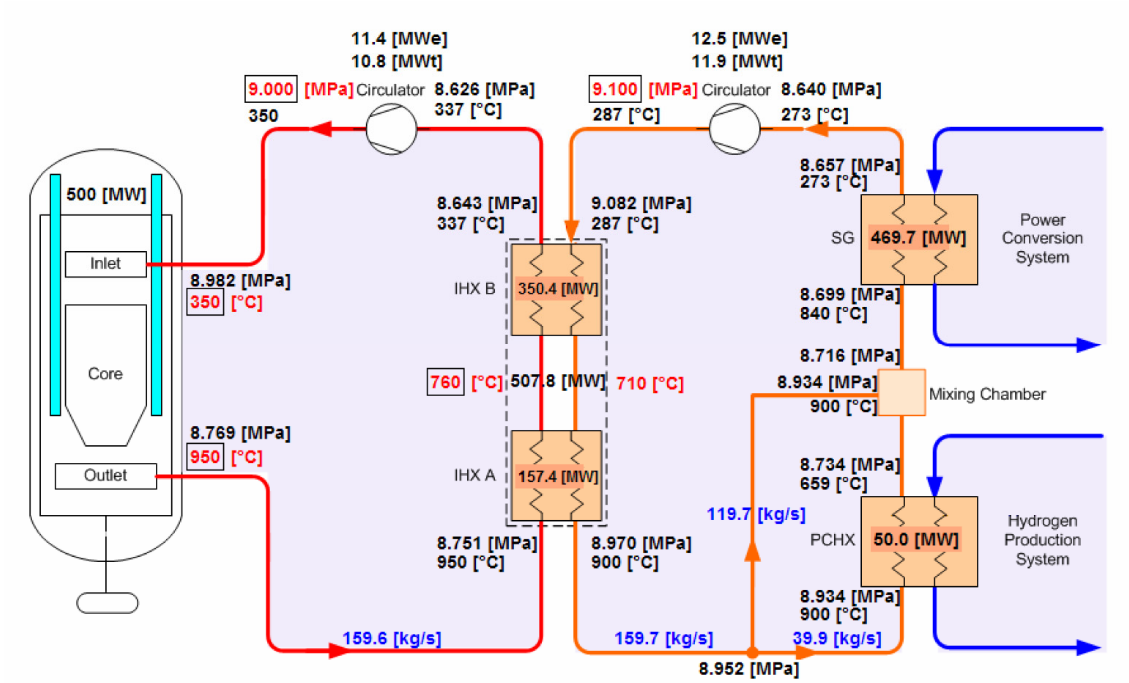


**Figure 6-1: Nominal Temperatures of HTS Piping (950℃)**

The primary functions and operating requirements of the HTS piping are to:

- In the PHTS, channel the He from the reactor to the IHX units and onward to the circulator and back to the reactor.
- In the SHTS, channel the He from the high-temperature exit of IHX A to the mixing chamber and the PCHX, from the PCHX to the mixing chamber, from the mixing chamber to the SG, and onward to the circulator and IHX B.
- Limit heat losses from the HTS to the remainder of the system in order to maintain the highest possible thermal efficiency. The goal here is to have the temperature of the external surface of the HTS piping (or its insulation if provided) at <100°C.
- Prevent high-temperature He from making direct contact with the HPB and limit the temperature of the HPB piping material to no greater than that approved under ASME Section III (or ASME VIII where applicable), less adequate margin. The most desirable option for a pressure boundary piping material is SA 533 steel. It is approved for continuous service only to 371°C but for short-term (1000 h) service to as high as 537°C under ASME Code Case N-499-2.
- Resist a primary system pressure of ~9 MPa.
- Operate without preventive maintenance for 60 years.

### 6.1.1 PHTS Piping

The basic design currently assumed (*NGNP PCDR Section 6, May 2007,* [6-1]) for the RPV to IHX A and IHX A to IHX B portions of the PHTS Piping is based on the DPP design

(*NGNP Metallic Component Schedule Risk and Cost Uncertainty Assessment Report,* [6-3]). Both the DPP and NGNP designs incorporate an internal hot gas duct (HGD) consisting of internal concentric ducts separated by layers of insulation (see Figure 6-2). Active cooling is provided in the outer annulus between the HGD and the HPB. The 1000 mm ID innermost duct (the HGD liner) for the NGNP design provides only for directing the He flow and, as with the DPP, is not pressure retaining. The liner and insulation package is surrounded by an inner pressure-retaining pipe and this package is surrounded by a larger pipe that is part of the primary system HPB. The annulus between the HPB and the HGD is cooled by a flow of 350°C He bypassed from the PHTS circulator exit.

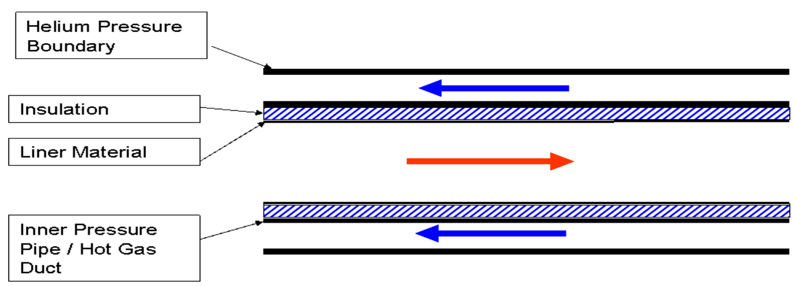


**Figure 6-2: Example of Active Cooling Configuration**

However, there are two significant differences between conditions applicable to the DPP versus the NGNP and both of these are temperature related. First, the temperature of the He from the DPP reactor is 50°C lower than that from the NGNP (900°C versus 950°C). Second, the coolant gas available for supply to the piping annulus in the DPP case is at nominally 110°C from the high-pressure compressor (HPC); for the NGNP the annulus is cooled by 350°C He bypassed from the circulator. Both of these points challenge the piping design.

Materials selected for the DPP design include SB 409 Alloy 800H for the liner and SA 335 Grade P1 for the concentric metal pipes. Because the reactor exit He temperature is higher for the NGNP, it is likely desirable to substitute a material of higher temperature capability for the liner. Such higher temperature capability materials would include metallic materials (Hastelloy X, Alloy 230, and Alloy 617) and composite materials (e.g., CFRC). The DPP is now also considering a Core Outlet Connection (COC) Transition (transition section between the core outlet plenum and the HGD) that has a combined liner of CFRC and Alloy 800H. The insulation material currently proposed for the DPP is fibrous $Al_20_3$; the insulation type for the NGNP has not yet been specified. The HPB and inner pressure pipe of the HGD for the NGNP designs are of SA 533B. These design options are shown in Figure 6-3 and Figure 6-4 for the various temperature sections in the PHTS piping.

As indicated earlier, goals for the NGNP piping between the reactor and IHX A and between IHX A and IHX B are to maintain the temperatures of the HPB pipes to below 371°C and to maintain the outer surface of the HPB pipes to <100°C. Similar considerations apply to the lower temperature PHTS piping downstream from IHX B, but the current design assumption (*NGNP PCDR Section 6, May 2007,* [6-1]) is that these sections would be of a passively cooled (insulated internally and perhaps externally) single pressure wall configuration. For normal operation, this appears to be a reasonable design solution. However, the insulation type and thickness necessary to accomplish these temperature goals has not been adequately addressed for transients where SHTS circulation might be lost.

Whether a passively cooled design can be developed and used for the high-temperature PHTS piping (at or greater than 760°C He has not been considered in detail at this point. Implementation of such a design would simplify manufacture and operation of the PHTS piping and be of lower cost. There are some early indications that, because of advancements in microporous insulation materials, a single wall design may be able to achieve the stated temperature goals while fitting within the size-envelope of the current concentric piping design. However, other tradeoff issues such as the influence of certain factors on reliability of the HPB remain to be assessed.

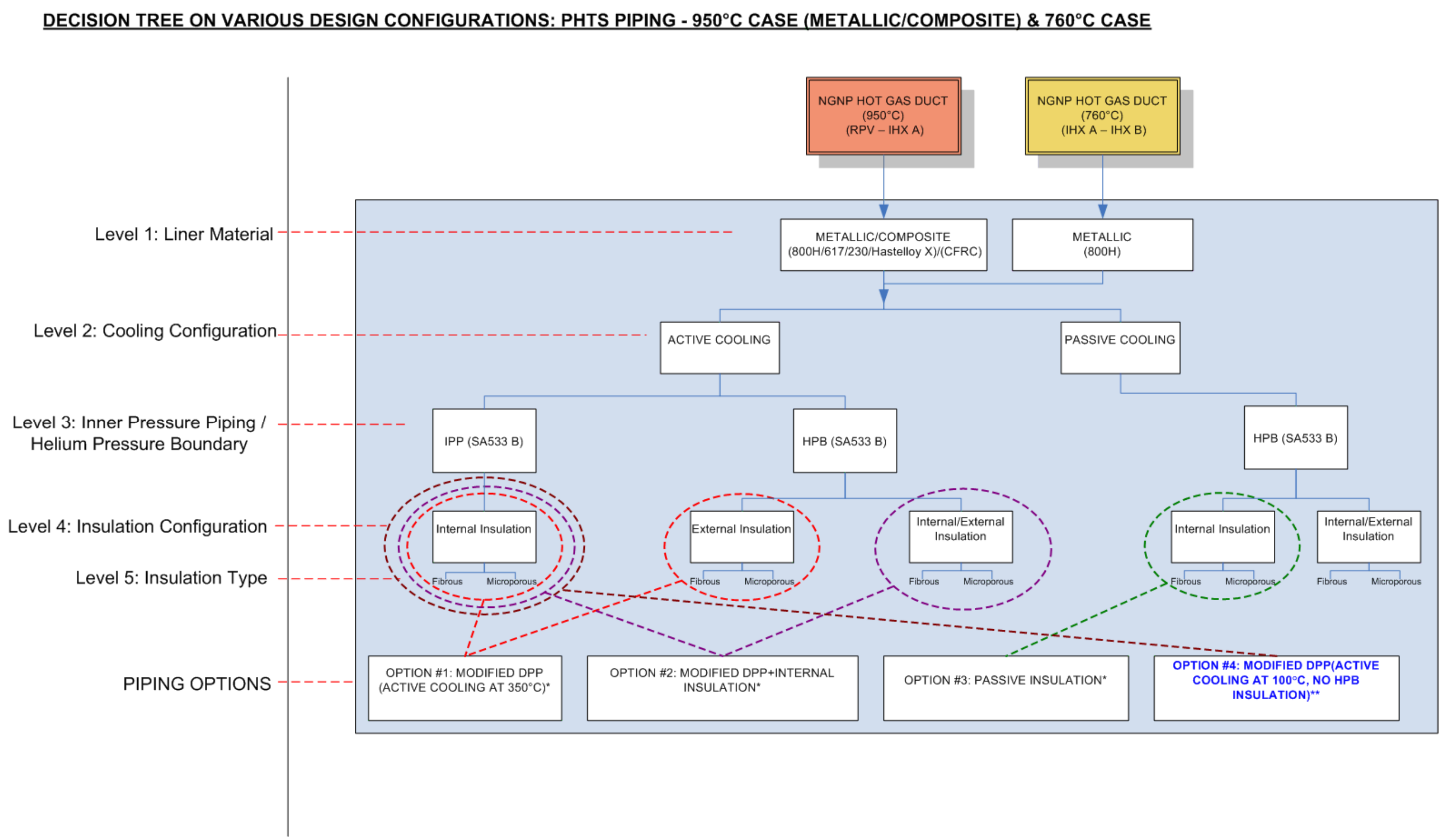


**Figure 6-3: Design Options for High Temperature PHTS Piping Sections (950°C and 760°C)**

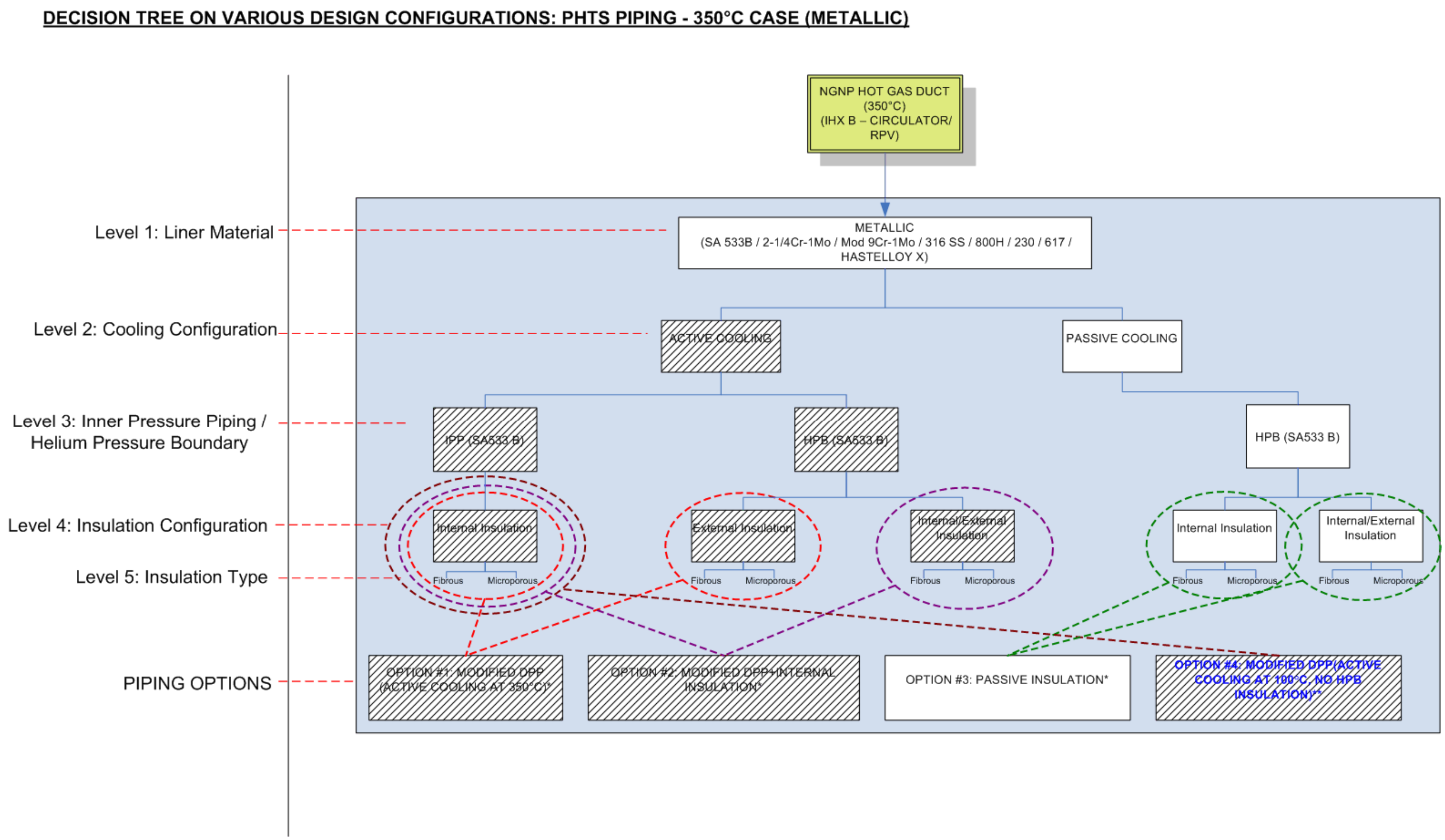


**Figure 6-4: Design Options for Low Temperature PHTS Piping Sections (350°C)**

### 6.1.2 SHTS Piping

According to *NGNP PCDR Section 6* [6-1], all sections of the SHTS piping are assumed to be of an insulated single-wall HPB (i.e., passively cooled) design (see Figure 6-5). Further, it is assumed that there are no feasible transients that can result in He temperatures higher than those seen during normal operations.

As with the PHTS piping described in Section 6.1.1, it is assumed that the internal diameter for gas flow for the high-temperature (840°C and 900°C) carrying sections of the SHTS piping is nominally 1000 mm and that the liner provides only for directing the He flow and is not pressure retaining. Also, the liner and the HPB pipes will have nominal thicknesses of 10 mm and 50 mm, respectively. The HPB pipe material is to be SA 533B steel; liner material choices include Alloy 800H, Hastelloy X, Alloy 230, and Alloy 617. Insulation will be required internally to the HPB pipe but insulation could, in addition, be used externally. As with the high-temperature PHTS piping described above, there is no existing proven design for a 900°C passively cooled SHTS pipe. (See Figure 6-6 for design options.)

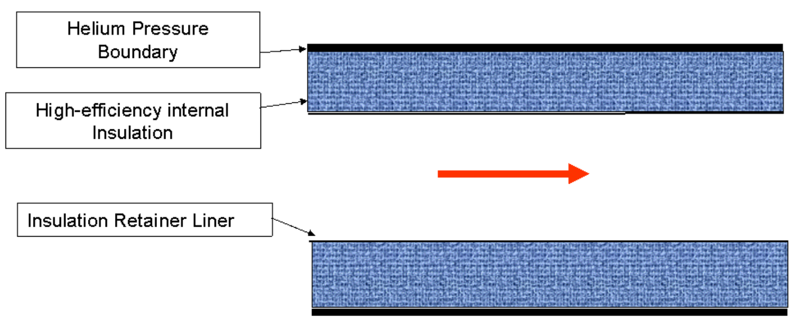


**Figure 6-5: Example of Passive Cooling Configuration**

The insulation requirements for the medium temperature (659°C and 700°C) carrying HPB sections of the PHTS piping will be quite similar to those for the high-temperature pipes described. However, the thicknesses of insulation required will obviously be less. Also, a less costly liner material (e.g., 316 SS or a Cr-Mo steel) of lower temperature capability will likely be appropriate. (See Figure 6-6 for design options.)

In the case of the low-temperature (<300°C) piping (see Figure 6-7), it may be possible to use a design with no internal insulation and no liner. All insulation would simply be applied externally to the HPB pipes.

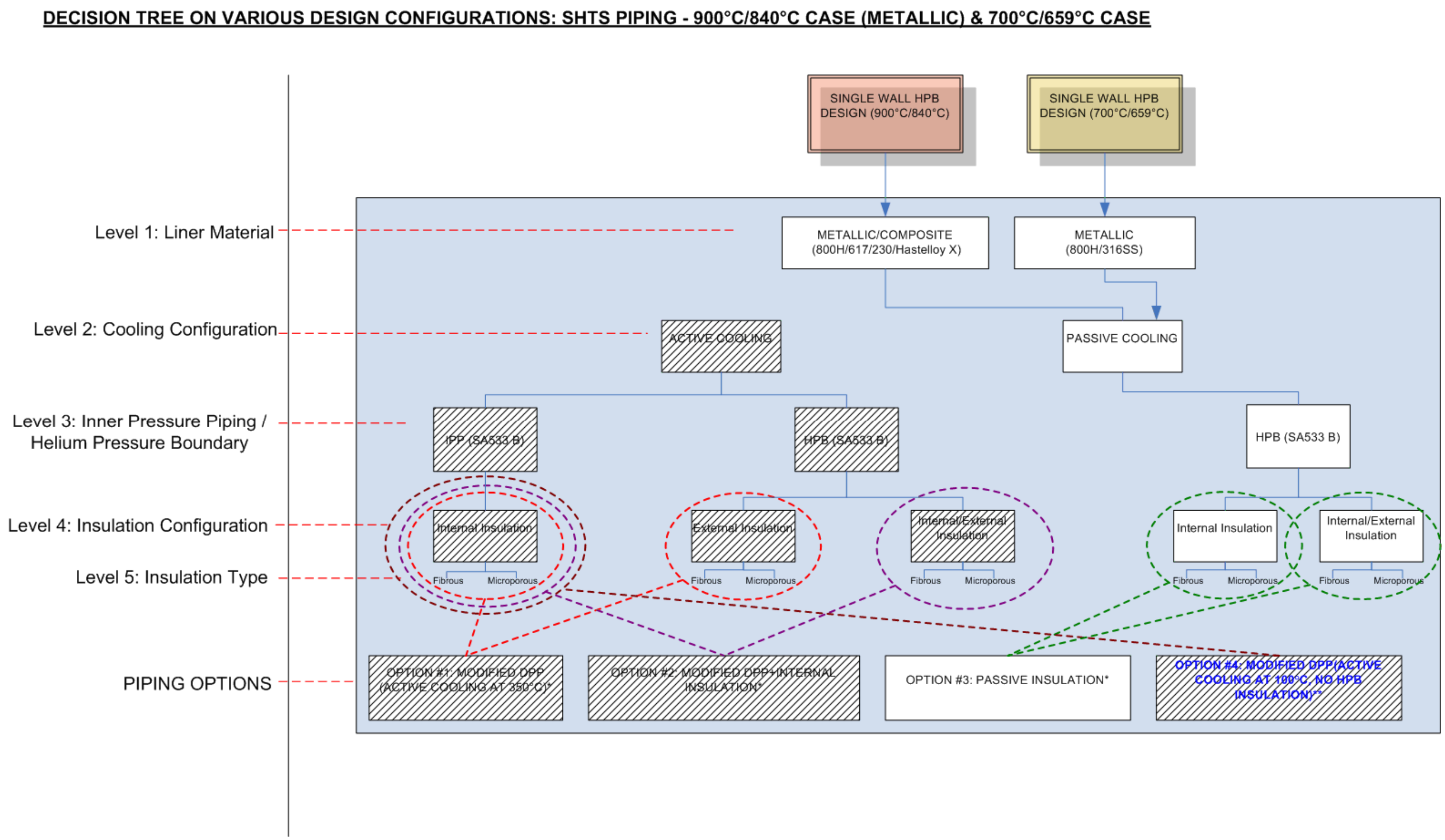


**Figure 6-6: Design Options for High Temperature SHTS Piping Sections (900°C /840°C and 700°C/659°C)**

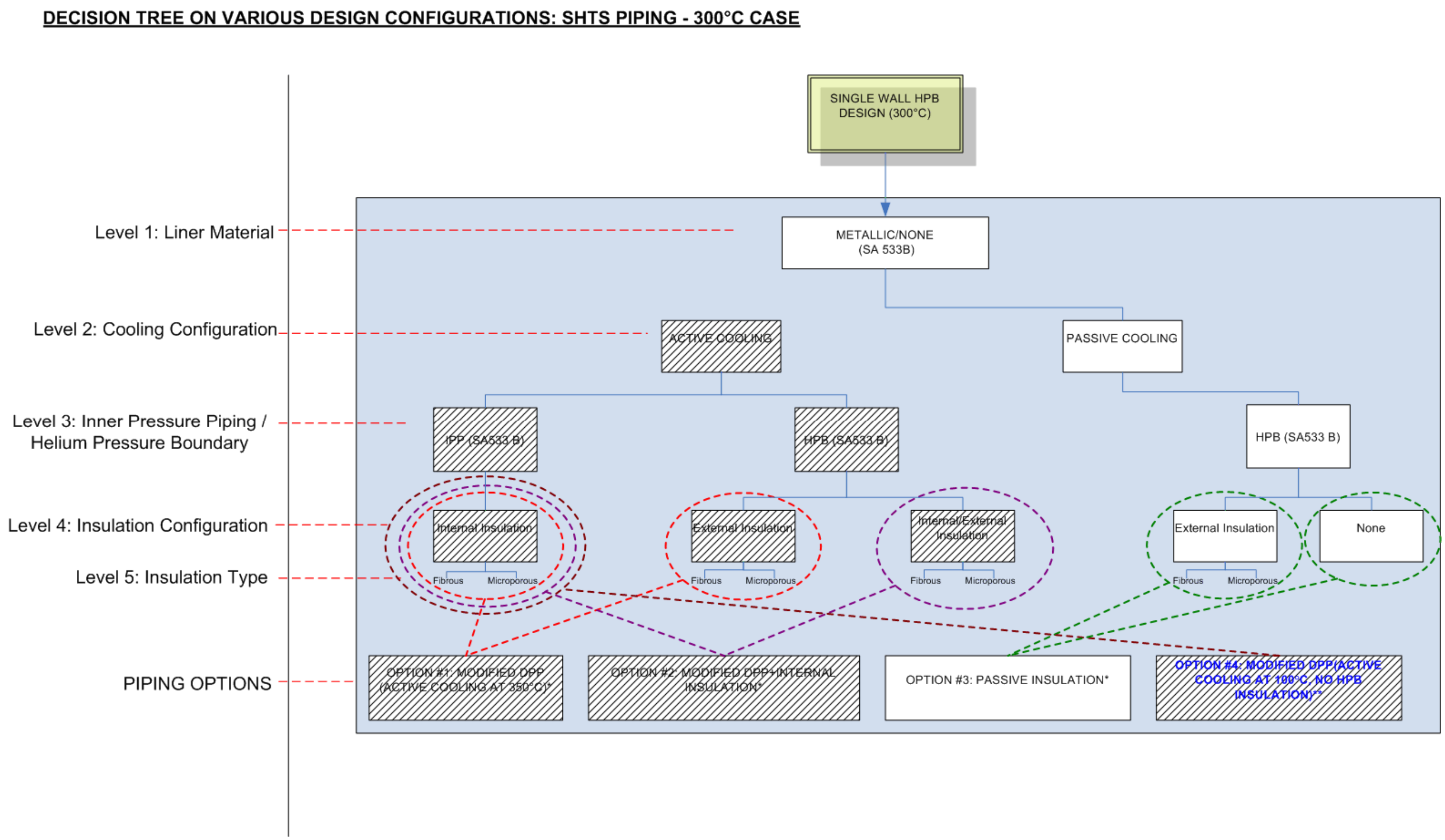


**Figure 6-7 – Design Options for Low Temperature SHTS Piping Sections (300°C)**

## 6.2 TRL Status

An evaluation of the status of technology for the high-temperature section HTS piping was made and resulted in the determination of a level of TRL 4. The underlying basis for this selection is described in the TRL rating sheet (refer to Appendix A).

## 6.3 Technology Development Road Map

### 6.3.1 Overview

The TDRM for HTS piping provides a listing of the Maturation Tasks that are necessary to advance the status of technology to succeedingly higher levels from a Validated TRL 4 to a Validated TRL 8. Selected designs for the HTS piping sections will be achieved through trade studies performed to advance technology to TRL 5.

The TDRM for the HTS piping is attached in Appendix B; Maturations Tasks are described in Section 6.4.

## 6.4 Technology Maturation Plan Summary

This section describes the maturation tasks needed to advance the technology of all portions of the HTS piping from a validated TRL 4 to a validated TRL 8. Technology progress from a level of TRL 4 to TRL 5 involves Trade Studies to evaluate cooling (active and passive), liner material, and insulation options for the high, medium and low temperature piping sections. Additionally, it is necessary to determine the effects of He infiltration (pure and impure) and moisture infiltration on the thermal conductivity of the insulation material selected for the piping options. Further, the results of the Trade Studies may provide insights that necessitate the development and conduct of additional maturation tasks.

Advancement of the technology for the HTS piping from TRL 5 to TRL 6 and from TRL 6 to TRL 7 will require performance and environmental testing of representative piping sections, including the response of insulation materials to sudden depressurization. Moving from TRL 7 to TRL 8 will require the testing of full sized piping systems in the NGNP.

The maturation tasks involved in advancing the technology of the HTS piping from TRL 4 to TRL 8 are in general agreement with DDN HTS-04-01 presented in Section 6 of the PCDR. This DDN (High Temperature Ducts and Insulation) addresses, in very general terms:

- *Insulation systems*
- *Hot duct liner characterization*
- *Metallic materials selection*

- *Qualification and performance verification*

The DDN applies both to PHTS piping and SHTS piping.

Costs and schedules associated with the completion of development activities for HTS piping were identified in Section 16 of the PCDR. These will be addressed further in connection with the Maturation Plans.

The detailed Technology Maturation Plans required to mature the technology of the HTS piping to a level of TRL 8 are provided in Appendix C.

## 6.5 Core Outlet Connection Technology Development

The Core Outlet Connection (COC) is an element of the HTS piping and its functions and design has been discussed in detail in the NGNP Conceptual Design Study on Composites R&D (NGNP-NHS-RPT-TI002).

The DPP COC will be tested as part of the DPP testing programme in a facility commissioned specifically for that purpose. This testing will be unique to the DPP configuration and operational conditions.

Currently the anticipated technology development testing requirements for the NGNP COC are covered by the DDNs identified in the NGNP Conceptual Design Study on Composites R&D (NGNP-NHS-RPT-TI002). These are focused on materials and are thus covered by the TDRM as described in this document and consequently the COC will not be uniquely discussed further.

## 6.6 Inputs to CTF

Representative mass flows might have to be utilized in the testing of prototypical piping sections, and might require a testing facility in addition to the CTF.

## 6.7 References

[6-1] PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007
[6-2] NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001,
Rev 0, April 2008
[6-3] Metallic Component Schedule Risk and Cost Uncertainty Assessment report

# APPENDIX A: TRL RATING SHEETS

**Table A-2: Technology Readiness Levels for the HTS Piping**

| TRL Rating Sheet | | |
|---|---|---|
| Vendor Name: | Document Number: | Revision: |
| ☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology | | |
| Title: HTS Piping | | |
| Description: | | |
| The Technology Readiness Level for high-temperature and low-temperature PHTS piping and high-temperature, medium-temperature, and low-temperature SHTS piping operating in the NGNP for 60 years has been assessed as TRL 4 based on studies shown below; actions needed to advance the level to TRL 5 are also given below. | | |
| Island(s): ☐ NHSS ☑ HTS ☐ HPS ☐ PCS ☐ BOP | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A |

| Technology Readiness Level | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Application formulated | Proof of concept | Bench scale testing |
| **TRL** | 3 | **4** | 5 |

Basis for Rating (Attach additional sheets as needed)

Designs and materials for PHTS piping operating at up to 950°C were proposed and evaluated in recent studies reported in:

- Special Study 20.3: High-Temperature Process Heat Transfer and Transport, NGNP-20-RPT-003, Rev 0, January 2007
- PCDR Section 6: Heat Transport System, NGNP-06-RPT-003, Rev 0, April 2007
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008.
- Successful long-term service experience with large gas carrying pipes.

TRL has been re-evaluated from the TRL set out in "NGNP-TRL & DRL Report, Rev 0, September 2007" (which stated the TRL as a TRL 5), to be a TRL 4 due to temperature differences between the DPP design and the proposed NGNP design (cooling gas and reactor outlet temperatures)

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (K$) |
|---|---|---|
| • High-Temperature [760°C and 950°C] PHTS piping cooling, liner, and insulation options trade study | 2009 - 2010 | Refer to Section C4 |

| | | |
|---|---|---|
| • Low-Temperature [350°C] PHTS piping liner and insulation options trade study<br>• High-temperature [840°C and 900°C] SHTS piping liner and insulation options trade study<br>• Medium-temperature [659°C and 700°C] SHTS piping liner and insulation options trade study<br>• Low-temperature [<300°C] SHTS piping liner and insulation options trade study<br>• | | |
| DDN(s) supported: HTS-04-01 | Technology Case File: N/A | |
| Subject Matter Expert Making Determination: Phil Rittenhouse | | |
| Date: 12 September 2008 | Originating Organization: Technology Insights | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

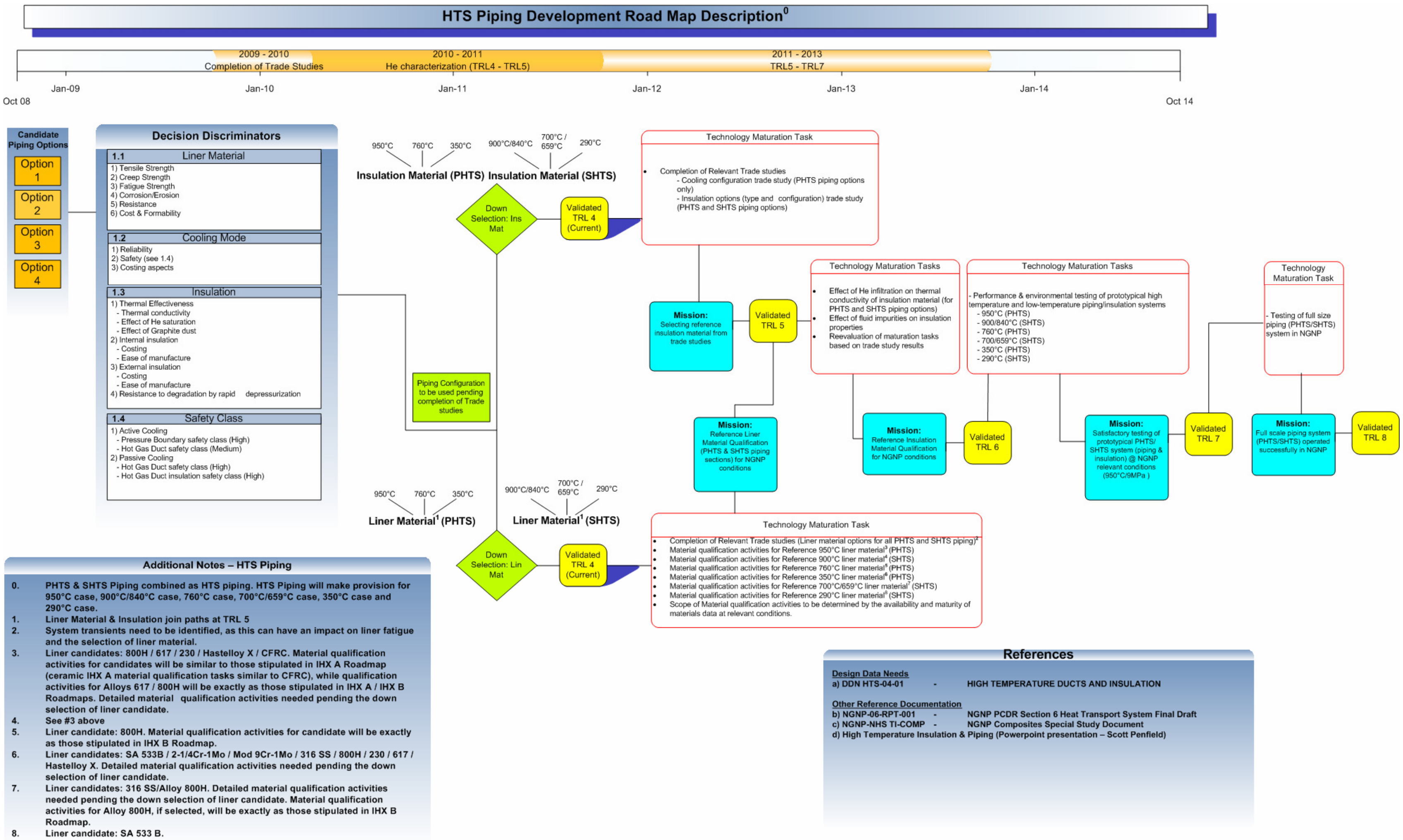


Figure B-8: TDRM for the HTS Piping

# APPENDIX C: TECHNOLOGY MATURATION PLAN – HTS PIPING

## TABLE OF CONTENTS

## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

**TRL 4 to TRL 5:**

- Specification 1: PHTS high-temperature [760°C and 950°C] piping cooling, liner, and insulation options trade study
- Specification 2: PHTS low-temperature [350°C] piping liner and insulation options trade study
- Specification 3: SHTS high-temperature [840° and 900°C] piping liner and insulation trade study
- Specification 4: SHTS medium-temperature [659°C and 700°C] piping liner and insulation trade study
- Specification 5: SHTS low-temperature [<300°C] piping liner and insulation trade study

TRL 5 to TRL 6

- Specification 1: Effects of He infiltration on thermal conductivity of insulation material
- Specification 2: The effect of fluid impurities (C) on insulation properties
- Specification 3: Re-evaluation of needed maturation tasks based on Trade Study results

**TRL 6 to TRL 7:**

- Specification 1: Performance and environmental testing of prototypical high-temperature and low-temperature piping/insulation system

**TRL 7 to TRL 8:**

- Specification 1: Testing of full size PHTS piping in NGNP

# TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 4 TO TRL 5

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the technology of the HTS piping from a TRL level of 4 to a TRL level of 5. Each of the five tasks involve conducting trade studies on cooling, liner, and insulation options for the high- [760°C and 950°C] and low-temperature [350°C] PHTS piping sections and the high- [840°C and 900°C], medium- [659°C and 700°C], and low-temperature [<300°C] SHTS piping sections.

### C1.1.2 Scope

The maturations tasks and associated studies and testing necessary for advancement of the maturity of the technology for the HTS piping from TRL 4 to TRL 5 are as shown below.

- PHTS high-temperature [760°C and 950°C] piping cooling, liner, and insulation options trade study
- PHTS low-temperature [350°C] liner and insulation options trade study
- SHTS high-temperature [840° and 900°C] piping liner and insulation trade study
- SHTS medium-temperature [659°C and 700°C] piping liner and insulation trade study
- SHTS low-temperature [<300°C] piping liner and insulation trade study.

### C1.1.3 Anticipated Schedule

The trade studies indicated by the bullets in C1.1.2 should be able to be completed within a 6-month period (in FY2009 if possible), after system operating conditions (steady state & transients) have been defined.

### C1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

# C1.2 Test Specifications

## C1.2.1 PHTS High-temperature [760°C and 950°C] Piping Cooling, Liner, and Insulation Options Trade Study

### C1.2.1.1 Objectives

This Test Specification provides for trade studies to assess cooling, liner, and insulation options for the PHTS piping sections operating at 950°C (reactor to IHX A) and 760°C (IHX A to IHX B). Both active and passive cooling designs are included. Preferred designs will be recommended based on these studies. No actual physical testing is involved. This Test Specification responds in general terms to DDN HTS-04-01.

### C1.2.1.2 Test Conditions

*C1.2.1.2.1 Test Configuration/Set-up*

Not applicable

*C1.2.1.2.2 Test Duration*

The duration of this activity should require no more than 6 months.

*C1.2.1.2.3 Proposed Test Location*

The piping system designer should lead these studies. Refer to Section 17 of the document.

### C1.2.1.3 Measured Parameters

Parameters to be considered in this study are as follows.

- Maximum PHTS He temperatures achieved during loss of secondary circuit cooling capability.
- Liner and pressure boundary temperatures for each liner/cooling/insulation combination during normal operation and under transient conditions.
- Estimated relative cost and reliability of each liner/cooling/insulation combination.

### C1.2.1.4 Data Requirements

Industry-accepted transient and heat transport codes and models shall be employed for all calculations.

#### C1.2.1.5 Test Evaluation Criteria

Liner/cooling/insulation combinations will be evaluated on the basis of the following.

- Ability to maintain prescribed temperature limits (see bullet 3 in C1.2.1.6).
- Relative cost of each combination.
- Relative operational reliability estimate for each combination.

#### C1.2.1.6 Test Deliverables

Task deliverables are as follows.

- He temperatures in reactor-to-IHX A and IHX A-to IHX B piping sections during loss of secondary cooling capability transients.
- Decision trees describing liner, cooling, and insulation options for reactor-to IHX A and IHX A-to-IHX B piping sections.
- Analyses of the ability of liner/cooling/insulation combinations to achieve the temperature limits (nominally 350°C for pressure retaining pipes and <100°C at the external surface of these pipes) described in Section 6.1.
- Cost and reliability assessment of each liner/cooling/insulation combination.
- Recommendation as to preferred design for each piping section.

#### C1.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 4 to TRL 5 are addressed in Sections C1.1.3 and C1.1.4. The risk that satisfactory design options for high-temperature PHTS piping cannot be achieved is minimal.

### C1.2.2 PHTS Low-temperature [350°C] Piping Liner and Insulation Options Trade Study

#### C1.2.2.1 Objectives

This Test Specification provides for trade studies and supporting transient analyses to assess liner and insulation options for passively-cooled PHTS piping sections operating at ~350°C (IHX B to circulator and circulator to reactor). Preferred designs will be recommended based on these studies. No actual physical testing is involved. This Test Specification responds in general terms to DDN HTS-04-01.

### C1.2.2.2 Test Conditions

*C1.2.2.2.1 Test Configuration/Set-up*

Not applicable

*C1.2.2.2.2 Test Duration*

The trade study should require no more than 6 months.

*C1.2.2.2.3 Proposed Test Location*

**The piping system designer should lead these studies.** Refer to Section 17 of the document.

### C1.2.2.3 Measured Parameters

Parameters to be considered in this study are as follows.

- Maximum He temperatures achieved during loss of secondary circuit cooling capability.
- Liner and pressure boundary temperatures for each liner/insulation combination during normal operation and under transient conditions.
- Estimated relative cost and reliability of each liner/insulation combination.

### C1.2.2.4 Data Requirements

Industry-accepted transient and heat transport codes and models shall be employed for all calculations.

### C1.2.2.5 Test Evaluation Criteria

Liner/insulation combinations will be evaluated on the basis of the following.

- Ability to maintain prescribed temperature limits (see bullet 3 in C1.2.2.6).
- Relative cost of each combination.
- Relative reliability estimate for each combination.

### C1.2.2.6 Test Deliverables

Task deliverables are as follows.

- He temperatures in IHX B-to circulator and circulator-to-reactor piping sections during loss of secondary cooling capability transients.
- Decision trees describing liner and insulation options for IHX B-to-circulator and circulator-to-reactor piping sections.
- Analyses of the ability of liner/insulation combinations to achieve the temperature limits (nominally 350°C for pressure retaining pipes and <100°C at the external surface of these pipes) described in Section 6.1.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for the low-temperature piping sections.

#### C1.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 4 to TRL 5 are addressed in Sections C1.1.3 and C1.1.4. The risk that satisfactory design options for low-temperature PHTS piping cannot be achieved is minimal.

### C1.2.3 SHTS High-temperature [840°C and 900°C] Piping Liner and Insulation Options Trade Study

#### C1.2.3.1 Objectives

This Test Specification provides for trade studies to assess liner and insulation options for the SHTS piping sections operating at 840°C (mixing chamber to SG) and 900°C (IHX A to both PCHX and mixing chamber). Only passive cooling designs are included. Preferred designs will be recommended based on these studies. No actual physical testing is involved. This Test Specification responds in general terms to DDN HTS-04-01.

#### C1.2.3.2 Test Conditions

*C1.2.3.2.1 Test Configuration/Set-up*

Not applicable

*C1.2.3.2.2 Test Duration*

The trade study should require no more than 6 months.

*C1.2.3.2.3 Proposed Test Location*

**The piping system designer should lead these studies.** Refer to Section 17 of the document.

### C1.2.3.3 Measured Parameters

Parameters to be considered in this study are as follows.

- Liner and pressure boundary (HPB) temperatures for each liner/insulation combination during normal operation.
- Estimated relative cost and reliability of each liner/ insulation combination.

### C1.2.3.4 Data Requirements

Industry-accepted transient and heat transport codes and models shall be employed for all calculations.

### C1.2.3.5 Test Evaluation Criteria

Liner/cooling/insulation combinations will be evaluated on the basis of the following.

- Ability to maintain prescribed temperature limits (see bullet #2 in C1.2.3.6).
- Relative cost of each combination.
- Relative operational reliability estimate for each combination.

### C1.2.3.6 Test Deliverables

Task deliverables are as follows.

- Decision trees describing liner and insulation options for mixing chamber to SG piping sections and IHX A to mixing chamber and SG sections.
- Analyses of the ability of liner/insulation combinations to achieve the temperature limits (maximum of 371°C for pressure retaining pipes and <100°C at the external surface of these pipes) described in Section 6.1.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for each piping section.

### C1.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 4 to TRL 5 are addressed in Sections C1.1.3 and C1.1.4. The risk that satisfactory design options for high-temperature SHTS piping cannot be achieved is minimal.

## C1.2.4 SHTS Medium-Temperature [659°C and 700°C] Piping Liner and Insulation Options Trade Study

### C1.2.4.1 Objectives

This Test Specification provides for trade studies to assess liner and insulation options for the SHTS piping sections operating at 659°C (PCHX to mixing chamber) and 700°C (IHX B to IHX A). Only passive cooling designs are included. Preferred designs will be recommended based on these studies. No actual physical testing is involved. This Test Specification responds in general terms to DDN HTS-04-01.

### C1.2.4.2 Test Conditions

*C1.2.4.2.1 Test Configuration/Set-up*

Not applicable

*C1.2.4.2.2 Test Duration*

The trade study should require no more than 6 months.

*C1.2.4.2.3 Proposed Test Location*

**The piping system designer should lead these studies.** Refer to Section 17 of the document.

### C1.2.4.3 Measured Parameters

Parameters to be considered in this study are as follows.

- Liner and pressure boundary (HPB) temperatures for each liner/insulation combination during normal operation.
- Estimated relative cost and reliability of each liner/ insulation combination.

### C1.2.4.4 Data Requirements

Industry-accepted transient and heat transport codes and models shall be employed for all calculations.

### C1.2.4.5 Test Evaluation Criteria

Liner/cooling/insulation combinations will be evaluated on the basis of the following.

- Ability to maintain prescribed temperature limits (see bullet #2 in C1.2.4.6).
- Relative cost of each combination.
- Relative reliability estimate for each combination.

### C1.2.4.6 Test Deliverables

Task deliverables are as follows.

- Decision trees describing liner and insulation options for PCHX to Mixing Chamber piping sections and for the IHX B to IHX A sections.
- Analyses of the ability of liner/insulation combinations to achieve the temperature limits (maximum of 371°C for pressure retaining pipes and <100°C at the external surface of these pipes) described in Section 6.1.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for each piping section.

### C1.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 4 to TRL 5 are addressed in Sections C1.1.3 and C1.1.4. The risk that satisfactory design options for medium-temperature SHTS piping cannot be achieved is minimal.

## C1.2.5 SHTS Low-Temperature [<300°C] Piping Liner and Insulation Options Trade Study

### C1.2.4.1 Objectives

This Test Specification provides for trade studies to assess liner and insulation options for the SHTS piping sections operating at 273°C (SG to circulator) and 287°C (circulator to IHX B). Only passive cooling designs are included. Preferred designs will be recommended based on these studies. No actual physical testing is involved. This Test Specification responds in general terms to DDN HTS-04-01.

### C1.2.5.2 Test Conditions

*C1.2.5.2.1 Test Configuration/Set-up*

Not applicable

*C1.2.5.2.2 Test Duration*

The trade study should require no more than 6 months.

*C1.2.5.2.3 Proposed Test Location*

**The piping system designer should lead these studies.** Refer to Section 17 of the document.

### C1.2.5.3 Measured Parameters

Parameters to be considered in this study are as follows.

- Liner and pressure boundary (HPB) temperatures for each liner/insulation combination during normal operation.
- Estimated relative cost and reliability of each liner/ insulation combination.

### C1.2.5.4 Data Requirements

Industry-accepted transient and heat transport codes and models shall be employed for all calculations.

### C1.2.5.5 Test Evaluation Criteria

Liner/cooling/insulation combinations will be evaluated on the basis of the following.

- Ability to maintain prescribed temperature limits (see bullet #2 in C1.2.5.6).
- Relative cost of each combination.
- Relative reliability estimate for each combination.

### C1.2.5.6 Test Deliverables

Task deliverables are as follows.

- Decision trees describing liner and insulation options for SG to circulator and circulator to IHX B piping sections.

- Analyses of the ability of liner/insulation combinations to achieve the temperature limits (maximum of 371°C for pressure retaining pipes and <100°C at the external surface of these pipes) described in Section 6.1.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for each piping section.

#### C1.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 4 to TRL 5 are addressed in Sections C1.1.3 and C1.1.4. The risk that satisfactory design options for low-temperature SHTS piping cannot be achieved is minimal.

# TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 5 TO TRL 6

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the technology of the HTS piping from a TRL level of 5 to a TRL level of 6. It involves assessment of the effects of infiltration of He (pure He and He with controlled impurities such as moisture) and impurities such as carbon dust on the thermal conductivity of insulation options and such tasks are provided. Additionally, the trade studies noted above may result in requirements for additional maturation tasks and a Test Specification is included to cover the development of such tasks if necessary.

### C2.1.2 Scope

The maturations tasks and associated studies and testing necessary for advancement of the maturity of the technology for the HTS piping from TRL 5 to TRL 6 are as shown below.

- Effects of He infiltration on thermal conductivity of insulation material
- The effect of fluid impurities (C) on insulation properties
- Re-evaluation of needed maturation tasks based on trade study results

### C2.1.3 Anticipated Schedule

The He-infiltration work and the re-evaluations of maturation tasks based on the trade studies will likely not be initiated until the trade study work is complete or well along. Although the work relating thermal conductivity to He-infiltration and contaminants should require no more than 18 months, there is considerable schedule uncertainty related to what additional tasks the re-evaluations of technology based on the trade studies might dictate. An estimate here would be an overall total of 30 months. As a final note, the *NGNP Metallic Component Schedule Risk and Cost Uncertainty Assessment Report*, [6-3] recommended a mean value for the completion of HTS piping development of 34 months. This would have been for TRL 4 to TRL 7.

### C2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C2.2 Test Specifications

### C2.2.1 Effects of He Infiltration on Thermal Conductivity of Insulation Material

#### C2.2.1.1 Objectives

Work conducted under this Test Specification will provide data on the effects of He-infiltration on the thermal conductivity of insulation materials. The Test Specification responds to DDN HTS-04-01.

#### C2.2.1.2 Test Conditions

*C2.2.1.2.1 Test Configuration/Set-up*

These activities require the following.

- Equipment/facilities for exposing insulation materials (both fibrous and microporous) in He at pressures to 9 MPa and temperatures to 950°C
- Provisions for temperature and pressure control and measurement
- Equipment for measurement of thermal conductivity of insulation materials at pressures to 9 MPa and temperatures to 950°C

*C2.2.1.2.2 Test Duration*

Test equipment set-up and testing of the insulation should require no more than 18 months.

*C2.2.1.2.3 Proposed Test Location*

Insulation manufacturers, universities, and National Laboratories are candidates. Refer to Section 17 of the document.

### C2.2.1.3 Measured Parameters

Parameters to be measured and controlled in this study are as follows.

- He temperature
- He pressure
- He impurity levels
- Duration of exposure
- Thermal conductivity.

### C2.2.1.4 Data Requirements

Data shall be required employing industry accepted techniques and standards and appropriate QA.

### C2.2.1.5 Test Evaluation Criteria

Evaluation criteria include reproducibility of results in multiple tests and agreement of results with existing data.

### C2.2.1.6 Test Deliverables

Task deliverables are as follows for each insulation material tested (if more than one is suggested by the trade studies previously described).

- Report on thermal conductivity as function of temperature
- Report on thermal conductivity as function of pressure at temperature
- Report on thermal conductivity as function of time at pressure and temperature
- Report on thermal conductivity as function of impurity levels
- Abovementioned must all be in a He environment

#### C2.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 5 to TRL 6 are addressed in Sections C2.1.3 and C2.1.4. The risk that insulation of satisfactory thermal conductivity for HTS piping insulation will not be available is minimal.

### C2.2.2 The effect of fluid impurities (C) on insulation properties

#### C2.2.2.1 Objectives

Work conducted under this Test Specification will provide data on the effects of impurities in the testing fluid (graphite dust) on the thermal conductivity of insulation materials. The Test Specification responds to DDN HTS-04-01.

#### C2.2.2.2 Test Conditions

*C2.2.2.2.1 Test Configuration/Set-up*

These activities require the following.

- Equipment/facilities for exposing insulation materials (both fibrous and microporous) to He with controlled percentages of impurities at pressures to 9 MPa and temperatures to 950°C
- Provisions for temperature and pressure control and measurement
- Equipment for measurement of thermal conductivity of insulation materials at pressures to 9 MPa and temperatures to 950°C

*C2.2.2.2.2 Test Duration*

Test equipment set-up and testing of the insulation should require 18-to 24 months.

*C2.2.2.2.3 Proposed Test Location*

Insulation manufacturers, universities, and National Laboratories are candidates. Refer to Section 17 of the document.

#### C2.2.2.3 Measured Parameters

Parameters to be measured and controlled in this study are as follows.

- He temperature
- He composition
- He pressure
- Duration of exposure
- Thermal conductivity (determined from measurements of heat flux driven by a temperature gradient *dt/dx*).

#### C2.2.2.4 Data Requirements

Data shall be required employing industry accepted techniques and standards and appropriate QA.

#### C2.2.2.5 Test Evaluation Criteria

- Satisfactory limits of change in thermal conductivity of insulation material over a predetermined time of testing in Helium with controlled percentages of (C) impurities.

#### C2.2.2.6 Test Deliverables

Task deliverables are as follows for each insulation material tested (if more than one is suggested by the trade studies previously described).

- Report on thermal conductivity as function of temperature for selected material/s.
- Report on thermal conductivity as function of pressure at temperature for selected material/s.
- Report on thermal conductivity as function of time at pressure and temperature for selected material/s.
- Abovementioned must all be in a He environment with controlled percentages of (C) impurities

#### C2.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 5 to TRL 6 are addressed in Sections C2.1.3 and C2.1.4. The risk that insulation of satisfactory thermal conductivity for HTS piping will not be available is minimal.

## C2.2.3 Re-evaluation of Needed Maturation Tasks Based on Trade Study Results

### C2.2.3.1 Objectives

Work conducted under this Test Specification will provide for re-evaluation of maturation task needs based on the results of the trade studies described by Test Specifications C1.2.1 to C1.2.5.

### C2.2.3.2 Test Conditions

*C2.2.3.2.1 Test Configuration/Set-up*

Not applicable

*C2.2.3.2.2 Test Duration*

Re-evaluation of needs based on the results of Test Specifications C1.2.1 through C1.2.5 should require no more than three months.

*C2.2.3.2.3 Proposed Test Location*

The piping system designer should lead the re-evaluation. Refer to Section 17 of the document.

### C2.2.3.3 Measured Parameters

N/A

### C2.2.3.4 Data Requirements

N/A

### C2.2.3.5 Test Evaluation Criteria

N/A

### C2.2.3.6 Test Deliverables

The task deliverable is to provide recommendation for additional maturation tasks, as needed, for advancing the technology of HTS piping from TRL 5 to TRL 6.

### C2.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of HTS piping from TRL 5 to TRL 6 are addressed in Sections C2.1.3 and C2.1.4. There is no risk associated with Test Specification C1.2.3.

# C3 TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 6 TO TRL 7

## C3.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C3.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the HTS piping from a TRL level of 5 to a validated TRL 7. The maturation tasks required to achieve this goal involve the performance and environmental testing of prototypical high-temperature and low-temperature piping/insulation systems in a representative testing environment. Test Specifications are provided to cover these maturation tasks (given in Section C3.2).

### C3.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the HTS piping from TRL 5 to TRL 7 are as shown below.

- Specification 1: Performance and environmental testing of prototypical high-temperature and low-temperature piping/insulation system

The task above will be described in the test specification provided hereafter.

### C3.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan will be accomplished during the period FY 2011 through FY 2013.

### C3.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C3.2 Test Specifications

## C3.2.1 Performance and environmental testing of prototypical high-temperature and low-temperature piping/insulation system

### C3.2.1.1 Objectives

The objectives of testing the HTS prototypical piping system are:

- To demonstrate the performance of the HTS piping system, i.e.
  - Limited heat losses at enveloping conditions
  - Required surface temperatures of the Hot Gas Duct and Helium Pressure Boundary
  - Pressure drop through piping system
  - Possible flow induced vibrations and the effect of such events on the insulation configuration integrity.
- To demonstrate the environmental behavior of HTS insulation/liner material in NGNP typical conditions
  - Response of insulation material subsystem to sudden depressurization
  - Effect of certain fluid impurities on insulation material (with special reference made to reduction reactions that may take place over time, thereby increasing the insulation thermal conductivity and effectively that of the system)
  - Thermal fatigue of liner material in subsystem in NGNP relevant environment

The applicability of the above mentioned objectives to the various HTS piping sections vary since the threshold conditions of each piping section differ throughout the PHTS and SHTS loops. Table C-1 summarizes in short the applicability of these objectives to the various piping sections. For the purpose of the HTS piping, only one maturation plan detailing all piping tasks is given and should be evaluated against Table C-1.

**Table C-1: Applicability of maturation plan objectives to HTS piping sections**

| Objectives | PHTS | | SHTS | | |
|---|---|---|---|---|---|
| | 950°C/760°C | 350°C | 900°C/840°C | 700°C/659°C | 290°C |
| **TMP (TRL5-TRL7)** | | | | | |
| a) Performance | | | | | |
| - Limited heat losses | ☑ | ☑ | ☑ | ☑ | ☑ |
| - Required surface temperatures | ☑ | ☑ | ☑ | ☑ | ☑ |
| - Pressure drop | ☑ | ☑ | ☑ | ☑ | ☑ |
| - Flow induced vibrations | ☑ | ☑ | ☑ | ☑ | ☑ |
| b) Environmental behavior | | | | | |
| - Depressurization (insulation subsystem) | ☑ | ☑ | ☑ | ☑ | ☑ |
| - Fluid Impurities (reduction reactions on insulation) | ☑ | ☑ | ☑ | n/a | n/a |
| - Thermal fatigue (liner in subsystem) | ☑ | n/a | ☑ | ☑ | n/a |

### C3.2.1.2 Test Conditions

*C3.2.1.2.1 System Requirements*

Subsystem and system requirements include the following:

- Size limitation: TBD
- Certain interface design requirements: TBD
- Testing fluid – Helium with controlled impurities
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Mass flow threshold – see test requirements

*C3.2.1.2.2 Measurement Requirements*

- Measurement of pressures
  - internal and external pressures (inner and outer annuli) for active cooling
  - internal pressure for passive cooling
- Measurement of surface and fluid temperatures
  - HGD, HPB, insulation, testing fluid temperatures for active cooling
  - Insulation, HPB, testing fluid temperatures for passive cooling
- Measurement of mass flows
- Measurement of fluid compositional changes (controlled impurities) over time

*C3.2.1.2.3 Test Requirements*

Test requirements for the HTS piping tests (integrated) are as follows:

1) Test environmental behavior and performance of HTS piping in typical steady state pressure and temperature environment (Helium)
   i. Temperature = 950°C[1]
   ii. Pressure = 9MPa
   iii. Pressure Δ[2] = $A_O$ pressure > $A_I$ pressure (magnitude tbd)
   iv. Mass flow = tbd
   v. He environment with varied composition
   vi. Duration of tests = tbd

2) Test HTS piping behavior in typical pressure transient environment:
   i. Expose HTS piping to a high frequency, **normal** operating pressure transient
      1. De-pressurizing transient (9MPa to ambient in certain time frame)
      2. Number of cycles and temperature level TBD

3) Test HTS piping behavior in typical temperature transient environment:
   i. Expose piping to a high frequency, **normal** operating temperature transient (ambient to 950°C[3])

[1] Subject to change for all PHTS/SHTS piping sections according to threshold conditions
[2] Applicable only to active cooling configuration
[3] See footnote #1

1. Heat up transient
2. Cool down transient
3. Number of cycles and pressure level TBD

ii. Tests should include performance testing of the HGD in the event of loss of secondary cooling for all active cooling piping configurations.

Proposed setup and important parameters (see following page).

1. Thermal fatigue of liner material
2. Creep of liner material & liner material joints
3. Thermal efficiency of insulation in integrated system
    a. Effect of various impurities on insulation properties if liner joint integrity is compromised
        i. Thermal Conductivity
4. Required surface temperatures vs. actual surface temperatures (HPB & HGD surfaces)
5. Percentage of specific elements (determined by fluid composition) as added over time to internal insulation or liner at a certain depth
6. HGD Interfacing to be addressed as a separate SSC at a later stage

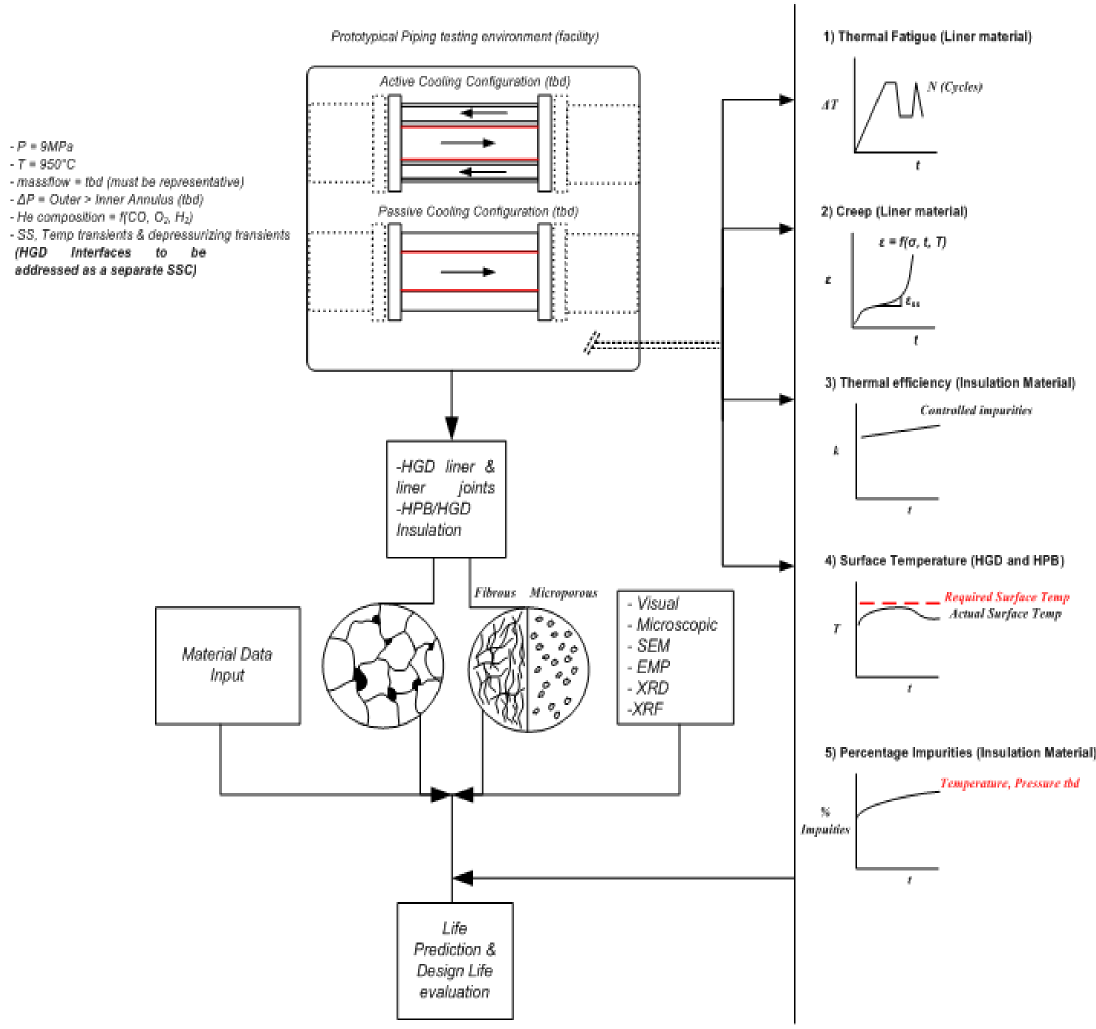


**Figure C-1: Proposed setup and relevant parameters in testing the prototypical HTS piping (active and passive cooling configurations noted pending the down selection of design options)**

*C3.2.1.2.4 Tests Duration*

The duration of this activity will be a minimum of **24** months.

*C3.2.1.2.5 Facility Requirements*

The following facilities will be required:

1. Prototypical piping testing facility (TBD)
2. Facilities for testing sampled fluid composition
3. Facilities required for metallographic analysis (or other analysis means) of insulation material and liner material & joints after testing

*C3.2.1.2.6 Proposed Test Location*

Proposed tests will take place at a testing facility providing for/representing the performance envelope conditions of the prototypical piping sections (Envelope Temperature, Pressure, Pressure Drop and Mass flow). Refer to Section 17 of the document.

**C3.2.1.3 Measured Parameters**

The following parameters will be measured:

- Temperatures
- Pressures
- Fluid composition
- Thermal fatigue observations of liner material through SEM and other analyses techniques
- Post test analysis of insulation material condition (visual inspection and other tests/procedures)
- Post test analysis of structural integrity of liner material joints, inferred from SEM and metallographic/microscopic evaluations and tests.
- 

**C3.2.1.4 Data Requirements**

It is assumed that the prototypical piping sections (HPB, HGD and Liner) will be produced by a vendor of high temperature piping sections. The fabricated prototype piping system will require the following before progressing with testing:

- Materials certificates
- Weld certificates (where applicable)
- Inspection certificates
- All other quality assurance documents

The candidate insulation materials to be used should be accompanied with the appropriate materials certificates and quality assurance documents.

Procedures for taking fluid samples for analyses purposes shall be conducted according to specification to eliminate or reduce possibility of contamination of samples, especially if expressed in ppm.

All new data shall be acquired using recognized techniques, codes, standards, and QA

**C3.2.1.5 Test Evaluation Criteria**

- Satisfactory structural integrity and condition of the integrated piping components, joints (liner material) and insulation material as evidenced by
  - Visual inspection
  - metallographic procedures and tests
  - analyses inclusive of remaining life assessments (if applicable)
  - comparison of data with assessment models, FEM's or other calculations
- Satisfactory surface temperature values for the HGD and HPB respectively at enveloping conditions.
- Satisfactory change in thermal conductivity properties for insulation material (local) after exposure to certain impurities for a predetermined time.

**C3.2.1.6 Test Deliverables**

Deliverables are as follows.

- Test Data for all areas as indicated in section C3.2.1.3
- Documentation containing test requirements, performance verification criteria and test results verified against stress/strain models of the HTS piping and material properties.

**C3.2.1.7 Cost, Schedule, and Risk**

Cost and schedule for the overall Technology Maturation Plan for advancing technology for HTS piping from TRL 5 to TRL 7 is addressed in Sections C3.1.3 and C3.1.4.

Depending on the failure modes of the HTS prototypical piping sections, new liner material candidates will have to be evaluated or slight modifications to the selected piping/insulation configuration will have to be implemented.

# C4 TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 7 TO TRL 8

## C4.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C4.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the HTS piping from a TRL level of 7 to a TRL level of 8. The maturation task required to achieve this goal involves the testing of the full size HTS piping in the NGNP. A Test Specification is provided to cover the maturation task (given in section C4.2).

### C4.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the HTS piping from TRL 7 to TRL 8 is as shown below.

- Specification 1: Testing of full sized HTS piping in the NGNP

This task will be described in the following test specification.

### C4.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2019 through FY 2020.

### C4.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

# C4.2 Test Specifications

## C4.2.1 Specification of testing of full sized HTS Piping in the NGNP

### C4.2.1.1 Objectives

The objective of testing the full sized HTS Piping is:

- To determine the effectiveness of the HTS piping utilized in the NGNP regarding heat losses encountered and required surface temperatures achieved and maintained.

The HTS piping will be fully tested and commissioned in the NGNP. Details of the testing and commissioning of the HTS piping will be finalized at later stage.

**NGNP-CTF MTECH-TDRM-007** **November 2008**
**Revision 1**

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 7: SHTS Flow Mixing Chamber

**APPROVALS**

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# BACKGROUND INTELLECTUAL PROPERTY CONTENT

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## ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |

| Acronym | Definition |
|---|---|
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |

| Acronym | Definition |
|---|---|
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |

| Acronym | Definition |
|---|---|
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# SUMMARY AND CONCLUSIONS

The secondary heat transport system (SHTS) flow mixing chamber is a critical component of the NGNP with its main function being to minimize the thermal effects associated with the mixing of two helium streams that are joined together at significantly different temperatures. At 100% nominal steady-state operation the higher temperature stream enters the chamber at 900 °C, while the other lower temperature stream enters at 659 °C. At this stage of the Next Generation Nuclear Plant (NGNP) design, only a very high level concept of the SHTS flow mixing chamber is available.

Discriminators have been identified to assist in the selection of an optimum design for the SHTS flow mixing chamber. These discriminators address the required technology development, the availability of a manufacturing base, the SHTS flow mixing chamber operation and maintenance, the safety and investment implications and the lifecycle costs.

Several arrangements and design options are available for the SHTS flow mixing chamber that satisfy the preconceptual functions and design requirements. The simplest SHTS flow mixing chamber design option comprises of a single chamber (plenum) with two inlets (one for the hotter helium and one for the colder helium) and one outlet. Additionally, mixing and acoustic or/and flow induced vibration damping devices can be added within the SHTS flow mixing chambers' plenum to enhance the mixing process, reduce size of the chamber and prevent fatigue damages. The pressure drop added by the mixing devices should not compromise the total SHTS loop pressure drop allocation. Alternative designs of the SHTS flow mixing chamber could replace single inlets with multiple inlets to reduce the pressure drop and the streams inlet velocities.

Hence, several design selections remain to be made. It is not clear at this point how many inlets/outlets are required and the need for enhanced mixing/flow vibration damping devices. Trade studies that will use computational modeling and analysis, previous experience, similar designs and engineering judgment will determine the advantages and disadvantages of each option with the help of the decision discriminators specified in Section 7.2.2. The only key design selection provided by reference documentation [7-1] is the use of high temperature metallic alloy and other suitable materials for the walls of the SHTS flow mixing chamber.

All the SHTS flow mixing chamber components are at TRL 8, while the integrated assembly of these components as a subsystem is at TRL 6 because it has not been demonstrated in a loop similar to the SHTS within a relevant environment. Following the selection of a reference SHTS flow mixing chamber design, the components that require technology development will be validated with supporting single effect tests. After that, the SHTS flow mixing chamber subsystem will be validated with a partial scale or full-scale integrated test, subsequently qualifying the subsystem at TRL 7. Advancement to a validated TRL 8 will comprise the final integrated tests of the SHTS flow mixing chamber to take place in the first NGNP nuclear power plant.

# 7 SHTS FLOW MIXING CHAMBER

## 7.1 SHTS Flow mixing Chamber Description

A SHTS flow mixing chamber fabricated from a high temperature metallic alloy or other suitable material is required in the secondary heat transport system (SHTS) of the NGNP [7-1]. The function of this flow mixing chamber is to minimize the thermal effects associated with the mixing of two helium streams that are joined together at significantly different temperatures.

At this stage of the NGNP design, only a very high level concept of the SHTS helium flow mixing chamber is available. This concept will be revisited and further developed during the plant conceptual design phase. The technology development required for the flow mixing chamber will follow two paths: (1) development and verification of the flow mixing chamber design and (2) selection of the insulation and the high temperature materials for the chamber walls.

The first path addresses design development/verification of the flow mixing chamber as it relates to some key design requirements. One of these requirements is the extent of the mixing of the two secondary coolant streams before entering the duct leading to the steam generator (SG). If perfect mixing occurs inside the chamber, the temperature of the helium entering the duct leading to the SG would be 852 °C, at nominal operating conditions. On the other hand, perfect mixing being very difficult to achieve, local hot streaks at temperatures higher than 852 °C will be present in the stream leading to the SG. The allowed temperature deviations from the mean for these hot streaks has a major affect on the scope of the flow mixing chamber design and development and has to be analyzed first with computational fluid dynamics (CFD) modeling and then verified with an integrated partial or full scale test. The same applies for a requirement of suppressing the excitation of the natural frequencies of the flow mixing chamber from acoustic and/or flow induced vibrations. The flow mixing chamber design will be affected by how stringent these requirements are and the complexity of the design will dictate the scope of an integrated partial or full scale model of the flow mixing chamber to verify its compliance with the requirements. The second path of the SHTS flow mixing chamber technology development addresses the selection of the insulation and the high temperature materials for the chamber walls.

Table 7.1 summarizes the design operating requirements for the flow mixing chamber under full power steady state operation. During plant raise to power and design transients care must be taken to contain the magnitude of the hot/cold streaks in the flow leading to the SG and not to excite the cavity natural frequencies from acoustic loads generated by the helium streams entering the flow mixing chamber or by flow induced vibrations generated by the interaction of the two streams inside the chamber.

**Table 7-1: SHTS Flow Mixing Chamber Design Operating Requirements**

| Flow Conditions | SHTS Loop |
|---|---|
| **High Temperature Stream at Nominal Operating Conditions** | |
| He temperature, °C | 900 |
| He pressure, MPa | 8.345 |
| He flow rate, kg/s | 159.6 |
| | |
| **Low Temperature Stream at Nominal Operating Conditions** | |
| He temperature, °C | 659 |
| He pressure, MPa | 8.145 |
| He flow rate, kg/s | 39.9 |
| | |
| **Mixing Requirements** | |
| Maximum temperature deviation from average at SG duct inlet during steady state operations, °C | **±TBD** |
| Maximum temperature deviation from average at SG duct inlet during key AOOs & DBAs , °C | **±TBD** |
| | |
| **Acoustic/Flow Induced Loads Requirements** | |
| Maximum acoustic power at each mixing chamber natural frequencies during steady state operations, Db | **TBD** |
| Maximum acoustic power at each mixing chamber natural frequencies during key AOOs & DBAs, Db | **TBD** |
| Maximum flow induced load at each mixing chamber natural frequencies during steady state operations, kPa | **TBD** |
| Maximum flow induced load at each mixing chamber natural frequencies during key AOOs & DBAs, kPa | **TBD** |

## 7.2 Technology Selections Status

### 7.2.1 Candidates SHTS Flow Coupling and Mixer

There are several arrangements and design options for the SHTS flow mixing chamber that could satisfy the preliminary requirements identified during the preconceptual design of the NGNP. The simplest design option comprises of a single plenum (flow mixing chamber) with two inlets, one for the hotter and one for the colder helium and one outlet. Additionally, mixing devices can be added within the plenum to enhance the mixing process and reduce size of the chamber. The pressure drop added by the mixing devices should not compromise the total SHTS loop pressure drop allocation. Alternative designs of the flow mixing chamber could replace single inlets with multiple inlets to reduce the pressure drop and the inlet stream velocities. Figure 7-1 shows a schematic illustration of all these design options.

These designs will be evaluated by trade studies that will use computational modeling and analysis, previous experience, similar designs and engineering judgment to determine the advantages and disadvantages of each option with the help of the decision discriminators specified in Section 7.2.2.

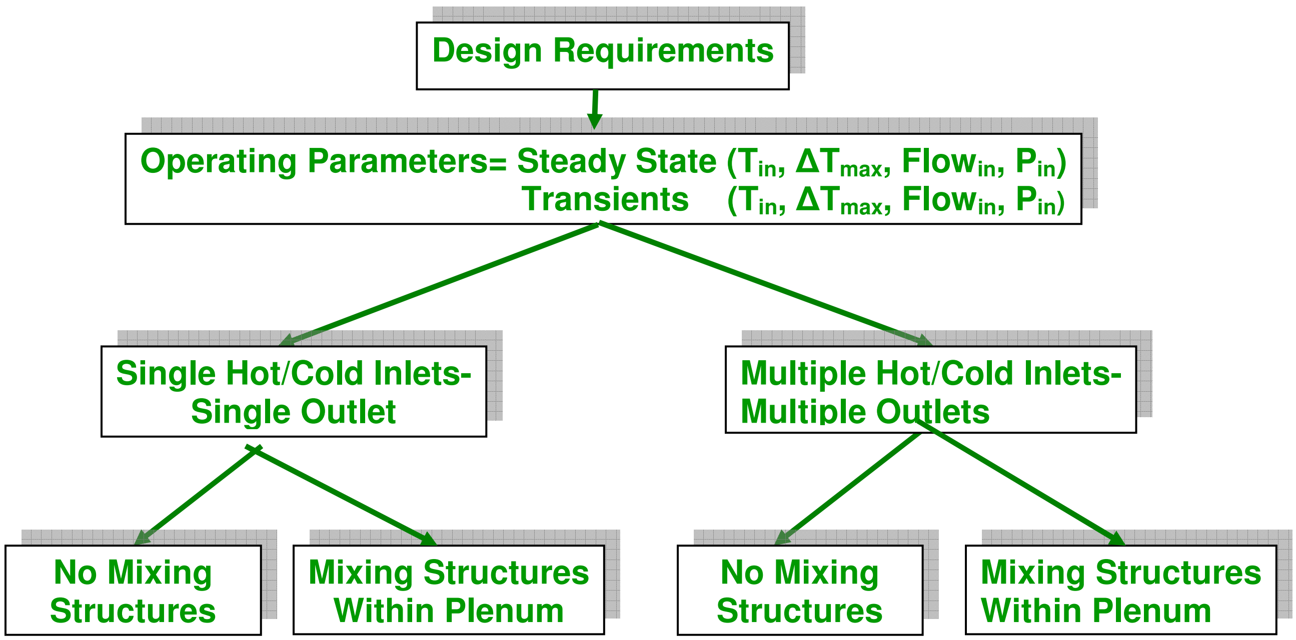



**Figure 7-1: Design Options for the SHTS Flow Mixing Chamber**

### 7.2.2 Decision Discriminators

#### 7.2.2.1 Introduction

Discriminators have been identified to help in the selection of an optimum design for the SHTS flow mixing chamber. These discriminators address the required technology development, the availability of a manufacturing base, the SHTS flow mixing chamber operation and maintenance, the safety and investment implications and the lifecycle costs.

A Kepner-Tregoe (K-T)-based comparative analysis will be used to facilitate the selection of the reference SHTS flow mixing chamber design. The discriminating factors will be rated based on the relative success with which each design meets them. Each discriminating factor will be further weighted proportionally to its perceived importance

#### 7.2.2.2 Design / Technology Development

Mixing two or more streams of gasses at different temperatures is a common practice in industrial applications. Previous experiences with high temperature gas cooled reactors include the mixing of gas streams of different temperatures in the plenum below a prismatic core. Although the NGNP SHTS flow mixing chamber can certainly take advantage of these previous experiences, additional technology development is required because of the high temperature of one of the streams (900 °C), the large flow rates of gasses that need to be processed and the limited tolerance of the downstream structures (e.g. SG) to hot streaks of the SHTS flow mixing chamber output.

The following discriminating factors will inter alia assist in selecting an optimal design for the SHTS flow mixing chamber:

- Can the selected technology be validated from similar proven technologies using only computational modeling and analysis?
- Are additional ad hoc structures required to enhance the mixing process inside the SHTS flow mixing chamber and can the performance of these structures be validated using computational modeling and analysis and single effects bench scale tests?
- Can the performance of the SHTS flow mixing chamber be validated in air at room temperature in a scale model?
- Will the SHTS flow mixing chamber require a full-scale test in helium to be validated?

#### 7.2.2.3 Manufacturing and Transportability

This type of flow mixing chamber for high temperatures steams of helium has not been built for several years for a nuclear environment. There are several companies capable of developing the design, validating the required technology and building the flow mixing chamber for a nuclear application, but they have lost a lot of the specialized manufacturing experience and experienced personnel.

The discriminating factors that could be used in this case are:

- Have flow mixing chambers with similar requirements been built recently?
- What type of enhance mixing structures have been recently used in a similar environment?
- Does the manufacturing process require integration among several suppliers?
- Is the specific technology to be used for the SHTS flow mixing chamber available from several suppliers or can it only be provided by a few specialized suppliers?
- Can the SHTS flow mixing chamber be assembled at the supplier site and transported to the NGNP site for mounting in the SHTS loop or must it be assembled at the NGNP site?

#### 7.2.2.4 Operation and Maintenance

The operation of the NGNP SHTS flow mixing chamber is strongly affected by its design. For example, if there are only two inlet ducts, instead of several, the chance of interferences among the inlet streams that could excite the SHTS flow mixing chamber natural frequencies is decreased. On the other hand, multiple inlets will decrease the inlet helium streams velocity and consequently the loop pressure drop, thus enhancing the SHTS performance. On the other hand, maintenance should not play a big role in the selection of the flow mixing chamber design. Each option should not require maintenance during the plant operating life, except for access to inspect the insulation on the mixing chamber walls.

The discriminating factors that could be used in this case are as follows:

- Does the design require the development of specialized instrumentation to monitor the effectiveness of the mixing process?
- Does the design require additional access for inspection?
- How often does the flow mixing chamber need to be inspected?

#### 7.2.2.5 Safety and Investment Protection

The key safety and investment protection concern for the SHTS flow mixing chamber is related to the formation of excessive hot streaking that could damage the SG structure causing water ingress into the SHTS loop and the opening of the pressure relieve valve(s). A further concern is the damaging of the flow mixing chamber walls because of a combination of high temperatures and stresses with consequent depressurization of the SHTS loop. Plant level analyses will be done to determine design basis transients that cover all these scenarios and evaluate their probability of occurrence and their consequences to the plant personnel and the public and the impact on the plant investment. Once verified, the CFD models of the flow mixing chamber could be used to provide thermal and pressure loadings for the nominal full power and part load steady-state operational conditions, as well as for abnormal and fault transients. If necessary, the SHTS flow mixing chamber design will be modified to satisfy the plant safety and investment goals.

#### 7.2.2.6 Lifecycle Cost

Cost and impact on the plant schedule will be evaluated for each of the SHTS flow mixing chamber designs. The discriminating factors that could be used in this case are:

- Design development cost (not recurring)
- Capital cost (recurring)
- Operating costs (including effect on capacity factor)
- Impact on the plant delivery schedule.

### 7.2.3 Reference Design

The present reference design for the SHTS flow mixing chamber is described in Section 6 of the PCDR [7-1]. No real design selections were made during the preconceptual design. The only decision addresses the use of high temperature metallic alloy and/or other suitable materials for the walls of the flow mixing chamber.

### 7.2.4 Alternatives for Further Evaluation

During the NGNP conceptual design the performance of the flow mixing chamber will be established. The conceptual layout (shape and number of inlet and outlet nozzles) will be determined and the requirements for mixing enhancing devices will be included in the design, if needed. Several design options will be analyzed and compared with each other on the basis of computational modeling and analysis, similar design and operating experience, recent applicable reactor designs, and engineering judgment. Decision discriminators will be used to facilitate this selection. The proposed trade studies will form a basis for the selection of a mature reference design for the flow mixing chamber. These studies will be done with the support of qualified suppliers.

Down Selection Task

Some of the trade studies required for the flow mixing chamber design selection will be done at a system level in order to provide clear requirements to the designers while other trade studies will be done at the subsystem level to select a flow mixing chamber design that best satisfies the requirements. A third type of trade study requires the close collaboration and interfacing between the system and subsystem designers in order to ensure that the selected design can be adequately integrated in to the System. Table 7.2 lists the recommended trade studies.

Trade studies identified as "System Level" are presumed to be done by the SHTS systems designers, trade studies identified as "Subsystem Level" are presumed to be done by the flow mixing chamber suppliers and trade studies identified as "System/Subsystem Level" are presumed to be done in close collaboration between the system and subsystem designers.

**Table 7-2: Trade Studies Recommended for the SHTS Helium Flow Coupling and Mixer**

| Recommended Trade Studies | System Level | Subsystem Level | System/Subsystem Level |
|---|---|---|---|
| a) Allowed pressure drops and hot streaks magnitude | X | | X |
| b) Number of inlets and outlets for the flow mixing chamber | | X | |
| c) Type of mixing enhancing devices | | X | |

Each of these trade studies will evaluate the technical maturity of each design, establish the availability of the suppliers, perform a Reliability, Availability, Maintainability and Inspectability (RAMI) analysis and supporting plant level analyses to develop a mature reference flow mixing chamber design with the best relative costs and impact on the plant schedule.

## 7.3 TRL Status of SHTS Flow Mixing Chamber

The NGNP and Hydrogen Production Report on Design Readiness Levels and Technology Readiness Levels [7-2] assessed the SHTS flow mixing chamber as TRL 6. This assessment was based on the fact that similar helium flow mixing plena have been successfully used in a nuclear environment for other relevant applications. For example, the Fort St. Vrain HTGR reactor had a plenum under the reactor core where streams of helium coming from the core at different temperatures were mixed before going to the SG. Similar application can be found in other gas cooled reactors. On the other hand, none of the previous applications had the large flow rates and the high temperatures that are present in the NGNP application.

Tables A-1 and A-2 in Appendix A provide a detailed explanation of the technology readiness levels of the SHTS flow mixing chamber subsystem and its components. The Tables show that although some of the SHTS flow mixing chamber components are at TRL 8, the integrated assembly of these components as a subsystem is at TRL 6, only because it has not been demonstrated in a loop similar to the SHTS in a relevant environment.

## 7.4 Technology Development Road Map Summary

### 7.4.1 Overview

The design of the SHTS flow mixing chamber design is only at a preconceptual level. The TDRM identifies several design options that will be addressed during the plant conceptual design phase. From these options a mature reference design will be selected with the support of trade studies and selection criteria.

Once a mature reference design is selected, a partial or full scale model of the flow mixing chamber will be tested to validate its performance as an integrated subsystem in a relevant environment. This validation will verify that each component of the SHTS flow mixing chamber subsystem performs within its specifications. Successful completion of this test will advance the SHTS flow mixing chamber from TRL 6 to TRL 7.

Following successful demonstration of a partial or full-scale SHTS flow mixing chamber model, a prototype of the SHTS flow mixing chamber will be built and shipped to the NGNP site where further testing will take place in an environment integrated with the rest of the primary and secondary loop Systems, Structures and Components (SSCs). These tests will be done during the NGNP cold commissioning phase. As a result of these integrated tests, small modifications on the SHTS flow mixing chamber design could be performed if necessary, before declaring the SHTS flow mixing chamber TRL 8.

## 7.5 Technology Maturation Plan Summary

The Technology Maturation Plans required to mature the SHTS flow mixing chamber to TRL 8 are attached in Appendix C.

The section below describes the maturation tasks needed to advance the technology of the Mixing Chamber from TRL 6 to TRL 8.

Advancement from TRL 6 to TRL 7 will require the following:

- Conducting of trade studies during the conceptual design phase, to support the down selection from various design options to a single mature reference design.
- Performing tests on components of the subsystem during the preliminary design phase, to validate the selected technologies.

- Design and fabrication of the SHTS flow mixing chamber system (partial or full-scale) and facilities alike during the final design phase.
- Validation testing of the Mixing Chamber engineering scale model to be done at the CTF or at the supplier facilities.

Advancement from TRL 7 to TRL 8 will require the following:

- Manufacturing of a full scale SHTS flow mixing chamber.
- Integration of the SHTS flow mixing chamber into the SHTS within the NGNP.
- Testing of the SHTS flow mixing chamber within the integrated SHTS at the maximum temperatures, pressures and flow rates achievable during the cold commissioning of the NGNP.

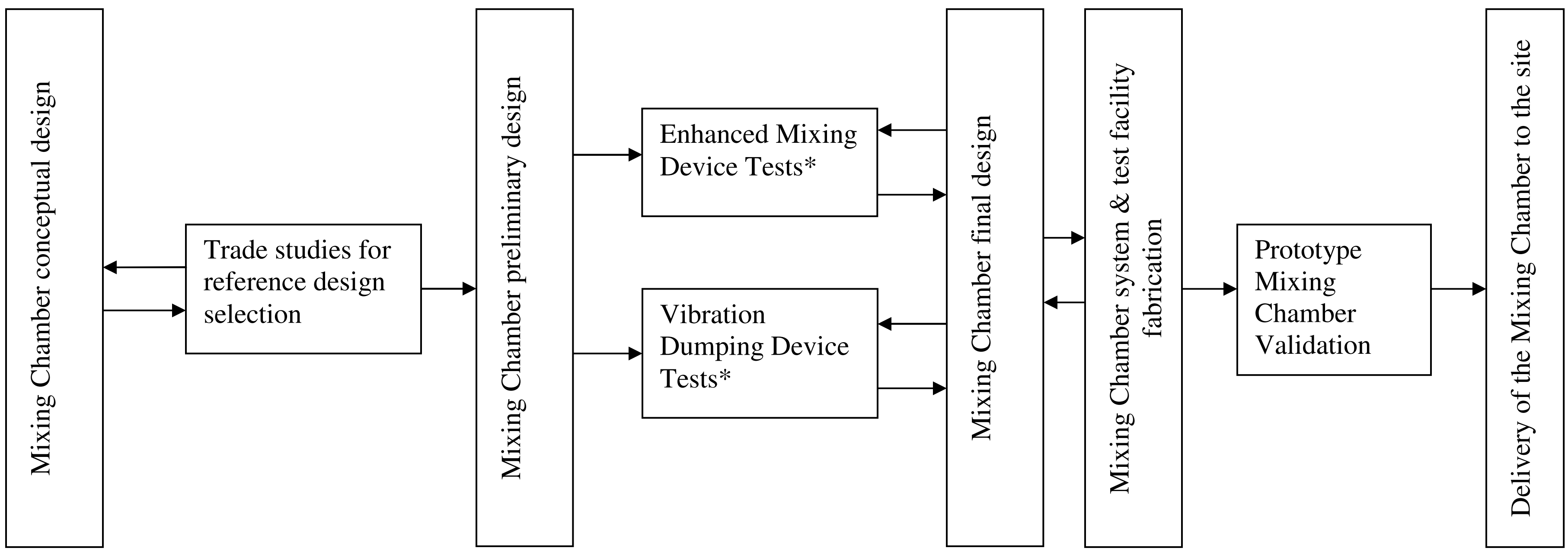
## 7.6 Inputs into CTF

The Mixing Chamber will be tested in the CTF for qualification of a TRL 7. This will require the provision of 2 different streams of pressurized Helium at different (and variable) temperatures, pressures and flow rates along with the necessary instrumentation to measure the performance of the SHTS flow mixing chamber.

## 7.7 References

[7-1] NGNP-06-RPT-001, Rev 0, NGNP and Hydrogen Production Pre-Conceptual Design Report, Section 6, Heat Transport Systems; Westinghouse Electric Company, May 2007.

[7-2] NGNP-TRL & DRL Report, Rev 0, NGNP and Hydrogen Production Report on Design Readiness Levels and Design Technology Readiness Levels, Westinghouse Electric Company, 27 September 2007




* Indicates activity only required if these technologies form part of the design

**Figure 7-2: SHTS Mixing Chamber Development Logic**

# Appendix A: TRL Rating Sheets

**Table A-3: TRL for the SHTS Flow Mixing Chamber Subsystem**

| **TRL Rating Sheet** | | |
|---|---|---|
| Vendor Name: | Document Number: | Revision: 0 |
| ☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology | | |
| Title: SHTS Flow Mixing Chamber Subsystem | | |
| Description: | | |
| The SHTS flow mixing chamber combines helium flows of different temperatures before they reach the SG. For the purpose of defining its readiness level, the SHTS flow mixing chamber identified during the NGNP preconceptual design is classified as a subsystem within the SHTS. The flow mixing chamber subsystem comprises of two components: the mixing plenum with enhanced mixing devices and the devices required to control flow and acoustic induced vibrations. | | |
| Island(s): ☐ NHSS ☑HTS ☐ HPS ☐ PCS ☐ BOP | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A |

| **Technology Readiness Level** | | | |
|---|---|---|---|
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Component Verified at Experimental Scale | Subsystem Verified at Pilot scale | System demonstration at Engineering Scale |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed)

There is relevant operating experience with gas flow mixing chambers in several gas-cooled reactors that have been built and tested. There is experience with similar helium flow mixing chamber in the Fort St. Vrain reactor.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

Following the selection of a mature reference design, the components of the SHTS flow mixing chamber that require technology development will be validated with supporting single effect tests. After that, the SHTS flow mixing chamber subsystem will be validated with a partial scale or full-scale integrated test.

| Actions (list all) | Schedule | Cost (K$) |
|---|---|---|

| | | |
|---|---|---|
| • Validation of enhanced flow mixing devices, if they are included in the design.<br>• Validation of vibrations damping devices, if they are included in the design.<br>• Integrated test of a partial or full-scale model of the SHTS flow mixing chamber subsystem. | August 2010<br>August 2010<br>August 2012 | Refer to Section 17 |
| DDN(s) supported: None | Technology Case File: N/A | |
| Subject Matter Expert Making Determination: G. Baccaglini | | |
| Date: 5 September 08 | Originating Organization: Technology Insights | |

**Table A-4: TRL for the SHTS Flow mixing chamber components**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: | Document Number: | | Revision: 0 |
| ☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: SHTS Flow Mixing Chamber Components – Mixing Plenum, Enhanced Mixing Devices and Vibrations Damping Devices | | | |
| Description: | | | |
| The mixing plenum and its enhanced mixing devices (if present in the design) comprises of the part of the subsystem in which the actual mixing of the helium streams occurs.<br>The other components of the SHTS flow mixing chamber subsystem are the devices required to damp (eliminate or dump) acoustic and/or flow induced vibrations that could excite the natural modes of the SHTS flow mixing chamber | | | |
| Island(s): ☐ NHSS ☑HTS ☐ HPS ☐ PCS ☐ BOP | | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A | |
| **Technology Readiness Level** | | | |
| | **Next Lower Rating Level** | **Calculated Rating** | **Next Higher Rating Level** |
| Generic Definitions *(abbreviated)* | Component Verified at Experimental Scale | Subsystem Verified at Pilot scale | System demonstration at Engineering Scale |
| **TRL** | **7** | **8** | **9** |
| Basis for Rating (Attach additional sheets as needed)<br>There is operating experience with gas flow mixing chambers with similar components in several industrial applications and in gas-cooled reactors. There is experience with similar helium flow mixing chamber in the Fort St. Vrain reactor, | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed)<br>The SHTS flow mixing chamber components, integrated in the flow mixing chamber prototype, will be verified in the NGNP when the performance of the flow mixing chamber in its final configuration is verified during NGNP cold commissioning testing in hot operational environment. | | | |
| Actions (list all) | | Schedule | Cost (K$) |

| | | |
|---|---|---|
| • Test the flow mixing chamber prototype while mounted in the SHTS loop, to verify its interaction with the other loop subsystems in an environment that will still allow access for inspection and adjustments.<br>• It is noted that the mixing chamber will likely be tested in air and helium. | August 2016<br><br>August 2017 | Refer to Section 17 |
| DDN(s) supported: None | Technology Case File: N/A | |

| | |
|---|---|
| Subject Matter Expert Making Determination: G. Baccaglini | |
| Date: 5 September 08 | Originating Organization: Technology Insights |

# Appendix B: Technology Development Road Map

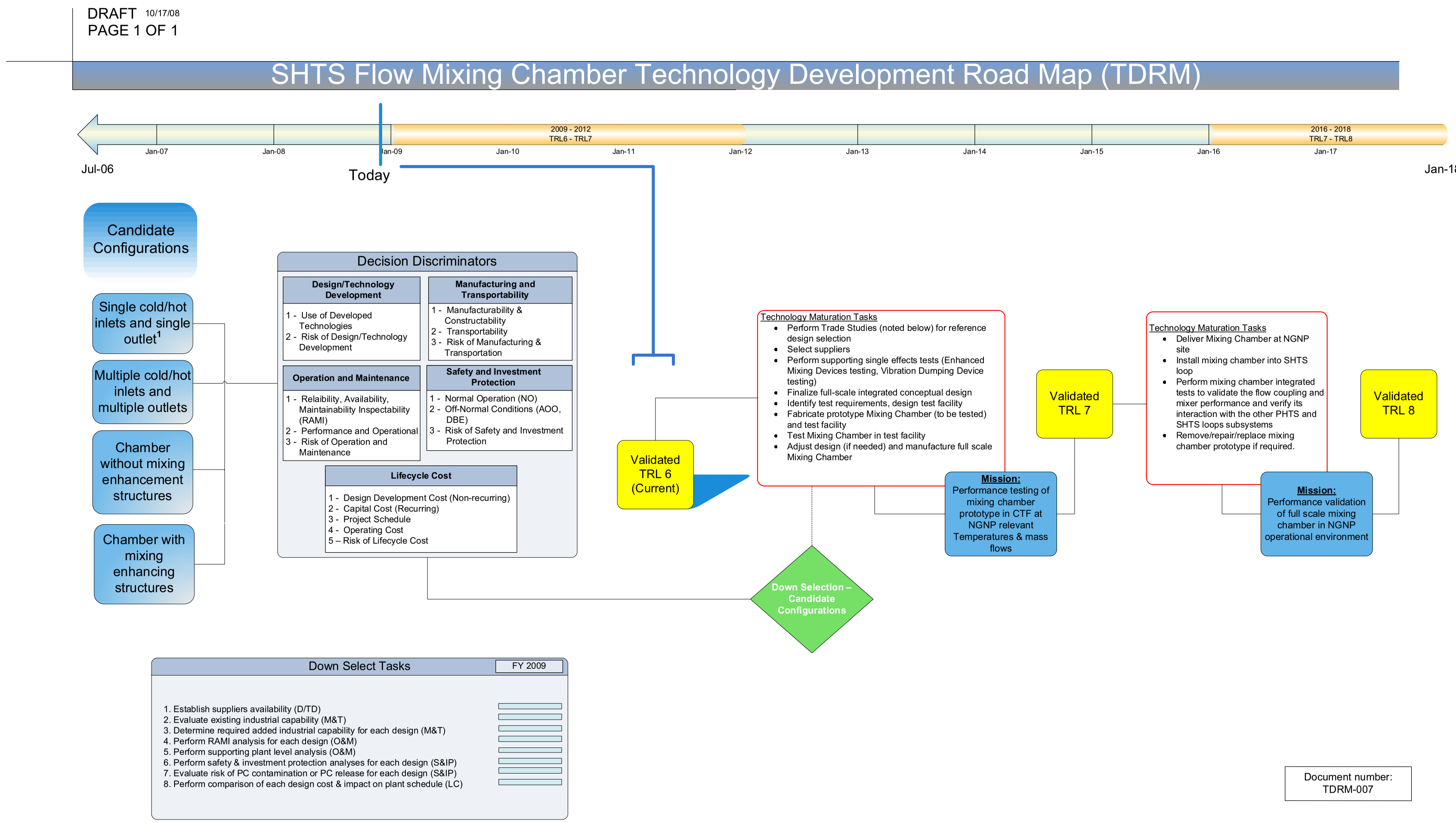



**Figure B-3: Technology Development Road Map for SHTS Flow Mixing Chamber**

# Appendix C: Technology Maturation Plan

## TABLE OF CONTENTS



## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

**TRL 6 to TRL 7:**

- Specification 1: Enhanced Mixing Devices Test Specification
- Specification 2: Vibration Damping Devices Test Specification
- Partial or Full Scale Flow Mixing Chamber Model Test Specification

**TRL 7 to TRL 8:**

- Prototype Flow Mixing Chamber Test Specification

# C1 TECHNOLOGY MATURATION PLAN FOR SHTS FLOW MIXING CHAMBER: TRL 6 TO TRL 7

## C1.1 Technology Maturation Plan Summary

### C1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the SHTS flow mixing chamber from TRL 6 to TRL 7. The SHTS flow mixing chamber design is currently only at a preconceptual level. The TDRM identifies several design options that will be addressed during the plant conceptual design phase. From these options a mature reference design will be selected, with the support of trade studies that will use computational modeling and analysis, previous experience, similar designs and engineering judgment, selection criteria, and validation from components tests. This will be followed by testing of a partial or full scale model of the SHTS flow mixing chamber to validate its performance as an integrated subsystem in a relevant environment. This validation will verify that each component of the SHTS flow mixing chamber subsystem performs within its specifications. Successful completion of this test will advance the SHTS flow mixing chamber from TRL 6 to TRL 7. This integrated test is required because some of the operating conditions and design features (depending on which SHTS flow mixing chamber design will be selected) to be used in the NGNP do not match the experience with similar flow mixing chambers used in previous gas cooled reactors.

A Test Specification is provided to cover the maturation tasks as shown in Section C1.2.

### C1.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the SHTS flow mixing chamber from TRL 6 to TRL 7 are as shown below.

- Validation of the performance of the enhanced mixing devices, if included in the design.
- Validation of the performance of the vibrations damping devices, if included in the design.
- Integrated test of a partial or full-scale model of the SHTS flow mixing chamber subsystem.

The tasks above will be described fully in individual Test Specifications provided in sections to follow.

### C1.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY2009 through FY2012. Work described in the Test Specifications to validate the performance of the mixing and vibration damping devices can be done in parallel

### C1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

## C1.2 Test Specifications

### C1.2.1 Enhanced Mixing Devices Test Specification

#### C1.2.1.1 Objectives

If enhanced mixing devices are included in the SHTS flow mixing chamber, some technology development may be required depending the requirements for the suppression of hot/cold streaks. Several configurations may be tested using partial or full scale models to verify their performance.

The technical issues to be addressed by the enhanced mixing devices validation tests are:

- Mixing effectiveness under full and partial loads plant operating conditions
- Pressure drop under full and partial loads plant operating conditions
- Validation of the CFD models used to predict the performance of the enhanced mixing devices
- Validation of techniques for fabrication of mixing devices using high temperature metal alloys.

#### C1.2.1.2 Test Conditions

*C1.2.1.2.1 Test Configuration/Set-Up*

A full or partial scale model of several configurations of enhanced mixing devices will be tested in an air (or helium) loop.

*C1.2.1.2.2 Test Duration*

The duration of this activity could be up to 6 months.

*C1.2.1.2.3 Proposed Test Location*

The enhanced flow mixing tests will be done at the supplier site.

#### C1.2.1.3 Measured Parameters

The supplier is to determine the measured parameters, which may include the following:

- Gas pressure at inlet and outlet
- Gas flow rates at inlet and outlet
- Average gas temperatures at the inlets and outlet, and

- Local streaks temperature deviation from the mean at the mixing chamber walls and at the outlet.

#### C1.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C1.2.1.5 Test Evaluation Criteria

The enhanced flow mixing devices tests must be performed according to specifications during simulated steady state plant operation, Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA). CFD analyses will support the selection of the testing environment for the simulation of transient operations.

#### C1.2.1.6 Test Deliverables

Deliverables are as follows.

- Validated enhanced flow mixing devices performance specifications
- Report confirming that the enhanced flow mixing devices meets all specifications and requirements

#### C1.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the SHTS flow enhanced mixing devices technology for TRL 6 to TRL 7 is addressed in Sections C1.1.3 and C1.1.4. There is only minimal risk associated with this task.

### C1.2.2 Vibration Damping Devices Test Specification

#### C1.2.2.1 Objectives

If vibrations damping devices are included in the SHTS flow mixing chamber, some technology development may be required depending the requirements for the suppression of the excitation of the chamber natural frequencies. Several configurations may be tested using partial or full scale models to verify their performance.

The technical issues to be addressed by the vibrations damping devices validation tests are:

- Damping effectiveness under full and partial loads plant operating conditions
- Pressure drop under full and partial loads plant operating conditions
- Validation of the CFD models used to predict acoustic or/and flow induced vibrations and the performance of the damping devices.
- Validation of techniques for fabrication of damping devices using high temperature metal alloys.

### C1.2.2.2 Test Conditions

*C1.2.2.2.1 Test Configuration/Set-Up*

A full or partial scale model of several configurations of vibrations damping devices will be tested in an air (or helium) loop.

*C1.2.2.2.2 Test Duration*

The duration of this activity could be up to 6 months.

*C1.2.2.2.3 Proposed Test Location*

The vibration damping devices tests will be done at the supplier site.

### C1.2.2.3 Measured Parameters

The supplier is to determine the measured parameters, which may include the following:

- Average gas temperatures, pressures and flow rates at the inlets and outlet, and
- Acoustic and flow induced spectra
- Loads and temperatures along the chamber walls.

### C1.2.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

### C1.2.2.5 Test Evaluation Criteria

The vibrations damping devices tests must be performed according to specifications during simulated steady state plant operation, Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA). CFD analyses will support the selection of the testing environment for the simulation of transient operations.

Test Deliverables

Deliverables are as follows.

- Validated vibrations damping devices performance specifications
- Report confirming that the vibrations damping devices meets all specifications and requirements.

### C1.2.2.6 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the SHTS flow vibrations damping devices technology for TRL 6 to TRL 7 is addressed in Sections C1.1.3 and C1.1.4. There is only minimal risk associated with this task.

### C1.2.3 Partial or Full Scale SHTS Flow Mixing Chamber Model Test Specification

#### C1.2.3.1 Objectives

The SHTS flow mixing chamber comprises of a mixing plenum with the possibility of enhanced flow mixing devices and vibrations damping devices, if required.

The objective of this task is to test a partial or full-scale model of the SHTS flow mixing chamber assembly to verify the performance of each of its components in an integrated representative environment. This integrated test is required because some of the operating conditions and design features (depending on which reference design will be selected) of the SHTS flow mixing chamber in the NGNP do not match the previous experience with in gas cooled reactors.

At this early stage of the design, a full-scale model of the SHTS flow mixing chamber is recommended because of the different scaling requirements of its various components and their complex interaction. The test environment and the scale of the SHTS flow mixing chamber model will be better defined when a mature reference design is selected.

The technical issues to be addressed by the partial or full-scale SHTS flow mixing chamber model test are:

- Performance of the SHTS flow mixing chamber with single (one for the hotter and one for the cooler gas) or multiple inlets without enhance mixing devices.
- Performance of the SHTS flow mixing chamber with enhanced mixings devices versus increased pressure drop.
- Magnitude of hot streaks leaving the mixing chamber.
- Measurement of the amplitude and frequency of acoustic and flow induce vibrations.
- Validation of the CFD models used to predict the performance of the enhanced mixing devices and of the acoustic or/and flow induced vibrations damping devices.
- Verification of access and inspection techniques.

#### C1.2.3.2 Test Conditions

*C1.2.3.2.1 Test Configuration/Set-Up*

A full or partial scale model of the SHTS flow mixing chamber will be tested in an air (or helium) loop.

*C1.2.3.2.2 Test Duration*

The duration of this activity could be up to 12 months.

*C1.2.3.2.3 Proposed Test Location*

The SHTS flow mixing chamber integrated tests will be done at the CTF or at the supplier site.

### C1.2.3.3 Measured Parameters

The supplier is to determine the measured parameters, which may include the following:

- Average gas temperatures, pressures and flow rates at the inlets and outlet, and
- Local streaks temperature deviation from the mean at the mixing chamber walls and at the outlet.
- Frequency and amplitudes of loads caused by flow or acoustic induced vibrations
- Loads and temperatures along the chamber walls.
- 

### C1.2.3.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

### C1.2.3.5 Test Evaluation Criteria

The full or partial scale SHTS flow mixing chamber must perform according to specifications during simulated steady state plant operation, Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA). CFD analyses will support the selection of the testing environment for the simulation of transient operations.

### C1.2.3.6 Test Deliverables

Deliverables are as follows.

- Validated SHTS flow mixing chamber model performance specifications
- Report confirming that the SHTS flow mixing chamber model meets all specifications and requirements.

### C1.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the SHTS flow mixing chamber technology for TRL 6 to TRL 7 is addressed in Sections C1.1.3 and C1.1.4. There is only minimal risk associated with this task.

# C2 TECHNOLOGY MATURATION PLAN FOR SHTS FLOW MIXING CHAMBER: TRL 7 TO TRL 8

## C2.1 Technology Maturation Plan Summary

### C2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the SHTS flow mixing chamber from TRL 7 to TRL 8. The final integrated tests of the prototype SHTS flow mixing chamber will take place in the first NGNP nuclear power plant.

In the first phase, the testing will take place without a nuclear heat source and the PHTS and SHTS circulators will be used to move the coolant around the primary and secondary loops and provide heat of compression. The main objective of these tests is to verify the integrated performance of all the PHTS and SHTS subsystems operating as a system in the first NGNP plant. More specifically, the purpose for the prototype SHTS flow mixing chamber tests will be similar to that of the integrated partial or full-scale model test done to progress from TRL 6 to TRL 7, with the difference that the remaining PHTS and SHTS subsystems will also be involved. There will still be access during and after these tests for inspection and possible design improvements of the SHTS flow mixing chamber, if necessary.

### C2.1.2 Scope

The maturation tasks and associated testing and other activities necessary to advance the maturity of the technology of the SHTS flow mixing chamber from TRL 7 to TRL 8 involves the non-nuclear testing of the mixing chamber in the SHTS loop.

### C2.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY2016 through FY2018.

### C2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 17 of this document.

# C2.2 Test Specifications

## C2.2.1 Prototype SHTS Flow Mixing Chamber Test Specification

### C2.2.1.1 Objectives

The SHTS flow mixing chamber comprises of a mixing plenum with the possibility of enhanced flow mixing devices and vibrations damping devices, if required.

The objective of testing the SHTS flow mixing chamber prototype in helium without nuclear heat, while mounted in the SHTS loop, is too verify its interaction with the other loop subsystems in an environment that is as close as possible with the NGNP operating conditions. The heat to bring the helium to temperatures representative of the NGNP nuclear operation is provided by the circulator compression. The PCHX and the SG will be acting as heat sinks.

The technical issues to be addressed by the prototype SHTS flow mixing chamber test in helium are:

- Performance of the SHTS flow mixing chamber prototype for the point of view of pressure drops and magnitude of hot streaks at the mixing chamber outlet.
- Measurement of the amplitude and frequency of acoustic and flow induce vibrations.
- Verification of access and inspection techniques.

It is anticipated that initial testing will be also conducted while the SHTS is filled with another medium such as helium or air. This will be specified at a later stage.

### C2.2.1.2 Test Conditions

#### *C2.2.1.2.1 Test Configuration/Set-up*

The SHTS flow mixing chamber prototype will be tested in the SHTS loop mounted with all the other subsystems in helium under pressures and temperatures selected to represent as close as possible the NGNP operating environment.

#### *C2.2.1.2.2 Test Duration*

The duration of this activity could be up to 12 months.

#### *C2.2.1.2.3 Proposed Test Location*

The prototype SHTS flow mixing chamber integrated tests in helium will be done at the NGNP site.

### C2.2.1.3 Measured Parameters

The supplier is to determine the measured parameters, which may include the following:

- Average gas temperatures and pressures at the inlets and outlet
- Local streaks temperature deviation from the mean at the mixing chamber walls and at the outlet
- Frequency and amplitudes of loads caused by flow or acoustic induced vibrations.

### C2.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

### C2.2.1.5 Test Evaluation Criteria

The prototype SHTS flow mixing chamber must perform according to specifications during simulated steady state plant operating conditions, Anticipated Operational Occurrences (AOO) and Design Basis Accidents (DBA).

### C2.2.1.6 Test Deliverables

Deliverables are as follows.

- Validated SHTS flow mixing chamber prototype performance specifications in helium
- Report confirming that the SHTS flow mixing chamber prototype meets all specifications and requirements
- Report on maintainability and inspectability.

### C2.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the SHTS flow mixing chamber technology from TRL 7 to TRL 8 is addressed in Sections C2.1.3 and C2.1.4. There is only minimal risk associated with Section C2.2.1.

**NGNP-CTF MTECH-TDRM-008** **December 2008**
**Revision 0**

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 8: Hydrogen Production System

**APPROVALS**

| Function | Printed Name and Signature | Date |
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| Reviewer | Name: Tom St Louis<br>Company: Shaw Group | December 3, 2008 |
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| William Summers<br>Savannah River National Laboratory | November 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | | |

## REVISION HISTORY

# RECORD OF CHANGES

| Revision No. | Revision Made by | Description | Date |
|---|---|---|---|
| A | Daniel Allen | Initial release | October 20, 2008 |
| B | Daniel Allen | Second release – Detailed review in progress. | October 28, 2008 |
| C | Daniel Allen | Interim reviewer response | October 31, 2008 |
| D | Daniel Allen | Third release – Final reviewer response | November 7, 2008 |
| E | Daniel Allen | Fourth release – Incorporate comments from NHI and NGNP | November 28, 2008 |
| 0 | Daniel Allen | Document for release to WEC | December 3, 2008 |

# DOCUMENT TRACEABILITY

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|---|---|---|
| N/A | | |

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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |

| | |
|---|---|
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |

| | |
|---|---|
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |

| | |
|---|---|
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

The report documents the technology readiness evaluation of the prospective Hydrogen Production Systems (HPSs) for the NGNP with hydrogen production. The readiness evaluation consists of a look at the present Technology Readiness Levels (TRLs) and the plans to move forward to readiness for application to the NGNP Demonstration.

Included with the specific Technology Development Road Maps (TDRMs) are summaries of the plans for technology maturation.

In association with the general development plan and steps to maturation of the technology, the report identifies where the Component Test Facility can be used for the HPS technology advancement.

Test Plans for the Hybrid Sulfur thermo- electro-chemical water splitting technology are appended.

# 8 HYDROGEN PRODUCTION SYSTEM

Hydrogen production development is organized into four separate process technology areas. These are the following, and for each the Technology Development status, needs and plans are covered in a separate section following (Sections 8.1through 8.4):

1. Sulfuric Acid Decomposition (common to both Sulfur-Iodine and Hybrid Sulfur hydrogen production systems)
2. Sulfur Dioxide Electrolysis (principal step in Hybrid Sulfur thermo-electro-chemical water splitting)
3. Bunsen Reaction and HI Decomposition (steps in Sulfur-Iodine thermo-chemical water splitting)
4. High Temperature Steam Electrolysis

For each area the technology development needs and plans are addressed in two parts. First the design of the each technology area, as progressed to this point, is presented from the perspective of the functions, requirement of the process steps and in context of present design status and Design Data Needs (DDNs). Design status includes discussion of candidate designs, decisions already made, design options yet to be resolved and how they will be decided.

The second part of Technology Development is the path forward. This consists of the assessment of present Technology Readiness Level (TRL), the Technology Development Road Map (TDRM), which is a graphic format outline showing present status and plans to advance the TRL rank and the Technology Maturation Plans. For each of the four process technology areas, the TRLs, TDRMs and summary Maturation Plans are organized by subsystems in each of the technology areas. Within each subsystem only the Critical Systems, Structures and Components (SSCs) are evaluated for TRL.

Critical Systems, Structures and Components are those identified aspects or portions of the systems which must be developed prior to commercialization and are not commercially available or do not have proven industry experience.

**Technology Readiness Level (TRLs)**

TRL ranks for the Critical SSCs of the hydrogen generation process are assigned according to the definitions in Table 8-1, which is revised from Ref. 0. Note the addition of a rating "U" for the situations where requirements are undefined and technology readiness is unclear. This categorization is necessary for a few of the SSCs of the HPSs.

### Table 8-1: TRL Generic Definition

| Rating Level | |
|---|---|
| U | **Uncertain** at this phase in design and development. |
| 1 | **Basic principles observed** and reported in white papers, industry literature, lab reports, etc. Scientific research without well-defined application. |
| 2 | **Technology concept and application formulated.** Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation |
| 3 | **Proof-of concept:** Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service. |
| 4 | **Technology or Component is tested at bench scale to** demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties. |
| 5 | **SSC demonstrated at experimental scale in relevant environment**. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection. |
| 6 | **SSCs have been demonstrated at a pilot scale** in a relevant environment. |
| 7 | **SSCs integrated engineering scale** demonstration in a relevant environment. |
| 8 | **Integrated prototype of the SSC is demonstrated** in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for applicatrion. |
| 9 | **The project is in final configuration** tested and demonstrated in operational environment. |
| 10 | **Commercial-scale demonstration** is achieved. Technological risks minimized by multiple units built and running through several years of service cycles – Multiple Units |

Distinctions between TRLs are generally a function of three factors. These are 1) the scale of the technology demonstration, 2) the closeness of the design to prototype and 3) the extent to which test conditions match the operating conditions in application. Note also that, while not listed or quantified in the table, the duration and stability of demonstration tests is in most cases the test to pass to the next level.

In the listings following of present TRL ranking, a large number of supporting SSCs (in contrast to the systems that are the focus of hydrogen process development) can be seen to be TRL-6. This is the assignment where there will be no new technology required for the hydrogen process, only extension of present technology to more extreme operational environments and maybe new materials of construction. These technologies are clearly beyond experimental demonstration of feasibility (TRL-4) but no prototype has been tested in the operational environment (TRL-8). TRL-5, -6 and -7 are all demonstrations in relevant environments, and the gradation is on scale and closeness to prototype. Striking the middle value of TRL-6 seems logical.

Several places in this report specific hydrogen outputs, heat or power inputs, scale factors and scale-up steps are quantified. These are all estimates based the TDRMs developed here and on the present plans of the technology developers in the US DOE Nuclear Hydrogen Initiative (NHI) who have been consulted. Far more progress in development and work on specific designs is required before these numbers can be confirmed. They should be used only for general planning purposes and not as bases for design.

Where scale relative to the NGNP Demonstration or the NGNP commercial application is expressed, the reference plants are single nuclear reactor-powered units of 550MWt rating, and the sizes of the Hydrogen Production Facility in the NGNP Demonstration is based on thermal input of 50 MWt for the Sulfur-Iodine and Hybrid Sulfur technologies and 5 MWt for High Temperature Steam Electrolysis. The 50, 50 and 5 MWt numbers were preliminarily judged to correspond to the scale of the minimum commercially viable hydrogen production train for each of the three technologies [Ref. 0].

For each process concept the Hydrogen Production Facility is made up of the Hydrogen Production System and the Hydrogen Production Buildings and Structures. For discussion of technology development, the buildings and structures are assumed to be entirely commercially available or having proven industry experience. Therefore, the technology assessment following relates only to the Hydrogen Production Systems.

**Test Plans**

For the Hybrid Sulfur thermo- electro-chemical water splitting HPS, the Test Plans to accomplish the Maturation Plan are in Appendix C.

# 8.1 SULFURIC ACID DECOMPOSITION TECHNOLOGY AREA

## 8.1.1 SSC DESCRIPTION/ FUNCTION AND OPERATING REQUIREMENTS

This section is shared with the Sulfur-Iodine (S-I) thermo-chemical water splitting process and the Hybrid Sulfur (HyS) thermo- electro-chemical process. These are described in detail in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0]. The common subsection of the two process concepts that is addressed here are shown in Figures 8.1-1 and 8.1-2.

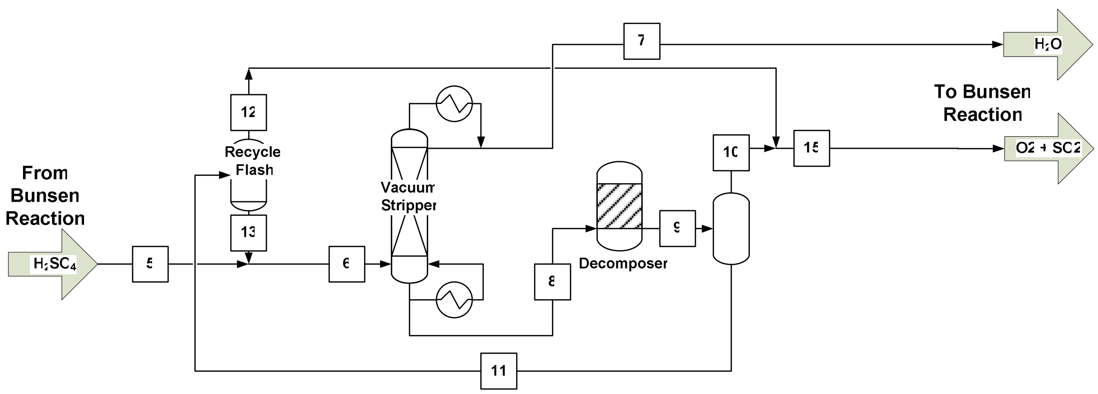


**Figure 8-1: Sulfuric Acid Decomposition Section in S-I**

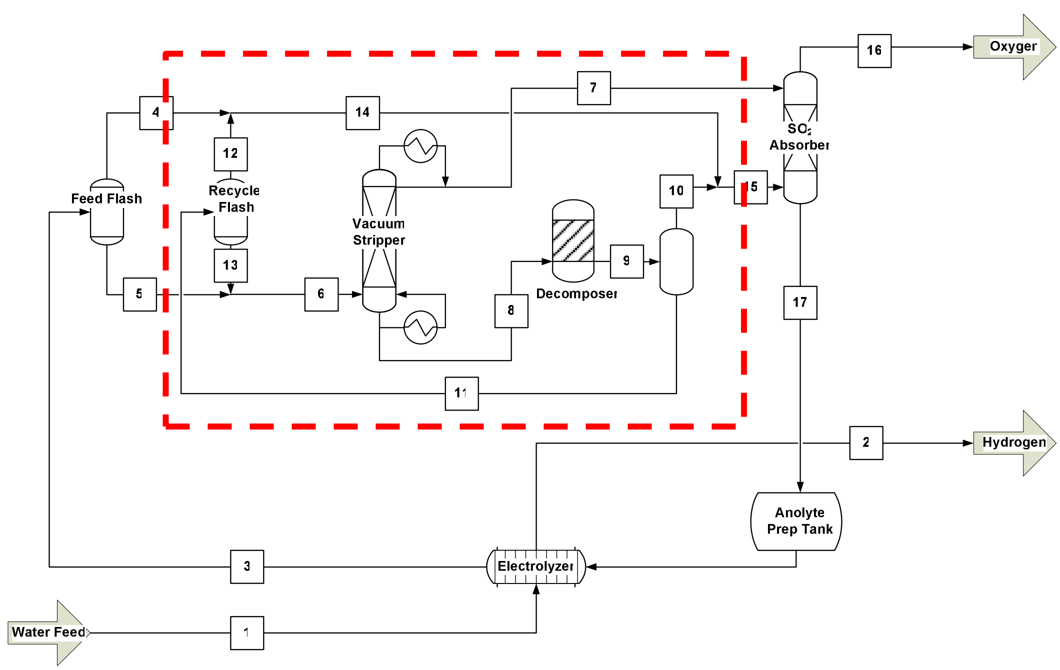

**Figure 8-2: Sulfuric Acid Decomposition Section in HyS**

The sulfuric acid decomposition subsection is made up of the Sulfuric Acid Decomposer, the Reactor Product and Recycle Flash System and the Vacuum Stripper System.

**Functions and Operating Requirements**

The Sulfuric Acid Decomposition section receives aqueous sulfuric acid at a concentration of 59% (weight percent). First the acid is concentrated to 75% and then thermally decomposed into oxygen, sulfur dioxide ($SO_2$) and water. The water is separated from the $SO_2$ and oxygen. The products are delivered to the subsequent sections of the respective HPS overall system (S-I or HyS). The water is delivered as liquid and the $SO_2$ and oxygen in the gas phase.

The system is further described in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

## 8.1.2 TECHNOLOGY/DESIGN SELECTION STATUS

### 8.1.2.1 Candidate Technologies

There are several preconceptual designs that have been proposed for the Acid Decomposer. In the most straight-forward design, the heat source is flowing helium, which would flow across or along the outside of tubes containing the process fluids in a shell-in-tube configuration.

Another concept that is under study in the DOE Nuclear Hydrogen Initiative has the features of a compact heat exchanger of the plate-fin or "printed circuit" construction [Refs. 0 & 0]. A novel feature of one embodiment of this concept is the inclusion of platinum catalyst in the material of a "printed circuit" heat exchanger [Ref. 0].

Two similar designs consider a bayonet tube configuration with the process flow in the tube and helium on the shell side. One has the tubesheet at the top and one at the bottom. These are the Westinghouse Electric Company (WEC) decomposer design [Ref. 0] and the Sandia National Laboratory (SNL) design [Ref. 0].

Also there are optional conventional technologies for acid concentration, such as using mechanically pumped vacuum or vapor compression, but since they are conceptually well developed, there is no justification for further discussion of the choice of vacuum flash with the vacuum provided by steam air ejectors. All of the alternatives are TRL 7.

### 8.1.2.2 Decision Discriminators

A tentative choice was made for the SNL decomposer design for the S-I ILS Experiment. The WEC design was proposed after that test was defined. In the TDRM the final decision is in sequence after a number of experimental and analytical tasks.

The decision on designs and materials for the Acid Decomposer will consider these factors:

- Corrosion resistance
- High temperature operation, especially thermal expansion
- Sealing and transition from ceramics to metals
- Thermal performance: (longitudinal and transverse temperature profiles in each tube and among tubes, recuperation, heat transfer rate)
- Ease of catalyst replacement
- Hydraulic performance: (need for gravity flow, even flow distribution between tubes, pressure drop, *etc*.)

#### 8.1.2.3 Reference Design

The Sulfur-Iodine (S-I) and the Hybrid Sulfur (HyS) processes and chosen designs are discussed in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

#### 8.1.2.4 Alternative for Further Evaluation

Alternatives already considered were mentioned in Section 8.1.2.1.

#### 8.1.2.5 Down-Selection Tasks

Decisions will be made on the alternatives at the Conceptual Design stage. Note in the TDRM that considerable additional testing and experimental development is charted ahead of Conceptual Design. (Considerable design work is also required before final selections can be considered.) Testing in full thermal and hydraulic similitude will be needed to establish a basis for performance going into the Conceptual Design.

Additional decision discriminators will be the performance in testing and anticipated operational features, such as fill and drain procedure, leak detectability, access for catalyst removal, *etc.*

#### 8.1.2.6 Design Data Needs (DDNs)

The Design Data Needs (DDNs) for the Sulfuric Acid Decomposition section are itemized in Table 8-2.

**Table 8-2: Sulfuric Acid Decomposition Section DDNs**

| DDN | Title |
|---|---|
| HPS-SAD-01 | Confirm Thermodynamic Data for the Sulfuric Acid Decomposition Process |
| HPS-SAD-02 | Develop a Commercial Sulfuric Acid Decomposition Catalyst |
| HPS-SAD-03 | Gather Decomposition Reaction Kinetics Data |
| HPS-SAD-04 | Test Silicon Carbide and other Ceramic Material in Decomposition Service |
| HPS-SAD-05 | Test Alloy 230 and Alloy 617 in a High Temperature Sulfuric Acid, Sulfur Dioxide, and Oxygen Atmosphere. |

| | |
|---|---|
| HPS-SAD-06 | Develop a Method to Bond Alloy 230 or Alloy 617 or Similar Materials to Silicon Carbide and other Ceramics. |
| HPS-SAD-07 | Develop Materials to Seal the Joints between Ceramic Decomposer Elements and the Metallic Tube Sheet or Vessel. |
| HPS-SAD-08 | Test a Pilot-Scale Decomposer. |
| HPS-SAD-09 | Provide Data Supporting a Design Code Case |
| HPS-SAD-10 | Develop Gasket Materials and Design |
| HPS-SAD-11 | Develop Seal Materials and Design |
| HPS-SAD-12 | Develop Welding Materials |
| HPS-SAD-13 | Develop Cladding and Coating Materials |
| HPS-SAD-14 | Develop Piping Materials and Design Methods |
| HPS-SAD-15 | Measure the Height Equivalent to a Theoretical Plate (HETP) for the Concentrator (Vacuum Tower) |
| HPS-SAD-16 | Measure the Height Equivalent to a Theoretical Plate (HETP) for the SO2 Absorber |

## 8.1.3 TRL STATUS

In summary, the current TRLs for the critical SSCs of the Sulfuric Acid Decomposition section are evaluated as in Table 8-3. The critical SSCs other than the Acid Decomposer and the Helium Control Valves are generally established technology lacking only design definition and/or the choice of and verification of materials compatibility for the operational environment.

**Table 8-3: Sulfuric Acid Decomposition Section TRLs**

| | TRL |
|---|---|
| Sulfuric Acid Decomposition Section | 3 |
| Acid Decomposer (decomposition reactor) [$H_2SO_4 \rightarrow ½O_2 + SO_2 + H_2O$] – including tubes, seals, manifolds and vessel | 3 |
| Tube Array | 4 |
| Manifolds and Seals | 4 |
| Vessel | 4 |
| Decomposer Catalyst | 3 |
| Decomposer product handling equipment | 6 |
| Acid concentration vacuum column | 6 |
| Feed acid handling and concentrating equipment | 6 |
| Steam ejectors and vacuum pump | 6 |
| Helium Control Valves | 4 |

| | |
|---|---|
| Sensors and Instruments | 6 |

In Appendix A1 are the detailed rating sheets of the TRLs for the five SSCs in Table 8.1-1 that make up the Sulfuric Acid Decomposition Section.

## 8.1.4 TECHNOLOGY DEVELOPMENT ROAD MAP SUMMARY

The Technology Development Road Map (TDRM) for the Sulfuric Acid Decomposition section, which is generally common to both the S-I and HyS HPSs, is in Appendix B1.

The S-I ILS Experiment is in progress and successful operation of the Acid Decomposer in the S-I ILS provides feasibility and functional demonstration and supports the computational modeling that has gone into the S-I and HyS flow sheets. The S-I ILS brings the Acid Decomposer to TRL 4.

Before a Pilot Test, further maturation of the technology will move along parallel tracks. One is for materials compatibility verification and another concerns the decomposition: verification of the equilibrium thermodynamic model and characterization of reaction kinetics. The third track is determination of a workable Decomposer Catalyst. These tests are essential to prove the technology is feasible and functional and to support analytical modeling. Thus, TRL 5 can be accomplished.

The Pilot test and balance of system tests are in sequence ahead of Conceptual Design. The Pilot test will be the first test in a fully relevant environment (*e.g.*- convective tube heating). Because it is also to be a full-scale test of one tube, the step to test at experimental-scale is skipped. The two alternative decomposer designs can be tested at this stage. With the Pilot test the technology goes to TRL 6.

The balance of the Sulfuric Acid Decomposition section consists of the feed and recycle concentration equipment and the effluent handling, for which tests are needed to advance their TRLs.

TRL 8 can be reached in two steps from the Conceptual Design: Engineering and Prototype Tests, both of which are multi-tube sections of a full-scale Acid Decomposer.

## 8.1.5 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL TO TRL 8)

Following are brief descriptions of the objectives of the nineteen tests shown with numbered ovals on the TDRM. More detailed Test Plans for these steps are in Appendix C.

**S-I Integrated Laboratory Scale (ILS) Experiment (#1)**

The S-I ILS, which is in progress, is a test of the SNL Acid Decomposer on a small scale and with heating from an electric furnace rather convective heating with helium. However, it is a significant test that will demonstrate feasibility and functionality. Test results will provide data to support further analytical modeling of the S-I and HyS cycles. Particular results anticipated are effects of catalyst and process side flow distribution. For the S-I process, but not HyS, this ILS will give initial data on time effects of iodine impurities on the decomposition process and on materials compatibility when operated for an extended period.

The completion of this test advanced the Acid Decomposer to TRL 4, skipping TRL 3, because operation in the S-I ILS accomplishes both proof of concept and demonstration of technical functionality.

**Materials Testing (#2)**

The S-I ILS Experiment will validate the compatibility of the SiC tubes with the process fluids, which is to be expected from initial decomposer demonstration tests. Separate tests are needed for materials other than the SiC tubes. In particular, the seals between the SiC tubes and their manifolds or tubesheets need to be tested in anticipated pulse and cycle conditions. For the S-I process the tests need to determine effects of iodine impurities on corrosion and seal life.

**Thermal-Hydraulic Analysis (#3)**

The alternative decomposer designs that are the most advanced (SNL and WEC, as described in Section 8.1.2.1) have significantly different fluid follow patterns, and this thermal-hydraulic analysis may be a discriminator in the choice of which design to carry forward to the Pilot Test. This task will require iteration with the Bench-scale Tests for Decomposer Catalyst Development to account for the effects of flow and temperature on the catalyst and the decomposition reaction.

**Acid Decomposer Data Verification (#4)**

Experimental confirmation of the equilibrium and kinetic model implicit in the simulations generated thus far are essential. Much of the modeling has involved extrapolations of data that need confirmation. Results will provide data to support further analytical modeling of the S-I and HyS cycles.

**Bench-scale Tests for Decomposer Catalyst Development (#5)**

The Decomposer Catalyst requires development testing to assure reasonable performance stability and lifetime, since periodic replacement is expected. Chemical industry practice would dictate a lifetime of 20,000 hours, which often can be established by accelerated testing.

The characteristic of the Decomposer Catalyst, combined with thermodynamic analyses, determines whether the Decomposer design is set by limits on heat transfer or by the Decomposer Catalyst performance, and this is essential input to the Conceptual Design. This task will require iteration with the Thermal-Hydraulic Analysis to account for the effects of flow and temperature on the Decomposer Catalyst and the decomposition reaction.

Catalyst bench testing will reveal the mechanisms and parameters of catalyst poisoning and degradation, and from those results one can initiate meaningful accelerated testing to support the overall HPS design.

The completion of this test will advance the Decomposer Catalyst to TRL 5, skipping TRL 4, because operation in the S-I ILS demonstrates technical functionality and in a relevant environment.

**HyS Integrated Laboratory Scale (ILS) Experiment (#6)**

An Integrated Laboratory Scale test is in the program plan for the HyS process development. The HyS ILS is to use the same or an improved Acid Decomposer based on the design of the S-I ILS, according to present plans. The alternative WEC decomposer design needs to be considered for the Acid Decomposer in the HyS ILS, in which case the Conceptual Design would have the test results from each decomposer design to choose from.

Note that the HyS ILS will not advance the Decomposer technology to a higher level.

**Technology Decision Point (#7)**

The two alternative designs for the Decomposer (WEC and SNL) may need to be carried to this stage in development to discriminate sufficiently to make a final choice. The principal factors in the choice will be the feasibility and buildability as determined by the testing of the materials of construction and the catalyst and by the verified thermodynamic data. Other discriminators will be the relative technology readiness, economics of the cycle in application and schedule and risk in the context of the overall programmatics.

**Pilot Test (#8)**

The combined tests and analyses following the ILS Experiment will bring the Acid Decomposer to TRL 5. At this point in development a decision can be made on the preferred concept (SNL or WEC, as described in Section 8.1.2.1) to carry forward.

In the Pilot Test a full-scale-length, single-tube, convection-heated bayonet tube assembly will be tested at design conditions. The test assembly will also include a reference sealing configuration and replaceable catalyst to verify the function of these features. This will be the first test with helium convective heating, rather than furnace heating, of the Decomposer. Only in this configuration are the catalyst bed and wall temperature profiles correct in detail. Helium flow in this test can be in one end and out the other, in contrast to the Engineering Test for which the flow return to the same end as entry will be required.

Possibly this test (and the later Engineering and Prototype Tests) could be conducted at a sulfuric acid plant, since sulfuric acid decomposition is nothing more than undoing what a sulfuric acid plant does. It would draw a continuous feed from the plant and put its effluent product back into their feed.

A nominal goal of 1000 hours of steady operation without degradation of performance exceeding 5% per 1000 hours would constitute success. Ideally, the testing would also include startup, shutdown and accident transients to the degree confirmed at that design phase.

The test provides the thermal and hydraulic data needed for integration of the decomposer into the HPS, either S-I or HyS. The single full-length tube will have been tested at relevant conditions and so this will advance the TRL of the Acid Decomposer to TRL 6.

Integration of this test with the HyS ILS should be considered for program efficiency.

**VLE Data Verification (#9)**

The design of the reactor product and recycle concentration system requires verification and refinement of the vapor-liquid equilibrium data.

**Vacuum Stripper Tower Design Data (#10)**

Determinations of mass transfer coefficients or Heights Equivalent to the Theoretical Plate (HETPs) are needed along with good VLE data in order to confidently design this tower and, for the HyS system, the $SO_2$ absorber.

A vendor would supply a suitable packing that will be tested to measure an HETP or mass transfer coefficient. It may be useful also to do small bench scale tests to determine whether and how much the mass transfer in this system of components and conditions deviates from that of similar known systems.

**Decomposer Product Materials Test (#11)**

The materials of construction of the decomposer product handling equipment need to be tested for compatibility. Because of the effects of material transport, simple immersion of material coupons will not be sufficient. A circulating test loop should be considered.

**Feed Handling Materials Test (#12)**

Testing of the materials of construction feed acid handling and concentrating equipment and the verified VLE data completes development to the TRL 8 level for prototype application.

**Valve Test (#13)**

The valves that control the flow of high-temperature helium in the NHSS Secondary Heat Transport System (SHTS) between series and parallel PCHXs (the number of which is dependent on the process – S-I or HyS – and on the scale of eventual application) are part of the HPS. These valves are not anticipated to be new technology, but they are critical SSCs because there is no recent industrial experience with such valves. The valves will need verification testing. These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application, and therefore experience with smaller valves will not apply. Once the technology is validated at the pressures and temperatures of the NGNP application, the TRL will advance from 4 to 8.

**Sensor Tests (#14)**

Thermocouples, pressure sensors and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing the sensors are TRL-8.

**Decomposer Model (#15)**

A computational model of the Conceptual Design unit in a system will be based on data from the Pilot-scale Test testing. This computer model will provide a basis for design of the Engineering Test unit and confidence that the results of the Engineering Test will work in the NGNP Demonstration.

**Engineering Test (#16)**

In order to reach TRL 7 there needs to be a further scale-up and approach to prototype configuration. The test proposed is for a hexagonal matrix of 19 full-length tubes with helium heating. In such a configuration the central 5 tubes would be tested in full-scale thermo-hydraulic conditions on the outside, and likewise for the process flow in the tubes.

Note that this test precedes the Final Design and so will not necessarily include the prototypical tube seals, process side valves or instrumentation sensors. The test will provide design verification for these components.

The goal is 1500 hours of steady operation without degradation of performance exceeding 2% per 1000 hours

**System Model (#17)**

The input from the Acid Decomposer calculational model will be used in the S-I and HyS HPS models.

**Prototype Test (#18)**

This final test in the sequence of technology maturation would be the same configuration as the Engineering Test but with the final design features including the prototype seals, valves and instruments. The testing would cover the full operational environment and through the design cycles as determined by final system design. In addition, stable operation (less than 1% decline per 1000 hours) for a time period, 2000 hours, would be expected. This is full prototypic testing of a full-scale section of the Decomposer and constitutes advancement to TRL 8.

**Sulfuric Acid Decomposition Section for S-I or HyS Development (#19)**

The Sulfur Dioxide Electrolysis and the Bunsen Reaction and HI Decomposition TDRMs show system tests which would require a Sulfuric Acid Decomposition Section. These are discussed in Sections 8.2.5 and 8.3.5.

A S-I Systems Engineering Testis in the Bunsen Reaction and HI Decomposition TDRM is an optional step before the NGNP, and that will have integrated an Sulfuric Acid Decomposition Section approximately 1/20 of the NGNP size. This would be a design derived from the Acid Decomposer Engineering Test.

An optional HyS Systems Engineering Tests is shown in the Sulfur Dioxide Electrolysis TDRM before the NGNP, and that would have an Sulfuric Acid Decomposition Section of as yet undetermined size. This could be also a design derived from the Acid Decomposer Engineering Test.

Neither of these tests or test articles is essential to the Sulfuric Acid Decomposition technology development, but their execution would support the other steps and as a minimum reduce risk in the final application. In addition, use of the Acid Decomposer developmental test article might be cost effective for the $SO_2$ supply needed for these other tests.

## 8.1.6 INPUTS TO CTF

The TDRM for the Acid Decomposer has two scale-up steps after the S-I ILS. The first is to the Pilot Test, which is one full-length Decomposer tube. The thermal power for the convective helium heat input to one tube depends on the number of tubes and the total Decomposer heat duty. For planning purposes one can calculate from the WEC decomposer design [Ref. 0] that one tube has a heat duty that would require several hundred kWt for the test facility. This might not require a special facility for testing, if local electric heating can be provided. The Helium Testing Facility (HTF) of PBMR in South Africa, for example, might be modified for this test.

The next step is a 19-tube assembly that would, if calculated on the same basis require helium heating of several MWt. The CTF would be used for this level of heating.

# 8.2 SULFUR DIOXIDE ELECTROLYSIS TECHNOLOGY AREA

## 8.2.1 SSC DESCRIPTION/ FUNCTION AND OPERATING REQUIREMENTS

The Hybrid Sulfur (HyS) thermo- electro-chemical water splitting HPS is made up of the following systems. There are three major systems and of these, the Sulfuric Acid Decomposition System is partially the same as the Sulfuric Acid Decomposition System addressed in Section 8.1. The three systems marked with asterisks are those that are covered in Section 8.1 and are not discussed further here.

- Sulfuric Acid Decomposition System (SAD)
  - Acid Concentration System *
  - Acid Steam Preheater and Vacuum Stripping *
  - $H_2SO_4$ Decomposition and Acid Separation *
  - Anolyte Processing
  - $SO_2$ Recovery System
  - $SO_2$ Compression
- Electrolyzer System (ELE)
  - $SO_2$ Electrolysis Cells
  - Electrolyzer Internal Components
  - Electrolyzer Module Pressure Boundary
- Feed and Utility System (FUS)
  - Acid and Caustic Storage
  - Water Treatment
- Product Purification System (PPU)
  - $H_2$ Compression and Drying
  - $H_2$ Purification System
  - $O_2$ Purification System
- Instrumentation and Control (I&C) System

A schematic flow diagram of the HyS process is shown in Figure 8-3.

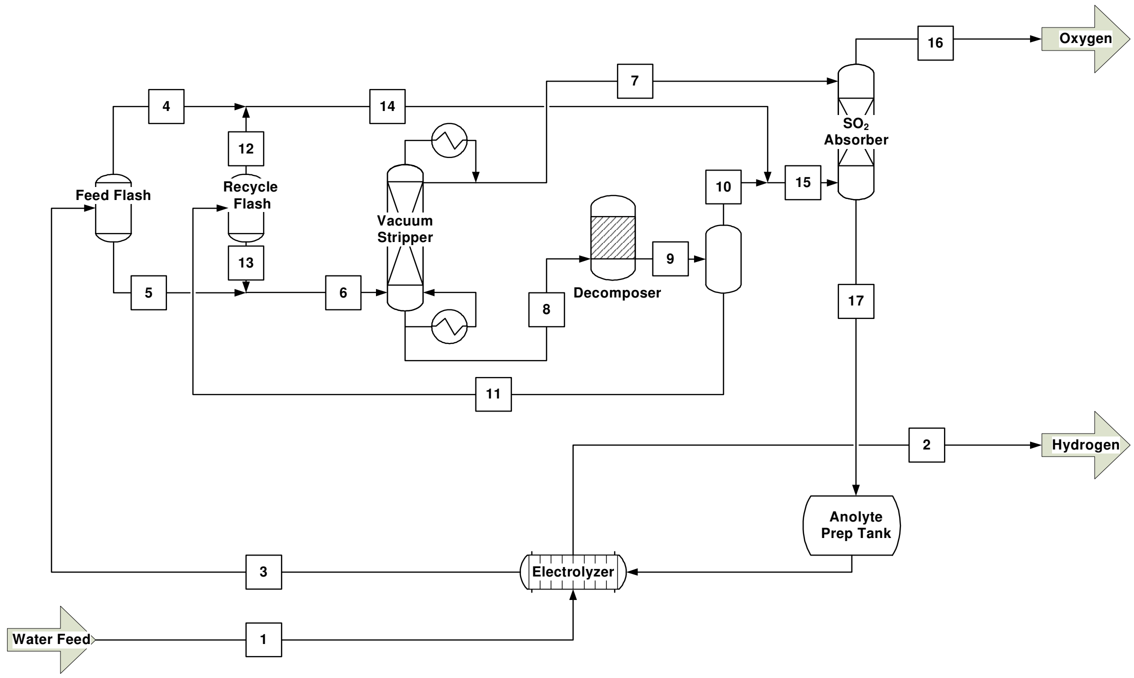


**Figure 8-3: Hybrid Sulfur Cycle**

**Functions and Operating Requirements**

The Sulfur Dioxide Electrolysis section of the HyS HPS accepts the output of the Acid Decomposer. It separates the sulfuric acid ($H_2SO_4$) and water for concentration and recycle from the sulfur dioxide ($SO_2$) and oxygen ($O_2$), and then in multi-cell Sulfur Dioxide Electrolyzers converts water and the $SO_2$ into $H_2SO_4$ and the hydrogen product.

The system is further described in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

## 8.2.2 TECHNOLOGY/DESIGN SELECTION STATUS

### 8.2.2.1 Candidate Designs

The focus of the HyS technology development is the $SO_2$ Electrolyzer cell. Alternate configurations and materials have been proposed for the cells. The membrane-electrode assembly (MEA) consists of one of several choices of proton exchange membranes coated with alternative electrode layers.

### 8.2.2.2 Decision Discriminators

The early phase of HyS electrolysis cell development has consisted of experimental testing of various MEAs in different configurations within a systematic approach. The process going forward will be successive interaction between design and experimental functions to iteratively arrive at an optimum electrolyzer sized for practical and economical application to the HyS HPS.

#### 8.2.2.3 Reference Design

The HyS process and design used as a reference for this Technology Development analysis are presented in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

#### 8.2.2.4 Design Data Needs (DDNs)

The Design Data Needs (DDNs) for the Sulfur Dioxide Electrolysis technology area are itemized in Table 8-4.

**Table 8-4: Sulfur Dioxide Electrolysis DDNs**

| DDN | Title |
|---|---|
| **Design Data Needs for Feed Purification (FUS)** | |
| HPS-FUS-01 | Identify Critical Impurities and Determine Critical Component Tolerance |
| HPS-FUS-02 | Develop Feed Water Purification Methods |
| HPS-FUS-03 | Develop Process Fluid Purification Methods |
| **Design Data Needs for the Electrolyzers (ELE)** | |
| HPS-ELE-01A | Develop a Cell Membrane |
| HPS-ELE-02 | Optimize Catalyst Loading in the Electrodes |
| HPS-ELE-03 | Develop a Cell Configuration and Materials |
| HPS-ELE-04 | Build and Test a Laboratory-scale Cell |
| HPS-ELE-05 | Build and Test Pilot-scale Cells |
| HPS-ELE-06 | Build and Test a Stack of Cells at Engineering Scale |
| **Design Data Needs for Product Purification (PPU)** | |
| HPS-PPU-01 | Identify Product Impurities |
| HPS-PPU-02 | Test Product Purification Methods |
| **Design Data Needs for Instrument and Controls (PCN)** | |
| HPS-PCN-01 | Test Sensors in the Pilot Plant |
| HPS-PCN-02 | Develop Valves for High-Temperature Acid and/or Helium Service |
| HPS-PCN-03 | Test Valves in the Pilot Plant |

## 8.2.3 TRL STATUS

In summary, the current TRLs for the critical SSCs of the Sulfur Dioxide Electrolysis technology area are evaluated as in Table 8-5.

**Table 8-5: Sulfur Dioxide Electrolysis TRLs**

| | TRL |
|---|---|
| Electrolyzer System (ELE) | 2 |
| $SO_2$ Electrolysis Cells | 3 |
| Electrolyzer Internals | 2 |
| Electrolyzer Module Pressure Boundarys | 5 |
| $SO_2$ portions of the Sulfuric Acid Decomposition System (SAD) | 6 |
| $SO_2$ Absorber | 6 |
| Feed and Utility System (FUS) | - - |
| Water Treatment System | U |
| Instrumentation and Control (I&C) System – including sensors | 6 |

In Appendix A2 are the detailed rating sheets of the TRLs for the seven bottom-tier SSCs in Table 8.2-1 that are not rated TRL 8.

## 8.2.4 TECHNOLOGY DEVELOPMENT ROAD MAP SUMMARY

The Technology Development Road Map (TDRM) for Sulfur Dioxide Electrolysis is in Appendix B2. TRL 8 for the technology requires the design and development of an $SO_2$ Electrolyzer Module that is scaled appropriately such that a reasonable number of the units can be combined with the Sulfuric Acid Decomposition section to make up the HyS HPS for an NGNP heat source.

From the individual $SO_2$ cells being tested today there will be scale up in three steps: from the present 160 $cm^2$ of cell demonstration to 400 $cm^2$, then to 1000 $cm^2$ and finally to one square meter. Cells would be assembled in to $SO_2$ Electrolyzer Modules of progressively larger power input and hydrogen output. Although subject to further definition in the design process, the final $SO_2$ Electrolyzer Module for the NGNP Demonstration would be sized so that about 20 modules would comprise the HyS HPS. Since the NGNP commercial plant is to have ten such trains of the HPS, the eventual NGNP commercial application would have about 200 of the finally developed $SO_2$ Electrolyzer Modules.

Scale-up proposed for planning purposes and shown in the TDRM is approximately as follows:

| | Module Basis | System Basis |
|---|---|---|
| ILS to Pilot | x 140 | - - |
| Pilot to Engineering | x 10 | - - |
| Engineering to System Prototype | x 1.5 | - - |
| System Prototype to NGNP Demonstration Plant | x 1 | x 20 |
| NGNP Demonstration Plant to NGNP Commercial Plant | - - | x 10 |

In addition, demonstrations will be done on the $SO_2$ Recovery System, the Feed Purification System and the Instrumentation and Control system. These are conventional systems that can be assembled in prototype at sub-scale to bring them to TRL 8 in one step.

## 8.2.5 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL TO TRL 8)

Following are brief descriptions of the objectives of the sixteen tests shown with numbered ovals on the TDRM. More detailed Test Plans for these steps are in Appendix C.

**Cell Stability Demonstration (#1)**

Basic issues of cell degradation, due for example to migration of constituents across cell membranes, will be resolved through interaction of design and experiment.

**Single Cell testing at 100ºC, 10 atm (#2)**

Tests up to this point are in laboratory environment. This test is at elevated temperature and at pressure, as is the application. The stability demonstration and this test at relevant conditions accomplish TRL 4.

**Integrated Lab Scale Experiment (#3)**

This test will combine a small-scale Decomposition section to demonstrate the HyS cycle. As noted in the Sulfuric Acid Decomposition TDRM (Section 8.1.5), this could be combined with the Pilot Test of the Acid Decomposer.

**Optimized Cell Assembly Demonstration (#4)**

In parallel with the ILS and Preconceptual Design, the electrolysis cell design and materials will be reoptimized. This is an additional step in iteration of design and experiment.

### Cell Scale-up to 400 $cm^2$ (#5)

The plan has Electrolyzer Cells scaled-up from the ILS size in two steps – these correspondingly after Preconceptual and Conceptual Design. Cell scale-up to 400 $cm^2$ plus the ILS operation constitute experimental demonstration and advance Sulfur Dioxide Electrolysis to TRL 5. Note that this scale-up follows a step of Fabrication Development, which will transition the overall R&D from laboratory orientation to manufacturing orientation. The Fabrication Development envisions significant participation by a commercial entity with some relevant experience.

### Electrolyzer Module Internals Test (#6)

Following Preconceptual Design of the Electrolyzer Module Pressure Boundary, the Module Internal design will be tested. At this stage all components of the Electrolyzer Module (sells, internals and vessel) are TRL 5, because they are defined and demonstrated on experimental scale.

### Structural Test (#7)

The design requierements of the vessel or pressure retaining exterior boundary for the $SO_2$ Electrolysis Cell is not finally determined. However, there is a preferred concept of a pressurized module which qualifies for TRL-5 because it is defined and has been modeled analytically. It would be tested separately for pressure retention and material compatibility and then used in the Electrolyzer Pilot-scale Test.

### Electrolyzer Pilot-scale Test (#8)

This is the first test of an electrolyzer with 400 $cm^2$ cells and the first test of the Module Pressure Boundary and module internals. For this test the nominal goals, which are subject to change as the R&D program proceeds along the Road Map, are as follows:

| | |
|---|---|
| Electrolyzer | |
| Avg. cell voltage, mV | 700 |
| Current Density, mA/$cm^2$ | 500 |
| Cell Active Area, $cm^2$ | 400 |
| HyS System | |
| Hydrogen output, ℓ/h | 28,000 |
| Hydrogen output, kW (HHV) | 70 |
| Process heat input, kWt | 200 |
| Process electrical input, kWe | 100 |
| Time on line, hours | 1000 |

### Electrolyzer Engineering-scale Test (#9)

This is a test of one electrolyzer with full-scale cells (1000 $cm^2$) following Conceptual Design. It will suffice as an engineering scale test since this is the final electrolyzer scale-up, although not yet prototypical. Testing will not necessarily be to the full range of transients, and so the test will advance the TRL from 6 to 7.

The nominal goals of this test are as follows:

| | |
|---|---|
| Electrolyzer | |
| Avg. cell voltage, mV | 650 |
| Current Density, mA/cm$^2$ | 500 |
| Cell Active Area, cm$^2$ | 1000 |
| HyS System | |
| Hydrogen output, ℓ/h | 280,000 |
| Hydrogen output, kW (HHV) | 1000 |
| Process heat input, kWt | 2000 |
| Process electrical input, kWe | 1000 |
| Time on line, hours | 1500 |

**Prototype Electrolyzer Test (#10)**

This test will also be of one electrolyzer. It will be the full-scale prototype resulting from Final Design with the cell scaled up in area from 1000 cm$^2$ to 1 m$^2$. The heat and power input and the hydrogen output in this test will be only 1.5 times that of the Electrolyzer Engineering-scale Test.

It is anticipated that this test would be performed in the same facility as the Engineering Test. Tests will be in the operational environment and cover the appropriate number and duration of tests. This will accomplish TRL 8 for the Electrolyzer Module.

The goal of this test is 2000 hours of operation with production on the order of 420 Nm$^3$ of hydrogen per hour and stability of less than 1% decline per 1000 hours.

$SO_2$ Absorber Demonstration Test (#11)

System feasibility and functionality for the system can be assured from general industry experience, but design data is needed in the operating environment. Specifically for mass transfer in the $SO_2$ absorber column, the Heights Equivalent to the Theoretical Plate (HETPs) need to be experimentally determined. In order to be applied to the NGNP, sub-scale demonstration testing of the $SO_2$ Recovery System in the operational environment is expected. This is a jump from TRL 6 to TRL 8.

**Feed Purification System Demonstration Test (#12)**

There are a number of proven water purification processes that can provide ultra-pure water, but without requirements the scope of development of this SSC is uncertain.

System Modeling (#13)

Demonstration of integrated operation can be done by computer simulation given input of the performance of the discrete components in prototype or pilot testing in their operational environments. Results will be input to the final System Design.

**Sensor Tests (#14)**

Thermocouples, pressure sensors and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing the sensors are TRL-8.

**Prototype HPS Test (#15)**

This test is intended to be an assembly of one or more of the Prototype Electrolyzers from the previous test with a scaled-down Acid Decomposer section. It is not clear that this test is needed, because separate testing of the Acid Decomposer and one Prototype Electrolyzers with transfer of feed and products between them could be sufficient to assure TRL 8. Integrated operation would be demonstrated by analysis.

**Continuing Cell Testing (#16)**

As cell stack and system tests proceed, there is a need to accumulate lifetime data and quantify long-term degradation. One or more cell tests should continue after the cell scale-up to one square meter. The attainment of TRL levels elsewhere on the Road Map would be supported by the Continuing Cell Testing according to the criteria in Table 8-6.

**Table 8-6: Duration and Maximum Rates Degradation for Cell Tests**

| TRL | Max. rate of degradation | Minimum test duration |
|---|---|---|
| 4 | 20%/1000 hours | 500 hours |
| 5 | 10%/1000 hours | 1000 hours |
| 6 | 5%/1000 hours | 2000 hours |
| 7 | 2%/1000 hours | 5000 hours |
| 8 | 1%/1000 hours | 10,000 hours |

## 8.2.6 INPUTS TO CTF

The specific tests in the TDRM for Sulfur Dioxide Electrolysis do not particularly require the CTF. The optional Prototype HPS Test would incorporate an Acid Decomposer section and require some helium heating. If one prototype electrolyzer module it tested and that is on the order of 1/20 of the NGNP Demonstration plant output, several MWt of helium heating would be needed. The CTF would likely be used for this test.

# 8.3 BUNSEN REACTION AND HI DECOMPOSITION TECHNOLOGY AREA

## 8.3.1 SSC DESCRIPTION/ FUNCTION AND OPERATING REQUIREMENTS

The Bunsen Reaction and HI Decomposition technology area is part of the Sulfur-Iodine (S-I) thermochemical water splitting process. Combined with the Sulfuric Acid Decomposition section this makes up the S-I HPS. The S-I HPS has been discussed in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0]. The Bunsen and HI Decomposition sectionss are comprised of the following systems and major components:

1. Bunsen Reaction Section (Section 1 - reference version: Co-Current Reactor)
    a. Bunsen Reactor [ $I_2 + SO_2 + 2\ H_2O \rightarrow H_2SO_4 + 2\ HI$ ]
    b. Three-Phase Separator
2. HI Distillation Section (Section 3 - reference version: Reactive HI Distillation)
    a. Reactive Still [ $2\ HI \rightarrow I_2 + H_2$ ]
    b. Recuperators
    c. Process Coupling Heat Exchanger
    d. Power Recovery System
3. Balance of S-I Plant
    a. Feed Purification
    b. Product Purification
    c. Instrumentation and Controls

A schematic flow diagram of the Bunsen and HI Decomposition sections of the S-I HPS are shown in Figure 8-4 and Figure 8-5.

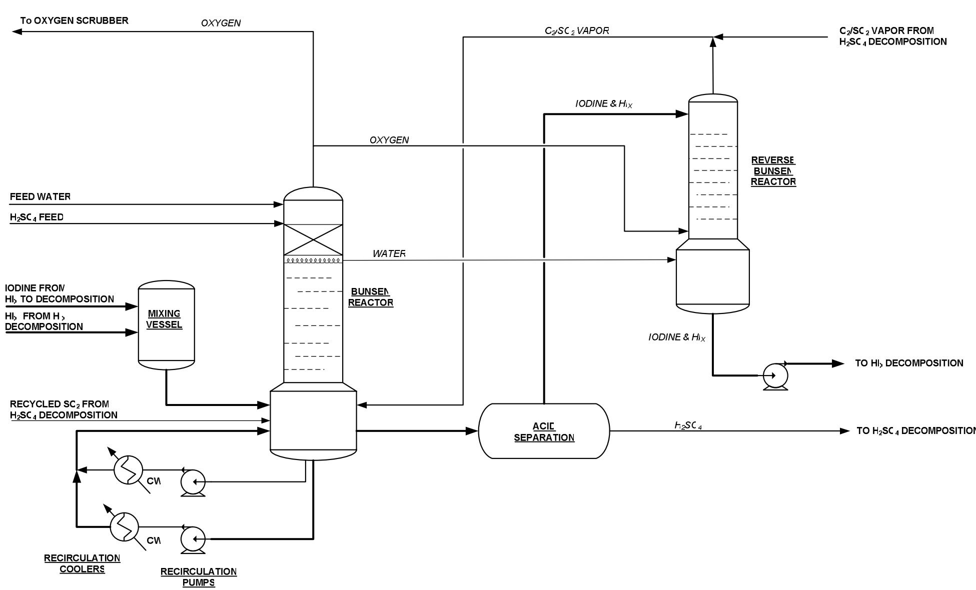

**Figure 8-4: Bunsen Section**

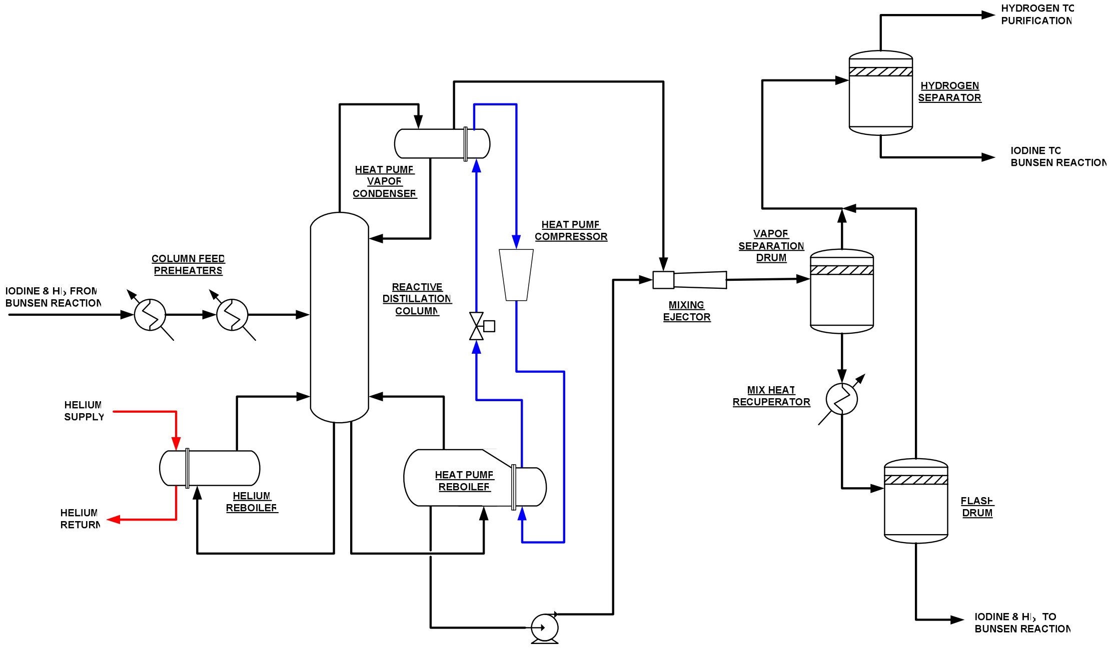


**Figure 8-5: HI Decomposition Section**

**Functions and Operating Requirements**

The Bunsen Reaction section of the S-I cycle ideally receives feed water ($H_2O$), sulfur dioxide ($SO_2$) from the Acid Decomposer section and iodine ($I_2$) from the HI Decomposition section and produces sulfuric acid ($H_2SO_4$) and hydro-iodic acid (HI). This is an exothermic reaction requiring cooling that is run at about 100°C. In actuality the cycle flowsheets balance with significant water, $H_2SO_4$ and HI recirculation.

In the HI Decomposition section HI is decomposed into $I_2$ and $H_2$ and these two separated. The reaction is endothermic, and so heat is added from the nuclear heat supply secondary helium circuit through a Process Coupling Heat Exchanger (PCHX) in order to maintain at from 300 to 400°C. The $I_2$ is recycled to the Bunsen Reaction section and the $H_2$ is delivered as product after purification.

The two systems are further described in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

## 8.3.2 TECHNOLOGY/DESIGN SELECTION STATUS

The three sections of the S-I cycle have been demonstrated separately in the laboratory and in small-scale glass apparatus. In addition, although there has been no final selection of the optimum alternatives from among various approaches, integrated systems have been assembled and tested. Testing of a complete system was reported in Japan several years ago [Ref. 0] and the S-I Integrated Laboratory Scale (ILS) Experiment is in work under an International Nuclear Energy Research Initiative (I-NERI) as part of the US DOE Nuclear Hydrogen Initiative (NHI).

These experiments are running ahead of S-I system design, which is only reaching Preconceptual Design phase. This Hydrogen Plant Alternatives Study is an initial step in that Preconceptual Design.

#### 8.3.2.1 Candidate Designs

Each of the three sections of the S-I cycle has two or more alternative candidate designs. The Sulfuric Acid Decomposer alternates are addressed in Section 8.1.2.1. The Bunsen Reaction section has the alternatives of a co-current reactor with separate phase separation and counter current reactor with integral phase separation. The former has been conceptually considered and used in flowsheets developed in the U.S. The latter is the design of the Commissariat à l'Énergie Atomique (CEA) which was developed under a US DOE International Nuclear Engineering Research Initiative (I-NERI) and has been selected for the S-I ILS.

There are two HI Decomposition section designs proposed. Distillation by extraction with phosphoric acid is the method chosen for the S-I ILS based upon the recommendation of the CEA. Reactive distillation is proposed for the NGNP and eventual commercial application.

#### 8.3.2.2 Decision Discriminators

In all cases of choices made thus far the discrimination has been a trade-off of the minimum critical path to demonstration *versus* the estimated cycle efficiency and anticipated cost to commercially produce hydrogen.

#### 8.3.2.3 Reference Design

The S-I process and design used as a reference for this Technology Development analysis are presented in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

#### 8.3.2.4 Design Data Needs (DDNs)

The Design Data Needs (DDNs) for the Bunsen Reaction and HI Decomposition Section are itemized in Table 8-7.

**Table 8-7: Bunsen Reaction and HI Decomposition Section DDNs**

| DDN | Title |
|---|---|
| **Design Data Needs for Feed Purification (FUS)** | |
| HPS-FUS-01 | Identify Critical Impurities and Determine Critical Component Tolerance |
| HPS-FUS-02 | Develop Feed Water Purification Methods |
| HPS-FUS-03 | Develop Process Fluid Purification Methods |

| | |
|---|---|
| **Design Data Needs for Bunsen Reaction (BUN)** | |
| HPS-BUN-01 | Confirm Thermodynamic Data for the Bunsen Reaction Process including Phase Equilibria |
| HPS-BUN-02 | Gather Kinetic and Mass Transfer Data for the Bunsen Reaction in the proposed reactor configuration |
| HPS-BUN-03 | Develop Gasket Materials and Design for Bunsen Reaction Environment |
| HPS-BUN-04 | Develop Seal Materials and Design for Bunsen Reaction Environment |
| HPS-BUN-05 | Develop Welding Materials for Bunsen Reaction Environment |
| HPS-BUN-06 | Develop Cladding and Coating Materials for Bunsen Reaction Environment |
| HPS-BUN-07 | Develop Piping Materials and Design Methods for Bunsen Reaction Environment |
| Design Data Needs for Hydroiodic Acid Decomposition (HID) | |
| HPS-HID-01 | Demonstrate Hydroiodic Acid Reactive Distillation Decomposition in Principle |
| HPS-HID-02 | Confirm Thermodynamic Data for the Hydroiodic Acid Decomposition Process including Phase Equilibria |
| HPS-HID-03 | Develop commercial HI Decomposition Catalyst |
| HPS-HID-04 | Gather Kinetic and Mass Transfer Data for the Hydroiodic Acid Decomposition in the proposed reactor configuration based on the commercial catalyst |
| HPS-HID-05 | Develop Gasket Materials and Design for Hydroiodic Acid Decomposition Environment |
| HPS-HID -06 | Develop Seal Materials and Design for Hydroiodic Acid Decomposition Environment |
| HPS-HID -07 | Develop Welding Materials for Hydroiodic Acid Decomposition Environment |
| HPS-HID -08 | Develop Cladding and Coating Materials for Hydroiodic Acid Decomposition Environment |
| HPS-HID-09 | Develop Piping Materials and Design Methods for Hydroiodic Acid Decomposition Environment |
| **Design Data Needs for Product Purification (PPU)** | |
| HPS-PPU-01 | Identify Product Impurities |
| HPS-PPU-02 | Test Product Purification Methods |
| **Design Data Needs for Instrument and Controls (PCN)** | |
| HPS-PCN-01 | Test Sensors in the Pilot Plant |
| HPS-PCN-02 | Develop Valves for High-Temperature Acid Service |
| HPS-PCN-03 | Test Valves in the Pilot Plant |

# 8.3.3 TRL STATUS

The three sections of the S-I cycle have been demonstrated separately in the laboratory and in small-scale glass apparatus. However, the three sections tested do not have the same flow sheets as the reference designs for nuclear hydrogen production with the NGNP. The useful results from these tests are the basis for the S-I ILS Experiment. For the Bunsen section the concepts have been formulated and issues related to performance are identified. General proof of principle was demonstrated and critical functions proven. These put the Bunsen section at TRL 3.

The HI Decomposition section of the ILS, however, was a solvent extraction cycle not the reference concept, which is reactive distillation, and so that section remains TRL 2.

In summary, the current TRLs for the Bunsen Reaction and HI Decomposition sections are evaluated as in Table 8-8.

**Table 8-8: Bunsen Reaction and HI Decomposition Section TRLs**

| | TRL |
|---|---|
| Bunsen Reaction System | 3 |
| Bunsen Reactor -- including seals and vessel | 3 |
| Three-Phase Separator | 3 |
| HI Decomposition Systems | 2 |
| Reactive Still -- including catalyst, seals and vessel | 2 |
| Process Coupling Heat Exchanger | 5 |
| Power Recovery System | 6 |
| Balance of S-I Plant | 6 |
| Reactor Product Handling Equipment | 6 |
| Feed Purification | U |
| Product Purification | U |
| Helium Control Valves | 4 |
| Instrumentation and Controls -- including sensors | 6 |

In Appendix A3 are the detailed rating sheets of the TRLs for the ten SSCs in Table 8.3-3 that make up the Bunsen Reaction and HI Decomposition sections.

## 8.3.4 TECHNOLOGY DEVELOPMENT ROAD MAP SUMMARY

The Technology Development Road Map (TDRM) for Bunsen Reaction and HI Decomposition is in Appendix B3. From today's status, the next step is for the reactive HI distillation concept to be brought up to the same level of proof of concept that the Bunsen Reaction Section design will have reached at the end of the S-I ILS Experiment. Following that will be the Preconceptual Design of a flowsheet and components that will meet the performance goals of the NGNP. Then the steps to TRL 8 are successive tests of scaled-up assemblies.

The Preconceptual Design will lead to Experimental-scale tests of the Bunsen Reaction Section and the HI Decomposition Section separately to demonstrate progress in basic unit operations and to confirm the design. The two sections will then be combined for integrated operation into a Pilot-scale Test, the results of which will support Conceptual Design.

The next juncture on the Road Map is a Bunsen & HI Sections Engineering Scale Test. This should bring these sections of the S-I HPS to readiness for the NGNP Demonstration where they would be combined with the Sulfuric Acid Decomposition section. However, if necessary could be a S-I System Engineering Prototype Test including the Sulfuric Acid Decomposition Section.

Scale-up proposed for planning purposes and shown in the TDRM is approximately as follows:

| | |
|---|---|
| ILS to Pilot | x 100 |
| Pilot to Engineering | x 20 |
| Engineering to NGNP Demonstration Plant | x 20 |
| NGNP Demonstration Plant to NGNP Commercial Plant | x 10 |

## 8.3.5 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL TO TRL 8)

Following are brief descriptions of the objectives of the thirteen steps shown with numbered ovals on the TDRM.

**S-I ILS Experiment (#1)**

This is a presently ongoing system test. The apparatus has advanced from glass laboratory assembly to metal and SiC in contact with the process fluids. A major distinction is that the HI Distillation section is not of a design that appears to be feasible in a commercial application, because of the low overall system efficiency. Therefore, this system test advances only the Bunsen section to TRL 4. The development skips TRL 3, because operation in the S-I ILS accomplishes both proof of concept and demonstration of technical functionality.

**Kinetic and Thermodynamic Data (#2)**

In order to design the HI reactive distillation section the reaction kinetic and thermodynamic data is required. At this point in development of the reactive distillation option, thermodynamic and mass transfer data have been approximated and/or extrapolated. The cycle requires work (electric power) input, and the calculation of this is indeterminate without more reliable data. Gathering this data fulfills the TRL 3 criterion to prove analytical and experimental critical function and/or characteristic in the laboratory.

**HI Section Experimental Test (#3)**

Following Preconceptual Design an experimental scale design verification test of the HI Decomposition section will advance it to TRL 4. (It falls short of TRL 5 because without the Bunsen section the test is not in a relevant environment.)

**Bunsen & HI Sections Pilot Test (#4)**

Before Preconceptual Design the results of the S-I ILS will be reviewed. Following Preconceptual Design further maturation requires a test of the Bunsen section combined with the reactive distillation HI section. Separate tests would not be adequate because of the high interchange of $I_2$ and HI between the sections in operation. This test assembly would be equivalent in scale to an HPS producing about one half gram/second of hydrogen. This test will provide the data for S-I HPS Conceptual Design, and the test size is the minimum that would provide confidence to proceed with the system design.

The goal of this test is 1000 hours of operation with production on the order of 20 $Nm^3$ of hydrogen per hour and stability of less than 10% decline per 1000 hours.

**Bunsen & HI Sections Engineering Test (#5)**

The design and experimental iterative process will continue according to the design resulting from the Conceptual Design. This test assembly would be equivalent in scale to an HPS producing about ten gram/second of hydrogen. The assembly will be tested in the full operating conditions (temperatures, pressures) and for dynamics, startup, shutdown, emergencies, *etc*. The test assembly would include designed seals, valves and instrumentation sensors, and the testing would provide design verification for the Final Design exercise.

The goal of this test is 2000 hours of operation with production on the order of 420 $Nm^3$ of hydrogen per hour and stability of less than 1% decline per 1000 hours.

This completes the maturation of the Bunsen Reaction and HI Decomposition sections to TRL 8.

**Process Coupling Heat Exchanger Tests (#6)**

This heat exchangers is and conventional will require materials compatibility testing at the temperatures and pressures at which it will operate. If necessary, a pilot assembly of the PCHX would be tested at sub-scale but with appropriate similitude at its high temperature operational environment. Further definition of these tests requires the completion of design.

**Reactor Products Handling Equipment (#7)**

Basic fluid data and materials compatibility data are needed for the various compositions of iodine and HI. No specific handling equipment technology development is intended. Materials testing after the designs are established advances this technology to TRL 8.

**Feed Purification System Demonstration Test (#8)**

Design of the water purification system of the Feed and Utility System (FUS) need to mitigate the effects of various contaminants on the Bunsen and HI decomposition reactions. Concern is with impurities dissolved in iodine that build up in the system or precipitate out at the liquid/liquid interface. Without requirements the scope of development of this SSC is uncertain.

**Product Purification System Demonstration Test (#9)**

The overall system design must assure that the hydrogen product purity requirements are realized. The concern is iodine presence in the hydrogen. In theory it could be removed, but this would have to be demonstrated convincingly before the hydrogen could be put into any pipeline. Without requirements the scope of development of this SSC is uncertain.

**Valve Test (#10)**

The valves that control the flow of high-temperature helium in the NHSS Secondary Heat Transport System (SHTS) between series and parallel PCHXs (the number of which is dependent on the process – S-I or HyS – and on the scale of eventual application) are part of the HPS. These valves are not anticipated to be new technology, but they are critical SSCs because there is no recent industrial experience with such valves. The valves will need verification testing. These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application, and therefore experience with smaller valves will not apply. Once the technology is validated at the pressures and temperatures of the NGNP application, the TRL will advance from 4 to 8.

**System Modeling (#11)**

The Instrumentation and Control (I&C) requires design verification that can be accomplished by analysis. The model will use data from the Bunsen & HI Sections Pilot Scale Test. Since the HPS is made of discrete thermal-hydraulic components connected by piping, the demonstration of integrated operation can be done by computer simulation given input of the performance of the discrete components in prototype or pilot testing in their operational environments. Results will be input to the final System Design.

Specific I&C concern is interface measurement and control of the liquid/liquid interface in the 3-phase separator and elsewhere in the system. There is a need to test available methods of interface determination and assess their effectiveness. If none were suitable, a new technology might have to be developed.

Completion of system modeling will constitute demonstration of the I&C System, and so the I&C System advances to TRL 8.

**Sensor Tests (#12)**

Thermocouples, pressure sensors and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing the sensors are TRL-8.

S-I System Engineering Prototype Test (#13)

This test is not considered useful to advance the technology, because the separate testing of the Acid Decomposer and the combined Bunsen & HI Sections in the engineering scale could assure TRL 8. It is included as an option in the case that an integrated S-I system HPS assembly is required. Depending on design work yet to be done, the test will be built for input power of about 2.5 MWt, which is 1/20 of the minimum commercial scale and 1/200 of the ultimate commercial plant scale. This test assembly would be producing about 10 grams/second of hydrogen.

## 8.3.6 INPUTS TO CTF

Test steps in the Bunsen Reaction and HI Decomposition TDRM will not require significant heating. The Bunsen reaction is exothermic and the HI Decomposition as conceptualized has a Process Coupling Heat Exchanger with a maximum temperature of 300 to 400°C. This would not require a dedicated heating system such as the CTF.

There is in the Bunsen Reaction and HI Decomposition TDRM an optional S-I System Engineering Test that will require an Acid Decomposer section. If scaled as shown in the TDRM, the S-I System Engineering Test would require helium heating of several MWt. This test would be most likely use the CTF.

# 8.4 HIGH TEMPERATURE STEAM ELECTROLYSIS

## 8.4.1 SSC DESCRIPTION/ FUNCTION AND OPERATING REQUIREMENTS

The High Temperature Steam Electrolysis (HTSE) overall system is divided into the four major systems, and itemized below each are the principal systems and major components

1. ELE System (Electrolyzer System)
    a. Electrolyzer Modules
        i. Solid Oxide Electrolysis (SOE) Cells
        ii. Other Electrolyzer Module Internals
    b. Process Coupling Heat Exchangers
    c. Piping, Manifolds & Insulation
2. HRS System (Heat Recovery System)
    a. Heat Exchangers
    b. Recirculator
3. FUS System (Feed & Utility System)
    a. Feed Purification Systems
    b. Sweep Gas Turbine
4. PPU System (Product Purification Unit)

A schematic flow diagram of the HTSE HPS is shown in Figure 8-6.

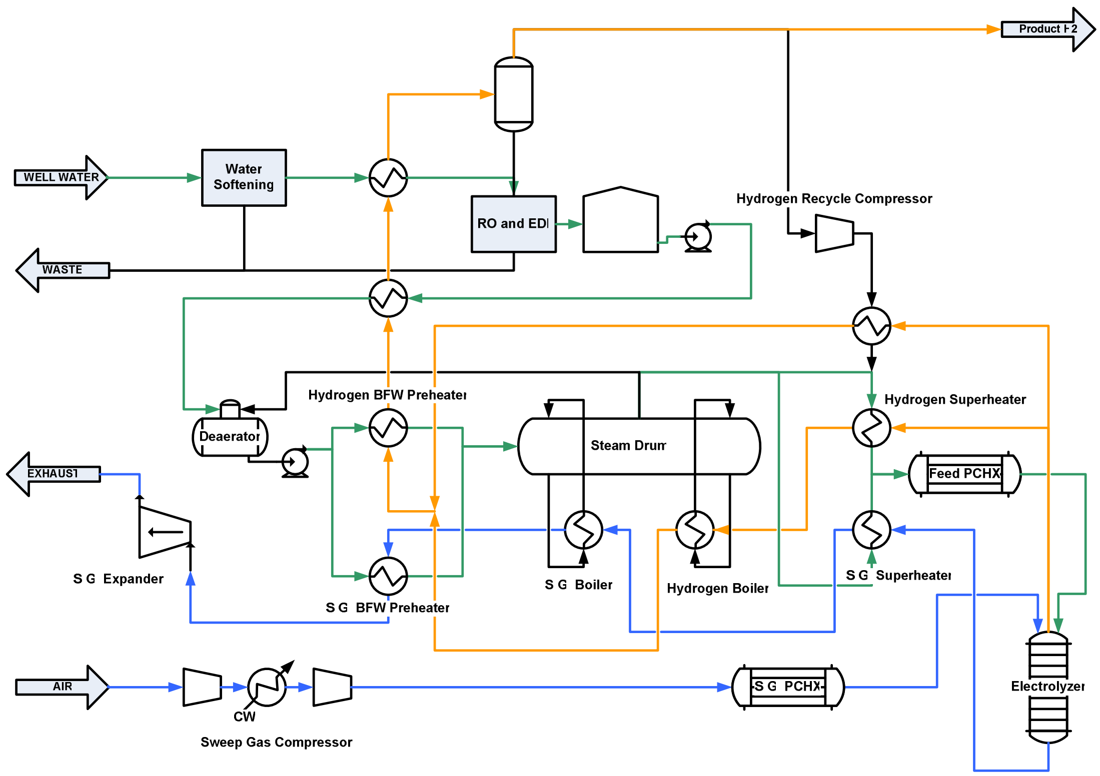


**Figure 8-6: HTSE HPS**

## Functions and Operating Requirements

The HTSE Hydrogen Production System (HPS) accepts heat from the plant Nuclear Heat Supply System (NHSS). Heat is provided to the Process Coupling Heat Exchangers of the HTS ELE system by the NHSS Secondary Heat Transport System (SHTS) which is a circuit of flowing helium.

The HPS also takes electric power from the plant Power Conversion System (PCS) and imports additional electric power from the offsite electric grid through the plant Balance of Plant (BOP).

The HPS gets process feed water and certain other consumables from the BOP, and the water is further purified for use in the HPS. The heat and electric energy converts the feed water into hydrogen and oxygen gas. The hydrogen is directly provided to a pipeline for export after drying, and the oxygen is vented to the atmosphere in the form of oxygen enriched air after drying. Wastewater streams are released to the environment after treatment.

Hydrogen production occurs in the Electrolyzer System (ELE). Functions of the other major systems that comprise the HTSE HPS are implied from their names: Heat Recovery System (HRS), Feed & Utility System (FUS) and Product Purification System (PPU).

Operating requirements are to meet project requirements with respect to safety, availability, product output and environmental impact in accordance with the overall plant design. Therefore, cell and stack performance must be safe and meet the economic target of the project. Minimum requirements to accomplish this are:

1) Oxygen-rich and hydrogen-rich environments must not communicate with one another.
2) Cell area-specific resistance should be minimized
3) Cell current density should be maximized
4) Electrical potential between contiguous stack sections must be minimized.
5) Flow distribution among cells, stacks of cells and modules must be equalized
6) Sweep gas requirements should be minimized
7) Transfer adequate heat to the operating cells and maintain them at the required operating temperature
8) Maximize energy recuperation within practical engineering limits
9) Purify the feed water and sweep gas to the extent required by economical cell operation
10) Purify the products to the extent required by the customer
11) Treat waste streams to the extent required by applicable environmental regulations
12) Design the plant so that it can be operated in a safe manner and operate the plant in a safe manner in accordance with the design

Further specific statements of functions and requirements of the HTSE HPS will result from the Conceptual Design.

The system is further described in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

## 8.4.2 TECHNOLOGY/DESIGN SELECTION STATUS

The most advance design of the HTSE HPS is the design as described in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0]. This is a Preconceptual Design for the overall system. Although much work has been carried out in the design of bench-scale cells and stacks, significant work has yet to be done in the design of commercial scale cells, stacks and modules. Future technology development must work in tandem with design work to arrive at a practical initial design concept. There are four levels at which electrolyzer design issues must be addressed:

1) Individual SOECs:

a. Maximize current density and minimize area specific resistance.
b. Seal the cells such that the hydrogen-rich side does not communicate with the oxygen-rich side in spite of differences in thermal expansion coefficient between cell components.
c. Avoid cell de-lamination in spite of differences in thermal expansion coefficient between cell components.
d. Optimize resistance to flow of the feed and sweep gases.
e. Minimize or eliminate the need for sweep gas.

2) Stacks of cells:

a. Equalize the resistance to flow through the cells such that individual cells are neither flooded with nor starved of feed steam. This may be an issue of control of variability in the manufacture of cells.
b. Minimze the electric potential between contiguous sections of the stack.

Seal the edges of the stacks to the manifolds such that hydrogen-rich and oxygen-rich environments do not communicate.

Mantain electrical connectivity between the power supply and the cell stacks and between cells within the enclosure environment.

c. Maintain adequate pressure on the stack to hold the inter-cell seals within the enclosure environment.

3) Enclosure of the stacks:

a. Optimize the operating pressure of the stacks. The higher the operating pressure, the lower product and sweep gas compression requirements. On the other hand, high operating pressures pose difficult sealing and safety issues.
b. Maintain the required operating temperature of the stacks while minimizing heat losses and maintaining a safe environment for plant operators
c. Allow electrical connectivity to the enclosed stacks while sealing the stack environment from the ambient environment.

4) System design

a. Low current density in the cells requires that very large cell area is required for a commercial installation. This, in turn, requires a large number of modules (76 in the pre-conceptual design) each of which is a high pressure vessel operating at very high temperatures.
b. Plant layout must be carried out so as to minimize piping run length and pipe growth due to thermal expansion. A 1½% to 2% (2m/100m) growth from ambient to operating temperature is expected. Moreover, adequate access for repair and replacement of modules must also be provided.

c. Pressure drop in the feed lines must be limited to ensure adequate distribution among the modules.

The Solid Oxide Electrolysis Cells (SOECs) have been developed to a “laboratory” or “bench scale” level and electrolyzer stacks have been designed and tested to the degree necessary to demonstrate feasibility and functionality at low pressure. Commercial scale cell and stack design has received only very preliminary attention and enclosure and system design has received little. These levels of design interact with one another and with the technology development effort. Sealing requirements may be different for one stack or enclosure design than for another. One set of requirements may necessitate a new sealing technology whereas an alternative design may not.

In addition to the electrolyzers, heat recovery, heat transmission and feed require design attention:

Heat recovery and heat transmission from the NHSS requires operation at elevated temperature. Selection of materials of construction and design of the higher temperature heat exchangers, piping and valving require attention.

Adequate heat transmission to the cells now requires that the PCHX heating the feed steam and that heating the sweep gas operate in parallel.

#### 8.4.2.1 Candidate Technologies

The SOEC design progressed in the early stages of conceptual development to the choice of stacked individual planar cells with peripheral feed supply and product removal. An alternative is tubular cells [Ref. 0]. The tubular configuration appears to have inferior current and flow access and an inherently lower packing density. However, the tubular design would be considered as a back-up to be revisited in the conceptual design phase in the event difficulties with planar cells in manufacturing, sealing, accommodating thermal stress or assembling cells into modules make the tubular option appear more practical.

Electrode materials and electrolyte materials have been chosen, but alternative materials continue to be considered.

Sealing techniques have been designed and tested in the partial stack tests. They will be further tested in the HTSE ILS. Sealing problems are connected with cell size and issues surrounding assembling cells into modules. Design refinements are expected in the course of development.

The most significant design issue is the size of the planar cell. The cells are now sized based upon a rectangular electrolyte 100 mm on a side. If physical limits – particularly differential thermal expansion – permit, the cells need to be scaled up to 500 mm on a side to approach commercial economic viability. This size has been selected for the design in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

#### 8.4.2.2 Decision Discriminators

Decisions regarding the size and configuration of the cells include individual cell performance, primarily current density, area specific resistance and resistance to flow.

#### 8.4.2.3 Reference Design

The High Temperature Steam Electrolysis (HTSE) process and design corresponding to this technology evaluation is documented in the NGNP and Hydrogen Production Hydrogen Plant Alternatives Study [Ref. 0].

#### 8.4.2.4 Alternative for Further Evaluation

Alternatives already considered were mentioned in Section 8.4.2.1. At this point in the development phase no alternatives are being considered.

#### 8.4.2.5 Down Selection Task

While one electrolyzer concept has been chosen for development, the conceptual design phase of the NGNP is still ahead. When that design phase is entered, it is recommended that alternatives be reviewed. In practical terms that will be the down-selection for going forward to full-scale cell tests and then to Pilot Test.

#### 8.4.2.6 Design Data Needs (DDNs)

The Design Data Needs (DDNs) for High Temperature Steam Electrolysis are itemized in Table 8-9.

**Table 8-9: HTSE HPS DDNs**

| DDN | Title |
|---|---|
| **Design Data Needs for Feed Purification (FUS)** | |
| HPS-FUS-01 | Identify Critical Impurities and Determine Critical Component Tolerance |
| HPS-FUS-02 | Develop Feed Water Purification Methods |
| HPS-FUS-03 | Develop Process Fluid Purification Methods |
| **Design Data Needs for the Electrolyzers (including PCHX) (ELE)** | |
| HPS-ELE-01B | Develop a Cell with a commercially acceptable activity and life |
| HPS-ELE-02 | Optimize Catalyst Loading in the Electrodes |
| HPS-ELE-03 | Develop a Cell Configuration and Materials |
| HPS-ELE-04 | Build and Test a Prototype Cell |
| HPS-ELE-05 | Build and Test a Pilot-scale Cell |
| HPS-ELE-06 | Build and Test a Stack of Cells in a Pilot Plant |

| | |
|---|---|
| HPS-ELE-07 | Test Alloy 230 and Alloy 617 in High Temperature Helium and Air/Oxygen and Steam/Hydrogen Mixtures |
| HPS-ELE-08 | Test a Pilot-Scale PCHX |
| HPS-ELE-09 | Provide Data Supporting a Design Code Case |
| HPS-ELE-10 | Develop Gasket Materials and Design |
| HPS-ELE-11 | Develop Seal Materials and Design |
| HPS-ELE-12 | Develop Welding Materials |
| HPS-ELE-13 | Develop Piping Materials and Design Methods |
| **Design Data Needs for Instrument and Controls (PCN)** | |
| HPS-PCN-04 | Develop and Test High Temperature Helium Control Valves |

## 8.4.3 TRL STATUS

The current TRLs for the HTSE HPS and its constituent systems are evaluated as in Table 8.4-3. In summary, the Solid Oxide Electrolysis (SOE) Cells are furthest advanced with the other systems lagging in development because of the low degree of design definition at this phase.

**Table 8-10: HTSE HPS TRLs**

| | TRL |
|---|---|
| Overall HTSE HPS | 3 |
| ELE System (Electrolysis System) | 3 |
| Electrolyzer Module | 3 |
| SOE Cells | 3 |
| Internal Manifolds | 5 |
| Seals | 4 |
| Sweep Gas Coupling Heat Exchanger | 5 |
| Process Coupling Heat Exchanger | 5 |
| Piping, Manifolds | U |
| HRS System (Heat Recovery System) | 5 |
| Heat Exchangers | 5 |
| FUS System (Feed & Utility System) | 7 |
| Feed Purification System | U |
| Sweep Gas Turbine | 7 |
| Helium Control Valves | 4 |

| | |
|---|---|
| Instrumentation & Controls -- including sensors | 6 |

The HRS System Recirculator and the PPU System are ranked TRL 8. This is an indication that the technology is ready for the demonstration of the overall system, and therefore these SSCs are "critical" but do not need testing, and only need vendor confirmation as the design is detailed.

In Appendix A4 are the detailed rating sheets of the TRLs for the eight SSCs in Table 8-10 shown with asterisks. The other SSCs in the listing are either TRL 8 or have the lowest TRL rating of their constituent parts, and so separate sheets for them are not necessary. Each sheet includes the summary basis for the rating and for each SSC an outline of a plan to get from current level to next level.

## 8.4.4 TECHNOLOGY DEVELOPMENT ROAD MAP SUMMARY

The Technology Development Road Map (TDRM) for the HTSE HPS is in Appendix B4. The critical path through the TDRM toward maturation of the technologies pertaining to the HTSE HPS follows the following course.

The maturation plan can not be more precise because of the early stage of design and of the low levels of technology readiness (TRLs) today. The present phase is between preconceptual and conceptual design with supporting development at laboratory or bench scale. In those circumstances, design and development are in a chicken-or-the-egg relationship. Although we identify steps (mainly experiments and tests) to advance the technology, these can not be more definitely specified until the designs advance further. In some cases whether the test is really necessary or if the technology is already nearly ready (TRL 6, -7 or -8) cannot be decided until after the design details are done.

The above describes the appropriate cycle of design and development, where initial concepts frame technical issues and produce data needs (DDNs). The technology is then developed to answer the need, the design moves to further detail. The further design raises more technical uncertainties. More DDNs are written and through development testing technology moves ahead. This circuit is repeated numerous times maturing as it goes. In the current case of HTSE technology the processes is between preconceptual and conceptual design and at a low degree of technical maturity.

Note that the TDRM and maturation plans will need to be adjusted as new DDNs evolve as part of the conceptual and detail designs.

**Advance the Electrolyzer Module**

The Materials Test Facility is in operation, and the ILS Experiment is running. Electrolyzers are presently TRL 4, their feasibility and functionality having been proved in earlier partial cell stack tests, but the specific issue of stable operation needs to be resolved in the ILS test.

The successful completion of the ILS Experiment will support the overall system conceptual design, which will include SOE cell and Electrolyzer Module re-design. A this point the cell production will be re-engineered to meet the requirements of cell area scale-up, and a round of fabrication development tasks can be anticipated.

Scale-up proposed for planning purposes and shown in the TDRM is approximately as follows:

| | |
|---|---|
| ILS to Pilot | x 13 |
| Pilot to NGNP Demonstration Plant | x 200 |
| NGNP Demonstration Plant to NGNP Commercial Plant | x 10 |

This conceptual design will be followed by electrolyzer internal component (internal manifolds and connectors) tests and cell stack tests of the new cell design. With completion of these tests the Electrolyzer Module will attain TRL 5.

The next task is final design and testing of a prototypical Electrolyzer Module in operational conditions. In the Pilot Test of the unit the TRL will advance to -6, -7 and -8 as tasks identified are accomplished. Because in the ultimate application they are highly modular, testing one full-scale Electrolyzer Module satisfies the scale requirement to reach TRL 8.

**Advance the ELE HXs**

Two heat exchangers interface with the Nuclear Heat Supply System (NHSS). These are the Process Coupling Heat Exchanger and the Sweep Gas Coupling Heat Exchanger. The former transfers heat from the SHTS helium to the HPS sweep gas (electrolyzer anode input flow) and the latter transfers heat from the SHTS helium to HPS process feed (electrolyzer cathode input flow).

As designed thus far, these heat exchangers are not novel technology, although there is no significant similar experience at the temperatures and pressures of the superheating sections. Materials testing will advance these heat exchangers to TRL 6 or -8. The latter will be achieved if tested at operational conditions and at suitable scale. If only the former, then a separate pilot test is an alternative to assure TRL 8.

These heat exchangers have requirements for valves on the process side at inlet and outlet. In addition there is a requirement for valves or other flow balancing components on the colder helium side to assure proper division of helium flow to the heat exchangers. These valves are not considered items requiring technology development based on the definition of the design at this stage. As system functional requirements are clarified and design proceeds there could be DDNs for these valves that lead to development tasks on the TDRM.

**Advance the ELE Piping and Manifolds**

Piping and manifolds have a severe duty to accommodate significant differential thermal expansion, because of the very high fluid temperatures. Piping very high temperature gas to several dozen cell modules will be an extremely difficult problem. Thermal expansion of the pipe is expected to be from 1 ½ to 2 %. Pipe runs will be on the order of 100+ meters. The growth that must be accommodated is therefore about 2m. Absorbing this amount of expansion in very high temperature piping has not been done commercially and a design for this requirement is not at hand. It is not possible to say the technology has reached "proof-of-principle".

Piping and manifolds on the process circuit will require thermal insulation to assure the efficiency of the overall system. The concept for this insulation needs to be determined, particularly when the insulation is integrated with the thermal expansion features. There would clearly be a trade-off between efficiency, internal insulation, external insulation, operating temperature of the external surface and pipe material. If internal insulation is used, a concern is fact that the lines carry steam and are subject to condensation as the vapor cools in the insulation. This is a design problem that needs to be addressed before the degree of technology development can be fully assessed.

When designed there is an insulation test for design verification of the resulting configuration and move it to TRL 8.

**Advance the HRS System**

The recuperative heat exchangers of the HRS System will, like the ELE HXs, be operating at higher temperature and pressure that current-state-of-the-art. A materials test can advance these to TRL 8 directly, or a pilot test may be needed.

**Advance the FUS System**

The FUS System has two main parts. The Feed Purification System is likely to be critical to the stable operation of the cells. Results from the ILS Experiment will clarify the design requirements for this system.

The Sweep Gas Turbine is a standard turbomachine. Vendor design verification of compatibility of the materials of construction with air/oxygen mixture will give it TRL 8.

## 8.4.5 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL TO TRL 8)

Following are brief descriptions of the objectives of the fifteen tests shown with numbered ovals on the TDRM.

**ILS Experiment (#1)**

The ILS is a first assembly intended to demonstrate performance of the HTSE process in realistic conditions at or near temperatures needed for system feasibility [Ref. 0]. Test objectives are closed-loop operation with good flow distribution and heat transport performance, stable operation for extended periods of operation or, if not, identification of degradation and/or failure mechanisms and results on materials compatibility testing.

**Alternate Cell Testing (#2)**

Following the HTSE ILS there will be a new development activity in the main "Road". It will entail testing of all ceramic, electrode-supported cells, which being metal-free may resolve some "poisoning" issues, such as the suspected effect of chromium displaced from the show promise of being scaled-up to larger area. Cell designs to be considered are being developed for Solid Oxide Fuel Cells by Saint-Gobain (originally by Forschungszentrum Jülich) an NASA-Glenn Research Center. Accomplishment of this step will result in TRL-4.

**Full-scale Cell Demonstration (#3)**

Cells will be scaled-up in crossection in the Conceptual Design. Following that the re-designed cells will be tested. Long-term, stable operation will be the test objective.

**Full-scale Stack Demonstration (#4)**

A stack of the scaled-up cells will be tested. The goal of this test is 1000 hours of operation stability of less than 10% degradation per 1000 hours.

Combined with the demonstration of an Electrolyzer Module in the ILS, this will advance the technology to TRL 5.

**Pilot Test (#5)**

The Pilot Test is to generate data needed to confirm or fine tune the design and to provide confidence to go on to the first application. The currently planned INL pilot test [Ref. 0] may be this test, although the scope and scale of the test as presently planned appears to be less than what is proposed in the TDRM.

The HTSE Electrolyzer Pilot Test in reality would be most likely a series of tests with more-or-less the same test article design. The Pilot Test is intended to move the technology on from TRL 5. It begins with the completion of the cell and cell stack tests of the SOEC re-designed for full sized cells, which are assumed for the purpose of the TDRM to be 500 mm x 500 mm in nominal area (actual active cell surface area of approximately 2,300 $cm^2$).

To reach TRL 8 an SSC must a prototype, meaning as close as possible to the form, fit and function for final application. It also must be close to full scale (no less than approximately ¼ scale) and rigorously tested in its operational environments. Because feed purity is anticipated to be an issue influencing cell performance stability, the testing includes an appropriately sized water purification and deaeration system configured in the design for the NGNP Demonstration plant. It should also test variability of gas distribution by varying the flow of sweep gas and steam/hydrogen to this module.

The test article is to be a prototypical of the Electrolyzer design progression to that stage (based on the Conceptual Design of the system). It would ultimately be a complete modular unit of the form and size intended for final application, although the initial tests in the series might use fewer than the design number of cells in the stacks or fewer stacks than the final arrangement. Therefore, the scale of the Pilot Test is 100%.

What then needs to be demonstrated in order to reach TRL 8 is sufficient performance in operational environments. Testing in the ILS will be testing of the 100 mm cells at temperature and flows but not at pressure. The Pilot Test article, since prototypical, includes the pressure vessel. Basic operation in the Pilot Test in full normal operating temperature, flows and *pressure* will accomplish TRL 6, because that will pass the "gate" of test at scale and in the relevant environment.

The goal of this test is 2000 hours of operation with production on the order of 50 $Nm^3$ of hydrogen per hour and stability of less than 1% decline per 1000 hours.

**ELE HX Tests (#6)**

The preheaters, boilers and superheaters of the HRS are anticipated to be multiple modular units of conventional configuration. Particularly the boilers and superheaters are being used at temperatures, pressures and differential pressures that may challenge the present state-of-the-art. Therefore, in accord with chemical engineering industry practice, pilot tests will be done with actual fluids and at operational conditions.

If necessary, pilot assemblies would be tested at sub-scale. The issues are with the heat transfer equipment are material selections and thermal/mechanical properties.

**Piping Thermal Design and Insulation Test (#7)**

Accommodating differential thermal expansion is expected to be a significant design issue. Mechanical analysis, possibly supported by experiment, will be needed ahead of Conceptual Design. It is possible that technology development could be required for the expansion design, but this requirement is not demonstrated and is left off the TDRM at this phase until a specific DDN is prepared. Demonstration by analysis will suffice for TRL 5.

A section of the ELE Piping & Manifolds will be tested with flows at temperature to confirm the calculational bases for pressure drop and thermal losses through the insulation in finally designed material and configuration.

**Valve Test (#8)**

The valves that control the flow of high-temperature helium in the NHSS Secondary Heat Transport System (SHTS) between series and parallel PCHXs (the number of which is dependent on the process – S-I or HyS – and on the scale of eventual application) are part of the HPS. These valves are not anticipated to be new technology, but they are critical SSCs because there is no recent industrial experience with such valves. The valves will need verification testing. These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application, and therefore experience with smaller valves will not apply. Once the technology is validated at the pressures and temperatures of the NGNP application, the TRL will advance from 4 to 8.

**HRS HX Tests (#9)**

These heat exchangers are conventional will require materials compatibility testing at the high temperatures and pressures and differential pressures at which they will operate. If necessary, pilot assemblies would be tested at sub-scale. Further definition of these tests requires the completion of design.

**FUS System Demonstration Test (#10)**

Without requirements for feed water purity the scope of development of this SSC is uncertain.

If necessary, air sweep gas pre-treatment requirements may be specified and subject to operational verification tests.

**Sweep Gas Turbine Materials Test (#11)**

This will be a vendor test to verify the compatibility with the application.

**Sensor Tests (#12)**

Thermocouples, pressure sensors and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing the sensors are TRL-8.

**System Modeling (#13)**

Since the HTSE HPS is made of discrete thermal-hydraulic components connected by piping, the demonstration of integrated operation can be done by computer simulation given input of the performance of the discrete components in prototype or pilot testing in their operational environments.

**ELE System Demonstration Test (#14)**

If separate, lower Level (subsystem) tests together with system computational modeling are not sufficient, this hardware assembly and test series will demonstrate the integrated operation of the ELE and HRS systems.

**Continuing Cell Testing (#15)**

As cell stack and system tests proceed, there is a need to accumulate lifetime data and quantify long-term degradation. One or more cell tests should continue after the Full Scale Cell Demonstration (#3). The attainment of TRL levels elsewhere on the Road Map would be supported by the Continuing Cell Testing according to the criteria in Table 8-6.

## 8.4.6 INPUTS TO CTF

The tests in the HTSE TDRM will use electric power mainly. The smaller amount of direct heat required can be provided electrically to the process flows in all tests except the optional System Engineering Prototype Test. The Road Map study does not propose a power level for the test. Only that test, if included, would be likely to use the CTF for convective helium heat input.

## 8.5 SCHEDULE AND BUDGET FOR MATURATION PLANS

Summary Maturation Plans were included as Sections 8.1.5, 8.2.5, 8.3.5 and 8.4.5 of this report. Test Plans for the Hybrid Sulfur hydrogen production (Sulfuric Acid Decomposition and Sulfur Dioxide Electrolysis technologies) are given in Appendix C to the extent that these can be detailed at this stage of R&D.

The cost and schedule for the four TDRMs that are developed in this study are summarized in Table 8-11 through Table 8-14 following. The cost and completion years are keyed to stages along the Road Maps as indicated by the step number from TDRMs (numbers in red ovals).

**Table 8-11: Cost and Schedule for the Sulfuric Acid Decomposition Technology Area**

| TRL Achievement | Step Numbers from TDRM | Cost Completion |
|---|---|---|
| Up to completion of S-I ILS – TRL-2➔3 | #1 | - - |
| Complete analysis, supporting data, materials testing and catalyst choice & tests – TRL-4➔5 | #2, #3, #4, #5, #6 | 1.5 $M 2011 |
| Pilot test of Decomposer – TRL- 5➔6 | #7, #8, #14 | 10.3 $M 2014 |
| Engineering test of Decomposer – TRL-6➔7 | #15, #16 | 22.0 $M 2016 |
| Prototype test of Decomposer – TRL-7➔8 | #17, #18 | 27.0 $M 2018 |
| Balance of system design verification – TRL-x➔8 | #9, #10, #11, #12, #13 | 4.9 $M |

**Table 8-12: Cost and Schedule for the Sulfur Dioxide Electrolysis Technology Area**

| TRL Achievement | Step Numbers from TDRM | Cost Completion |
|---|---|---|
| Up to completion of cell demonstration at temperature and pressure – cells: TRL-3→4 | #1, #2, #3, #4 | 3.0 $M 2009 |
| HyS ILS and optimized cell demonstration – cells: TRL-4→5 | #5, #6 | 4.8 $M 2010 |
| Scale-up cells to 400 cm2 – TRL-4→5, and Electrolyzer Pilot Test – module: TRL-2→6 | #7, #8 | 36.5 $M 2013 |
| Scale-up cells to 1000 cm2 and Engineering test of Electrolyzer – TRL-6→7 | #9 | 59.0 $M 2016 |
| Scale-up cells to 1 m2 and Prototype test of Electrolyzer – TRL-7→8 | #10 | 22.0 $M 2018 |
| (Prototype HPS Test) | (#15) | - - |
| Balance of system design verification – TRL-x→8 | #11, #12, #13, #14 | 2.9 $M |

**Table 8-13: Cost and Schedule for the Bunsen Reaction and HI Decomposition Technology Area**

| TRL Achievement | Step Numbers from TDRM | Cost Completion |
|---|---|---|
| Up to completion of S-I ILS – Bunsen: TRL-2→4 | #1 | - - |
| HI Section Experimental Test – HI: TRL-1→4 | #2, #3 | 3.0 $M 2010 |
| Bunsen and HI Systems Pilot Test – TRL-4→5 | #4 | 43.0 $M 2013 |
| Bunsen and HI Systems Engineering Test – TRL-5→8 | #5, #6 | 58.0 $M 2017 |
| (Prototype HPS Test: Sulfuric Acid, Bunsen & HI Sections - optional) | (#13) Test is not needed, but . . | |
| | if done at scale of NGNP Demo | (140.0 $M) |
| | if done using duplicate of previous Engineering Test (or actual hardware) | ( 15.0 $M) 2018 |
| Balance of system design verification – TRL-x→8 | #7, #8, #9, #10, #11, #12 | 8.1 $M |

**Table 8-14: Cost and Schedule for the High Temperature Steam Electrolysis Technology Area**

| TRL Achievement | Step Numbers from TDRM | Cost Completion |
|---|---|---|
| Up to completion of ILS – TRL-3→4 | #1, #2 | - - |
| Full-scale stack demonstration – TRL-4→5 | #3, #4 | 35.0 $M 2012 |
| Pilot Test – TRL-5→8 | #5 | 30.0 $M 2016 |
| (Prototype HPS Test) | (#14) | (50.0 $M) 2018 |
| Balance of system design verification – TRL-x→8 | #6, #7, #8, #9, #10, #11, #12, #13 | 13.8 $M |

# REFERENCES


[8-1] "Technical Readiness Level Plan, Next Generation Nuclear Plant", report INL/EXT-08-14251, draft, May 12, 2008.

[8-2] "NGNP and Hydrogen Production Preconceptual Design Report, Special Study 20.7: NGNP By-Products and Effluents Study", NGNP-20-RPT-006, January 2007.

[8-3] "NGNP and Hydrogen Production Conceptual Design Study, Hydrogen Plant Alternatives Study", in work.

[8-4] Peterson, Per F., *et al.*, "Development of C-SiC Ceramic Compact Plate Heat Exchangers for High Temperature Heat Transfer Applications", AIChE Winter Meeting, San Francisco, November 16, 2006.

[8-5] Mylavarapu, Sai K., *et al.,* "Investigation of Printed Circuit Heat Exchanger for VHTRs", 4th International Topical Meeting on High Temperature Reactor Technology, HTR2008-58097, September 28-October 1, 2008, Washington, DC.

[8-6] Miu, K. K., *et al.,* "The Development of Autocatalytic Structural Materials for Use in the Sulfur-Iodine Process for the Production of Hydrogen", Transactions of the American Nuclear Society, 2006, vol. 94, pp. 613-614.

[8-7] Hu, Tzu-Yu, *et al.*, "Design and Cost of the Sulfuric Acid Decomposition Reactor for the Sulfur Based Hydrogen Processes", 4th International Topical Meeting on High Temperature Reactor Technology, HTR2008-58009, September 28-October 1, 2008, Washington, DC.

[8-8] Moore, R.C., *et al.*, "$H_2SO_4$ Section Performance Assessment and the Next Generation Design" Sandia National Laboratories, September 15, 2007.

[8-9] Terada, Atsuhiko, *et al.*, "Research and Development on Hydrogen Production By Thermochemical Water-Splitting I-S Process", 4th International Topical Meeting on High Temperature Reactor Technology, HTR2008-58088, September 28-October 1, 2008, Washington, DC.

[8-10] "NGNP and Hydrogen Production Preconceptual Design Report", Westinghouse Electric Company LLC, May 2007.

[8-11] "Preconceptual Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production, NGNP and Hydrogen Production Preconceptual Design Studies Report", General Atomics, 911107, 10JUL07, Sec. 3.8.1.1.

[8-12] Herring, J.S., *et al.*, "Test Plan for Three-Module Operation of the High Temperature Electrolysis Integrated Laboratory Scale Experiment", INL/EXT-08-14303 rev 1, November 17, 2008.

[8-13] Stoots, C.M., *et al.*, "Conceptual Design Documentation for High-Temperature Electrolysis Pilot-Scale Experiment at 200 kW", Idaho National Laboratory, August 15, 2005.

[8-14] Parma, E., *et al*., "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston.

[8-15] O'Brien, J.E., "Documentation of Short Stack and Button Cell Experiments Performed at INL and Ceramatec during FY-07", September 2007.

# APPENDIX A: TRL RATING SHEETS

**Table A1-1: TRL Rating Sheet for Sulfuric Acid Decomposition**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 009 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: $H_2SO_4$ Decomposer Tubes and Tube Array | | | |
| Description: an SSE of the $H_2SO_4$ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |
| Basis for Rating (Attach additional sheets as needed)<br>The silicon carbide bayonet tube $H_2SO_4$ Decomposer has been demonstrated as a separate component, as documented in reports by Sandia Laboratories [Ref. Parma, E., *et al.* "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston] and has functioned in the S-I ILS. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| | | | |
| DDN(s) supported: HPS-SAD-01 through HPS-SAD-13 | | | |
| Subject Matter Expert Making Determination: meeting, Denver, 20NOV08 | | | |
| Date: 20NOV08 | Originating Organization: - - | | |

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**Table A1-2: TRL Rating Sheet for Sulfuric Acid Decomposition**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| Document Number: 031 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: $H_2SO_4$ Decomposer Internal Manifolds and Seals | | | |
| Description: an SSE of the $H_2SO_4$ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |

Basis for Rating (Attach additional sheets as needed)

The silicon carbide bayonet tube $H_2SO_4$ Decomposer has been demonstrated as a separate component, as documented in reports by Sandia Laboratories [Ref. Parma, E., *et al.* "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston] and has functioned in the S-I ILS.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| | | |
| DDN(s) supported: HPS-SAD-01 through HPS-SAD-13 | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: meeting, Denver, 20NOV08 | |
| Date: 20NOV08 | Originating Organization: - - |

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**Table A1-3: TRL Rating Sheet for Sulfuric Acid Decomposition**

## TRL Rating Sheet

Document Number: 032 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: $H_2SO_4$ Decomposer Vessel

Description: an SSE of the $H_2SO_4$ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |

Basis for Rating (Attach additional sheets as needed)

The silicon carbide bayonet tube $H_2SO_4$ Decomposer has been demonstrated as a separate component, as documented in reports by Sandia Laboratories [Ref. Parma, E., *et al.* "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston] and has functioned in the S-I ILS.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| | | |

DDN(s) supported: HPS-SAD-01 through HPS-SAD-13

Subject Matter Expert Making Determination: meeting, Denver, 20NOV08

Date: 20NOV08 Originating Organization: - -

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**Table A1-4: TRL Rating Sheet for Sulfuric Acid Decomposition**

| TRL Rating Sheet | | | |
|---|---|---|---|
| | Document Number: 030 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Decomposer Catalyst | | | |
| Description: an SSE of the $H_2SO_4$ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology concept and application formulated | Proof-of concept | Technology or component is tested at bench scale. |
| **TRL** | 2 | **3** | 4 |
| Basis for Rating (Attach additional sheets as needed)<br>Performance and candidate catalytic materials have been identified, but not fully defined. Lab tests (SNL) have been performed, but one of the critical performance issues, catalyst life, has not been proven. Therefore all critical functions have not been proven in the laboratory. Candidate catalytic materials that have a reasonable operating life must be identified before the catalyst can be properly designed. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | | Schedule | Cost (k$) |
| | | | |
| DDN(s) supported: HPS-SAD-2 | | | |
| Subject Matter Expert Making Determination: Charles O. Bolthrunis | | | |
| Date: 08AUG07 | Originating Organization: Shaw Stone & Webster | | |
| Modified: Daniel Allen | Changed TRL 1 to TRL 3, consequence of review meeting in Denver, 07NOV08. | | |

| Date: 07NOV08 | Originating Organization: Technology Insights |
|---|---|

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**Table A1-5: TRL Rating Sheet for Sulfuric Acid Decomposition**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 010 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Decomposer Product Handling Equipment | | | |
| Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>The design will be typical of standard technology. However, there need to be testing of compatibility with materials of construction. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality and has operated in relevant environments, but adequate scale of demonstration is unclear. Could be TRL 7 but needs demonstration in the operational environment to get to TRL 8. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| | | | |
| DDN(s) supported: HPS-SAD-1, HPS-SAD-12, HPS-SAD-13, HPS-SAD-14 | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 29OCT08 | Originating Organization: Technology Insights | | |

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**Table A1-6: TRL Rating Sheet for Sulfuric Acid Decomposition**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 011 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: $H_2SO_4$ Concentrator Vacuum Column | | | |
| Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>Vapor-liquid equilibrium data is needed as well as adequate mass and heat transfer data. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality. Once the design concept has been defined, sub-scale testing will confirm readiness for the prototype system test (TRL 8). | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | | Schedule | Cost (k$) |
| | | | |
| DDN(s) supported: HPS-SAD-15 | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 29OCT08 | Originating Organization: Technology Insights | | |

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**Table A1-7: TRL Rating Sheet for Sulfuric Acid Decomposition**

| | | | |
|---|---|---|---|
| **TRL Rating Sheet** | | | |
| Document Number: 012 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Feed Acid Handling and Concentrating Equipment | | | |
| Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>Vapor-liquid equilibrium data is needed as well as compatibility testing of materials. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality. Then once the design concept has been defined, sub-scale testing will confirm readiness for the prototype system test (TRL 8). | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| | | | |
| DDN(s) supported: | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 29OCT08 | Originating Organization: Technology Insights | | |

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**Table A1-8: TRL Rating Sheet for Sulfuric Acid Decomposition**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 013 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Steam Ejectors and Vacuum Pump | | | |
| Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>The design will be typical of standard technology. However, there need to be testing of compatibility with materials of construction. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| | | | |
| DDN(s) supported: HPS-SAD-1, HPS-SAD-10 through HPS-SAD-14 | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 29OCT08 | Originating Organization: Technology Insights | | |

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**Table A1-9: TRL Rating Sheet for Sulfuric Acid Decomposition**

## TRL Rating Sheet

Document Number: 033 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Helium Control Valves

Description: an SSE of Sulfuric Acid Decomposition Section of the S-I and HyS HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

| | Technology Readiness Level | | |
|---|---|---|---|
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |

Basis for Rating (Attach additional sheets as needed)

The feasibility of a valve is not in question but qualification testing will be required. Valves of this size in the high-temperature helium environment may require development.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| | | |
| | | |

Subject Matter Expert Making Determination: Daniel Allen

Date: 28NOV07 | Originating Organization: Technology Insights

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**Table A1-10: TRL Rating Sheet for Sulfuric Acid Decomposition**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 034 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Sensors and Instruments | | | |
| Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed)<br>Chief concerns in this sub-system are control valves (process side), sensors and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Actions (list all) | Actions (list all) | |
| | . | . | |
| DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03 | | | |
| Subject Matter Expert Making Determination: Charles O. Bolthrunis | | | |
| Date: 08AUG07 | Date: 08AUG07 | | |
| Modified: Daniel Allen | Modified: Daniel Allen | | |
| Date: 28NOV08 | Originating Organization: Technology Insights | | |

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# A2 SULFUR DIOXIDE ELECTROLYSIS

**Table A2-1: Sulfur Dioxide Electrolysis**

## TRL Rating Sheet

Document Number: 023 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: SO2 Electrolysis Cells

Description: an SSE of the Electrolyzer System (ELE) of the HyS HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Technology concept and application formulated | Proof-of concept | Technology or component is tested at bench scale. |
| **TRL** | 2 | **3** | 4 |

Basis for Rating (Attach additional sheets as needed)

Tests completed at SRNL constitute proof-of-principle. Testing at expected pressures has not been accomplished. All acceptable materials have not been identified and materials issues have not been quantified. A multicell stack has been demonstrated at bench-scale (3 cell stack, 160 sq. cm per cell) but suitable catalyst and membrane materials have not been determined to allow the individual components to work with suitable performance at the laboratory scale. Based on information available from the labs, Westinghouse and industry, a basic cell configuration selection must be made shortly.
.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| A number of membranes tested show formation of a sulfur-rich layer that degrades cell performance. Effects of membrane materials, fabrication methods, and operating conditions on transport of SO2 through the membranes have been hypothesized but are not fully understood at this time. Development and testing of candidate membranes must continue until a suitable membrane can be demonstrated.<br><br>Electrocatalytic activity shown in testing to-date is not | | |

| | | |
|---|---|---|
| sufficient for target operating conditions: 0.5 A/cm2 at 0.6 V at 50 wt% sulfuric acid. Development and testing of candidate catalysts must continue until suitable activity can be achieved.<br><br>Define operating conditions and conduct electrolyzer testing using the final selected Membrane-Electrode Assembly (MEA) at true process conditions (temperature, pressure, reactant concentration). This can only be completed after membrane selection and catalyst development are complete.<br><br>Complete longevity tests using final selected MEA at true process conditions. This can only be completed after membrane selection and catalyst development are complete. | | |
| DDN(s) supported: HPS-ELE-01A through HPS-ELE-06 | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Kathleen McHugh | |
| Date: 10/20/08 | Originating Organization: MPR |
| Modified: Daniel Allen | Changed TRL 2 to TRL 3, basis discussion modified; DDNs added |
| Date: 29OCT08 | Originating Organization: Technology Insights |

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**Table A2-2: Sulfur Dioxide Electrolysis**

## TRL Rating Sheet

Document Number: 024 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Electrolyzer Module Internals

Description: an SSE of the Electrolyzer System (ELE) of the HyS HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Basic principles observed | Technology concept and application formulated | Proof-of concept |
| **TRL** | 1 | **2** | 3 |

Basis for Rating (Attach additional sheets as needed)

An intermediate scale multicell stack will be needed before going to larger scale. R&D is needed to fabricate larger area cells and refine the design of electrical distribution within the multicell stack. Further advancement beyond concept requires design.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| An intermediate scale multicell stacks and electrolyzer module demonstrations will be needed before going to 1 sq. meter cell size for NGNP. R&D is needed to fabricate larger area cells and refine the design of electrical distribution within the multicell stack. This can be completed only after selecting final Membrane-Electrode Assembly (MEA) and demonstrating performance and longevity in true process conditions. | | |
| DDN(s) supported: | | |

Subject Matter Expert Making Determination: Kathleen McHugh

| | |
|---|---|
| Date: 10/20/08 | Originating Organization: MPR |
| Modified: Daniel Allen | Changed TRL 3 to TRL 2, basis discussion and actions list modified |
| Date: 29OCT08 | Originating Organization: Technology Insights |

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**Table A2-3: Sulfur Dioxide Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 025 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Electrolyzer Module Pressure Boundary | | | |
| Description: an SSE of the Electrolyzer System (ELE) of the HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. | SSC demonstrated at pilot scale in relevant environment |
| **TRL** | 4 | **5** | 6 |
| Basis for Rating (Attach additional sheets as needed)<br>Once the requirement for an electrolyzer container is established, no further testing is required. A commercial vessel can be designed. Selection of the configuration of the Electrolyzer will determine the need for a container. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| . | | | |
| DDN(s) supported: | | | |
| Subject Matter Expert Making Determination: Charles O. Bolthrunis | | | |
| Date: 08AUG07 | Originating Organization: Shaw Stone & Webster | | |

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**Table A2-4: Sulfur Dioxide Electrolysis**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| | Document Number: | 026 | Revision: |

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: $SO_2$ Absorber

Description: an SSE of the Sulfuric Acid Decomposition System (SAD) of the HyS HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

| | Technology Readiness Level | | |
|---|---|---|---|
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed)

Absorption operations are used commonly throughout industry. Packed columns are available for use at all scales. Preliminary process parameters for the HyS process have been defined in a conceptual design flowsheet. Further flowsheet optimization for pilot scale is expected, which may impact key process parameters for separation equipment. This absorption column accepts streams containing SO2, H2O, H2SO4, and trace amounts of O2; a corrosion-resistant material will be needed. Pressure in the current flow sheet is too high for use of a glass-lined column; fabrication from a corrosion resistant metal (*e.g.*, Hastelloy B3) may be needed. Equipment scaling and manufacturing processes for packed columns are well understood in industry, but the selected material will need to be tested in the operating environment for corrosion resistance.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| Identify suitable materials of construction and test in process conditions. Complete optimization and prepare a design specification considering final operating conditions for the column for procurement at the pilot scale. | | |

| | |
|---|---|
| DDN(s) supported: HPS-SAD-16 | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Kathleen McHugh | |
| Date: 10/20/08 | Originating Organization: MPR |
| Modified: Daniel Allen | Revised from TRL 4 to TRL 6, as per meeting, Denver, 20NOV08 |
| Date: 20NOV08 | Originating Organization: Technology Insights |

Rev. AUG08, DTA

**Table A2-5: Sulfur Dioxide Electrolysis**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| | Document Number: | 028 | Revision: |

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Water Treatment System

Description: an SSE of the Feed and Utility System (FUS) of the HyS HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | | | |
| **TRL** | | **U** | |

Basis for Rating (Attach additional sheets as needed)

Feed purification is critical to all water splitting technologies. Preliminary work on critical component tolerance has not yet been done. Commercially available feed water purification may not be adequate; process fluid purification may be required. TRL for this cannot be assigned until the requirements are known.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| . | | |
| DDN(s) supported: HPS-FUS-01, HPS-FUS-02, HPS-FUS-03 | | |

Subject Matter Expert Making Determination: Daniel Allen

| Date: 27OCT08 | Originating Organization: Technology Insights |
|---|---|

Rev. AUG08, DTA

**Table A2-6: Sulfur Dioxide Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 029 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Instrument and Controls System | | | |
| Description: an SSE of the HyS HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed)

Chief concerns in this sub-system are control valves (process side), sensors and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| . | | |
| DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03 | | |

| Subject Matter Expert Making Determination: Charles O. Bolthrunis | |
|---|---|
| Date: 08AUG07 | Originating Organization: Shaw Stone & Webster |
| Modified: Daniel Allen | Revised from TRL 2 to TRL 6, basis discussion modified; DDNs added |
| Date: 27OCT08 | Originating Organization: Technology Insights |

Rev. AUG08, DTA

# A3 BUNSEN REACTION AND HI DECOMPOSITION

**Table A3-1: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

Document Number: 014 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Bunsen Reactor

Description: an SSE of the Bunsen Reaction Section of the S-I HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Technology concept and application formulated. | Proof-of concept | Technology or component is tested at bench scale. |
| **TRL** | 2 | **3** | 4 |

Basis for Rating (Attach additional sheets as needed)

General feasibility is supported by laboratory bench-scale tests and the initial operation of the S-I ILS. Bunsen reactors were operated successfully at GA in the 1980s, in France and more recently in Japan (for a period of a week). These experiments meet the required proof-of-concept. The critical functions have been proven. To advance, Basic thermodynamic data is needed. Compatibility with materials of construction uncertain, particularly with seals. Hydraulic, kinetic, and thermal design and analyses are needed.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| Successful completion of the ILS and its operation in integrated mode for X,XXX hours with no more than Y% degradation in output will advance the Bunsen Reactor to TRL 4. | | |
| DDN(s) supported: HPS-BUN-01 through HPS-BUN-06 | | |

Subject Matter Expert Making Determination: meeting, Denver, 20NOV08

Date: 20NOV08 Originating Organization: - -

Rev. AUG08, DTA

**Table A3-2: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| Document Number: 015 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Three-phase Separator | | | |
| Description: an SSE of the Bunsen Reaction Section of the S-I HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology concept and application formulated. | Proof-of concept | Technology or component is tested at bench scale. |
| **TRL** | 2 | **3** | 4 |

Basis for Rating (Attach additional sheets as needed)

General feasibility is supported by laboratory bench-scale tests and the initial operation of the S-I ILS.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| Successful completion of the ILS and its operation in integrated mode for X,XXX hours with no more than Y% degradation in output will advance the Three-phase Separator to TRL 4. | | |
| DDN(s) supported: | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Daniel Allen | |
| Date: 28NOV08 | Originating Organization: Technology Insights |

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**Table A3-3: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| | Document Number: | 016 | Revision: |

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Reactive Still

Description: an SSE of the HI Decomposition Section of the S-I HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Basic principles observed | Technology concept and application formulated | Proof-of concept |
| **TRL** | 1 | **2** | 3 |

Basis for Rating (Attach additional sheets as needed)

Although results are unpublished, GA has done batch experiments in glass that produced relatively high H2 yield in I2-lean experiments. Independent ongoing experiments at ENEA (Italy) support this result. These experiments go beyond “Basic principles observed and reported in … research without well-defined application.” (TRL-1), but they are short of “critical function … proven” (TRL-4).

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| Verification of kinetic and thermodynamic data will advance the Reactive Still to TRL 3. | | |
| DDN(s) supported: HPS-HID-01 through HPS-HID-08 | | |

Subject Matter Expert Making Determination: meeting, Denver, 20NOV08

| | |
|---|---|
| Date: 20NOV08 | Originating Organization: - - |

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**Table A3-4: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

Document Number: 018 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Process Coupling Heat Exchanger

Description: an SSE of the HI Decomposition Section of the S-I HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. | SSC demonstrated at pilot scale in relevant environment |
| **TRL** | 4 | **5** | 6 |

Basis for Rating (Attach additional sheets as needed)

The extreme high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested. RL-5 assigned because technology is beyond demonstration of feasibility and functionality but has not operated in relevant environments.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Actions (list all) | Actions (list all) |
|---|---|---|
| The level can be increased to TRL 6 when materials are tested for the relevant environment, because at that point components will have been defined, acceptable technologies identified and technology issues quantified. | | |

DDN(s) supported:

Subject Matter Expert Making Determination: Daniel Allen

Date: 27OCT08 | Originating Organization: Technology Insights

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**Table A3-5: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| | Document Number: 031 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Reactor Product Handling Equipment | | | |
| Description: an SSE of the Balance of the S-I HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed)

Reactor product handling equipment (both Bunsen and HI Decompostion reactors) are pumping and handling very large streams of iodine and hydroiodic acid is a problem that has not been dealt with commercially. The large flows required are beyond the experience of chemical plants. The possibility of very large spills has to be considered. Economic solutions need to be found.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| . | | |
| DDN(s) supported: HPS-BUN-07, HPS-HID-09 | | |

Subject Matter Expert Making Determination: Daniel Allen

| | |
|---|---|
| Date: 31OCT08 | Originating Organization: Technology Insights |

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**Table A3-6: Bunsen Reaction and HI Decomposition**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 020 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Feed Purification System | | | |
| Description: an SSE of the Balance of the S-I HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | | | |
| **TRL** | | **U** | |
| Basis for Rating (Attach additional sheets as needed)<br>The concept purification for feed streams (water and air) and the application are established. Requirements are not resolved and require operation of test loops. Until then the feasibility can't be determined. . | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| . | | | |
| DDN(s) supported: HPS-FUS-01 through HPS-FUS-03 | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 16OCT08 | Originating Organization: Technology Insights | | |

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**Table A3-7: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

| | | | |
|---|---|---|---|
| Document Number: 021 | Revision: | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Product Purification System | | | |
| Description: an SSE of the Balance of the S-I HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | | | |
| **TRL** | | **U** | |
| Basis for Rating (Attach additional sheets as needed)<br>Can not rate without requirements. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| . | | | |
| DDN(s) supported: HPS-PPU-01, HPS-PPU-02 | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 29OCT08 | Originating Organization: Technology Insights | | |

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# TRL Rating Sheet

| | | | |
|---|---|---|---|
| Document Number: 022 | | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Instrument and Controls System | | | |
| Description: an SSE of the Balance of the S-I HPS | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed)

Chief concerns in this sub-system are control valves (process side), sensors and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| . | | |
| DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03 | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Charles O. Bolthrunis | |
| Date: 08AUG07 | Originating Organization: Shaw Stone & Webster |
| Modified: Daniel Allen | Revised from TRL 2 to TRL 6, basis discussion modified; DDNs added |
| Date: 27OCT08 | Originating Organization: Technology Insights |

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**Table A3-8: Bunsen Reaction and HI Decomposition**

## TRL Rating Sheet

Document Number: 035 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Helium Control Valves

Description: an SSE of the Balance of the S-I HPS

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |

Basis for Rating (Attach additional sheets as needed)

The feasibility of a valve is not in question but qualification testing will be required. Valves of this size in the high-temperature helium environment may require development.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| | | |
| | | |

Subject Matter Expert Making Determination: Daniel Allen

Date: 28NOV07 | Originating Organization: Technology Insights

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# A4 HIGH TEMPERATURE STEAM ELECTROLYSIS

**Table A4-1: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 001 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Solid Oxide Electrolyzer (SOE) Cells | | | |
| Description: an SSE of the Electrolyzer Modules of the HTSE Electrolyzer System (ELE) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology concept and application formulated. | Proof-of concept | Technology or component is tested at bench scale. |
| **TRL** | 2 | **3** | 4 |

Basis for Rating (Attach additional sheets as needed)

The required environment requires the cells to operate under pressure and temperature. The cells have never been operated in a pressurized environment. The manufacturing process for the cells is still being identified. Currently the process is to hand-make each cell, which would not be effective for a pilot scale component which requires far more cells than are currently available. The cells currently have a high rate of degradation at operating temperature. This does not meet functionality requirements for this component.

Reference: O'Brien, J.E., "Documentation of Short Stack and Button Cell Experiments Performed at INL and Ceramatec during FY-07", September 2007.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| More research must be accomplished to determine a suitable manufacturing method for the electrolyzer cells.<br><br>More research must be accomplished to increase cell longevity.<br><br>Testing of the cells concurrently at the process | | |

| | | |
|---|---|---|
| temperature (800℃) and pressure (50 bar) must be accomplished. | | |
| DDN(s) supported: HPS-ELE-01B through HPS-ELE-6, HPS-ELE-10, HPS-ELE-11 | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Demetrius Siachames | |
| Date: 09SEP08 | Originating Organization: MPR Associates |
| Modified: Daniel Allen | Revised from TRL 2 to TRL 3, as per meeting, Denver, 20NOV08 |
| Date: 20NOV08 | Originating Organization: Technology Insights |

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**Table A4-2: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 002 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Electrolyzer Manifolds | | | |
| Description: an SSE of the Electrolyzer Modules of the HTSE Electrolyzer System (ELE) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. | SSC demonstrated at pilot scale in relevant environment |
| **TRL** | 4 | **5** | 6 |

Basis for Rating (Attach additional sheets as needed)

The basic design of the manifolds is still being determined for the pilot scale. Design adequacy is supported by the CFD analyses done at INL on flow distribution and tby he experimental results in cell stack tests where operation was satisfactory over a wide range of flow conditions.

Reference: O'Brien, J.E., "Documentation of Short Stack and Button Cell Experiments Performed at INL and Ceramatec during FY-07", September 2007.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| More research must be accomplished to determine a suitable solution for the electrolyzer manifold.<br><br>A manifold system must be tested ate operating pressure and temperature. | | |
| DDN(s) supported: | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Demetrius Siachames | |
| Date: 09SEP08 | Originating Organization: MPR Associates |

| | |
|---|---|
| Modified: Daniel Allen | Revised from TRL 3 to TRL 5, per 20NOV08 meeting in Denver |
| Date: 28NOV08 | Originating Organization: Technology Insights |

Rev. AUG08, DTA

**Table A4-3: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 002 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Seals | | | |
| Description: an SSE of the Electrolyzer Modules of the HTSE Electrolyzer System (ELE) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |
| Basis for Rating (Attach additional sheets as needed)<br>Basis is the stack demonstrations done at INL. Concern about the adequacy of the response to leaks and internal combustion were ameliorated in discussion. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| | | | |
| DDN(s) supported: | | | |
| Subject Matter Expert Making Determination: 20NOV08 meeting in Denver | | | |
| Date: 20NOV08 | Originating Organization: - - | | |

Rev. AUG08, DTA

**Table A4-4: High Temperature Steam Electrolysis**

## TRL Rating Sheet

Document Number: 003 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Sweep Gas Coupling Heat Exchanger

Description: an SSE of the HTSE Electrolyzer System (ELE)

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

| | Technology Readiness Level | | |
|---|---|---|---|
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. | SSC demonstrated at pilot scale in relevant environment |
| **TRL** | 4 | **5** | 6 |

Basis for Rating (Attach additional sheets as needed)

The extreme high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested.

Reference: UNLV, “Crack Growth Rate of Structural Materials for Heat Exchanger Applications”, August 2007; UCB, “Composite Heat Exchanger Fabrication Methods and Test Results”, February 2007; Ceramatec, “FY-07a Annual Report – Heat Exchanger Scale-up”, July, 2007; Xiuqing Li, Meggit Ltd., “Heat Exchangers for the Next Generation of Nuclear Reactors”, June, 2006.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| Determine industry available materials capable of high temperatures (800°C) and suitable for fluids considered.<br><br>Test heat exchanger materials to determine their feasibility for continuous operation. | | |
| DDN(s) supported: HPS-ELE-07 through HPS-ELE-09 | | |

| | | |
|---|---|---|
| Subject Matter Expert Making Determination: Demetrius Siachames | | |
| Date: 09SEP08 | Originating Organization: MPR Associates | |
| Modified: Daniel Allen | | Revised from TRL 2 to TRL 5; removed requirement to test complete heat exchanger and left testing materials. |
| Date: 27OCT08 | Originating Organization: Technology Insights | |

Rev. AUG08, DTA

**Table A4-5: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: | 004 | Revision: |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Process Coupling Heat Exchanger | | | |
| Description: an SSE of the HTSE Electrolyzer System (ELE) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. | SSC demonstrated at pilot scale in relevant environment |
| **TRL** | 4 | **5** | 6 |

Basis for Rating (Attach additional sheets as needed)

The high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested.

Reference: UNLV, "Crack Growth Rate of Structural Materials for Heat Exchanger Applications", August 2007; UCB, "Composite Heat Exchanger Fabrication Methods and Test Results", February 2007; Ceramatec, "FY-07a Annual Report – Heat Exchanger Scale-up", July, 2007; Xiuqing Li, Meggit Ltd., "Heat Exchangers for the Next Generation of Nuclear Reactors", June, 2006.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| Determine industry available materials capable of high temperatures (800°C) and suitable for fluids considered.<br><br>Test heat exchanger materials to determine their feasibility for continuous operation. | | |
| DDN(s) supported: HPS-ELE-07 through HPS-ELE-09 | | |

<table>
<tr><td colspan="3">Subject Matter Expert Making Determination: Demetrius Siachames</td></tr>
<tr><td>Date: 09SEP08</td><td colspan="2">Originating Organization: MPR Associates</td></tr>
<tr><td colspan="2">Modified: Daniel Allen</td><td>Revised from TRL 2 to TRL 5; removed requirement to test complete heat exchanger and left testing materials.</td></tr>
<tr><td>Date: 27OCT08</td><td colspan="2">Originating Organization: Technology Insights</td></tr>
</table>

Rev. AUG08, DTA

**Table A4-6: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 005 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Piping and Manifolds | | | |
| Description: an SSE of the HTSE Electrolyzer System (ELE) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | | | |
| **TRL** | | **U** | |

Basis for Rating (Attach additional sheets as needed)

Manufacturing of required piping is technically possible, but has not been manufactured or tested in a laboratory setting to validate feasibility for the temperatures and pressures required. It is uncertain without further study and design work whether new technology is needed to accommodate pipe thermal expansion.

Reference: INEEL, “High Temperature Electrolysis System Configuration Study”.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| An engineering solution requiring a pipe-in-pipe design will have to be developed and manufactured which can withstand 50 bar and 800℃.<br><br>The engineering solution for a pipe-in-pipe will have to be tested at the required conditions. | | |
| DDN(s) supported: HPS-ELE-10 through HPS-ELE-13 | | |

Subject Matter Expert Making Determination: Demetrius Siachames

| | |
|---|---|
| Date: 09SEP08 | Originating Organization: MPR Associates |
| Modified: Daniel Allen | Revised from TRL 2 to TRL U, as per 20NOV08 meeting in Denver |
| Date: 28NOV08 | Originating Organization: Technology Insights |

Rev. AUG08, DTA

**Table A4-7: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 006 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Heat Exchangers | | | |
| Description: SSEs of the HTSE Heat Recovery System (HRS) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. | SSC demonstrated at pilot scale in relevant environment |
| **TRL** | 4 | **5** | 6 |

Basis for Rating (Attach additional sheets as needed)

The extreme high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested.

Reference: UNLV, “Crack Growth Rate of Structural Materials for Heat Exchanger Applications”, August 2007; UCB, “Composite Heat Exchanger Fabrication Methods and Test Results”, February 2007; Ceramatec, “FY-07a Annual Report – Heat Exchanger Scale-up”, July, 2007; Xiuqing Li, Meggit Ltd., “Heat Exchangers for the Next Generation of Nuclear Reactors”, June, 2006.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Actions (list all) | Actions (list all) |
|---|---|---|
| Determine industry available materials capable of high temperatures (800°C) and suitable for fluids considered.<br><br>Test heat exchanger materials to determine their feasibility for continuous operation. | | |

| | |
|---|---|
| DDN(s) supported: HPS-ELE-07 through HPS-ELE-09 | |
| Subject Matter Expert Making Determination: Demetrius Siachames | |
| Date: 09SEP08 | Originating Organization: MPR Associates |
| Modified: Daniel Allen | Revised from TRL 2 to TRL 5 |
| Date: 27OCT08 | Originating Organization: Technology Insights |

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**Table A4-8: High Temperature Steam Electrolysis**

## TRL Rating Sheet

Document Number: 007 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Feed Purification System

Description: an SSE of the HTSE Feed and Utility System (FUS)

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | | | |
| **TRL** | | **U** | |

Basis for Rating (Attach additional sheets as needed) Can not rate without requirements.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| | | |

DDN(s) supported: HPS-FUS-01 through HPS-FUS-03

Subject Matter Expert Making Determination: Daniel Allen

Date: 27OCT08 | Originating Organization: Technology Insights

Rev. AUG08, DTA

**Table A4-9: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| | Document Number: 008 | Revision: | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Sweep Gas Turbine | | | |
| Description: an SSE of the HTSE Feed and Utility System (FUS) | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment | Integrated prototype demonstrated in operational environment. |
| **TRL** | 6 | **7** | 8 |

Basis for Rating (Attach additional sheets as needed)

Such as standard turbogenerator requires only design verification testing, presumably by the vendor to his standards in the design environment.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| | | |
| DDN(s) supported: | | |

| | |
|---|---|
| Subject Matter Expert Making Determination: Daniel Allen | |
| Date: 02OCT08 | Originating Organization: Technology Insights |

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**Table A4-10: High Temperature Steam Electrolysis**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Document Number: 037 Revision: | | | |
| ☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component | | | |
| Title: Helium Control Valves | | | |
| Description: an SSE of the HTSE | | | |
| | | | |
| Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP | | | |
| | | | |
| | **Technology Readiness Level** | | |
| | Next Lower Rating Level | Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Proof-of concept | Technology or component is tested at bench scale. | SSC demonstrated at experimental scale in relevant environment. |
| **TRL** | 3 | **4** | 5 |
| Basis for Rating (Attach additional sheets as needed)<br>The feasibility of a valve is not in question but qualification testing will be required. Valves of this size in the high-temperature helium environment may require development. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (k$) | |
| | | | |
| | | | |
| Subject Matter Expert Making Determination: Daniel Allen | | | |
| Date: 28NOV07 | Originating Organization: Technology Insights | | |

Rev. AUG08, DTA

**Table A4-11: High Temperature Steam Electrolysis**

## TRL Rating Sheet

Document Number: 038 Revision:

☐ Facility ☑ System ☐ Subsystem ☐ Structure ☐ Component

Title: Instrumentation and Control

Description: an SSE of the HTSE

Facility: ☐ NHSS ☐ HTS ☑ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | SSC demonstrated at experimental scale in relevant environment | SSC demonstrated at pilot scale in relevant environment | SSC demonstrated at engineering scale in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed)

Chief concerns in this sub-system are control valves (process side), sensors and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (k$) |
|---|---|---|
| . | | |
| DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03 | | |

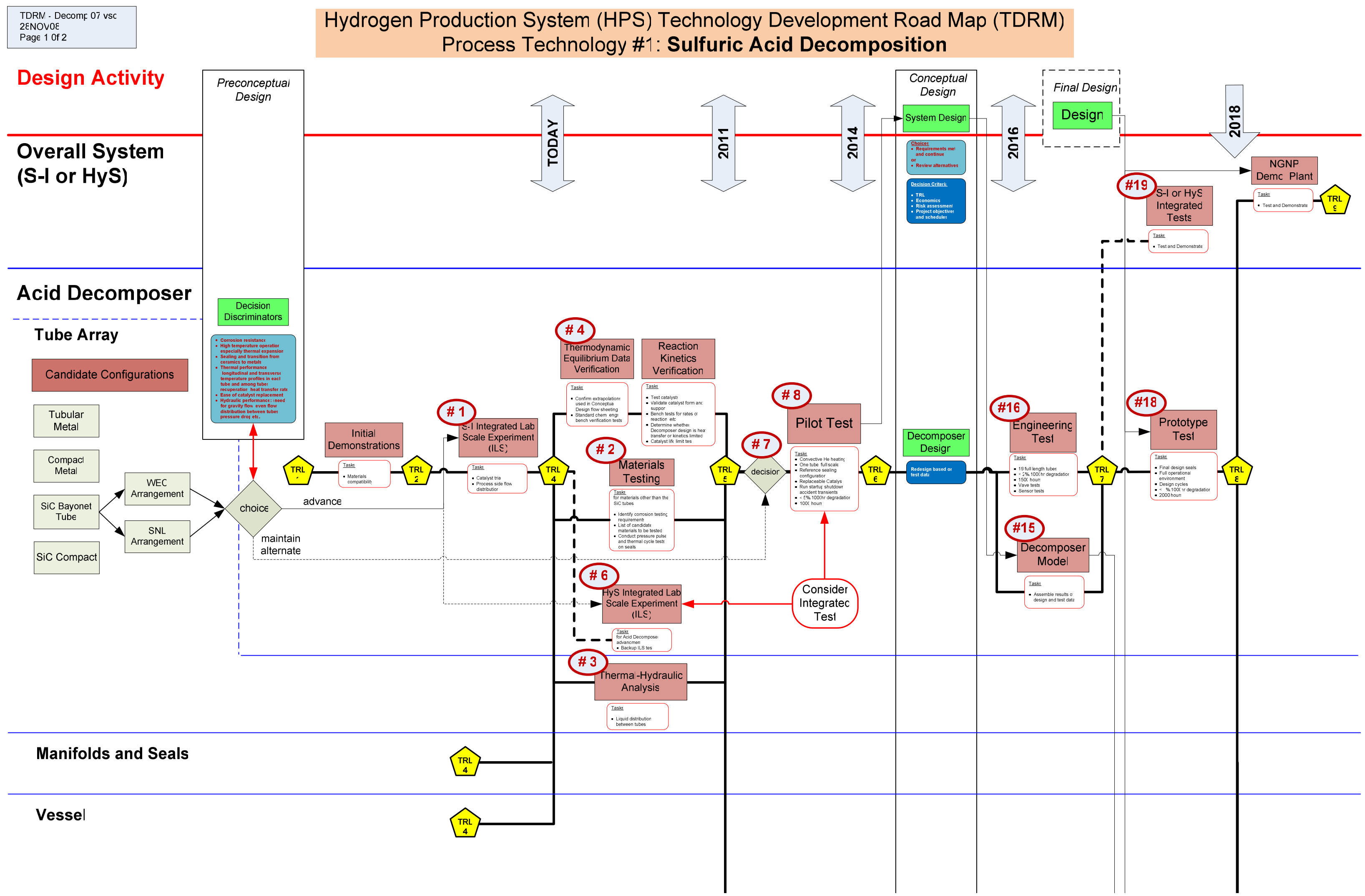
Subject Matter Expert Making Determination: Charles O. Bolthrunis

| | |
|---|---|
| Date: 08AUG07 | Originating Organization: Shaw Stone & Webster |
| Modified: Daniel Allen | Revised from TRL 2 to TRL 6, basis discussion modified; DDNs added |
| Date: 27OCT08 | Originating Organization: Technology Insights |

Rev. AUG08, DTA

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

## B1 SULFURIC ACID DECOMPOSITION


TDRM - Decomp 07 vsc
28NOV08
Page 1 of 2
Hydrogen Production System (HPS) Technology Development Road Map (TDRM)
Process Technology #1: Sulfuric Acid Decomposition
Design Activity
Preconceptual Design
Conceptual Design
Final Design
System Design
Design
Overall System (S-I or HyS)
TODAY
2011
2014
2016
2018
NGNP Demo Plant
#19 S-I or HyS Integrated Tests
Acid Decomposer
Tube Array
Candidate Configurations
Tubular Metal
Compact Metal
SiC Bayonet Tube
SiC Compact
WEC Arrangement
SNL Arrangement
choice
advance
maintain alternate
Decision Discriminators
Initial Demonstrations
# 1 S-I Integrated Lab Scale Experiment (ILS)
# 4 Thermodynamic Equilibrium Data Verification
Reaction Kinetics Verification
# 2 Materials Testing
# 6 HyS Integrated Lab Scale Experiment (ILS)
# 3 Thermal-Hydraulic Analysis
# 7 decision
# 8 Pilot Test
Consider Integrated Test
Decomposer Design
#16 Engineering Test
#15 Decomposer Model
#18 Prototype Test
Manifolds and Seals
Vessel
TRL 4

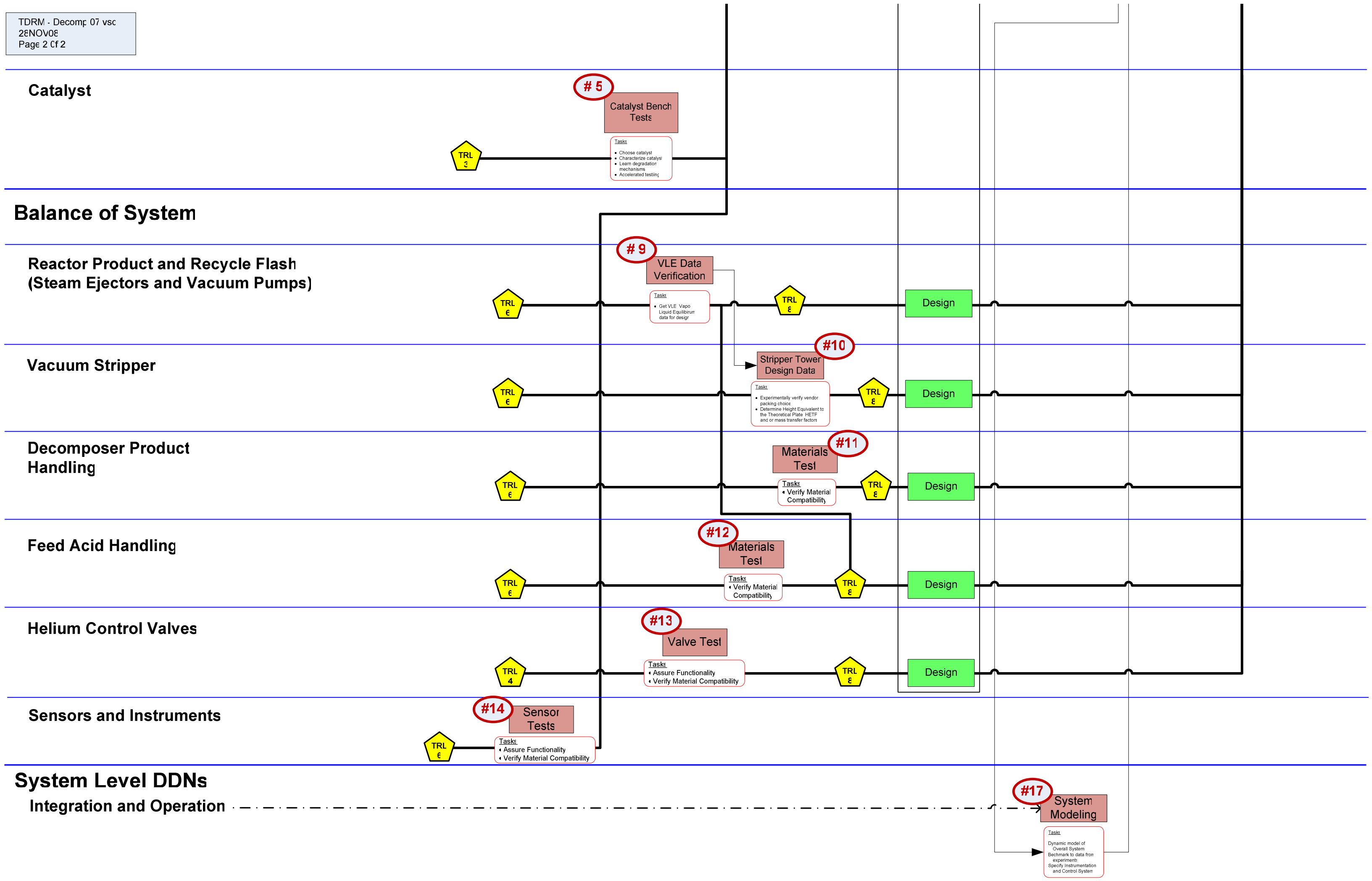
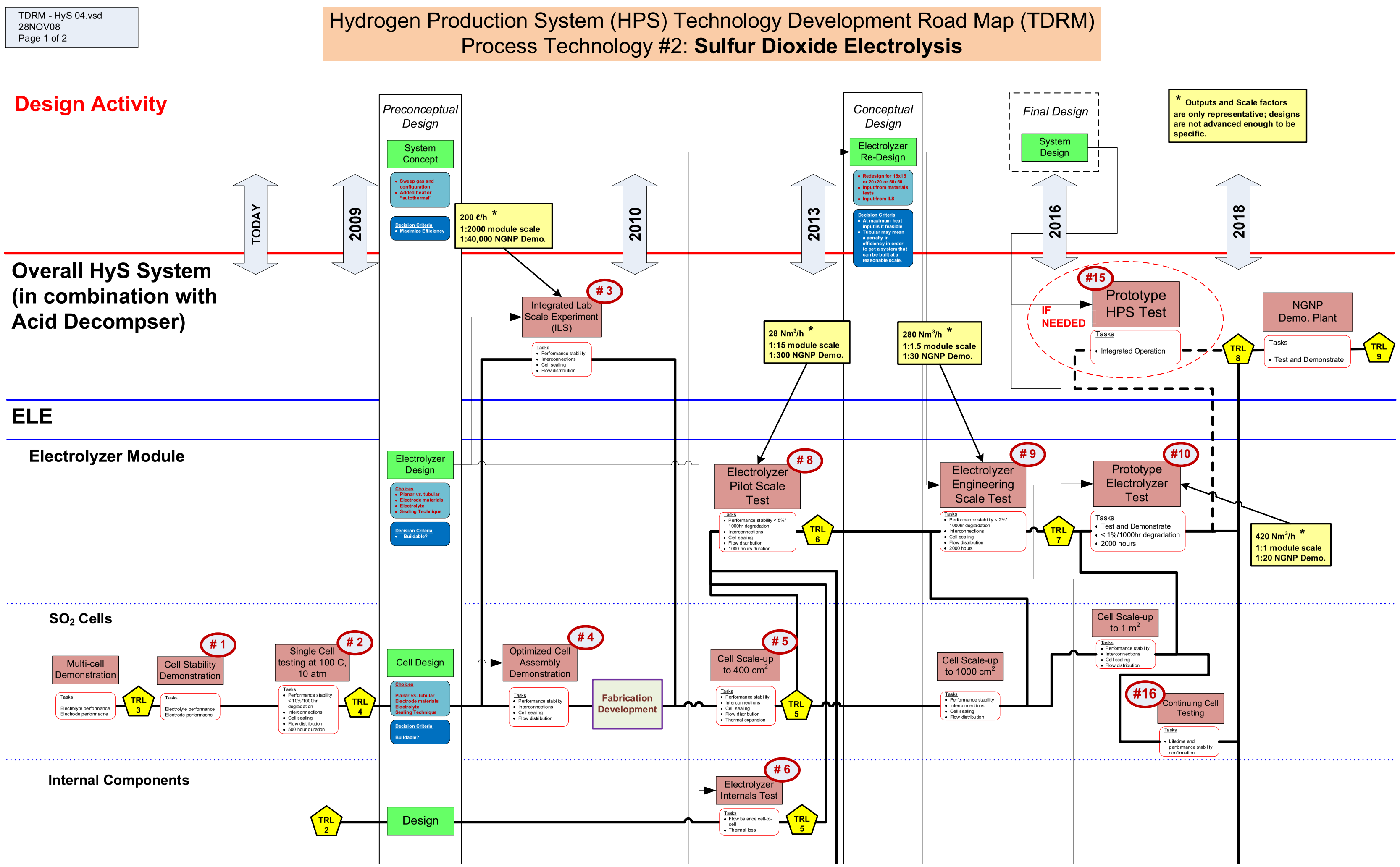



Figure B1-1: Technology Development Road Map of Sulfuric Acid Decomposition

# B2 SULFUR DIOXIDE ELECTROLYSIS


TDRM - HyS 04.vsd
28NOV08
Page 1 of 2
Hydrogen Production System (HPS) Technology Development Road Map (TDRM)
Process Technology #2: Sulfur Dioxide Electrolysis
Design Activity
Preconceptual Design
Conceptual Design
Final Design
TODAY
2009
2010
2013
2016
2018
* Outputs and Scale factors are only representative; designs are not advanced enough to be specific.
Overall HyS System (in combination with Acid Decompser)
System Concept
200 ℓ/h *
1:2000 module scale
1:40,000 NGNP Demo.
# 3
Integrated Lab Scale Experiment (ILS)
Electrolyzer Re-Design
System Design
#15
Prototype HPS Test
IF NEEDED
Tasks
Integrated Operation
NGNP Demo. Plant
Test and Demonstrate
TRL 8
TRL 9
ELE
Electrolyzer Module
Electrolyzer Design
28 Nm³/h *
1:15 module scale
1:300 NGNP Demo.
280 Nm³/h *
1:1.5 module scale
1:30 NGNP Demo.
# 8
Electrolyzer Pilot Scale Test
TRL 6
# 9
Electrolyzer Engineering Scale Test
TRL 7
#10
Prototype Electrolyzer Test
Test and Demonstrate
< 1%/1000hr degradation
2000 hours
420 Nm³/h *
1:1 module scale
1:20 NGNP Demo.
SO2 Cells
Multi-cell Demonstration
TRL 3
# 1
Cell Stability Demonstration
# 2
Single Cell testing at 100 C, 10 atm
TRL 4
Cell Design
# 4
Optimized Cell Assembly Demonstration
Fabrication Development
# 5
Cell Scale-up to 400 cm²
TRL 5
Cell Scale-up to 1000 cm²
Cell Scale-up to 1 m²
#16
Continuing Cell Testing
Internal Components
TRL 2
Design
# 6
Electrolyzer Internals Test
TRL 5

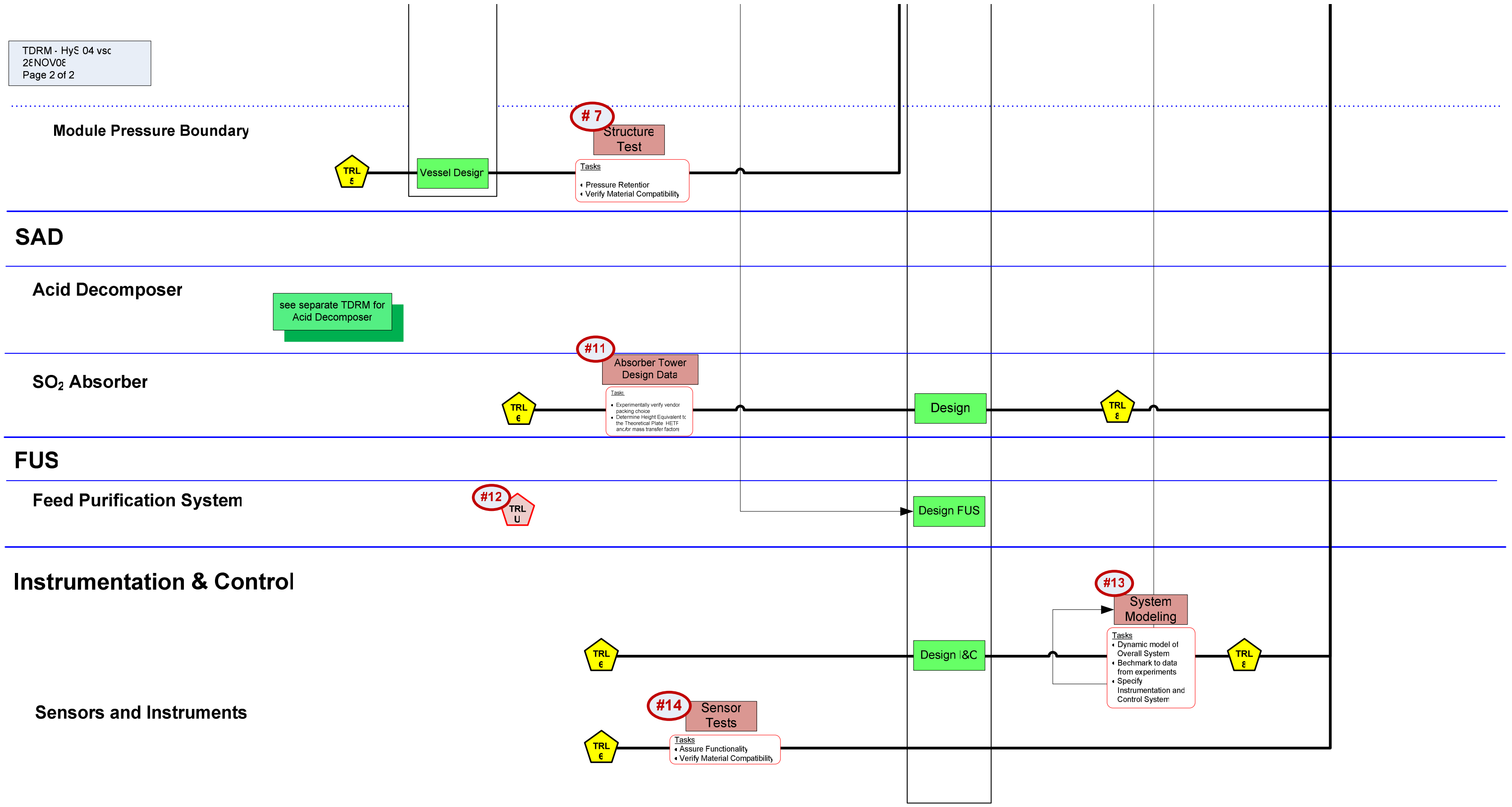
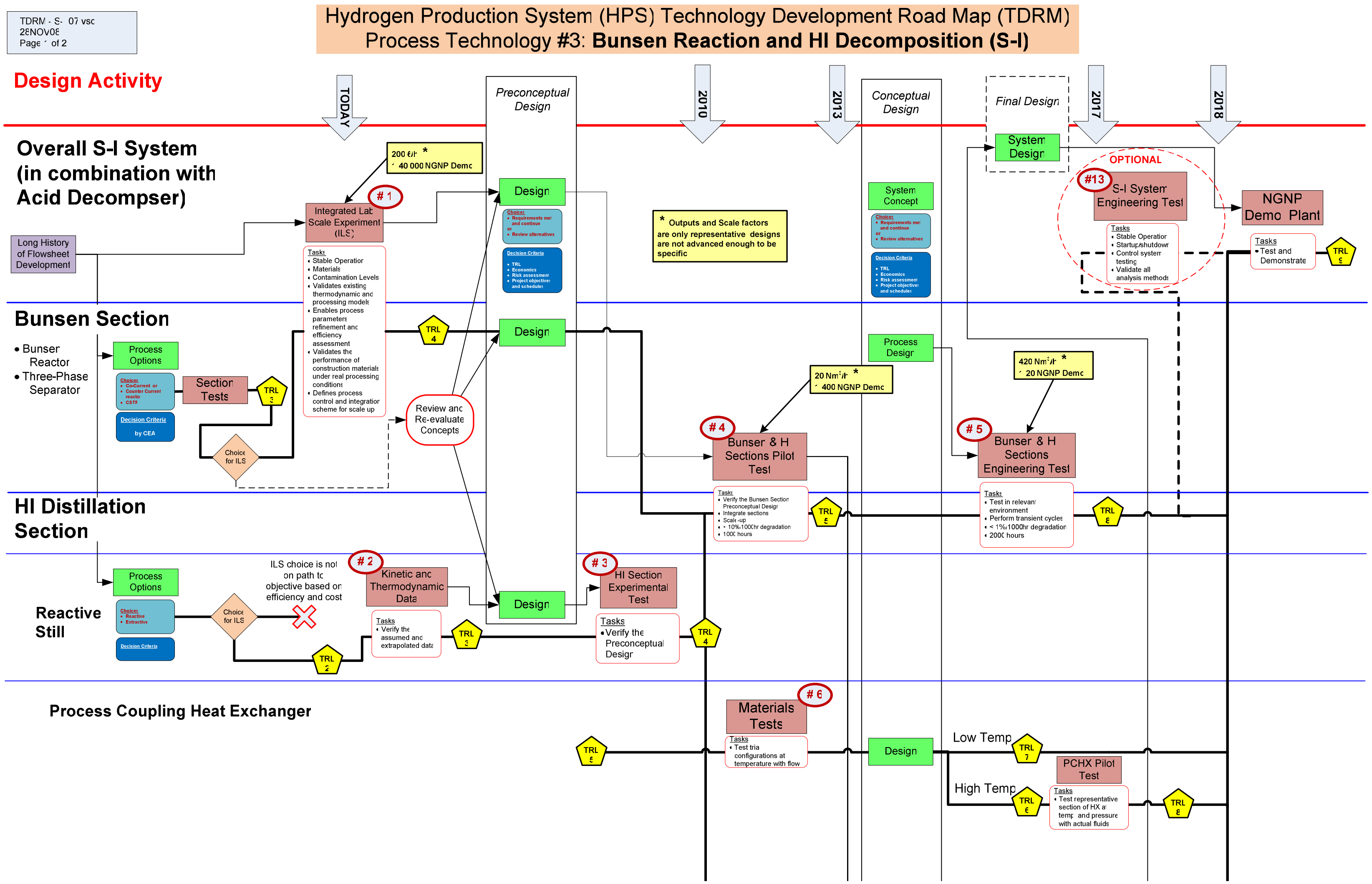



Figure B2-1: Technology Development Road Map of Sulfur Dioxide Electrolysis

# B3 BUNSEN REACTION AND HI DECOMPOSITION


Hydrogen Production System (HPS) Technology Development Road Map (TDRM)
Process Technology #3: Bunsen Reaction and HI Decomposition (S-I)
Design Activity
TODAY
2010
2013
2017
2018
Preconceptual Design
Conceptual Design
Final Design
Overall S-I System (in combination with Acid Decompser)
Long History of Flowsheet Development
Integrated Lab Scale Experiment (ILS)
# 1
200 ℓ/hr * 40 000 NGNP Demo
Tasks
Stable Operation
Materials
Contamination Levels
Validates existing thermodynamic and processing models
Enables process parameters refinement and efficiency assessment
Validates the performance of construction materials under real processing conditions
Defines process control and integration scheme for scale up
Design
Review and Re-evaluate Concepts
* Outputs and Scale factors are only representative designs are not advanced enough to be specific
System Concept
System Design
OPTIONAL
#13
S-I System Engineering Test
Tasks
Stable Operation
Startup/shutdown
Control system testing
Validate all analysis methods
NGNP Demo Plant
Tasks
Test and Demonstrate
Bunsen Section
Bunsen Reactor
Three-Phase Separator
Process Options
Section Tests
Decision Criteria by CEA
Choice for ILS
Process Design
20 Nm³/hr * 400 NGNP Demo
# 4
Bunsen & HI Sections Pilot Test
Tasks
Verify the Bunsen Section Preconceptual Design
Integrate sections
Scale-up
10%/1000hr degradation
1000 hours
420 Nm³/hr * 20 NGNP Demo
# 5
Bunsen & HI Sections Engineering Test
Tasks
Test in relevant environment
Perform transient cycles
< 1%/1000hr degradation
2000 hours
HI Distillation Section
Reactive Still
ILS choice is not on path to objective based on efficiency and cost
# 2
Kinetic and Thermodynamic Data
Tasks
Verify the assumed and extrapolated data
# 3
HI Section Experimental Test
Tasks
Verify the Preconceptual Design
Process Coupling Heat Exchanger
# 6
Materials Tests
Tasks
Test trial configurations at temperature with flow
Design
Low Temp
High Temp
PCHX Pilot Test
Tasks
Test representative section of HX at temp and pressure with actual fluids
TRL

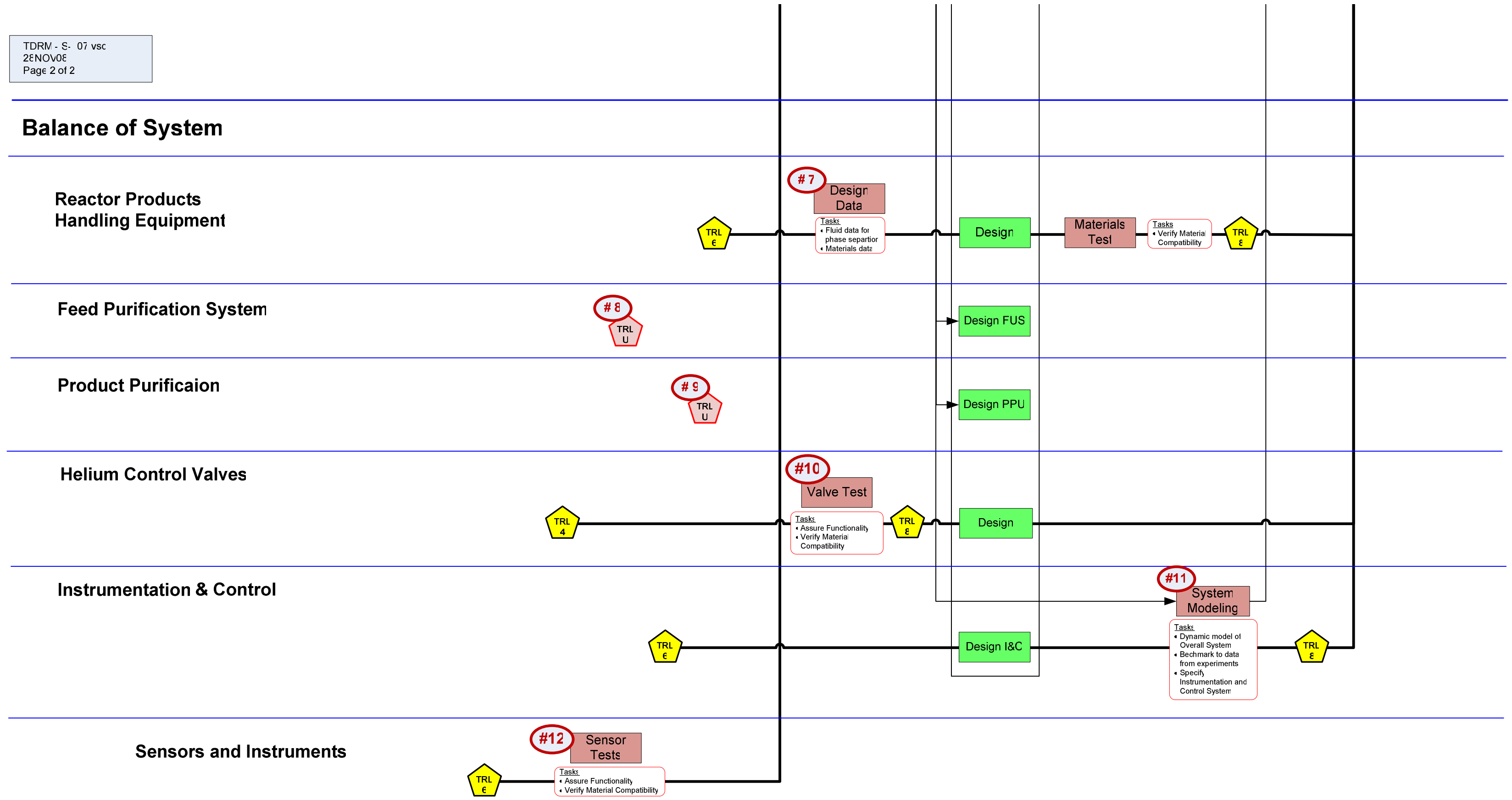
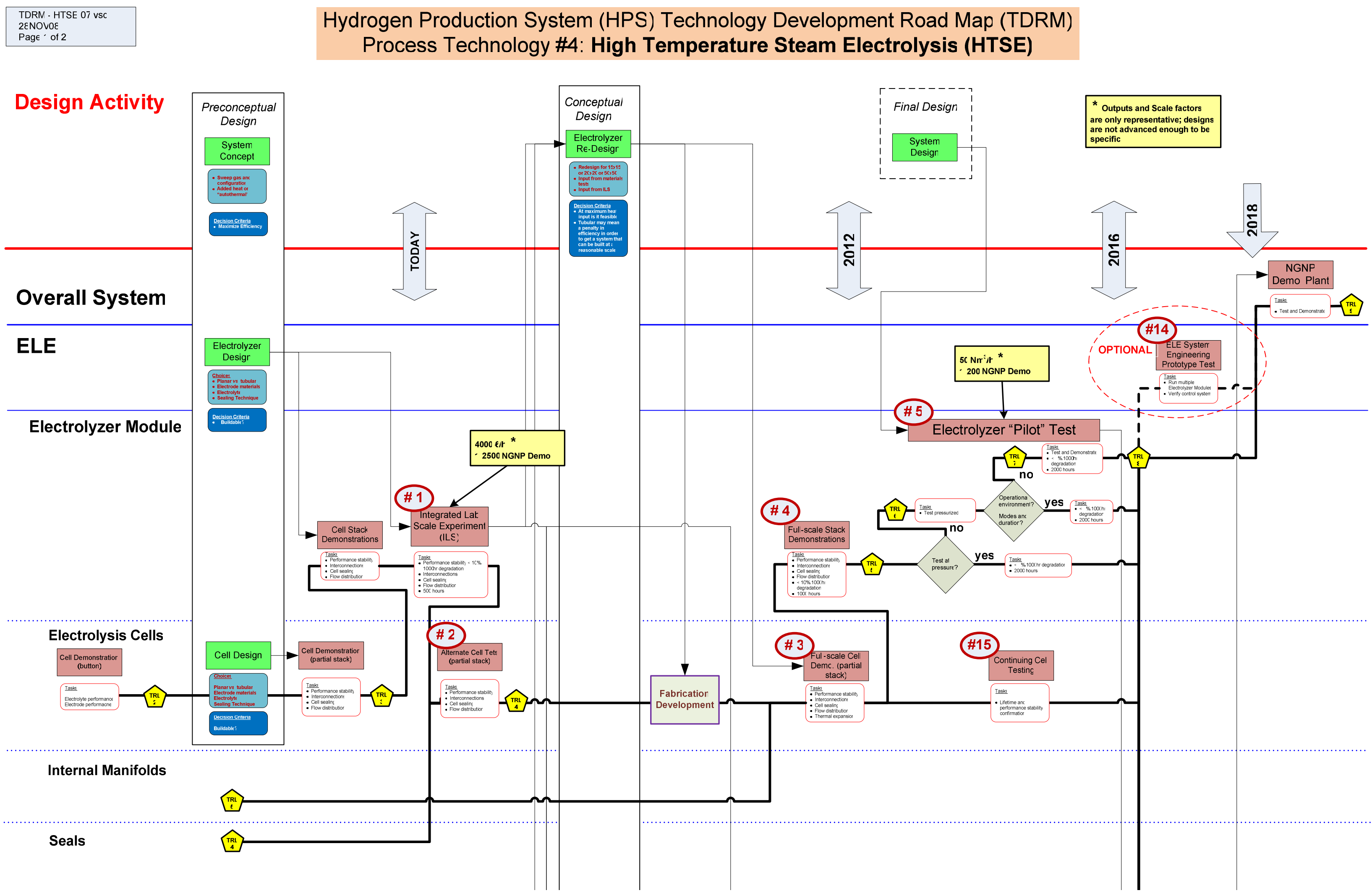



Figure B3-1: Technology Development Road Map of Bunsen Reaction and HI Decomposition

# B4 HIGH TEMPERATURE STEAM ELECTROLYSIS


TDRM - HTSE 07 vsc
28NOV08
Page 1 of 2
Hydrogen Production System (HPS) Technology Development Road Map (TDRM)
Process Technology #4: High Temperature Steam Electrolysis (HTSE)
Design Activity
Overall System
ELE
Electrolyzer Module
Electrolysis Cells
Internal Manifolds
Seals
Preconceptual Design
System Concept
Electrolyzer Design
Cell Design
Conceptual Design
Electrolyzer Re-Design
Final Design
System Design
* Outputs and Scale factors are only representative; designs are not advanced enough to be specific
TODAY
2012
2016
2018
NGNP Demo Plant
OPTIONAL
#14
ELE System Engineering Prototype Test
50 Nm³/h
200 NGNP Demo
4000 €/h
2500 NGNP Demo
# 5
Electrolyzer "Pilot" Test
# 1
Integrated Lab Scale Experiment (ILS)
Cell Stack Demonstrations
# 4
Full-scale Stack Demonstrations
Operations environment?
Modes and duration?
Test at pressure?
yes
no
# 2
Alternate Cell Tests (partial stack)
Cell Demonstration (button)
Cell Demonstration (partial stack)
Fabrication Development
# 3
Full-scale Cell Demo. (partial stack)
#15
Continuing Cell Testing

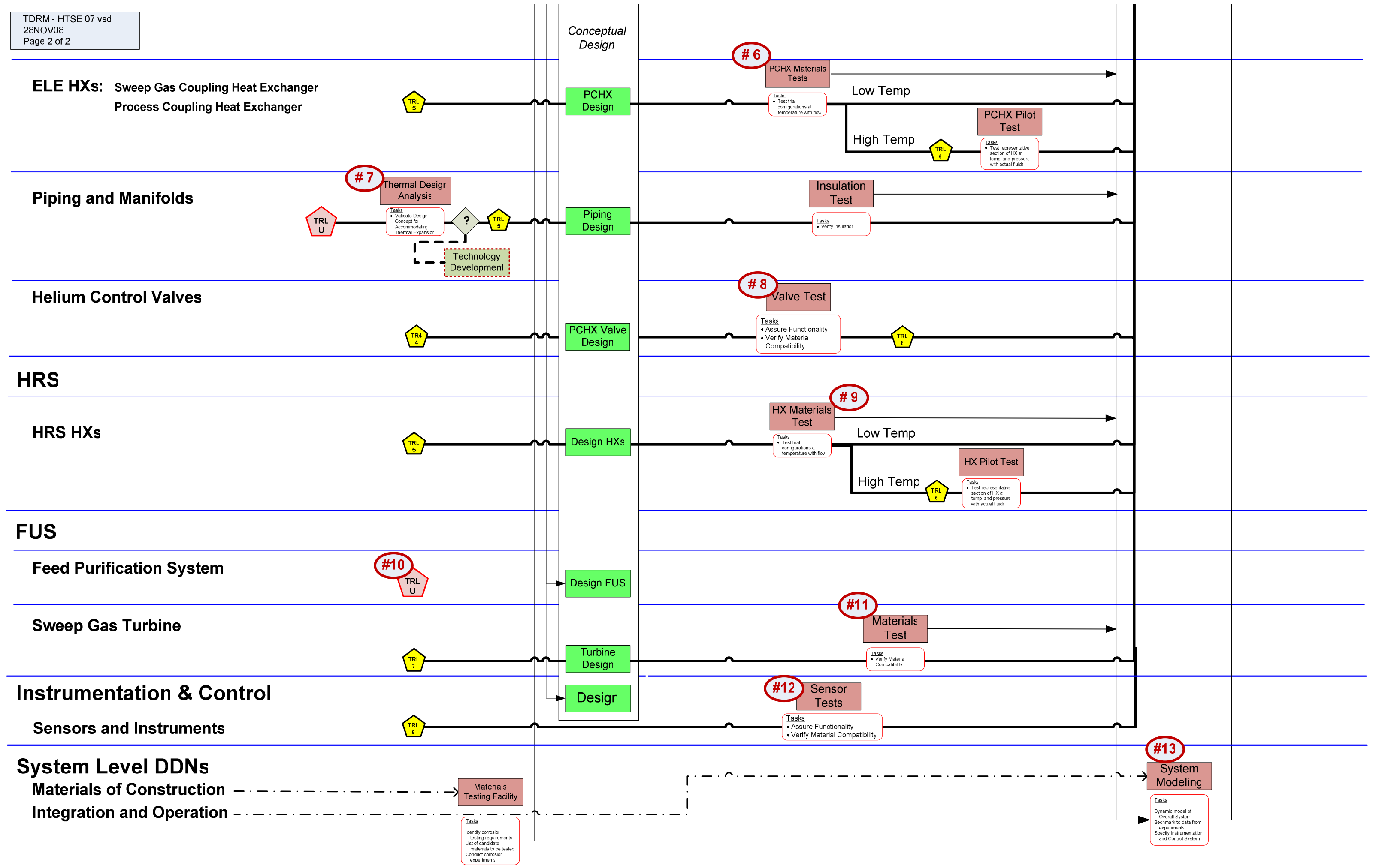



Figure B4-1: Technology Development Road Map of High Temperature Steam Electrolysis

# APPENDIX C: TECHNOLOGY MATURATION PLANS

Sections 8.1.5, 8.2.5, 8.3.5 and 8.4.5 of the report summarize the steps on the Road Maps toward maturation of the technologies of the Critical SSCs for the four technology areas. Following are more detailed Test Plans for the Sulfuric Acid Decomposition technology (above Section 8.1) and the $SO_2$ Electrolysis technology (above Section 8.2). These two sections comprise the Hybrid Sulfur (HyS) hydrogen production system.

Some analyses appear on the TDRMs, and these are not included in the Test Plan details. Ongoing and complete steps in the TDRMs are also not included in the Plans.

## TABLE OF CONTENTS

# C1 MATERIALS TESTING – DECOMPOSITION REACTOR

(Test #2 on the Sulfuric Acid Decomposer Road Map)

The S-I ILS Experiment will validate the compatibility of the SiC tubes with the process fluids, which is to be expected from initial decomposer demonstration tests. Separate tests are needed for materials other than the SiC tubes.

## C1.1 TEST OBJECTIVE

The materials of the Sulfuric Acid Decomposer, in particular, the seals between the SiC tubes and their manifolds or tubesheets need to be tested in anticipated steady state and transient conditions.

## C1.2 TEST DESCRIPTION

Further test details will require design effort to, as a minimum, determine 1) the materials, 2) their configuration and 3) the static and cyclic environments they will see in service.

No location for these tests can be decided at this time.

## C1.3 MEASURED PARAMETERS

In general, materials testing involves qualitative examination of test articles for corrosion or other damage and quantitative, generally destructive, measurement of dimensional and/or gravimetric change. Further testing would be comparison of mechanical strength and ductility with the unexposed duplicates.

## C1.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would apply to structural and sealing components of the process coupling heat exchangers, which the Sulfuric Acid Decomposer is one.

## C1.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C1.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C1.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C2 THERMODYNAMIC AND REACTION KINETICS VERRIFICATION

(Test #4 on the Sulfuric Acid Decomposer Road Map)

Experimental confirmation of the equilibrium and kinetic model implicit in the simulations generated thus far are essential. Much of the modeling has involved extrapolations of data that need confirmation.

## C2.1 TEST OBJECTIVE

Provide data to support further analytical modeling of the HyS cycle.

## C2.2 TEST DESCRIPTION

These are laboratory based tests. Further details are not specific at this time.

## C2.3 MEASURED PARAMETERS

Indeterminate at this time.

## C2.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C2.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C2.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C2.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C3 CATYLIST BENCH TEST

(Test #5 on the Sulfuric Acid Decomposer Road Map)

The Decomposer Catalyst requires development testing to assure reasonable performance stability and lifetime, since periodic replacement is expected. Chemical industry practice would dictate a lifetime of 20,000 hours, which often can be established by accelerated testing.

The characteristic of the Decomposer Catalyst, combined with thermodynamic analyses, determines whether the Decomposer design is set by limits on heat transfer or by the Decomposer Catalyst performance, and this is essential input to the Conceptual Design. This task will require iteration with the Thermal-Hydraulic Analysis to account for the effects of flow and temperature on the Decomposer Catalyst and the decomposition reaction.

## C3.1 TEST OBJECTIVE

Catalyst bench testing will reveal the mechanisms and parameters of catalyst poisoning and degradation, and from those results one can initiate meaningful accelerated testing to support the overall HPS design.

## C3.2 TEST DESCRIPTION

These are laboratory based tests. Further details are not specific at this time.

## C3.3 MEASURED PARAMETERS

Indeterminate at this time.
Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C3.4 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C3.5 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C3.6 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C4 DECOMPOSER PILOT TEST

(Test #8 on the Sulfuric Acid Decomposer Road Map)

## C4.1 TEST OBJECTIVE

The test provides the thermal and hydraulic data needed for integration of the decomposer into the HyS HPS.

## C4.2 TEST DESCRIPTION

In the Pilot Test a full-scale-length, single-tube, convection-heated bayonet tube assembly will be tested at design conditions. The test assembly will also include a reference sealing configuration and replaceable catalyst to verify the function of these features. This will be the first test with helium convective heating, rather than furnace heating, of the Decomposer. Only in this configuration are the catalyst bed and wall temperature profiles correct in detail. Helium flow in this test can be in one end and out the other, in contrast to the Engineering Test for which the flow return to the same end as entry will be required.

### C4.2.1 Test Conditions

Indeterminate at this time.

### C4.2.2 Test Configuration/Set-up

Test a full-scale-length, single-tube, convection-heated bayonet tube. The test assembly will also include a reference sealing configuration and replaceable catalyst. Helium flow in this test can be in one end and out the other, in contrast to the Engineering Test for which the flow return to the same end as entry will be required.

### C4.2.3 Test Duration

A nominal goal of 1000 hours of steady operation at less than 5% per 1000 hour degradation in output would constitute success. Ideally, the testing would also include startup, shutdown and accident transients to the degree confirmed at that design phase.

### C4.2.4 Proposed Test Location

Possibly this test (and the later Engineering and Prototype Tests) could be conducted at a sulfuric acid plant, since sulfuric acid decomposition is nothing more than undoing what a sulfuric acid plant does. It would draw a continuous feed from the plant and put its effluent product back into their feed.

## C4.3 MEASURED PARAMETERS

Input and output flow rates, conditions and compositions and input and output heat. Instrumentation for temperature measurement will also be included to compare to models.

## C4.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C4.5 TEST EVALUATION CRITERIA

The criterion is stable conversion of sulfuric acid to sulfur dioxide at the design flow rates for the inputs and outputs.

## C4.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C4.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C5 VLE DATA VERIFICATION

(Test #9 on the Sulfuric Acid Decomposer Road Map)

The design of the reactor product and recycle concentration system requires verification and refinement of the vapor-liquid equilibrium data.

## C5.1 TEST OBJECTIVE

Complete, accurate VLE data in the ranges needed.

## C5.2 TEST DESCRIPTION

These are laboratory based tests. Further details are not specific at this time.

## C5.3 MEASURED PARAMETERS

Indeterminate at this time.

## C5.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C5.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C5.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C5.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C6 STRIPPER TOWER DESIGN DATA

(Test #10 on the Sulfuric Acid Decomposer Road Map)

Determination of data in order to confidently design this tower and, for the HyS system, the $SO_2$ absorber.

## C6.1 TEST OBJECTIVE

Determinations of mass transfer coefficients or Heights Equivalent to the Theoretical Plate (HETPs) are needed.

## C6.2 TEST DESCRIPTION

A vendor would supply a suitable packing that will be tested to measure an HETP or mass transfer coefficient. It may be useful also to do small bench scale tests to determine whether and how much the mass transfer in this system of components and conditions deviates from that of similar known systems.

## C6.3 MEASURED PARAMETERS

Determinations of mass transfer coefficients or Heights Equivalent to the Theoretical Plate (HETPs).

## C6.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C6.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C6.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C6.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C7 MATERIALS TESTING- DECOMPOSER PRODUCT

(Test #11 on the Sulfuric Acid Decomposer Road Map)

The materials of construction of the decomposer product handling equipment need to be tested for compatibility. Because of the effects of material transport, simple immersion of material coupons will not be sufficient. A circulating test loop should be considered.

## C7.1 TEST OBJECTIVE

The materials of the decomposer product handling equipment need to be tested in anticipated steady state and cyclic conditions.

## C7.2 TEST DESCRIPTION

Further test details will require design effort to, as a minimum, determine 1) the materials, 2) their configuration and 3) the static and cyclic environments they will see in service.

No location for these tests can be decided at this time.

## C7.3 MEASURED PARAMETERS

In general, materials testing involves qualitative examination of test articles for corrosion or other damage and quantitative, generally destructive, measurement of dimensional and/or gravimetric change. Further testing would be comparison of mechanical strength and ductility with the unexposed duplicates.

## C7.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C7.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C7.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C7.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C8 THERMODYNAMIC AND REACTION KINETICS VERRIFICATION

(Test #4 on the Sulfuric Acid Decomposer Road Map)

Experimental confirmation of the equilibrium and kinetic model implicit in the simulations generated thus far are essential. Much of the modeling has involved extrapolations of data that need confirmation.

## C8.1 TEST OBJECTIVE

Provide data to support further analytical modeling of the HyS cycle.

## C8.2 TEST DESCRIPTION

These are laboratory based tests. Further details are not specific at this time.

## C8.3 MEASURED PARAMETERS

Indeterminate at this time.

## C8.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C8.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C8.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C8.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C9 MATERIALS TESTING FEED HANDLING

(Test #12 on the Sulfuric Acid Decomposer Road Map)

Testing of the materials of construction feed acid handling and concentrating equipment and the verified VLE data completes development to the TRL 8 level for prototype application.

## C9.1 TEST OBJECTIVE

The materials of the feed acid handling and concentrating equipment need to be tested in anticipated steady state and cyclic conditions.

## C9.2 TEST DESCRIPTION

Further test details will require design effort to, as a minimum, determine 1) the materials, 2) their configuration and 3) the static and cyclic environments they will see in service.

No location for these tests can be decided at this time.

## C9.3 MEASURED PARAMETERS

In general, materials testing involves qualitative examination of test articles for corrosion or other damage and quantitative, generally destructive, measurement of dimensional and/or gravimetric change. Further testing would be comparison of mechanical strength and ductility with the unexposed duplicates.

## C9.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C9.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C9.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

# C9.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C10 VALVE TEST

(Test #13 on the Sulfuric Acid Decomposer Road Map)

The valves that control the flow of high-temperature helium in the NHSS Secondary Heat Transport System (SHTS) between parallel Sulfuric Acid Decomposers are part of the HPS.

## C10.1 TEST OBJECTIVE

First objective is the integrity of the valve exterior pressure boundary at the design temperature conditions. This can probably be proven by analysis, but any testing will confirm the calculations. Operability is the main objective of this testing. A final objective may be to test the internal pressure retaining capability (flow sealing) but this is not a definite requirement of the valve, as far as the requirements are known at this stage of overall design.

## C10.2 TEST DESCRIPTION

Valve (and actuator) will be cycled under design flow and temperature conditions. This testing would be done at the vendor's facility.

### C10.2.1 Test Conditions

To be determined in design phases not yet done.

### C10.2.2 Test Configuration/Set-up

These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application. Test articles should be large enough that flow similitude should be defensible.

### C10.2.3 Test Duration

Indeterminate at this time.

### C10.2.4 Proposed Test Location

This testing would be done at the vendor's facility. No vendor is yet identified.

## C10.3 MEASURED PARAMETERS

Indeterminate at this time.

## C10.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would apply to structural and sealing components of the process coupling heat exchangers, of which the HPS control valves are.

## C10.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C10.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C10.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C11 SENSOR TESTS

(Test #14 on the Sulfuric Acid Decomposer Road Map)

Thermocouples, pressure sensors and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments

## C11.1 TEST OBJECTIVE

The materials of construction need to be tested in anticipated steady state and transient conditions.

## C11.2 TEST DESCRIPTION

Further test details will require design effort to, as a minimum, determine 1) the materials, 2) their configuration and 3) the static and cyclic environments they will see in service.

No location for these tests can be decided at this time.

## C11.3 MEASURED PARAMETERS

Sensed variable measurement would be compared to results from reference instruments. Operation would be of sufficient duration to validate the instrument reliability and lifetime requirements, but these requirements will not be available until further system design has progressed. In addition, materials testing involves qualitative examination of test articles for corrosion or other damage and quantitative, generally destructive, measurement of dimensional and/or gravimetric change.

## C11.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would apply to any helium side instrumentation. Process side instrumentation would not be NQA-1.

## C11.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C11.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C11.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C12 DECOMPOSER ENGINEERING TEST

(Test #16 on the Sulfuric Acid Decomposer Road Map)

A test of the Decomposer scaled-up and approaching prototype configuration.

# C12.1 TEST OBJECTIVE

The test provides the thermal and hydraulic data needed for integration of the decomposer into the HyS HPS.

# C12.2 TEST DESCRIPTION

The test proposed is for a matrix of full-length tubes with helium heating and prototypic flow configuration on helium and process sides.

## C12.2.1 Test Conditions

Indeterminate at this time.

## C12.2.2 Test Configuration/Set-up

The test proposed is for a hexagonal matrix of 19 full-length tubes with helium heating. In such a configuration the central 5 tubes would be tested in full-scale thermo-hydraulic conditions on the outside, and likewise for the process flow in the tubes.

Note that this test precedes the Final Design and so will not necessarily include the prototypical tube seals, process side valves or instrumentation sensors. The Prototype Test will provide design verification for these components.

## C12.2.3 Test Duration

A nominal goal of 1500 hours of steady operation at less than 2% per 1000 hour degradation in output would constitute success. Ideally, the testing would also include startup, shutdown and accident transients to the degree confirmed at that design phase.

## C12.2.4 Proposed Test Location

Possibly this test (and the later Prototype Test) could be conducted at a sulfuric acid plant, since sulfuric acid decomposition is nothing more than undoing what a sulfuric acid plant does. It would draw a continuous feed from the plant and put its effluent product back into their feed.

# C12.3 MEASURED PARAMETERS

Input and output flow rates, conditions and compositions and input and output heat. Instrumentation for temperature measurement will also be included to compare to models.

# C12.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C12.5 TEST EVALUATION CRITERIA

The criterion is stable conversion of sulfuric acid to sulfur dioxide at the design flow rates for the inputs and outputs.

## C12.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C12.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C13 PROTOTYPE TEST

(Test #18 on the Sulfuric Acid Decomposer Road Map)

This final test in the sequence of technology maturation would be the same configuration as the Engineering Test but with the final design features including the prototype seals, valves and instruments.

## C13.1 TEST OBJECTIVE

The test provides the thermal and hydraulic data needed for integration of the decomposer into the HyS HPS.

## C13.2 TEST DESCRIPTION

The test proposed is for a matrix of full-length tubes with helium heating and prototypic flow configuration on helium and process sides.

### C13.2.1 Test Conditions

Indeterminate at this time.

### C13.2.2 Test Configuration/Set-up

The test proposed is for a hexagonal matrix of 19 full-length tubes with helium heating. In such a configuration the central 5 tubes would be tested in full-scale thermo-hydraulic conditions on the outside, and likewise for the process flow in the tubes.

This test precedes the Final Design and so will include the prototypical tube seals, process side valves or instrumentation sensors. Test Duration

The testing would cover the full operational environment and through the design cycles as determined by final system design. In addition, stable operation for a time period, nominally 2000 hours at less than 1% per 1000 hour degradation in output, would be expected.

### C13.2.3 Proposed Test Location

Possibly this test could be conducted at a sulfuric acid plant, since sulfuric acid decomposition is nothing more than undoing what a sulfuric acid plant does. It would draw a continuous feed from the plant and put its effluent product back into their feed.

## C13.3 MEASURED PARAMETERS

Input and output flow rates, conditions and compositions and input and output heat. Instrumentation for temperature measurement will also be included to compare to models.

## C13.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C13.5 TEST EVALUATION CRITERIA

The criterion is stable conversion of sulfuric acid to sulfur dioxide at the design flow rates for the inputs and outputs.

## C13.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C13.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C14 SINGLE CELL TESTING

(Test #2 on the Sulfur Dioxide Electrolysis Road Map)

Cell testing at elevated temperature and at pressure, as is the application.

## C14.1 TEST OBJECTIVE

Iterate with design function to determine an optimal configuration of cell assembly, including design of HyS ILS.

## C14.2 TEST DESCRIPTION

The test will demonstrate the design choice MEA (Membrane-Electrode Assembly) in a single cell. The cell electrical and flow connections and sealing of the cell are to be features proof tested in this experiment.

### C14.2.1 Test Conditions

This test would be performed in ambient laboratory conditions.

### C14.2.2 Test Configuration/Set-up

Indeterminate at this time.

### C14.2.3 Test Duration

This test would not have a specific duration for evaluation purposes. A nominal duration would be 500 hours.

### C14.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C14.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values and prior tests.

Post-test destructive examination will provide data on electrode chemical and mechanical stability. The examination will also yield data for evaluation of material transport, particularly sulfur transport through the membrane to the cathode that has been observed in earlier tests.

## C14.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C14.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

The above-mentioned sulfur and other material transport will be qualitatively characterized and quantitatively compared to design allowable values.

Performance stability will be compared to system design factors that determine economic optimization, namely the reliability, service requirements, replacement frequencies and mean output of product. Target value for acceptable degradation is 20% per 1000 hours.

## C14.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C14.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C15 HYS ILS TEST

(Test #3 on the Sulfur Dioxide Electrolysis Road Map)

This test will combine a small-scale Decomposition section to demonstrate the HyS cycle.

## C15.1 TEST OBJECTIVE

Demonstrate a complete Hybrid Sulfur thermo- electro-chemical water splitting system.

## C15.2 TEST DESCRIPTION

Operate an experimental assembly of the HyS system including the Sulfuric Acid Decomposer. Output goal is 200 ℓ/h of hydrogen.

### C15.2.1 Test Conditions

The test will be conducted at steady-state temperature, gas flow, current density and voltage conditions typical of expected commercial operation.

### C15.2.2 Test Configuration/Set-up

The Sulfur Dioxide Electrolyzer assembly will be comprised of cells of 160 $cm^2$ area and in the configuration of the Preconceptual Design. Sulfuric Acid Decomposer would be the unit or a duplicate of the Decomposer in the S-I ILS.

### C15.2.3 Test Duration

The test would operate at least 1000 hours under the following ground rules:

- The tests will be operated for a minimum of 150 hours per week.
- No components of the cell can be replaced during the test.
- Between the beginning and end of the test up to 100 hours of operating data can be ignored to eliminate startup transients, interruptions in power and gas supplies and any final, rapid degradation in cell performance. The 100 hours would not be included in the minimum test duration.

### C15.2.4 Proposed Test Location

At this point in the DOE NHI program the HyS ILS would be performed at Savannah River National Laboratory. As noted in the Sulfuric Acid Decomposition TDRM (Section 8.1.5), this could be combined with the Pilot Test of the Acid Decomposer, the location for which has not been specified.

## C15.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values and separate cell tests.

## C15.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C15.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

Acceptable performance degradation is 10% per 1000 hours. The degradation will be measured as the change in electrical energy input to the cells per kilogram of hydrogen produced.

## C15.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C15.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C16 OPTIMIZED CELL TESTING

(Test #4 on the Sulfur Dioxide Electrolysis Road Map)

In parallel with the ILS and Preconceptual Design, the electrolysis cell design and materials will be reoptimized. This is an additional step in iteration of design and experiment.

## C16.1 TEST OBJECTIVE

Test the result of cell redesign for optimum performance.

## C16.2 TEST DESCRIPTION

### C16.2.1 Test Conditions

This test would be performed in ambient laboratory conditions.

### C16.2.2 Test Configuration/Set-up

Indeterminate at this time. $SO_2$ input would be laboratory grade.

### C16.2.3 Test Duration

This test would not have a specific duration for evaluation purposes. A nominal duration would be 1000 hours.

### C16.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C16.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values, prior cell tests and the ILS results.

## C16.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C16.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

Acceptable performance degradation is 10% per 1000 hours. The degradation will be measured as the change in electrical energy input to the cells per kilogram of hydrogen produced.

## C16.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C16.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C17 CELL SCALE-UP TESTING

(Test #5 on the Sulfur Dioxide Electrolysis Road Map)

The plan has Electrolyzer Cells scaled-up from the ILS size in two steps – these correspondingly after Preconceptual and Conceptual Design.

## C17.1 TEST OBJECTIVE

Test the result of cell scale-up to 400 $cm^2$.

## C17.2 TEST DESCRIPTION

### C17.2.1 Test Conditions

This test would be performed in ambient laboratory conditions.

### C17.2.2 Test Configuration/Set-up

This is a single cell test. $SO_2$ input would be laboratory grade. Further set-up detail is indeterminate at this time.

### C17.2.3 Test Duration

This test would not have a specific duration for evaluation purposes. A nominal duration would be 1000 hours.

### C17.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C17.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values, prior cell tests and the ILS results.

## C17.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C17.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

Acceptable performance degradation is 10% per 1000 hours. The degradation will be measured as the change in electrical energy input to the cells per kilogram of hydrogen produced.

## C17.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C17.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C18 ELECTROLYZER INTERNALS TEST

(Test #6 on the Sulfur Dioxide Electrolysis Road Map)

Following Preconceptual Design of the Electrolyzer Module Pressure Boundary, the Module Internal design will be tested.

## C18.1 TEST OBJECTIVE

This is a design verification and support test.

## C18.2 TEST DESCRIPTION

### C18.2.1 Test Conditions

The test will be conducted at steady-state temperature and gas flow conditions typical of expected commercial operation.

### C18.2.2 Test Configuration/Set-up

Indeterminate at this time.

### C18.2.3 Test Duration

This test would not have a specific duration for evaluation purposes.

### C18.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C18.3 MEASURED PARAMETERS

Temperatures, flows and dimensional parameters are data needed to compare with design values.

## C18.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C18.5 TEST EVALUATION CRITERIA

The design must demonstrate acceptable cell-to-cell flow distribution and pressure retention Thermal performance data must support projected heat losses. The quantities of these criteria need to be developed in future design steps.

## C18.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C18.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C19 PRESSURE BOUNDARY STRUCTURE TEST

(Test #7 on the Sulfur Dioxide Electrolysis Road Map)

The design requirements of the vessel or pressure retaining exterior boundary for the $SO_2$ Electrolysis Cell is not finally determined. However, there is a preferred concept which would be tested separately for pressure retention and material compatibility and then used in the Electrolyzer Pilot-scale Test.

## C19.1 TEST OBJECTIVE

This is a design verification and support test.

## C19.2 TEST DESCRIPTION

### C19.2.1 Test Conditions

The test will be conducted at steady-state temperature and gas flow conditions typical of expected commercial operation.

### C19.2.2 Test Configuration/Set-up

Indeterminate at this time.

### C19.2.3 Test Duration

This test would not have a specific duration for evaluation purposes.

### C19.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C19.3 MEASURED PARAMETERS

Temperatures, flows, feedthrough currents and mechanical boundary conditions are parameters needed to compare with design values.

## C19.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C19.5 TEST EVALUATION CRITERIA

The design must demonstrate acceptable pressure retention and dimensional stability. The quantities of these criteria need to be developed in future design steps.

## C19.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C19.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C20 ELECTROLYZER PILOT TEST

(Test #8 on the Sulfur Dioxide Electrolysis Road Map)

This is the first test of an electrolyzer with 400 $cm^2$ cells and the first test of the Module Pressure Boundary and module internals.

## C20.1 TEST OBJECTIVE

For this test the nominal goals, which are subject to change as the R&D program proceeds along the Road Map, are as follows:

| Electrolyzer | |
|---|---|
| Avg. cell voltage, mV | 700 |
| Current Density, $mA/cm^2$ | 500 |
| Cell Active Area, $cm^2$ | 400 |

| HyS System | |
|---|---|
| Hydrogen output, ℓ/h | 28,000 |
| Hydrogen output, kW (HHV) | 70 |
| Process heat input, kWt | 200 |
| Process electrical input, kWe | 100 |
| Time on line, hours | 1000 |

## C20.2 TEST DESCRIPTION

### C20.2.1 Test Conditions

The test will be conducted at steady-state temperature, gas flow, current density and voltage conditions typical of expected commercial operation.

### C20.2.2 Test Configuration/Set-up

Indeterminate at this time. $SO_2$ input would reproduce the composition of the output of (or be actual product of) the Sulfuric Acid Decomposition section as being developed in parallel.

### C20.2.3 Test Duration

The test would operate at least 1000 hours. (Refer to ground rules for measure in C15.2.3)

### C20.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C20.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values, prior cell tests and the ILS results.

## C20.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C20.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

Acceptable performance degradation is 5% per 1000 hours. The degradation will be measured as the change in electrical energy input to the cells per kilogram of hydrogen produced.

## C20.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C20.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C21 ELECTROLYZER ENGINEERING TEST

(Test #9 on the Sulfur Dioxide Electrolysis Road Map)

This is a test of one electrolyzer with full-scale cells (1000 $cm^2$) following Conceptual Design.

## C21.1 TEST OBJECTIVE

The nominal goals of this test are as follows:

| | |
|---|---|
| Electrolyzer | |
| Avg. cell voltage, mV | 650 |
| Current Density, $mA/cm^2$ | 500 |
| Cell Active Area, $cm^2$ | 1000 |
| HyS System | |
| Hydrogen output, ℓ/h | 280,000 |
| Hydrogen output, kW (HHV) | 1000 |
| Process heat input, kWt | 2000 |
| Process electrical input, kWe | 1000 |
| Time on line, hours | 1500 |

## C21.2 TEST DESCRIPTION

### C21.2.1 Test Conditions

The test will be conducted at temperature, gas flow, current density and voltage conditions typical of expected commercial operation. Transient testing will not necessarily be to the full range of design transients.

### C21.2.2 Test Configuration/Set-up

Indeterminate at this time. $SO_2$ input would reproduce the composition of the output of (or be actual product of) the Sulfuric Acid Decomposition section as being developed in parallel.

### C21.2.3 Test Duration

The test would operate at least 1500 hours. (Refer to ground rules for measure in C15.2.3)

### C21.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C21.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values, prior cell tests and the Pilot Test results.

## C21.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C21.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

Acceptable performance degradation is 2% per 1000 hours. The degradation will be measured as the change in electrical energy input to the cells per kilogram of hydrogen produced.

## C21.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C21.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C22 PROTOTYPE ELECTROLYZER TEST

(Test #10 on the Sulfur Dioxide Electrolysis Road Map)

This test will be of one prototype electrolyzer of the full-scale with the number of cells resulting from Final Design with the cell scaled up in area from 1000 $cm^2$ to 1 $m^2$.

## C22.1 TEST OBJECTIVE

The goal of this test is electrolyzer performance corresponding to an HPS production on the order of 420 $Nm^3$ of hydrogen per hour.

## C22.2 TEST DESCRIPTION

### C22.2.1 Test Conditions

The test will be conducted at temperature, gas flow, current density and voltage conditions typical of expected commercial operation. Transient testing will be to the full range of design transients.

### C22.2.2 Test Configuration/Set-up

Indeterminate at this time. $SO_2$ input would reproduce the composition of the output of (or be actual product of) the Sulfuric Acid Decomposition section as being developed in parallel.

### C22.2.3 Test Duration

The test would operate at least 2000 hours. (Refer to ground rules for measure in C15.2.3)

### C22.2.4 Proposed Test Location

At this point in the DOE NHI program the testing of the cells would be performed at Savannah River National Laboratory.

## C22.3 MEASURED PARAMETERS

Power input and product output flows and conditions are data needed to compare with design values, prior cell tests and the Pilot Test results.

## C22.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C22.5 TEST EVALUATION CRITERIA

The evaluation of the test will be based on the comparison of performance, as quantified by the above data, to design values.

Acceptable performance degradation is 1% per 1000 hours. The degradation will be measured as the change in electrical energy input to the cells per kilogram of hydrogen produced.

## C22.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C22.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C23 ABSORBER TOWER DESIGN DATA

(Test #11 on the Sulfur Dioxide Electrolysis Road Map)

System feasibility and functionality for the system can be assured from general industry experience, but design data is needed in the operating environment. Specifically for mass transfer in the $SO_2$ absorber column, the Heights Equivalent to the Theoretical Plate (HETPs) need to be experimentally determined. In order to be applied to the NGNP, sub-scale demonstration testing of the $SO_2$ Recovery System in the operational environment is expected.

## C23.1 TEST OBJECTIVE

Determinations of mass transfer coefficients or Heights Equivalent to the Theoretical Plate (HETPs) are needed.

## C23.2 TEST DESCRIPTION

A vendor would supply a suitable packing that will be tested to measure an HETP or mass transfer coefficient. It may be useful also to do small bench scale tests to determine whether and how much the mass transfer in this system of components and conditions deviates from that of similar known systems.

## C23.3 MEASURED PARAMETERS

Determinations of mass transfer coefficients or Heights Equivalent to the Theoretical Plate (HETPs).

## C23.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C23.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C23.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C23.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C24 SENSOR TESTING

(Test #14 on the Sulfur Dioxide Electrolysis Road Map)

Thermocouples, pressure sensors and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments.

## C24.1 TEST OBJECTIVE

The materials of construction need to be tested in anticipated steady state and transient conditions.

## C24.2 TEST DESCRIPTION

Further test details will require design effort to, as a minimum, determine 1) the materials, 2) their configuration and 3) the static and cyclic environments they will see in service.

No location for these tests can be decided at this time.

## C24.3 MEASURED PARAMETERS

Sensed variable measurement would be compared to results from reference instruments. Operation would be of sufficient duration to validate the instrument reliability and lifetime requirements, but these requirements will not be available until further system design has progressed. In addition, materials testing involves qualitative examination of test articles for corrosion or other damage and quantitative, generally destructive, measurement of dimensional and/or gravimetric change.

## C24.4 DATA REQUIREMENTS

Specific accuracy and other requirements can not be specified at this time. QA requirements are similarly unclear at this stage of development. It is anticipated that NQA-1 requirements will only apply to the HPS at its interface of with the NHSS, if at all. As such the requirements of NQA-1 would not apply to this data.

## C24.5 TEST EVALUATION CRITERIA

Indeterminate at this time.

## C24.6 TEST DELIVERABLES

A test report and data package would be delivered to NGNP Project.

## C24.7 COST AND SCHEDULE

Cost and Schedule for the Maturation Plans for the four hydrogen production technology areas are in Section 8.5.

# C25 PROTOTYPE HPS TEST

(Test #19 on the Sulfuric Acid Decomposer Road Map and Test #15 on the Sulfur Dioxide Electrolysis Road Map)

This test would be an assembly of one or more of the Prototype Electrolyzers from the previous test with a scaled-down Acid Decomposer section. The Road Maps are composed with the assumption that such a test is not needed, because separate testing of the Acid Decomposer and one Prototype Electrolyzers with transfer of feed and products between them could be sufficient to assure TRL 8. Integrated operation would be demonstrated by analysis.

No Test Plan is provided for this optional test at this time.

## C26 CONTINUING CELL TESTING

(Test #16 on the Sulfur Dioxide Electrolysis Road Map)

This would be a continuation of the cell scale-up to one square meter as described in C17. One or more cells would remain on test for up to 10,000 hours. The purpose of the testing is to develop lifetime experience on the prototype design cells and to quantify long-term performance trends.

Evaluation would be according to the criteria in Table 8-6.

The Test Plan is the same as in C17.

NGNP-CTF MTECH-TDRM-009 December 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 9: Power Conversion System Steam Generator

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |

| | |
|---|---|
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |

| | |
|---|---|
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |

| | |
|---|---|
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

The Steam Generator (SG) is a major component of the NGNP Power Conversion System (PCS) and interfaces with the Secondary Heat Transport System (SHTS). Location of the SG in the SHTS is based on maximizing the amount of high temperature thermal energy available for hydrogen production and is a significant departure from prior High-Temperature Gas-Cooled Reactor (HTGR) applications in which the SG was located in the Primary Heat Transport System (PHTS).

In the context of the NGNP Hydrogen Production System PCS, the Steam Generator is a developmental component that is based on proven technologies. These technologies must be reestablished, adapted and extrapolated for the NGNP. Based on prior applications such as Fort St. Vrain and the Thorium High-Temperature Reactor (THTR), the SG has been rated at a technology readiness level of TRL 6.

In the current context, the road map for TRL6 to TRL 8 requires two phases:

### TRL 6 to TRL 7:

- Perform a down selection trade study to determine the preferred conceptual arrangement of the SG
- Define requirements and design details for the SG in the PCS system context
- Perform configuration development tests to substantiate the design
- Design and supply a scale prototype for testing in the CTF
- Conduct performance testing in the CTF.

### TRL 7 to TRL 8:

- Complete final design of the prototype SG for the NGNP
- Fabricate and deliver to NGNP to the Site
- Install and operate.

The basic features of the reference preconceptual design of the SG are described along with an indication of the development testing needed.

To add detail to the roadmap in terms of technology maturation plans, it is important to first advance the SG to the conceptual design level.

# 9 POWER CONVERSION SYSTEM STEAM GENERATOR

## 9.1 Functions and Operating Requirements

The function of the Steam Generator (SG) is to produce superheated high pressure steam for conversion into mechanical work in the Steam Turbine of the Power Conversion System (PCS). In the Steam Generator, feedwater acquires heat from the higher temperature helium circulating in the Secondary Heat Transport System (SHTS). Feedwater enters as a sub-cooled liquid and exits as superheated steam. The Main Steam/Extraction System piping transports the steam to the Steam Turbine inlet.

Representative SG performance parameters are listed in Table 9-1.

**Table 9-1: Typical Steam Generator Performance Parameters**

| Parameter | HPS in Operation | HPS not in Operation |
|---|---|---|
| | | |
| **Thermal Power, MWt** | 470 | 520 |
| | | |
| **Hot Side** | | |
| Fluid | Helium | |
| Inlet Press, MPa | 8.7 | |
| Inlet Temp, °C | 840 | 900 |
| Flow Rate, kg/s | 160 | 160 |
| Outlet Temp, °C | 273 | |
| Outlet Press, MPa | 8.6 | |
| Design Temp, °C | [TBD] | |
| Design Press, MPa | > 13.2 | |
| | | |
| **Cold Side** | | |
| Fluid | Water | |
| Superheater Outlet Press, MPa | 12.8 | |
| Superheater Outlet Temp, °C | 540 | |
| Main Steam Flow, kg/s | 206 | 228 |
| Feedwater Temp, °C | 219 | |
| Feedwater Press, MPa | 18.3 | |
| Design Temp, °C | ~300 | |
| Design Press, MPa | >18.5 | |

## 9.2 Technology/Design Selection Status

While the helical-coil once-through steam generator was identified as the reference SG design for developing the NGNP Preconceptual Design Report (PCDR), additional work in the form of conceptual design trade studies is required to confirm the PCDR selection or to identify an alternate concept.

Unlike prior HTGR steam cycles designed for electricity production, the SG in the PBMR NGNP design is located in the SHTS and serves as a bottoming process to the Hydrogen Production System's Process Coupling Heat Exchanger (PCHX). As described in the PBMR NGNP Preconceptual Design Report (PCDR), this configuration allows the maximum amount of high temperature thermal energy to be utilized for hydrogen production, particularly in the NGNP Commercial Plant. While lower temperature (e.g., 750°C reactor outlet) NGNP concepts are expected to be evaluated, specific applications, along with their functions and requirements have not been identified and the location of the SG in the PHTS or SHTS for such applications has not yet been assessed through appropriate trade studies. Hence, the discussion herein is limited to the 950°C application to hydrogen production, as documented in the PCDR.

In the PCDR arrangement, location of the steam generator in the power conversion area and its coupling to the SHTS provide a great deal of flexibility. This is not the case with earlier HTGRs in which the SG was integrated within the PHTS and located within the expensive real estate of the Reactor Building or, in some cases, the Reactor Pressure Vessel itself (e.g., Fort St. Vrain and THTR). In the present case, less compact designs and/or splitting the steam generator into multiple sections and/or vessels are options that may be considered. An example would be a recirculating economizer/evaporator in one vessel, plus a separate superheater in a second vessel.

Candidate SG technologies are identified in Section 9.2.1. Decision discriminators leading to a final design selection are discussed in Section 9.2.2. The PCDR reference SG used as a surrogate in the development of this report is described in Section 9.2.3. Note that establishing a reference conceptual design for the steam generator is presently expected to be based upon trade studies and analyses only. Given the relative maturity of the underlying technologies, testing is not presently expected to be required as a basis for establishing the reference SG design.

### 9.2.1 Candidate Technologies

Candidate technologies include the following:

**Helical Coil Shell & Tube Heat Exchanger**

The helical coil shell and tube heat exchanger has been the basis for prior High-Temperature Gas-Cooled Reactors (HTGRs), including Fort St. Vrain in the U.S. and the Thorium High-Temperature Reactor (THTR) in Germany.

**Serpentine Tube Heat Exchanger**

Designs of the serpentine tube type have been utilized in Advanced Gas-Cooled Reactors (AGRs) in the UK.

**Other**

The conceptual design trade study leading to the selection of a reference steam generator will consider other conventional steam generator technologies (e.g., designs based upon heat recovery steam generators, presently used in conjunction with combined cycle gas turbine plants).

### 9.2.2 Decision Discriminators

**Design/Technology Development**

The steam generator for the NGNP is largely based upon existing and/or previously utilized conventional technologies, including design features, materials and operating conditions. The advantages of prior experience are best realized by maximizing commonality with previously developed and demonstrated designs.

**Manufacturing and Transportability**

Key manufacturing considerations include:

- Manufacturing of the pressure vessel
- Coiling and/or bending of the tubes
- Installing the tubes within the heat transfer bundle
- Installing the heat transfer bundle within the pressure vessel
- Attaching the tubes to the tubesheets and/or internal headers that provide the interfaces with the feedwater and steam piping

Transportability is principally a function of the size (particularly diameter) and weight of the completed assembly. In this regard, the compactness of the heat exchanger is of particular importance.

**Operation and Maintenance**

Operation and maintenance considerations include:

- The use of steam in a closed circuit for electricity production. This arrangement facilitates stringent control of feedwater quality and is consistent with a once-through boiling configuration
- Cleaning requirements and provisions for tube cleaning
- Inspection requirements and provisions for detecting and isolating leaks

**Safety and Investment Protection**

There are no nuclear safety functions or requirements assigned to the SG.

In order to meet overall plant requirements, the SG must have a high reliability/availability.

**Lifecycle Cost**

Lifecycle costs include the initial capital cost and the costs associated with operation and maintenance. Features tending to reduce capital costs include effective utilization of the heat transfer surface ($MWt/m^2$) and minimizing the size of the heat exchanger ($MWt/m^3$). Operation and maintenance costs are reduced by high reliability and minimizing the need for maintenance functions, such as water-side cleaning.

### 9.2.3 Reference Design

The PCDR reference Steam Generator for the NGNP is an extrapolation of the design developed for the steam cycle version of the Modular HTGR (MHTGR-SC), as described in Reference [9-1]. It represents a further extension of the evolutionary path from FSV to THTR to MHTGR. The resulting design provides the context for the technology development planning discussed in this section.

The SG is a vertically oriented, counter-flow, shell-and-tube, once-through, non-reheat tubular heat exchanger, with helium on the shell side and water/steam in the tubes. It incorporates an economizer, an evaporator and first-stage superheater in one helical tube bundle, followed by a finishing superheater in a second helical tube bundle. Helium flows downward across the helical tube bundles, between the inner and outer shrouds. Cooled helium flows out of the SG bundle, turns 180°, and flows upward through an annulus created by the SG outer shroud and the Steam Generator Vessel I.D. Feedwater is introduced at the bottom of the unit and flows counter current to the helium flow, with superheated steam exiting from the top. A single SG provides high pressure steam for the PCS.

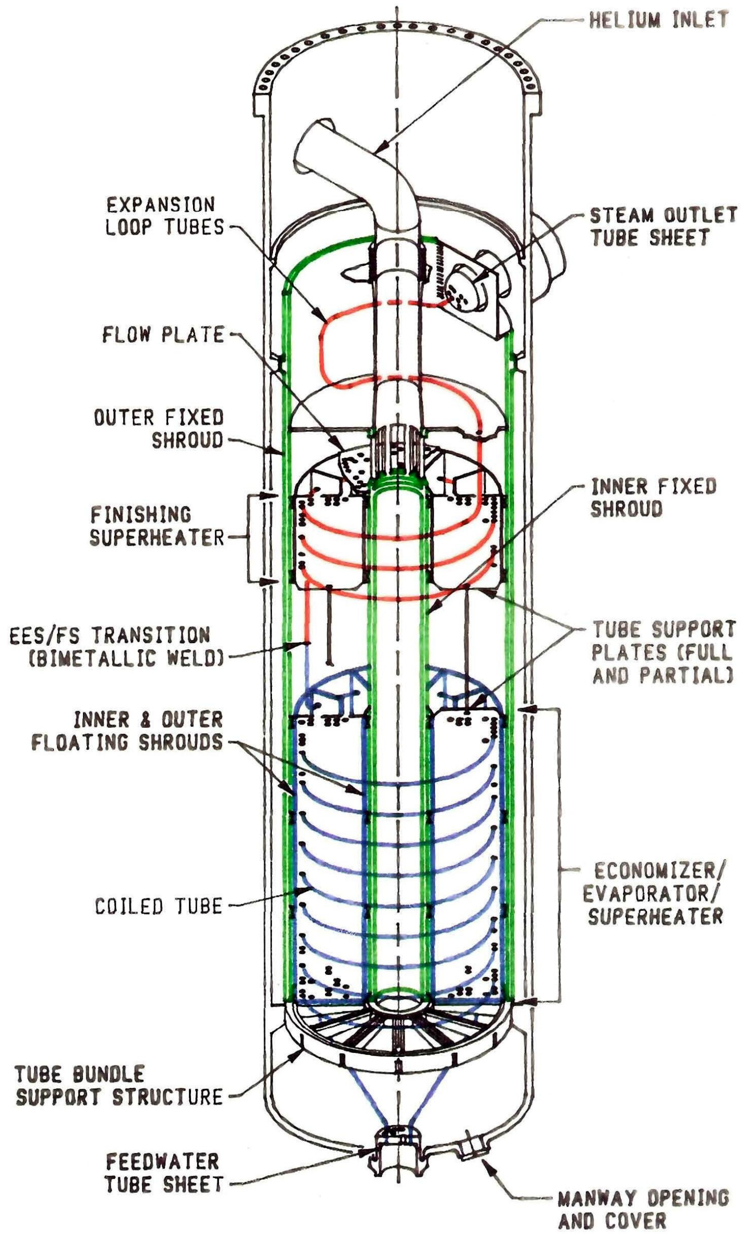


**Figure 9-1: Steam Generator (PCS-SG-001)**

For the proposed NGNP application, the flow path of the helium is arranged so that the enclosing vessel operates at the cooler shell-side outlet helium conditions. Internal structure materials (tube supports, shrouds) are selected consistent with their respective operating temperatures. For the NGNP application (as with prior MHTGR designs), the steam generator is a scale-up in thermal rating relative to early experience. The impact of this scale-up is reflected in a previously recognized and documented set of design data needs:

- The enclosing vessel is designed and fabricated of low alloy steel and is generally within the current state-of-the-art of light water reactor and petrochemical vessel technology.
- The overall size and weight of the completed steam generator is consistent with the current technology basis of large pressure vessels and heat exchangers. As a frame of reference, the steam generator design for the MHTGR had an overall height and diameter of 60 feet and 17 feet and estimated weight of 650 US Tons. This configuration was considered transportable to the INL site via a carefully planned and executed transportation scheme. Similar envelopes are likely for the NGNP application.
- The feedwater tubesheet penetration requires special attention from a detailed design perspective and includes a removable/replaceable orifice at the inlet of each tube circuit.
- The superheated steam outlet tubesheet is an Alloy 800H forging of large size compared to typical practice with this material. This condition may lead to more than one shell penetration as detailed design proceeds.
- The relatively large thermal rating, compared to the operating experience base, is typically accommodated by adding tube circuits. This design introduces uncertainties in the performance characteristics on both the helium and water sides of the tubes and in the structural design of the tube bundle, as well as in fabrication and assembly techniques.
- Other configuration specific needs include consideration of wear protection of tube surfaces at support locations.

An alternate configuration is the serpentine arrangement of heat transfer surface which is typical of some AGR reactors.

### 9.2.4 Alternatives for Further Evaluation

The main alternative to the helical-coil design is the serpentine arrangement used in AGR applications; however, other conventional steam generator technologies will be evaluated. In addition, packaging of the SG into one or more vessels will be evaluated, as will once-through versus recirculating.

### 9.2.5 Down Selection Task

A trade study is required to further compare the helical-coil, serpentine-tube and other SG concepts in terms of the decision discriminators summarized in Section 9.2.2.

## 9.3 Technology Readiness Level Status of the Steam Generator

The TRL status of the Steam Generator has been assessed and it is concluded that the present status is TRL 6. The associated rating sheet is provided as Appendix A.

The steam generator proposed in the PCDR is clearly developmental from the perspective of being a new embodiment of a previously applied technology. As noted earlier, the design is based on technology developed for early gas-cooled reactors such as Peach Bottom, AVR, FSV and the THTR. The steam generators in these plants operated successfully and the essential supporting technology in terms of materials, design methods and fabrication methods was demonstrated. It is notable that the AVR steam generator operated for extended periods at 950°C reactor outlet temperature. Further design development of the steam generator for the MHTGR-SC application was accomplished under DOE sponsored programs in the 1980's and early 1990's. This development includes the compact helical arrangement of heat transfer surface and the once-through configuration. Tubing materials are based on conventional boiler materials, 2-1/4 Cr -1Mo for the lower temperature portions of the once-thru tube circuit and Alloy 800H for the higher temperature portions of the tube circuit.

## 9.4 Technology Development Road Map Summary

The Steam Generator Technology Development Road Map is provided as Appendix B. The associated maturation tasks are summarized in Section 9.5.

As already noted, a key prerequisite to advancing the SG from the present level of TRL 6 to TRL 7 and 8 is the conduct of the conceptual design trade study to establish the preferred conceptual design of the steam generator. Once that is done, a series of development activities and tests will be required to reestablish the technology basis for the SG and to validate its performance for the NGNP application. These activities and tests are based upon DDNs identified during preconceptual design and documented in the PCDR. A summary of these DDNs is provided in Table 9-2.

The activities required to advance the SG from TRL 6 to TRL 7 are generally associated with reestablishing the technology base for steam generators in HTGRs. The activities for advancing the steam generator from TRL 7 to TRL 8 are those associated with preparation for and fabrication of the NGNP steam generator.

## 9.5 Technology Maturation Plan Summary

The sections below summarize the maturation tasks needed to advance the technology of the Steam Generator from a validated TRL 6 to a validated TRL 8. The general basis and assumptions for advancing from a TRL level of 6 are:

- Completion of the SG conceptual design trade study, described above

- Apply FSV+THTR+ MHTGR development basis for helical steam generator
- Establish materials
- ASME Code basis available (ASME B&PV Code, Section VIII)
- Essential analysis tools available
- Need to reassemble/refresh the technology base for the NGNP application. Application of the technology is dormant.
- Confirmation of performance
- Demonstration of steam generator fabrication technology

The Steam Generator maturation tasks are summarized below and discussed in more detail in Appendix C.

### 9.5.1 Maturation Tasks from TRL 6 to TRL 7

The SG will be advanced from TRL 6 to TRL 7 via three groups of activities:

- SG Design Development – When placed in the context of the NGNP, the SG becomes a first-of–a-kind application of an established technology in the PCS system context of operational parameters, as yet unspecific plant layout and other integrated system related requirements. In this regard, the first step is completion of a conceptual design trade study to establish the reference conceptual design of the SG.
- Reestablishment of SG Technology Basis – Design Data Needs for the SG are described in Reference 9-1 and listed in Table 9-2. Some DDNs listed in Table 9-2 are sensitive to SG configuration while others are generic to the helium and water/steam operational environment. A majority of the DDNs in Table 9-2 that are identified as being associated with the transition between TRL 6 and TRL 7 are those necessary to reestablish the SG technology basis.
- SG Feature Tests - in addition, certain tests identified in Table 9-2 are required to establish or confirm SG features.

### 9.5.2 Maturation Tasks to Advance from TRL 7 to TRL 8

Maturation tasks associated with the transition from TRL 7 to TRL 8 are those supporting final confirmation of the established SG design and fabrication of the prototype NGNP SG. These activities and tests correspond to those DDNs in Table 9-2 identified as being associated with the transition between TRL 7 and TRL 8.

**Table 9-2: Design Data Needs**

| DDN # | Design Data Need | Category | TRL 6→7 | TRL 7→8 | Expected Outcome | Recommended Performer |
|---|---|---|---|---|---|---|
| PCS-01-18 | Review and Reassemble Existing SG Development Data Base | All | X | | Establish baseline for development tasks in the context of NGNP | Designer/fabricator |
| PCS-01-01 | Secondary Side Corrosion Characteristics of 800H & 2-1/4Cr-1Mo and Weldments | Materials | X | | Confirmation of assumptions regarding corrosion performance of SG tube materials and welds | Material testing lab with support from designer |
| PCS-01-02 | Helium Environment Effects on 2-1/4 Cr-1Mo | Materials | X | | Validation of assumptions regarding long time behavior of selected material in helium environment | Material testing lab |
| PCS-01-03 | Helium Environment Effects on 800H | Materials | X | | Validation of assumptions regarding long time behavior of selected material in helium environment | Material testing lab |
| PCS-01-04 | Acoustic Response of Helical Bundle | Performance | | X | Determine acoustic characteristics of the tube bundle in response to input noise and self generated noise. Provide acoustic loads on various internal structures | Designer/fabricator<br>CTF? |
| PCS-01-05 | Large Helical Coil Fabrication Test | Fabrication | | X | Verification of design assumptions and assembly process for large diameter helical bundle | Designer/fabricator |

| DDN # | Design Data Need | Category | TRL 6→7 | TRL 7→8 | Expected Outcome | Recommended Performer |
|---|---|---|---|---|---|---|
| PCS-01-06 | Inlet Flow Distribution | Performance | X | X | Design configuration of inlet geometry to maintain acceptable velocity and temperature profile | Designer/fabricator<br><br>CTF? |
| PCS-01-07 | Insulation Verification Test | Design | X | | Verify acceptable mechanical performance of thermal insulation and related structures. | Designer/fabricator |
| PCS-01-08 | Fretting & Sliding Wear Protection Tests | Materials | X | | Confirm acceptable mechanical performance of wear protection devices used at interface between tubes and supports. | Material testing lab |
| PCS-01-09 | Tube Wear Protection Device Testing | Design | X | | Confirm functional performance of wear protection devices | Designer/fabricator |
| PCS-01-10 | Shroud Seal Test | Design | X | X | Confirm acceptable performance of seal features to control bypass flows | Designer/fabricator<br><br>CTF? |
| PCS-01-11 | Lead-in/Lead-out/Transition/Expansion Loop Mockups | Fabrication | | X | Verify space envelope and assembly sequence for tube circuit transitions from tubesheet to helical bundle, etc. | Designer/fabricator |
| PCS-01-12 | Flow Induced Vibration Testing of Helical Bundle | Performance | | X | Establish FIV characteristics of tube bundle | Designer/fabricator<br><br>CTF? |
| PCS-01-13 | Orifice Qualification Test | Performance | X | | Confirm acceptable performance of orifices in helical tube circuits | Designer/fabricator |
| PCS-01-14 | Instrumentation Attachment Test | Design | X | | Establish design features for final design | Designer/fabricator |
| PCS-01-15 | Bi-Metallic Weld Structural Integrity | Materials | X | | Confirm design criteria | Designer/Materials Lab |

| DDN # | Design Data Need | Category | TRL 6→7 | TRL 7→8 | Expected Outcome | Recommended Performer |
|---|---|---|---|---|---|---|
| PCS-01-16 | Helical Bundle and Transition Region Heat Transfer Test | Performance | X | | Confirm heat transfer coefficient assumptions | Designer/fabricator<br><br>CTF? |
| PCS-01-17 | Tubing Inspection Methods and Equipment | Design | | X | Demonstrate acceptable methods and equipment | Designer/fabricator |
| PCS-01-19 | Testing of Scale Prototype SG in CTF | Integrated system performance | X | | Demonstrate acceptable performance of SG in a simulated PCS loop | Designer/fabricator/system designer<br><br>CTF |

## 9.6 Inputs to CTF

As noted in Table 9-2 ( DDN PCS-01-19), the testing which is suitable for CTF testing is a scale prototype test series. It is expected that both individual testing of the SG and integrated testing with other PCS loop components may be performed.

It may also be possible to address other DDNs via testing in the CTF. For example, PCS-01-04, PCS-01-06, PCS-01-10, and PCS-01-12 may be addressed by appropriate testing in the CTF.

## 9.7 References

[9-1] NGNP-08-RPT-001, Revision 0, NGNP and Hydrogen Production Preconceptual Design Report, "Section 8: Power Conversion System", May 2007.

# APPENDIX A: TECHNOLOGY READINESS LEVEL RATING SHEETS

**Table A-1: TRL Rating Sheet of the PCS Steam Generator**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: Document Number: Revision: | | | |
| ☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: **Steam Generator** | | | |
| Description:<br>The Steam Generator transfers thermal energy from the SHTS helium to the Rankine cycle power generation circuit. It is part of the Main Steam System within the Power Conversion system. | | | |
| | | | |
| Area(s): ☐NHSS ☐ HTS ☐ HPS ☑ PCS ☐ BOP | | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Component or system breadboard in relevant environment | Similar SSC in relevant environment in another application | Pilot/engineering scale demonstration in relevant environment. |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating:<br>Steam Generators have been demonstrated in numerous gas-cooled reactors and in other high temperature gas reactors, specifically Peach Bottom, AVR, Fort Saint Vrain, THTR, HTTR and HTR-10. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (K$) | |
| • Development tests<br>• Scale prototype testing in CTF<br>• NGNP Prototype SG | FY 2009 – FY 2013<br>TBD | Refer to Section #<br>TBD<br>TBD | |
| DDN(s) supported: PCS-01-01 to PCS-01-18 | | | |
| SME Making Determination: D. T. Allen Revised by A. H. Spring 10-18-08 | | | |
| Date: 09AUG07 | Originating Organization: Technology Insights | | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

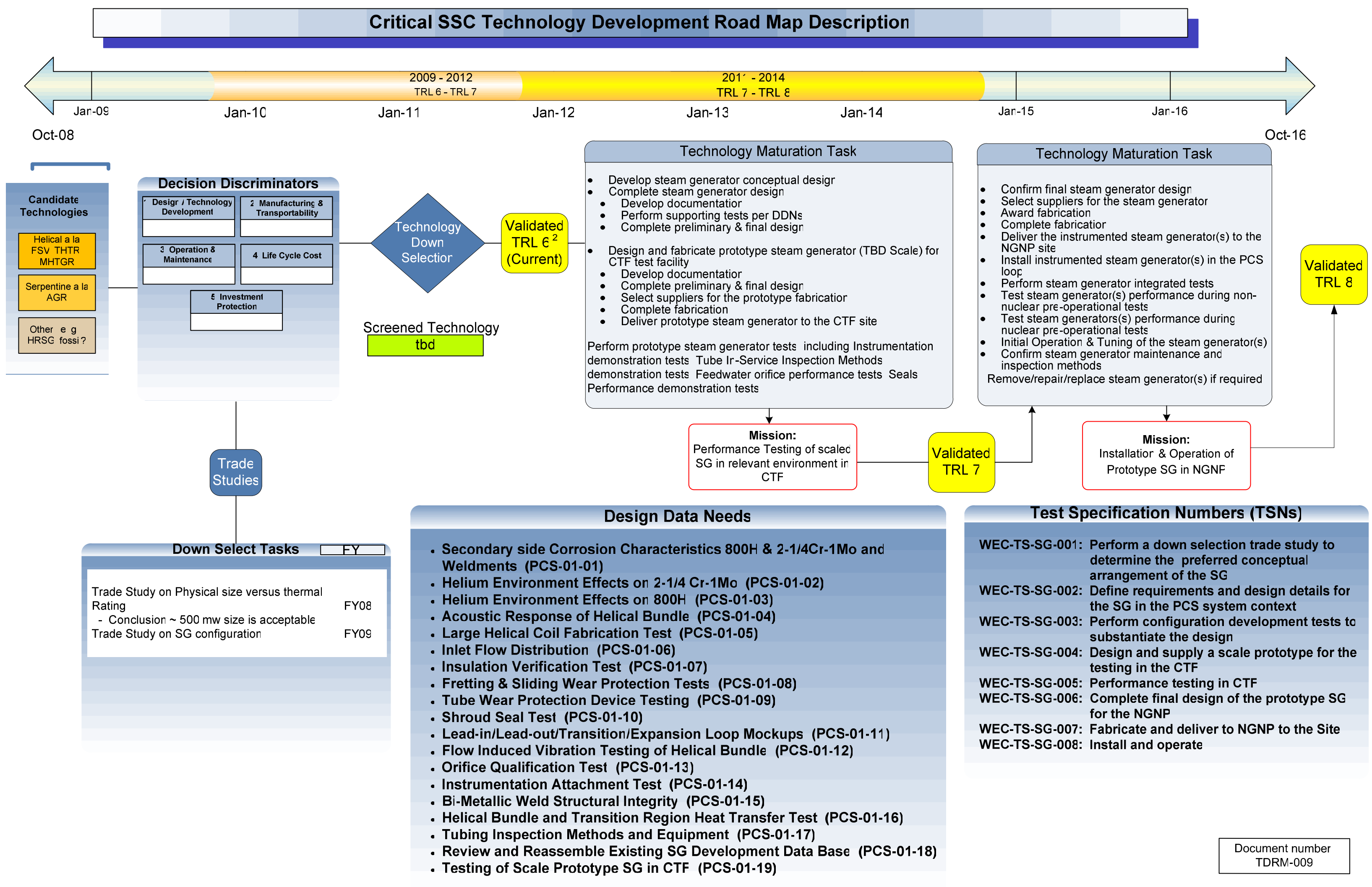


**Figure B-1: Technology Development Road Map of the PCS Steam Generator**

# APPENDIX C: TECHNOLOGY MATURATION PLAN

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## REQUIRED SPECIFICATIONS/TESTS TO ACHIEVE NEXT TRL

**TRL 6 to TRL 7**

- Perform a down selection trade study to determine the preferred conceptual arrangement of the SG
- Define requirements and design details for the SG in the PCS system context
- Perform configuration development tests to substantiate the design
- Design and supply a scale prototype for testing in the CTF
- Conduct performance testing in CTF

**TRL 6 to TRL 7**

- Complete final design of the prototype SG for the NGNP
- Fabricate and deliver to NGNP to the Site
- Install and operate

# C1 TECHNOLOGY MATURATION PLAN FOR STEAM GENERATOR (TRL 6 TO TRL 7)

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Objectives

The objectives of the plan to advance from TRL 6 to TRL 7 relate to the issues or uncertainties of the steam generator that generally revolve around concerns with fluid flow and temperature effects for the specific NGNP configuration and the lack of a significant long term operating experience base. The basic issues of flow distribution and limited operating experience may be divided into six areas of uncertainty which are addressed and quantified in the course of steam generator development. These areas are:

1. Level of Design Detail
2. Helium Flow and Temperature Effects in the Steam Generator Tube Bundle
3. Materials Response to Water/Steam and Helium Environment
4. Subcomponent Design and Performance
5. Development of Fabrication Methods
6. Operation, Maintenance and Inspection
7. Integrated system performance in the context of the NGNP plant

These uncertainties will be addressed in a concurrent program of design definition of the SG for the specific NGNP application and the definition of appropriate development tests to satisfy data needed to complete or verify a final design.

### C1.1.2 Scope

The maturation tasks and associated testing to advance from TRL 6 to TRL 7 include:

- Develop steam generator conceptual design
  - Define functions and requirements of the SG in the context of the PCS
    - Steady state performance
    - Transient performance
    - Interfaces including geometry and loads
      - Helium ducts
      - Feedwater
      - Steam
      - Circulator
      - Vessel Supports
    - Codes and standards
    - Maintenance and inspection requirements
  - Evaluate alternative configuration(s)

    - Reference design is helical arrangement of heat transfer surface
    - Alternate is serpentine arrangement of heat transfer surface
    - Perform trade study

  - Define conceptual arrangement and perform analyses to support system and component definition:
    - Component layout and arrangement drawings including external interfaces, vessel design, tube bundle and internal features
    - Thermal sizing and performance analysis
    - Structural analysis to support basic sizing of pressure boundary and support components
    - Assessment of operating performance
    - Assessment of design versus requirements
    - Define scope, cost and schedule of supporting development tests.

- Do preliminary design and analysis of SG concurrent with NGNP system design

- Perform supporting tests per Design Data Needs (DDNs) for the SG:
  - Subcomponent and special feature development are based on the DDNs identified in the PCS pre-conceptual design phase.
  - All of these needs may be met through a combination of analysis and special purpose tests to establish and verify design features in the NGNP context.
  - Item PCS-01-18 is particularly important to complete early in the conceptual phase of the NGNP project since active application of the relevant steam generator technology has been dormant since about 1993.
  - Table 9-2 lists the DDN's expected outcome of work performed to satisfy the needs and recommended performer of work.

- Complete NGNP steam generator design
  - Develop documentation
  - Design reviews
  - Complete preliminary & final design of NGNP SG

- Design and fabricate prototype steam generator (TBD Scale) for CTF test facility
  - CTF specific functions and requirements for prototype SG
  - Develop documentation
  - Complete preliminary & final design
  - Select suppliers for the prototype fabrication
  - Complete fabrication
  - Deliver prototype steam generator to the CTF site

- Perform scale prototype steam generator tests, including Instrumentation demonstration tests, Tube In-Service Inspection Methods demonstration tests, Feedwater Orifice performance tests, Seals Performance demonstration tests

- Support integrated system testing.

Assumptions regarding CTF:

- The CTF will provide a source of high temperature helium consistent with the NGNP plant operating parameters.
- The CTF will provide a feedwater system to supply the steam generator and as a minimum a steam dump system such that continuous operation of the scale prototype of the SG can be cycled through a specified test series to demonstrate steady state and transient operation at NGNP plant conditions.
- It is also anticipated that integrated non-nuclear testing of prototype PHTS and SHTS components may be performed.

### C1.1.3 Anticipated Schedule

The schedule for advancing from TRL 6 to TRL 7 is highly dependent on the pace and timing of the overall NGNP program. An approximate time frame for the TRL 6 to TRL 7 effort on the SG is about 4 years.

### C1.1.4 Overall Costs

To be determined.

## C1.2 TEST SPECIFICATIONS

Since most testing needs of the SG are dependent on the requirements and configuration of the PCS and SG design, test specifications should be developed in the course of the conceptual design of the SG.

# C2 TECHNOLOGY MATURATION PLAN FOR STEAM GENERATOR (TRL 7 TO TRL 8)

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C2.1.1 Objectives

- Incorporate results of TRL 6 to TRL 7 program into final design of SG
- Supply and deliver FOAK SG to NGNP site
- Installation and initial operation.

### C2.1.2 Scope

- Confirm final steam generator design for NGNP
- Select suppliers for the steam generator
- Award fabrication
- Complete fabrication
- Deliver the instrumented steam generator(s) to the NGNP site
- Install instrumented steam generator(s) in the PCS loop
- Perform steam generator integrated tests

### C2.1.3 Anticipated Schedule

Dependent on overall NGNP schedule. Typically this work would have a 40 to 50 month span.

### C2.1.4 Overall Cost

To be determined.

## C2.2 TEST SPECIFICATIONS

To be determined during conceptual design phase.

**NGNP-CTF MTECH-TDRM-010** **November 2008**
**Revision 1**

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 10: Software Code Verification and Validation

**APPROVALS**

| Function | Printed Name and Signature | Date |
|---|---|---|
| Author | Name: Peter Robinson<br>Company: PBMR | November 19, 2008 |
| Reviewer | Name: Heinrich Stander<br>Company: PBMR | November 19, 2008 |
| Reviewer | Name: Frederik Reitsma<br>Company: PBMR | November 19, 2008 |
| Approval | Name: Jan van Ravenswaay<br>Company: M-Tech Industrial | November 19, 2008 |

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| Peter Robinson (PBMR) | November 15, 2008 |
| Heinrich Stander (PBMR) | November 15, 2008 |
| Frederik Reitsma (PBMR) | November 15, 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | N/A | N/A |

**REVISION HISTORY**

# RECORD OF CHANGES

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| 0 | Peter Robinson | Document for approval | November 16, 2008 |
| 0A | Peter Robinson | Editorial changes | November 23, 2008 |
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# DOCUMENT TRACEABILITY

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| NGNP and Hydrogen Production Preconceptual Design Report | NGNP-01-RPT-001 | 0 |

## LIST OF TABLES



## LIST OF FIGURES

## ACRONYMS & ABBREVIATIONS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |

| Acronym | Definition |
|---|---|
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |

| Acronym | Definition |
|---|---|
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |

| Acronym | Definition |
|---|---|
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

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# SUMMARY AND CONCLUSIONS

The document presents a summary of the high level PBMR V&V process as applied for the PBMR Demonstration Power Plant (DPP). The key DPP phenomena being tested are listed together with the status of the software development and validation tests as well as a summary of the codes and facilities used for the tests.

The PBMR DPP software codes used is expected to envelope the NGNP Software Code Validation requirements for the Nuclear Heat Supply System (NHSS), recognizing that the DPP commissioning itself forms an integral part of the V&V program. However, only once the NGNP plant level conceptual design analyses have been done will it be possible to confirm this statement and quantify specific further testing needs. It is noted that all NGNP evaluation models, once established, will remain to be Verified and Validated.

The NGNP core design with its higher gas outlet temperatures and power densities may increase the risk that the best estimate analysis plus uncertainties are too close to the safety margins. In certain cases this may imply more advanced methods, software and models to be developed – see proposed tests in Table 10-2.

It is noted that the software V&V employed for the Rankine Power Conversion System (PCS) and Hydrogen Production System (HPS) remain to be considered as it has not been covered by the PBMR DPP V&V process. However, at this point no V&V is expected to be done in CTF for the Power Conversion System (PCS), Steam Generator (SG) nor the Hydrogen Production System (HPS).

In order to analyze various aspects of the integrated NGNP Plant, the software currently used for the PBMR DPP design is proposed to be further enhanced and extended to have an integrated core neutronic/thermal hydraulic analysis tool coupled to the Power Conversion and Hydrogen Production Systems models for simulating normal and off-design conditions. This tool will allow for steady-state and transient analyses of the integrated NGNP plant and will enable operational and control studies. Such a tool remains to be developed and V&Ved.

# 10 V&V ACTIVITIES

## 10.1 PBMR V&V Process

An analysis verification and validation (V&V) program is required to provide confidence in the design and safety analysis performed in support of the product development of the PBMR Demonstration Power Plant (DPP). This requirement is mandated by the South African National Nuclear Regulator (NNR) Regulatory Requirement RD0016 which is based on IAEA, US-NRC and ANSI best practice. The PBMR DPP V&V program is extensive and PBMR has a dedicated division committed to the fulfillment of V&V requirements.

PBMR verifies and validates all Evaluation Models (EMs) used in support of Chapter 15 (Accident Analysis) of the DPP Safety Analysis Report (SAR) - as well as the models, software and calculations used in design and safety analysis.

The software used in analysis is split into two categories: Commercial off the Shelf (COTS) software and Software under Development (SUD). A further category is “Legacy Software” which is defined as software that has been developed in the past for specific applications relevant to the PBMR design, but where current V&V and Quality Assurance processes were not sufficiently applied.

The purpose of COTS software V&V is to provide objective confirmation that the Software Product is fit for the purpose of analyzing the applicable physical model(s) for which it is applied in PBMR. Initially, the software developer’s V&V and Quality Assurance are assessed to determine whether it meets the requirements of 10CFR50 Appendix B, 10CFR21, NQA-1 and RD-0016. If these requirements are met, PBMR will qualify the developer. However, if the developer of the COTS analysis software does not provide supporting evidence that confirms compliance with the requirements, or if PBMR cannot gather sufficient proof of compliance from the developer’s applicable documentation, the Software Product shall be dedicated. Dedication of COTS analysis software is an acceptance process undertaken to provide reasonable assurance that the software will perform its intended function and can be validated against results obtained by other validation methods. This assurance is achieved by identifying the relevant functionalities of the software product which enables PBMR to assess the applicable software capabilities over the ranges that it requires. Validation tests are selected or developed that comprehensively test the applicable software capabilities by comparison with relevant analytical solutions, experimental data, plant data or other calculation methods. For both Qualification and Dedication approaches, a select set of installation tests is performed by PBMR to ensure the software is installed correctly and verify its accuracy on PBMR’s platforms.

New software (i.e. SUD) by definition includes Software Products currently being developed or planned to be developed in future. V&V is implemented throughout the software project life cycle of acquisition, supply, development, operation and maintenance, similar to the approach followed by the Institute of Electrical and Electronics Engineers (IEEE). The V&V process includes theory and Software Product Verification activities, and the development and performance of Validation tests to comprehensively assess the Software Product and its components.

In the case of Legacy Software, it is reverse engineered by PBMR where after their development is essentially the same as that for new software developed. Such Software Products may be verified and validated using an 'a posteriori' V&V review. The 'a posteriori' approach takes advantage of V&V documentation that is available, as well as user experience. It is a verification to determine if the Legacy Software Product produces valid responses when used for calculations within the specified application and to document the level of V&V and/or software testing that has been carried out by the original developers or by users. Depending on the specifications in the V&V Task Report, it may be required to repeat some of the developer and user tests, and to conduct additional tests if original test coverage is found to be inadequate. If required, 'a posteriori' baselines may also be established for development and V&V. The establishment of both development and V&V baselines enables the determination of the outstanding V&V necessary to validate the software completely for its requirements. In parallel, the outstanding V&V activities are executed in order to ensure that the software is finally proven to meet all regulatory requirements.

V&V of models basically accounts for the demonstration of adequate nodalisation, dimensionality, local detailing, initial and boundary conditions and data processing. V&V of Evaluation Models (EMs) for Chapter 15 Accident Analysis consists of assessing the EM's adequacy to represent the complex scenario it is required to, and a top-down and bottom-up review of the EM's constituents.

The schematic presented in Figure 10-1 is a simplified and partially representative depiction of the analysis roadmap followed by PBMR which highlights the importance of software selection and model development.

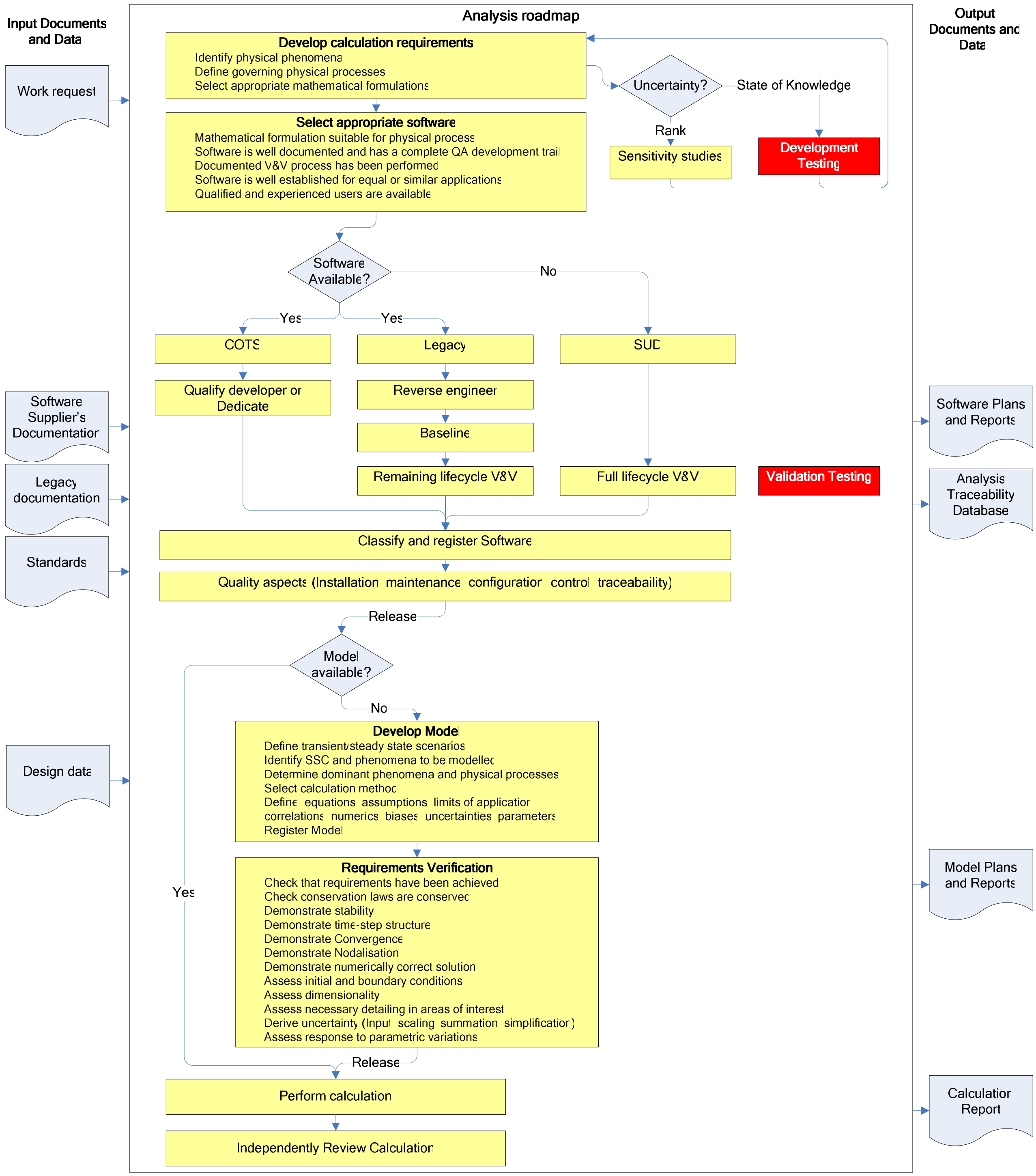


**Figure 10-1: PBMR Analysis Roadmap Schematic**

## 10.2 Testing Facilities

Section 16.2.1 of the NGNP PCDR (NGNP-16-RPT-001) presented an overview of PBMR utilized test facilities. Find below a list of test facilities listed in this report:

- ASTRA
- AVR
- Heat Transfer Test Facility (HTTF)
- Helium Test Facility (HTF)
- HFR
- HTTU
- HPTU
- HTR-10 (High Temperature Gas-cooled reactor-test Module)
- JAEA reversed-U-shape tube
- NACOK (Natural Convection Oxidation Facility)
- Pebble Bed Micro Model (PBMM)
- SANA (Selbstatige Abfuhr der Nachwarme)
- STORM
- ThAI
- VELUNA

See Appendix A for a brief description of these facilities. Note that not all these facilities have Software V&V tests planned or underway.

## 10.3 Ongoing DPP V&V Testing

The PBMR V&V data acquisition program is progressing well. The current focus is the performance of software validation using the acquired data.

### 10.3.1 Key Phenomena Verification

The derivation of the phenomological groupings below are based on a number of requirements and expert knowledge. Aspects of the design modeling to be covered are prescribed by the NNR's design requirements given in document RD0019 which addresses also reactor design and the associated phenomena. The thermal hydraulic phenomena are standard for gas-cycle plants. The radionuclide release and transport phenomena are derived from experience from the German AVR and THTR reactors and fuel development programs. The source term, activation, transport and dispersion phenomena are derived in the accident analysis process using the US-NRC RG1.203 Evaluation Model Development and Assessment Process (EMDAP) which starts with the Phenomena Identification and Ranking Table (PIRT).

The following key phenomena are modeled:

- Annular vs. Cylindrical Bed Pressure Drop Characteristics
- Atmospheric Dispersion

- Core Thermal-Hydraulics
- Dust Generation And Transport
- Forced Convection
- Heat Transfer
- Heat Transfer Coefficients
- Natural Convection
- Near Wall Heat Transfer
- Neutronics
- Oxidation
- Pebble Flow In Pebble Bed
- Pressure Drop Through The Pebble Bed
- Radionuclide Release From Fuel
- Radionuclide Transport
- Reactor Cavity Cooling System (RCCS) Two Phase Flow
- Seismic Analysis
- System Thermal-Hydraulics
- Turbulent Mixing (Braiding)

### 10.3.2 Software Codes

The following software codes are used in design and safety analysis. Their classification is given as Commercial Off The Shelf (COTS) for codes that are purchased and used as is, Software Under Development (SUD) for codes that are developed by PBMR, and Legacy for codes that have been developed in the past for specific applications relevant to the PBMR design, where current V&V and Quality Assurance processes were not applied.

**Table 10-1: DPP Safety Analysis Software Codes**

| Code | Classification |
|---|---|
| ACS SASSI NQA | COTS |
| ASTEC | COTS |
| DAMD | SUD |
| FIPREX | SUD |
| FISPACT/EASY | COTS |
| FLOWNEX NUCLEAR | COTS |
| Fluent (CFD) | COTS |
| GETTER | Legacy |
| MCNP | COTS |
| NobleG | Legacy |
| ORIGEN-SCALE | COTS |
| PC-Cosyma | COTS |
| PFC3D | COTS |
| RELAP5 | COTS |
| SPECTRA | COTS |

| Code | Classification |
|---|---|
| STAR-CD (CFD) | COTS |
| TINTE | Legacy |
| T-REX | SUD |
| VSOP99 | Legacy |
| VSOP99 (THERMIX) | Legacy |

Description on the various software codes are presented in Appendix B.

### 10.3.3 DPP V&V Status Overview

**Table 10-2: Tests planned for development or validation of codes used in the DPP**

| Phenomenon | Code | Development and Validation (Qualification) tests planned or completed | Facility | Status | Applicable to NGNP |
|---|---|---|---|---|---|
| Annular Vs. Cylindrical Bed Characteristics | Code independent | Confirmation of KTA rule applicability for pressure drop | HTTF | Tests Completed | ☑ |
| Complex Flows With Combined Effects | CFD | Matched index of reflection test proposed at Idaho National Labs or Texas A&M | INL or Texas A&M | Keen To Explore Collaboration Opportunities | ☑ |
| Dust Characterization | DAMD | Validation of circulating products distribution, deposition, resuspension, plate-out and lift off. | AVR | Tests Completed | ☑ |
| Forced Convection Through The Pebble Bed Reactor | CFD | CFD development testing No validation tests planned | HTTF | Testing Underway | ☑ |
| Heat Transfer | TINTE | TINTE has been compared with SANA, VELUNA and NACOK experiments and AVR plant data. TINTE is considered reliable and adequate for HTR modeling. | AVR | Tests Completed | ☑ |
| Heat Transfer | TINTE | TINTE has been compared with SANA, VELUNA and NACOK experiments and AVR plant data. TINTE is considered reliable and adequate for HTR modeling. Heat production in a pebble bed in different gas media (illustrated with the SANA test facility). | SANA | Tests Completed | ☑ |
| Heat Transfer Coefficients | CFD | CFD validation testing | HTTF | Tests Completed | ☑ |
| Natural Convection | CFD | CFD validation testing | HTTF | Testing Underway | ☑ |

| Phenomenon | Code | Development and Validation (Qualification) tests planned or completed | Facility | Status | Applicable to NGNP |
|---|---|---|---|---|---|
| Natural Convection For Air Ingress | CFD | Benchmarking for oxidation | NACOK | Tests Completed | ☑ |
| Near Wall Heat Transfer | CFD | CFD Development Testing | HTTF | Tests Completed | ☑ |
| Neutronics | MCNP | Benchmarking against completed experiments: core reactivity, control rod worth and reaction rate profiles | ASTRA | Tests Completed | ☑ |
| Neutronics | MCNP | Benchmarking against completed experiments: core reactivity and control rod worth | HTR-10 | Tests Completed | ☑ |
| Neutronics | VSOP99 | The burn-up calculations in VSOP include the essential nuclides for both the U-Pu and the Th-U fuel cycles. Validation studies for the AVR, Thorium High-temperature Reactor (THTR), and the Fort St Vrain reactors have been performed for the thorium cycle, while studies on the HTR-Modul, Light Water Reactor (LWR), RBMK, and MAGNOX reactors describe the burn-up characteristics of the uranium cycle. VSOP has proven to be a suitable tool for analyzing both fuel cycles. Comparisons with output from other models such as MCNP and TINTE will be done, as well as independent comparison with other VSOP models (VSOP-NTC). | ASTRA | Tests Completed | ☑ |
| Oxidation | CFD | Experimental Benchmarking | JAEA reversed-U-shape tube | Tests Completed | ☑ |
| Oxidation | CFD | Experimental Benchmarking | NACOK | Tests Completed | ☑ |
| Oxidation | TINTE | TINTE has been compared with SANA, VELUNA and NACOK experiments and AVR plant data. TINTE is considered reliable and adequate for HTR modeling. Natural convection modeling (illustrated with the NACOK test facility). | NACOK | Tests Completed | ☑ |

| Phenomenon | Code | Development and Validation (Qualification) tests planned or completed | Facility | Status | Applicable to NGNP |
|---|---|---|---|---|---|
| Oxidation | TINTE | TINTE has been compared with SANA, VELUNA and NACOK experiments and AVR plant data. TINTE is considered reliable and adequate for HTR modeling. Small pebble bed with flow of air (illustrated with the VELUNA test facility). | VELUNA | Tests Completed | ☑ |
| Radionuclide Release | GETTER | Benchmark: EU fuel development program | HFR | Testing Underway | ☑ |
| Radionuclide Release | GETTER | Benchmark: German fuel development program | HFR, FRJ2, R2 | Testing Underway | ☑ |
| Radionuclide Release | NobleG | Benchmark: EU fuel development program | HFR | Tests Completed | ☑ |
| Radionuclide Release | NobleG | Benchmark: PBMR fuel qualification | HFR | Tests In Concept Definition Phase | ☑ |
| Radionuclide Transport | ASTEC | ASTEC has been developed jointly over a number of years by the IRSN and its German counterpart, the Gesellschaft für Anlagen und Reaktorsicherheit mbh (GRS). The main applications of the software package are safety analyses for nuclear reactors (e.g. The European Pressurized Reactor - EPR), source term evaluations (e.g. The re-evaluation of the S3 source term for the French Pressurized Water Reactors (PWRs)), and the development of severe accident management guidelines. ASTEC is widely used in IRSN level 2 probabilistic safety assessments (PSA2) for 900 MWe and 1 300 MWe PWR reactors. It is also used in the preparation and interpretation of experimental programs, in particular the Phébus PF integral test program and in the tests carried out as part of the International Source Term Program (ISTP). | Thai | Tests In Concept Definition Phase | ☑ |
| Radionuclide Transport | DAMD | Validation of circulating products distribution, deposition, resuspension, plate-out and lift off. | STORM | Tests In Concept Definition Phase. | ☑ |

| Phenomenon | Code | Development and Validation (Qualification) tests planned or completed | Facility | Status | Applicable to NGNP |
|---|---|---|---|---|---|
| Reactor Cavity Cooling System (RCCS) Two Phase Flow | RELAP5 | Modeling of two phase flow. | TBD | Tests In Concept Definition Phase. | ☑ |
| System Thermal Hydraulics | Flownex Nuclear | Cycle analysis demonstration | PBMM | Tests Completed | ☑ |
| Turbulent Mixing (Braiding) | CFD | CFD Development Testing | Heat Transfer Test Facility (HTTF) | Tests Completed | ☑ |
| Forced Convection Through The Pebble Bed Reactor | CFD / TINTE | Quantification of local effects in an unstructured pebble bed including wall channel effects, braiding effects, localized densification, etc. | TBD | Test Proposed | |
| Forced Convection Through The Pebble Bed Reactor | CFD / TINTE | Leak flow characterization tests may be required | TBD | Test Proposed | ☑ |
| Near Wall Heat Transfer | TINTE | A similar test facility to SANA is needed to study the heat transfer effects at the core/reflector interface in TINTE. | TBD | Test Proposed | ☑ |
| Neutronics | MCNP | Reactivity measurements, Control rod worth tests, Neutron flux measurements. | TBD | Test Proposed | ☑ |
| Pebble Flow In A Pebble Bed Reactor | PFC3D | Pebble bed structuredness, packing density and seismic response testing. | TBD | Test Proposed | ☑ |
| Radionuclide Transport | ASTEC | Suppression pool design testing and code comparison, confinement chemistry experiments, fission product transport and deposition experiments | TBD | Test Proposed | ☑ |

## 10.4 Additional NGNP V&V Activities

The PBMR DPP software codes used is expected to envelope the NGNP Software Code Validation requirements for the Nuclear Heat Supply System (NHSS), recognizing that the DPP commissioning itself forms an integral part of the V&V program. However, only once the NGNP plant level conceptual design analyses have been done will it be possible to confirm this statement and quantify specific further testing needs. It is noted that all NGNP evaluation models, once established, will remain to be Verified and Validated.

The NGNP core design with its higher gas outlet temperatures and power densities higher than the PBMR DPP may increase the risk that the best estimate analysis plus uncertainties are too close to the safety margins. In certain cases this may imply more advanced methods, software and models to be developed. One such example could be basic cross section data at high temperatures. For more examples see the "Tests Proposed" in Table 10-2 above. The fuel qualification program is expected to contribute to the fission product release data needed at higher temperatures (see Section 11).

It is noted that the software V&V employed for the Rankine Power Conversion System (PCS) and Hydrogen Production System (HPS) remain to be considered as it has not been covered by the PBMR DPP V&V process.

- Power Conversion System (PCS) – Thermoflex is the preferred software to be used for the Rankine NGNP PCS performance modeling. This is commercial software that is not yet V&Ved in accordance with nuclear procedures. The PEPSE code is already qualified and can be used as benchmark to qualify Thermoflex. It is not expected that testing is needed in the CTF to qualify Thermoflex. The software used to design the Steam Generator (SG) is unknown and will most likely be provided by the SG supplier. There may be other software used for detailed design. These are expected to be commercial packages (ANSYS, etc.) and will not generally require support from CTF for V&V.

- NHSS Coupling – PBMR uses Flownex Nuclear software to model the NHSS. To date, no SG Flownex Nuclear model has been V&Ved. Since the NGNP PCS will employ two-phase flow, Flownex Nuclear will need to be V&Ved for SG modeling purposes.

- Hydrogen Production System (HPS) – Currently, ChemCad and ASPEN are used to model the HPS. These are both commercial codes. At this point, no need is foreseen to validate these codes. The V&V of the hydrogen process models is expected to take place in the normal development of the technology. As engineering scale and pilot scale units are built and tested, the models will be validated against the results from those tests. It is noted that the choice of the platform (Aspen Plus, Hysys, ChemCAD or some other) may change as work progresses. The chief V&V step that is needed is the validation of the thermodynamic data being used in the models, not the software that does the calculations.

In order to analyze various aspects of the integrated NGNP, the software currently used for the PBMR–DPP design will be enhanced and extended to have an integrated core neutronic/thermal hydraulic analysis tool coupled to the Power Conversion and Hydrogen Production Systems models for simulating normal and off-design conditions. This tool will allow for steady-state and transient analyses of the integrated NGNP plant and will enable operational and control studies. Such a tool remains to be further developed and V&Ved. See also Section 16.9.4 of the PCDR (NGNP-16-RPT-001).

## 10.5 Inputs into CTF

At this point, no specific physical tests are foreseen to validate the NGNP software codes. As part of the conceptual design, the need for additional software V&V testing will be re-evaluated.

The CTF will however be instrumented to such an extent that software V&V could be achieved.

# Appendix A: Test Facilities

**Figure A-2: Test Facilities**

| Facility | Location | Description |
|---|---|---|
| ASTRA | Russian Research Centre - Kurchatov Institute, Russia | The ASTRA critical facility represents a cylindrical side reflector consisting of graphite blocks with an octagon shaped core in the centre and a solid cylindrical centre column. The core is filled with fuel spheres and absorber spheres. Control rods, shutdown rods and a single regulating rod are situated in the first set of blocks closest to the core in the side reflector. |
| AVR | AVR GmbH, Juelich, Germany | A German operated pebble bed HTR with graphite reflectors and moderators. |
| Heat Transfer Test Facility (HTTF) | North West University, Potchefstroom, South Africa | This test facility consists of two units: the High Pressure Test Unit (HPTU) and the High Temperature Test Unit (HTTU). The HPTU has a maximum operating pressure of 50 Bar and maximum operating temperature of 100°C. The HPTU comprises 12 modular test sections. These modular units allow for a variety of tests to be conducted on the HPTU, ranging from Pressure drop testing to Near wall effects testing. The HTTU is electrically heated and has a maximum operating temperature of 1600°C (bed temperature). The facility is also capable of vacuum testing at 10KPa. The maximum operating pressure is 100KPa. Both nitrogen and helium are used as working fluids. The HTTU can perform either forced flow or natural convection tests. |
| Helium Test Facility (HTF) | Pelindaba, South Africa | The HTF consists of blowers, valves, heaters, coolers, recuperator and other components that allow articles to be tested at pressures up to 9 MPa and temperatures to 1100°C. The facility consists of a totally enclosed 40m high (8 levels) test tower with a 10m x 13m footprint and a 20 ton overhead crane with a passenger lift (ground - level 6). The facility is designed to accommodate 5 independent process streams, with each able to operate at up to 9MPa, 50ºC - 580ºC (1100ºC local) and up to 2kg/s. |
| HFR | Petten, the Netherlands | High flux material test reactor. |
| HFR, FRJ2, R2 | Europe | European material test reactors used for fuel testing. |
| HTR-10 (High Temperature Gas-cooled reactor-test Module) | Tsinghua University, Beijing, China | A 10-MW pebble bed high temperature gas-cooled reactor. The reactor vessel is approx. 11.2 m in height and contains a 1.8 m diameter core that is 1.97 m high with approximately 27000 pebbles. The reactor is designed to operate at 10 MWt. The average power density is 2 $MW/m^3$ and the core inlet temperature is 250 to 300 °C and the core outlet temperature range from 700 to 900 °C. |

| Facility | Location | Description |
|---|---|---|
| JAEA reversed-U-shape tube | Japan Atomic Energy Agency (JAEA) | The apparatus consists of a reverse U-Shape tube and a gas tank. A bent pipe connecting the two pipes is also heated. The inner diameter of the tube is 52.7mm. This experiment was designed to test the first stage of air ingress – diffusion. The entire experiment was conducted at isothermal conditions at 18 C. [5] The two gases used were helium in the tube and nitrogen in the lower tank. |
| NACOK (Natural Convection Oxidation Facility) | FZJ, Juelich, Germany | The main section of the facility is made up of a vertical channel of 300mmx300mm and 7.5m tall. The experimental channel is composed of sections representing a bottom reflector, sphere packing (pebble bed) and a top reflector. The experimental set-up was designed to be able to represent different breaks in pipes connecting to the reactor. Breaks that can be created includes the co-axial duct (reactor outlet pipe), the defueling chute at the bottom of the reactor and the fuelling line at the top of the reflector. By a sectional design, different core heights can also be realized. All sections of the experimental channel and of the return pipe can be heated to accident-relevant temperatures. At different positions, the local gas compositions can be measured. |
| PBMM | North West University, Potchefstroom, South Africa | The Pebble Bed Micro Model (PBMM) at North-West University was used to gather data for separate and integrated effects validation of Flownex Nuclear. This data was used for the validation of both steady-state and transient phenomena. |
| SANA (Selbstatige Abfuhr der Nachwarme) | FZJ, Juelich, Germany | Consists of a bed of graphite spheres in a cylindrical arrangement. This part of the core of a pebble bed reactor has a diameter of 1.5 m as well as a height of 1 m. Approximately 9500 graphite pebbles of a diameter of 6 cm fit into the volume of 1.77 $m^3$, with a random arrangement. The heat production is effected in up to four electrical resistance elements which are inserted vertically into the bed. The installed maximum power of 50 kW permits a maximum power density of 28 $kW/m^3$. That means 0.93% of the full power is transferred to the MODUL reactor and corresponds to a time of 3 to 4 hours after the beginning of the depressurization accident. To endure a predominantly radial heat flux, insulation systems limit the bed at the top and the bottom. |

| Facility | Location | Description |
|---|---|---|
| STORM | Joint Research Centre, Europe | The STORM test facility consists of 5m long test section which is 63mm in diameter. Dust deposition and resuspension experiments can be carried out in this facility. In the deposition phase, the carrier gas and aerosols pass through a mixing 10 cubic meter mixing vessel, a first straight pipe and into the test section and then straight to the wash and filtering system. In the resuspension phase, the clean gas is injected directly into the test section and the resuspended aerosols are collected in the main filter before the gas goes through the wash and filtering system. The aerosol concentration and size distribution is measured upstream of the test section in the resuspension phase. The test section is enclosed in an oven which was kept open during the deposition phase to maximize thermophoretic deposition and was closed and heated immediately after the deposition phase, to ensure a constant temperature between the two phases and avoid thermophoretic redeposition during the resuspension phase. |
| ThAI | Becker Technologies | The ThAI facility is a unique technical scale experimental facility for research in the area of nuclear reactor containment safety. The acronym ThAI stands for Thermal Hydraulics, Aerosols and Iodine. The facility enables to simulate various thermal-hydraulic scenarios ranging from turbulent free convection to stagnant stratified containment atmospheres. It is equipped with innovative measuring, sampling and data acquisition tools including a radiological control area to utilize radiotracer I-123 in the experiments. It allows one to investigate safety relevant phenomena and component behavior under thermal hydraulics typical for severe accidents, including hydrogen phenomena, e.g. combustion and/or recombiner effects. ThAI is also equipped for aerosol investigation. |

| Facility | Location | Description |
|---|---|---|
| VELUNA | University of Duisburg in Germany | The VELUNA experimental installation was erected to investigate the corrosion of the fuel spheres and reflectors in the core of a pebble bed under natural convection conditions. It had a vertical square cylinder, 240 mm x 240 mm, made of heat resistant steel, 4 mm thick. There were fireproof bricks at the bottom. A graphite sphere pile, up to 3.6 m high, could be stacked on top of the fireproof bricks in the square cylinder. A bottom reflector made of graphite could also be installed on the fireproof bricks before a graphite sphere pile, up to 3.6 m high, was stacked on top of it. Heating elements were installed around the circular cylinder. These elements heated the contents of the square cylinder to a certain desired temperature, up to a maximum of 1 200 C. An air stream with a defined water vapor content and defined variable speed could then enter the square cylinder from below. Corrosion of the graphite spheres (and bottom reflector, if installed) occurred in the square cylinder, and waste gases were removed at the top. The installation essentially acted like an oven: air entered the square cylinder from below, combustion of graphite took place in it, and the waste gases left through a chimney at the top. |

# Appendix B – Software Code Descriptions

**Figure B-3**: Software Code Description

| **Code** | **Description** |
|---|---|
| ACS SASSI NQA | ACS SASSI (System for Analysis of Soil Structure Interaction) NQA is a highly specialized, highly interactive, user-friendly finite element computer code for performing 3D seismic soil-structure analysis of complex geometry structures with shallow or embedded foundations subjected to spatially varying seismic coherent or incoherent waves. |
| ASTEC | The purpose of the ASTEC (Accident Source Term Evaluation Code) software package is to simulate all the phenomena that occur during a severe accident in An LWR, from the initiating event to the possible release of radioactive products (the 'source term') outside the containment. |
| DAMD | The purpose of the code is to approach the source term calculation of an HTGR using a Top-to-Bottom approach. This means that the integrated effects of the phenomena are modeled in order to provide source term levels and distributions in systems and components of the HTGR. The code allows for the construction of a 1D flow model (pipe model) of an HTGR plant which can be used for the modeling of production, migration and distribution of graphite and metallic dust in the coolant flow paths of the plant. The code is also able to calculate, as for dust, the migration, deposition and distribution of fission and activation products released from the fuel during operation, and activation products produced from impurities in the coolant. Furthermore, the reactor core is modeled in a simplified 1D/1G (neutron group) fashion which allows for the neutronic removal/activation of isotopes. |
| FIPREX | FIPREX is a wrapper program around GETTER. FIPREX is a new Software Product that determines radionuclide releases, from spherical fuel elements, for the total core of an HTR, for both the expected and design cases under normal and accident conditions. |
| FISPACT/EASY | Fispact is an inventory code that has been developed for neutron-induced activation calculations. |
| FLOWNEX NUCLEAR | Flownex Nuclear is an implicit thermal-fluid network analysis code used for the analysis of temperatures, pressures and mass flows in the PBMR. (www.flownex.com) |
| FLUENT - CFD | FLUENT is a CFD code (solver and pre-post processor) for calculating fluid flow and heat transfer in the PBMR. FLUENT will in future be known as ANSYS CFD. |
| GETTER | GETTER is a diffusion code used to calculate the time-dependent release of long-lived metallic fission products such as caesium, silver and strontium, from the fuel elements of the PBMR equilibrium core under operational and experimental conditions. |
| MCNP | MCNP is a general-purpose, continuous-energy, generalized geometry, time-dependent, coupled neutron-photon-electron Monte Carlo transport code system for radiation shielding and nuclear criticality calculations |

| Code | Description |
|---|---|
| NobleG | NOBLEG calculates the steady state release of noble gases (Kr, Xe) and the halogens (Br, I) from the fuel spheres and equilibrium core of the PBMR in operational and experimental conditions: Release from the fuel elements from failed fuel particles, fuel particle failure under irradiation, release from the fuel elements from fuel contamination of the matrix material. |
| ORIGEN-SCALE | ORIGEN-SCALE is an isotope generation and depletion code used in nuclear safety-related analyses to calculate time-dependent isotopic inventories in irradiated nuclear reactor fuel and activated components, and associated quantities including decay heat, and neutron and gamma radiation spectra. The code also provides methods that integrate time-dependent quantities such as source terms and decay heat, and includes methods that model fuel reprocessing. |
| PC-Cosyma | PC-COSYMA is a probabilistic accident consequence assessment system used for calculating the potential radiological dose and risk to the public from a nuclear plant accident. This software models the atmospheric dispersion of released materials taking into account the range of conditions which may prevail should an accident occur. |
| PFC3D | PFC3D is a COTS product that is developed by the Itasca Consulting Group. It is an implementation of the Distinct Element Method (DEM), specifically for particulate systems, where the particles are separate spheres surrounded by rigid wall segments. The code simulates the mechanics of interacting particles by means of a rigid body, soft contact formulation. This is combined with an explicit, time marching solution scheme to solve both steady state and transient dynamic problems. PFC3D is used at PBMR as a simulation tool to examine systems of spherical particles, such as graphite and fuel spheres in the PBMR Reactor Core, or Small Absorber Spheres (SAS) in the SAS channels. Typically, the interaction, such as flow paths, particle positions and interaction forces, between spheres and structural components is observed. |
| RELAP5 | RELAP5/MOD3 is a computer code used for the thermal-hydraulic analysis of transients and small-break type accidents. In this version of the code, a three-dimensional simulation of thermal-hydraulic and neutronic phenomena occurring in a reactor can be simulated. The code is used to validate the design of the Reactor Cavity Cooling System (RCCS) in both active and passive modes. |
| SPECTRA | SPECTRA (Sophisticated Plant Evaluation Code for Thermal-hydraulic Response Assessment) is a fully integrated system analysis code, that models thermal-hydraulic behavior of Nuclear Power Plants, including reactor cooling system, emergency and control systems, containment, reactor building, etc. of various reactor types, like BWR, PWR, HTR. Spectra is developed by NRG (Holland) |
| STAR-CD - CFD | STAR-CD is a CFD code (solver and pre-post processor) for calculating fluid flow and heat transfer in the PBMR. |
| TINTE | TINTE (Time dependent Neutronics and Temperatures) is a reactor dynamics program for computing the nuclear and thermal transient behavior of the primary circuit of an HTGR, taking into account mutual feedback effects in two-dimensional R-Z geometry. |

| Code | Description |
|---|---|
| T-REX | The flux solver used in VSOP, namely CITATION, solves the neutron diffusion equation by using finite element methods. Since the diffusion approximation becomes invalid in the presence of strong absorbers, a different method has to be employed to model the control rod regions in CITATION. For this, T-REX was developed, making use of the method of equivalent cross-sections to determine equivalent parameters for the control rod regions. |
| VSOP99 | VSOP 99 is a suite of FORTRAN Software Products, interlinked as a collection of modules into a single executable. It is used to simulate the operational history of a nuclear reactor and to perform in-depth, quasi-steady state reactor core neutronics analysis. It comprises neutron cross-section libraries and processing routines for repeated neutron spectrum evaluation, two-dimensional diffusion calculation with depletion and shutdown features, in-core and out-of-core fuel management, fuel cycle cost analysis, and feedback from the thermal hydraulics (currently restricted to High Temperature Reactors (HTRs)). |

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Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 11: Fuel Elements

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
| Author | Name:<br>Company: | B Nel<br>M-Tech Industrial | November 18, 2008 |
| Reviewer | Name:<br>Company: | D Geduld<br>Pebble Bed Modular Reactor | November 19, 2008 |
| Reviewer | Name:<br>Company: | R Greyvenstein<br>Pebble Bed Modular Reactor | November 19, 2008 |
| Reviewer | Name:<br>Company: | RM Young<br>Pebble Bed Modular Reactor | November 19, 2008 |
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# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| | |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| | |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |

| | |
|---|---|
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

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# SUMMARY AND CONCLUSIONS

The Pebble Bed Modular Reactor (PBMR) Demonstration Power Plant (DPP) is rated at 400MWt and has a reactor outlet temperature of 900°C. The DPP fuel qualification consists of irradiating fuel spheres up to a temperature of 1250°C and to a burn-up value of approximately 111900 MWD/tU[1]. The fast neutron dose for these irradiation tests is specified at 2.7 x $10^{21}$cm$^{-2}$. Post-irradiation heat-up tests will be performed at 1600°C and 1800°C to determine delayed radionuclide releases thereby simulating Loss of Forced Cooling (LOFC) events. The maximum design fuel temperature for the DPP during normal operation is 1130°C and for the DLOFC is 1593°C. Irradiation tests for the PBMR-DPP fuel qualification program will be performed at INM in Russia and HFR Petten in the Netherlands and will be used to achieve an equivalent fuel Technology Readiness Level (TRL) of 8 for the DPP.

The NGNP and Hydrogen Production Pre-Conceptual Design Report [1] describes the 500MWt power and 950°C reactor outlet temperature design. The initial analyses predicted a peak fuel temperature of 1168°C during normal operation and 1750°C during a depressurized LOFC event. Based on these results, the PCDR states that the fuel should have a capability to achieve a maximum temperature of at least 1300°C and a burn-up value of 109000 MWD/tU. The fast neutron dose is specified at 2.7 x $10^{21}$ cm$^{-2}$. The recent Reactor Parametric NGNP Conceptual Design Study [11-2] refined the maximum fuel temperature to 1235°C during normal operation and the peak maximum temperature to 1703°C during a DLOFC event.

Based on the above best estimate results per the Reactor Parametric study [11-2] and PCDR [11-1] values and incorporating comparable margins for uncertainties[2], the fuel qualification envelope parameters for the DPP and the NGNP are provided in Table 11-1. The fuel for the NGNP is outside the DPP fuel envelope with regards to temperature while the fast neutron flux and burn-up are the same and within the DPP envelope. Note that if the NGNP program focuses on lower temperature applications (<800°C ROT), it is expected that the DPP qualification envelope would suffice.

**Table 11-1:** Fuel Qualification Envelope for the DPP and the NGNP

| Parameter | PBMR-DPP Qualification Envelope | PBMR-NGNP Qualification Envelope |
|---|---|---|
| Normal Operations Maximum Temperature (sphere centre) | 1250°C | 1335°C |
| DLOFC Peak Maximum Temperature | Up to 1800°C | Up to 1900°C |
| Fast neutron flux (n) | 2.7 x $10^{21}$ cm$^{-2}$ | 2.7 x $10^{21}$ cm$^{-2}$ |
| Burn-up | 1119000 MWd/tU | 109000 MWd/tU |

[1] All the qualification envelope values are still subject to change as the analysis is refined with actual design & manufacturing feedback of fuel and reactor.
[2] It is accepted that the measurement tolerance of temperature above 1000°C in test reactors is typically in the order of ±50°C which forms a significant portion of the applied margins.

# 11 FUEL ELEMENTS

## 11.1 Fuel Element Description/Function and Operating Requirements

### 11.1.1 Description & Function of the Fuel Elements

The PBMR fuel pebbles are as described in detail in section 5 of the NGNP PCDR [11-1]. Essentially the fuel pebbles comprise of Triple Coated Isotropic (TRISO) particles containing Low Enriched Uranium (LEU) kernels, embedded in a pressed graphite matrix.

The selected fuel for the PBMR NGNP is the same as the PBMR DPP which is based on the fuel manufactured by HOBEG for the 1988 HTR-Modul proof test and bulk tested in the AVR21-2 reload.

The functions of the fuel system and the fuel elements are provided in section 5 of the NGNP PCDR [11-1].

The success of HTGR fuel could largely be ascribed to the characteristically small, ceramic-coated fuel particles. The breakthrough development considering layering of the uranium-oxide kernels originally led to each particle being surrounded by a porous carbon buffer layer followed by high density pyrolytic carbon layers with a silicon carbide (SiC) layer incorporated in-between the two high density pyrolytic carbon layers. PBMR uses this same German designed TRISO coated particle fuel as reference for its fuel design. This fuel has shown very low particle failure when restrictive parameters are imposed consistent with fuel irradiation and heat-up testing, e.g., burn-ups, fluences, and maximum temperatures. The outstanding high temperature performance has been established by years of irradiation and testing experience where a very small fraction of particle failure and/or fission product release occurred under simulated accident conditions at elevated temperatures up to 1600°C over tens of hours of isothermal and transient simulation temperature tests. This experience performance base of TRISO fuel is extensive and consists of mechanical and irradiation tests performed on a number of fuel types developed in Germany during the 1960s and through 1988.

A total of three DDNs have been identified for the Fuel [11-1]. These DDNs address Fuel irradiation and heating tests as well as graphite irradiation tests, and can be subdivided in to the following:

- Fuel Irradiation Tests for Normal Operational Conditions (DDN NHSS-01-01)
- Fuel Heating Tests for Accident Conditions (DDN NHSS-01-02)
  Fuel Graphite Irradiation Tests (DDN NHSS-01-03)

In addition to power level, the main design parameter differences between the proposed NGNP and the DPP is the difference between the ROT and RIT which is 400°C (900°C-500°C) for the 400MWt DPP reactor versus 600°C (950°C-350°C) for the 500MWt NGNP reactor.

### 11.1.2 Operational Requirements

The normal operational irradiation requirements (including margin for uncertainty) for the PBMR-NGNP fuel were defined during the Pre-Conceptual Design Phase [11-1] as:

Maximum Fuel Temperature : 1300°C
Burn-up : 109000 MWD/tU
Fast Neutron Dose : $2.7 \times 10^{21}$ $cm^{-2}$

The more recent Reactor Parametric Conceptual Design Study [11-2] predicts a best estimate maximum fuel temperature of 1235°C during normal operation and a maximum peak DLOFC temperature of 1703°C. These results suggest a lower DLOFC temperature than presented in Section 5 of the PCDR, but a slightly higher normal operating temperature.

When defining irradiation and heating tests, temperature uncertainties need to be taken into account. Currently, the magnitudes of these uncertainties are assumed in the PCDR to be as large as 100°C until the temperature uncertainties have been refined after the PBMR DPP Software Verification and Validation is completed [11-1].

The PBMR-DPP fuel qualification program will advance the fuel for the NGNP from TRL 6 to TRL 7 by extending the fuel qualification envelope for several parameters. In order for it to advance from TRL 7 to TRL 8, additional irradiation testing to a maximum fuel temperature of ~1335°C at a burn-up value of ~ 109000 MWD/tU is necessary. The fast neutron dose remains unchanged at $2.7 \times 10^{21}$ $cm^{-2}$. Irradiation tests on these additionally irradiated fuel spheres are to be followed up with post-irradiation examination and heat-up tests at temperatures up to 1900°C. On successful completion of these activities, the TRL for PBMR-based NGNP fuel will advance from TRL 7 to TRL 8. It is noted that for the 500MWt NGNP operating with a ROT of <800°C, the DPP qualification program is expected to provide the technical basis for a TRL 8.

## 11.2 Technology/Design Selection Status

### 11.1.3 Candidate Technologies

PBMR Fuel is based on the proven German pebble design.

### 11.1.4 Decision Discriminators

The pebble fuel is the only TRISO fuel capable of supporting on-line refueling which is a strategic advantage of the PBMR.

#### 11.2.1.1Readiness and Design Maturity

Pebble LEU TRISO fuel has been tested and proven in various forms in various reactors and has successfully operated in HTR pebble reactors, thus the technology and design can be considered to be mature. However, due to the time elapsed since the demise of the German programmes and the initiation of the NGNP, the fuel is no longer available from the original German production line. In addition, the evolved reactor design will impose conditions on the operation of the fuel which were not covered with sufficient depth by the German programmes. These two factors have lead to the assessment of the readiness and design maturity as being DRL-5, specifically driven down by the design of the fuel production line, not the specification of the fuel elements.

### 11.1.5 Reference Design

The reference design for the PBMR-based NGNP is the PBMR DPP Fuel which is based on the Low Enriched Uranium (LEU) SiC TRISO fuel developed for the HTR Modul concept in Germany. There are minor adjustments in enrichment and sphere particle loading to adopt the PBMR service conditions. The development of the German fuel design arriving at the LEU $UO_2$ TRISO pressed sphere is summarized in the following report:

- *VDI-Verlag GmbH, 'AVR – Experimental High-Temperature Reactor, 21 Years of Successful Operation for a future Energy Technology', June 1990*

The same LEU $UO_2$ TRISO design used as basis for the PBMR fuel is described in the following report:

- *J Venter, H Nabielek, 'Fuel: Performance Envelope of Modern HTR TRISO Fuel', Proceedings HTR 2006, October 2006*

The Fuel Qualification program for the PBMR DPP is set out in the Technology Maturation Plan (TMP) in appendix C.

### 11.1.6 Alternative for Further Evaluation

No alternative. The PBMR NGNP Fuel will be the same as (or modest extension of) the PBMR-DPP fuel derived from the German pebble fuel.

### 11.1.7 Down Selection Task

N/a.

## 11.3 TRL Status

Evaluations of the status of the current technology for pebble fuel resulted in a TRL 6 [11-3]. The generic definition for this selection level states:

"Similar structure, system or component used in a relevant environment but in another configuration or application".

The specific definition (related to the NGNP pebble fuel program TRL level 6) states:

"Pebble bed reactors have been built and operated with comparable performance capability".

The TRL sheets explaining the underlying bases for the current TRL selection are provided in appendix A – refer to section Appendix A.

## 11.4 Technology Development Road Map Summary

### 11.1.8 Overview

The present PBMR fuel element irradiation and thermal test program is adequate to support DPP licensing and to advance the PBMR-based NGNP TRL from 6 to 7. Fuel irradiation tests are planned in Dutch Petten HFR and Russian IVV-2M reactors to test pre-production fuel, production fuel and fuel matrix graphite.

Irradiation on pre-production PBMR fuel will commence in FY 2009, whilst irradiation on production PBMR fuel will commence in FY 2012.

### 11.1.9 PBMR DPP Fuel Irradiation Program Description

The PBMR DPP fuel program includes a pre-production fuel irradiation program. This program is only mentioned here out of interest and credit is not claimed on the NGNP for it, as it does not advance the PBMR-NGNP fuel from one TRL to another.

The pre-production irradiation program consists of:

- Pre-irradiation characterization of fuel spheres.
- Fuel sphere irradiation tests involving the following:
- Fuel Spheres irradiated to a burn-up value of 97 438 $MWd/t_{HM}$, i.e. 10.1 ± 1.0 % FIMA vs. the specified operating maximum burn-up value for PBMR-DPP of 95723 $MWd/t_{HM}$.
- Fuel spheres are irradiated to a maximum center temperature of 1200 °C ± 50 °C vs. the expected operating maximum fuel temperature for PBMR-DPP of 1130°C.
- The fast neutron dose for PBMR-DPP under normal conditions is specified at $2.72 \pm 0.2 \times 10^{21}$ $cm^{-2}$.
- Irradiation time is ~ 500 calendar days.
- Post-irradiation examination of fuel spheres.
- Processing of all irradiated and tested samples and fuel.

The PBMR DPP production fuel irradiation program will advance the PBMR-based NGNP fuel from TRL 6 to TRL 7 and consists of the following:

Pre-irradiation characterization of fuel spheres.

Fuel sphere irradiation tests involving the following:

Fuel Spheres irradiated to a burn-up value of 111895 $MWd/t_{HM}$, i.e. 11.61 % FIMA vs. the expected operating maximum burn-up value of 95723 $MWd/t_{HM}$.

Fuel spheres are irradiated to a maximum center temperature of 1250 °C vs. the expected operating maximum fuel temperature for PBMR-DPP of 1130 °C.

The fast neutron dose for PBMR-DPP under normal conditions is specified at $2.72 \pm 0.2 \times 10^{21}$ $cm^{-2}$.

Non-destructive PIE and Küfa heat-up tests at 1600 °C and 1800 °C against the expected DLOFC temperature for the PBMR-DPP of 1593 °C.

Processing of all irradiated and tested samples and fuel.

Fuel graphite qualification entails irradiation tests of extruded and pressed graphite samples at 900°C and 1100°C at different fluences of respectively 1-, 2- and $4 \times 10^{21}$ $cm^{-2}$. These tests are not to determine for the 1st time the properties of the graphite to be used, but rather to verify that the newly manufactured graphite properties are similar to those of the historical A3-3 matrix graphite and the MLRF1 machined graphite.

### 11.1.10 PBMR NGNP Fuel Irradiation Program Description

Additional irradiation testing may be necessary to advance the PBMR-based NGNP fuel from TRL 7 to TRL 8 due to the elevated fuel temperatures[3]. This gives rise to the following:

Pre-irradiation characterization of PBMR produced fuel spheres (if different production line used to that of DPP).

Fuel sphere irradiation tests involving the following:

- Fuel Spheres irradiated to a burn-up value of ~ 109000 $MWd/t_{HM}$ vs. the expected burn-up value for the PBMR-based NGNP of 94079 $MWd/t_{HM}$.
- Fuel spheres are to be irradiated to at least a maximum center temperature of 1335°C against an expected operating maximum fuel temperature for PBMR-based NGNP of 1235°C [11-2], to which a 100°C uncertainty factor has been added.
- The fast neutron dose remains unchanged at $2.72 \pm 0.2 \times 10^{21}$ $cm^{-2}$.
- Non destructive PIE and Küfa heat-up tests to be performed at 1700 °C and 1900 °C to envelope the expected DLOFC fuel temperature for PBMR-based NGNP of 1703 °C [11-2], taking uncertainty margin into account.
- Processing of all irradiated and tested samples and fuel.

[3] All the qualification envelope values are still subject to change as the analysis is refined with actual design & manufacturing feedback of fuel and reactor.

## 11.2 Technology Maturation Plan Summary (TRL 6 to TRL 8)

PBMR-DPP fuel qualification tests are deemed sufficient to develop the current TRL 6 to a TRL 8 for the PBMR-DPP, but only TRL 7 for the PBMR NGNP. The PBMR-DPP fuel qualification consists of two sets of irradiation tests, namely initial tests on pre-production fuel followed by irradiation tests on production fuel.

### 11.2.1 TRL 6 to TRL 7

This advancement relies solely on the PBMR-DPP fuel qualification effort:

The PBMR-DPP fuel qualification tests to be performed are:

- Production fuel sphere irradiation at HFR and INM.
- Production fuel sphere PIE followed by subsequent heat-up tests at 1600°C and 1800°C.
- Fuel Graphite irradiation tests.

These tests will be performed on fuel spheres fabricated on a qualified PBMR fuel plant (production fuel) while the fuel graphite tests will be performed on pre-production matrix graphite and production extruded graphite[4].

### 11.2.2 TRL 7 to TRL 8

Any additional PBMR-NGNP fuel qualification tests required to progress the PBMR-NGNP fuel from TRL 7 to TRL 8 are activities unique to NGNP:

Production fuel sphere irradiation at a suitable test reactor at an operational temperature of 1335°C to 1350°C which caters for an uncertainty of 100°C[5]. Other parameters are burn-up of 11.61 % FIMA and fast neutron dose of >2.7 x$10^{21}$ $cm^{-2}$.

Production fuel sphere PIE followed by subsequent heat-up tests sampled at various temperatures up to 1900 °C.

Fuel Graphite irradiation tests[6] with adjusted temperature sample points of 1000°C and 1250°C.

[4] It is possible that the requirement to irradiate the extruded graphite of the machined graphite spheres may be deemed to be superfluous and enveloped by the irradiation of the structural graphite of the core.
[5] The uncertainty factor is provisional, should the DPP V&V be completed prior to the NGNP qualification, the selected temperatures could be adjusted accordingly.
[6] The requirement to irradiate the graphite to higher temperatures may be shown to be unfounded as the DPP testing may be sufficient to verify the curves produced.

## 11.5 Inputs to CTF

If CTF is not a nuclear irradiation facility then no input into CTF is required.

## 11.6 References

[11-1] NGNP-01-RPT-01: NGNP and Hydrogen Production Pre-Conceptual Design Report; Westinghouse Electric Company, May 2007

[11-2] NGNP Conceptual Design Study: Reactor Parametric Study, Michael Correia, August 2008

[11-3] NGNP-TRL & DRL Report; NGNP and Hydrogen Production Report on Design Readiness Levels and Design Technology Readiness Levels, Revision 0, Westinghouse Electric Company, September 2007

# APPENDIX A: TRL RATING SHEETS

**Table A-1:** TRL Rating Sheet for the Fuel Elements

## TRL Rating Sheet

Vendor Name: WEC Document Number: 002 Revision: 0

☐ Island ☐ System ☐Subsystem/Structure ☑Component ☐ Technology

Title: Fuel Elements (Spheres)

Description:

The Technology Readiness Level for fuel elements has been assessed as TRL 6 based on Pebble bed reactors having been built and pebble fuel having been operated with comparable performance capability.

Island(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: | Parent: | WBS: |
|---|---|---|

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Component or system breadboard in relevant environment | Similar SSC in relevant environment in another application | Pilot/engineering scale demonstration in relevant environment. |
| Specific Definitions *(if applicable)* | Irradiation test results of representative fuel elements from earlier German tests are acceptable | Pebble bed reactors have been built and operated with comparable performance capability | The present PBMR fuel element irradiation and thermal test program is adequate support DPP licensing. Commitments made for fuel irradiation tests in Dutch Petten HFR and Russian IVV-2M reactors |
| **TRL** | 5 | **6** | 7 |

Fuel testing and qualification identified as per Design Data Needs (DDN) NHS-01-01, NHS-01-02 and NHS -01-03. The following accompanying reports and special studies were evaluated:

- NGNP and Hydrogen Production Pre-conceptual Design Report: Section 5: Reactor Fuel, Rev 0, May 2007. NGNP Conceptual Design Study: Reactor Parametric Study, August 2008.

Outline of a plan to get from current level to next level.

| Actions | Schedule | Cost (K$) |
|---|---|---|
| • Production fuel sphere irradiation at INM.<br>• Production fuel sphere heat-up tests at 1600°C and 1800°C.<br>• Fuel Graphite irradiation tests. | Starting FY2012<br>Following Irradiation tests<br>Starting FY2012 | Costs not provided due to business confidentiality reasons. |

DDN(s) supported: NHS-01-01, NHS-01-02 & NHS-01-03

SME Making Determination: D.T Allen

| | |
|---|---|
| Date: 12 Sep 2007 | Originating Organization: Technology Insights |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

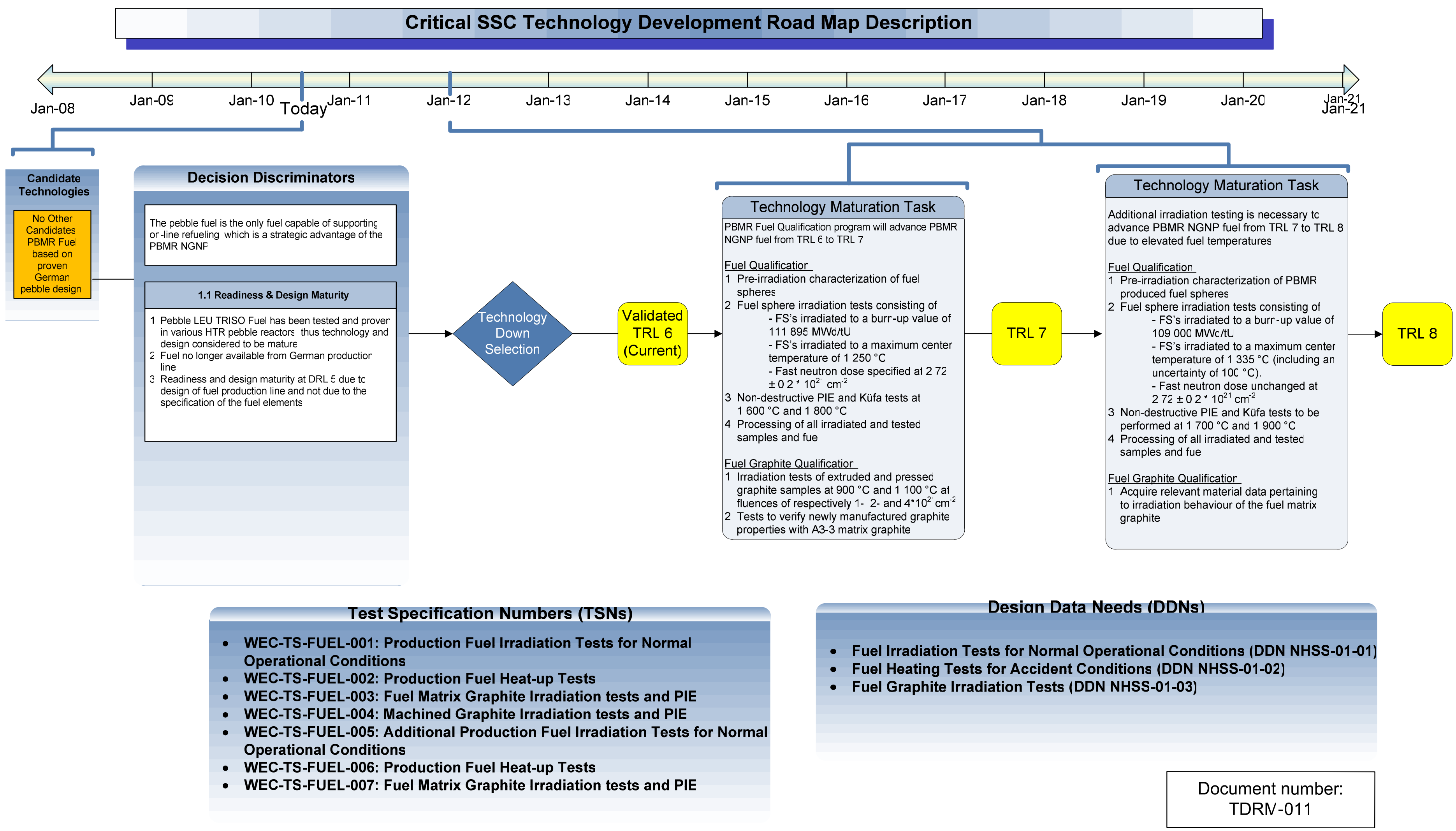


**Figure B-1: Technology Development Road Map for the Fuel Elements**

# APPENDIX C: TECHNOLOGY MATURATION PLAN

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## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

### TRL 6 to TRL 7:

Specification C1.2.1: Production Fuel Irradiation Tests for DPP Normal Operational Conditions.
Specification C1.2.2: Production Fuel Heat-up Tests at 1600°C and 1800°C.
Specification C1.2.3: Fuel Matrix Graphite Irradiation Tests and PIE.
Specification C1.2.4: Machined Graphite Irradiation Tests and PIE.

### TRL 7 to TRL 8:

Specification C2.2.1: Production Fuel Irradiation Tests for NGNP Normal Operational Conditions (at an irradiation temperature of 1335°C). Burn-up to take place up to ~ 109 000 MWd/tU and fast neutron dose to be >2.72 x $10^{21}$ $cm^{-2}$.
Specification C2.2.2: Production Fuel Heat-up Tests at 1700°C and 1900°C.
Specification C2.2.3: Fuel Matrix Graphite Irradiation Tests and PIE.

# C1 TECHNOLOGY MATURATION PLAN FOR FUEL - TRL 6 TO TRL 7

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Opjectives

The purpose of the TMP is to give more information regarding the activities to advance PBMR NGNP fuel from TRL 6 to TRL 8. PBMR-based NGNP fuel uses the German HTR-Modul Proof Test fuel design as reference design and a manufacturing process equivalent to that used by Hobeg for the production of German fuel. The PBMR-based NGNP fuel design will thus build upon this experience base through supplemental irradiation and post irradiation examination (PIE) tests to be performed on the PBMR-DPP fuel. The objective is to extend the German LEU-TRISO fuel performance statistical database to show that the PBMR NGNP fuel is capable of meeting the NGNP demands.

Fuel spheres meeting the required specification and quality control standards need to be manufactured on a qualified production line so as to pass the ‘Fuel Qualification’ test. This implies that the manufactured fuel spheres will meet all mechanical as well as radiation requirements set out by the PBMR design.

The PBMR approach to fuel qualification as far as manufacturing is concerned is to:

Use the same fuel specification that was used by Hobeg to produce the superior quality German fuel.
Apply Quality Control (QC) as per reference fuel.
Use the same process steps as per reference manufactured fuel.
Use direct materials that comply with similar specifications as per reference fuel.

### C1.1.2 Scope

In order to advance the maturity of the PBMR-based NGNP fuel element technology from a TRL 6 to TRL 7, the following tasks needs to be performed as per the PBMR-DPP Qualification program. The fuel sphere irradiation programme consists of the following fuel qualification programs:

Production fuel irradiation including pre-irradiation characterization and PIE.
- Fuel Graphite irradiation, including pre-irradiation characterization and PIE.

Each of these programs can be divided into the following test specifications:

- Specification C1.2.1: Production Fuel Irradiation Tests for Normal Operational Conditions
- Specification C1.2.2: Production Fuel Heat-Up Tests for Accident Conditions
- Specification C1.2.3: Fuel matrix Graphite Irradiation Tests and PIE

- Specification C1.2.4: Machined Graphite Irradiation Tests and PIE

### C1.1.3 Anticipated Schedule

The anticipated work for the production irradiation tests is set to start in FY 2012.

### C1.1.4 Overall Cost

Costs not provided due to business confidentiality reasons.

## C1.2 TEST SPECIFICATIONS

### C1.2.1 Production Fuel Irradiation Tests for Normal Operational Conditions

#### C1.2.1.1 Objectives

To demonstrate that the performance of PBMR production fuel satisfies PBMR fuel qualification requirements. A two-phased approach will be used i.e. partial burn-up and full burn-up of fuel spheres.

#### C1.2.1.2 Test Conditions

*C1.2.1.2.1 Test Configuration/Set-up*

INM Irradiation Test Program (IVV-2M):

Pre-irradiation tests (19 fuel spheres)

- Partial Burn-up irradiation tests (4 Fuel Spheres)
- Burn-up irradiation tests (12 Fuel Spheres)
- Non-destructive PIE (16 Fuel Spheres)

| Parameter | DPP Design Requirements | Nominal Partial Proof Test Irradiation Target | Nominal Proof Test Irradiation Target |
|---|---|---|---|
| Average residence time (days) | 925 | As required | 731 |
| End of life fast neutron dose (E > 0.1 MeV)($cm^{-2}$) | $2.72 \times 10^{21}$ | $1.7 \times 10^{21}$ | $3.63 \times 10^{21}$ |

| Parameter | DPP Design Requirements | Nominal Partial Proof Test Irradiation Target | Nominal Proof Test Irradiation Target |
|---|---|---|---|
| Average discharge burn-up (MWd/t / % FIMA) | 91012 / 9.44 | 48200 / 5 | 111895 / 11.61 |
| Normal operation temperature ( C) (sphere surface temperature)[7] | 1068 | 1200 constant | 900 / 1150 cycles |
| DLOFC ( C) | 1592 | 1600 / 1800 | 1600 / 1800 |
| PLOFC ( C) | 1319 | N/A | 1350 |
| Maximum power per fuel sphere (kW) | 2.76 | As required | 3 |

*C1.2.1.2.2 Test Duration*

The duration of this activity can be subdivided into the following activities:

| | |
|---|---|
| Irradiation planning & Preparation | ca 260 calendar days |
| Irradiation of Pre-Production Fuel | ca 1045 calendar days |
| PIE and Analysis | ca 130 calendar days |

*C1.2.1.2.3 Proposed Test Location*

Production fuel to be irradiated and tested at the INM facility.

**C1.2.1.3 Measured Parameters**

The following PIE will be performed on the irradiated fuel spheres:
Appearance
Mass
Diameter
Burn-up
Fission product inventory
Deconsolidation
Fission product distribution in fuel sphere
Optical ceramography of coated particles
IMGA on coated particles
Fission product distribution in coated particles

**C1.2.1.4 Data Requirements**

All data shall be acquired using recognized techniques, codes, standards, and QA.

**C1.2.1.5 Test Evaluation Criteria**

The production test will enable comparison of performance of PBMR Fuel manufactured on a qualified Fuel Plant with former German production pebble fuel.

[7] The surface temperatures specified in the test aim to achieve the required centre temperatures as required and quoted elsewhere in this document.

#### C1.2.1.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph C1.2.1.3.

#### C1.2.1.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

### C1.2.2 Production Fuel Heat-up Tests

#### C1.2.2.1 Objectives

The objective of the heat-up tests are to simulate accident transient temperature conditions (DLOFC), nominally set at 1800 °C to verify the integrity of the coated particles and fuel spheres in such simulated conditions. The PBMR-DPP's performance will be used to evaluate fuel integrity for PBMR NGNP.

#### C1.2.2.2 Test Conditions

*C1.2.2.2.1 Test Configuration/Set-up*

Fuel spheres to be subjected to heating tests at 1600 °C and at 1800 °C for ca 100 hours respectively.

*C1.2.2.2.2 Test Duration*

The heat up tests consists of the following subsections:

- Physical Heating Test: 130 days
- PIE and analysis of Heated Spheres: 130 days

*C1.2.2.2.3 Proposed Test Location*

At the same test station where irradiation was performed.

#### C1.2.2.3 Measured Parameters

Upon deconsolidation, the following measurements will be performed:

- Optical Ceramography
- Fission product inventory measurements
- 

#### C1.2.2.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards, and QA.

#### C1.2.2.5 Test Evaluation Criteria

Results to be evaluated against current NGNP DLOFC temperature requirements.

#### C1.2.2.6 Test Deliverables

Deliverables for this test specification shall include:

Report on all the measured parameters listed in paragraph C1.2.2.3. Of particular interest will be the measurement of particle failure fraction, which is related to the free uranium content.

#### C1.2.2.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

### C1.2.3 Fuel Matrix Graphite Irradiation Tests and PIE

#### C1.2.3.1 Objectives

To acquire relevant material data pertaining to irradiation behaviour of the fuel matrix graphite over the fluence-temperature regime for PBMR fuel as part of PBMR fuel qualification. Data can be used for validation for PBMR NGNP DDNs.

#### C1.2.3.2 Test Conditions

*C1.2.3.2.1 Test Configuration/Set-up*

*C1.2.3.2.2 It is proposed that matrix graphite samples are irradiated to three different fast neutron doses at the specified irradiation temperatures as follows:*

- Fluence = 1.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 900 °C
- Fluence = 2.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 900 °C
- Fluence = 4.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 900 °C
- Fluence = 1.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 1100 °C
- Fluence = 2.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 1100 °C
- Fluence = 4.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 1100 °C

*C1.2.3.2.3 Test Duration*

The duration of this activity can be subdivided into the following activities:

| | |
|---|---|
| Irradiation Planning & Preparation | ca 265 calendar days |
| Irradiation and PIE | ca 1042 calendar days |

*C1.2.3.2.4 Proposed Test Location*

The IVV-2M Russian will be used to test the fuel matrix graphite.

#### C1.2.3.3 Measured Parameters

Samples for investigation and irradiation will be cut from fuel-free matrix graphite spheres provided for the test. These samples will be cut parallel and perpendicular to the grain direction. Following irradiation, the listed characteristics will be measured prior to and after the irradiation tests.

Pre-irradiation characterisation for fuel matrix graphite will consist of:

Geometrical size
Mass
Calculation of sample density
Measurement of sample density
Sample porosity
Thermal conductivity in the range 20 °C to $T_{irr}$ °C
Electric conductivity in the range 20 °C to $T_{irr}$ °C
Thermal coefficient of linear expansion in the range 20 °C to $T_{irr}$ °C
Dynamic Young's modulus
Compression strength
Ultimate bending strength
Optical ceramography
Uranium and thorium content
Visual record of samples selected for irradiation

The measured characteristics will then be compared to the values obtained during pre-irradiation characterization.

#### C1.2.3.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards (ASTM) and QA. Neutron Activation Analysis (NAA) will be used for measuring U and Th content.

#### C1.2.3.5 Test Evaluation Criteria

$T_{irr}$ is anticipated to be at a maximum of 1100°C for the purposes of these tests. Some graphite properties shown in the list are measured to a maximum temperature of 1100°C, which covers normal operation conditions, while it is known that graphite temperatures might reach higher values than this during temperature transients. This is due to measurement limits imposed by the instrumentation used to measure these properties.

Property values for higher temperatures are found by means of conservative extrapolation from known values.

#### C1.2.3.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph C1.2.3.3.
- 

#### C1.2.3.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

### C1.2.4 Machined Graphite Irradiation Tests and PIE

#### C1.2.4.1 Objectives

To acquire relevant material data pertaining to irradiation behaviour of the machined graphite spheres over the fluence-temperature regime applicable for the use of these spheres in the PBMR DPP, as part of PBMR fuel qualification. Data can be used for validation for PBMR NGNP DDNs.

#### C1.2.4.2 Test Conditions

*C1.2.4.2.1 Test Configuration/Set-up*

*C1.2.4.2.2 NOTE: The anticipated cumulative dose to be seen by the machined graphite spheres during their life-cycle profile is expected to be in the order of 1.5 x $10^{21}$ $cm^{-2}$. The test description presented here is identical to the requirements of the matrix graphite in order that the tests can be conducted simultaneously in the same reactor. There is thus scope for reducing the fluence and consequently the duration of the tests.*

*C1.2.4.2.3 It is proposed that extruded graphite samples are irradiated to three fast neutron doses at two different irradiation temperatures as follows:*

- Fluence = 1.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 900°C
- Fluence = 2.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 900°C
- Fluence = 4.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 900°C
- Fluence = 1.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 1100°C
- Fluence = 2.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 1100°C
- Fluence = 4.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature = 1100°C

*C1.2.4.2.4 Test Duration*

The duration of this activity can be subdivided into the following activities:

| | |
|---|---|
| Irradiation Planning & Preparation | ca 265 calendar days |
| Irradiation and PIE | ca 1042 calendar days |

*C1.2.4.2.5 Proposed Test Location*

The IVV-2M Russian will be used to test the machined graphite spheres.

#### C1.2.4.3 Measured Parameters

Samples for investigation and irradiation will be cut from fuel-free machined graphite spheres provided for the test. These samples will be cut parallel and perpendicular to the extrusion direction.
Following irradiation, the listed characteristics will be measured prior to and after the irradiation tests:

Pre-irradiation characterisation for machined graphite will consist of:
Geometrical size
Mass
Calculation of sample density
Measurement of sample density
Sample porosity
Thermal conductivity in the range 20°C to $T_{irr}$ °C
Electric conductivity in the range 20°C to $T_{irr}$ °C
Thermal coefficient of linear expansion in the range 20°C to $T_{irr}$ °C
Dynamic Young's modulus
Compression strength
Ultimate bending strength
Optical ceramography
Uranium and thorium content
Visual record of samples selected for irradiation

The measured characteristics will then be compared to the values obtained during pre-irradiation characterization.

#### C1.2.4.4 Data Requirements

All data shall be acquired using recognized techniques, codes, standards (ASTM) and QA. Neutron Activation Analysis (NAA) will be used for measuring U and Th content.

#### C1.2.4.5 Test Evaluation Criteria

$T_{irr}$ is anticipated to be at a maximum of 1 100 °C for the purposes of these tests. Some graphite properties shown in the list are measured to a maximum temperature of 1 100 °C, which covers normal operation conditions, while it is known that graphite temperatures might reach higher values than this during temperature transients. This is due to measurement limits imposed by the instrumentation used to measure these properties.

Property values for higher temperatures are found by means of conservative extrapolation from known values.

#### C1.2.4.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph C1.2.4.3.

#### C1.2.4.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

# C2 TECHNOLOGY MATURATION PLAN FOR FUEL - TRL 7 TO TRL 8

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C2.1.1 Objectives

The purpose of this TMP is to give more information regarding the activities to advance PBMR-based NGNP fuel from a TRL 7 to TRL 8, should the V&V not succeed in reducing the uncertainty component of the margins to such a degree that the DPP testing can be considered enveloping of the NGNP.

### C2.1.2 Scope

In order to advance the maturity of the PBMR-based NGNP fuel element technology from TRL 7 to TRL 8, the following tasks may need to be performed in addition to the PBMR-DPP fuel qualification program.

Production fuel irradiation including pre-irradiation characterization and PIE at a higher irradiation centre temperature than for the PBMR-DPP fuel qualification program (~ 1350 °C).

Production fuel heat-up tests at slightly higher LOFC-simulated temperatures than for the PBMR-DPP fuel qualification program (~ 1 700°C & 1 900°C).

### C2.1.3 Anticipated Schedule

The anticipated work for the additional production irradiation tests to extend the PBMR-DPP fuel qualification program is set to start in FY 2012.

### C2.1.4 Overall Cost

The cost for these tests will depend on the demand for test facilities at the time of testing as well as the number of rigs used in addition to the post irradiation heating and evaluation costs. Any estimates at this time would be based on the DPP costs which are considered to be confidential.

# C2.2 TEST SPECIFICATIONS

## C2.2.1 Additional Production Fuel Irradiation Tests for Normal Operational Conditions

### C2.2.1.1 Objectives

To demonstrate that PBMR fuel will fulfil the NGNP requirements as per NGNP and Hydrogen Production PCDR [11-1].

### C2.2.1.2 Test Conditions

*C2.2.1.2.1 Test Configuration/Set-up*

Pre-irradiation tests

- Burn-up irradiation tests
- Non-destructive PIE

Irradiation Requirements:
Fuel sphere center temperatures : 1350 °C
Burn-up : 11.61% FIMA
Fast Neutron Dose (E > 0.1 MeV)[8] : $>2.7 \times 10^{21}$ $cm^{-2}$

*C2.2.1.2.2 Test Duration*

The duration of this activity can be subdivided into the following activities:

| | |
|---|---|
| Irradiation planning & Preparation | ca 260 calendar days |
| Irradiation of Pre-Production Fuel | ca 1045 calendar days |
| PIE and Analysis | ca 130 calendar days |

*C2.2.1.2.3 Proposed Test Location*

Production fuel to be irradiated and tested at a suitable test reactor facility such as ATR.

### C2.2.1.3 Measured Parameters

The following PIE will be performed on the irradiated fuel spheres:
Appearance
Mass
Diameter
Burn-up
Fission product inventory
Deconsolidation

[8] The fast neutron dose will nominally be in the order of $3.63 \pm 0.2 \times 10^{21}$ $cm^{-2}$ to achieve the burn-up at temperature.

Fission product distribution in fuel sphere
Optical ceramography of coated particles
IMGA on coated particles
Fission product distribution in coated particles

**C2.2.1.4 Data Requirements**

All data shall be acquired using recognized techniques, codes, standards, and QA.

**C2.2.1.5 Test Evaluation Criteria**

The production test will enable comparison of performance of PBMR-based NGNP Fuel manufactured on a qualified Fuel Plant with former German production pebble fuel.

**C2.2.1.6 Test Deliverables**

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph C2.2.1.3.

**C2.2.1.7 Cost, Schedule, and Risk**

See paragraph C2.1.4.

### C2.2.2 Production Fuel Heat-up Tests

**C2.2.2.1 Objectives**

The objective of the heat-up tests on the additionally irradiated fuel spheres are to verify acceptance of PBMR fuel as per NGNP requirements as set out in the NGNP PCDR [11-1] and the Reactor Parametric Study [11-2].

**C2.2.2.2 Test Conditions**

*C2.2.2.2.1 Test Configuration/Set-up*

Fuel spheres to be subjected to heating tests at 1700°C and at 1900°C for ~ 100 hours respectively.

*C2.2.2.2.2 Test Duration*

The heat up tests consists of the following subsections:

- Physical Heating Test: 130 days
- PIE and analysis of Heated Spheres: 130 days

*C2.2.2.2.3 Proposed Test Location*

At the same test station where irradiation will be performed.

**C2.2.2.3 Measured Parameters**

Upon deconsolidation, the following measurements will be performed:

- Optical Ceramography
- Fission product inventory measurements.

**C2.2.2.4 Data Requirements**

All data shall be acquired using recognized techniques, codes, standards, and QA.

**C2.2.2.5 Test Evaluation Criteria**

Results to be evaluated against NGNP DLOFC temperature requirements.

**C2.2.2.6 Test Deliverables**

Deliverables for this test specification shall include:

Report on all the measured parameters listed in paragraph C2.2.2.3. Of particular interest will be the measurement of particle failure fraction, which is related to the free uranium content.

**C2.2.2.7 Cost, Schedule, and Risk**

See paragraph C2.1.4.

### C2.2.3 Fuel Matrix Graphite Irradiation Tests and PIE

**C2.2.3.1 Objectives**

To acquire relevant material data pertaining to irradiation behaviour of the fuel matrix graphite over the fluence-temperature regime for PBMR fuel as part of PBMR fuel qualification. Data can be used for validation for PBMR NGNP DDNs.

**C2.2.3.2 Test Conditions**

*C2.2.3.2.1 Test Configuration/Set-up*

*C2.2.3.2.2 It is proposed that matrix graphite samples are irradiated to three fast neutron doses at two different irradiation temperatures as follows:*

- Fluence = 1.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature ($T_{irr}$) = 1000°C
- Fluence = 2.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature ($T_{irr}$) = 1000°C

- Fluence = 4.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature ($T_{irr}$) = 1000°C
- Fluence = 1.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature ($T_{irr}$) = 1250°C
- Fluence = 2.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature ($T_{irr}$) = 1250°C
- Fluence = 4.0 x $10^{21}$ $cm^{-2}$ (E>0.1 MeV); Temperature ($T_{irr}$) = 1250°C

*C2.2.3.2.3 Test Duration*

The duration of this activity can be subdivided into the following activities:

| | |
|---|---|
| Irradiation Planning & Preparation | ca 265 calendar days |
| Irradiation and PIE | ca 1042 calendar days |

*C2.2.3.2.4 Proposed Test Location*

A suitable test reactor such as ATR will be used to test the fuel matrix graphite.

**C2.2.3.3 Measured Parameters**

Samples for investigation and irradiation will be cut from fuel-free matrix graphite spheres provided for the test. These samples will be cut parallel and perpendicular to the grain direction. Following irradiation, the listed characteristics will be measured prior to and after the irradiation tests:

Pre-irradiation characterisation for fuel matrix graphite will consist of:

Geometrical size
Mass
Calculation of sample density
Measurement of sample density
Sample porosity
Thermal conductivity in the range 20 °C to $T_{irr}$ °C
Electric conductivity in the range 20 °C to $T_{irr}$ °C
Thermal coefficient of linear expansion in the range 20 °C to $T_{irr}$ °C
Dynamic Young's modulus
Compression strength
Ultimate bending strength
Optical ceramography
Uranium and thorium content
Visual record of samples selected for irradiation

The measured characteristics will then be compared to the values obtained during pre-irradiation characterization.

**C2.2.3.4 Data Requirements**

All data shall be acquired using recognized techniques, codes, standards (ASTM) and QA. Neutron Activation Analysis (NAA) will be used for measuring U and Th content.

#### C2.2.3.5 Test Evaluation Criteria

$T_{irr}$ is anticipated to be at a maximum of 1250°C for the purposes of these tests. Some graphite properties shown in the list are measured to a maximum temperature of 1250°C, which covers normal operation conditions, while it is known that graphite temperatures might reach higher values than this during temperature transients.

Property values for higher temperatures are found by means of conservative extrapolation from known values.

#### C2.2.3.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph C2.2.3.3.

#### C2.2.3.7 Cost, Schedule, and Risk

See paragraph C2.1.4

**NGNP-CTF MTECH-TDRM-012** **November 2008**
**Revision 1**

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 12: Core Structure Ceramics

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
| Author | Name:<br>Company: | Riaan de Bruyn<br>M-Tech Industrial | November 18, 2008 |
| Reviewer | Name:<br>Company: | Jaco Lindeboom<br>Pebble Bed Modular Reactor | November 19, 2008 |
| Reviewer | Name:<br>Company: | Mark Mitchell<br>Pebble Bed Modular Reactor | November 19, 2008 |
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| Jaco Lindeboom (PBMR) | October 31, 2008 |
| Mark Mitchell (PBMR) | October 31, 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| | | |

## REVISION HISTORY

# RECORD OF CHANGES

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| NGNP and Hydrogen Production Pre-conceptual Design Report | NGNP-01-RPT-001 | 0 |

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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |
| FHSS | Fuel Handling and Storage System |

| | |
|---|---|
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |
| NAA | Neutron Activation Analysis |

| | |
|---|---|
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |
| S-I | Sulfur Iodine |

| | |
|---|---|
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

The WEC proposed NGNP is envisaged to utilize core internals similar to those of the PBMR DPP. These core internal consists of the core barrel assembly and the core structure ceramics of which the latter is identified as a critical SSC. The core structure ceramics (CSC) can further be broken down into the graphite, composites, ceramic and metallic components. The graphite components are mostly made up by the reflector blocks while the composites comprises of the lateral restrain straps and tie rod assemblies. The ceramic components refer to the insulation material at the bottom of the reactor while numerous metallic parts are also present.

In order to utilize these technologies in the NGNP a technology readiness level of 8 (TRL-8) needs to be achieved by the specific technology under investigation. Based on this requirement a study was conducted in which the TRL rating of the different proposed technologies were determined. During this study the CSC were subdivided into two sections, namely the graphite components and the ceramics, composites etc. The graphite components were given a TRL-6 rating while the other components were rated as a 4. In order to utilize these components in the NGNP it now needs to be elevated to the required TRL-8 rating.

This TRL elevation process has been divided into two main activities. The first step is to advance the CSC to a TRL-7 and is achieved by the complete PBMR qualification process which ends with operational testing in the DPP. This qualification process is briefly discussed in the report while references have been provided to typical procedures and tests.

The additional activities need to advance this system to the required TRL-8 are mainly due to the fact that the NGNP operate at a lower inlet temperature as well as a higher outlet temperature. These activities have been captured in Design Data Needs (DDN) from either the NGNP Pre-Concept Design Report or related Special Studies and include the following:

- NHSS-02-01 Extended Properties of Irradiated Graphite at Low Temperatures
- NHSS-02-02 Extended Properties of Irradiated Graphite at High Temperatures
- COMP-01-01 Characterize Race Track Strap and Tie Rod Materials (irradiation tests)
- COMP-01-04 Insulation Materials (Unirradiated data needed)

These activities have been identified to provide the incremental qualification needed to use the PBMR CSC in the NGNP. Each of these DDN's is also presented as a high level test specification, indicating typical test configurations as well deliverables.

# 12 SSC : CORE STRUCTURE CERAMICS (CSC)

## 12.1 CSC DESCRIPTION/ FUNCTION AND OPERATING REQUIREMENTS

### 12.1.1 CSC Description

The CSC can generally be divided in the graphite, ceramics, metallic and insulation components. The graphite consists mainly of the reflectors while the ceramic and composite materials are used in the Lateral Restraint Straps (LRS) and Tie Rods assemblies. The insulation components are used to the bottom of the CSC with the primary function of reducing the temperature with regards to the metallic components. Figure 12-1 illustrates the probable position for these different components as part of the PBMR CSC.

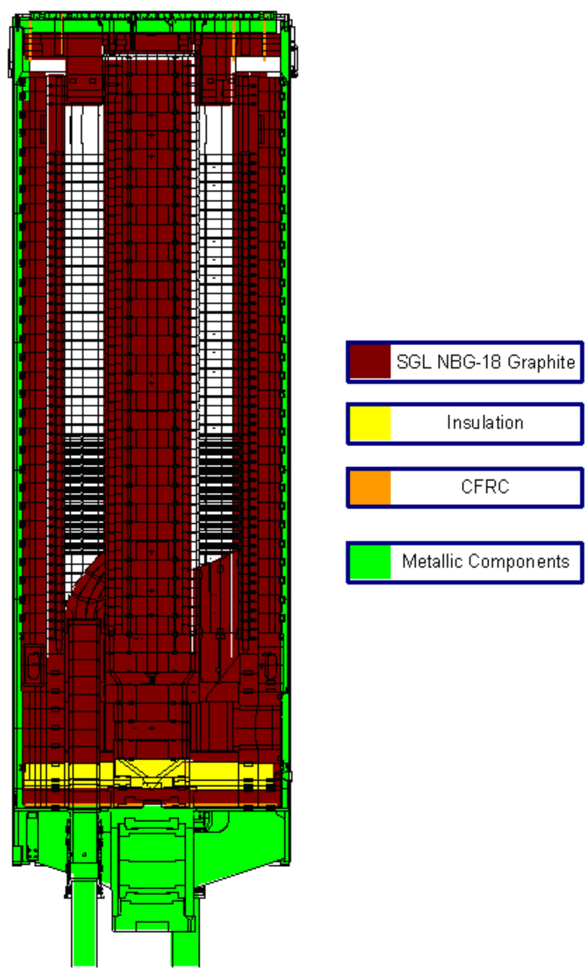


**Figure 12-1: Probable location of different materials for the CSC**

**Graphite Components**

The graphite components consist mainly of the reflectors and are made of bricks arranged to accommodate thermal and radiation induced deformations throughout the life of the reactor, while maintaining its functions. The general arrangement and principles that form the basis for the design of the CSC are based on the German designs for the Thorium High Temperature Reactor (THTR) and later reactors.

The reflectors can be further subdivided into the Bottom Reflector (BR), Side Reflector (SR), Top Reflector (TR), and the Centre Reflector (CR) with a brief summary of the reflectors as follow:

*Bottom reflector (BR)*

The bottom reflector is supported by the Core Barrel Support Structure (CBSS). This construction forms the base of the Core Structure by supporting the side and central reflectors as well as the fuel core. The stability and the exact location of the bottom reflector are essential for this requirement.

*Side reflector (SR)*

The side reflector is divided into the inner and outer side reflector. The outer side reflector (OSR) is constructed from 18 20° blocks, which are supported by the 40° bottom reflector outer blocks and form single columns to the top of the reactor.

The inner side reflector (ISR) is constructed from 24 blocks, 15° segments. Four of these blocks are supported by a bottom reflector inner block, which are 60° segments. This configuration also complies with the single column principle, which ensures that relative motion between the columns (due to temperature or irradiation induced dimensional changes) is accommodated without the generation of internal loads. A horizontal section through the side reflector is shown in the following Figure 12-2.

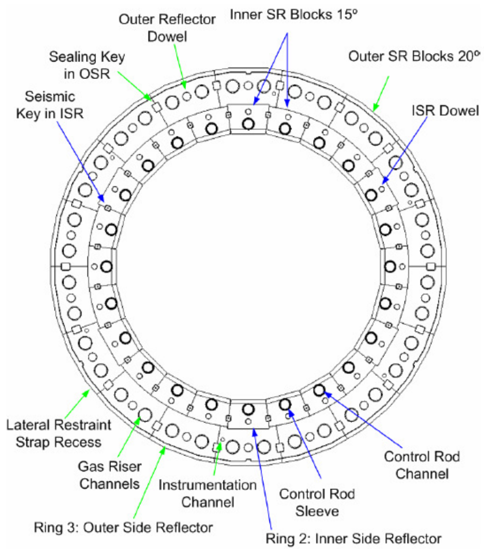


**Figure 12-2: Side reflector**

*Top reflector structure*

The Top Reflector (TR) is suspended from the Core Barrel top plate by means of tie-rods, manufactured from CFRC (Carbon Fibre Reinforced Carbon). The Top Reflector provides for neutron absorption and shielding above the core and also protects the top plate from high temperature gas (particularly during accident conditions). The top layer of blocks is manufactured from a solid insulation material. The Top Reflector blocks are also staggered to prevent a direct gap forming from the hot gas in the core to the top plate.

The structural integrity of the Top Reflector ensures that the interfaces, specifically for the RSS and RCS that pass through it, are ensured. The tie rods are designed to prevent the Top Reflector from dropping onto the pebble bed, even during Design Based Accidents. The top plate plug and the reflector suspended from it can be removed to access the core. Figure 12-3 indicates this sub-assembly.

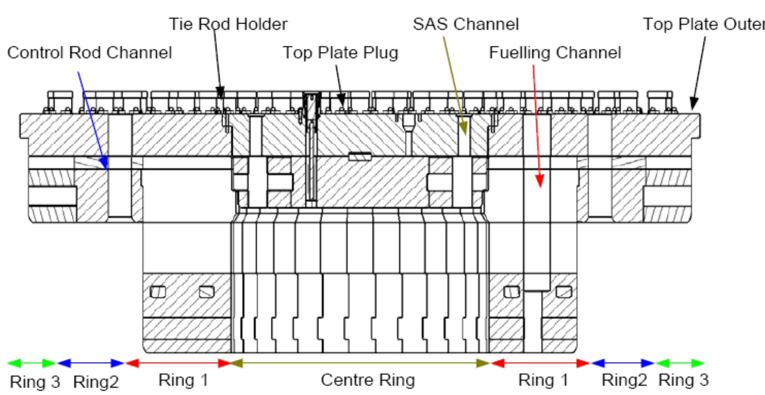


**Figure 12-3: Top reflector**

*Central reflector structure*

The Central Reflector, which is manufactured from graphite blocks, comprises the Centre Reflector Structural Spine and the Outer Centre Reflector (OCR). The OCR protects the CR Structural Spine from the high levels of fast neutron irradiation. This ensures that the CS Structural Spine is dimensionally stable. The structural spine ensures the structural integrity of the Central Reflector. A section through the Central Reflector is shown in the Figure 12-4.

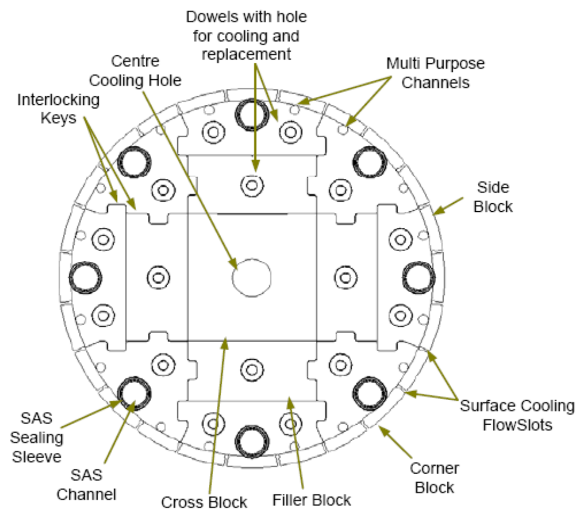


**Figure 12-4: Central Reflector**

The remaining subsystems include the ceramics and composite components as well as the bottom insulation. A brief description of these systems is as follow:

**Ceramic and Composite components**

*Lateral Restraint Strap (LRS)*

The Lateral Restraint Straps (Figure 12-5) surround and contribute to the support and stability of the Bottom and Side Reflectors of the CSC, providing circumferential support to the enclosed graphite reflector assemblies. They interface with the CBA, which in turn transmits lateral loads to the RPV. These circumferential supports must expand to maintain the same inner diameter as the outer diameter of the reflector assembly and, therefore, it is essential that they have effective rates of thermal expansion that are similar to those of the reflector assembly that they enclose. These components are being developed for the PBMR DPP and are applicable to the PBMR NGNP.

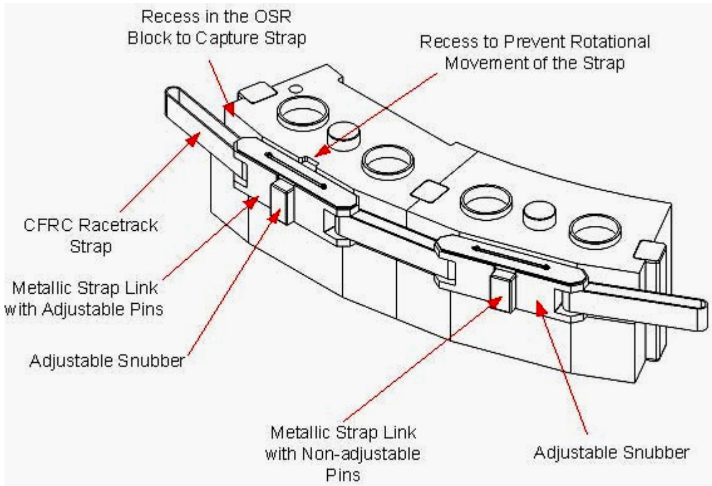


**Figure 12-5: Lateral restrain strap**

*Tie Rod Assemblies (TR)*

The tie rod assemblies are used to suspend the top reflector from the core barrel assembly and are manufactured from flat CFRC plate. Figure 12-6 indicates the tie rod geometry.

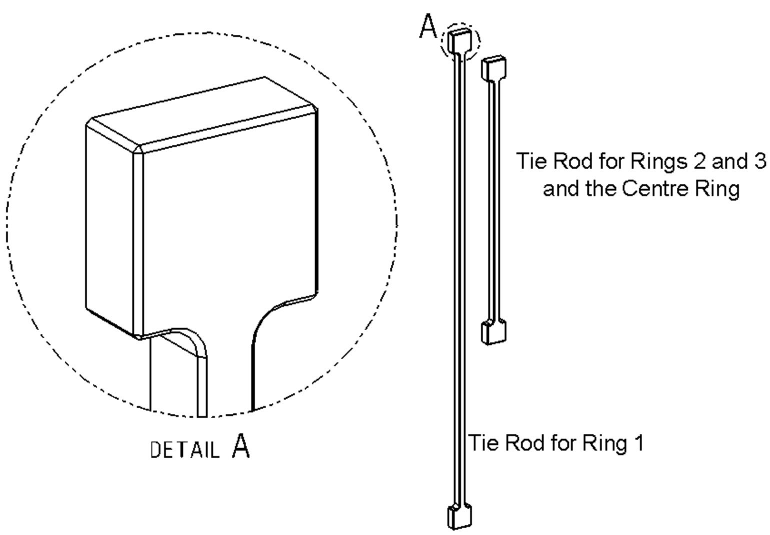


**Figure 12-6: Tie rod geometry**

## Insulation components

*Bottom insulation components*

Insulation components are used in the bottom reflector region of the PBMR NGNP CSC design to reduce the temperature exposure of metallic load-bearing components. These components are subjected to compressive stresses and are fabricated in the form of carbon blocks, fused ceramic forms or plate material that can be fabricated into complex shapes. The key properties needed for this type of application are low thermal conductivity, material stability under compressive loading and machinability for the specific application. Material choices include baked carbon or fused silica insulation materials, based on investigations that have been performed for the DPP design.

### 12.1.2 CSC Function & Interfaces

The following section provides a brief summary of the CSC functions together with a condensed list of interfaces with other components and systems.

**Functions**

**Sustain Fission Reaction**

- The CSC is required to form and maintain the pebble bed in a mechanically stable configuration.
- The CSC helps to maintain the nuclear reaction by providing neutron reflection for the core.
- The CSC is required to provide access for the In-core Delivery System to the Central Reflector, in order to start the nuclear reaction.
- The CSC is required to maintain flow passage configuration
- The CSC limit the temperatures and the fast neutron fluence in the metallic CBA and the RPV.

**Control Radiation Exposure from NHSS**

- The CSC protects the metallic components of the CBA and RPV from exposure to high neutron fluence levels.

**Limit Component Temperature**

- Under normal operation, the CSC is required to protect the metallic components of the Core Structures, including the CBA and RPV from extreme temperatures.
- Under accident conditions, the CSC is required to conduct decay heat from the core to the Core Barrel in order to maintain the maximum fuel temperature at an acceptable level.

**Enable Maintenance**

- The CSC is required to be assembled in a way that permits replacement of the Central Reflector.

**Maintain Configuration under Accident Conditions**

- The CSC is required to bear the mechanical loads due to dead weight, lateral loading due to the pebble bed, seismic loadings and the pressure drops established in the core.
- These loads must be transferred to the CBA, which transmits the loads to the RPV as described in the previous section.

- Ensure continued core cooling by the circulating helium in the coolant circuit. In case none of the Active Cooling Systems (ACSs) are available following an accident, the residual heat is transferred by natural processes from the core in such a way that the maximum core fuel temperature does not exceed the allowable limit. For this to happen, the core and reflector thermal characteristics (especially the conductivity) must not fall below specified values.

**General Functions**

- Provide access borings for insertion of the control elements of both the Reactivity Control System (RCS) and Reserve Shutdown System (RSS). The requirement is that control rods and/or SASs must be able to be freely inserted or dropped into their channels by gravity. Therefore any deformation of these channels following any event must not hinder the insertion of the control rod elements.
- Assure fuel flow by preventing bridging and crystal structure formation
- Provide for the insertion of instrumentation and sensors on the Demonstration Power Plant (DPP) during start-up phase.

**Interfaces**

The following is a brief summary of the CSC interface with other components and systems.

- RSS and RCS interfaces: The CSC is required to provide access for the RCS and RSS within the Side Reflector and Central Reflector respectively.
- FHSS interface: The CSC is required to provide access at the top for the refueling pipes, as well as the three defueling chutes at the bottom in order to permit circulation of fuel through the core in a uniform flow pattern.
- The CBA - the Top Reflector is suspended from the Core Barrel top plate while the Bottom Reflector is constructed on top the Core Barrel bottom plate.
- Bottom Reflector – Should provide an interface in order for the Small Absorber Spheres to be inserted at the top and extracted at the bottom.
- The FHSS Defueling Chutes
- The PHTS Piping.

### 12.1.3 CSC Operating Conditions

The CSC provides access for the In-Core Delivery System in a Multipurpose Channel in the Central Reflector. The helium flow is introduced into the Bottom Reflector of the Core Structure Ceramics, from where it is channelled to the top of the pebble bed in the gas riser channels, located in the Side Reflector. The gas then flows through the pebble bed from top to bottom, being heated in the process. At the bottom of the pebble bed, the gas is collected in the outlet plenum through flow slots between the blocks. The flow is then channelled from the outlet plenum into the core outlet pipe and out of the reactor unit system.

***Operating Conditions***

Simplified operating conditions of the CSC are provided below:

- Nominal Reactor outlet temperature of 950°C
- Nominal Reactor Inlet Temperature of 350°C
- Nominal Reactor Power level of 500 MWt
- Nominal helium pressure of 9 MPa
- Service Life:
  - Non-replaceable components: 60 equivalent full-power years
  - Replaceable components:
    - Minimum: [15] equivalent full-power years
    - Target: [20] equivalent full-power years

## 12.2 TECHNOLOGY/DESIGN SELECTION STATUS

The NGNP Core Structure Ceramics is anticipated to be identical to those of the PBMR DPP. Due to this reason the following section will not include any information on a down selection process. The PBMR DPP core structure ceramics are however in their final stages of detail design and component manufacturing is due thereafter. An inquiry into the PBMR design documentation status revealed a total of 685 documents and 500 appropriate drawings. Of these documents approximately 180 reports and 400 drawings currently describe the DPP design baseline used for final review and release for manufacturing.

### 12.2.1 Decision Discriminators

Not applicable to the NGNP CSC.

### 12.2.2 Reference Design

Not applicable to the NGNP CSC.

### 12.2.3 Alternative for Further Evaluation

Not applicable to the NGNP CSC.

### 12.2.4 Down Selection Task

Not applicable to the NGNP CSC.

## 12.3 TRL STATUS

The following section provides a summary of the TRL levels of the NGNP CSC as prepared by Technology Insights per NGNP-TRL & DRL Report. These technology readiness levels are presented separately for the graphite and the ceramics, composites and other components and are indicated in Table 12-1. A copy of the original TRL rating sheet can be found in Appendix A.

**Table 12-1: TRL & DRL ratings**

| ***Critical Structure, System or Component*** | ***DRL Level*** | ***TRL Level*** |
|---|---|---|
| *Core Structure Ceramics – Graphite* | *5* | *6* |
| *Core Structure Ceramics – Ceramics, composites, etc.* | *4* | *4* |

**Basis for Rating: Graphite**

The graphite components consist of the reflector blocks within the reactor system and were given a DRL rating of 5. This value was given due to the fact that the core internals for the NGNP will be identical to the internals of the DPP as well as the fact that the preliminary design is complete. An inquiry into the current status of the graphite internals design process however indicated that the detail design phase is nearing its end with manufacturing to follow thereafter.

The TRL level of the graphite internals were determined as 6 due to the fact that current experience with graphite core internals from several graphite moderated and gas-cooled nuclear reactors exists. These existing systems is however not prototypical to that of the PBMR and the designs are based on the German THTR designs.

**Basis for Rating: Ceramics, composites, etc.**

The ceramic and composites internals for the NGNP was given a DRL rating of 4 and will be similar to the core internals for the DPP. This initial DRL level was assigned due to the fact that the preliminary design of the DPP is underway. An inquiry in the current status of the design might elevate this level to a DRL-5 level.

The TRL rating of 4 was also given to the core internal ceramics & composites and was mainly due to the fact that current HTR operating experience does not apply to these materials. The technology is however beyond the proof-of-concept, which does not make it a TRL-3.

## 12.4 TECHNOLOGY DEVELOPMENT ROAD MAP SUMMARY

### 12.4.1 Overview

The tasks needed to advance the CSC to the required TRL-8 rating are accomplished by means of the PBMR equipment qualification process, together with additional tasks. During this process the PBMR qualification tasks advance the CSC up to a TRL-7 while the supplement tasks, as identified through design data needs in either the NGNP Pre Concept Design Report or associated special studies, provide the further enhancement up to a TRL-8.

These additional tasks include extending the irradiation materials properties database for the graphite components as well as additional characterization of the lateral strap and tie rod components. Quartz insulation has also been proposed to supplement the baked carbon insulation, of which numerous material data need to be obtained.

These additional tests can be performed in independent laboratories and does not necessarily create any input to the CTF.

## 12.5 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL'S TO TRL 8)

The CSC is divided into the graphite components and the ceramic, composites etc. Of these two the graphite is currently on a TRL-6 while the ceramic, composites etc. are rated as a TRL-4. Both of these will be elevated to a TRL-7 by means of the PBMR qualification process while the incremental maturation tasks as from identified DDN's will provide the final advancement to a TRL-8.

## 12.6 INPUTS TO CTF

In order to advance the CSC from the current determined TRL levels to the required TRL-8 rating, a number of qualification tasks need to be performed. These tasks consist of the PBMR related qualification plan, being supplemented by incremental additional qualification in order to satisfy the NGNP conditions. All of these incremental activities can be regarded as laboratory type work and does not necessarily need to be performed as part of the CTF. These tests could be performed on a much earlier timescale and by means of independent organizations or companies.

# APPENDIX A: TRL RATING SHEETS

**Table A-1: Core Structure Ceramics: Graphite**

## TRL Rating Sheet

Vendor Name: Document Number: Revision:

☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology

Title: **Core Structure Ceramics - Graphite**

Description:
The graphite components within the Reactor Vessel, principally the bottom died, top en central reflector blocks, part of the Reactor Unit System

Area(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Component of system breadboard in relevant environment. | Similar SSC in relevant environment in another application. | Pilot/engineering scale demonstration in relevant environment. |
| **TRL** | 5 | **6** | 7 |

Basis for Rating

There is operating experience with graphite core internals form the several graphite moderated and gas-cooled nuclear reactors, but none is prototypical of the PBMR. Particularly the design basis is the German designs for the Thorium High Temperature Reactor (THTR) and later reactors, but these are not considered prototypical. It the were to be considered prototypical, then this is TRL 7. It also can be elevated to TRL 7 when PBMR DPP graphite qualification is completed. The graphite qualification for NGNP is to bring it to TRL 8.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (K$) |
|---|---|---|
| • | | |

DDN(s) supported: None

SME Making Determination: D.T. Allen

Date: 16 Aug 07 | Originating Organization: Technology Insight

**Table A-2: Core Structure Ceramics: Ceramic, composites etc.**

**TRL Rating Sheet**

Vendor Name: Document Number: Revision:

☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology

Title: **Core Structure Ceramics – Ceramics, composites, etc.**

Description:

The ceramic and composite components within the Reactor Vessel; part of the Reactor Unit System.

Area(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Proof-of-concept in laboratory or analytical model. | Component or system breadboard or analytical model. | Pilot/engineering scale demonstration in relevant environment. |
| **TRL** | 3 | **4** | 5 |

Basis for Rating

Operating experience with other HTRs does not apply to advanced materials, such as composites. Technology is beyond proof-of-concept, and so above TRL 3, but lacks experimental validation and so is not TRL 5.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (K$) |
|---|---|---|
| | | |

DDN(s) supported: None

SME Making Determination: D.T. Allen

Date: 10 Aug 07 | Originating Organization: Technology Insight

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

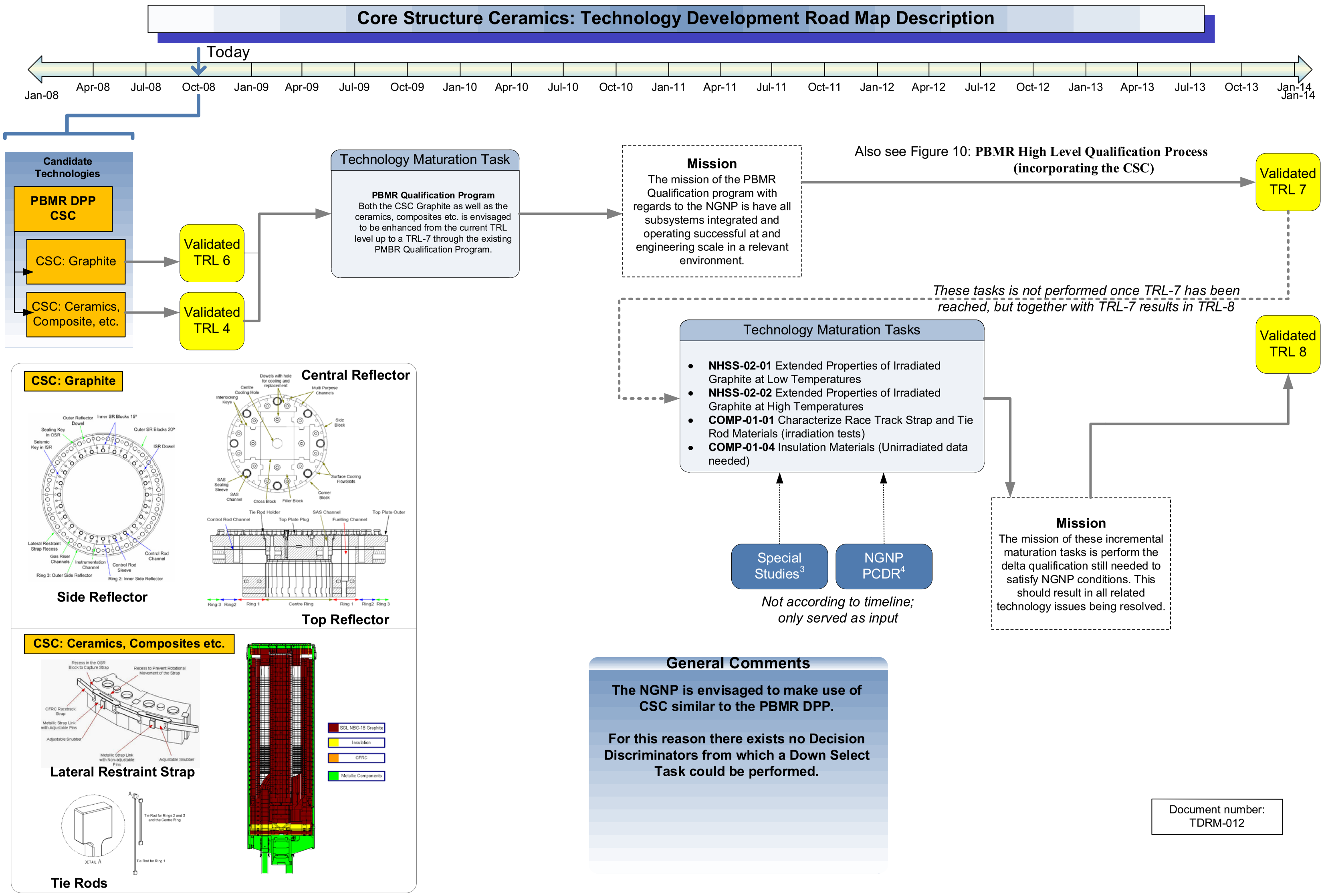


Figure B-1: Technology Development Road Map of the CSC

# APPENDIX C: TECHNOLOGY MATURATION PLAN

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## REQUIRED SPECIFICATIONS/TESTS TO ACHIEVE NEXT TRL

**TRL 6 (Graphite) & TRL 4 (Ceramics, composites etc.) to TRL 7**

- SSC Test Specifications #1: PBMR Relevant (WEC-TS-CSC-001)

**TRL 7 (Graphite) & TRL 7 (Ceramics, composites etc.) to TRL 8**

- SSC Test Specification #2: Extended Properties of Irradiated Graphite at Low Temperatures (WEC-TS-CSC-002)
- SSC Test Specification #3: Extended Properties of Irradiated Graphite at High Temperatures (WEC-TS-CSC-003)
- SSC Test Specification #4: Characterize Race Track Strap and Tie Rod Materials (WEC-TS-CSC-004)
- SSC Test Specification #5: Insulation Materials (Unirradiated Data Needed) (WEC-TS-CSC-005)

# C1 TECHNOLOGY MATURATION PLAN FOR SSC (CURRENT TRL TO TRL 7)

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL TO TRL 7)

### C1.1.1 Objectives

The PBMR NGNP Core Structure Ceramics (CSC) comprise the non-metallic components enclosed within the core barrel and its underlying support structure, plus the additional non-metallic components that form and support the top reflector assembly. These components are subdivided into the graphite and other (consisting of the ceramics, composites, etc) and are envisaged to be identical to those of the PBMR DPP. These subsystems has been reviewed and rated in terms of DRL and TRL as indicated in section 12.3.

In order to advance these systems from the determined TRL/DRL levels up to the required NGNP level of TRL-8, a certain number of maturation tasks need to be performed. These maturation tasks have been identified and consist of the qualification process as per PBMR DPP.

### C1.1.2 Scope

The PBMR related TRL advancement can be regarded as either development or qualification tests, depending on the relative position with regards to the overall equipment qualification plan. Table C-1-1 provides an extract from the complete list of PBMR qualification and development tests due to business confidentiality reasons.

**Table C-1-1: Extract from PBMR Equipment Qualification Test List**

| Test ID | CSC TQC Test Catalogue Extract[1] |
|---|---|
| CSC-QT-1 | Graphite Material Characterisation - Virgin Material Properties |
| CSC-QT-3 | Graphite Material Characterisation - Irradiated Material Properties |
| CSC-QT-4 | Graphite Wear Characterisation |
| CSC-QT-5 | Lateral Restraint Strap Testing. |
| CSC-QT-6 | Part Type Testing |
| CSC-QT-11 | Sleeve Burst Tests |
| CSC-QT-13 | Dowel Ultimate Load Tests |

[1] This table represent 12 of 71 tests over the entire CSC qualification process.

| | |
|---|---|
| CSC-QT-14 | Tie Rod Ultimate Load Tests |
| CSC-QT-25 | Integrated Insulation Mechanical Test |
| CSC-QT-32 | CIL Core connection HTF Tests |
| CSC-QT-36 | CFRC Material Characterisation - Virgin Material Properties |
| CSC-QT-41 | Insulation Characterisation |

### C1.1.3 Anticipated Schedule

**PBMR Schedule**

The PBMR CSC material qualification testing is currently underway with a proposed completion date in the third quarter of 2009. This completion will be followed by numerous design review activities where after all components will be released for manufacturing (also refer to Figure C-4). Figure C-2 provides an extract from the current CSC Engineering schedule.

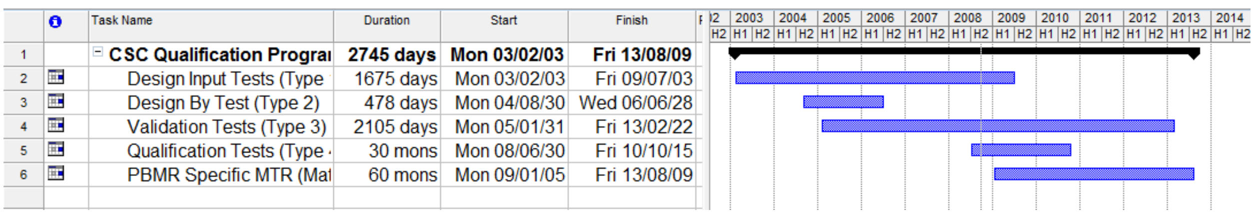


**Figure C-1: PBMR CSC Qualification Schedule**

### C1.1.4 Overall Cost

The overall cost needed to advance the CSC from the determined TRL rating to the required TRL-8 is a combination of the in-kind development costs as incurred by PBMR together with the incremental cost from the additional indentified DDN's. The PBMR related costs is omitted due to business confidentially reasons.

## C1.2 TEST SPECIFICATIONS (UP TO TRL 7)

In order to advance the TRL rating of the CSC to the required TRL-8, a number of qualification tests and tasks need to be performed. These tasks consists of the PBMR related qualification activities as previously mentioned together with the incremental tasks as defined in the additional DDN's. Successful completion of the PBMR activities would result in the required TRL-7 rating as per the following the test specifications.

### C1.2.1 SSC Test Specifications #1: PBMR Relevant (WEC-TS-CSC-001)

A simplified version of the PBMR equipment qualification process, together with their higher level qualification lifecycle process is indicated in Figure C-2. This figure, illustrating the typical PBMR qualification process, has also been overlaid with the TRL levels as determined from the technology readiness review.

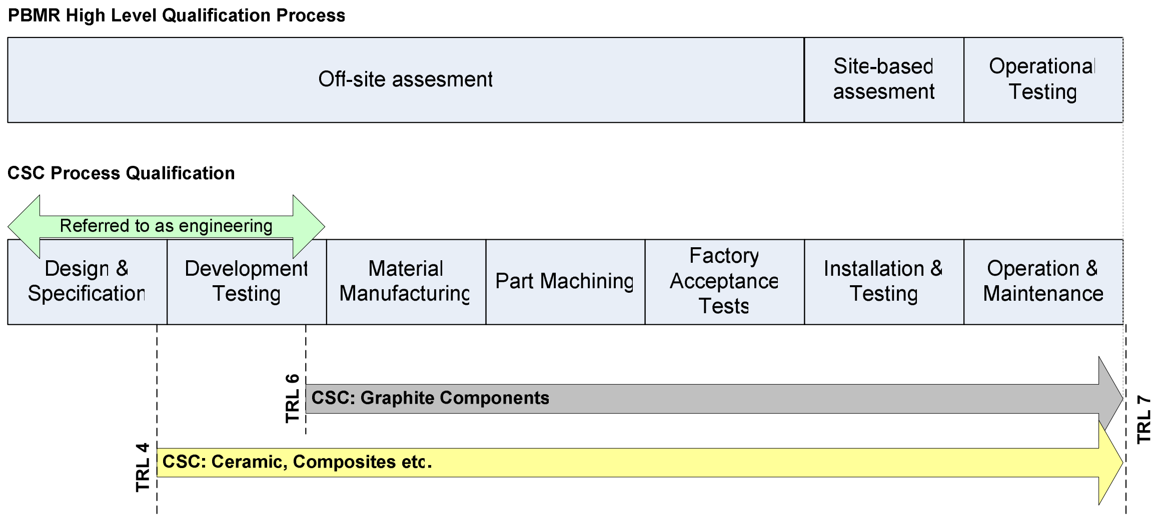


**Figure C-2: PBMR High Level Qualification Process (incorporating the CSC)**

The complete process includes numerous CSC tests and evaluations, and depending on when they are performed can be categorized as either development or qualifications tests. Figure C-5 indicates the relative position of both these types of test in terms of the overall progress.

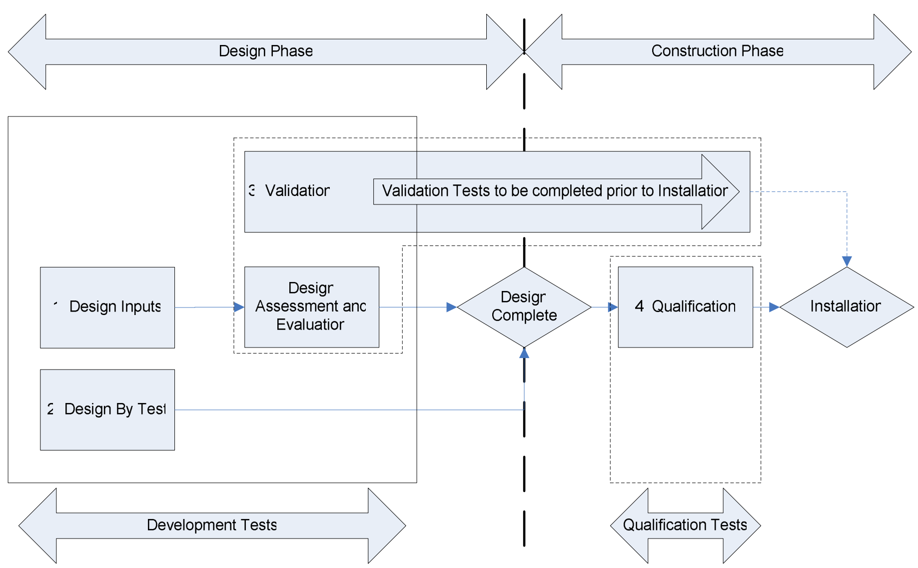


**Figure C-3: PBMR Qualification Test Types**

These tests are all initiated as part of a qualification program logic, as indicated for a specific test in Figure C-4. This logic uses the CSC functions as a starting point, from which numerous qualifications activities are developed. The activities are then translated into tests, and are presented as contract activities (either AN-XX or PA-XX) according to a general test requirements specification.

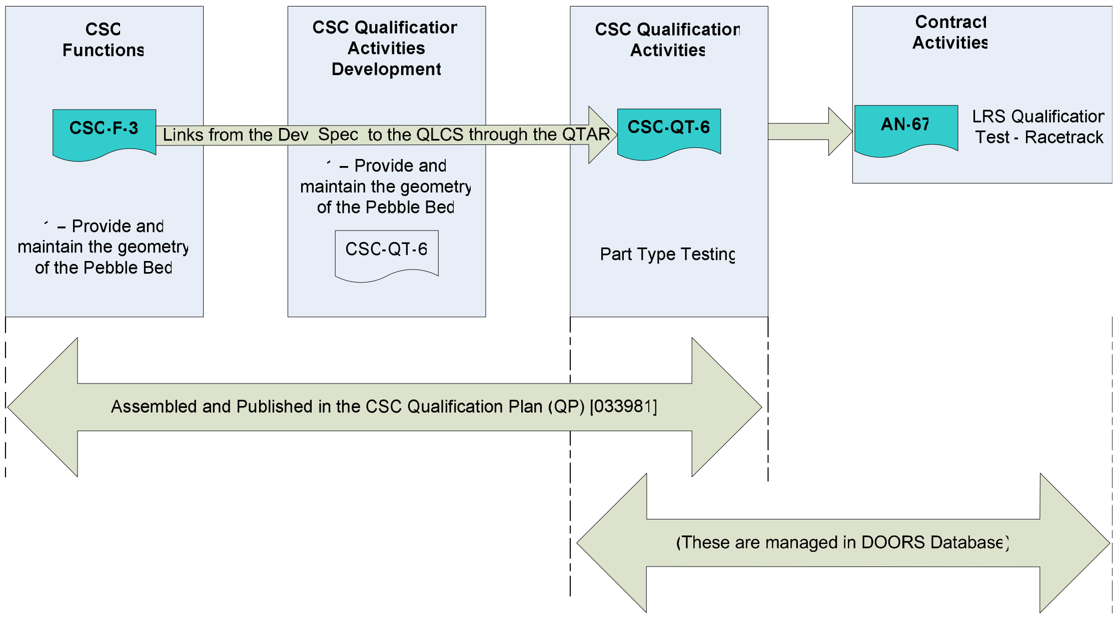


**Figure C-4: PBMR Qualification Program Logic**

The following list of tests represents an extract from the PBMR CSC development and qualifications tests. This list include only some of the tests over the entire qualification process of the CSC as well limited information regarding these tests. Appendix D indicates a typical Test Requirement Specification as documented for the bottom reflector insulation integrated test.

**CSC-QT-1: Graphite Material Characterisation - Virgin Material Properties**

Material input data is generated by means of the material characterisation defined in Section 3.1 of the Material Qualification Plan. For this Qualification Class, data from the completed tests are to be completed and collated in the NBG-18 Material Data Sheet Justification report. These data are then published in the NBG-18 Material Data Sheet.

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-3: Graphite Material Characterisation - Irradiated Material Properties**

The characterisation of materials response to Irradiation is to be completed. The highest level requirements for this activity are the defined in section 5 of the Graphite MQP. These requirements are derived from the RDMCI and the NNR's requirements. The final specifications for the PBMR Specific Materials Test Reactor Programme (PSMP) are defined in the Requirements Specification. The Completion date for this is reflected as prior to the end of commissioning. This reflects that MTR data will be available prior to fuel load and operation. While the available MTR data at this stage may not cover the full life of the graphite components, data enveloping the operation of the plant will always be available.

Qualification Life Cycle Phase: Off-site
Test Type: Environmental Assessment

**CSC-QT-4: Graphite Wear Characterisation**

PBMR plans to make use of the Westinghouse design basis. As required by LD-1097, where provision is made for the use of historical data similarly will be proven by duplicating some of the original test and direct comparison of the results. The correlation of these results determines the acceptability of the historical data in the qualification of the PBMR. The tests requirements for this test are defined in the CSC SGL Test Requirements Specification.

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-5: Lateral Restraint Strap Testing.**

The Lateral Restraint Straps (Specifically the CFRC components) are classed as FOAKE. Component level testing is defined as part of the development and qualification of these items. The following tests are completed:

- Manufacture of prototype straps to verify Manufacturability.
- Strength testing of prototype straps to provide for input into the design.
- Fatigue testing of CFRC strap parts.
- Full scale testing of the CFRC part, including the metallic interface components in representative environmental conditions (Temperature, Helium)

The specific test requirements for these tests are defined in the CSC SGL Test Requirements Specification .

Qualification Life Cycle Phase: Off-site
Test Type: Environmental Assessment

**CSC-QT-6: Part Type Testing**

Representative tests of full size components to be executed to provide further validation of assessment methodologies.

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-11: Sleeve Burst Tests**

The specific test requirements for this test are defined in the CSC SGL Test Requirements Specification.

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-13: Dowel Ultimate Load Tests**

The specific test requirements for this test are defined in the CSC SGL Test Requirements Specification.

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-14: Tie Rod Ultimate Load Tests**

The specific test requirements for this test are defined in the CSC SGL Test Requirements Specification.
These tests verify:

- The CFRC tie rod strengths
- The top interface strength and functionality
- The bottom interface strength and functionality
- The fatigue behaviour of the tie rod."

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-25: Integrated Insulation Mechanical Test**

Test is completed on a section of the BR assembly under load, at temperature and in helium to verify the mechanical design of the BR insulation.

Qualification Life Cycle Phase: Off-site
Test Type: Environmental Assessment

**CSC-QT-32: Core connection HTF Tests**

Testing of a Core Connection interface in the HTF verifies the design and performance of the Core Connection Interface design.

Qualification Life Cycle Phase: Off-site
Test Type: Functional Assessment

**CSC-QT-36: CFRC Material Characterisation - Virgin Material Properties**

Material input data is generated by means of the material characterisation defined in Section 3.1 of the Material Qualification Plan for this Qualification Class. This is described in a referenced document for the Plate Material and in another referenced document for the Strap Material. These data are then published in the Material Data Sheets:
Plate Material,
Strap Material.

| | |
|---|---|
| Qualification Life Cycle Phase: | Off-site |
| Test Type: | Functional Assessment |

**CSC-QT-41: Insulation Characterisation**

Material input data is generated by means of the material characterisation defined in Section 3.1 of the Material Qualification Plan for this Qualification Class. These data are then published in the Insulation Material Data Sheet.

| | |
|---|---|
| Qualification Life Cycle Phase: | Off-site |
| Test Type: | Functional Assessment |

# C2 TECHNOLOGY MATURATION PLAN FOR SSC (TRL 7 TO TRL 8)

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY (TRL 7 TO TRL 8)

### C2.1.1 Objectives

The PBMR NGNP Core Structure Ceramics (CSC) comprise the non-metallic components enclosed within the core barrel and its underlying support structure, plus the additional non-metallic components that form and support the top reflector assembly. These components are subdivided into the graphite and other (consisting of the ceramics, composites, etc) and are envisaged to be identical to those of the PBMR DPP. These subsystems has been reviewed and rated in terms of DRL and TRL as indicated in section 12.3.

In order to advance these systems from the determined TRL/DRL levels up to the required NGNP level of TRL-8, a certain number of maturation tasks need to be performed. These maturation tasks have been identified and consist of the qualification process as per PBMR DPP requirements as well additional DDN's that need to be addressed.

These additional DDN's were derived from the NGNP Pre-Concept Design Report as well as associated Special Studies. This section will provide the test specifications for the incremental task that need to be performed due to the identified DDN's.

### C2.1.2 Scope

The NGNP related TRL advancement consists of addressing the additional DDN's as identified for the NGNP relevant conditions. These DDN's represent an incremental development due to varying operating conditions between the PBMR DPP and the NGNP. The NGNP has both a lower reactor inlet temperature as well as a higher outlet temperature. Figure C-1 indicate these incremental requirements by means of comparison between the NGNP and PBMR DPP fluence-temperature conditions envelope.

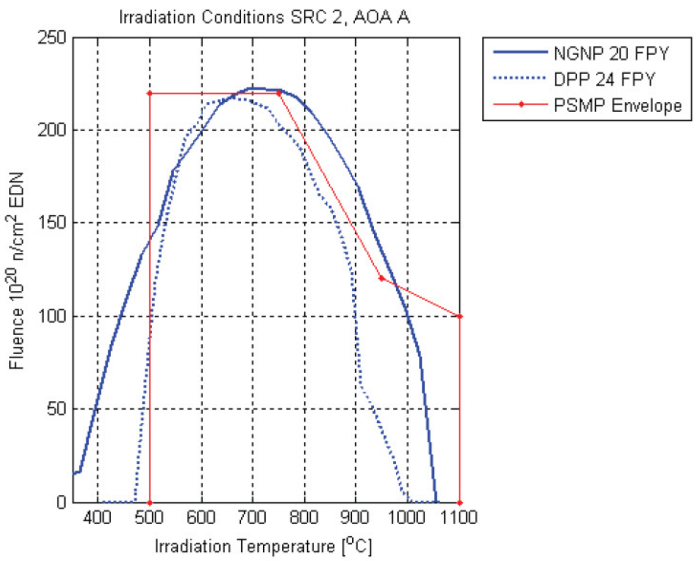


**Figure C-1: Irradiation Requirements for the NGNP Reflector Graphite**

The following should be noted regarding Figure C-1:

- The enveloping conditions apply only to a small fraction of the replaceable reflector graphite that is immediately adjacent to the pebble core. These components have been given the designation "Structural Reliability Criteria (SRC) 2, Area of Application (AOA) A"

- The NGNP estimates are preliminary and do not have the same detailed basis as the PBMR DPP estimates.

As can been seen in Figure C-2, there are two parts of the PBMR NGNP operating envelope that are not presently addressed by the PSMP. These are in the low-temperature operating range, below about 500 ºC, and in the high-temperature, high-fluence range, above about 750 ºC and 120x1020 n/cm$^2$ EDN, respectively. These areas correspond to the lower reactor inlet temperature and higher reactor outlet temperature of the PBMR NGNP relative to the PBMR DPP.

To accommodate the expanded operating range of the PBMR NGNP, the following DDN's have been identified for the CSC. These DDN's were taken from the NGNP and

Hydrogen Production PCDR (Section 4.3) as well as the NGNP Composite Special Study (NGNP-NHS-RPT.000.S05) and include:

- NHSS-02-01 Extended Properties of Irradiated Graphite at Low Temperatures
- NHSS-02-02 Extended Properties of Irradiated Graphite at High Temperatures
- COMP-01-01 Characterize Race Track Strap and Tie Rod Materials (Irradiation Tests)
- COMP-01-04 Insulation Materials (Unirradiated Data Needed)

These DDN's provide for acquiring the incremental qualification necessary to achieve a required level of technology readiness for the PBMR NGNP. More details regarding these DDN's can be found in section C1.2.12.

### C2.1.3 Anticipated Schedule

**NGNP Schedule (for incremental DDN)**

The NGNP schedule consists of the incremental tasks that need to be performed. As shown in the schedule, Figure C-3, planning for the initial Graphite and composites irradiations and the preparation of samples and capsules is to be completed near the end of FY2009 or beginning FY 2010. The initial irradiations will take place starting in FY2010, with post-irradiation examination (PIE) completed by end-FY2012. This schedule will support the Safety Review in conjunction with the COL that starts in FY2012.

Preparation for the more extended irradiation will be initiated in FY2011, with the irradiation being started in FY20121. The irradiation and PIE will be completed by the end of FY2014. This schedule will support the initial pre-commissioning operations that begin in FY2016 with about one year of margin to accommodate uncertainties. The additional insulation unirradiated material data requirements could be performed later and need to be completed by the end of FY2014.

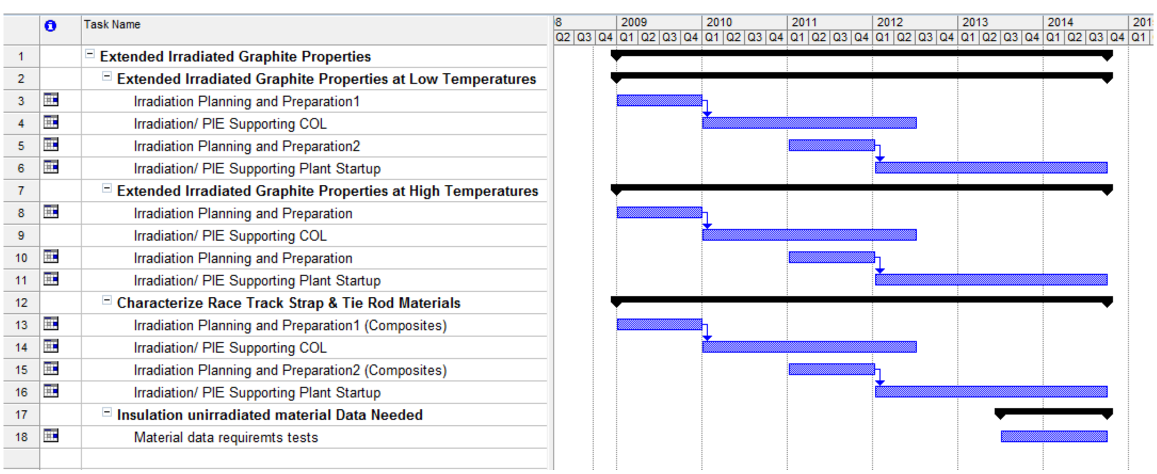

**Figure C-3: NGNP Incremental Graphite Qualification Schedule**

### C2.1.4 Overall Cost

**Current NGNP cost related information:**

The estimated costs of the R&D activities supporting the Reflector Graphite qualification program are shown in Table C-1. Estimates are provided in terms of the labor man-years over time and the total labor and non-labor costs in 2007 dollars. An average labor rate of [$150/hour] has been applied, which is judged to be representative of a U.S. National Laboratory when considering a composite of technicians, engineers/scientists and managers. An average of 2080 man-hours/man-year (MY) has been assumed for the development of MY estimates. These estimates are presently based on judgment and are acknowledged to have significant uncertainties. The total cost of the extension to the PBMR DPP PSMP is $5M ($2.05M for Labor/$2.95M for Materials & Other) over the period 2009 through 2014.

**Table C-1: NGNP Incremental Graphite Qualification Costs**

| Item | FY08 | FY09 | FY10 | FY11 | FY12 | FY13 | FY14 | Total |
|---|---|---|---|---|---|---|---|---|
| Labor (MY) | | | | | | | | |
| Materials Development | 1.1 | 0.8 | 1.0 | 0.6 | 0.6 | 1.3 | 1.1 | 6.5 |
| Methods V&V | | | | | | | | |
| Total | 1.1 | 0.8 | 1.0 | 0.6 | 0.6 | 1.3 | 1.1 | 6.5 |
| Labor Cost (K$ @ $150/hr and 2080hr/MY) | | | | | | | | |
| Materials Development | 350 | 250 | 300 | 200 | 200 | 400 | 350 | 2050 |
| Methods V&V | | | | | | | | |
| Subtotal | 350 | 250 | 300 | 200 | 200 | 400 | 350 | 2050 |
| Materials & Other (K$) | | | | | | | | |
| Materials Development | 150 | 350 | 500 | 600 | 500 | 500 | 350 | 2950 |
| Methods V&V | | | | | | | | |
| Subtotal | 150 | 350 | 500 | 600 | 500 | 500 | 350 | 2950 |
| Total Cost (K$) | | | | | | | | |
| Materials Development | 500 | 600 | 800 | 800 | 700 | 900 | 700 | 5000 |
| Methods V&V | | | | | | | | |
| Total | 500 | 600 | 800 | 800 | 700 | 900 | 700 | 5000 |

## C2.2 TEST SPECIFICATIONS (TRL 7 TO TRL 8)

In order to advance the TRL rating of the CSC to the required TRL-8, a number of qualification tests and tasks need to be performed. These tasks consists of the PBMR related qualification activities as previously mentioned together with the incremental tasks as defined in the additional DDN's. The following test specifications provide the details of the incremental tests in order to advance the CSC from a TRL-7 to a TRL-8.

### C2.2.1 SSC Test Specification #2: Extended properties of irradiated graphite at low temperatures (WEC-TS-CSC-002)

#### C2.2.1.1 Objectives

The objective of this test is to extend the PSMP envelope by obtaining irradiated properties of the applicable graphite grades in the lower temperature range, possibly at 350°C. This objective is subjective to the following assumptions:

Assumptions
- The graphite grade selected for the PBMR NGNP is the same as that for the PBMR DPP.
- The PBMR-Specific Materials Test Reactor Program (PSMP) basis established for the graphite structures of the PBMR DPP is also acceptable for the PBMR NGNP, specifically:
    - Confirmation via the PSMP that the materials databases developed for similar graphite in earlier gas-cooled reactor applications can be applied to the PMBR DPP/NGNP graphite
    - The proposed balance between pre-operational experimental assessment of the CSC graphite and post-operational surveillance, testing, inspection and maintenance (STIM) will be acceptable for the PBMR NGNP as for the PBMR DPP.

#### C2.2.1.2 Test Conditions

*C2.2.1.2.1 Test Configuration/Set-up*

Extended irradiation tests on PBMR reflector graphite need to be performed at 350°C in a fully instrumented, contained radiation capsule. These tests should be at specified fluence intervals on a number of specimens.

The material to be irradiated shall be exactly the same as is currently being used by the PBMR DPP design. This material shall be sampled from production charges that have been accepted and certified. Attention should be given to a traceable specimen extraction and preparation plan, while test samples should conform to size and geometry requirements of the applicable standard.

*C2.2.1.2.2 Test Duration*

Typical test categories include sample preparation, pre-irradiation characterisation, irradiation tests and post-irradiation examinations. Detail test durations depend on the number of test specimens and material type to be tested. Due to the uncertainty of a final design the overall incremental time schedule (C1.1.3) could be regarded as the time necessary to complete these tests.

*C2.2.1.2.3 Proposed Test Location*

A National Laboratory or University could perform the irradiation tests on sample scale together with the post irradiation examinations that is needed. Commercial organizations involved in similar process can also participate in this process.

### C2.2.1.3 Measured Parameters

The following table provides a list of the minimum parameters that should be determined as a function of irradiation. These parameters should be measured / obtained in accordance with specific standards were applicable or acceptable alternatives if standards are not available.

**Table C-2: Parameters to measure**

| ID | | Property |
|---|---|---|
| 1 | Physical | Mass |
| 2 | | Dimensions |
| 3 | | Volume |
| 4 | | Density |
| 5 | | Open Porosity |
| 6 | | Pore Size Distribution |
| 7 | | Electrical Resistivity |
| 8 | | Coefficient of Thermal Expansion |
| 9 | | Emissivity |
| 10 | | Specific heat |
| 11 | | Oxidation rate |
| 12 | | Thermal Conductivity |
| 13 | | Specific Gamma dose rate |
| 14 | Mechanical | Dynamic Elastic modulus |
| 15 | | Irradiation creep |
| 16 | | Shear Modulus |
| 17 | | Poisons Ratio |
| 18 | | Tensile strength |
| 19 | | Strain to failure |
| 20 | | Static Elastic Modulus |

Additional parameters to be determined include the irradiation temperature and neutron fluence measurements. All measurements should be conducted according to test specification guidelines with data requirements as indicated here after.

### C2.2.1.4 Data Requirements

The data requirements of the test measurement parameters should be captured in the test specifications and should as a minimum define the following:

- Method of measurement (according to appropriate standards)
- Accuracy and precision of measurement
- Differential between measured and calculated values

#### C2.2.1.5 Test Evaluation Criteria

The extended irradiation tests does not necessarily have a failing criteria, except that irradiation exposures need to be obtained within the specified accuracies and precisions.

#### C2.2.1.6 Test Deliverables

The test deliverables include a Test Specification, Test Design Justification and the final Test Report. The Test Specification should typically include the following:

- Method of temperature measurement and associated uncertainties.
- Method of fluence measurement and associated uncertainties.
- Specimen Extraction Plan.
- Test Specimen Preparation Procedures.
- Test Methods and uncertainties associated with each method.
- Size and Geometry of Test Specimens (including control materials).
- Number of Specimens per irradiation test condition (Including control material).
- Identification and traceability of test specimens.
- Storage conditions of irradiated test specimens.

The Test Design Justification should be provided as a confirmation of all applicable procedures, test methods and test conditions which will be employed in fulfillment of the Test Specification requirements. Both an approved Test Specification as well as Test Design Justification is required before commencing with any irradiation tests.

The final deliverable consists of the Test Report and need to be provided upon completion of the irradiation tests. This document shall as a minimum report in the following:

- Pre-irradiation test specimen data, i.e. dimensions, surface finish, etc.
- Any applicable test data gathered prior to the applicable irradiation stage.
- Post-irradiation test data and associated uncertainties.
- Irradiation conditions (target temperature, fluence) for the applicable irradiation stage.
- Irradiation conditions per test specimen for the applicable irradiation stage.
- All applicable test specifications.
- All applicable test procedures and test reports.
- Non-conformances in respect of the specified requirements.

Additional to these documents a quality assurance plan also needs to be provided. This plan should meet the requirements of PBMR, the applicable nuclear authorities as well additional client related requirements.

#### C2.2.1.7 Cost, Schedule, and Risk

The anticipated cost and schedule for these irradiation tests are captured in section C1.1.3 & C1.1.4. Due to the nature of these tests, there are no acceptable fallback positions for the NGNP. The consequences of non-execution might include failure to meet licensing objectives and/or unacceptable operational limitations.

### C2.2.2 SSC Test Specification #3: Extended properties of irradiated graphite at high temperatures (WEC-TS-CSC-003)

#### C2.2.2.1 Objectives

The objective of this test is to extend the PSMP envelope by obtaining irradiated properties of the applicable graphite grades in the higher temperature range. This test is needed due insufficiency of the current envelope above 750°C and $120x10^{20}$ n/cm$^2$ and is proposed to be conducted at 950°C and at higher fluence levels, corresponding to the PBMR NGNP conditions. This test is again subject to the same assumptions as the previous test, while all other requirements can be taken from test C1.2.12.

### C2.2.3 SSC Test Specification #4: Characterize race track strap and tie rod materials (WEC-TS-CSC-04)

#### C2.2.3.1 Objectives

The objective of this test is to characterize the race track strap and tie rod materials under irradiation conditions in order to capture the irradiation properties such as swelling. This test is however subject to the following assumptions:

Assumptions

- The assumption is that the current and planned unirradiated databases for CFRC Grades 1502YR and 2002YR materials are inadequate for the Race Track Strap and Tie Rod applications for the NGNP.

### C2.2.3.2 Test Conditions

*C2.2.3.2.1 Test Configuration/Set-up*

The following test configuration utilizes information from the NGNP Composites Special Study and provides information regarding the test configuration should irradiated properties be necessary. The test set-up will require comprehensive pre-characterization as well post-irradiation test data on all specimens. Irradiation test data for the specimens up to 1 dpa (carbon) or 1.4x1021n/cm2 (E>0.1 MeV) in increments of 0.5 dpa (carbon) at irradiation temperatures of 600ºC and 800ºC is required.

*C2.2.3.2.2 Test Duration*

Typical test categories include sample preparation, pre-irradiation characterisation, irradiation tests and post-irradiation examinations. Detail test durations depend on the number of test specimens and material type to be tested. Due to the uncertainty of a final design the overall incremental time schedule (C1.1.3) could be regarded as the time necessary to complete these tests.

*C2.2.3.2.3 Proposed Test Location*

A National Laboratory or University could perform the irradiation tests on sample scale together with the post irradiation examinations that is needed. Commercial organizations involved in similar process can also participate in this process.

### C2.2.3.3 Measured Parameters

The following list indicates pre-irradiation and post-irradiation test data that would be required. These parameters should be measured / obtained in accordance with specific standards were applicable or acceptable alternatives if standards are not available.

- Linear (parallel to length of racetrack and length of Tie Rod) shrinkage or swelling and volumetric shrinkage or swelling following irradiation compared to pre-irradiation data.
- Density (CEN ENV 1389 (1994))
- CTE (RT to 800ºC, CEN ENV 1159-1 (1994))
- Flexural Strength ( 3 point, RT, 600ºC, 800ºC ASTM C-1341-00 (2005))
- Interlaminar Shear Strength (RT, ASTM C 1425-05),
- Tensile Strength (RT, 600ºC, 800ºC, ASTM C 1275-00 (2005) and ASTM C 1359-05).

Additional parameters to be measured include the irradiation temperature and neutron fluence. All measurements should be conducted according to test specification guidelines with data requirements as indicated here after. Non irradiated properties to determine include thermal creep as per ASTM C 1337-96(2005)

### C2.2.3.4 Data Requirements

The data requirements of the test measurement parameters should be captured in the test specifications and should as a minimum define the following:

- Method of measurement (according to appropriate standards)
- Accuracy and precision of measurement
- Differential between measured and calculated values

### C2.2.3.5 Test Evaluation Criteria

The extended irradiation tests does not necessarily have a failing criteria, except that irradiation exposures need to be obtained within the specified accuracies and precisions.

### C2.2.3.6 Test Deliverables

The test deliverables include a Test Specification, Test Design Justification and the final Test Report. The Test Specification should typically include the following:

- Method of temperature measurement and associated uncertainties.
- Method of fluence measurement and associated uncertainties.
- Specimen Extraction Plan.
- Test Specimen Preparation Procedures.
- Test Methods and uncertainties associated with each method.
- Size and Geometry of Test Specimens (including control materials).
- Number of Specimens per irradiation test condition (Including control material).
- Identification and traceability of test specimens.
- Storage conditions of irradiated test specimens.

The Test Design Justification should be provided as a confirmation of all applicable procedures, test methods and test conditions which will be employed in fulfillment of the Test Specification requirements. Both an approved Test Specification as well as Test Design Justification is required before commencing with any irradiation tests.

The final deliverable consists of the Test Report and need to be provided upon completion of the irradiation tests. This document shall as a minimum report in the following:

- Pre-irradiation test specimen data, i.e. dimensions, surface finish, etc.
- Any applicable test data gathered prior to the applicable irradiation stage.
- Post-irradiation test data and associated uncertainties.
- Irradiation conditions (target temperature, fluence) for the applicable irradiation stage.
- Irradiation conditions per test specimen for the applicable irradiation stage.

- All applicable test specifications.
- All applicable test procedures and test reports.
- Non-conformances in respect of the specified requirements.

Additional to these documents a quality assurance plan also needs to be provided. This plan should meet the requirements of PBMR, the applicable nuclear authorities as well additional client related requirements.

#### C2.2.3.7 Cost, Schedule, and Risk

The anticipated cost and schedule for these irradiation tests are captured in section C1.1.3 & C1.1.4. Due to the nature of these tests a fallback position is to assume that irradiation effects on these materials properties are not significant and that the DPP design and data could be used as is.

### C2.2.4 SSC Test Specification #5: insulation materials (unirradiated data needed) (WEC-TS-CSC-005)

#### C2.2.4.1 Objectives

The objective of this test is to obtain unirradiated material data for the quartz insulation material that will be used to supplement the baked carbon insulation in the lower reflector based on the NGNP design requirements. This test is subjective to the following assumptions:

Assumptions

- NBC-07 baked carbon insulation will be the primary insulation used in the lower reflector

#### C2.2.4.2 Test Conditions

*C2.2.4.2.1 Test Configuration/Set-up*

Unirradiated test need to be conducted in order to determine the material properties as per Measured Parameters section. These test need to conform to applicable standards and should be similar to the PBMR Materials Datasheet.

*C2.2.4.2.2 Test Duration*

Typical test categories include sample preparation, pre-testing characterisation, materials property tests and post-testing examinations. Detail test durations depend on the number of test specimens and material type to be tested. Due to the uncertainty of a final design the overall incremental time schedule (C1.1.3) could be regarded as the time necessary to complete these tests.

*C2.2.4.2.3 Proposed Test Location*

A National Laboratory or University could perform the tests on sample scale together with the examinations that is needed. Commercial organizations involved in similar process can also participate in this process.

### C2.2.4.3 Measured Parameters

The following is an extract of the test data that would be required and has been taken from a PBMR material datasheet. These parameters should be measured / obtained in accordance with specific standards were applicable or acceptable alternatives if standards are not available. These properties include:

**Table C-3: Selected Physical Properties of Quartz Insulation**

| Property | Units | Orientation | 20°C | 200°C | 400°C | 600°C | 800°C | 1000°C |
|---|---|---|---|---|---|---|---|---|
| Bulk Density | $kg.m^{-3}$ | - | To be Tested | To be Tested | To be Tested | To be Tested | To be Tested | To be Tested |
| Coefficient of Thermal Expansion* (CTE) (20°C – T) | $10^{-6} K^{-1}$ | With grain | To be Tested | To be Tested | | | | |
| | | Against grain | | To be Tested | | | | |
| | | Combined | | To be Tested | | | | |
| Isotropy Ratio | - | - | To be Tested | Not Applicable | | | | |
| Thermal Conductivity | 800°C Bake $W.m^{-1}.K^{-1}$ | With grain | To be Tested | To be Tested | | | | |
| | | Against grain | To be Tested | To be Tested | | | | |
| | | Combined | To be Tested | To be Tested | | | | |
| | 1050°C Bake $W.m^{-1}.K^{-1}$ | With grain | To be Tested | To be Tested | | | | |
| | | Against grain | To be Tested | | | | | |
| | | Combined | To be Tested | | | | | |
| Emissivity | - | - | N/A | To be Tested | | | | |

**Table C-4: Selected Mechanical properties of Quartz Insulation Material**

| Property | Units | Orientation | 20°C |
|---|---|---|---|
| Tensile Strength | MPa | With grain | To be Tested |
| | | Against grain | To be Tested |

| | | | |
|---|---|---|---|
| | | Combined | To be Tested |
| Compressive Strength | MPa | With grain | To be Tested |
| | | Against grain | To be Tested |
| | | Combined | To be Tested |
| Flexural Strength (4-point) | MPa | With grain | To be Tested |
| | | Against grain | To be Tested |
| | | Combined | To be Tested |
| Dynamic Elastic Modulus | GPa | With grain | To be Tested |
| | | Against grain | To be Tested |
| | | Combined | To be Tested |

**Table C-5: Selected Room Temperature Mechanical Properties of Quartz Insulation Material**

| Property | Units | Orientation | 0% | 1% | 3% | 5% | 7% | 10% |
|---|---|---|---|---|---|---|---|---|
| Tensile Strength | MPa | With grain | 17.7 ± 1.2 [1] | 13.4 | 10.5 | 8.2 | 6.4 | 4.4 |
| | MPa | Against grain | 18.0 ± 1.7 [1] | 13.4 | 10.5 | 8.2 | 6.4 | 4.4 |
| Compressive Strength | MPa | With grain | 137.3 ± 6.7 [1] | 103.6 | 88.8 | 76.0 | 65.1 | 51.6 |
| | MPa | Against grain | 139.7±19.2 [1] | 69.7 | 59.7 | 51.1 | 43.8 | 34.7 |

### C2.2.4.4 Data Requirements

The data requirements of the test measurement parameters should be captured in the test specifications and should as a minimum define the following:

- Method of measurement (according to appropriate standards)
- Accuracy and precision of measurement
- Differential between measured and calculated/theoretical values

### C2.2.4.5 Test Evaluation Criteria

The extended irradiation tests does not necessarily have a failing criteria, except that irradiation exposures need to be obtained within the specified accuracies and precisions.

### C2.2.4.6 Test Deliverables

The test deliverables include a Test Specification, Test Design Justification and the final Test Report. The Test Specification should typically include the following:

- Method of temperature measurement and associated uncertainties.
- Specimen Extraction Plan.
- Test Specimen Preparation Procedures.
- Test Methods and uncertainties associated with each method.
- Size and Geometry of Test Specimens (including control materials).
- Identification and traceability of test specimens.

The Test Design Justification should be provided as a confirmation of all applicable procedures, test methods and test conditions which will be employed in fulfillment of the Test Specification requirements. Both an approved Test Specification as well as Test Design Justification is required before commencing with any irradiation tests.

The final deliverable consists of the Test Report and need to be provided upon completion of the irradiation tests. This document shall as a minimum report in the following:

- Pre-test specimen data, i.e. dimensions, surface finish, etc.
- Post-test data and associated uncertainties.
- Testing conditions (target temperature) for the applicable test.
- All applicable test specifications.
- All applicable test procedures and test reports.
- Non-conformances in respect of the specified requirements.

Additional to these documents a quality assurance plan also needs to be provided. This plan should meet the requirements of PBMR, the applicable nuclear authorities as well additional client related requirements.

### C2.2.4.7 Cost, Schedule, and Risk

The anticipated cost and schedule for these irradiation tests are captured in section C1.1.3 & C1.1.4. Due to the nature of these tests a fallback position is to assume that irradiation effects on these materials properties are not significant and that the DPP design and data could be used as is.

# APPENDIX D: TEST REQUIREMENT SPECIFICATION SAMPLE

**(As provided by PBMR)**

# CORE STRUCTURE CERAMICS

# SGL TRS SHEET AN 43: TIE ROD QUALIFICATION TEST - LOWER BLOCK INTERFACE

| | | |
|---|---|---|
| **Document Number** | **:** | **048375** |
| **Revision** | **:** | **3** |
| **Status** | **:** | **Approved** |

**Signatures for approved documents are held on file in the Document Control Centre of PBMR (Pty) Ltd**

# ABSTRACT

This document describes the requirements of test AN 43. The information in this document for the test was extracted from the CSC Test Requirement Specification [4]. This test will form part of an ongoing effort to fulfil and comply with numerous requirements for the CSC.

# CONFIGURATION CONTROL

## Document History

| Rev. | Date | Preparer | ECPs | Changes |
|---|---|---|---|---|
| A | 2006/10/10 | Jaco Lindeboom | None | First Draft |
| 1 | 2006/10/10 | Jaco Lindeboom | None | Updated with comments from review |
| 1A | 2007/05/10 | Jaco Lindeboom | None | The following changes were made:<br>1. Page 17, Table 1, Heading: Test conditions – The initial load was changed from 35kN to 18kN.<br>2. Page 5, Section 1 and Page 17, Section 4: Sections were updated to refer to Test Requirement Specification and not to duplicate information.<br>3. Added: “This length can be modified to accommodate the design of the test setup.” Under the heading: Test Description on page 10.<br>4. Page 10, Table 1, Heading: Test description the symbols β and α were changed around in the sentences where used.<br>5. Page 10, Heading: Test description and Page 15, Table, Heading Test scope: The requirement was changed from using 4 (Four) assemblies to changing the interfacing components for each test.<br>6. Page 6: Updated reference table |
| 2 | 2007/05/15 | Jaco Lindeboom | None | No updates from reviewers. |
| 3 | 2007/05/21 | Jaco Lindeboom | None | Changed document to incorporate the changes mentioned in the document history of REV 1A (Update 1 – 35kN to 18 kN), but not made in document body. |

## Document Approval

| Action | Function | Designate | Signature |
|---|---|---|---|
| Prepared | CSC Design Engineer | Jaco Lindeboom | See signatures on file |
| Reviewed | CSC Design Engineer | Marius Van Wyk | See signatures on file |
| 2nd Reviewer | TQC Engineer | Gert Jansen Van Rensburg | See signatures on file |
| Approved | CSC Design Engineer | Mark Mitchell | See signatures on file |

**Document Retention Time**

This document is a Quality Record and shall be retained in accordance with PRC0012.

# CONTENTS



# FIGURES



# TABLES

## ABBREVIATIONS

This list contains the abbreviations used in this document.

| Abbreviation or Acronym | Definition |
|---|---|
| CFRC | Carbon Fibre Reinforced Composites |
| CSC | Core Structure Ceramics |
| ECP | Engineering Change Proposal |
| GmbH | Gesellschaft mit beschraenkter Haftung (German for Proprietary Limited) |
| ID | Identity |
| ID | Internal Diameter |
| No. | Number |
| PBMR | Pebble Bed Modular Reactor |
| PBMR (Pty) Ltd | Pebble Bed Modular Reactor (Pty) Ltd |
| ROD | Record of Decisions |
| TBD | To be Determined |
| TBV | To be Verified |
| TQC | Testing, Qualification and Commissioning |
| TR | Top Reflector |

# 1. INTRODUCTION

## 1.1 SCOPE

This document describes a test identified by PBMR on parts and materials that will be used in the CSC. The information regarding the requirements for this test formed part of the Test Requirement Specification [4]. The Test Requirements Specification grew into a large document and it became difficult to track any updates or changes to individual test requirements. These requirements were extracted from the Test Requirement Specification [4] to this separate document named the Test Requirement Specification Sheets.

These test requirements identified by PBMR are described for the test. This requirement specification sheet provides inputs to the test specifications, experiment design, design reports and results required for each test.

This document states the test objectives, a general description of the test, the test configuration, the test conditions, a basis layout of the test and the reporting requirements.

For this test the test documentation required is mentioned under the section deliverables in Table 1 in accordance with the TRS [4].

## 1.2 BACKGROUND

During the design phase of the PBMR the CSC Development Specification was constructed [2]. As a means of complying with the requirements PBMR is executing a qualification program.

## 2. REFERENCES

The following documents are referenced within this document.

| | Document Title | Preparer/Author | Document Number | Revision or Date of Issue | Proprietary Classification | Applicable*[1] (Yes/No) |
|---|---|---|---|---|---|---|
| [1] | CSC Qualification Plan | M. Mitchell | 033981 | B | 2 | No |
| [2] | CSC Development Specification | Pauline Prinsloo | 026223 | C | 2 | No |
| [3] | Engineering Contract | PBMR Procurement | CONPBMR001681 | 1 | 1 | No |
| [4] | CSC Test requirement specification | J. Lindeboom | 040926 | 1 | 2 | No |
| [5] | CSC TR Ring 1 Tie Rod PDF drawing | T. Bennie | MR120-015372-1501-IS01 | 3 | 2 | Yes |
| [6] | CSC TR Centre Ring Tie Rod PDF drawing | T. Postma | MR120-016522-1501-IS01 | 3 | 2 | Yes |
| [7] | CS TR Block Layer 1,0 DEG PDF drawing | T. Postma | MR120-025576-1501-IS01 | E | 2 | Yes |
| [8] | CSC TR Insert Assy, Back, 6 DEG PDF drawing | T. Postma | MR120-027659-1502-IS01 | C | 2 | Yes |
| [9] | CS TR Insert 2, Back, 0 DEG PDF drawing | T. Postma | MR120-027650-1501-IS01 | C | 2 | Yes |
| [10] | CS TR INSERT, BACK, 0 DEG PDF drawing | T. Postma | MR120-027658-1501-IS01 | C | 2 | Yes |
| [11] | CSC TR LOCATOR PIN PDF drawing | T. Postma | MR120-025878-1501-IS01 | D | 2 | Yes |
| [12] | CSC TR Block RNG, LAYR1, 22_5DEG PDF drawing | T. Postma | MR120-015282-1501-IS01 | D | 2 | Yes |
| [13] | CSC TR Ring 1 Tie Rod UG drawing | T. Bennie | MR120-015372-1501-IS01 | 3 | 2 | Yes |
| [14] | CSC TR Centre Ring Tie Rod UG drawing | T. Postma | MR120-016522-1501-IS01 | 3 | 2 | Yes |
| [15] | CS TR Block Layer 1,0 DEG UG drawing | T. Postma | MR120-025576-1501-IS01 | E | 2 | Yes |
| [16] | CSC TR Insert Assy, Back, 6 DEG UG drawing | T. Postma | MR120-027659-1502-IS01 | C | 2 | Yes |
| [17] | CS TR Insert 2, Back, 0 DEG UG drawing | T. Postma | MR120-027650-1501-IS01 | C | 2 | Yes |
| [18] | CS TR INSERT, BACK, 0 DEG UG drawing | T. Postma | MR120-027658-1501-IS01 | C | 2 | Yes |
| [19] | CSC TR LOCATOR PIN UG drawing | T. Postma | MR120-025878-1501-IS01 | D | 2 | Yes |
| [20] | CSC TR Block RNG, LAYR1, 22_5DEG UG drawing | T. Postma | MR120-015282-1501-IS01 | D | 2 | Yes |
| [21] | CSC TR Ring 1 Tie Rod UG model | T. Bennie | 015372 | 3 | 2 | Yes |
| [22] | CSC TR Centre Ring Tie Rod UG model | T. Postma | 016522 | 3 | 2 | Yes |
| [23] | CS TR Block Layer 1,0 DEG UG model | T. Postma | 025576 | E | 2 | Yes |

[1] Applicable documents are applicable to the extent specified within this document and thus deemed to form part of this document.

| Document Title | Preparer/Author | Document Number | Revision or Date of Issue | Proprietary Classification | Applicable*[1] (Yes/No) |
|---|---|---|---|---|---|
| [24] CSC TR Insert Assy, Back, 6 DEG UG model | T. Postma | 027659 | C | 2 | Yes |
| [25] CS TR Insert 2, Back, 0 DEG UG model | T. Postma | 027650 | C | 2 | Yes |
| [26] CS TR INSERT, BACK, 0 DEG UG model | T. Postma | 027658 | C | 2 | Yes |
| [27] CSC TR LOCATOR PIN UG model | T. Postma | 025878 | D | 2 | Yes |
| [28] CSC TR Block RNG, LAYR1, 22_5DEG UG model | T. Postma | 015282 | D | 2 | Yes |

# 3. DESCRIPTION OF TEST

## 3.1 GENERAL DESCRIPTION OF TEST

The test is defined by PBMR and will be carried out by SGL Carbon GmbH. PBMR will specify all requirements. These requirements are listed in Table 1.

## 3.2 TEST REQUIREMENTS

The following table contains the requirements for the test to be executed:

**Table 1: Test Requirement Specification Sheet: AN-43**

| **Test Requirement Specification Sheet** | |
|---|---|
| **Test ID**<br>**AN-43** | **Tie Rod Qualification tests - Bottom interface** |
| Test Objectives: | The objectives of this test are to:<br>• determine the maximum tensile load of a standard full size CFRC tie-rod under ideal loading conditions with the authentic bottom interface<br>• determine the maximum tensile load of a standard full size CFRC tie-rod under non-ideal loading conditions with the authentic bottom interface<br>The ideal loading conditions represents the CFRC tie-rod when installed, within the allowed installation tolerances.<br>The non-ideal loading conditions are represented by an angular misalignment in the two vertical planes between the top head and bottom head of the tie-rod. |

<table>
<tr><th colspan="2">Test Requirement Specification Sheet</th></tr>
<tr><td>Test Description:</td><td>The tests will be carried out in air at room temperature.<br><br>The test will be carried out on a full size short (+/-850mm long) CFRC tie rod. This length can be modified to accommodate the design of the test setup.<br><br>Two different bottom interfaces exist namely :<br>• CFRC tie-rod to graphite block, with CFRC plate insert (Ring 1)<br>• CFRC tie rod to graphite block, without CFRC plate insert (Ring 2)<br><br>Both of these interfaces will be tested separately.<br><br>To ensure that the tests provide the desired results both sides of the tie-rod interface should replicate the bottom interface of the tie-rod during the tests or one head of the tie rod should be designed larger in order for failure to occur at the other head of the CFRC tie rod.<br><br>For the ideal loading conditions test the tie-rod must be installed into the testing machine with the correct interfaces as mentioned above. The alignment must be correct within the specified installation tolerances of the tie-rod.<br><br>In this configuration the ultimate tensile load test must be executed. In this test the test specimen must be loaded to failure. The direction of the applied force must be in the direction on the original normal operating conditions.<br><br>In order to perform the non-ideal loading conditions test one side of the test piece should be able to move in the X and Y direction to provide the angles β and α.<br><br>The tie rod must be installed into the testing machine with the correct interfaces as mentioned above. When perfectly aligned a tensile initial-load must be applied.<br><br>Next the angular misalignment of the tie rod must be done by:<br><br>Moving one side of the tie-rod in the X-direction to obtain angle β<br><br>Next moving one side of the tie-rod in the Y-direction to obtain angle α<br><br>This misalignment can also be done in 1 (one) movement in the resultant direction.<br><br>In this configuration the ultimate tensile load test must be executed. In this test the test specimen must be loaded to failure. The direction of the applied force must be in the direction on the original normal operating conditions and not in the direction of the deflected tie rod.<br><br>Measure and record the angles between the tie rods and the interfacing material after installation in the X-Y plane.<br><br>The graphite blocks, parts and all CFRC parts shall be changed for each test in order to have a repeatable test result.</td></tr>
</table>

**Test Requirement Specification Sheet**

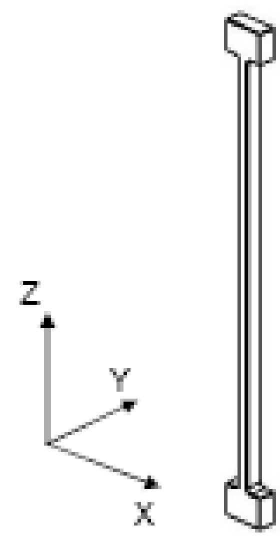


**Figure 1: Reference Axis for CFRC Tie-Rod**

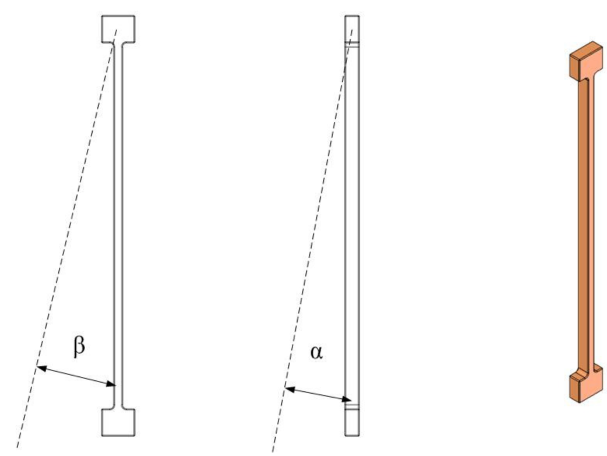


**Figure 2: Angles and Displacements to Obtain Non-Ideal Loading Conditions**

**Test Requirement Specification Sheet**

- **CFRC tie-rod to graphite block, with CFRC plate insert (Ring 1)**

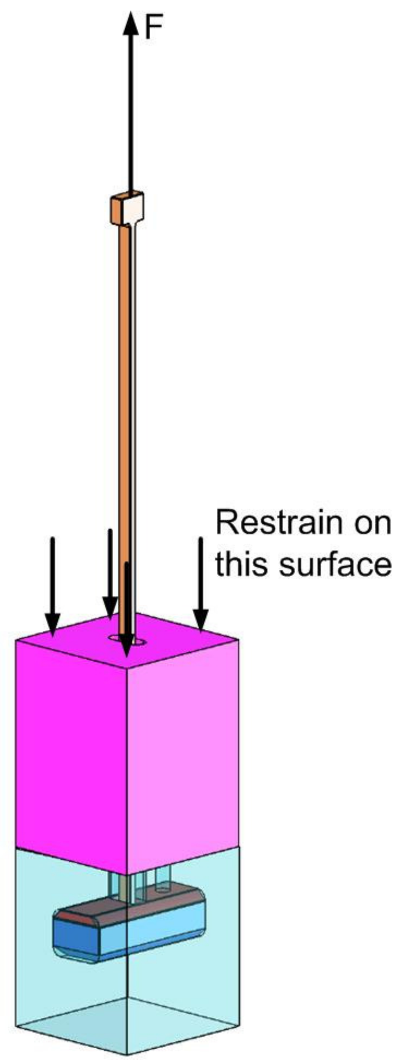


**Figure 3: CFRC Tie-Rod to Graphite Block, with CFRC Plate Insert**

**Test Requirement Specification Sheet**

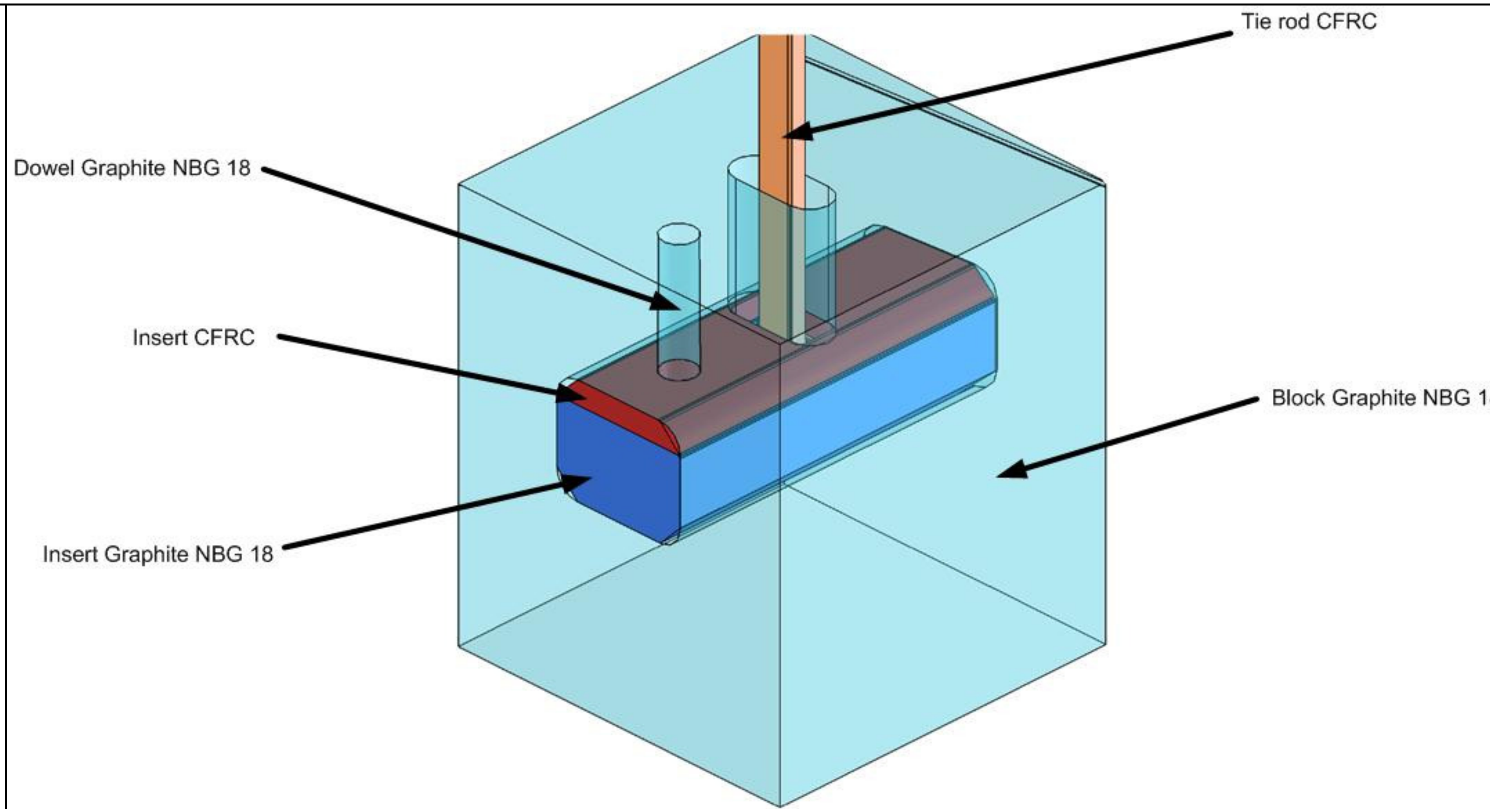


**Figure 4: CFRC Tie-Rod to Graphite Block, with CFRC Plate Insert**

**Test Requirement Specification Sheet**

- **CFRC tie rod to graphite block, without CFRC plate insert (Ring 2)**

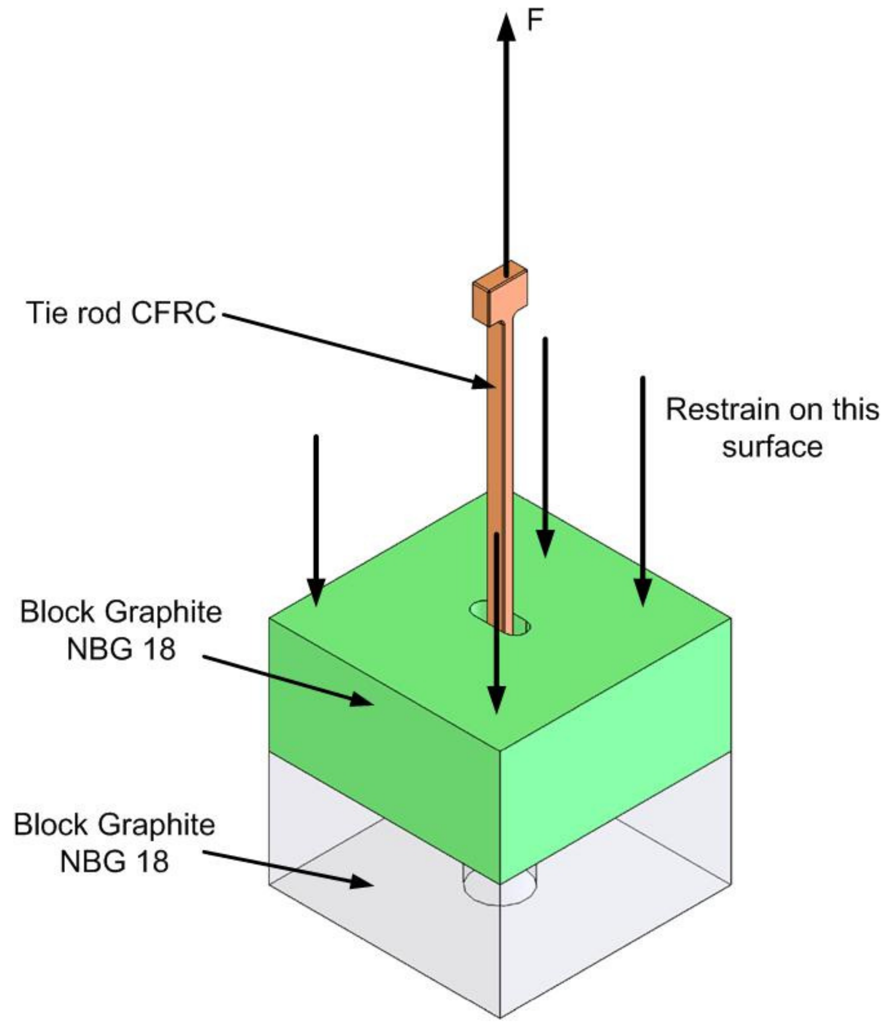


**Figure 5: CFRC Tie Rod to Graphite Block, without CFRC Plate Insert**

**Test Requirement Specification Sheet**

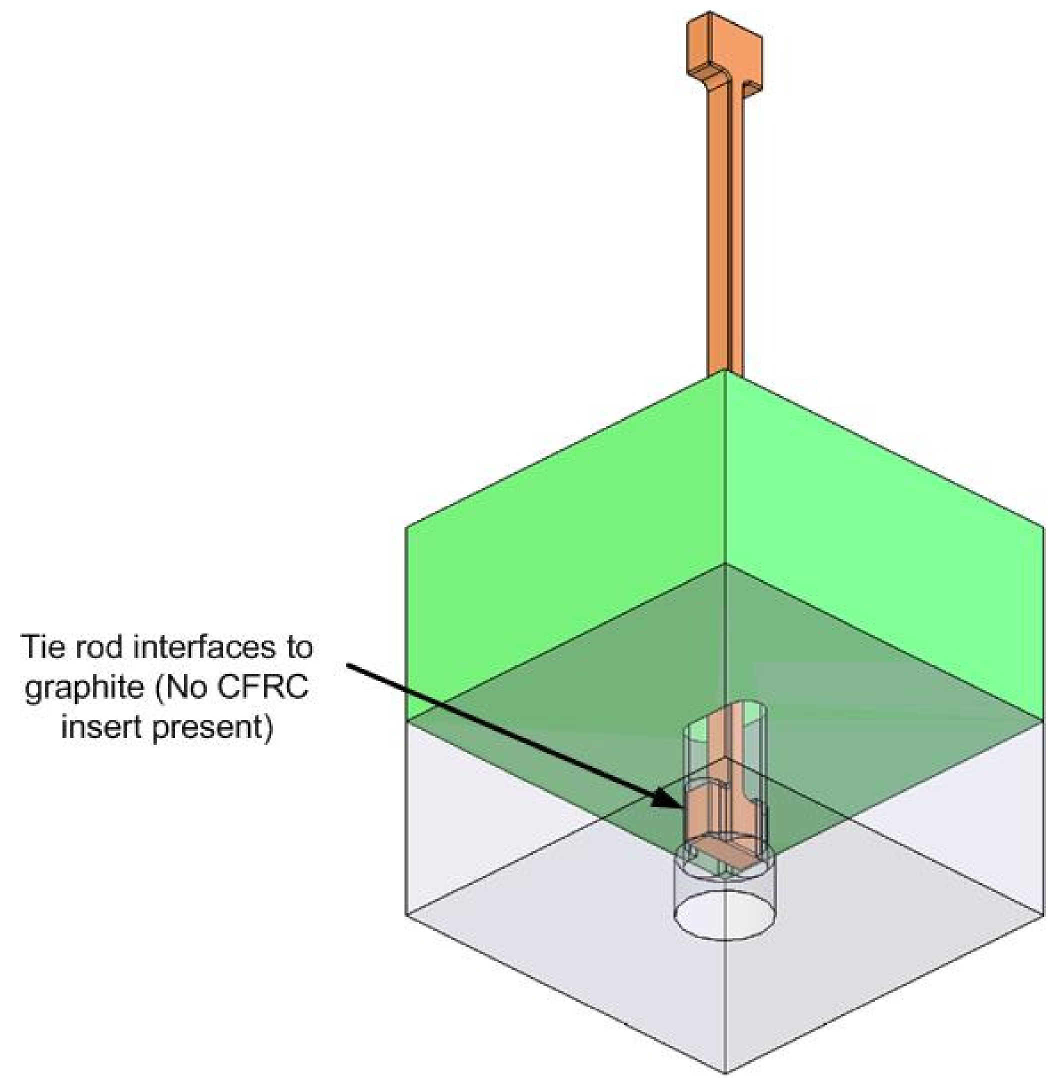


**Figure 6: CFRC Tie Rod to Graphite Block, without CFRC Plate Insert**

| **Test Requirement Specification Sheet** | |
|---|---|
| Test Scope: | There are 2 different test configurations and for each the amount of tested are:<br>• for ideal loading conditions at least 6 specimens<br>• for non-ideal loading conditions at least 6 specimens<br>This means that a total of at least 24 specimens shall be tested.<br>The graphite block, parts and CFRC parts that form part of the direct interface to the tie rod must be changed for each test, but the block that doesn't interface with the tie rod directly doesn't have to be changed each time. |
| Test Limitations: | None |
| **Test Configuration:** | |
| Test Item: | **Test Items as Per Drawings** |
| Analysis Requirements: | TBD SGL |
| Test Equipment Requirements: | TBD SGL |
| Test Parameters: | The test parameters are as follows:<br>• Tie-rod tensile force<br>• Tie-rod elongation (ΔHead distance sufficient)<br>• Misalignment angles:<br>  • α or distance ΔY<br>  • β or distance ΔX<br>• Atmosphere<br>• Pressure |
| Instrumentation Requirements: | TBD SGL |
| Test Control Systems and Data Acquisition: | TBD SGL |
| Test Facilities and Interfaces: | TBD SGL |
| Test Personnel | SGL Carbon GmbH to provide. |

| **Test Requirement Specification Sheet** | |
|---|---|
| **Test Conditions:** | The tests will be performed in the following conditions:<br>• Initial-load (tensile force) to simulate normal operation approximately 18 kN<br>• Misalignment angles:<br>  • $\alpha < 0.5°$ between the top and bottom of the tie-rod in the Y-direction<br>  • $\beta < 0.5°$ between the top and bottom of the tie-rod in the X-direction<br>• Atmosphere and Temperature will be air at room temperature<br>• Ultimate tensile load under ideal conditions will be < 100 kN (TBD) approximately<br>• Ultimate tensile load under non-ideal conditions will be < 100 kN (TBD) approximately |
| **Test Set-up/Layout:** | When applying the misalignment angles α and β the movement cannot be done in the vertical plane only. The head moved must be allowed to move in the Z direction in order not to increase the initial-load due to the movement. |
| | |
| **Test Deliverables:** | Test specification<br>Test design report<br>Test report |
| **Comments:** | |

# 4. TEST MANAGEMENT

## 4.1 TEST RESPONSIBILITIES

Test Responsibilities as per TRS [4].

## 4.2 QUALITY ASSURANCE

All Quality Assurance related matters are as per the document: TRS [4], except for required PBMR interaction that differs for this test as stated in 4.2.1.

### 4.2.1 Required PBMR Interaction

PBMR interaction must occur in according to the hold and witness points indicated in Table 2. The actions listed are from TRS [4].

**Table 2: PBMR Interaction Required**

| Action | PBMR Intervention | Applicable |
|---|---|---|
| Requirements Definition | None | Yes |
| Experiment Design | None | N/A |
| Test Readiness Review 1 | Hold point | Yes |
| Experiment Preparation | None | N/A |
| Test Readiness Review 2 | Hold point | Yes |
| Experiment Execution | Witness point | Yes |
| Test Execution and Data Review | Hold point | Yes |

## 4.3 REQUIRED TEST DOCUMENTATION

Required Test Documentation as per TRS [4] and under heading: “Test Deliverables” in Table 1.

NGNP-CTF MTECH-TDRM-013 December 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 13: Reserve Shutdown System

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
| Author | Name:<br>Company: | D.J. Viljoen<br>M-Tech Industrial (Pty) Ltd | December 3, 2008 |
| Reviewer | Name:<br>Company: | Steven Pieterse<br>Pebble Bed Modular Reactor (Pty) Ltd | December 3, 2008 |
| Reviewer | Name:<br>Company: | Justin Mann<br>Pebble Bed Modular Reactor (Pty) Ltd | December 3, 2008 |
| Approval | Name:<br>Company: | Jan van Ravenswaay<br>M-Tech Industrial (Pty) Ltd | December 3, 2008 |

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| Name and Company | Date |
|---|---|
| D.J. Viljoen (M-Tech Industrial) | October 27, 2008 |
| Steven Pieterse (PBMR) | October 27, 2008 |
| Pieter Coetzer (PBMR) | October 27, 2008 |
| Renée Greyvenstein (PBMR) | October 27, 2008 |

## BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | | |

REVISION HISTORY

## RECORD OF CHANGES

| Revision No. | Revision Made by | Description | Date |
|---|---|---|---|
| A | D.J. Viljoen | Comments Review | September 12, 2008 |
| B | D.J. Viljoen | Formal Review | October 6, 2008 |
| C | D.J. Viljoen | Changes to TDRM roadmap | October 27, 2008 |
| 0 | D.J. Viljoen | Document for Approval | October 27, 2008 |
| 0A | D.J. Viljoen | Incorporating BEA comments | December 2, 2008 |
| 1 | D.J. Viljoen | Document for release to WEC | December 3, 2008 |

## DOCUMENT TRACEABILITY

| Created to Support the Following Document(s) | Document Number | Revision |
|---|---|---|
| N/A | | |

## TABLE OF CONTENTS

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## LIST OF FIGURES

# ACRONYMS

| Acronym | Definition |
|---|---|
| A | Ampere |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| $B_4C$ | Boron Carbide |
| BOP | Balance of Plant |
| CB | Core Barrel |
| CTF | Component Test Facility |
| DBA | Design Bases Accident |
| DDN | Design Data Need |
| DPP | Demonstration Power Plant |
| FHSS | Fuel Handling and Storage System |
| FY | Fiscal Year |
| HPS | Hydrogen Production System |
| HTF | Helium Test Facility |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| NGNP | Next Generation Nuclear Plant |
| NHSS | Nuclear Heat Supply System |
| PBMR | Pebble Bed Modular Reactor |
| PCS | Power Conversion System |
| PSU | Power Supply Unit |
| QCP | Quality Control Programme |
| RPV | Reactor Pressure Vessel |
| RSS | Reserve Shutdown System |
| SAS | Small Absorber Spheres |
| SCADA | Supervisory Control and Data Acquisition |
| TRL | Technology Readiness Level |
| V | Volt |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# SUMMARY AND CONCLUSIONS

The Reserve Shutdown System (RSS) has been identified as a critical system in the development of the Next Generation Nuclear Plant (NGNP). The RSS forms part of the Reactivity Control and Shutdown System and is a totally diverse reactor shutdown system. The RSS is used to keep the reactor subcritical and below an average core temperature of at least 100°C during shutdown. The NGNP WEC-team envisages utilizing a RSS similar to that of the Pebble Bed Modular Reactor (PBMR) Demonstration Power Plant (DPP).

The RSS development for the PBMR DPP is currently in its basic design phase, with a number of development tests being performed, resulting in a Technology Readiness Level (TRL) rating of 6. A number of development and qualification tests will be performed on the Helium Test Facility (HTF) in South Africa before the RSS will be commissioned in the DPP. Upon the completion of these tests, the DPP RSS will have a TRL status of 7, where after the completion of DPP tests will advance the DPP RSS TRL status to an 8. If the NGNP Requirements are enveloped by the DPP, these development and qualification tests will be sufficient to advance the NGNP RSS to a TRL of 8. If the NGNP requirements are not enveloped by the DPP, then the RSS will be re-qualified in the HTF to progress the NGNP RSS to TRL 7 in which case it will obtain TRL 8 status in the NGNP itself. The need for potential further qualification can however only be defined once more analyses have been performed to determine what the exact requirements would be for application in the NGNP.

It is not believed that any additional testing would be required in the NGNP Component Test Facility (CTF) since additional testing is likely to take place at the existing PBMR HTF facility.

# 13 RESERVE SHUTDOWN SYSTEM (RSS)

## 13.1 RSS Description / Function, Components and Operating Requirements

### 13.1.1 RSS Description

The Reserve Shutdown System (RSS) is a totally diverse reactor shutdown system. It consists of eight identical units that can insert Small Absorber Spheres (SAS) into the eight borings of the centre reflector of the Core. SAS are typically inserted to shut the reactor down to 'cold' conditions for maintenance operations. When inserted, the RSS by itself keeps the reactor subcritical to an average core temperature of 100 °C or less.

The SAS are comprised of 10 mm diameter graphite spheres that contain 10% (weight) natural $B_4C$. The $^{10}B$ isotope in the natural $B_4C$ acts as the neutron absorber.

When shutdown is required, the valves of the SAS storage units are opened allowing the SAS to flow under gravity into the centre reflector borings.

The RSS interfaces with both the Reactor Pressure Vessel (RPV) and Core Barrel (CB) and operates under the same pressure and temperature as the reactor. The SAS are extracted from the centre reflector borings (all eight channels are removed simultaneously) and pneumatically transported back via the sphere return pipe to the feeder bin at the top of the reactor. The feeder bin distributes the SAS to each of the eight individual SAS storage containers. Gas flow from the Fuel Handling and Storage System (FHSS) blower fluidizes and moves the SAS. The transportation gas is returned to the blower via the gas extraction line after the SAS have been separated out from the conveying gas stream. During SAS transport, the FHSS does not transport fuel and is isolated from the reactor. Pneumatic SAS transportation can only be done at gas temperatures amenable to the valves and other components wetted by gas flow [13-1].

A schematic layout of the RSS is shown in Figure 13-1.

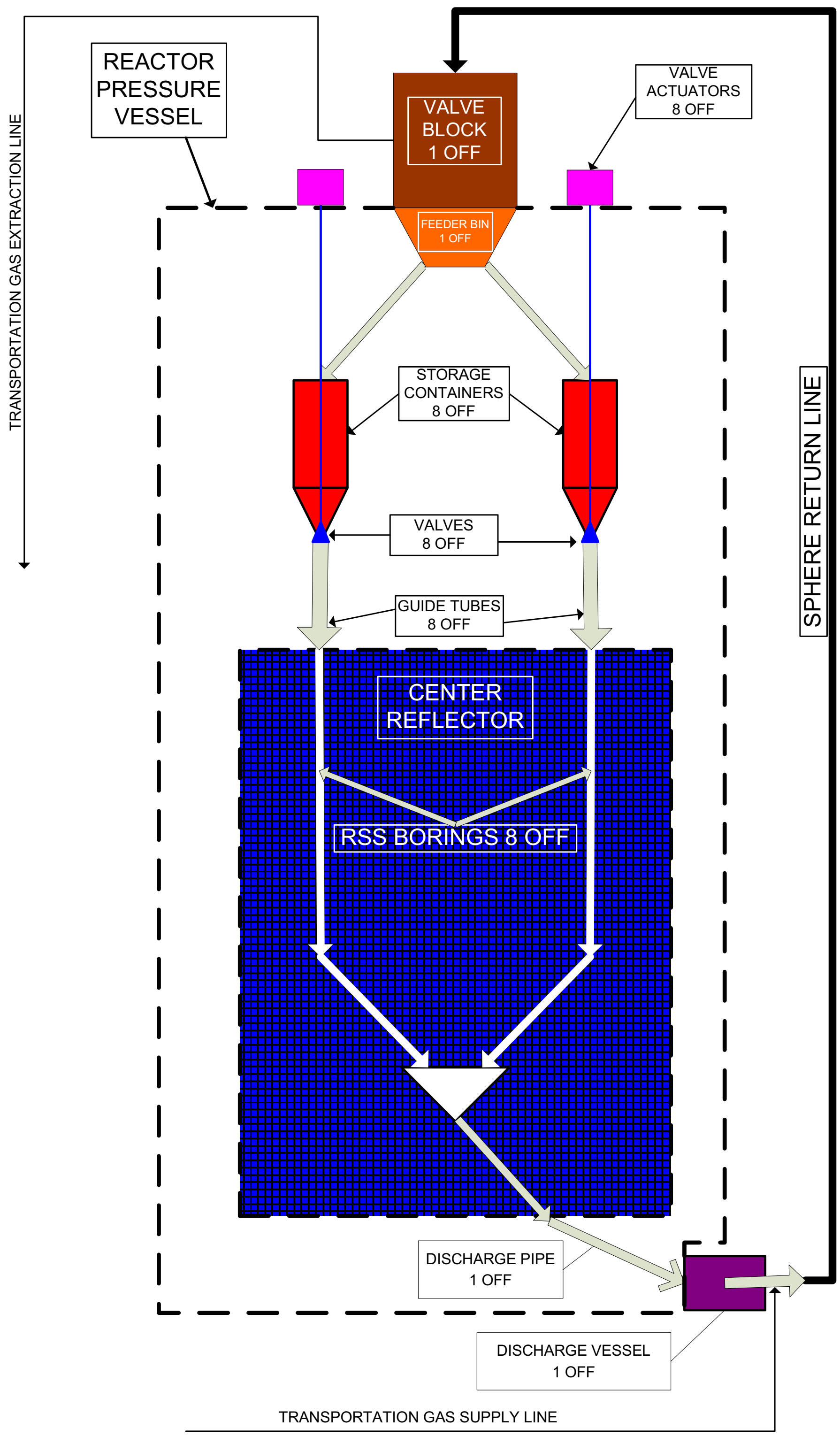


**Figure 13-1: Reserve Shutdown System Schematic Layout.**

### 13.1.2 Helium Test Facility (HTF)

The Helium Test Facility (HTF) provides the capability to test components and sub assemblies in a high-temperature and high-pressure helium environment that is similar to the operating conditions expected for the PBMR DPP. The HTF was mandated in part to support the design, development, functional and integrated performance testing of the RSS up to delivery of the RSS to the DPP.

One full scale RSS unit will be accommodated in the HTF in the form of the RSS test set-up. The RSS test set-up represents one full-scale RSS unit of the 8 units comprising the complete RSS of the PBMR reactor unit. The aim of the HTF main loop for the RSS test set-up is to simulate the dimensions, environmental and certain postulated operational conditions of the RSS inside the PBMR reactor [13-3]. The test set-up will simulate the steady state environment of the PBMR RSS during normal, abnormal and shutdown conditions.

Figure 13-2 shows a photo of a section of the HTF during construction. Figure 13-3 shows part of the RSS test setup during installation.

**Figure 13-2: The HTF (Left) and its Main Loop (Right)**

**Figure 13-3: Part of the RSS during installation.**

### 13.1.3 Functions

The RSS performs the following functions:

**Maintain RPV Pressure Boundary**

- Certain RSS components mount onto the RPV and penetrate the RPV therefore forming part of the Helium Pressure Boundary. As a result one of the main functions of the RSS is to maintain the Helium Pressure Boundary of the RPV.

**Perform Volume Separation**

- The RSS is linked to both the RPV upper volume as well as the Core volume. One of the functions of the RSS is to provide separation between the upper RPV volume and the Core volume to prevent cooling gas inside the RPV upper volume from entering into the Core.

**Load SAS**

- The RSS must make provision to replenish SAS that could potentially be damaged during the operating life of the plant.

**Store SAS**

- SAS must be stored inside the RSS Storage Containers in the RPV upper volume above the reactor centre reflector in a "ready to insert" state during plant operation.

**Insert SAS**

- Insert SAS into the centre reflector borings (for shutdown) under gravity when electrical power supply to the RSS Valve Actuators is removed.

**Confirm SAS Insertion**

- Provide a means of indicating that the SAS has been released from the SAS Storage Containers and that the Storage Container Valves are open.

**Keep SAS Inserted**

- Ensure that SAS are contained within the centre reflector borings, SAS Discharge Pipe and Sphere Return Pipe.

**Absorb neutrons**

- The main function of the RSS is to shut down the reactor through neutron absorption inside the reactor. The SAS contain $B_4C$ to absorb the neutrons.

**Check SAS Availability for Insertion**

- Provision must be made to verify the capability to insert SAS.

**Remove SAS**

- Extract SAS from the centre reflector borings and pneumatically convey it back the feeder bin at the top of the reactor.

**Contain SAS**

- SAS must be contained within the system boundary during and after removal.

**Confirm SAS Removal**

- Provide a means of indicating that the SAS has been removed from the centre reflector borings and conveyed back to the SAS Storage Containers.

**Unload SAS**

- Provide a means of unloading SAS into a place from where it can be moved into storage.

**Guide SAS**

- Provide a positive guide to transfer SAS between the RPV (top) and Core Barrel Top Plate, between the Core Barrel Top Plate and Core Structures Ceramics, and between the Core Barrel and RPV (bottom) respectively.

### 13.1.4 Interfaces

The RSS interfaces with the following systems or components:

- Module Decontamination System
- Reactor Pressure Vessel
- Core Barrel Assembly
- Core Structures Ceramics
- Auxiliary Electrical Power System
- Equipment Handling System

- Reactor Building Structure
- Helium Leak Detection and Monitoring System
- Waste Handling System
- Automation System (AS)
- Heating, Ventilation and Air Conditioning (HVAC)
- In-Core Delivery System
- Fuel Handling and Storage System
- Compressed Air System

### 13.1.5 NGNP Operating Requirements

The DPP reactor operates at a power level of 400MWt with the core inlet and outlet temperatures at 500˚C and 900˚C respectively. This differs from the proposed NGNP core inlet and outlet temperatures of 350˚C and 950˚C respectively and a reactor power level of 500MWt. These operating conditions should not have a significant influence on the RSS under normal operation. This may however lead to higher SAS temperatures during accident conditions, which in turn would require additional qualification tests for application in the NGNP. The balance of the RSS system design should however remain unchanged for the NGNP.

## 13.2 Technology/Design Selection Status

The use of the RSS on the NGNP could demand additional qualification in some components of the RSS, as the RSS environment i.e. centre reflector boring could potentially be at a higher temperature and flux level during certain conditions.

The component that will mainly require possible further qualification is the SAS. Currently this component is made from graphite containing $B_4C$ for neutron absorption. No alternative technologies will be considered at this point in time though.

### 13.1.6 Candidate Technologies – RSS

N/A

### 13.1.7 Decision Discriminators

N/A

### 13.1.8 Reference Design

The PBMR RSS will serve as the reference design for the NGNP.

### 13.1.9 Alternative for Further Evaluation

Not Applicable.

### 13.1.10 Down Selection Task

Not applicable.

## 13.3 TRL Status

The DPP RSS is currently at a TRL 6 based on the fact that operating experience exists for similar shutdown systems in other gas-cooled, graphite moderated reactor applications, in particular Fort Saint Vrain and the Japanese HTTR as well as results from the German HTR-Modul qualification programme. The DPP RSS will reach a TRL of 8 when HTF development and qualification tests as well as DPP testing have been completed.

Due to the NGNP's different operating envelope, additional validation for the SAS might be required as well as testing in an upgraded / revised HTF to bring the NGNP RSS from a possible TRL of 6 to a TRL of 7. The NGNP will then receive the RSS at a TRL of 7 and will be advanced to a TRL 8 during commissioning in the NGNP.

The TRL rating sheet for the RSS is shown in Appendix A.

## 13.4 Technology Development Road Map Summary

### 13.1.11 Overview

The RSS technology development road map shows the maturation tasks necessary to advance the RSS from its current TRL status to a TRL status of 8. The road map is divided into a DPP and a NGNP section. The roadmap shows that further SAS validation may be required for NGNP application due to the environmental differences that exist between the DPP and NGNP. During this maturation process, experience from the DPP (then already at a TRL 8) will be fed into the NGNP RSS maturation tasks to help advance the NGNP RSS from its current TRL 6 to a TRL of 8. An already developed technology for the RSS will be used for the NGNP and there will thus be no down selection in terms of potential new technologies but rather an evaluation of the suitability of the current technology for application in the NGNP. The technology development road map is shown in Appendix B.

## 13.5 Technology Maturation Plan Summary (Current TRL to TRL 8)

The DPP RSS is currently at a TRL of 6 and will achieve a TRL of 8 when HTF development and qualification tests as well as testing in the DPP have been completed. The qualification of the full-scale DPP RSS is achieved against a technology maturation plan that includes design, analysis, testing, inspection or a combination hereof.

In order to achieve qualification, the following different functional requirements have been identified for the RSS requiring verification. These functional requirements are as follows [13-4]:

- Maintain RPV pressure boundary
- Perform volume separation
- Store SAS
- Insert SAS
- Confirm SAS insertion
- Check SAS availability for insertion
- Remove SAS
- Confirm SAS removal
- Load SAS
- Unload SAS
- Keep SAS inserted
- Guide SAS
- Absorb neutrons
- Contain Helium

The qualification activities can be classified as one of the following, depending on the requirements of the specific function:

- Manufacturing
- Functional assessment
- Seismic assessment
- Environmental assessment

It is foreseen that certain components of the NGNP RSS will operate at higher temperatures and flux than in the DPP i.e. SAS and as a result additional qualification may be required for the SAS. The following tasks will aid in determining the extent of additional qualification required for the SAS for application in the NGNP:

- Design calculations to evaluate the operational environment of the RSS in the NGNP for Normal Operation, AOOs and DBA

Qualification of the DPP RSS will be achieved by means of testing, design or analysis or a combination of these actions. To achieve this, procedures and facilities such as the HTF are developed. Successful completion and demonstration of the maturation tasks in the HTF as well as the DPP will take the DPP RSS to a TRL of 8.

## 13.6 Inputs to CTF

It is not foreseen that any additional testing will be conducted in the CTF to mature the RSS technology to a TRL suitable for use in the NGNP. Should additional qualification of the SAS be required, it is likely that this will be done in the HTF.

## 13.7 References

[13-1] PBMR Technical Description, Doc no.016956 Rev 5

[13-2] NGNP CTF Feasibility and Recommendations

[13-3] System Operational Description, Doc no. HTF-000000-225

[13-4] Qualification Life Cycle Strategy, Doc no. 066776 Rev A

[13-5] SAS Dosing Test, Doc no. PEL000180

# APPENDIX A: TRL RATING SHEETS

**Table A-1: TRL Rating Sheets for the RSS**

**TRL Rating Sheet**

Vendor Name: WEC | Document Number: 007 | Revision: 0

☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology

Title: Reserve Shutdown System (RSS)

Description:

Reserve Shutdown System consists of the Small Absorber Spheres and their associated storage, delivery and recovery equipment; part of the Reactor Unit System.

Area(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: N/A | Parent: N/A | WBS: N/A |
|---|---|---|

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Component or system breadboard in relevant environment | Similar SSC in relevant environment in another application | Pilot/engineering scale demonstration in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating:

Operating experience exists for similar shutdown systems in other gas-cooled, graphite moderated reactor applications, in particular Fort Saint Vrain and the Japanese HTTR as well as results from the German HTR-Modul qualification programme.

The DPP RSS can be at a TRL-7 when the present HTF test program provides demonstration and a TRL-8 when DPP commissioning is complete.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost ($) |
|---|---|---|
| • Functional/Performance testing of the RSS in the HTF<br>o SAS Valve actuation<br>o Insertion & transportation at 9Mpa, 700°C<br>o Hot drop test (Pre-heated SAS at 900°C<br>o SAS thermal induced lock-up test in discharge pipe<br>o Etc. | FY 2009 – FY 2012 | Refer to Section C1.1.4 |

DDN(s) supported: Nil

SME Making Determination: S. Pieterse

| Date: September 2008 | Originating Organization: N/A |
|---|---|

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

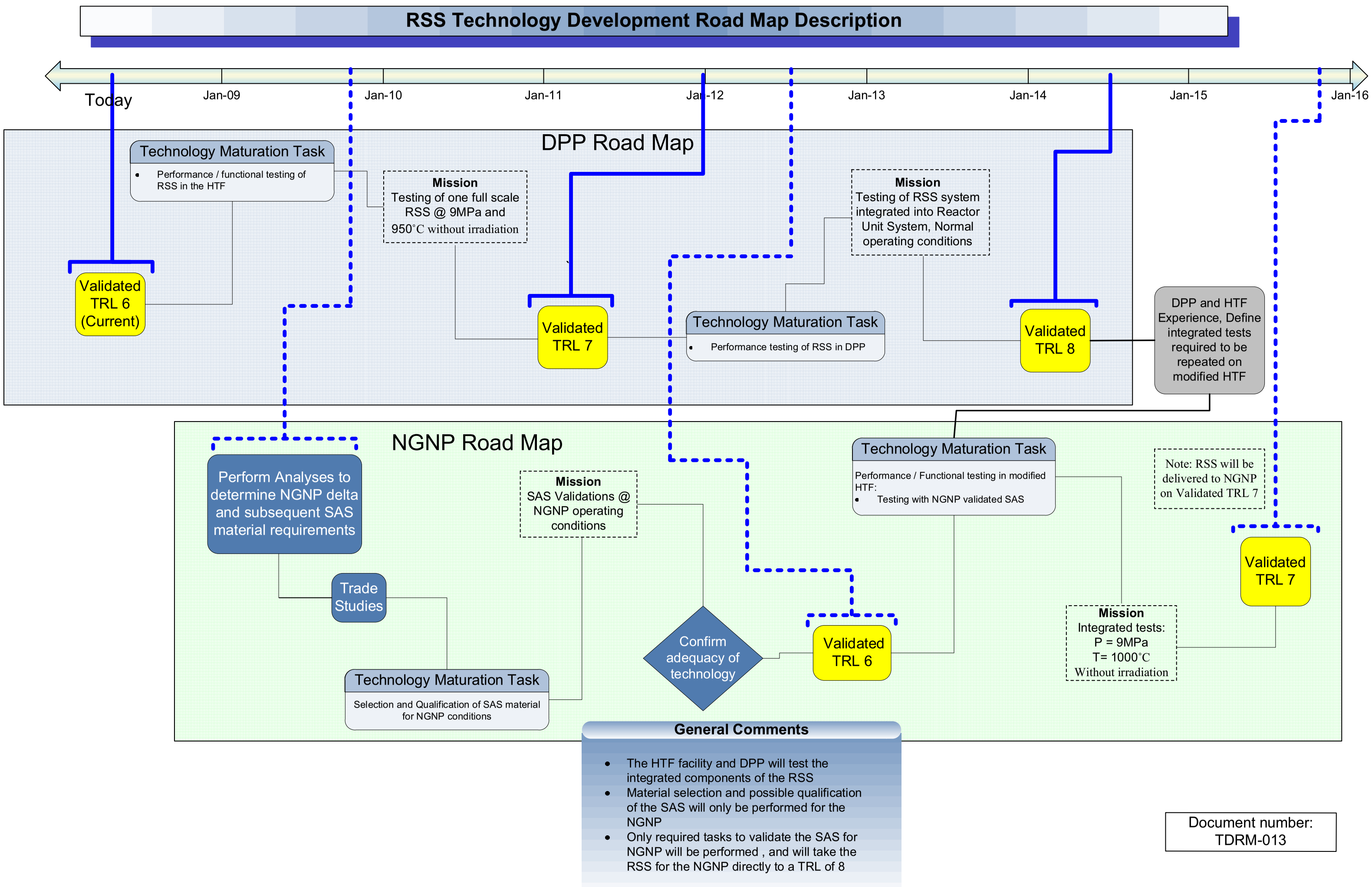


**Figure B-1: Technology Development Road Map for the RSS**

# APPENDIX C: TECHNOLOGY MATURATION PLAN

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**Section** **Title** **Page**

# C13 TECHNOLOGY MATURATION PLAN FOR RSS (CURRENT TRL TO TRL 8)

## C13.1 TECHNOLOGY MATURATION PLAN SUMMARY (CURRENT TRL TO TRL 8)

### C13.1.1 Objectives

The objective of the technology maturation plan is to mature the RSS technology from its current TRL to a TRL of 8 in order to qualify the technology ready for use in the DPP reactor.

### C13.1.2 Scope

The qualification of the full-scale RSS involves a maturation process which includes testing, design and analysis. These maturation tasks are summarized as follows:

- Testing the RSS in its relevant operating envelope, as provided in the HTF, will verify that each component of the RSS subsystem performs within its design specifications.
- Design is used to qualify the RSS technology. Relevant design codes such as ASME III NB for pressure boundary components, ASME III NG for internals, ASME III NF for pipe supports and EJEMA 8 for bellows are used for this purpose.
- Analysis of the RSS and its subsystems is also used to qualify the RSS. This is done using relevant analysis procedures, methods and validated software.

As an example, **Table C-1** lists some of the maturation tasks required for each of the functional requirements (shown in bold) and also lists the maturation methods and maturation actions to mature the DPP RSS to a TRL of 8 [13-4].

**Table C-1: Example of Maturation Tasks to mature the RSS to a TRL of 8.**

| Maturation task description | Maturation method | Maturation action |
|---|---|---|
| **Store SAS** | | |
| Containers seismic analysis | Analysis | Seismic |
| **Insert SAS** | | |
| Valve weld test | Test | Environmental |
| **Test SAS insertion** | | |
| Open and close valve actuator | Test | Functional |
| **Remove SAS** | | |
| Discharge pipe structural integrity | Test | Environmental |
| **Keep SAS inserted** | | |
| Seismic analysis | Analysis | Seismic |
| **Absorb neutrons** | | |
| Neutron analysis | Analysis | Functional |
| **Maintain RPV pressure boundary** | | |
| Leak sensitivity analysis | Analysis | Functional |
| **Support storage container** | | |
| Supplier QCP (ASME III NG) | Design | Manufacture |

### C13.1.3 Anticipated Schedule

The testing is expected to last at least three years which will be followed by continuous lifecycle testing (availability, reliability, etc.).

### C13.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

## C13.2 TEST SPECIFICATIONS

### C13.2.1 Typical RSS Test Specification

A typical test specification [13-5] used to mature the RSS technology to a TRL of 7 is given below:

#### C13.2.1.1 Objectives

There were two main objectives with this test, namely:

- SAS sensing: investigate the SAS detection capability of the level probes.
- SAS dosing (insertion): to determine the dosing time of the RSS system by investigating and recording the status of the level probes for predetermined and repeatable durations of SAS dosing (insertion).

SAS transportation was done only to move the SAS back to the feeder bin and not to characterize transportation.

#### C13.2.1.2 Test Conditions

SAS dosing was done by inserting a dosing time value, in seconds, into the Supervisory Control and Data Acquisition (SCADA) module and then executing that. This execution then resulted in the SCADA opening the SAS valve and then closing it again after the set time value has been reached. This was done for dosing times ranging from 5 seconds to 14 seconds. It was intended that 5 repetitions per dosing time should be done to ensure repeatability of the results.

A full SAS load (feeder bin filled to 100 mm from transport line inlet) was used to do this test.

The test matrix (Table C-2:) lists all the test runs that were required by the Test Specification. The test numbers that were used are an extension of the overall test number. The “-001”, “-002” up to “-010” correspond to a specific test condition while the “-01” up to “-05” at the end denotes the repetitions at these test conditions.

**Table C-2: Test Matrix.**

| Test run number | Pressure | Temperature | Helium Flow | SAS dosing duration |
|---|---|---|---|---|
| | MPa | °C | kg/s | seconds (s) |
| HTF-TST000035-001-01 to 05 | 1 | ambient | only to transport SAS | 5 |
| HTF-TST000035-002-01 to 05 | 1 | ambient | only to transport SAS | 6 |
| HTF-TST000035-003-01 to 05 | 1 | ambient | only to transport SAS | 7 |
| HTF-TST000035-004-01 to 05 | 1 | ambient | only to transport SAS | 8 |
| HTF-TST000035-005-01 to 05 | 1 | ambient | only to transport SAS | 9 |
| HTF-TST000035-006-01 to 05 | 1 | ambient | only to transport SAS | 10 |
| HTF-TST000035-007-01 to 05 | 1 | ambient | only to transport SAS | 11 |
| HTF-TST000035-008-01 to 05 | 1 | ambient | only to transport SAS | 12 |
| HTF-TST000035-009-01 to 05 | 1 | ambient | only to transport SAS | 13 |
| HTF-TST000035-010-01 to 05 | 1 | ambient | only to transport SAS | 14 |

### C13.2.1.3 Measured Parameters

During the test runs the instruments listed in Table C-3 were logged on the data historian.

**Table C-3: List of Instruments used for Data Capturing.**

| Instrument No. | Position/Description | Units | Range | Class | Accuracy | Samples/s |
|---|---|---|---|---|---|---|
| Z ALGC20 CL001 | Feeder Bin Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CL008 | Feeder Bin Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CL002 | Storage Container Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CL003 | Storage Container Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CL004 | Storage Container Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CL005 | Discharge Vessel Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CL006 | Discharge Vessel Level | ohm | 0 - 1000 | C | N/A | 1 |
| Z ALGC20 CE101 | Storage Container Valve PSU Voltage | V | 0 - 200 | C | N/A | 1 |
| Z ALGC20 CE202 | Storage Container Valve PSU Current | A | 0 – 2.5 | C | N/A | 1 |
| Z ALGC20 CF001.PV | Sphere Transport Supply Line Flow rate | nm3/h | 0 - 2100 | C | N/A | 1 |

#### C13.2.1.4 Test Deliverables

No data analysis was requested. The data was only packaged and presented in graphed form as requested in the Test Specification.

NGNP-CTF MTECH-TDRM-014 November 2008
Revision 0

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 14: Reactivity Control System

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
| Author | Name: | André van der Walt | November 18, 2008 |
| | Company: | M-Tech Industrial | |
| Reviewer | Name: | Steven Pieterse | November 20, 2008 |
| | Company: | Pebble Bed Modular Reactor | |
| Reviewer | Name: | Pieter Coetzer | November 20, 2008 |
| | Company: | Pebble Bed Modular Reactor | |
| Approval | Name: | Jan van Ravenswaay | November 20, 2008 |
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| Renée Greyvenstein – PBMR (Pty) Ltd. | September 10, 2008 |
| Roger Young – PBMR (Pty) Ltd. | September 10, 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | | |

**REVISION HISTORY**

# RECORD OF CHANGES

| Revision No. | Revision Made by | Description | Date |
|---|---|---|---|
| A | André van der Walt | Comments Review | September 12, 2008 |
| B | André van der Walt | Formal Review | September 23, 2008 |
| C | André van der Walt | Pending incorporation of final comment | October 07, 2008 |
| D | André van der Walt | Final comments review | October 29, 2008 |
| 0 | André van der Walt | Document for release to WEC | October 30, 2008 |

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| Created to Support the Following Document(s) | Document Number | Revision |
|---|---|---|
| NGNP and Hydrogen Production Pre-conceptual Design Report | NGNP-01-RPT-001 | 0 |

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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| | |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| | |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |

| | |
|---|---|
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

## SUMMARY AND CONCLUSIONS

The Reactivity Control System (RCS) has been identified as a critical system in the development of the Next Generation Nuclear Plant (NGNP). The RCS forms part of the Reactivity Control and Shutdown System, and serves the purpose of controlling the reactivity in the core, and shutting the reactor down quickly. The NGNP WEC-team envisages to utilise a RCS similar to that of the PBMR PBMR DPP.

Operating experience exists on reactivity control systems similar to that of the RCS on other Gas Cooled Reactors. The RCS development for the PBMR Demonstration Power Plant is nearing basic design completion, with a number of development tests being performed, resulting in a TRL rating of 6.

A number of development and qualification tests will be performed on the Helium Test Facility (HTF) in South Africa before the RCS can be commissioned in the PBMR DPP. Upon the completion of these tests, the RCS will have a TRL Rating of 7. It has however been identified that the environment in which the RCS must operate in the NGNP, may be at a higher temperature than that of the PBMR DPP. For this reason it is possible that alternative materials may need to be investigated for certain components of the RCS.

Carbon composite materials have been identified as potential candidate materials for the components in question. Decision discriminators have been identified to aid in the selection between the conventional metallic materials and the alternative candidate materials. The TRL Rating of the candidate materials has however not yet been fixed or validated. This can only be done once more analyses have been performed to determine what the exact requirements of the materials would be for application in the NGNP.

A Technology Development Roadmap (TDRM) has been compiled to outline the process that needs to be followed for the RCS to obtain a TRL Rating of 8. The TDRM indicates that the experience obtained in the development of the RCS for the PBMR DPP can be fed back into the development of the RCS that may need to be done for application in the NGNP. Any additional qualification tests for temperature effects that may need to be performed for the NGNP RCS can be conducted at the HTF, depending on the details of the test requirements. Testing required in an environment where radiation is present will have to be performed outside the HTF. It is however not foreseen at this stage that any RCS tests will need to be performed in the Component Test Facility (CTF).

The PBMR NGNP RCS is expected to be operated at slightly different conditions than PBMR DPP and hence detailed system level analyses are required to confirm the operating envelope. It is noted that the technology roadmap and maturation plans will need to be adjusted as new DDNs evolve as part of the conceptual basic and final designs.

# 14 REACTIVITY CONTROL SYSTEM

## 14.1 RCS Description/ Function and Operating Requirements

### 14.1.1 Description

The RCS is used to control the reactivity in the core, to quickly shut the reactor down and to keep it in a shutdown state. The RCS consists of 24 identical units, comprising one group of 12 control rods and a second group of 12 shutdown rods. The only difference between the control rods and the shutdown rods are the length of the chain from which the rods are suspended. The longer length of the shutdown rod chains allows these rods to protrude deeper into the side reflector borings than the control rods, thereby providing absorption over the full active length of the core. The control system moves each group of rods alternatively to an equal depth into the side reflector. Following a scram or shutdown signal, the control rods are fully inserted into the top part of the reflector whereas the shutdown rods are fully inserted into the bottom part of the reflector.

The RCS rods are raised and lowered mechanically inside the borings in the side reflector. The system will also hold it steady in any position over its entire range of travel. Insertion of the rods is by gravity when power to the drive motors is cut (scram activation). During this event, the drop velocity of the RCS units is limited to a pre-determined value. The safety function of ensuring hot shutdown by means of the RCS is performed by inserting the control rods into the boring channels provided in the side reflector.

Each rod consists of six segments containing absorber material in the form of sintered $B_4C$ rings between two coaxial claddings. Gaps between the cladding and $B_4C$ rings prevent constraint forces from arising due to radiation-induced swelling of the $B_4C$. Pressure equalizing openings expose the $B_4C$ to the surrounding coolant gas to avoid any pressure build-up.

The individual segments are connected by means of articulated joints and suspended from one another to form a complete rod. This configuration minimizes torsion caused by asymmetric temperature profiles across the rod. Each segment joint is held in place by mechanical stops.

The rods are freely suspended in the side reflector boring by chains. A relatively large annular gap (25 mm) exists between the rod and the side reflector boring sleeve to avoid jamming of the rods resulting in no guide being required between the Core Structure Ceramics (CSC) and the rods. The rod is cooled inside and outside by a stream of cold gas to remove the heat generated in the absorber during normal operations.

The chains link the rods to the Rod Drive Mechanism (RDM) that is used to raise and lower the rods in the rod channels and to hold it at any position in its travel range. The RDM's are installed above the core and are integrated into the Reactor Pressure Vessel (RPV) head. The essential parts of the drive mechanisms are:

- A link chain to connect the drive mechanism and rod. When the rod is raised, the chain is stored in a loose pile inside a chain container from which it is extracted when the rod is lowered.
- An electric drive motor, which holds the rod in position or moves the rod up or down.
- A gearbox, comprising a reducing bevel gear and spur gear in between a chain sprocket and the drive motor.
- An eddy current brake with permanent magnets, which is integrated as part of the gearbox to limit the drop velocity of the rod in the case of a reactor SCRAM.
- A shock absorber to absorb the kinetic energy of the inserted rod and the rotating masses (installed at the drive-side end of the link chain) in case of a reactor SCRAM.
- A rod position indicator as well as proximity sensors for the upper and lower limit positions to indicate fully inserted and fully extracted positions of the rod.

A secondary shock absorber is installed at the bottom of each of the side reflector borings to absorb the impact and protect the graphite blocks of the side reflector in the unlikely event of a rod becoming disengaged from the link chain and dropping to the bottom of the boring.

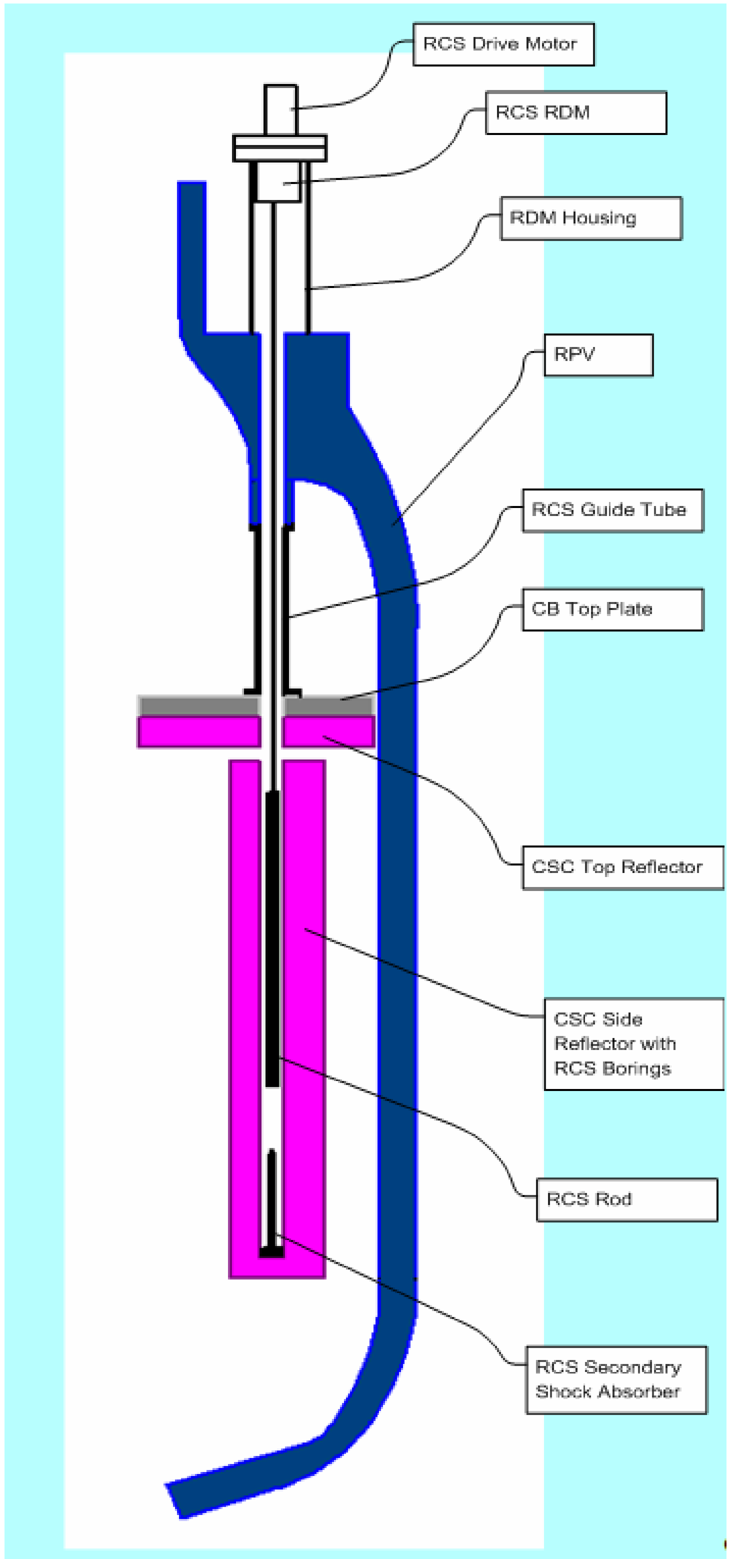


**Figure 14-1: Layout and position of the Reactivity Control System.**

### 14.1.2 RCS in the HTF

One full scale RCS shutdown unit will be accommodated in the HTF in the form of the RCS test set-up. The test set-up will simulate the steady state environment of the PBMR RCS during normal and abnormal conditions.

The main features of the RCS test set-up are as follows:

1) Temperatures, pressure and flow rates are adjustable through six inlet channels to create representative environments.
2) Longitudinal temperature distribution along the length of the rod channel (6 zones over the length of the rod representing temperature variations along the length of the side reflector borings).
3) Radial temperature distribution on the circumference of the rod channel (6 zones representing a side reflector boring).
4) Rod internal heating simulating neutronic heating due to neutron absorption.
5) Simulation of the PBMR PBMR DPP demonstration plant environment conditions at the following positions:
    a) Upper reactor citadel.
    b) Reactor pressure vessel (RPV) top volume.
    c) Drive motor housing.
    d) Rod drive mechanism (RDM) housing.
    e) Side reflector boring.
    f) Side reflector boring bottom volume (position of secondary shock absorber).
6) Measure vibration of the rod inside the channel.

The RCS test set-up will be utilised to verify the performance of the different sub-systems and components integrated into the RCS, at certain operating conditions. The HTF main loop will create the required conditions in the RCS test set-up for the simulation of PBMR conditions.

Each of the respective supply lines from the main loop of the HTF will be utilised in a specific part of the RCS test set-up to simulate the different conditions in the PBMR.

**Figure 14-2: Photo of the HTF tower where the RCS test setup is located.**

### 14.1.3 Functions

**Perform Volume Separation**

- The RCS interfaces with both the RPV and the Core. As a result one of the functions of the RCS is to provide separation between the upper RPV volume and the Core volume to keep cooling gas inside the upper RPV volume from entering into the Core.

**Confine Process Gas and Contaminants**

- In order to keep the dose to the public low, the Reactor gasses need to be confined inside the Reactor.

**Prevent Air Ingress**

- Air ingress into the Core at elevated temperatures is detrimental to the CSC and as a result the amount of air that enters the Core during an event that the Reactor pressure boundary is breached needs to be limited as far as possible.

**Prevent Damage to CSC**

- The RCS shall not damage the CSC during normal operation (e.g. rod scuffing) or as a result of RCS failures (e.g. rod drop).

**Absorb neutrons**

- The main function of the RCS is to perform reactivity control through neutron absorption inside the reactor. The RCS rods contain sintered B4C rings to absorb the neutrons.

**Maintain Rod Position**

- The RCS shall stop and hold a rod in position when commanded to do so.
- When the capability to hold the RCS rod in position fails, it must always fail to the fully inserted position.

**Change Rod Position**

- The RCS shall move the rod to any position in the entire range of travel of the rod when commanded to do so by the Automation System (AS).

**Perform Emergency Shutdown**

- The RCS rods shall be fully inserted under gravity from any stationary position in its entire range of travel when no electrical power is supplied to the RCS (SCRAM).

**Guide rods**

- A positive guide function must be provided to guide the rods in the cavity between the RPV and the core during installation of the rods.

**Monitor and Communicate the RCS Status**

- The RCS must detect that the control and shutdown rods have been fully inserted and communicate its status to the Automation System.
- The RCS must detect that the control and shutdown rods have been fully extracted and communicate its status to the Automation System.
- The RCS must continuously monitor and report to the Automation System the position of each rod.
- The RCS must detect the status of the rod (stuck or free running).
- The RCS must continuously monitor the current system health of the RCS system and communicate it back to the Automation System. It must also alarm situations where the RCS has deteriorated to such an extent that it starts to operate outside its normal operating parameters.

### 14.1.4 Interfaces

The RCS interfaces with the following systems or components:

- Module Decontamination System.
- Reactor Pressure Vessel.
- Core Barrel Top Plate.
- Core Structure Ceramics.
- Auxiliary Electrical Power System.
- Equipment Handling System.
- Reactor Building Structure.
- Helium Leak Detection and Monitoring System.
- Waste Handling System.
- Automation System (AS).
- Heating, Ventilation and Air Conditioning (HVAC).

### 14.1.5 Operating Conditions

The RCS will be subjected to the reactor core inlet and outlet temperatures. The NGNP nominal operating conditions are:

- Nominal outlet temperature of 950°C.
- Nominal inlet temperature of 350°C.
- Nominal Reactor Power level of 500 MWt.
- Nominal Helium pressure of 9 MPa.
- Service Life:
  - o Non-replaceable components: 60 equivalent full-power years.
  - o Replaceable components:
    - Minimum: [15] equivalent full-power years.
    - Target: [20] equivalent full-power years.

The RCS operating conditions for the NGNP are expected to be as follows:

- 750°C maximum normal operating temperature – based on PBMR DPP temperatures plus 50°C (0).
- For DBA temperatures up to 1000°C are projected.
- The RCS cladding and joints are estimated to be exposed to a neutron fluence of up to $5x10^{21}$ n/cm2 (E > 0.1 MeV) (about 3.6dpa) for the NGNP design at 60 years. The estimate is based on PBMR DPP fluence +25% multiplied by 1.5 for NGNP fluence (0).

The different postulated plant transients will need to be analysed for the above reactor design in order to determine whether or not the current design will envelope these transients.

## 14.2 Technology / Design Selection Status

The PBMR DPP RCS technology will be used in the NGNP. The PBMR DPP RCS is nearing the completion of its basic design phase while development tests are also being performed.

The use of the PBMR DPP RCS on the NGNP could demand further development in some materials of the RCS, as the RCS operating environments could potentially be at higher temperatures during certain plant conditions e.g. DBA's. The component that mainly needs possible further development is the control rod cladding used to contain the $B_4C$ rings. Currently this component is made from Incoloy 800H. Other candidate materials need to be considered for this component, with potential candidate materials already having been identified.

### 14.2.1 Candidate Technologies – RCS

The candidate technologies currently under consideration are:

- Conventional metallic rods as being developed for the PBMR DPP.
- Non-metallic, carbon composite (e.g. SiC/SiC) control rods.
- Carbon Fiber Reinforced Composites (CFRC)

### 14.2.2 Decision Discriminators

**Design / Technology development**

The primary decision discriminators are the temperature and fluence to which the control rods will be subjected during normal as well as accident conditions. These discriminators will determine whether the conventional material (i.e. the material used for the PBMR DPP RCS) can be used, or whether it will be required to investigate alternative materials.

Since conventional metallic material will be used in the PBMR DPP RCS and its application validated by means of development and qualification tests, the potential risk of using this material should be lower, provided the operating envelope for the two applications are the same.

**Operations and Maintenance**

The influence that each of the materials could potentially have on the reliability, availability and maintainability of the RCS, will need to be evaluated. The potential operation and maintenance risk also needs to be determined.

**Life Cycle Cost**

The total system life cycle cost needs be evaluated.

A trade-off study needs to be performed, weighing up the difference in manufacturing costs against the operating and maintenance costs for the different solution.

**Manufacturing and Availability**

The manufacturing capabilities as well as the materials availability need to be considered in the selection of the material.

### 14.2.3 Reference Design

The PBMR PBMR DPP RCS will serve as the reference design for the NGNP.

### 14.2.4 Alternatives for Further Evaluation

Control rod (cladding) materials, which include:

- SiC/SiC control rods.
- CFRF control rods.
- Conventional metallic control rods as applied in the PBMR DPP RCS design (Incoloy 800H).

### 14.2.5 Down Selection Task

The final control rod design for the NGNP RCS will be done during the basic design phase, based on available material data, calculated operating and accident conditions for the NGNP RCS as well as prototype testing.

The following tasks will aid in selecting the most appropriate material:

- Design calculations to evaluate the operational environment of the RCS in the NGNP for Normal Operation, AOOs and DBA;
- Perform a reliability, availability and maintainability analysis;
- Perform life cycle cost analysis;
- Establish suppliers availability; and
- Perform trade off studies between the cost and impact on schedule based on the selection of each material.

## 14.3 TRL Rating

The NGNP RCS is currently rated at a Technology Readiness Level of 6, based on the fact that operating experience exists for similar reactivity control systems in other gas-cooled, graphite moderated reactor applications. The applicable TRL sheets are attached in Appendix A.

Since the NGNP will operate at 500MWt, instead of 400MWt as in the case of the PBMR PBMR DPP, the RCS may be required to operate in an environment falling outside the material qualification limits of the control rod cladding. Further material qualification may therefore be required for the NGNP application. Candidate materials have been defined as potentially acceptable technologies. The TRL Rating for the materials used on the NGNP RCS will only be determined once the requirements for the NGNP RCS have been confirmed through analyses.

## 14.4 Technology Development Road Map Summary

### 14.4.1 Overview

Since the RCS that is being developed for the PBMR PBMR DPP will be used in the NGNP, no decision criteria are required for the selection of the integrated reactivity control system technology. However, design calculations could prove it necessary to evaluate alternative materials for the control rod cladding, for the RCS application in the NGNP. The RCS for the PBMR DPP is at a TRL Rating of 6. Possible candidate materials have been identified for the control rod claddings for the RCS for application in the NGNP.

## 14.5 Technology Maturation Plan Summary (Current TRL 6 to TRL 7)

The PBMR DPP RCS is currently at a TRL Rating of 6, and will reach a TRL Rating of 7 after HTF development and qualification tests have been completed.

It is envisaged that the NGNP RCS will operate at higher temperatures and fluence than in the PBMR PBMR DPP. Material selection and qualification could therefore be required for the control rod cladding. The alternative materials is not on a validated TRL level, since further analyses needs to be performed to determine the exact requirements of the control rod cladding in the NGNP.

Before the alternative materials can be incorporated into the NGNP RCS design, material qualification tests needs to be performed. After the required material qualification tests have been completed, the alternative material can be incorporated into RCS design for the NGNP. This design can then be regarded to be on a TRL Rating of 6.

Only certain tests performed to mature the PBMR DPP RCS to a TRL Rating of 7 may need to be repeated with NGNP RCS design with the possible alternative material. Therefore a number of tests which are to be performed for the PBMR PBMR DPP RCS are not expected to be repeated for NGNP RCS. The technology maturation plan can therefore be divided into:

- Tasks to be performed to mature the PBMR PBMR DPP RCS from its current TRL to a TRL Rating of 7; and
- Tasks to be performed to qualify the materials used for the control rod cladding in the NGNP and tasks to be repeated to mature the PBMR DPP RCS design, with the material selected for the NGNP, to a TRL Rating of 7.

### 14.5.1 Maturation plan for the PBMR DPP RCS

The maturation plan of the RCS for the PBMR DPP consists of a number of qualification actions that are aimed at validating certain functions of the RCS. The qualification activities can be classified as one of the following, depending on the requirements of the specific function:

- Manufacturing Inspection
- Functional Assessment
- Environmental Assessment or
- Seismic Assessment

Each of the functions can be verified by means of design, analysis, testing, inspection or a combination hereof. The different functions that will require verification include the following:

- Perform Volume separation
- Confine Process Gas and Contaminants
- Prevent Air Ingress
- Prevent Damage to CSC
- Absorb neutrons
- Maintain Rod Position
- Change Rod Position
- Perform Emergency Shutdown
- Guide rods
- Monitor and Communicate the RCS Status

### 14.5.2 Tasks to be performed to qualify the materials used for the control rod cladding in the NGNP

Since the specific requirements of the materials are not yet clearly defined, no such qualification tasks can yet be fixed in a plan. Some tests may need to be repeated in the HTF for the selected material of the control rod cladding to ensure that the functional requirements of the RCS are still fulfilled for the new material. Tasks required for qualification of the materials and integrated testing of the NGNP RCS could include, but is not limited to, the following:

1) A review of the adequacy of the Alloy 800H material for the control rods is required for the NGNP application.

2) Modeling is required of the Inner Side Reflector (ISR) to determine the fluences experienced by the control rods and chains for the NGNP application.
3) A modeling study to verify the temperature of the RCS control rods and chains needs to be performed for the NGNP design.
4) A study to determine qualification testing and procedures for the components of the RCS is needed for the NGNP design. These include tests that need to be repeated in the HTF, possibly at higher temperatures. This could include:
    a) SCRAM tests.
    b) Rod temperature distribution (thermal bending) tests.
5) Irradiation testing at the temperatures that is required in the NGNP.
6) Material characterization of the selected material in and outside a Helium environment.
7) Structural ageing tests of selected material due to radiation, Helium and elevated temperatures.

Note that the maturation plan for the NGNP RCS is not elaborated in Appendix C, since test specifications have not yet been developed.

## 14.6 Inputs to CTF

It is not envisaged that any of the tests will be performed on the CTF. Development and qualification tests of the RCS will be performed on the Helium Test Facility (HTF) or the PBMR PBMR DPP. Qualification of materials can be performed by means of laboratory scale tests. Once the selected materials have been incorporated into the RCS design, the affected components, sub-system or integrated system can once again be tested on the HTF.

## 14.7 References

[14-1] HTF-000000-225, Rev 1A: High Temperature High Pressure Helium Test Facility System Operational Description.

[14-2] 016974, Rev 1D: Reactivity Control System Development Specification.

[14-3] RCSS-A-000000-111/1, Rev 1: RCS HTF Movement and SCRAM Test Specification

[14-4] 001929-4, Rev 2: PBMR Safety Analysis Report: Reactor Unit and Fuel.

[14-5] 016956 Rev 5: Technical Description of the PBMR Demonstration Power Plant.

[14-6] 066780 Rev A: Qualification Test and Analysis Requirements.

[14-7] 066778 Rev A: Qualification Life Cycle Strategy.

[14-8] NGNP-NHS-RPT.000.S05: NGNP Conceptual Design Study Composites R&D Technical Issues

[14-9] TDRM-014: Reactivity Control System Visio Road Map

# APPENDIX A: TRL RATING SHEETS

**Table A-1: TRL Rating Sheet of the RCS**

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: WEC | Document Number: 006 | | Revision: 0 |
| ☐ Island ☐ System ☑Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: Reactivity Control System (RCS) | | | |
| Description:<br>The Reactivity Control System consists of the Control Rods and the Shutdown Rods; part of the Reactor Unit System. | | | |
| | | | |
| Area(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP | | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Component or system breadboard in relevant environment | Similar SSC in relevant environment in another application | Pilot/engineering scale demonstration in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating:<br>There is operating experience with similar reactivity control systems in other gas-cooled graphite-moderated reactors, particularly Fort Saint Vrain, Japanese HTTR and the German THTR, but those are not prototypical of the PBMR. The RCS can have a TRL-7 when the present HTF test program provides demonstration. The TRL can be elevated to a TRL-8 when PBMR PBMR DPP operates.<br>For the NGNP analyses need to be performed to determine whether the operating conditions are beyond the material capabilities of the PBMR DPP RCS. If this proofs to be the case, the NGNP RCS will probably be on a TRL-5, with further material qualification required to progress it to TRL-6. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | | Schedule | Cost (K$) |
| • Functional/performance testing in the HTF | | FY 2009 – FY 2012 | Refer to Section A |
| DDN(s) supported: DDN COMP-01-02 RCS Materials Characterization. | | | |
| SME Making Determination: D,T, Allen | | | |
| Date: 22Aug07 | Originating Organization: Technology Insights | | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

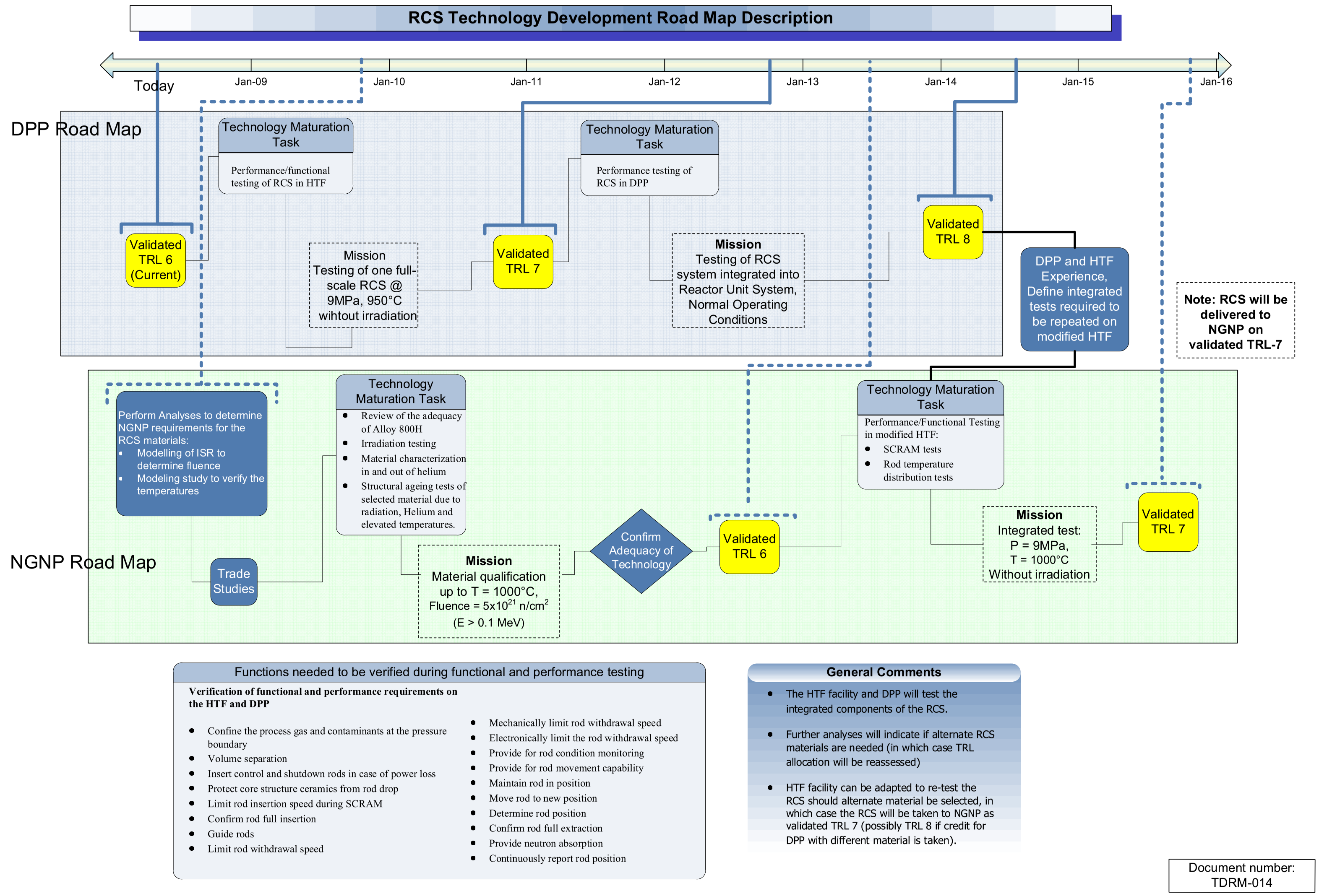


**Figure B-1: Technology Development Road Map of the RCS**

# APPENDIX C: TECHNOLOGY MATURATION PLAN

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# C1 TECHNOLOGY MATURATION PLAN FOR PBMR DPP RCS (TRL 6 TO TRL 7)

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY (TRL 6 to TRL 7)

### C1.1.1 Objectives

The objective of the maturation plan is to advance the RCS from a TRL Rating of 6 to a TRL Rating of 7. The plan proposes a number of tests aimed at verifying certain critical functions of the RCS prior to it being installed and commissioned in the PBMR DPP.

### C1.1.2 Scope

The tests that have been defined in support of the verification of the functions that needs to be performed for the RCS are listed in Table C-1 below. These are not individual tests (or test specifications), but rather a general outline of the tests. An example of a test specification is shown in C1.2.1.

**Table C-1: Groups of tests that need to be performed to verify critical RCS functions.**

| Qualification Test | Verification Method | Qualification Activity |
|---|---|---|
| **Confine Process Gas and Contaminants** | | |
| Pressure Test | Test | Functional Assessment |
| **Volume Separation** | | |
| Volume Separation verification | Inspection | Manufacturing Inspection |
| **Perform Emergency shutdown** | | |
| Verification of control and shutdown rods insertion upon power loss | Analysis | Functional Assessment |
| Verification of control and shutdown rods insertion upon power loss | Test | Functional Assessment |
| **Control rod withdrawal speed** | | |
| Mechanical limit | Test | Functional Assessment |
| Software limit | Test | Functional Assessment |
| **Control Rod Status** | | |
| Control rod status | Analysis | Functional Assessment |
| Control rod status | Test | Functional Assessment |
| Control rod fully inserted | Analysis | Functional Assessment |
| Control rod fully inserted | Test | Functional Assessment |
| Factory Acceptance Testing of RCS component assembly | Test | Functional Assessment |

| Qualification Test | Verification Method | Qualification Activity |
|---|---|---|
| Prototype production dry run | Inspection | Manufacturing Inspection |
| Control rod SCRAM simulation | Test | Functional Assessment |
| FAT inspection of the prototype without shroud | Test | Manufacturing Inspection |
| **Process Qualification of RCS Component Manufacture and Quality Surveillance** | Inspection | Manufacturing Inspection |
| RCS motor functional acceptance testing and characterisation | Test | Functional Assessment |
| **Installation inspection of the RCS subassemblies** | Inspection | Installation Assessment |
| **Installation inspection of the RCS assemblies** | Inspection | Installation Assessment |
| **Environmental Assessment of the CRDM Motor and Eddy Current Brake** | Test | Functional Assessment |
| Seismic qualification of position sensors | Test | Seismic Assessment |
| Control rod analyses | Analysis | Environmental Assessment |
| **Load Testing of the SCRAM shock absorber** | Test | Functional Assessment |
| Incoloy Qualification and certification | Test | Environmental Assessment |
| RCS chain weld evaluation | Analysis | Environmental Assessment |
| RCS chain weld evaluation | Test | Environmental Assessment |
| Control rod position functional test | Test | Functional Assessment |

### C1.1.3 Anticipated Schedule

The testing is expected to last at least three years which will be followed by continuous lifecycle testing (availability, reliability, etc.).

### C1.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

## C1.2 TEST SPECIFICATIONS

An example of one of the test specifications is given below. This test will form part of the verification process of the Control Rod SCRAM function.

### C1.2.1 RCS Test Specification #1: Control Rod SCRAM (WEC-TS-RCS-001)

#### C1.2.1.1 Objectives

The objectives of these tests are to verify the movement and SCRAM functions of the RCS system under different environmental conditions. One of the main objectives of these tests is to verify the operation of the RCS system in a Helium environment.

#### C1.2.1.2 Test Conditions

The test will be performed at different environmental conditions. Table 1 indicates all the different conditions with associated temperatures and pressures.

**Table C-2:** Test Conditions

| Nr. | Medium | Pressure | Motor Temp | Gearbox Temp | Guide tube Temp | Boring Temp |
|---|---|---|---|---|---|---|
| C1 | Air | Atmospheric | Ambient | Ambient | Ambient | Ambient |
| C2 | Helium | Atmospheric | Ambient | Ambient | Ambient | Ambient |
| C3 | Helium | 2 MPa | 100 °C | 200 °C | 200 °C | 200 °C |
| C4 | Helium | 3.6 MPa | 160 °C | 300 °C | 300 °C | 300 °C |
| C5 | Helium | 3.6 MPa | Measure | Measure | 300 °C | 300 °C |

*C1.2.1.2.11 Test Configuration/Set-up*

The unit under test for this test will consist of the following:

1. RCSS-A-000030 RDM Assembly
2. RCSS-A-000763 Stepper Motor, Eddy Current Assembly
3. HTF-A-004227 Control Unit, HTF RCS

The hardware will include 2 resolvers on the motor and a flexible coupling between the motor and the gearbox. The motor drive will also have a profibus capability.

The tests will be performed in the RCS test setup in the HTF, without the RDM Housing and Motor outer conditioning chamber installed.

*C1.2.1.2.12 Proposed Test Location*

The tests will be performed in the RCS test setup in the HTF in South Africa.

#### C1.2.1.3 Measured Parameters

The following measurements need to be logged during the tests:

1. Total distance that the rod moved (odometer).
2. Distance that the rod has SCRAMed (speed > 0.05 m/s)
3. Total number of SCRAMs performed by the rod.
4. Full-in and full-out sensor readings.
5. Temperature readings of the motor, gearbox, guide tube and boring.
6. Temperature readings of the outside of motor and RDM Housing.
7. Pressure.
8. Helium purity
9. Rod position.
10. Rod speed.
11. Motor drive current.

#### C1.2.1.4 Data Requirements

All measurements shall be for reference only.

#### C1.2.1.5 Test Evaluation Criteria

The Westinghouse Electric – South Africa (WE-SA) design engineer in conjunction with the HTF test team shall decide whether to continue testing, abort the test or repeat a test after each test has been finished. Specific criteria will be included in later test plans.

#### C1.2.1.6 Test Deliverables

All measurements shall be logged during the tests and the data shall be available after the test for review purposes. A Test Execution Report (TER) shall be compiled containing at least the following data:

1. Odometer readings at the beginning and end of the test.
2. Total number of SCRAMs that the rod have performed during the test.
3. Maximum speed during SCRAM for all SCRAMs.
4. One speed vs time curve during the SCRAM for each test condition.

5. Actual test conditions, including temperatures, pressure and Helium purity.
6. Temperature results for test condition C5.
7. Any failures that occurred during the tests.
8. Any deviations from the test instruction.
9. Any observations during the test.

NGNP-CTF MTECH-TDRM-015 November 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 15: Core Conditioning System

**APPROVALS**

| Function | Printed Name and Signature | | Date |
|---|---|---|---|
| Author | Name:<br>Company: | Lucas Pitso<br>M-Tech Industrial | November 19, 2008 |
| Reviewer | Name:<br>Company: | Alwyn Strauss<br>Pebble Bed Modular Reactor | November 19, 2008 |
| Reviewer | Name:<br>Company: | Adele Engelbrecht<br>Pebble Bed Modular Reactor | November 19, 2008 |
| Approval | Name:<br>Company: | Jan van Ravenswaay<br>M-Tech Industrial | November 19, 2008 |

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| Adele Engelbrecht (Pebble Bed Modular Reactor (Pty) Ltd) | September 10, 2008 |
| Roger Young (Pebble Bed Modular Reactor (Pty) Ltd) | September 10, 2008 |

# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | | |

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# RECORD OF CHANGES

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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| | |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| | |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |

| | |
|---|---|
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# SUMMARY AND CONCLUSIONS

The WEC proposed NGNP is envisaged to utilize a Core Conditioning System (CCS) similar to that of the Pebble Bed Modular Reactor (PBMR) Demonstration Power Plant (DPP). The CCS consists of a dual redundant system, each having a gas circulating blower, a high temperature water-cooled heat exchanger, isolation and blower control valves, hot gas ducts, pressure boundary and control instrumentation.

In order to utilize these technologies in the operational NGNP a technology readiness level of 8 (TRL 8) needs to be achieved by the specific technology under investigation. Based on this requirement a study was conducted in which the TRL rating of the different proposed technologies was determined. During this study the CCS components were given a TRL 6 rating. Thus the CCS now needs to be elevated to the required TRL 8 rating.

This TRL maturation process has been divided into two main activities, namely a maturation from the current TRL rating up to TRL 7, and then from TRL 7 to TRL 8. To reach a TRL 7, various tests will be done on the individual components of the CCS. The tests will qualify the technology to be used in the final designs of the CCS components. The final components will be integrated as a subsystem into the DPP and will be tested as an integrated unit. When the CCS subsystem tests are complete, it will have progressed to a TRL 8.

The NGNP CCS is expected to operate at slightly different conditions than the DPP CCS. Hence detailed system level analyses are required to confirm the DDN's and the operating envelope.

# 15 CORE CONDITIONING SYSTEM

## 15.1 Function and Operating Requirements

The Core Conditioning System (CCS) removes decay heat from the reactor in cases where the Heat Transport System (HTS) is not operational. When the CCS is in operation, hot gas is extracted from the core outlet pipe, passed through a water-cooled heat exchanger, through the CCS blower and then back into the annular cooling cavity of the hot gas ducts and the core inlet pipe. A CCS by-pass control valve regulates the amount of gas directed back to the core. This way the core temperature may be controlled. The CCS consists of two identical loops which are housed and operated separately for redundancy. A simplified diagram showing one loop of the CCS is presented in Figure 15.1 along with a simplified gas flow path through the reactor unit.

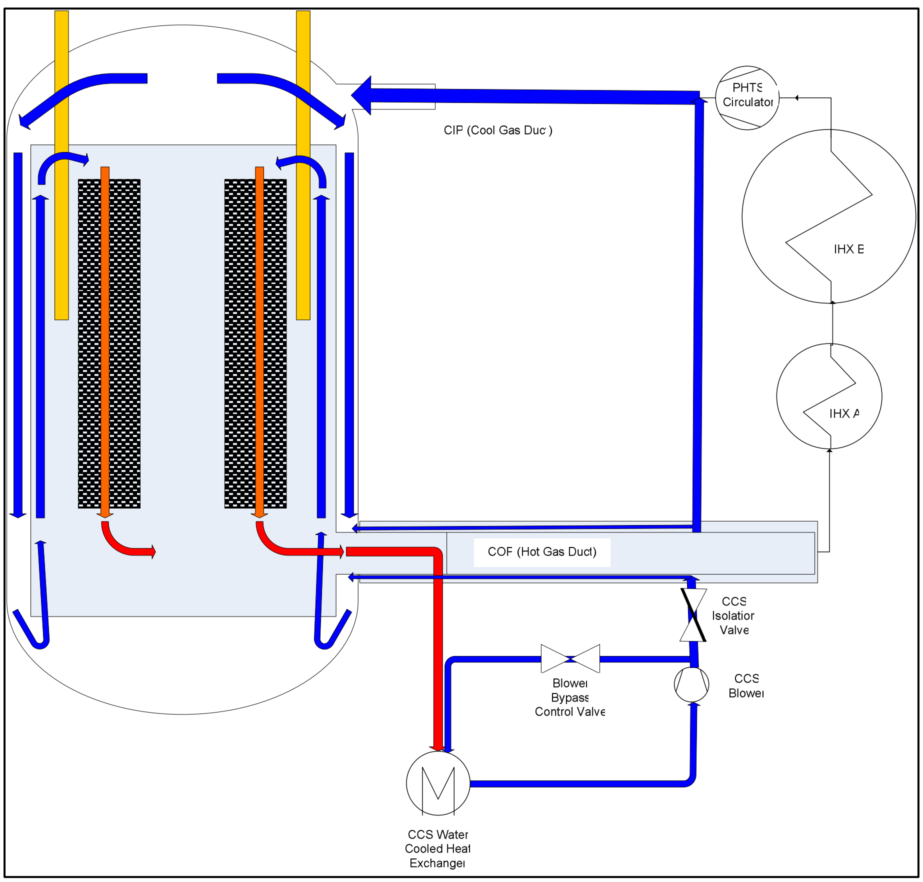


**Figure 15.1: Process Flow Diagram of the CCS**

The CCS operates in the following instances:

1. During normal maintenance operations to keep the core temperatures within set limits
2. During any incidences where use of the HTS is inhibited.

Other functions of the CSS are to:

1. Circulate heated nitrogen through the primary loop during commissioning of the Nuclear Heat Supply System (NHSS).
2. Provide cooling flow to the reactor during maintenance.
3. Cool the core down to maintenance conditions or keep it at operating conditions should there be small leaks in the Helium Pressure Boundary (HPB). This depends on the ability to isolate and repair small leaks.

### 15.1.1 Operating Modes and States

The CCS operational states as mapped to the NGNP Modes and States are detailed in Table 15-1.

**Table 15-1: The NGNP Modes and States with CCS Operation Mapped**

| NGNP Mode | NGNP State | | CCS Operation |
|---|---|---|---|
| Maintenance | 1 | Defueled Maintenance | No |
| | 2 | Fueled Maintenance | **Yes** |
| Shutdown | 3 | Shutdown -Heat Sink through CCS | **Yes** |
| | 4 | Shutdown -Heat Sink through PCS | No |
| Operation | 5 | NHSS and PCS Partially Operational | No |
| | 6 | NHSS and PCS Fully Operational | No |
| | 7 | HPS Ready | No |
| | 8 | Whole Plant in Operation | No |

### 15.1.2 Operating Conditions

Table 15-2 provides an indication of the steady-state operating conditions of the CCS, based on those of the DPP and slightly adjusted for NGNP, based on engineering judgment. The actual steady-state conditions for the NGNP CCS will only be determined through dynamic modeling as part of conceptual design.

**Table 15-2: CCS Steady State Characteristics for Active Cooling**

| Condition* | Inlet Pressure [kPa] | Inlet Temperature [°C] | Max. Outlet Temperature [°C] | Minimum flow rate [kg/s] | Maximum flow rate [kg/s] | Heat Removed [MW] | Description |
|---|---|---|---|---|---|---|---|
| Pressurized conditions | 9000 | 950 | 350 | 3 | 10** | Max. 35** | Higher temp operation after trip |
| Depressurized Forced Cooling | 101.3 | 950 | 350 | 1.6 | 1.9 | 4.35 | Start of DFC |
| Maintenance cooling | 101.3 | 250 | 90 | 1.6 | 1.9 | 2 | Maintenance |

**Notes:** ** Short durations only.

### 15.1.3 Components

Components of the CCS are:

#### 15.1.3.1 Blower

The blower is a 450 kW single stage centrifugal blower that has variable speed drive. It is submerged in the HPB and uses Electro-Magnetic Bearings (EMB). It will have the capability to circulate both nitrogen and helium within the pressure ranges stated in Table 15-2. The pressure loss through the cooling flow path is estimated to be less than 10 kPa at the specified mass flow rate and pressure combinations.

| | | |
|---|---|---|
| Design pressure | Min: 1 kPa | Max: 9700 kPa |
| Design temperature | Min: 18 °C | Max: 371 °C |

#### 15.1.3.2 Heat exchanger

A shell and tube heat exchanger will be used for cooling the gas from the reactor core. It should have the capability to cool the gas to temperatures required as stated in Table 15-2.

| | | |
|---|---|---|
| Helium side | | |
| Design pressure | Min: 1 kPa | Max: 9700 kPa |
| Design temperature | Min: 18 °C | Max: 1000 °C |
| Water side | | |
| Design pressure | Min: 100 kPa | Max: 300 kPa |
| Design temperature | Min: 18 °C | Max: 41 °C |

#### 15.1.3.3 Valves

The CCS has two valves, the blower bypass control valve and the blower isolation valve. The bypass control valve is a control valve and the isolation valve is a butterfly valve. Currently two technologies are short-listed for use for valve actuations. They are the hydraulic and electric actuations with a bias towards electric actuation. The maximum pressure across the isolation valve when closed is 300 kPa while the maximum flow rate is 10kg/s. The valve type will be re-evaluated during conceptual design when the NGNP specific operating parameters have been refined.

| | | |
|---|---|---|
| Design pressure | Min: 1 kPa | Max: 9700 kPa |
| Design temperature | Min: 18 °C | Max: 371 °C |

#### 15.1.3.4 Hot gas ducts & piping

The CCS hot gas ducts form part of the Primary Heat Transport System's (PHTS) HPB, thus they will not be considered here. Refer to Section 6 of the WEC NGNP report.

#### 15.1.3.5 Control & Instrumentation

The CCS will incorporate electrical power supply and a C&I system based on standard components and includes a Data Acquisition Unit (DAU).

#### 15.1.3.6 Pressure Boundary

All the components will be designed such that minimal leakage of helium is experienced. This is due to economical and safety reasons. Tests for leaks will be conducted but the maximum leak rates of the NGNP are yet to be established.

| | | |
|---|---|---|
| Hot gas ducts | | |
| Design pressure | Min: 1 kPa | Max: 9700 kPa |
| Design temperature | Min: 18 °C | Max: 1000 °C |
| Pressure boundary | | |
| Design pressure | Min: 1 kPa | Max: 9700 kPa |
| Design temperature | Min: 18 °C | Max: 371 °C |

## 15.2 TRL Status of the CCS

The status of technology for the CCS was evaluated and it resulted in a determination of TRL 6.

The justification for this rating is based on the following:

- A 100 kW blower of a similar design to the CCS is undergoing testing at the PBMR Helium Test Facility (HTF).
- Prototype valves with similar materials and configurations as the CCS valves have been tested in a helium environment to temperatures up to 350°C at 9 MPa Additional prototype valves (for the DPP Main Power System) will be tested at the HTF.
- The high temperature water cooled heat exchanger is similar to the CCS heat exchanger used in the Japanese High Temperature Test Reactor (HTTR).

(Refer to Appendix A for the TRL rating sheet)

## 15.3 Technology Development Road Map

### *15.3.1 Overview*

The technology development road map (TDRM) for the CCS starts where most of the CCS components are at this stage, at the technology testing stage. The technology to be used for the CCS is relatively advanced. Tests are currently ongoing to qualify it to be used in the final designs of the CCS components for the DPP.

The CCS Technology Development Roadmap is attached in Appendix B while the maturation tasks are described below.

# 15.4 Technology Maturation Status

## 15.4.1 Summary of Maturation Tasks for the CCS

In the sections below the tasks needed to advance the technology of the CCS system from a validated TRL 6 to a validated TRL 8 are described in detail. Various tests will be done on the individual components of the CCS. The tests will qualify the technology to be used in the final designs of the CCS components. Upon completion of the tests, the CCS components will be manufactured to designs which incorporate the feedback from the testing and assembled into an integrated system (in the DPP). On completion of successful integration, the system will be considered to be at TRL 7. During cold and hot commissioning of the DPP, the CCS will be tested as an integrated system within its operational environment. When the integrated CCS tests are complete, it would have progressed to a TRL 8.

### 15.4.1.1 Maturation Tasks form TRL 6 to TRL 7

The following tasks will be undertaken to mature the technology used on the CCS from TRL 6 to TRL 7.

**Blower:**
A 100 kW blower of a similar design to the CCS is undergoing testing at the HTF. The following tasks will be performed on the blower as part of the HTF main loop:
- Perform functionality tests.
- Run the blower in operating conditions similar to the DPP conditions for a continuous period of time and monitor the reliability and availability.
- Evaluate performance at sudden depressurization.

**Valves:**
Prototype valves with similar materials and configurations as the CCS valves have been tested up to temperatures of 350°C. Additional prototype MPS valves similar to the CCS valves will be tested at the HTF and modifications from the outcome will be incorporated into the production units. The following tasks will be performed to advance the valves to a TRL 7:
- Perform functionality and performance tests.
- Evaluate the reliability and endurance of the valves when exposed to operating conditions similar to the DPP conditions for a period of time.

**Heat Exchanger:**
The CCS high temperature water cooled heat exchanger is similar to the Primary Pressurized Water Cooler (PPWC) used in the Japanese HTTR. The HTTR has a 30 $MW_t$ PPWC with a helium inlet temperature of 950 °C and outlet temperature of 395°C. It operates at 4 MPa on the gas side and 3.5 MPa on the water side. The successful operation of the PPWC in

the HTTR under the stated conditions gives the CCS water-cooled heat exchanger technology a TRL of 7. Thus no further steps are necessary to mature it.

**Hot Gas Ducts:**
See Hot Gas Ducts technology development road map (Section 6 of the WEC NGNP TDRM report).

**Control and Instrumentation:**
The control and instrumentation technology is currently rated TRL 7.

**Pressure Boundary:**
All components of the CCS will be designed according to ASME III NB. The code effectively places the pressure boundary technology at TRL 7.

#### 15.4.1.2 Maturation Tasks from TRL 7 to TRL 8

Once all individual components are rated TRL 7, they will be assembled together to form the CCS at the DPP. The following tasks will then be undertaken to get the system as a whole to a TRL 8.

- Evaluate the functionality of the CCS as a system.
- Confirm the integrity of the pressure boundary at operating conditions.
- Evaluate performance of the CCS with the high temperature reactor connected.
- Confirm the capability of the CCS as per design requirements.
- Evaluate the reliability and availability of CCS over a period of time.

### *15.4.2 Test Maturation Plans Summary*

As explained above, several tests will be conducted on the technology used on the different components of the CCS. The data from the tests will be fed into the final design of the components. The components will be assembled at the DPP where further maturation tests will be performed on the system as a unit.

## 15.5 Inputs to CTF

The technology used in the CCS has progressed quite far and the components are at an advanced stage of testing. No CCS component tests are currently foreseen to be undertaken at the CTF.

## 15.6 References

[15-1] TDRM-015: Technology Development Road Map of the CCS visio file.

# APPENDIX A: TRL RATING SHEETS

**Table A-3: Technology Readiness Levels for the CCS**

**TRL Rating Sheet**

Vendor Name: Document Number: 009 Revision: 1

☐ Island ☑ System ☐Subsystem/Structure ☐ Component ☐ Technology

Title: Core Conditioning System

Description:

The Core Conditioning System removes decay heat from the reactor when the PHTS blower is not functional or during maintenance conditions

Area(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP

| ISSCTBS: N/A | Parent: N/A | WBS: N/A |
|---|---|---|

**Technology Readiness Level**

| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
|---|---|---|---|
| Generic Definitions *(abbreviated)* | Component or system breadboard in relevant environment | Similar SSC in relevant environment in another application | Prototype demonstration in relevant environment |
| **TRL** | 5 | **6** | 7 |

Basis for Rating (Attach additional sheets as needed):

There is substantial experience with different components of the CCS.

Blower: The blower is part of the subsystem of the HTF and is undergoing tests in a high pressure high temperature helium environment. When tests are complete it will be rated TRL 7.

Valves: The functionality and performance of the valves will be tested at the HTF and the University of Stellenbosch in RSA. When tests are complete they will be rated TRL 7.

Heat exchanger: It is based on the technology used successfully in the PPWC at the HTTR in Japan. The 30 $MW_t$ PPWC at the HTTR has the helium inlet at 950 °C and pressure is 4 MPa on the gas side and 3.5 MPa on the water side. It is currently rated TRL 7.

Piping: Refer to the hot gas ducting and piping TRL rating sheet.

Control and Instrumentation: The technology that will be used for C&I is relatively common in industry and is rated TRL 7.

Outline of a plan to get from current level to next level (Attach additional sheets as needed)

| Actions (list all) | Schedule | Cost (K$) |
|---|---|---|

| | | |
|---|---|---|
| • Performance & functionality tests on components<br>• Endurance tests<br>• Reliability and availability monitoring<br>• Sudden depressurization tests | FY 2009 – FY 2012 | Refer to Section C1.1.4 |
| DDN(s) supported: None | | |
| SME Making Determination: D.T. Allen | | |
| Date: 09 August 07 | Originating Organization: Technology Insights | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

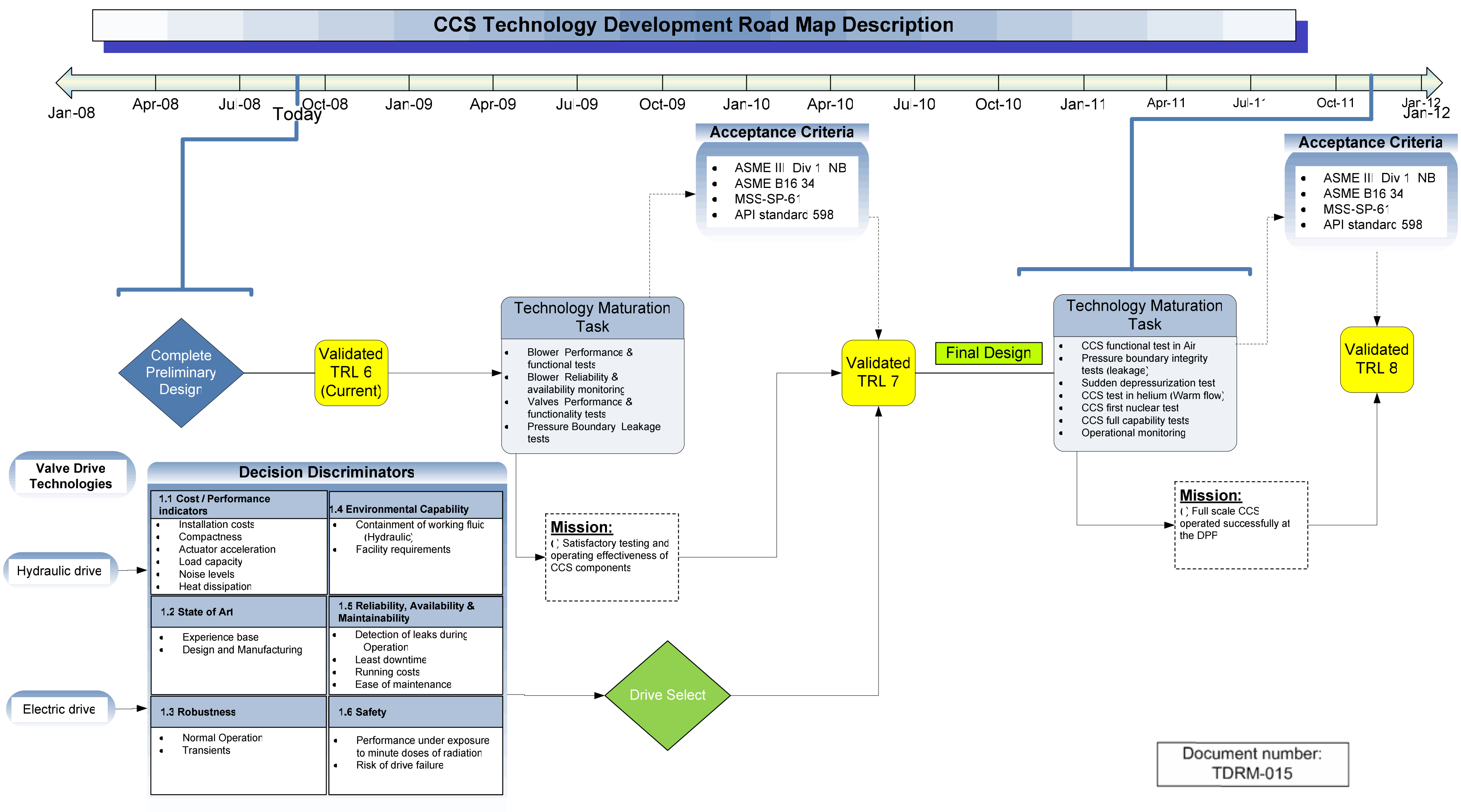


Figure B-2: Technology Development Road Map of the CCS.

# APPENDIX C: TECHNOLOGY MATURATION PLAN

## TABLE OF CONTENTS

# C1 TECHNOLOGY MATURATION PLAN FOR CCS (TRL 6 TO TRL 7)

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the CCS from a TRL level of 6 to a TRL of 7. The activities include testing the prototype components in a high pressure high temperature helium environment.

### C1.1.2 Scope

The maturation tasks and other associated activities to advance the maturity of the technology of the CCS from TRL 6 to TRL 7 are listed below:

- Conduct development tests for the valves.
- Conduct development tests for the blower.

### C1.1.3 Anticipated Schedule

All the work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY 2009 through FY 2011. Work on the two test specifications can be conducted in parallel and each has an expected duration of three years.

### C1.1.4 Overall Cost

The PBMR related costs is omitted due to business confidentiality reasons.

## C1.2 TEST SPECIFICATIONS

The following specifications/ tests to achieve the next TRL have been identified:

**TRL 6 to TRL 7:**

- Specification 1: Valves development test specification (WEC-TS-CCS-001)
- Specification 2: Blower development test specification (WEC-TS-CCS-002)

**TRL 7 to TRL 8:**

- Specification 3: CCS integrated testing (WEC-TS-CCS-003)
- Specification 4: CCS blower at operational temperatures (WEC-TS-CCS-004)

## C1.2.1

## C1.2.2CCS Test Specification #1: Valve (WEC-TS-CCS-001)

### C1.2.2.1 Objectives

The objectives of the test include:

a) Validation of the performance parameters for the valve, including:
   - Determination of the closing and opening time of the valve.
   - Leak rates (internal and external) at the maximum operating pressure as a function of time/usage.

b) Assessment of the position feedback for the bypass control valve and isolation valve.
c) Assessment of sealability of seals after a number of cycles.
d) Determination of key inputs for maintenance procedures.
e) Endurance of valve components including metals seals in a helium environment.

### C1.2.2.2 Test Conditions

The functionality test would be conducted at 70 bar air pressure. The response time test would need helium pressure at a minimum of 100 bar. The tests will be conducted at ambient temperature higher than 25 °C with relative humidity of 50-70 %. The maximum temperature for the test is 140 °C and the maximum pressure is 10 MPa. (Tests up to 350°C at 9MPa in a helium atmosphere has been conducted at the University of Stellenbosch)

#### *C1.2.2.2.1 Test Configuration/Set-up*

The following equipment would be needed for the test

a) The prototype valve incorporating instrumentation for position feedback and limit indicators on the housing would be installed in-between two high pressure vessels.
b) Inter-connecting pipe work with isolation of the pressure vessel from the prototype valve inlet before and after the test.
c) Analogue pressure gauges and transducers.
d) Electrical and C&I system which includes a Data Acquisition Unit (DAU).

The following facilities would be needed for the test:

a) High pressure air supply at a minimum of 70 bar supply pressure.
b) High pressure helium supply at a minimum of 100 bar supply pressure.
c) Two 90 bar pressure vessels for helium blow-down tests.

d) Three phase electrical supply rated 20 kW.
e) Minimal floor area of 40 $m^2$.
f) An overhead crane rated 10 tons covering the entire floor area.
g) High pressure (>120 bar) helium cylinder(s) with a regulator for leak test and endurance test.

*C1.2.2.2.2 Test Duration*

The test is estimated to run for a minimum of time period of three years.

*C1.2.2.2.3 Proposed Test Location*

The Helium Test facility (HTF) at Pelindaba is the preferred site for the test. The valve can be installed between two existing pressure vessels for setting up the maximum operating pressure differential with helium as the test medium.

### C1.2.2.3 Measured Parameters

Parameters for valve performance as specified in the valve specification and requirement.

### C1.2.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards and QA.

### C1.2.2.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the valve specification and requirements. Specifically:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

### C1.2.2.6 Test Deliverables

A test report shall be compiled after the tests containing the following:

- Test equipment and calibration
- Test software used
- Data recorder
- Type of observations

- Results and acceptability
- Actions taken in connection with any deviations noted
- Unresolved anomalies

#### C1.2.2.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality reasons. Actual testing, data reduction and the compilation of the test report are expected to take three years. There is a medium risk associated with the test due to the high working pressures.

### C1.2.3

### C1.2.4 CCS Test Specification #2: Blower (WEC-TS-CCS-002)

#### C1.2.4.1 Objectives

The objectives of the test include:

a) Validation of the performance parameters of the blower, including
   - Determination of availability of the blower.
   - Determination of the reliability of the blower.
   - Assessment of the performance of the electromagnetic bearings.

b) Endurance of the blower, including metal parts, in a helium environment.

c) Determination of key inputs for maintenance procedures.

d)

#### C1.2.4.2 Test Conditions

The blower is connected to the main loops of the HTF. It operates at a pressure of 90 bar and temperatures up to 140 °C with helium as a test medium.

*C1.2.4.2.1 Test Configuration/Set-up*

The blower acts as a circulator of the helium in the main loops.

*C1.2.4.2.2 Test Duration*

The duration of the test and monitoring is estimated to be three years.

*C1.2.4.2.3 Proposed Test Location*

The PBMR HTF at Pelindaba.

#### C1.2.4.3 Measured Parameters

Time available for tests, downtime, mass flow, power consumption, pressure rise across blower, blower speed across the pressure ranges as listed in the blower specifications and requirement.

#### C1.2.4.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards and QA.

#### C1.2.4.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower specification and requirements.

#### C1.2.4.6 Test Deliverables

A test report shall be compiled after the tests containing the following:

- Test equipment and calibration
- Test software used
- Data recorder
- Type of observations
- Results and acceptability
- Actions taken in connection with any deviations noted
- Unresolved anomalies
- Data inputs to the final design of the blower.

#### C1.2.4.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality reasons. Actual testing, data reduction and the compilation of the test report are expected to take three years. There is a medium risk associated with the test due to the high working pressures.

# C2 TECHNOLOGY MATURATION PLAN FOR CCS (TRL 7 TO TRL 8)

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the CCS from a TRL level of 7 to a TRL of 8. The activities include testing the final components of the assembled together as unit in operating conditions that are exactly the same as the system operating conditions. It is PBMR's contention that the operating conditions of the DPP are such that the requirements of an operational environment are met, so that a TRL-8 can be achieved through the use of the DPP prior to installation in the NGNP. The specific operational parameters of the NGNP CCS which are not enveloped by the DPP will be tested in the NGNP as part of the NGNP commissioning program, but do not contribute to the maturation of the technology of the CCS.

### C2.1.2 Scope

The maturation tasks and other associated activities to advance the maturity of the technology of the CCS from TRL 7 to TRL 8 are listed below:

- Conduct operational tests for the integrated CCS.
- Conduct blower tests at operational temperature.

### C2.1.3 Anticipated Schedule

The test is expected to last at least two years.

### C2.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality reasons.

# C2.2 TEST SPECIFICATIONS

## C2.2.1 CCS Test Specification #3: CCS Integrated Testing (WEC-TS-CCS-003)

### C2.2.1.1 Objectives

The objectives of the test include:

a) CCS functional test
b) Cold integrated flow test
c) Pressure boundary integrity test
d) CCS test in helium
e) CCS first nuclear test
f) CCS full capability test
g) Operational monitoring

### C2.2.1.2 Test Conditions

The functional test would be conducted in compressed air at 60 bar pressure and ambient temperature. Humidity would be in the region 50-70%. When confidence is built that the CCS is properly functional in air, the same test will proceed as a cold integrated flow test with helium as a medium. The helium temperatures will be elevated. The other tests will proceed with helium in the pressure ranges 100-6000 kPa and elevated temperatures. The CCS full capability test would be conducted with the CCS connected to the operating PBMR DPP reactor at temperatures of 900 °C and 90 bar pressure.

#### *C2.2.1.2.1 Test Configuration/Set-up*

The inlet pipe of the CCS is connected to the DPP reactor gas outlet pipe and the outlet pipe of the CCS is connected to the DDP reactor gas inlet pipe.

#### *C2.2.1.2.2 Test Duration*

The testing, data collection and report writing for the test will take approximately two years.

#### *C2.2.1.2.3 Proposed Test Location*

The test will be performed at the PBMR DPP power plant at Koeberg, Cape Town.

#### C2.2.1.3 Measured Parameters

Time available for operation, downtime, mass flow, leakage rates, power consumption, system pressure, cooling achieved, performance across pressure ranges as listed in the CCS specifications and requirements.

#### C2.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards and QA.

#### C2.2.1.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower specification and requirements. Specifically:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

#### C2.2.1.6 Test Deliverables

A test report shall be compiled after the tests containing the following:

- Test equipment and calibration
- Test software used
- Data recorder
- Type of observations
- Results and acceptability
- Actions taken in connection with any deviations noted
- Unresolved anomalies
- Data inputs for the refinement of the CCS system .

#### C2.2.1.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality reasons. Actual testing, data reduction and the compilation of the test report are expected to take one year. There is a medium risk associated with the test due to the high working pressures.

### C2.2.2 CCS Test Specification #4: CCS Blower at Operational Temperatures (WEC-TS-CCS-004)

#### C2.2.2.1 Objectives

The objectives of the test include:

a) Validation of the blower maps at various temperatures and pressures.

#### C2.2.2.2 Test Conditions

The blower is installed in the DPP main power system as part of the CCS. The DPP main power system is heated to 350°C using the primary loop initial clean-up system heaters with either nitrogen or helium and circulated through the main power system (including reactor core) using the CCS blower. The CCS blower commences circulating the gas while the system is being pressurized up to a maximum of 9MPa. The CCS heat exchanger is disabled allowing the circulation gas to reach the CCS blower at approximately 300°C. The CCS blower is monitored at this temperature to determine its functionality as part of the integrated system at high temperatures.

*C2.2.2.2.1 Test Configuration/Set-up*

DPP fully assembled and ready for commissioning. Reactor core filled with fuel-free machined graphite spheres.

The Primary Loop Initial Clean-up System is attached to the main power system helium pressure boundary.

Clean nitrogen is available for initial pressurization and evacuation of main power system.

*C2.2.2.2.2 Test Duration*

The duration of the test will be determined by the moisture content of the circulating nitrogen. (The main purpose of this phase of DPP commissioning is cleaning up the main power system, particularly the reactor core).

*C2.2.2.2.3 Proposed Test Location*

The PBMR DPP at Koeberg, Cape Town.

#### C2.2.2.3 Measured Parameters

- Time
- Blower speed

- Blower power consumption
- Mass flow rates
- Input temperature
- Output temperature
- Input pressure
- Output pressure
- Other condition monitoring parameters such as vibration, power factor, bearing cooling, etc.

#### C2.2.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards and QA.

#### C2.2.2.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower specification and requirements.

#### C2.2.2.6 Test Deliverables

A test report shall be compiled after the tests containing the following:

- Test equipment and calibration
- Test software used
- Data recorder
- Type of observations
- Results and acceptability
- Actions taken in connection with any deviations noted
- Unresolved anomalies
- Data inputs for the refinement of the CCS system.

#### C2.2.2.7 Cost, Schedule, and Risk

The PBMR related cost has not been specifically highlighted as this test forms part of the normal start-up of the DPP. It is not anticipated that the test will require the DPP schedule to be adjusted for the purposes of the data gathering. The risks should have been addressed by the time the DPP is ready for commissioning.

NGNP-CTF MTECH-TDRM-016 November 2008
Revision 1

# NGNP and Hydrogen Production Conceptual Design Study

# NGNP Technology Development Road Mapping Report

# Section 16: Reactor Cavity Cooling System

**APPROVALS**

| Function | Printed Name and Signature | Date |
|---|---|---|
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# BACKGROUND INTELLECTUAL PROPERTY CONTENT

| Section | Title | Description |
|---|---|---|
| N/A | | |

**REVISION HISTORY**

# RECORD OF CHANGES

| Revision No. | Revision Made by | Description | Date |
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| A | Werner van Antwerpen | Comments Review | September,15 2008 |
| B | Werner van Antwerpen | Formal Review | September, 25 2008 |
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| Created to Support the Following Document(s) | Document Number | Revision |
|---|---|---|
| NGNP and Hydrogen Production Preconceptual Design Report | NGNP-01-RPT-001 | 0 |

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# ACRONYMS

| Acronym | Definition |
|---|---|
| AI | Inner Annulus (active cooling piping) |
| AMS | Activity Measurement System |
| AO | Outer Annulus (active cooling piping) |
| AOO | Anticipated Operational Occurrence |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchs-Reaktor |
| BOP | Balance of Plant |
| BUMS | Burn-up Measurement System |
| CB | Core Barrel |
| CCS | Core Conditioning System |
| CEA | Commissariat à l'Énergie Atomique |
| CFD | Computational Fluid Dynamics |
| CHE | Compact Heat Exchanger |
| CIP | Core Inlet Pipe |
| CO2 | Carbon Dioxide |
| COC | Core Outlet Connection |
| COP | Core Outlet Pipe |
| COTS | Commercial Off The Shelf |
| CRADA | Co-operative Research and Development Agreement |
| CRD | Control Rod Drive |
| CSC | Core Structure Ceramics |
| CTF | Component Test Facility |
| CTF | Component Test Facility |
| CUD | Core Unloading Devices |
| DAU | Data Acquisition Unit |
| DBA | Design Base Accident |
| DBE | Design Base Event |
| DDN | Design Data Need |
| DFC | Depressurized Forced Cooling |
| DLOFC | De-pressurized Loss of Forced Cooling |
| DOE | Department of Energy |
| DPP | Demonstration Power Plant |
| DRL | Design Readiness Level |
| DWS | Demineralized Water System |
| ELE | Elecrolyser System |
| EM | Evaluation Model |
| EMB | Electomagnetic Bearing |
| EOFY | End of Fiscal Year |
| EPCC | Equipment Protection Cooling Circuit |
| EPCT | Equipment Protection Cooling Tower |
| F&OR | Functional and Operational Requirements |
| FHS | Fuel Handling System |

| | |
|---|---|
| FHSS | Fuel Handling and Storage System |
| FIMA | Fissions per Initial Metal Atoms |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| FS | Fuel Spheres |
| FTA | Fault Tree Analysis |
| FUS | Feed and Utility System |
| H2 | Hydrogen |
| H2SO4 | Sulfuric Acid |
| HC | Helium Circulator |
| He | Helium |
| HETP | Height Equivalent of the theoretical Plate |
| HGD | Hot Gas Duct |
| HI | Hydro-Iodic |
| HLW | High Level Waste |
| HPB | Helium Pressure Boundary |
| HPC | High Pressure Compressor |
| HPS | Helium Purification System |
| HPS | Hydrogen Production System |
| HPT | High Pressure Turbine |
| HPU | Hydrogen Production Unit |
| HRS | Heat Removal System |
| HTF | Helium Test Facility |
| HTGR | High Temperature Gas-Cooled Reactor |
| HTR | High Temperature Reactor |
| HTS | Heat Transport System |
| HTSE | High Temperature Steam Electrolysis |
| HTTR | High Temperature Test Reactor |
| HVAC | Heating Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| HyS | Hybrid Sulfur |
| I&C | Instrumentation and Control |
| I2 | Iodine |
| ID | Inner Diameter |
| IHX | Intermediate Heat Exchanger |
| ILS | Integrated Laboratory Scale |
| I-NERI | International Nuclear Energy Research Initiative |
| INL | Idaho National Laboratory |
| INL | Idaho National Laboratory |
| IPT | Intermediate Pressure Turbine |
| ISR | Inner Side Reflector |
| K-T | Kepner-Tregoe |
| KTA | German nuclear technical committee |
| LEU | Low Enriched Uranium |
| LOFC | Loss of Forced Cooling |
| LPT | Low Pressure Turbine |
| MES | Membrane-electrode assembly |
| MTR | Material Test Reactor |

| | |
|---|---|
| NAA | Neutron Activation Analysis |
| NCS | Nuclear Control System |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NHS | Nuclear Heat Supply |
| NHSS | Nuclear Heat Supply System |
| NNR | National Nuclear Regulator |
| NRG | Nuclear Research and consultancy Group |
| NRV | Non-Return Valve |
| O2 | Oxygen |
| OD | Outer Diameter |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Power Conversion System |
| PCDR | Pre-Conceptual Design Report |
| PCHE | Printed Circuit Heat Exchanger |
| PCHX | Process Coupling Heat Exchanger |
| PCS | Power Conversion System |
| PFHE | Plate Fin Heat Exchanger |
| PHTS | Primary Heat Transport System |
| PIE | Post-irradiation Examination |
| PLOFC | Pressurized Loss of Forced Cooling |
| POC | Power Conversion System |
| PPM | Parts per million |
| PPU | Product Purification Unit |
| PPWC | Primary Pressurized Water Cooler |
| QA | Quality Assurance |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RDM | Rod Drive Mechanism |
| RIM | Reliability and Integrity Management |
| RIT | Reactor Inlet Temperature |
| RM | Road Map |
| ROT | Reactor Outlet Temperature |
| RPS | Reactor Protection System |
| RPT | Report |
| RPV | Reactor Pressure Vessel |
| RS | Reactor System |
| RSS | Reserve Shutdown System |
| RUS | Reactor Unit System |
| SAD | Acid Decomposition System |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Spheres |
| SG | Steam Generator |
| SHTS | Secondary Heat Transport System |

| | |
|---|---|
| S-I | Sulfur Iodine |
| SiC | Silicon Carbide |
| SNL | Sandia National Laboratory |
| SO2 | Sulfur Dioxide |
| SOE | Sulfuric Oxide Electrolyzers |
| SOEC | Sulfuric Oxide Electrolyzers Cells |
| SR | Side Reflector |
| SSC | System Structure Component |
| SSCs | Systems, Structures and Components |
| SSE | Safe Shutdown Earthquake |
| SUD | Software Under Development |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TDL | Technology Development Loop (As incorporated in Concept 1) |
| TDRM | Technology Development Road Map |
| TER | Test Execution Report |
| THTR | Thorium High Temperature Reactor |
| TRISO | Triple Coated Isotropic |
| TRL | Technology Readiness Level |
| TRM | Technology Road Map |
| UCO | Uranium Oxycarbide |
| UO2 | Uranium Dioxide |
| USA. | United States of America |
| V&V | Verification and Validation |
| V&Ved | Verified and Validated |
| VLE | Vapor-Liquid Equilibrium |
| WBS | Work Breakdown Structure |
| WEC | Westinghouse Electric Company |

# SUMMARY AND CONCLUSIONS

The RCCS system is envisaged by the NGNP WEC-team to be utilized in a similar operational environment to that of the PBMR Demonstration Power Plant (DPP). The RCCS is required to maintain the reactor citadel concrete structure within allowable temperatures through heat removal and shielding of the concrete from direct thermal radiation during normal and abnormal conditions. The DPP RCCS design is expected to be employed as is for the PBMR NGNP, with possibly only minor changes to water reservoir requirements.

The current TRL status of the DPP RCCS is rated at TRL 6.

Progression from TRL 6 to TRL 7 will be achieved through analysis while progression to TRL 8 will be through the commissioning and operation of the DPP.

The current DPP RCCS strategy is to utilize two independent internationally recognized software codes RELAP5™ and SPECTRA™ to evaluate the passive operation of the RCCS. To date, both software codes have indicated that the RCCS will adequately satisfy its requirements.

However, the benefits of testing to reduce risk are acknowledged and therefore PBMR is investigating further means for validating RCCS software code models. The definition of these validation tests has not yet been fully developed – although it is favored to use representative part-scale testing.

Even though PBMR is investigating supplementary testing, additional testing by others will be welcomed by PBMR through a CRADA-type arrangement if 1) the tests are representative of the PBMR RCCS design (PBMR to provide test specification inputs), 2) the tests can be conducted by the 2010 timeframe and 3) if PBMR are involved with the test definitions and execution of such tests.

NOTE: The test specifications given in this document [CTF Deliverable] are only applicable to full-scale testing in the DPP (implying that analyses will progress the RCCS to TRL 7 and the DPP commissioning will progress the RCCS from TRL 7 to TRL 8).

# 16 REACTOR CAVITY COOLING SYSTEM

## 16.1 RCCS Description/ Function and Operating Requirements

In order to utilize common materials with the goal of keeping the PBMR affordable, a requirement arose for a system capable of keeping the selected citadel structural concrete within its code limits during normal operations and anticipated operational occurrences by removing waste heat from the cavity and shielding the concrete from thermal radiation. This gave rise to the Reactor Cavity Cooling System (RCCS).

The RCCS design is derived from the following functional requirements:

- Operational Functions
  - Remove normal operational waste heat from the reactor cavity with the following performance parameters:
    - Maintain reactor cavity concrete surface temperature below code limit to allow continuous operation for the full operational life of the plant.
- Safety Functions
  - Remove decay heat from reactor cavity during design bases events :
    - During passive operation the RCCS maintains the reactor supports and load bearing concrete within their design temperatures.

Although not a specifically allocated function, it is noted that through removing heat from the reactor cavity, the RCCS assists the primary cooling flow (internal to the RPV) to keep the RPV temperature below code limits for the full operational life of the plant.

In response to the above requirements, the RCCS design consists of the following:

- 72 overlapping oval standpipes located between the RPV and the cavity wall, the overlap ensuring that there is no thermal radiation line of sight between the RPV and the concrete
- Water storage tanks (with sufficient water for 72 hours of passive operation without refilling)
- Headers, filters, steam vents and associated piping
- Manually operated valves for maintenance operations
- Instrumentation

Redundancy is catered for by feeding the 72 standpipes from 18 independent tanks. The standpipes from the same tank are segregated to limit concentration of hot areas should one system fail. In terms of redundancy, significantly less than the full complement is needed to remove the full heat load, however due to the possibility of hot spots forming on the concrete when two or more adjacent standpipes are non-functional, credit is not taken for more than one train being unserviceable at a time.

The RCCS operates as follows:

The RCCS removes waste heat from the Reactor Cavity (RC). During normal operations, the RCCS operates in Active Mode when water is circulated through the standpipes by the Equipment Protection Cooling Circuit (EPCC) pumps. The heat is transferred to the water in the standpipes and dissipated through the main heat sink, or the Equipment Protection Cooling Tower (EPCT) as back-up.

In case of failure of the Active Mode, the RCCS is capable of operating in a Passive Mode. Water circulates through the standpipes by convection flow only, thus operating as thermal siphons with cool water descending through the standpipe's inner tube and the warm water rising in the outer section. The water is supplied from the storage tanks mounted above the reactor and boils off to the atmosphere after the initial heat-up period.

The different flow paths of the active and passive operation are illustrated in Figure 16-1 and Figure 16-2 below. Switching from active to passive operation will take place without any mechanical, electrical or human intervention.

Only the passive mode of operation of the RCCS is a safety classified function. The RCCS components are seismically designed to be capable of functioning during and after a Safe Shutdown Earthquake (SSE).

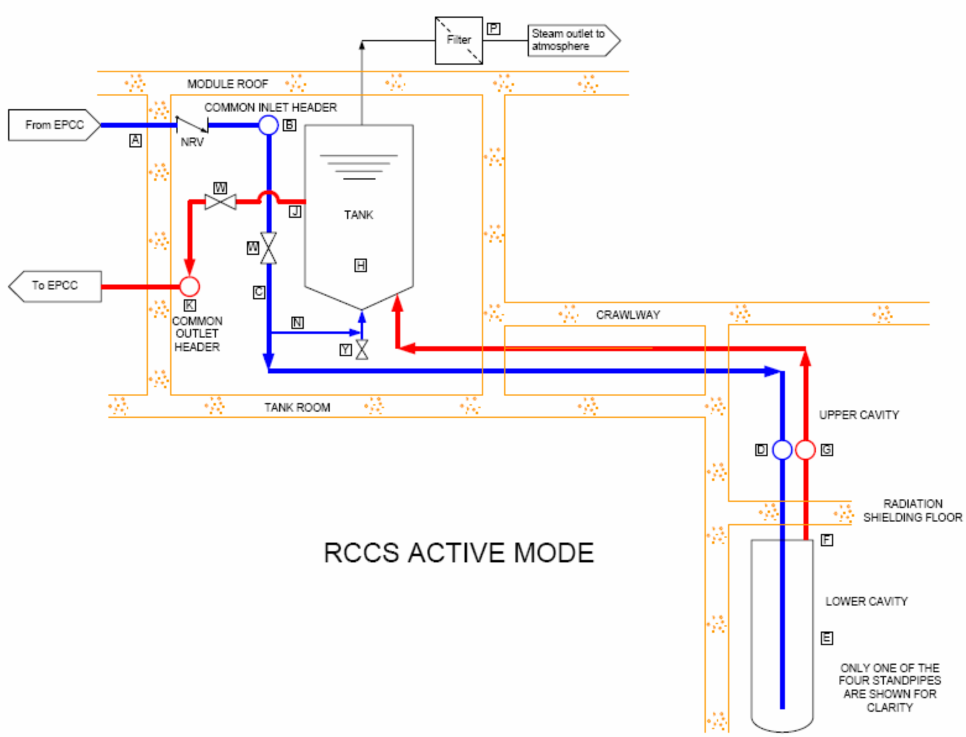



**Figure 16-1**: Flow direction of the water in the RCCS during active operation.

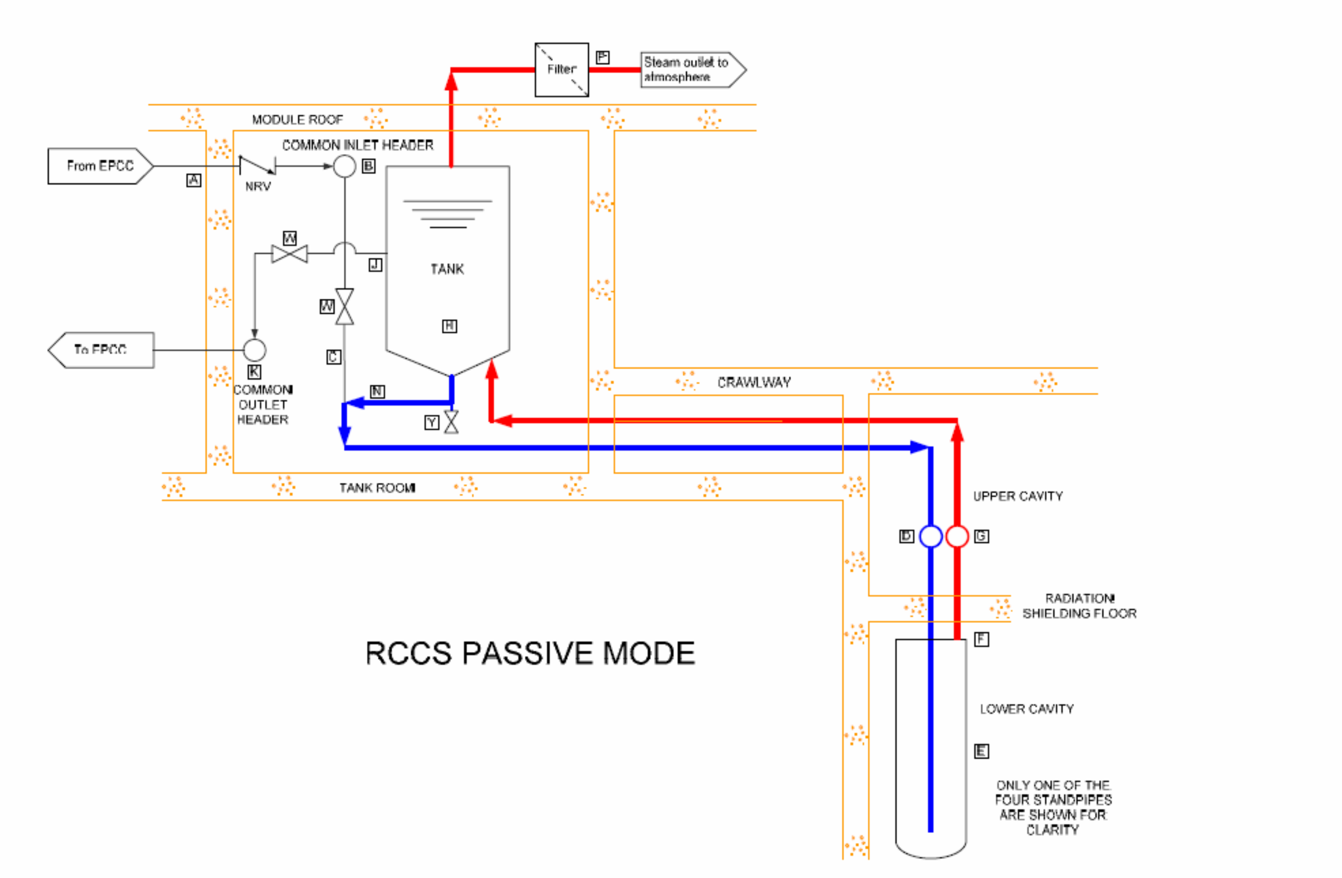



**Figure 16-2: Flow directions of the water in the RCCS during passive operation.**

Figure 16-3 shows the general layout of the RCCS, while Figure 16-4 and Figure 16-5 show details of various components. The water storage tanks are located above the reactor cavity to ensure the continuous feed of water into the thermal siphons during passive mode. The RCCS inlet header is connected to the EPCC via a non-return valve (NRV) and vacuum breaker valves to prevent the header emptying if the EPCC feed pipe should rupture. Backup water supply lines from the demineralized water system (DWS) and EPCT are attached between the NRV and the RCCS inlet header. A particle filter separates the steam header from outside air, and allows the tanks to remain at atmospheric pressure while preventing contaminants from entering the system.

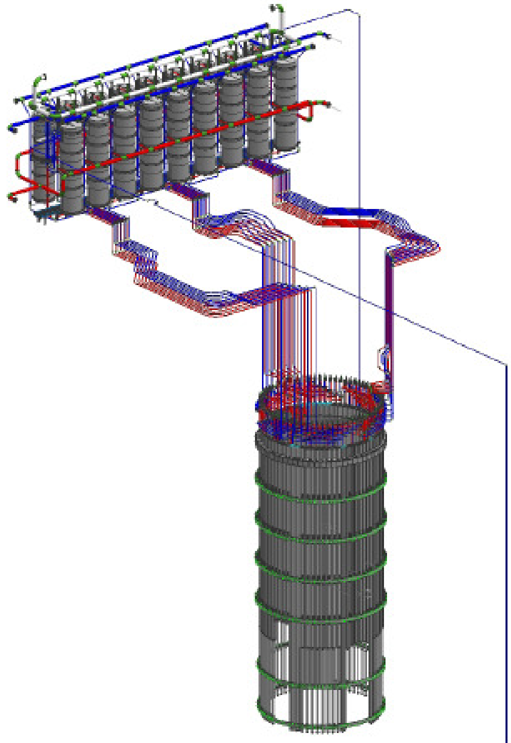


**Figure 16-3: General arrangement of RCCS components.**

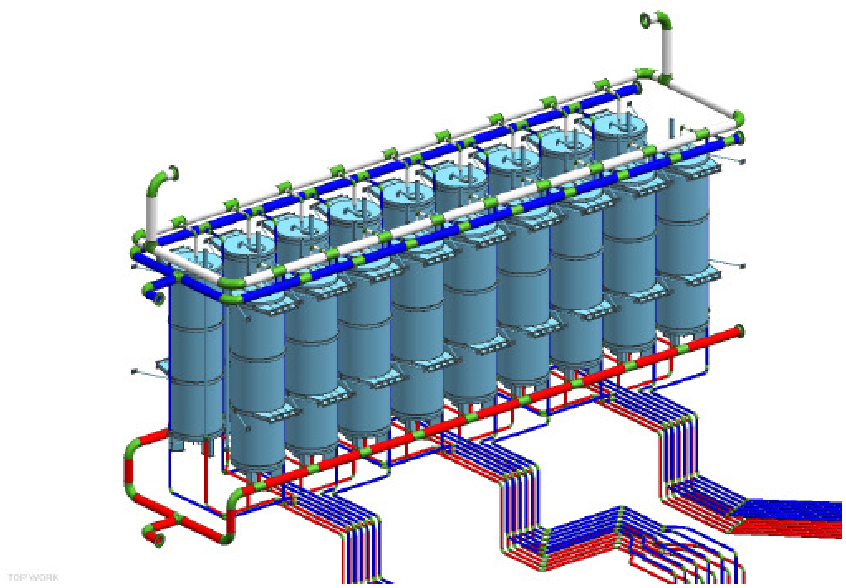
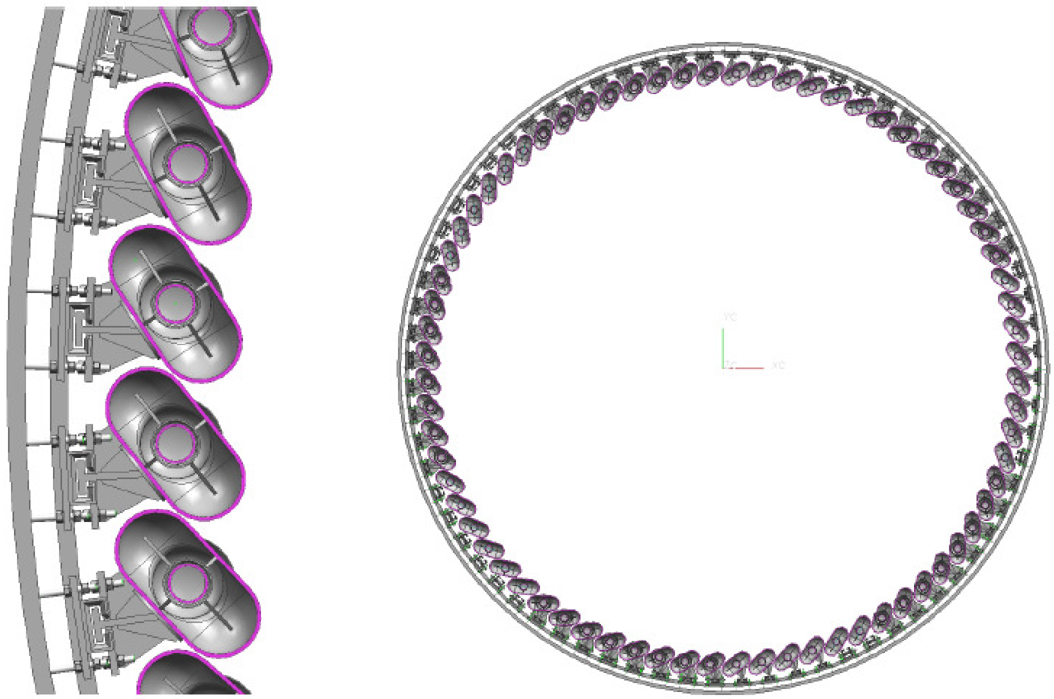


**Figure 16-4: Arrangement of water storage tanks. Top header is for steam release; second from top is the water inlet header. Bottom header returns water to the EPCC.**



**(a)** **(b)**

**Figure 16-5: Cross sectional view of the RCCS standpipes.**
**(a) Proposed details of the standpipes with their sliding supports.**
**(b) The 72 standpipes as they are arranged in the reactor cavity. The oval shape and overlapping arrangement prevents thermal radiation from the reactor pressure vessel from impinging directly onto the concrete walls of the cavity.**

Inside the reactor cavity, the surface of the standpipes facing the RPV may be exposed to temperatures of up to 350˚C during normal operation. Other components, such as distribution pipes and tanks, may experience temperatures up to approximately 100℃, but generally, environmental conditions during normal operation will be mild. The standpipes and supports are designed to safely withstand these conditions. The RCCS in active mode has a total mass flow of 135 kg/s with an inlet temperature of 18℃ and an outlet temperature of approximately 22℃.

## 16.2 Technology/Design Selection Status

The RCCS is nearing completion of its basic design. The technology base is considered to be established for the DPP, and no new technology needs to be examined. An alternative design utilizing heat pipes is being evaluated for future plants, though the DPP design remains the basis for the PBMR NGNP.

### 16.2.1 Candidate Technologies – RCCS

N/A

### 16.2.2 Decision Discriminators

N/A

### 16.2.3 Reference Design

N/A

### 16.2.4 Alternative for Further Evaluation

N/A

### 16.2.5 Down Selection Task

N/A

## 16.3 TRL Status

Evaluations of the status of technology for the RCCS system were made and resulted in a TRL 6 rating. This determination was made during compilation of the NGNP-DRL &TRL Report and is shown in Appendix A.

It should be noted that the HTTR Test Reactor in Japan to which reference is made is significantly smaller than the system being designed for the PBMR. However the technical concept of thermo-siphons is clearly a TRL 9 – it is just the specific design of the PBMR application which holds the system back from being a TRL of 8.

## 16.4 Technology Development Road Map Summary

### 16.4.1 Overview

Given the maturity of the DPP design and the exact applicability of this design to the NGNP, the left hand side of the TDRM is considered complete. The RCCS system begins with a TRL of 6 on the right hand side of the TDRM and matures to a TRL of 8 when all the tests are completed in the DPP.

## 16.5 Technology Maturation Plan Summary

The sections below describe in detail the maturation tasks needed to advance the technology of the RCCS from a validated TRL 6 to a validated TRL 8.

### *16.5.1 Maturation Tasks for RCCS*

The following section will show the Technology Maturation Plan required to progress this technology from a TRL 6 to a TRL 8.

#### 16.5.1.1 Maturation Tasks from TRL 6 to TRL 7.

To move from a TRL 6 to a TRL 7, the TRL definition requires:

- Subsystem integrated into a system for integrated engineering scale demonstration in a relevant environment.

Two independent internationally recognized software codes RELAP5™ and SPECTRA™ were used to evaluate the passive operation of the RCCS. Both software codes indicated that the RCCS will adequately satisfy its requirements. Verification and validation of the boundary conditions used in the models[1] will be performed as part of preparation for operational readiness (including sensitivity analysis). Software verification and validation has been considered as sufficient to advance the TRL level from 6 to 7.

Recognizing the benefits of testing to reduce risk, PBMR is investigating further means for validating the numerical model used to simulate the RCCS in the software. The definition of these validation tests has not yet been fully developed – although it is favored to use representative part-scale testing.

Even though PBMR is investigating supplementary testing, testing by others is welcomed through a CRADA-type of arrangement if:

- The tests are representative of the PBMR RCCS design.
- The tests can be conducted by the 2010 timeframe.
- If PBMR is involved in the test definitions and execution of such tests.

#### 16.5.1.2 Maturation Tasks from TRL 7 to TRL 8.

To move from a TRL 7 to a TRL 8, the TRL definition requires:

[1] Being nuclear approved codes the software has undergone V&V and its range of application has been defined. The issue of low pressure application has specifically been addressed. The V&V of the boundary conditions intends to show that the model of the RCCS used in the code is valid.

- Integrated prototype of the system is demonstrated in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance.
- Analyses, if used, support extension of demonstration to all design conditions.
- Analysis methods verified and validated.
- Technology issues resolved pending qualification (for nuclear application, if required).
- Demonstrated readiness for hot startup.

It is recognized that further testing will serve to reduce risks associated with the RCCS, notably to confirm input assumptions and integrated operation. However, the construction of a RCCS test set-up is complicated by the complexity of the interdependencies of the RCCS boundary conditions, namely heat transfer to adjacent standpipes, air circulation created by the specific arrangement of the RPV and other components in the cavity, and convection currents within each standpipe. A test setup will therefore have to simulate the reactor cavity. These reasons, and the subsequent timescales and budget, tend to favor that the RCCS be tested full-scale in the DPP for the first time. For the purposes of this document only the DPP "commissioning-type" tests of the RCCS are presented.

## 16.6 Inputs to CTF

Not applicable. For the purposes of the NGNP, the RCCS would be qualified to a TRL-8 by the DPP and hence no RCCS unique tests are required for the RCCS in the CTF.

## 16.7 References

[16-1] NGNP-TRL & DRL Report, Rev 0: Report on Design Readiness Levels and Technology Readiness Levels

# APPENDIX A: TRL RATING SHEET

**Table A-1**: TRL Rating Sheet of the RCCS

| **TRL Rating Sheet** | | | |
|---|---|---|---|
| Vendor Name: | Document Number: 010 | Revision: 1 | |
| ☐ Island ☑ System ☐Subsystem/Structure ☐ Component ☐ Technology | | | |
| Title: Reactor Cavity Cooling System | | | |
| Description:<br>The Reactor Cavity Cooling System removes heat from the reactor cavity and limits temperatures of the Reactor Unit System and NHS structure. | | | |
| Area(s): ☑ NHSS ☐ HTS ☐ HPS ☐ PCS ☐ BOP | | | |
| ISSCTBS: N/A | Parent: N/A | WBS: N/A | |
| **Technology Readiness Level** | | | |
| | Next Lower Rating Level | Calculated Rating | Next Higher Rating Level |
| Generic Definitions *(abbreviated)* | Component or system breadboard in relevant environment | Similar SSC in relevant environment in another application | Prototype demonstration in relevant environment |
| **TRL** | 5 | **6** | 7 |
| Basis for Rating (Attach additional sheets as needed):<br>There is operating experience with similar system in the HTTR, their Vessel Cooling System. Will be TRL-8 when PBMR DPP operates. | | | |
| Outline of a plan to get from current level to next level (Attach additional sheets as needed) | | | |
| Actions (list all) | Schedule | Cost (K$) | |
| | FY 2009 – FY 2012 | | |
| DDN(s) supported: None | | | |
| SME Making Determination: Ivan Drotsky | | | |
| Date: September 2008 | Originating Organization: PBMR (Pty) Ltd | | |

# APPENDIX B: TECHNOLOGY DEVELOPMENT ROAD MAP

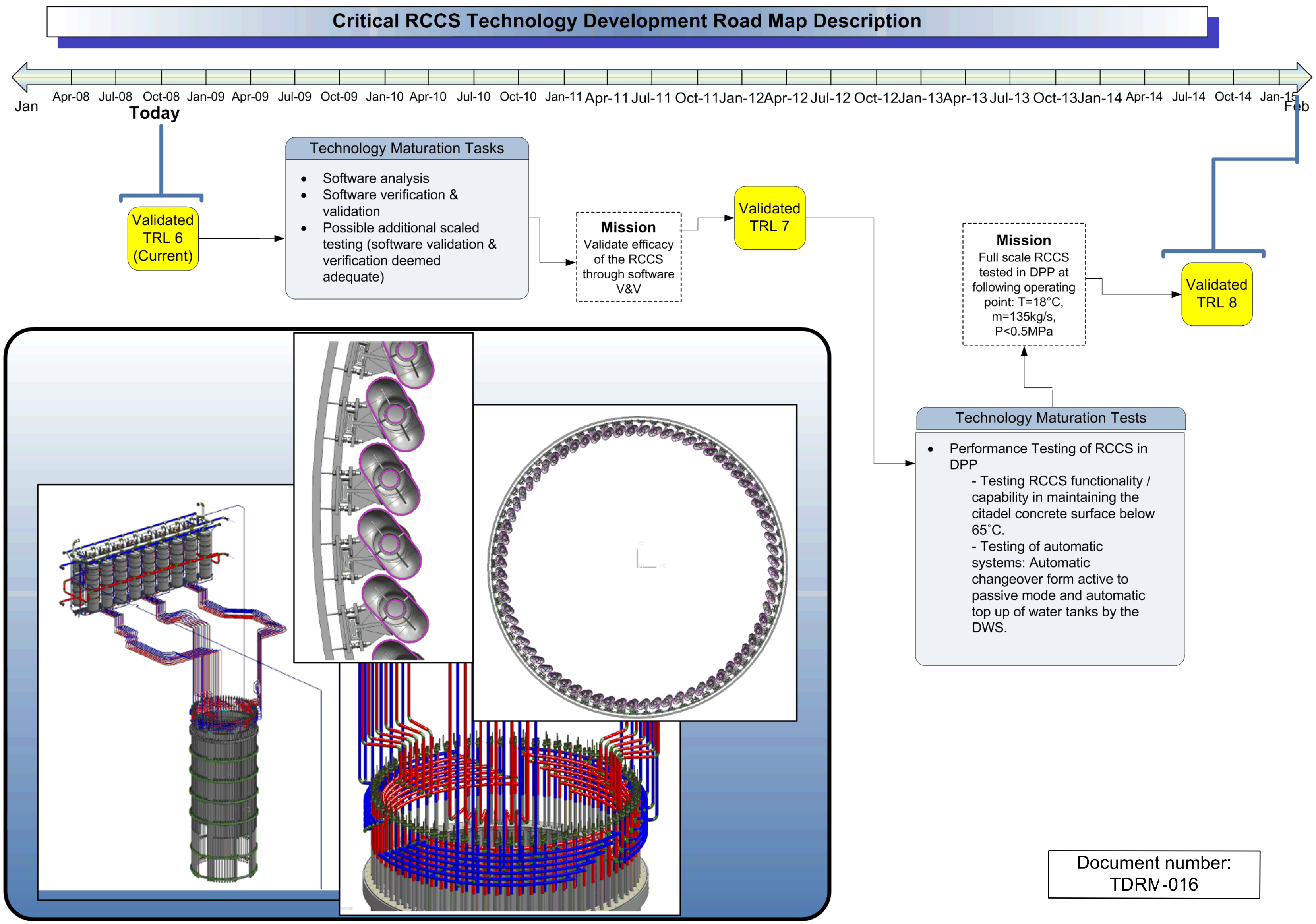



**Figure B-1**: Technology Development Road Map of the RCCS.

# APPENDIX C: TECHNOLOGY MATURATION PLAN

## TABLE OF CONTENTS

## REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

**TRL 6 to TRL 7:**

- No specifications have been defined as of yet. Only software analysis will be conducted. Physical testing to verify and validate the analysis may be considered in future.

**TRL 7 to TRL 8:**

- Specification 1: Verify the functioning of the RCCS with respect to maintaining Reactor Cavity concrete below code limits (WEC-TS-RCCS-001).
- Specification 2: Confirm operation of RCCS tank automatic water replenishment function (WEC-TS-RCCS-002).
- Specification 3: Validate analysis of DWS supply and heat sink performance (WEC-TS-RCCS-003).
- Specification 4: Validate theoretical analysis of pump trip effect on RCCS pressure (WEC-TS-RCCS-004).

# C1 RCCS TECHNOLOGY MATURATION PLAN (TRL 6 TO TRL 7)

## C1.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C1.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology from a TRL of 6 to a TRL of 7. The maturation tasks required to achieve this goal will be through analysis only. Physical testing may be considered to verify the input data used in the analysis.

### C1.1.2 Scope

Only if it is decided to perform physical tests, the scope of the tests will be defined.

### C1.1.3 Anticipated Schedule

The analysis of the RCCS could be accomplished during the period FY2008 through FY2010.

### C1.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

## C1.2 TEST SPECIFICATIONS

For the purpose of advancing the TRL to a 7, no tests have been defined as of yet. Advancement to the next TRL will only be achieved through software analysis. Physical testing may be considered to verify the input data used in the analysis.

# C2RCCS TECHNOLOGY MATURATION PLAN (TRL 7 TO TRL 8)

## C2.1 TECHNOLOGY MATURATION PLAN SUMMARY

### C2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology from a TRL of 7 to a TRL of 8. The maturation tasks required to achieve this goal involve testing at the DPP to commission and qualify the RCCS. Test specifications are listed below for the full-scale testing in the DPP, representing the required though not all expected testing.

### C2.1.2 Scope

The testing deemed necessary for technology maturation to TRL 8 are listed in Table C.1.

**Table C.1: Compliance tests (summary)**

| Description | Test Compliance |
|---|---|
| Verify the functioning of the RCCS with respect to maintaining Reactor Cavity concrete within specification (WEC-TS-RCCS-001). | Reactor Cavity wall remains below 65°C. |
| Confirm operation of RCCS tank automatic water replenishment function (WEC-TS-RCCS-002). | DWS automatically replenishes the RCCS tanks |
| Validate analysis of DWS supply and heat sink performance (WEC-TS-RCCS-003) | Based on a sea water temperature of 15 °C, 135 kg/s of inhibited demineralized water at a design temperature of 18 °C will be supplied to the RCCS. |
| Validate theoretical analysis of pump trip effect on RCCS pressure (WEC-TS-RCCS-004). | EPCC pump trip does not result in pressures outside of design limits |

### C2.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2010 through FY2015.

### C2.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

# C2.2 TEST SPECIFICATIONS

## C2.2.1 RCCS Test Specification #1 (WEC-TS-RCCS-001)

### C2.2.1.1 Objectives

Verify the functioning of the RCCS with respect to maintaining Reactor Cavity concrete below code limits.

### C2.2.1.2 Test Conditions

The test will be performed under normal operational conditions with active mode of cooling in progress.

*C2.2.1.2.1 Test Configuration/Set-up*

RCCS fully installed in the DPP. Thermocouples will be installed in the concrete behind the standpipes for temperature monitoring.

*C2.2.1.2.2 Test Duration*

Between FY2012 through FY2015.

*C2.2.1.2.3 Proposed Test Location*

PBMR DPP.

### C2.2.1.3 Measured Parameters

- Synchronized Time
- Reactor thermal power
- RPV temperature
- RCCS water temperature (in/out)
- RCCS water flow rate
- Cavity concrete temperature
-

#### C2.2.1.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C2.2.1.5 Test Evaluation Criteria

Concrete temperature must be below 65°C under normal operating conditions.

#### C2.2.1.6 Test Deliverables

Time based plots for all parameters

#### C2.2.1.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality.

### C2.2.2 RCCS Test Specification #2 (WEC-TS-RCCS-002)

#### C2.2.2.1 Objectives

Confirm operation of RCCS tank automatic water replenishment function.

#### C2.2.2.2 Test Conditions

Reactor non-operational: Water will be drained manually from the tanks until the water level drops to the set point. Confirm activation of the level transmitters, and subsequent activation of the DWS replenishment. Confirm DWS shuts off when water level is at upper limit.

*C2.2.2.2.1 Test Configuration/Set-up*

RCCS fully installed in the DPP.

*C2.2.2.2.2 Test Duration*

Between FY2012 through FY2015.

*C2.2.2.2.3 Proposed Test Location*

PBMR DPP.

#### C2.2.2.3 Measured Parameters

- Synchronized time
- RCCS Water tank level
- DWS Reaction time
- DWS input water flow rate
- 

#### C2.2.2.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C2.2.2.5 Test Evaluation Criteria

Ensuring an automatic activation of the DWS without any human intervention.

#### C2.2.2.6 Test Deliverables

Monitoring the confirmation of the level transmitters, subsequently activating the DWS.

#### C2.2.2.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality.

### C2.2.3

### C2.2.4RCCS Test Specification #3 (WEC-TS-RCCS-003)

#### C2.2.4.1 Objectives

To validate analysis of DWS supply and heat sink performance

#### C2.2.4.2 Test Conditions

The test will be performed under normal operational conditions with active mode of cooling in progress.

*C2.2.4.2.1 Test Configuration/Set-up*

RCCS fully installed in the DPP.

*C2.2.4.2.2 Test Duration*

Between FY2012 through FY2015.

*C2.2.4.2.3 Proposed Test Location*

PBMR DPP.

### C2.2.4.3 Measured Parameters

- Synchronized Time
- RPV temperature
- RCCS water temperature (in/out)
- RCCS water flow rate
- RCCS water pressure
- DWS water supply flow rate
- DWS water pressure

### C2.2.4.4 Data Requirements

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

### C2.2.4.5 Test Evaluation Criteria

Based on a sea water temperature of 15 °C, confirm that 135 kg/s of inhibited demineralized water at a design temperature of 18 °C is supplied to the RCCS.

### C2.2.4.6 Test Deliverables

Mass flows of all the flow meters. Also the temperature measurements of the inlet and outlet temperatures of the RCCS.

### C2.2.4.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality.

### C2.2.5 RCCS Test Specification #4 (WEC-TS-RCCS-004)

#### C2.2.5.1 Objectives

Validate theoretical analysis of pump trip effect on RCCS pressure.

#### C2.2.5.2 Test Conditions

Reactor non-operational: The EPCC pumps will be tripped in various configurations, and pressure measurements taken to confirm theoretical analyses.

*C2.2.5.2.1 Test Configuration/Set-up*

RCCS fully installed in the DPP.

*C2.2.5.2.2 Test Duration*

Between FY2012 through FY2015.

*C2.2.5.2.3 Proposed Test Location*

PBMR DPP.

#### C2.2.5.3 Measured Parameters

- Synchronized Time
- EPCC pump electrical power
- EPCC pump pressure
- EPCC pump flow rate
- RCCS water pressure
- RCCS water temperature
- RCCS water flow rate

#### C2.2.5.4 Data Requirements

Continuous synchronized measurements of pump power, pressure and flow rate versus RCCS water pressure are to be captured.

Measured parameters will be determined using recognized techniques, codes, standards, and QA.

#### C2.2.5.5 Test Evaluation Criteria

The measured data must confirm theoretical analysis.

#### C2.2.5.6 Test Deliverables

Time history of trip & restart / pressure relationships.

#### C2.2.5.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality.