NGNP-TDI-TDR-RPT-G-00024 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C (Combined Report)

APPROVALS

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NGNP-TDI-TDR-RPT-00024 is issued to combine all reports listed above into a single PDF file per Client request. Future changes if required shall be made to individual sections of this combined document prior to revision and reissue of this document.

ACRONYMS & ABBREVIATIONS

Acronym	Definition
ACS	Active Cooling System
AGR	Advanced Gas-cooled Reactor
AI	Inner Annulus (active cooling piping)
AMS	Activity Measurement System
ANL	Argonne National Laboratory
AO	Outer Annulus (active cooling piping)
AOO	Anticipated Operational Occurrence
AS	Automation System
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATL	Air Test Loop
AVR	Arbeitsgemeinschaft Versuchs-Reaktor
B_4C	Boron Carbide
BEA	Battelle Energy Alliance
BNL	Brookhaven National Laboratory
BOP	Balance of Plant
BR	Bottom Reflector
BR	Brazing
BUMS	Burn-up Measurement System
C	Carbon
CB	Core Barrel
CBSS	Core Barrel Support Structure
CCS	Core Conditioning System
CEA	Commissariat à l'Énergie Atomique
CFD	Computational Fluid Dynamics
CFRC	Carbon Fibre Reinforced Carbon
CHE	Compact Heat Exchanger
CIP	Core Inlet Pipe
CO2	Carbon Dioxide
COC	Core Outlet Connection
COP	Core Outlet Pipe
COTS	Commercial Off The Shelf
CQL	Component Qualification Loop
CR	Centre Reflector
CRADA	Co-operative Research and Development Agreement
CRD	Control Rod Drive
CSC	Core Structure Ceramics
CSIR	Council for Scientific and Industrial Research
CTC	Component Test Capability (previously Component Test Facility)
CTF	Component Test Facility
CTOD	Crack Tip Opening Displacement

CUD	Core Unloading Devices
DAU	Data Acquisition Unit
DB	Diffusion Bonding
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
DSI	Double Seat Isolation
DTL	Dust Test Loop
DWS	Demineralized Water System
E	Energy
ECC	Engineering, Construction and Commissioning
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
FAGS	FHSS Auxiliary Gas Subsystem
FAT	Factory Acceptance Test
FEA	Finite Element Analysis
FEM	Finite Element Model
FGCS	FHSS Gas Conveying Subsystem
FHS	Fuel Handling System
FHSS	Fuel Handling and Storage System
FIMA	Fissions per Initial Metal Atoms
FIV	Flow Induced Vibration
FMECA	Failure Modes, Effects and Criticality Analysis
FOAKE	First Of A Kind Equipment
FRI	Flow Restricting Indexer
FS	Fuel Spheres
FSCS	FHSS Sphere Conveying Subsystem
FSF	Fundamental Safety Function
FSRS	FHSS Sphere Replenishment Subsystem
FSSS	FHSS Sphere Storage Subsystem
FSV	Fort St. Vrain
FTA	Fault Tree Analysis
FUS	Feed and Utility System
FZJ	Forschungszentrum Jülich
HC	Helium Circulator
HCF	High Cycle Fatigue
He	Helium

HETP	Height Equivalent of the theoretical Plate
HGD	Hot Gas Duct
HLW	High Level Waste
HPB	Helium Pressure Boundary
HPC	High Pressure Compressor
HpGe	Hyper-pure Germanium
HPS	Helium Purification System
HPT	High Pressure Turbine
HRS	Heat Removal System
HTF	Helium Test Facility
HTGR	High Temperature Gas-Cooled Reactor
HTR	High Temperature Reactor
HTR-PM	High Temperature gas-cooled Reactor Pebble-bed Module
HTS	Heat Transport System
HTSE	High Temperature Steam Electrolysis
HTSST	Heat Transport Small-Scale Testing
HTTR	High Temperature Test Reactor
HVAC	Heating Ventilation and Air Conditioning
HX	Heat Exchanger
I&C	Instrumentation and Control
ID	Inner Diameter
IHX	Intermediate Heat Exchanger
I-NERI	International Nuclear Energy Research Initiative
INL	Idaho National Laboratory
IPT	Intermediate Pressure Turbine
ISR	Inner Side Reflector
Kc	Fracture Toughness
kg	Kilogram
K-T	Kepner-Tregoe
KTA	German nuclear technical committee
kW	Kilowatt
LANL	Los Alamos National Laboratory
LBE	Licensing Basis Events
LCF	Low Cycle Fatigue
LEU	Low Enriched Uranium
LOFC	Loss of Forced Cooling
LOSC	Loss of Secondary Cooling
LOSP	Loss of Secondary Pressure
LPT	Low Pressure Turbine
LRS	Lateral Restraint Strap
m	Meter
MAGNOX	Magnesium Non-Oxidizing
MeV	Mega electron-Volt
MHTGR-SC	Modular HTGR Steam Cycle
MPa	Megapascal
MPS	Main Power System

MTR	Material Test Reactor
MW	Megawatt
MWt	Megawatt Thermal
MY	Man Year
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
O_2	Oxygen
OD	Outer Diameter
OCR	Outer Centre Reflector
ORNL	Oak Ridge National Laboratory
OSR	Outer Side Reflector
PB	Pressure Boundary
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
PPWC	Primary Pressurized Water Cooler
PSMP	PBMR Specific Materials Test Reactor Programme
QA	Quality Assurance
QC	Quality Control
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
s	Second
SAR	Safety Analysis Report
SAS	Small Absorber Spheres
SCADA	Supervisory Control and Data Acquisition
SEM	Scanning Electron Microscope
SG	Steam Generator
SHTS	Secondary Heat Transport System
SiC	Silicon Carbide
SNL	Sandia National Laboratory
SOW	Statement of Work
SPU	Shaft Penetration Unit
SR	Side Reflector
SRNL	Savannah River National Laboratory
SSC	System Structure Component
SSCs	Systems, Structures and Components
SSDT	Small Scale Development Test
SSE	Safe Shutdown Earthquake
STIM	Surveillance, Testing, Inspection and Maintenance
SUD	Software Under Development
t	Ton
TBC	To Be Confirmed
TBD	To Be Determined
TDL	Technology Development Loop
TDRM	Technology Development Road Map
TER	Test Execution Report
THTR	Thorium High Temperature Reactor
TR	Tie Rod
TR	Top Reflector
TRISO	Triple Coated Isotropic
TRL	Technology Readiness Level
TRM	Technology Road Map
UCO	Uranium Oxycarbide
UO_2	Uranium Dioxide
USA	United States of America
V&V	Verification and Validation
V&Ved	Verified and Validated
W	Welding
WBS	Work Breakdown Structure
WEC	Westinghouse Electric Company

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NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 0: Introduction

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0 INTRODUCTION

0.1 Road to Technology Development Roadmapping Report for NGNP Steam Production (750℃-800℃)

The proposed reactor outlet temperature (ROT) for the Next Generation Nuclear Plant (NGNP) has been reduced from 950℃ down to 750℃-800℃. This change called for the creation of a Technology Development Roadmapping (TDRM) Report for NGNP Steam Production (750℃-800℃ ROT), and which would be based on the 950℃ TDRM Report [1]. The 950℃ TDRM Report was initially developed as part of the conceptual design studies of the NGNP.

As a precursor to this report, the Technology Readiness Levels of the NGNP SSCs were reviewed and updated taking into account the evolution of the design as well as the reduction in ROT [2]. Thereafter, through a careful review of the 950℃ TDRM Report for applicability to the new reference design (750℃-800℃), the list of critical SSCs was modified from that as given in [1]. Table 1 shows this list of critical SSCs applicable to the new reference design.

Table 1: Critical SSCs applicable to (i) 950℃ and (ii) 750℃-800℃ NGNP ROT

SSC	Applicability to 950℃	Applicability to 750℃-800℃	Comments
PHTS Circulator	☑	☑	-
IHX A	☑	-	Not required for 750°C-800°C
IHX B	☑	☑	Now denoted as IHX
HTS Piping	☑	☑	-
SHTS Flow Mixing Chamber	☑	-	Not required for 750°C-800°C
Hydrogen Production System[1]	☑	-	Not required for 750°C-800°C
PCS Steam Generator	☑	☑	-
Fuel Elements	☑	☑	-
Core Structure Ceramics	☑	☑	-
Reserve Shutdown System	☑	☑	-
Reactivity Control System	☑	☑	-
Core Conditioning System	☑	☑	-
Reactor Cavity Cooling System	☑	☑	-
Fuel Handling & Storage System	-	☑	New TDRM

[1] Although the HPS TDRM has not been included in this lower temperature baseline document, Hydrogen Production is still one of the long term goals of the NGNP.

An update of the Technology Development Roadmaps of these critical SSCs was consequently conducted in May 2009 [3]. Information updated herein entailed the descriptive text as well as the roadmaps of all critical SSCs (with the exclusion of the Technology Maturation Plans). This report firstly gives an update of all information captured in [3] and secondly sees the inclusion of updated Technology Maturation Plans and Test Specifications together with their associated cost and schedule considerations. Primary changes incorporated into the various TDRM report sections involve inputs from completed conceptual design studies, notably the 'IHX Development and Trade Studies' Study [4].

REFERENCES

[1] NGNP-CTF MTECH-TDRM, Rev 0, December 2008 – NGNP Technology Development Roadmapping Report

[2] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels for NGNP Steam Production at 750-800°C

[3] NGNP-TDI-TDR-RPT-G-00003, Rev 1, May 2009 – Report on Update of Technology Development Roadmaps for NGNP Steam Production at 750℃-800℃.

[4] NGNP-NHS-HTS-RPT-M-0004, Rev. 0, July 2009 - NGNP: Intermediate Heat Exchanger Development and Trade Studies.

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NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 1: PHTS Circulator

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1 PRIMARY HEAT TRANSPORT SYSTEM (PHTS) CIRCULATOR

1.1 Function and Operating Requirements

During the NGNP preconceptual design phase [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 energy at a rate of approximately 500MWt. 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 nominal operating conditions of the circulator for a reactor outlet temperature (ROT) of 750°C are summarized in Table 1-1.[2] Under these conditions, the required pumping power is 14.5 MWt, versus 11.7 MWt for the 800°C ROT case. 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. In the preconceptual design a self-acting backflow prevention valve is integrated with the circulator assembly or located 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 1-1: NGNP PHTS Circulator Operating Conditions for 750°C ROT

Performance Attribute	Value
Core power, MWt	500
Rotor shaft power, MWt	14.5
He flow rate, kg/s	204.5
Inlet He temp., C	267
Inlet He press, MPa	8.578
Outlet He temp., C	280
Outlet He pressure, MPa	9.0
Circ press rise, kPa	422
Compression ratio	1.049
Inlet density, Kg/m^3	7.638
Volumetric flow rate, m^3/s	26.8

1.2 Design Selection Status

1.2.1 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 1-1 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 1.2.2.

The left side of Figure 1-1 relates to the selection of the drive for the circulator impeller. An electric motor drive was recommended in [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 1-1).

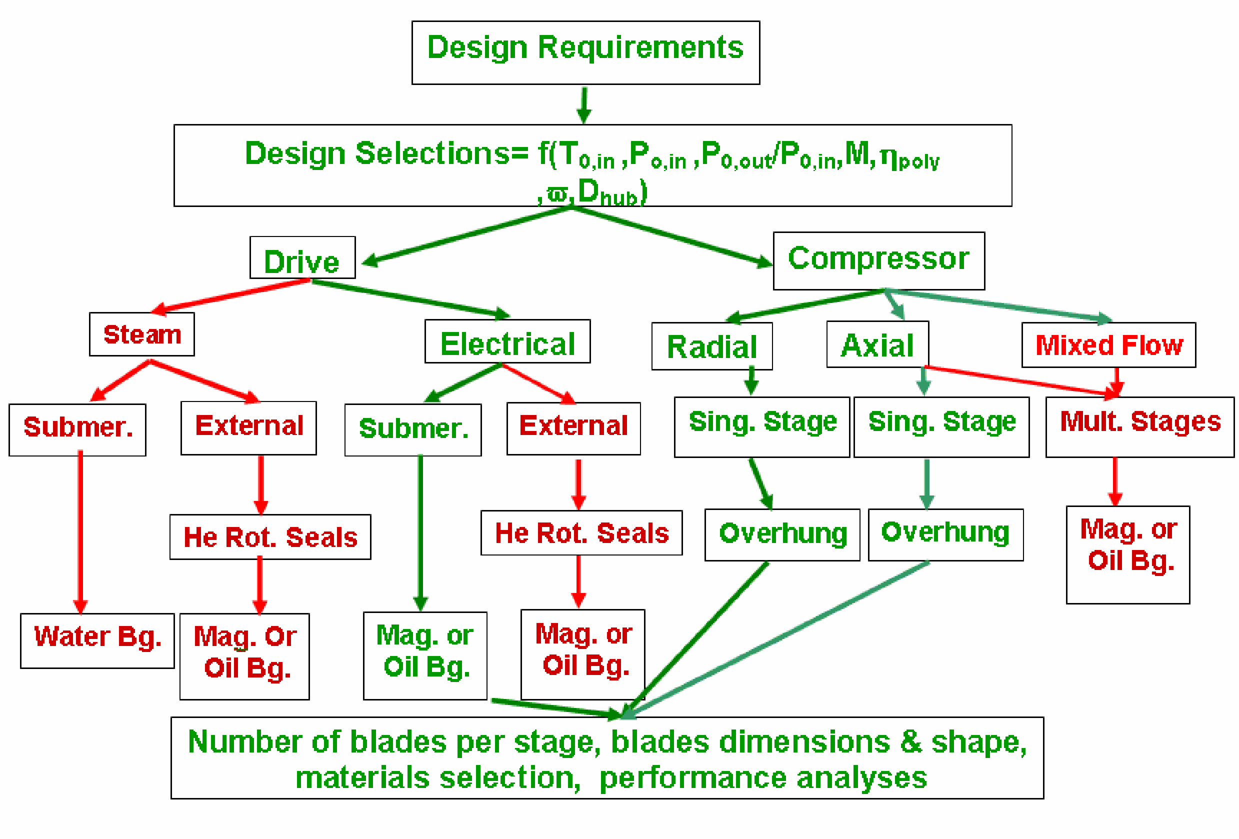


Figure 1-1: Design Options of the PHTS Circulator

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. This is especially true for units greater than 6MW, since no experience is available for larger sized units. Recent progress in magnetic bearing design and the advantage of not having to deal with oil inside the primary pressure boundary has made this option more appealing, especially as the British gas-cooled reactor sealing design may not be adequate to prevent oil ingress when operating in Helium. 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 1.5, 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. 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 1.5, down selection tasks are recommended to address these design options.

The right side of Figure 1-1 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. This will also assist in providing screening during circulator removal and replacement.
- Care must be taken to locate the circulator impeller away from large surfaces that could be affected by acoustic loads. Strengthening of the surrounding structure around the circulator is needed to prevent pressure boundary (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, which normally run at higher speeds.

- For a design selection that locates the circulator drive within the primary pressure boundary (submerged), consideration must be given to provide a flow of purified buffer helium in the driver cavity at a pressure slightly higher than the primary coolant pressure in order to prevent radionuclide contamination that will complicate maintenance.
- The impeller design must take requirements for decontamination into consideration. These considerations should include the possibility of remote removal and preference to single stage open designs that simplify decontamination.
- 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 and reliability considerations 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. At present, the experience limit for circulators in the nuclear industry is around 6MW electrical power, with possible expansion up to 7.5MW with minimal risk.

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 2.5.3. 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. 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.

1.2.2 Decision Discriminators

1.2.2.1 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 [4] in Section 2.5.3 – a similar rating and weighting scheme could be employed as basis for a circulator K-T.

1.2.2.2 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)

1.2.2.3 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?

1.2.2.4 Operation and Maintenance

Operation and maintenance of the NGNP PHTS circulator will strongly be affected by 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.)?
- Does the design increase plant component count and hence reduce overall reliability and availability?

1.2.2.5 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.

1.2.2.6 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 and recurring)

1.2.3 Reference Design

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

1.2.4 Alternatives for Further Evaluation

There are several design selections that are still to be made, as described in Section 1.2.1. 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.

1.2.5 Down Selection Task

Several design candidates have been identified for the PHTS circulator in Section 1.4.1. 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 1-2 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 1-2: 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.

1.3 TRL Status of PHTS Circulator

The reference design of the PHTS circulator subsystem (see Section 1.2.3) 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 CO_2 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 1-3 summarizes nominal operating conditions for key gas circulators previously used in the nuclear industry.

Table 1-3: Prior Experience with Gas Circulator in the Nuclear Industry

		AVR He	PB He	THTR He	FSV He	AGR 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 electromagnetic bearings is provided by Siemens, which has built a series of 26 MW motors for gas pipeline compressors in the Netherlands that operate on Waukesha EMBs.

In considering the above, none of the previous applications is an exact match to what could become the new PHTS circulator reference design after the trade studies, given the need for a high pumping power in a helium environment and the possibility of using EMBs.

The newest revision of the NGNP TRL/DRL Report [2] 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), 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.

1.4 Technology Development Road Map Summary

1.4.1 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 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.

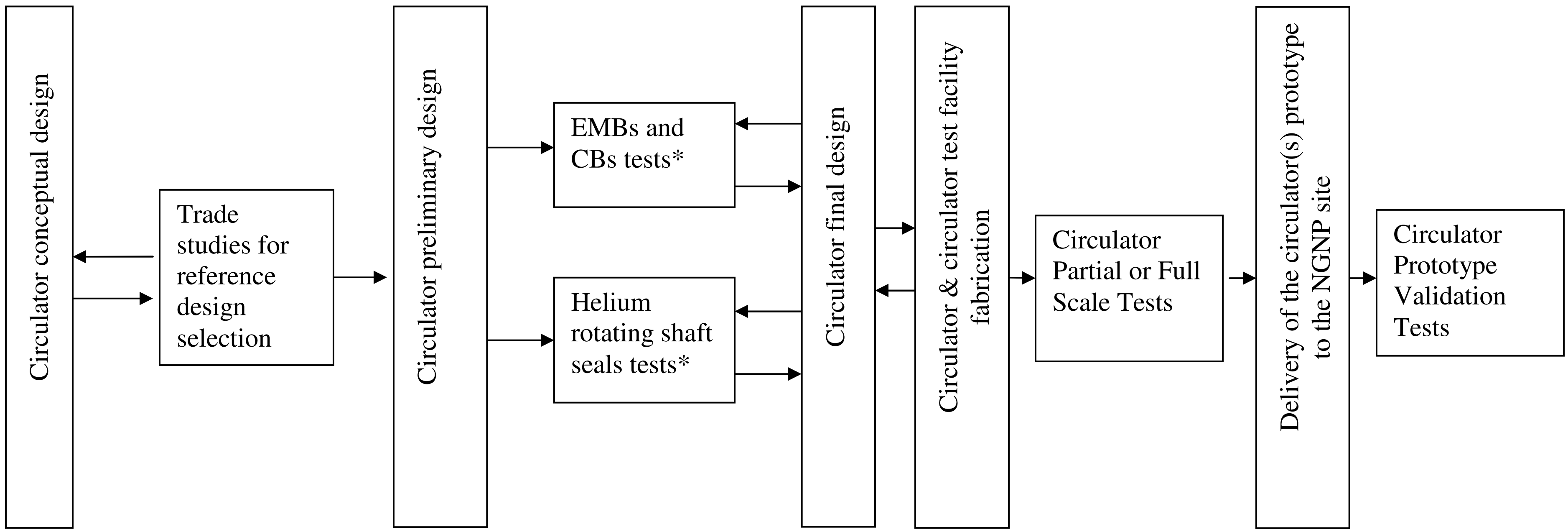
The PHTS Circulator Technology Development Roadmap can be seen in Appendix A while the maturation tasks are described below.

1.5 Technology Maturation Plan Summary

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 1-2). The components tests will be done during preliminary design to validate the selected technologies. The test facility (either partial or 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 1-2: PHTS Circulator Development Logic

1.6 SHTS Circulator and PHTS Backflow Prevention Valve Technology Development

1.6.1 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, does not warrant a separate discussion.

1.6.2 Backflow Prevention Valve

If the PHTS Backflow Prevention Valve is designed to be an integral part of the circulator assembly, the valve will be tested as part of the circulator test program.

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 Design Data Needs (DDNs) will be identified. Those DDNs which require testing for development of the technology will be included in Roadmapping, either together with the PHTS Circulator or as a separate PHTS component, at the appropriate time.

The Backflow Prevention Valve will most likely require confirmatory testing after design. There are several such performance verification tasks that can be envisioned, whether or not the valve is designed to be an integral part of the circulator. These might involve off-design testing, such that calculated backflow is confirmed. If the valve is reverse-flow activated, then thresholds for operation would be determined. If a closure assist device is needed, its performance also could be characterized experimentally more assuredly than by analysis. Cyclic testing of valve and, if it has one, of the actuator might be needed to support Probabilistic Risk Analysis. Associated pressure differential and/or valve status instrumentation might also need to be verified. As they are defined in the conceptual design phase, these testing requirements can also be put into the roadmap, but in general the tests would not be elements of the PHTS Circulator technology maturation.

1.7 References

[1] NGNP-06-RPT-001, Rev0, May 2007 – NGNP and Hydrogen Production Preconceptual Design Report, “Section 6: Heat Transport System”

[2] NGNP: Intermediate Heat Exchanger Development and Trade Studies, NGNP-NHS-HTS-RPT-M-0004, Rev. 0, July 2009

[3] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

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

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP - 750℃-800℃

TECHNOLOGY DEVELOPMENT ROADMAP – PHTS CIRCULATOR

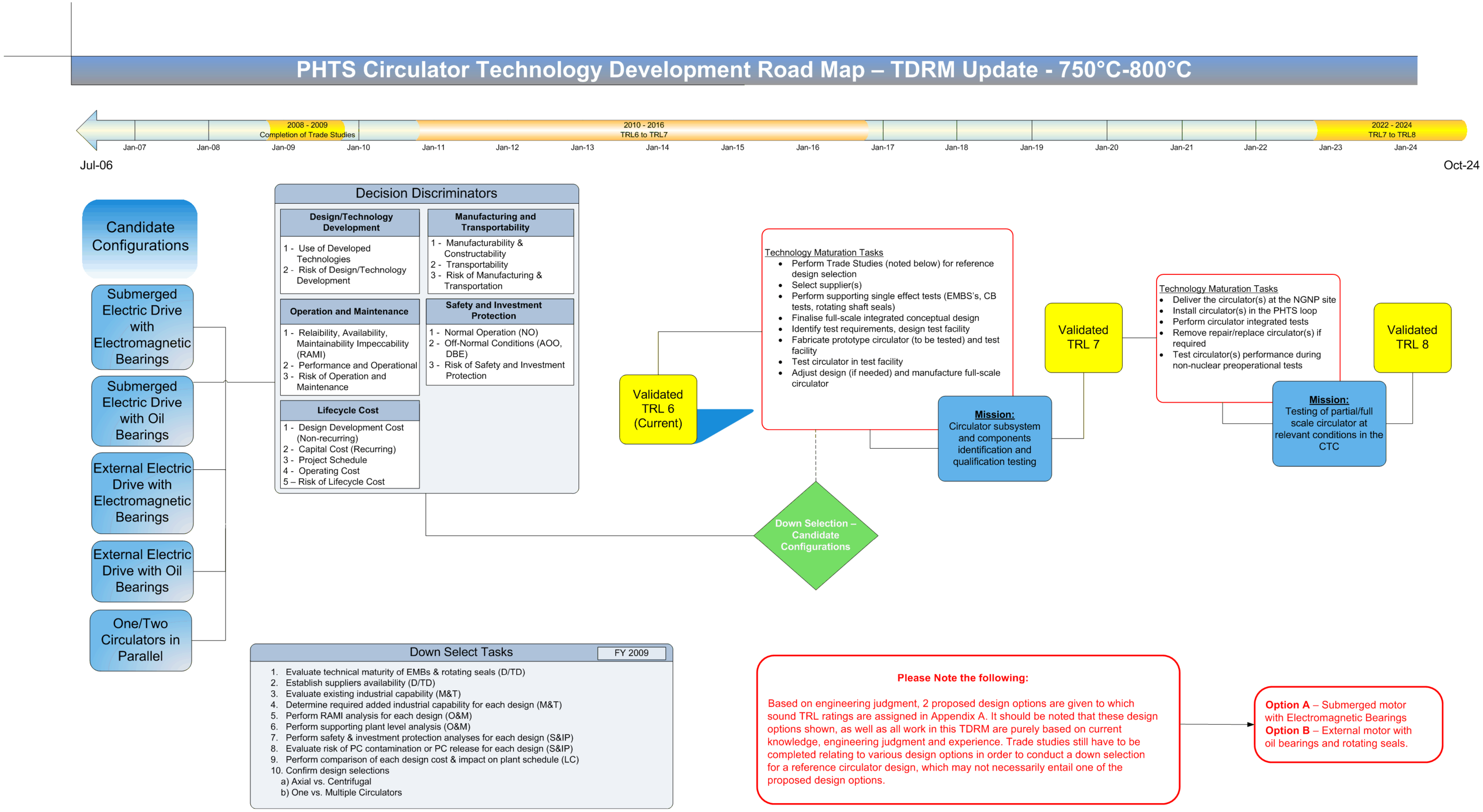


Figure A-1: TDRM for PHTS Circulator

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750℃-800℃

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TRL 6 to TRL 7:

- Specification 1: Electro Magnetic Bearings (EMBs), and Catcher Bearings Test Specification (WEC-TS-CIRC-001)
- Specification 2: Helium Rotating Seals Test Specification (WEC-TS-CIRC-002)
- Specification 3: Partial or Full Scale Circulator Model Test Specification (WEC-TS-CIRC-003)

TRL 7 to TRL 8:

- Specification 1: Prototype Circulator Test Specification (WEC-TS-CIRC-004)

B1 TECHNOLOGY MATURATION PLAN - TRL 6 TO TRL 7

B1.1 Technology Maturation Plan Summary

B1.1.1 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 B1.2.

B1.1.2 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.

B1.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY2010 through FY2016. Work described in the Test Specifications to validate the performance of individual portions on the circulator assembly can be done in parallel.

B1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B1.2 Test Specifications

B1.2.1 Electro Magnetic Bearings (EMBs), and Catcher Bearings Test Specification (WEC-TS-CIRC-001)

B1.2.1.1 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 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 rotordynamics

- 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.

B1.2.1.2 Test Conditions

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.

Test Duration

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

Proposed Test Location

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

B1.2.1.3 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.

B1.2.1.4 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.

B1.2.1.5 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).

B1.2.1.6 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

B1.2.1.7 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 B1.1.3 and B1.1.4. There is no or only minimal risk associated with Section B1.2.1.

B1.2.2Helium Rotating Seals Test Specification (WEC-TS-CIRC-002)

B1.2.2.1 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.

B1.2.2.2 Test Conditions

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.

Test Duration

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

Proposed Test Location

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

B1.2.2.3 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.

B1.2.2.4 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.

B1.2.2.5 Test Evaluation Criteria

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

B1.2.2.6 Test Deliverables

Deliverables are as follows.

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

B1.2.2.7 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 B1.1.3 and B1.1.4. There is no or only minimal risk associated with Section B1.2.2.

B1.2.3 Partial or Full Scale Circulator Model Test Specification (WEC-TS-CIRC-003)

B1.2.3.1 Objectives

The PHTS circulator comprises 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 bearing 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.

B1.2.3.2 Test Conditions

Test Configuration/Set-up

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

Test Duration

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

Proposed Test Location

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

B1.2.3.3 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.

B1.2.3.4 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.

B1.2.3.5 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).

B1.2.3.6 Test Deliverables

Deliverables are as follows.

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

B1.2.3.7 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 B1.1.3 and B1.1.4. There is only minimal risk associated with Section B1.2.3.

B2 TECHNOLOGY MATURATION PLAN FOR PHTS CIRCULATOR (TRL 7 TO TRL 8)

B2.1 Technology Maturation Plan Summary

B2.1.1 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 the PHTS circulator(s), if necessary.

B2.1.2 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.

B2.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY2022 through FY2024.

B2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B2.2 Test Specifications

B2.2.1 Prototype Circulator Test Specification (WEC-TS-CIRC-004)

B2.2.1.1 Objectives

The objective of testing the circulator in helium without nuclear heat, while mounted in the PHTS loop, is to 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 induced 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.

B2.2.1.2 Test Conditions

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.

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.

Proposed Test Location

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

B2.2.1.3 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.

B2.2.1.4 Data Requirements

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

B2.2.1.5 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 Events (DBE).

B2.2.1.6 Test Deliverables

Deliverables are as follows.

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

B2.2.1.7 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 B2.1.3 and B2.1.4. There is only minimal risk associated with Section B2.2.1.

NGNP-TDI-TDR-RPT-G-00009 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750℃-800℃

Section 2: Intermediate Heat Exchanger

APPROVALS

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C	Scott Penfield	Incorporation of conceptual design study outcomes	July 22, 2009
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2 INTERMEDIATE HEAT EXCHANGER (IHX)

2.1 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, originally separated into two regions, a high-temperature IHX A and a lower temperature IHX B, has now been changed to a single IHX operating in the range 750°C-800°C.

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 Heat Exchanger or 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 the IHX are as given below:

- The nominal helium temperature at the primary side entrance to the IHX is 750°C to 800°C.
- The nominal helium temperature at the secondary side entrance to the IHX for 800°C ROT is ~217°C°.

- The nominal helium temperature at the secondary side exit from the IHX for 800°C ROT is 750°C.
- The nominal helium temperature at the primary side exit from the IHX for 800°C ROT is ~267°C.
- IHX will provide for transfer of ~500 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 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, specifically pressure boundary vessel wall (e.g., IHX internal structures and fluid flow shall ensure that the vessel temperature be limited to below 371°C during normal operation)
- System Configuration (e.g., the IHX shall be a single unit)
- Operation (e.g., the components of the IHX 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. Specific IHX requirements are TBD.
- Structure (e.g., the IHX 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 shall be >99.98%)
- Maintenance (e.g., the IHX 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 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* [4] report.

2.2 IHX Down Select Status

2.2.1 Candidate Technologies

Various designs and materials for the IHX 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 [3]
- PCDR Section 6: Heat Transport Systems, NGNP-06-RPT-003, Rev 0, April 2007 [1]
- NGNP Conceptual Design Study: IHX and Heat Transport System, NGNP-HTS-RPT-TI001, Rev 0, April 2008 [4]
- NGNP: Intermediate Heat Exchanger Development and Trade Studies, NGNP-NHS-HTS-RPT-M-0004, Rev. 0, July 2009 [7]

The first of the above 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. At that time Alloy 800H was designated as the leading candidate for IHX B at temperatures to 760°C.

The second study confirmed the conclusions above relative to the 950°C system (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 was more comprehensive in its evaluation of designs, performance, and materials. It 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 compact heat exchanger was performed. A significant result of the third study was identification of corrosion of the thin materials utilized in the heat transfer surface of compact heat exchangers in the presence of the trace impurities typical of primary loop helium as a significant concern at high temperatures. Further consideration was given to material alternatives to Alloy 800H (e.g. Hastelloy X), but the recommendation at that time remained as Alloy 800H.

In the fourth study, the reactor outlet temperature was reduced to the range of 750°C-800°C and the design was consequently changed to a single IHX. Shell-side coupling of the IHX to the Primary Heat Transport System was selected as the reference configuration and concepts were developed for integration of the vessels, piping and enclosing structures. A more detailed assessment of materials issues was undertaken, notably including corrosion, leading to the recommendation of Hastelloy X as the preferred candidate material for the IHX heat transfer surface. Alloy 800H continues to be an alternate for the heat transfer surface and is recommended as the primary candidate for thicker cross section components at these intermediate temperatures.

2.2.2 Decision Discriminators

This section provides a detailed listing of the decision discriminators that were used in the *IHX and Heat Transport System* study [4] to evaluate various IHX designs. They were applied to the five 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
  - Hot Streaking
  - Flow Induced Vibrations
- 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 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 PFHE 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 PFHE 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.

Robustness

- Shell & tube designs are by far the most robust under normal operating conditions.
- The integrity of the braze joints in the PFHE 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 much 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 PFHE 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 PFHE designs are not currently quantitative and this is 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 PFHE 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 PFHE designs; further evaluation would be needed for the capillary and involute designs.
- The PCHE and PFHE 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 PFHE designs.

The metallic materials considered for the current application at 750°C-800°C were Alloy 800H, Alloy 230, Alloy 617, and Hastelloy X. 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*
    - *Creep-fatigue interactions*
    - *Aging and environmental effects*
    - *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 the materials down select process and the results are given below.

2.2.3 Application of the Decision Discriminators to the IHX Down Select

Application of the materials decision discriminators to the four alloy candidates noted earlier, resulted in the identification of the following factors which favor the selection of Hastelloy X and Alloy 800H for the IHX.

- Alloy 800H and Hastelloy X have the most mature databases 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 both Alloy 800H and Hastelloy X are more than adequate for use during normal operation and loss-of-secondary-pressure events.
- Corrosion performance of Alloy 800H in NGNP He at 750°C appears to be comparable to that for Alloy 617 and Alloy 230 but is much inferior to that of Hastelloy X.
- Fabrication and joining technologies for Alloy 800H and Hastelloy X are the most mature of the candidate alloys. (However, work is still needed on brazing and diffusion bonding processes and effects. In this regard, the alloy chemistry of Hastelloy X makes it superior in terms of brazing)
- Alloy 800H is the least expensive of the materials.

2.2.4 Reference Design

The reference design (the PCHE, PFHE or other compact design) will be chosen at the TRL 5 level.

2.2.5 Summary of the IHX Down Selection Task

The down select evaluation conducted for the IHX and reported in the *NGNP Conceptual Design Study: IHX and Heat Transport System* [4] *and extended in the IHX trade studies of Reference [7]* resulted in the various conclusions and recommendations listed below.

- The initial recommendation to utilize compact heat exchanger technology as the basis for the metallic IHX design has been confirmed. The PCHE or PFHE are the current reference designs; however, other compact designs will be evaluated.
- A compact IHX configuration (applicable to both PCHE and PFHE heat exchangers) that potentially allows leak detection, location and isolation at the module-level has been identified.

- Earlier assessments (Refs. [1] and [4]) recommended separating the IHX into IHX A and IHX B sections, based on temperature. However, systems now being considered have a maximum IHX temperature of 750°C-800°C and a single IHX unit is planned.
- At 750°C-800°C, Hastelloy X is evaluated to be more resistant to corrosion in the PHTS environment and, thus, most likely to achieve acceptable lifetimes in the heat transfer sections of the IHX module, which are characterized by thin cross-sections. Alloy 800H remains a candidate material for the heat transfer surface and may be the preferred material for thicker section components, based on cost.

2.3 TRL Status

Evaluations of the status of the technology for the 750°C-800°C IHX were made and resulted in the determination of a level of TRL 3. The bases for this selection are described in the TRL rating sheet [2].

2.4 Technology Development Road Map Summary

2.4.1 Overview

The TDRM lists the maturation tasks that are required to advance the maturity of the technology of the IHX from TRL 3 to TRL 8.

The IHX Technology Development Road Map is attached in Appendix A and the maturation tasks are discussed hereafter.

2.5 Technology Maturation Plan Summary

This section describes the maturation tasks needed to advance the technology of the IHX 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. The materials tasks include consideration of thermal/physical and mechanical properties of Alloy 800H and Hastelloy X, joining and fabrication techniques applicable to Alloy 800H and Hastelloy X in compact heat exchangers, and determination of corrosion allowances for both Alloy 800H and Hastelloy X. Significant levels of effort will also be devoted to methods for thermal/fluid and stress/strain modeling and to the 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 unit cells of the PFHE containing the heat transfer surface of the IHX or an equivalent PCHE section of size and geometry to be determined. These maturation tasks will be keyed to the DDNs described in the *NGNP: Intermediate Heat Exchanger Development and Trade Studies [7]* whenever possible.

At completion of the tasks above, the IHX will have achieved a level of validated TRL 5 and a PCHE versus PFHE (or other) design decision will have been made. Advancement to a validated TRL 6 requires manufacture of a nominally 1.2 MW module of the IHX, testing of the module in the HTSST or CTC, and verification of its performance. It will also be necessary to establish an ASME Code Case for the design of compact heat exchangers.

Moving the technology of the IHX 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 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* [4] report were first presented in *PCDR Section 6: Heat Transport System* [1]. 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* [5] as well as Section 17 of the *Technology Development Roadmapping Report* [6].

2.6 References

[1] NGNP-06-RPT-001, Rev0, May 2007 – NGNP and Hydrogen Production Preconceptual Design Report, "Section 6: Heat Transport System"

[2] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

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

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

[5] Metallic Component Schedule Risk and Cost Uncertainty Assessment report

[6] NGNP-CTF MTECH-TDRM-017, Rev 0, December 2008 – NGNP TDRM Report: Integrated Schedule & Cost Estimate

[7] NGNP: Intermediate Heat Exchanger Development and Trade Studies, NGNP-NHS-HTS-RPT-M-0004, Rev. 0, September 2009

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750°C-800°C

TECHNOLOGY DEVELOPMENT ROADMAP – IHX

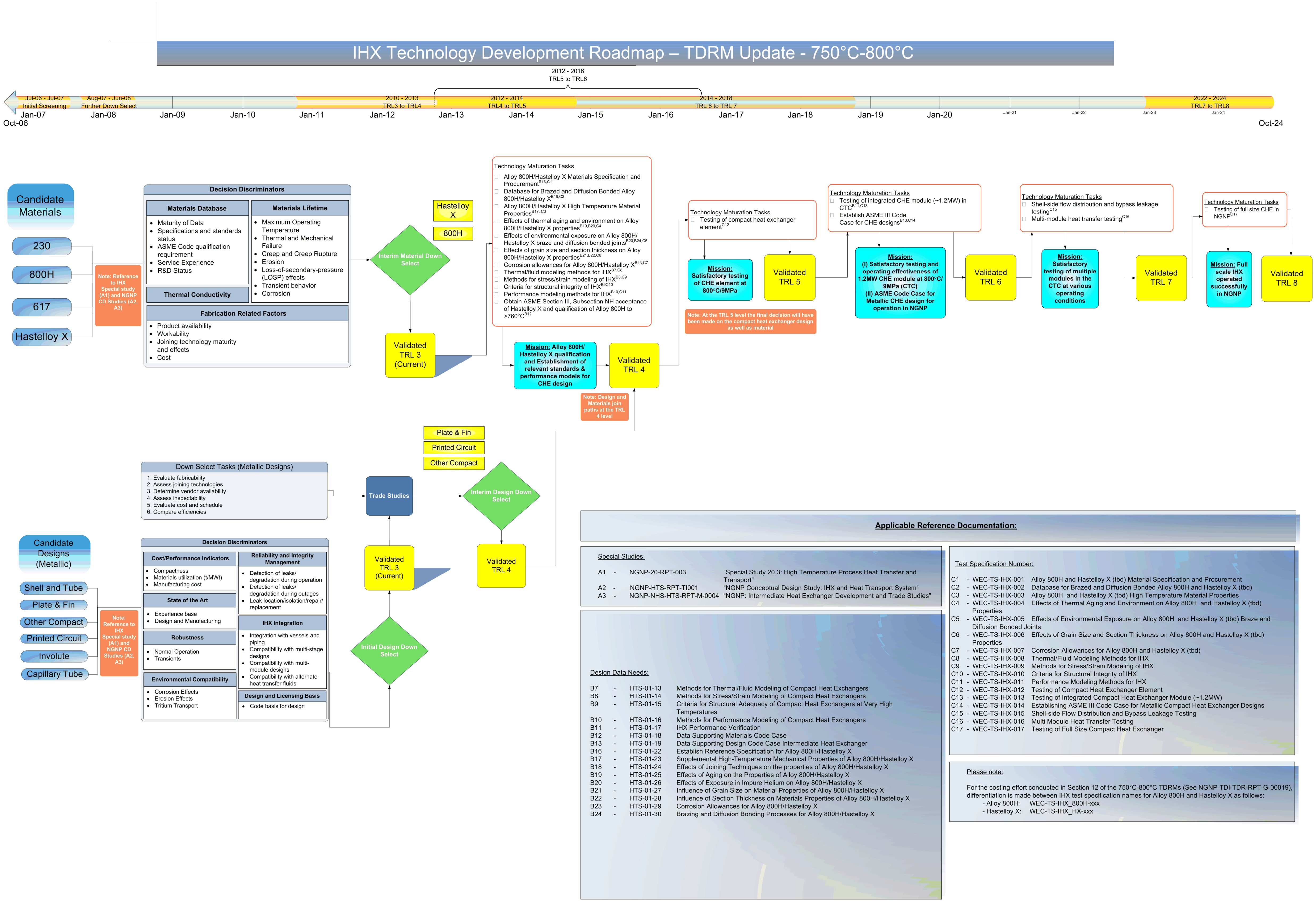

Figure A 1: TDRM for IHX

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

TRL 3 to TRL 4:

- Specification 1: Alloy 800H and Hastelloy X Material Specifications and Procurement *(WEC-TS-IHX-001)*
- Specification 2: Database for Brazed and Diffusion Bonded Alloy 800H and Hastelloy X *(WEC-TS-IHX-002)*
- Specification 3: Alloy 800H and Hastelloy X High Temperature Materials Properties *(WEC-TS-IHX-003)*
- Specification 4: Effects of Thermal Aging and Environment on Alloy 800H and Hastelloy X Properties *(WEC-TS-IHX-004)*
- Specification 5: Effects of Environmental Exposure on Alloy 800H and Hastelloy X Braze and Diffusion Bonded Joints *(WEC-TS-IHX-005)*
- Specification 6: Effects of Grain Size and Section Thickness on Alloy 800H and Hastelloy X Properties *(WEC-TS-IHX-006)*
- Specification 7: Corrosion Allowances for Alloy 800H and Hastelloy X *(WEC-TS-IHX-007)*
- Specification 8: Thermal/Fluid Modeling Methods for the IHX *(WEC-TS-IHX-008)*
- Specification 9: Methods for Stress/Strain Modeling of the IHX *(WEC-TS-IHX-009)*
- Specification 10: Criteria for Structural Integrity of the IHX *(WEC-TS-IHX-010)*
- Specification 11: Performance Modeling Methods for the IHX *(WEC-TS-IHX-011)*

TRL 4 to TRL 5:

- Specification 1: Testing of Compact Heat Exchanger Element *(WEC-TS-IHX-012)*

TRL 5 to TRL 6:

- Specification 1: Testing of Integrated Compact Heat Exchanger Module (~1.2MW) *(WEC-TS-IHX-013)*
- Specification 2: Establishing ASME III Code Case for Metallic Compact Heat Exchanger Designs *(WEC-TS-IHX-014)*

TRL 6 to TRL 7

- Specification 1: Shell-Side Flow Distribution and Bypass Leakage Testing *(WEC-TS-IHX-015)*
- Specification 2: Multi-Module Heat Transfer Testing *(WEC-TS-IHX-016)*

TRL 7 to TRL 8:

- Specification 1: Testing of Full Size Compact Heat Exchanger *(WEC-TS-IHX-017)*

B1TECNOLOGY MATURATION PLAN FOR THE IHX - TRL 3 TO TRL 4

B1.1 Technology Maturation Plan Summary

B1.1.1 Objectives

The objective of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the IHX 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 Hastelloy X 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 and Hastelloy X in NGNP primary and secondary helium 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 B1.2.

B1.1.2 Scope

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

- Alloy 800H and Hastelloy X material specifications and procurement
- Develop mechanical property database for brazed and diffusion bonded Alloy 800H and Hastelloy X.
- Accept existing high temperature properties databases for Alloy 800H and Hastelloy X.
- Accept existing Alloy 800H and Hastelloy X databases on effects of thermal aging and environment.
- Obtain environmental effects data for brazed and diffusion bonded joints of Alloy 800H and Hastelloy X.
- Assess effects of grain size and section thickness on Alloy 800H and Hastelloy X properties.
- Determine corrosion allowances for Alloy 800H and Hastelloy X.
- 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.

B1.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2010 through FY2013. No individual Test Specification describes work requiring more than 30 months and the work in most Test Specifications can be done in parallel.

B1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B1.2 Test Specifications

B1.2.1 Alloy 800H and Hastelloy X Material Specifications and Procurement (WEC-TS-IHX-001)

B1.2.1.1 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 Hastelloy X, and procurement of one or more heats of Alloy 800H and Hastelloy X, as necessary. With respect to material specifications, 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.

B1.2.1.2 Test Conditions

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 Alloy 800H and Hastelloy X materials procured meets specifications.

Test Duration

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

Proposed Test Location

Acceptance testing, as needed, can be performed by the supplier or in a materials testing laboratory.

B1.2.1.3 Measured Parameters

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

B1.2.1.4 Data Requirements

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

B1.2.1.5 Test Evaluation Criteria

Heats of Alloy 800H and Hastelloy X acquired shall meet all procurement requirements and material specifications.

B1.2.1.6 Test Deliverables

Deliverables are as follows.

- Alloy 800H and Hastelloy X materials purchase specification
- One or more heats of Alloy 800H and Hastelloy X (including consideration of appropriate product forms and amounts needed for testing) acquired per the above
- Report confirming that the heats of Alloy 800H and Hastelloy X meet all specifications and requirements (e.g. Certified Materials Test Report, for each heat).

B1.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. Risks include that the material doesn't qualify and that the overall schedule will be delayed.

B1.2.2 Database for Brazed and Diffusion Bonded Alloy 800H and Hastelloy X (WEC-TS-IHX-002)

B1.2.2.1 Objectives

Work conducted under this Test Specification is intended to demonstrate that brazed and diffusion-bonded joints of Alloy 800H and Hastelloy X 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.

B1.2.2.2 Test Conditions

Test 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
- Materials acquired according to B1.2.1

Test Duration

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

Proposed Test Location

Commercial organizations involved in compact heat exchanger manufacture would be appropriate for the joining studies, and to produce the bonded test specimens. A National Laboratory, university or other materials testing laboratory could perform the work on microscopic examination and mechanical properties. Refer to Section 12 of this document.

B1.2.2.3 Measured Parameters

Parameters to be measured include the following.

- Conditions and parameters applied in producing the joints
- Condition of the Alloy 800H and Hastelloy X 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.

B1.2.2.4 Data Requirements

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

B1.2.2.5 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 and Hastelloy X joints.

B1.2.2.6 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.

B1.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. The risks associated with Section B1.2.2 are very small but include the possibility that one or both of the joining techniques may prove unsuitable for thin sections of Alloy 800H and/or Hastelloy X.

B1.2.3 Alloy 800H and Hastelloy X High Temperature Material Properties (WEC-TS-IHX-003)

B1.2.3.1 Objectives

The objectives of this work are to agree to adopt the existing high temperature property database for Alloy 800H and Hastelloy X materials and to accept that these thermal/physical and mechanical properties are suitable for design and operation of compact heat exchanger IHX. This Test Specification responds to DDN HTS-01-23.

B1.2.3.2 Test Conditions

Test Configuration/Set-Up

N/A.

Test Duration

Collection of and agreement to accept the databases should require no more than 6 months.

Proposed Test Location

The databases should be collected and archived by a National Laboratory. Most of this has been accomplished for Alloy 800H in a joint DOE-ASME program. Refer to Section 12 of the document.

B1.2.3.3 Measured Parameters

Parameters to be recorded are:

- High temperature property data
- Source of the data.

B1.2.3.4 Data Requirements

All data shall meet ASTM and ASME standards and requirements.

B1.2.3.5 Test Evaluation Criteria

N/A

B1.2.3.6 Test Deliverables

The test deliverables are achieved Alloy 800H and Hastelloy X high temperature property databases.

B1.2.3.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. The risk associated with Section B1.2.3. is that the Alloy 800H and/or Hastelloy X high temperature property databases do not provide for certain conditions and might consequently need to be revisited.

B1.2.4 Effects of Thermal Aging and Environment on Alloy 800H and Hastelloy X Properties (WEC-TS-IHX-004)

B1.2.4.1 Objectives

The objective of this work is to agree to accept the existing databases on the effects of thermal aging and environmental exposure on the thermal/physical and mechanical properties of Alloy 800H and Hastelloy X materials. This Test Specification responds to DDN HTS-01-25 and DDN HTS-01-26.

B1.2.4.2 Test Conditions

Test Configuration/Set-Up

N/A.

Test Duration

Collection and archiving of information of the effects of thermal aging and environmental exposure on the properties of Alloy 800H and Hastelloy X should require no more than 9 months.

Proposed Test Location

The databases should be collected and archived by a National Laboratory. Most of this has been accomplished in a joint DOE-ASME program. Refer to Section 12 of the document.

B1.2.4.3 Measured Parameters

Parameters to be recorded are:

- Thermal aging and environmental exposure effects data
- Source of the data.

B1.2.4.4 Data Requirements

All data shall meet NGNP standards and requirements for data.

B1.2.4.5 Test Evaluation Criteria

N/A.

B1.2.4.6 Test Deliverables

The test deliverables are achieved databases on the effects of thermal aging and environmental exposure on the properties of Alloy 800H and Hastelloy X.

B1.2.4.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. The risk associated with Section B1.2.4 is that the relevant Alloy 800H and/or Hastelloy X property database do not provide for certain conditions and might consequently need to be revisited.

B1.2.5 Effects of Environmental Exposure on Alloy 800H and Hastelloy X Braze and Diffusion Bonded Joints (WEC-TS-IHX-005)

B1.2.5.1 Objectives

The objective of this task is to determine the response of the properties of welded, brazed, and diffusion bonded Alloy 800H and Hastelloy X to exposures in NGNP primary and secondary helium 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.

B1.2.5.2 Test Conditions

Test Configuration/Set-Up

The following are required relative determining the effects of NGNP He on the properties of Alloy 800H and Hastelloy X:

- Facility for exposure of specimens of welded, brazed, and diffusion bonded Alloy 800H and Hastelloy X to He environments 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

Duration

Preparation, exposure, and testing of the weld, braze, and diffusion bonded specimens of Alloy 800H and Hastelloy X could require up to 36 months.

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 12 of the document.

B1.2.5.3 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 and Hastelloy X 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

B1.2.5.4 Data Requirements

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

B1.2.5.5 Test Evaluation Criteria

Evaluation of the effects of environmental exposures on the properties of Alloy 800H and Hastelloy X welds, brazes, and diffusion bonds will be based on before and after values of tensile, creep, fatigue, and fracture toughness properties.

B1.2.5.6 Test Deliverables

Deliverables are as follows.

- Reports documenting the details of preparation of the Alloy 800H and Hastelloy X 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
- Reports describing the effects of environmental exposures of Alloy 800H and Hastelloy X on the structure of welds, braze joints, and diffusion bonds.

B1.2.5.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. The risk associated with B1.2.5 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 and/or Hastelloy X in a compact heat exchanger at up to 800°C for 60 years.

B1.2.6 Effects of Grain Size and Section Thickness on Alloy 800H and Hastelloy X Properties (WEC-TS-IHX-006)

B1.2.6.1 Objectives

The objectives of the work prescribed in this Test Specification are to (1) demonstrate that the very thin as-fabricated sections of Alloy 800H and Hastelloy X (significantly less than 1 mm) required in the IHX compact heat exchanger will have tensile, creep, fatigue, and creep-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 800H and Hastelloy X with typical grain sizes (ASTM 5-7) are acceptable for compact heat exchanger operation. This Test Specification responds to DDN HTS-01-27 and DDN HTS-01-28.

B1.2.6.2 Test Conditions

Test Configuration/Set-Up

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

Test Duration

The work relative to grain size and section thickness effects on Alloy 800H and Hastelloy X creep and fatigue properties should require about 30 months.

Proposed Test Location

Study and measurements relative to grain size and section thickness effects on properties are well suited to be conducted at a National Laboratory, but could also be done in other materials testing laboratories, with appropriate equipment and experience. Refer to Section 12 of the document.

B1.2.6.3 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.

B1.2.6.4 Data Requirements

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

B1.2.6.5 Test Evaluation Criteria

The creep and fatigue properties determined on thin section and standard grain size Alloy 800H and Hastelloy X materials must meet the requirements for fatigue and creep resistance in the IHX compact heat exchanger.

B1.2.6.6 Test Deliverables

Deliverables for this Test Specification shall include:

- Report on the influence of section thickness on creep and fatigue properties of Alloy 800H and Hastelloy X
- Report on the influence of grain size on creep and fatigue properties of Alloy 800H and Hastelloy X with emphasis on ASTM 5 to 7.

B1.2.6.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. The risk associated with B1.2.6 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 and/or Hastelloy X in the compact heat exchanger IHX.

B1.2.7 Corrosion Allowances for Alloy 800H and Hastelloy X (WEC-TS-IHX-007)

B1.2.7.1 Objectives

The major objective of this activity is to ensure that exposure of Alloy 800H as well as Hastelloy X at high temperatures (up to 800°C) for up to 60 years in NGNP helium 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.

B1.2.7.2 Test Conditions

Test Configuration/Set-Up

Determination of corrosion allowances for Alloy 800H and Hastelloy X will require the following.

- Facility for exposure in He (650°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

Test Duration

Conduct of this work will require 36 months.

Proposed Test Location

Determination of corrosion allowances and phenomena are likely best suited to be done at a National Laboratory or a commercial testing laboratory. Refer to Section 12 of the document.

B1.2.7.3 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.

B1.2.7.4 Data Requirements

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

B1.2.7.5 Test Evaluation Criteria

The corrosion allowances determined for Alloy 800H and Hastelloy X 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 compact heat exchanger IHX.

B1.2.7.6 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, Hastelloy X, and their joints for all temperatures and times of interest.

B1.2.7.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. The risk associated with B1.2.7 is that the corrosion allowances determined for one or both alloys may preclude the operation of the IHX for full life (~60 years) at 750-800°C.

B1.2.8 Thermal/Fluid Modeling Methods for the Compact IHX (WEC-TS-IHX-008)

B1.2.8.1 Objectives

The work to be conducted under this Test Specification is development of thermal/fluid 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.

B1.2.8.2 Test Conditions

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 6, TRL 6 to TRL 7, and TRL 7 to TRL 8.

Test Duration

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

Proposed Test Location

The supplier / design authority may be best suited to perform the modeling work. Refer to Section 12 of the document.

B1.2.8.3 Measured Parameters

The models to be developed will incorporate and combine the mechanical and thermal/physical property databases for Alloy 800H and Hastelloy X with finite element analysis (FEA) techniques and known relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

B1.2.8.4 Data Requirements

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

B1.2.8.5 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.

B1.2.8.6 Test Deliverables

The test deliverable is a model for predicting operation and performance characteristics of the IHX compact heat exchanger relevant to thermal, structural and fluid analyses.

B1.2.8.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. There are no risks associated with B1.2.8.

B1.2.9 Methods for Stress/Strain Modeling of the Compact IHX (WEC-TS-IHX-009)

B1.2.9.1 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 the compact IHX. This Test Specification responds to DDN HTS-01-14.

B1.2.9.2 Test Conditions

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 6, TRL 6 to TRL 7, and TRL 7 to TRL 8.

Test Duration

Development of the stress/strain models would occur over a 36-month period

Proposed Test Location

The supplier / design authority might be best suited for this task. Refer to Section 12 of the document.

B1.2.9.3 Measured Parameters

The models to be developed will incorporate and combine the mechanical property databases for Alloy 800H and Hastelloy X with finite element analysis (FEA) techniques and known relationships relative to temperature, fluid flow, interface conditions, and structural stresses.

B1.2.9.4 Data Requirements

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

B1.2.9.5 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 6).

B1.2.9.6 Test Deliverables

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

B1.2.9.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing technology for the compact IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. There is no risk associated with B1.2.9.

B1.2.10 Criteria for Structural Integrity of the Compact IHX (WEC-TS-IHX-010)

B1.2.10.1 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.

B1.2.10.2 Test Conditions

Test Configuration/Set-Up

None currently identified.

Test Duration

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

Proposed Test Location

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

B1.2.10.3 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 (also see activities associated with DDN HTS-01-14).

B1.2.10.4 Data Requirements

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

B1.2.10.5 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 6).

B1.2.10.6 Test Deliverables

Deliverables are as follows.

- Criteria for acceptable stresses and strains

- Safety factors for application to an ASME design code.

B1.2.10.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the compact IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. There is no risk associated with B1.2.10.

B1.2.11 Performance Modeling Methods for the IHX (WEC-TS-IHX-011)

B1.2.11.1 Objectives

The objective of the work described 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.

B1.2.11.2 Test Conditions

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 6, TRL 6 to TRL 7, and TRL 7 to TRL 8).

Test Duration

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

Proposed Test Location

The supplier / design authority might be best suited for this task. Refer to Section 12 of the document.

B1.2.11.3 Measured Parameters

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

B1.2.11.4 Data Requirements

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

B1.2.11.5 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 6, TRL 6 to TRL 7, and TRL 7 to TRL 8).

B1.2.11.6 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

B1.2.11.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the compact IHX from TRL 3 to TRL 4 is addressed in Sections B1.1.3 and B1.1.4. There is no risk associated with B1.2.11.

B2 TECHNOLOGY MATURATION PLAN FOR IHX - TRL 4 TO TRL 5

B2.1 Technology Maturation Plan Summary

B2.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the compact IHX from a TRL level of 4 to a TRL level of 5. The maturation task required to achieve this goal involve the testing of a compact heat exchanger element. A "heat exchanger element" is defined as the compact HX functional equivalent of a 1-tube shell & tube heat exchanger with manifolds. For the Plate-Fin HX addressed in the IHX report, the "Unit Cell" would be an example. A Test Specification is provided to cover the maturation task. This is given in Section B2.2.

B2.1.2 Scope

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

- Specification 1: Testing of Compact Heat Exchanger Element

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

B2.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY 2012 through FY 2014.

B2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B2.2 Test Specifications

B2.2.1 Specification of Testing of Compact Heat Exchanger Element (WEC-TS-IHX-012)

B2.2.1.1 Objectives

The objective of testing the compact heat exchanger element is:

- To determine the integrity of the compact heat exchanger element joints under tensile and compressive loads, plus cycling in a typical pressure environment at elevated temperatures.

B2.2.1.2 Test Conditions

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

Interfacing Requirements

n/a

Test Requirements

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

- Test environment to which compact heat exchanger element will be subjected before post test evaluation:
  - Temperature = 750-800°C
  - Pressure = 9MPa
  - Pressure Δ = 9MPa
  - Cyclic loading (magnitude and cycles TBD)

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

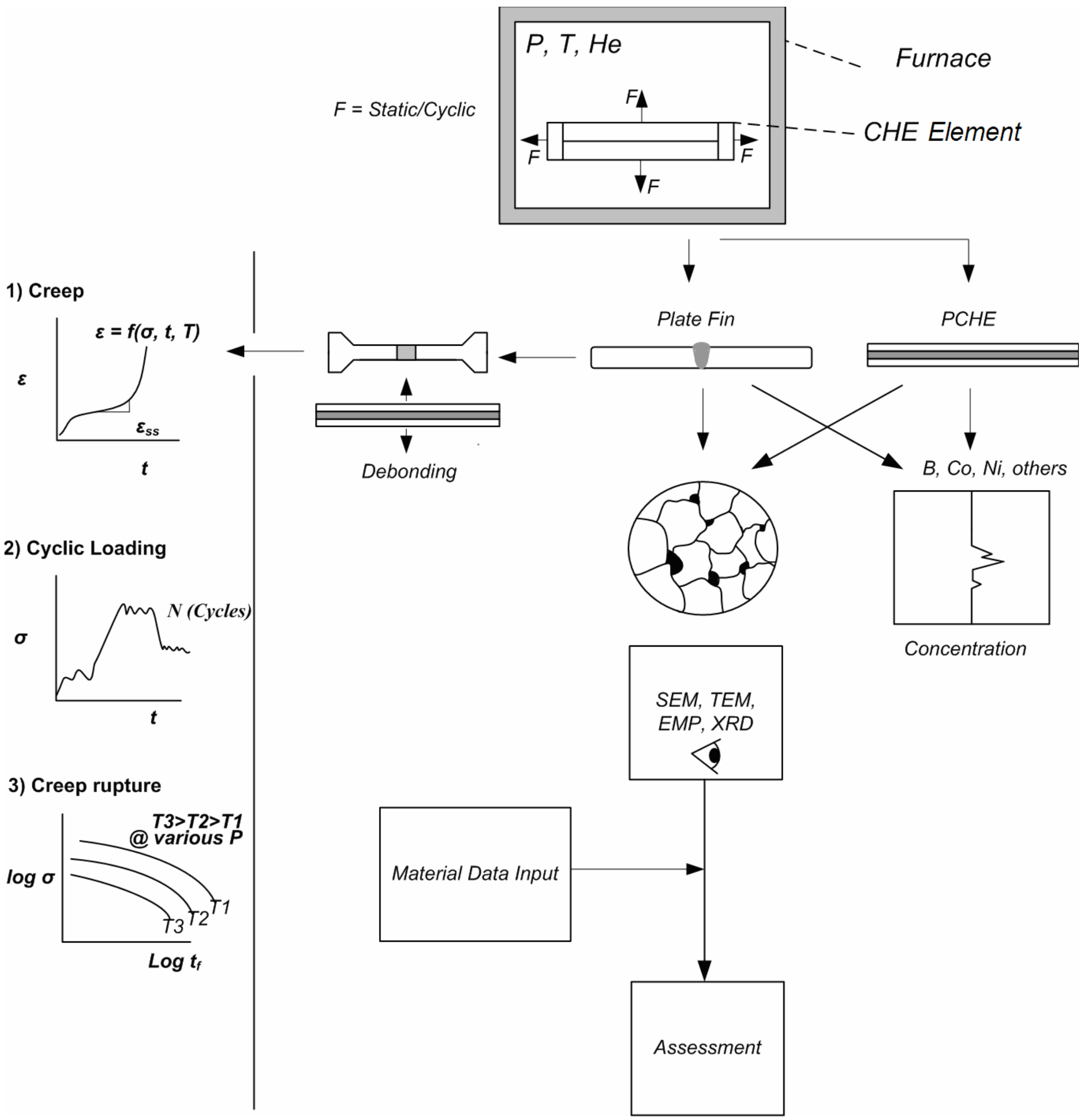

Figure B 1: Proposed Setup and Relevant Parameters in Testing the CHE Element

Test Duration

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

Facility Requirements

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

Proposed Test Location

Manufacturers of metallic heat exchanger elements would most appropriately evaluate the joint integrities of the as manufactured elements. Refer to Section 12 of the document.

B2.2.1.3 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.

B2.2.1.4 Data Requirements

It is assumed that a vendor of metallic heat exchangers will produce the compact heat exchanger elements. The fabricated elements 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

B2.2.1.5 Test Evaluation Criteria

The test evaluation criteria will be the structural integrity of the compact heat exchanger element joints, as evidenced by post-testing examinations relating to metallographic procedures and tests.

B2.2.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section B2.2.1.3

- Documentation containing performance verification criteria and test results relating to the joint integrities of the CHE elements, as observed through microscopic/metallographic evaluations and tests

B2.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology for the compact IHX from TRL 4 to TRL 5 is addressed in Sections B2.1.3 and B2.1.4.

The risk associated with Test Specification B2.2.1 involves the non-satisfactory condition/integrity of the CHE element joint, and may consequently require a reevaluation of the element design (or certain aspects thereof).

B3 TECHNOLOGY MATURATION PLAN FOR IHX - TRL 5 TO TRL 6

B3.1 TECHNOLOGY MATURATION PLAN SUMMARY

B3.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the compact IHX 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 CTC / HTSST (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 B3.2).

B3.1.2 Scope

The maturation tasks necessary to advance the maturity of the technology of IHX 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.

B3.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan will be accomplished during the period FY 2012 through FY 2016.

B3.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B3.2 Test Specification

B3.2.1 Specification of Testing of Integrated Compact Heat Exchanger Module (~1.2MW) (WEC-TS-IHX-013)

B3.2.1.1 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.*

B3.2.1.2 Test Conditions

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

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

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

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 = 750-800°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 800°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 = 750-800°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):

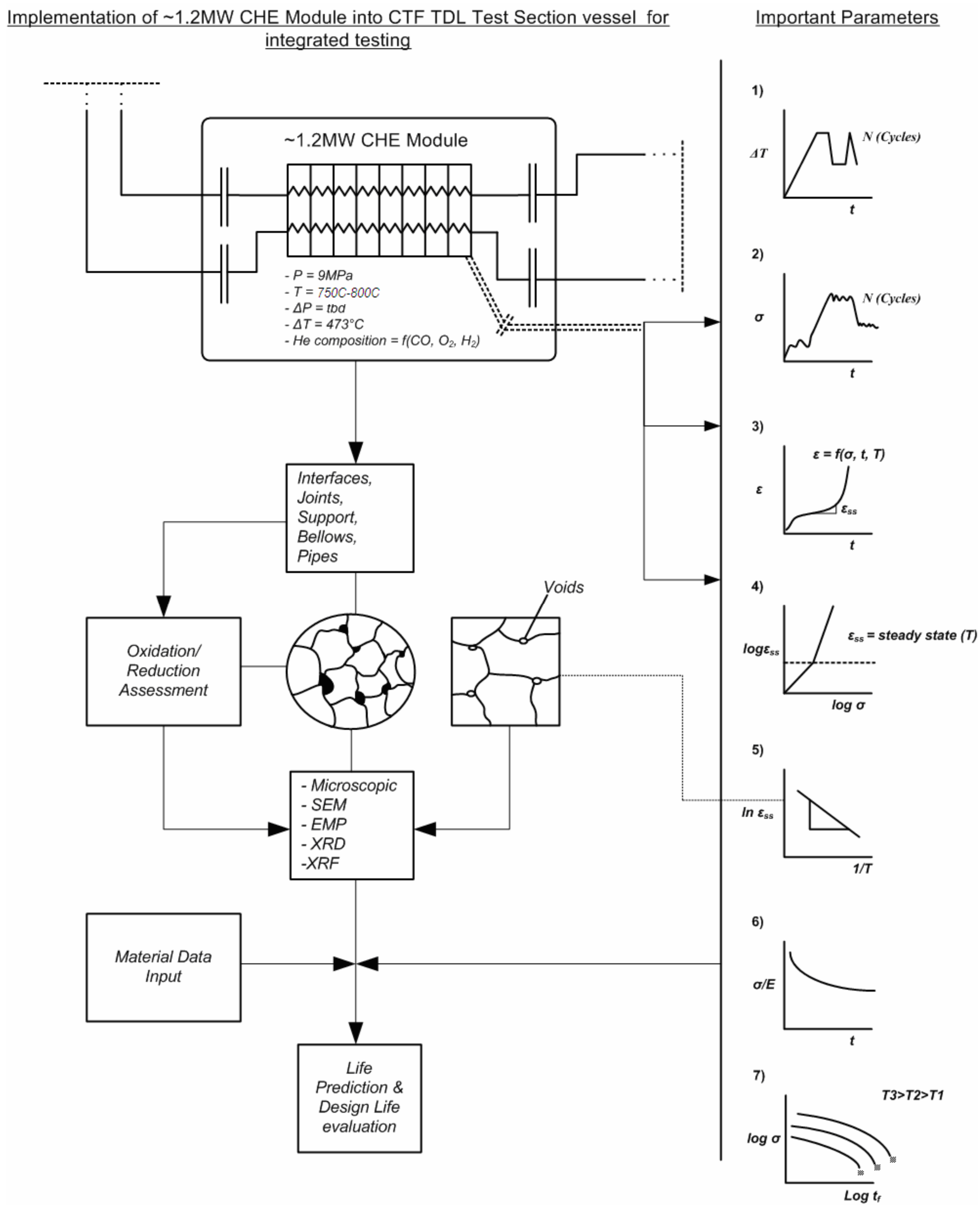

Figure B 2: Proposed Setup and Durability Parameters in Testing the CHE Module

Tests Duration

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

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

Proposed Test Location

Proposed tests will take place at the CTC / HTSST or in a representative environment. Refer to Section 12 of the document.

B3.2.1.3 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.

B3.2.1.4 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.

B3.2.1.5 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.

B3.2.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section B3.2.1.3
- Documentation containing performance verification criteria and test results verified against stress/strain models of the compact heat exchanger module and material properties.

B3.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing the technology of the IHX from TRL 5 to TRL 6 is addressed in Sections B3.1.3 and B3.1.4.

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.

B3.2.2 ASME Section III Code Cases for Metallic Compact Heat Exchanger Designs (WEC-TS-IHX-014)

B3.2.2.1 Objectives

This Test Specification has the overall objective of developing and establishing Section III ASME Code Cases for compact heat exchanger designs and materials. 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 and HTS-01-19.

B3.2.2.2 Test Conditions

Test Configuration/Set-up

No test equipment or facility is needed.

Test Duration

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

Proposed Test Location

The supplier / design authority might be best suited for this task. Refer to Section 12 of the document.

B3.2.2.3 Measured Parameters

N/A

B3.2.2.4 Data Requirements

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

B3.2.2.5 Test Evaluation Criteria

N/A.

B3.2.2.6 Test Deliverables

One of the deliverable is a Section III ASME Code case fully qualifying metallic compact heat exchanger designs for service in the NGNP IHX up to 800°C. Also, ASME Section III, Subsection NH will be modified to include the use of Hastelloy X up to at least 800°C. Similarly, Alloy 800H may be included in Subsection NH to 800°C if deemed desirable.

B3.2.2.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing technology for the compact IHX from TRL 5 to TRL 6 is addressed in Sections B3.1.3 and B3.1.4.

The risk associated with Test Specification B3.2.2 entails the failure to establish ASME Code Cases for compact heat exchanger designs and materials.

B4 TECHNOLOGY MATURATION PLAN FOR THE COMPACT IHX – TRL 6 TO TRL 7

B4.1 TECHNOLOGY MATURATION PLAN SUMMARY

B4.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the compact IHX 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 B4.2).

B4.1.2 Scope

The maturation tasks necessary to advance the maturity of the technology of the compact IHX 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 are described below.

B4.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan could be accomplished during the period FY 2014 through FY 2018.

B4.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B4.2 Test Specifications

B4.2.1 Shell-Side Flow Distribution and Bypass Leakage Testing (WEC-TS-IHX-015)

B4.2.1.1 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.

B4.2.1.2 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.

B4.2.2 Multi-Module Heat Transfer Testing (WEC-TS-IHX-016)

B4.2.2.1 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.

B4.2.2.2 Test Conditions

The multi-module test would be a heated test in the CTC / HTSST 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.

B5 TECHNOLOGY MATURATION PLAN FOR THE COMPACT IHX - TRL 7 TO TRL 8

B5.1 TECHNOLOGY MATURATION PLAN SUMMARY

B5.1.1 Objectives

The purpose of this Technology Maturation Plan is to describe the activities required to advance the maturity of the technology for the compact IHX 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-scale compact heat exchanger. (It is assumed that a compact heat exchanger vendor will provide the full-scale compact heat exchanger and/or the IHX will be 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 B5.2).

B5.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the compact IHX 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.

B5.1.3 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.

B5.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B5.2 Test Specifications

B5.2.1 Specification of Testing of a Full Scale Compact Heat Exchanger (WEC-TS-IHX-017)

B5.2.1.1 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 IHX will be fully tested and commissioned in the NGNP. Details of the testing and commissioning will be finalized at later stage.

NGNP-TDI-TDR-RPT-G-00010 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 3: HTS Piping

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Roger Young (Pebble Bed Modular Reactor (Pty) Ltd)	July 23, 2009

BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
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B	Phillip Rittenhouse	Reviewer comments incorporated	July 17, 2009
C	Scott Penfield	Incorporating Results from IHX Development and Trade Studies Report	July 23, 2009
0	Phillip Rittenhouse	Approved Document	July 30, 2009
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1	Phillip Rittenhouse	Document for release to BEA	September 18, 2009

DOCUMENT TRACEABILITY

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3 HTS PIPING

3.1 Description, Functions, and Operating Requirements

The Heat Transport System (HTS) involves pipes of varying temperature capabilities in both the Primary HTS (PHTS) and Secondary HTS (SHTS). High-temperature piping and insulation are utilized within the PHTS Core Outlet Pipe (COP) to direct helium flow from the reactor to the Intermediate Heat Exchanger (IHX). Lower temperature portions of the PHTS piping circuit transport the helium flow from the exit of the IHX to the circulator and from the circulator to the reactor. Low temperature piping also provides cooling flow from the circulator outlet to the cooling annulus of the high-temperature COP.

High-temperature piping and insulation are utilized within the SHTS to direct helium flow from the high-temperature exit of the IHX to the Steam Generator (SG) or the Process Coupling Heat Exchanger (PCHX), depending on the system/process involved. Low-temperature sections of the SHTS piping direct helium from the SG or PCHX to the circulator and from the circulator to the IHX.

The nominal helium temperatures, pressures and flow rates in each of the HTS piping sections are shown in Table 3-1 and Figure 3-1, which are based on the recent *NGNP: Intermediate Heat Exchanger Development and Trade Studies* Report.[1] The temperatures will vary depending on the details of the process served and whether a 750°C or an 800°C Reactor Outlet Temperature (ROT) is involved. The outer helium 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 Section VIII (preferred).

Table 3-1: Helium Temperatures in HTS Piping Sections

Piping Location	Temperature (°C)
PHTS	
RPV to IHX	750-800
IHX to Circulator*	~268
Circulator to RPV*	~280
SHTS	
IHX to SG or PCHX	700-750
SG or PCHX to circulator*	~209
Circulator to IHX*	~218

* For 800°C ROT.

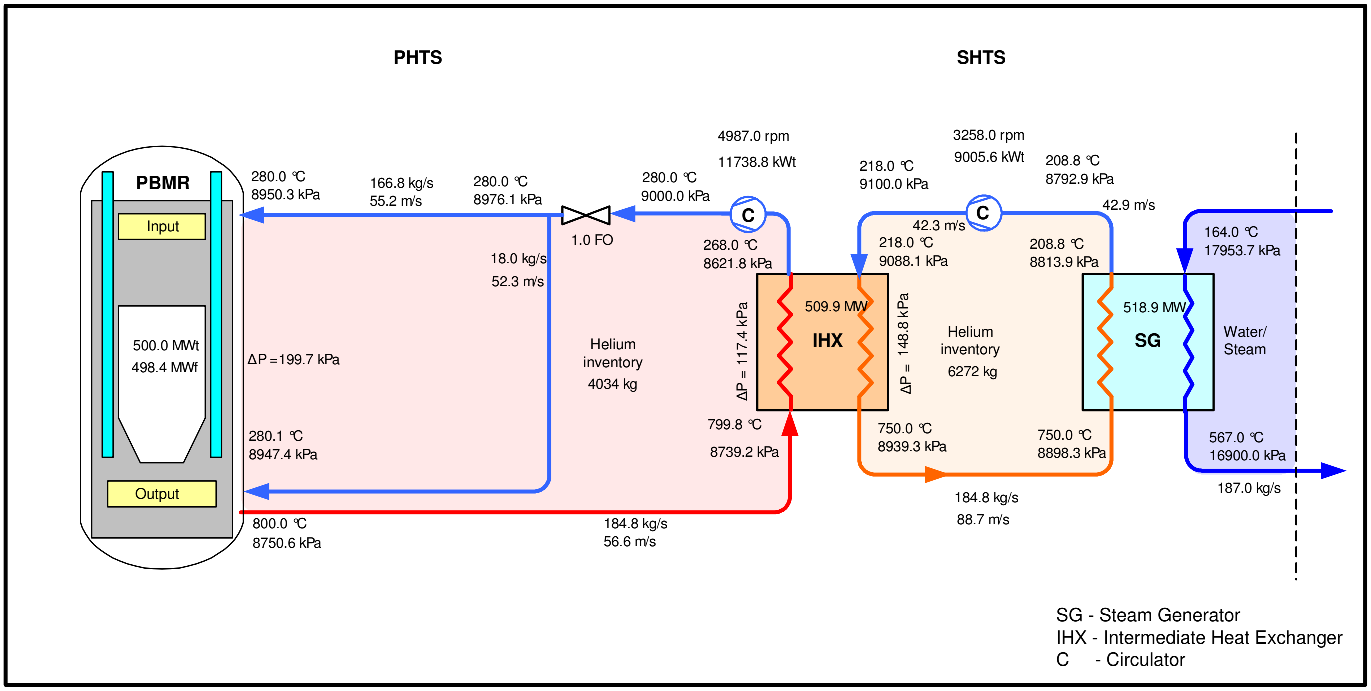

Figure 3-1: Nominal Temperatures of HTS Piping for an NGNP Steam Production Plant (800°C ROT)

The primary functions and operating requirements of the HTS piping are to:

- Form portions of the PHTS and SHTS pressure boundaries.
- In the PHTS, channel the helium from the reactor to the IHX, onward to the circulator and back to the reactor.
- In the PHTS, provide cooling flow for the COP HPB.
- In the SHTS, channel the helium from the high-temperature exit of the IHX to the SG or PCHX, and onward to the circulator and the IHX.
- 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 helium 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 low-alloy (SA-533B) 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.
- Resist circulator-induced pressure pulses and flow-induced vibrations.
- Operate without preventive maintenance for 60 years.

3.1.1 PHTS Piping

The basic design currently assumed (*NGNP PCDR Section 6, May 2007,* [1]) for the COP, connecting the RPV to the IHX, is based on the Demonstration Power Plant (DPP) design (*NGNP Metallic Component Schedule Risk and Cost Uncertainty Assessment Report,* [4]). Both the DPP and NGNP COP designs incorporate an internal hot gas duct (HGD) consisting of internal concentric ducts separated by layers of insulation (see Figure 3-2). 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 helium flow and, as with the DPP, is not pressure retaining. An inner pressure-retaining pipe surrounds the liner and insulation package and a larger pipe that is part of the primary system HPB surrounds this package. The annulus between the HPB and the HGD is cooled by a flow of ~280°C helium bypassed from the PHTS circulator exit (see Figure 3-1).

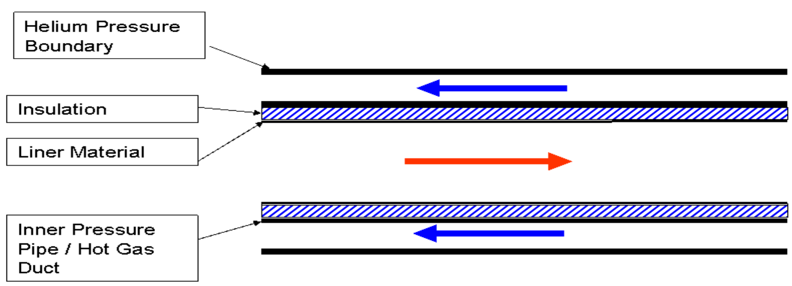

Figure 3-2: Example of Active Cooling Configuration

The NGNP and DPP designs are presently more aligned with each other in terms of temperature and, thus, the COP technology of the DPP is even more applicable to the required NGNP development. The temperature of the helium from the NGNP is 100-150°C lower than that from the DPP (750°C-800°C versus 900°C). Note, however, that the nominal temperature of the cooling gas available for supply to the COP annulus in the NGNP case is higher than that of the DPP (280°C for the NGNP vs. ~100°C for the DPP). While within the capability of the reference material (SA-533B), this suggests the need for internal or external insulation to reduce heat losses and minimize thermal impacts on nearby Structures, Systems and Components (SSCs). Temperatures reached at the circulator outlet and, hence, in the COP cooling annulus during transients remain to be determined through dynamic modeling as part of conceptual design. This consideration will, therefore, be included in a future TDRM update.

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 ROT is lower for the NGNP, these materials should be conservative in the NGNP application. 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 COP for the NGNP design are of SA-533B. These design options are shown in Figure 3-3 and Figure 3-4 for the various temperature sections in the PHTS piping.

As indicated earlier, goals for the NGNP piping between the reactor and the IHX 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 the IHX, but the current design assumption (*NGNP PCDR Section 6, May 2007,* [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 (up to 800°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 (e.g., Reference [6]) 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.

In the case of the low-temperature (<300°C) piping (see Figure 3-4), it should be possible to use a design without active cooling. Insulation might be applied internally or externally to the HPB pipes.

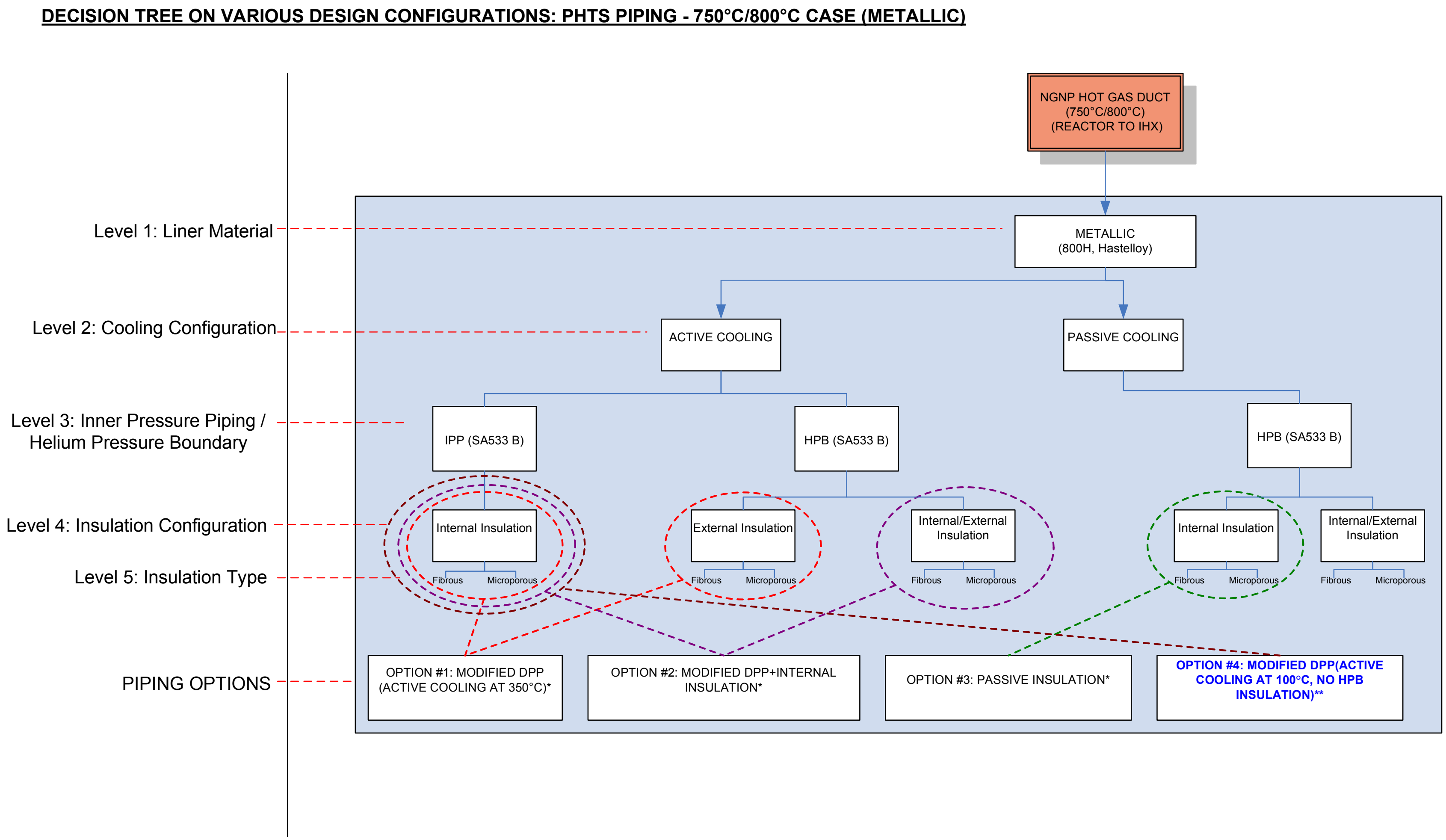

Figure 3-3: Design Options for High Temperature PHTS Piping Sections (750°C-800°C)

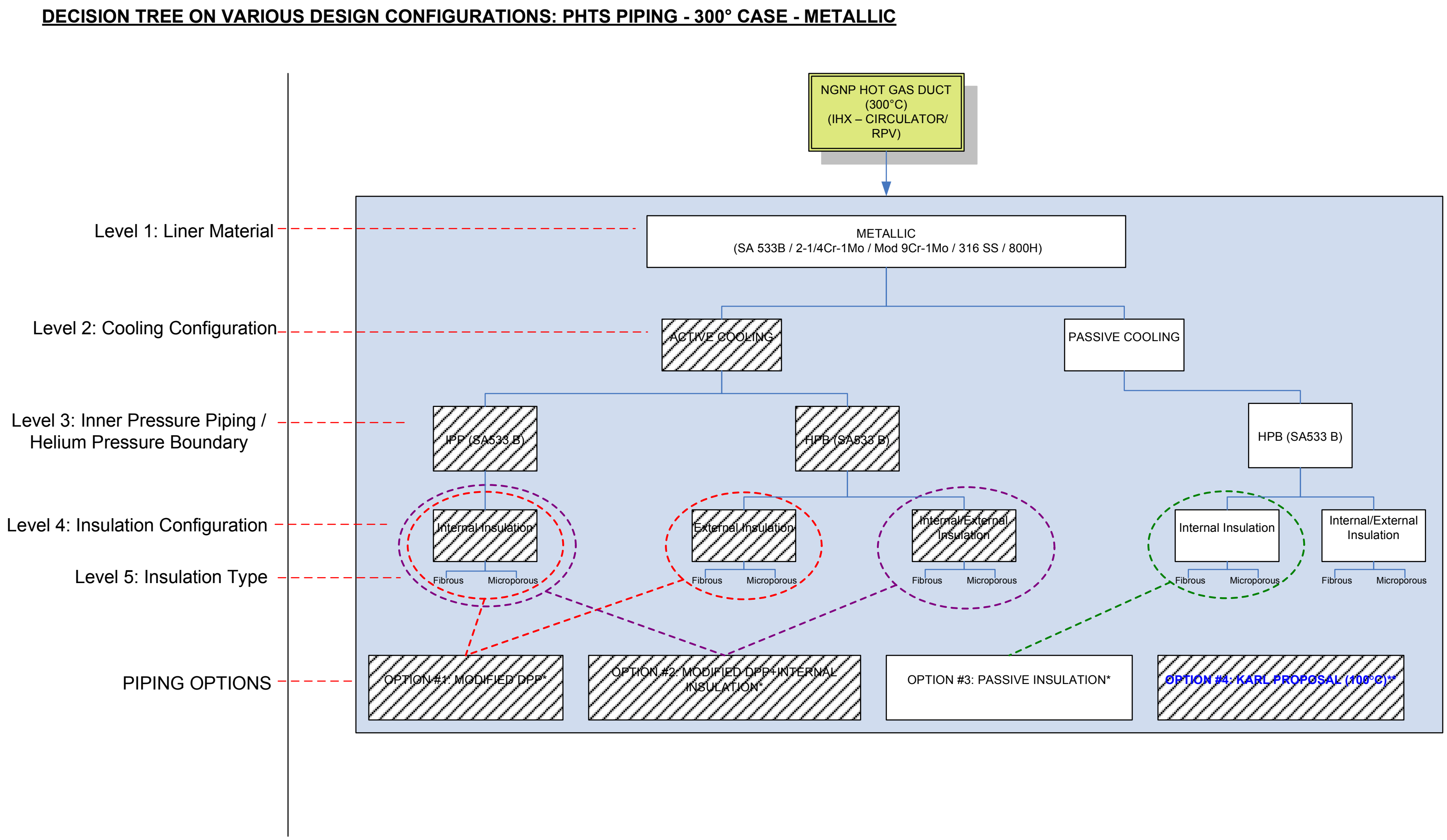

Figure 3-4: Design Options for Low Temperature PHTS Piping Sections (~300℃)

3.1.2 SHTS Piping

According to *NGNP PCDR Section 6* [1], all sections of the SHTS piping are assumed to be of an internally insulated single-wall HPB (i.e., passively cooled) design (see Figure 3-5).

As with the PHTS piping described in Section 4.1.1, it is assumed that the internal diameter for gas flow for the high-temperature (700°C-750°C) carrying sections of the SHTS piping is nominally 1000 mm and that the liner provides only for directing the helium 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; the liner material will likely be Alloy 800H, but Hastelloy X and other Ni-base alloys may also be candidates. 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 earlier, there is no existing proven design for a 700°C-750°C passively cooled SHTS pipe. (See Figure 3-6 for design options.)

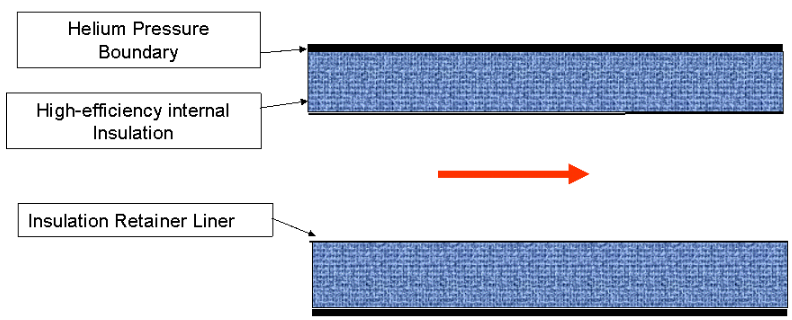

Figure 3-5: Example of Passive Cooling Configuration

In the case of the low-temperature (<250°C) SHTS piping (see Figure 3-7), 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. As with the PHTS piping, transient analyses will be required to define bounding conditions, and the TDRM will be appropriate updated at that time, if required.

DECISION TREE ON VARIOUS DESIGN CONFIGURATIONS: SHTS PIPING - 700°C/750°C CASE (METALLIC)

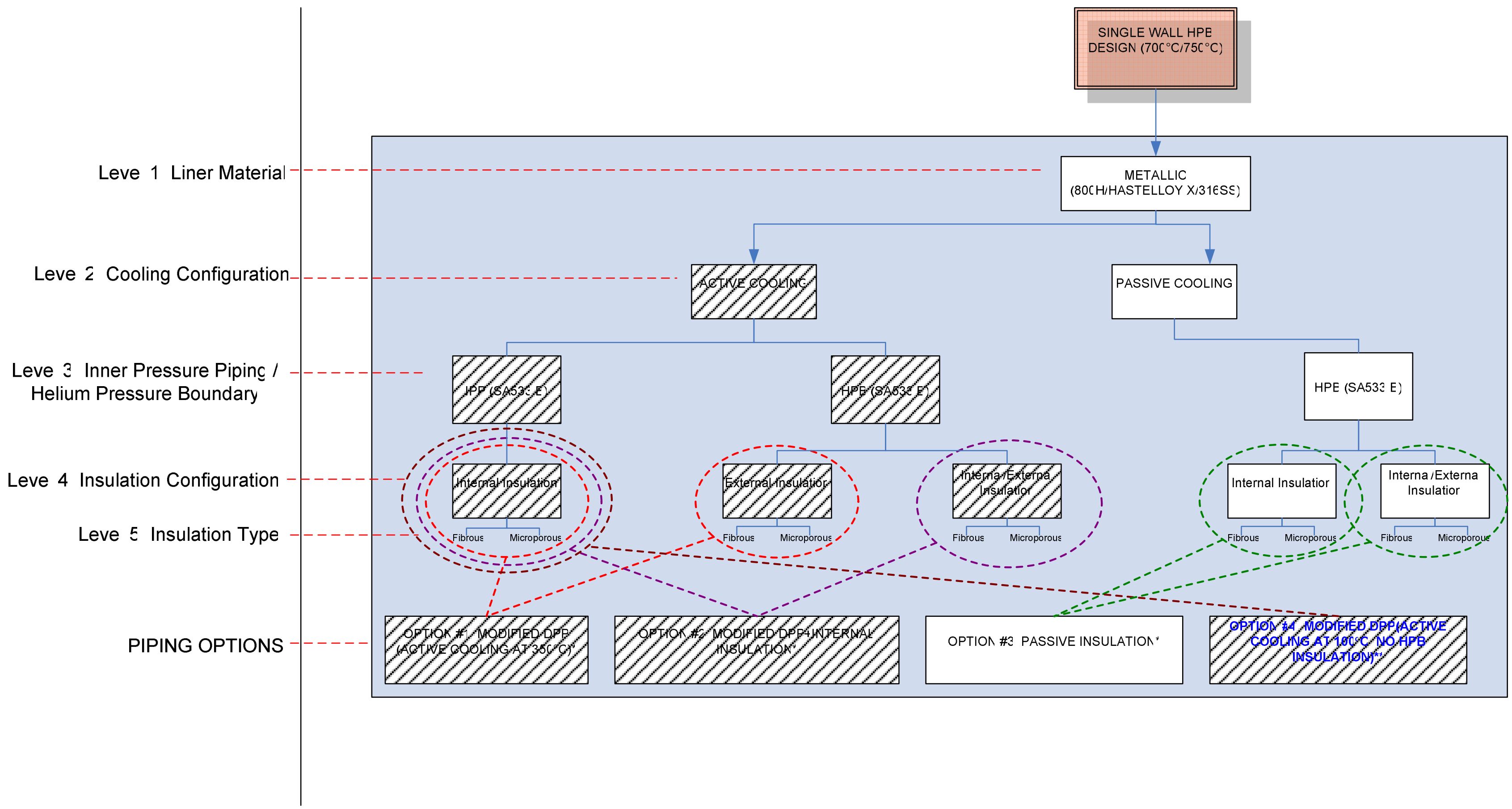

Figure 3-6: Design Options for High Temperature SHTS Piping Sections (700°C and 750°C)

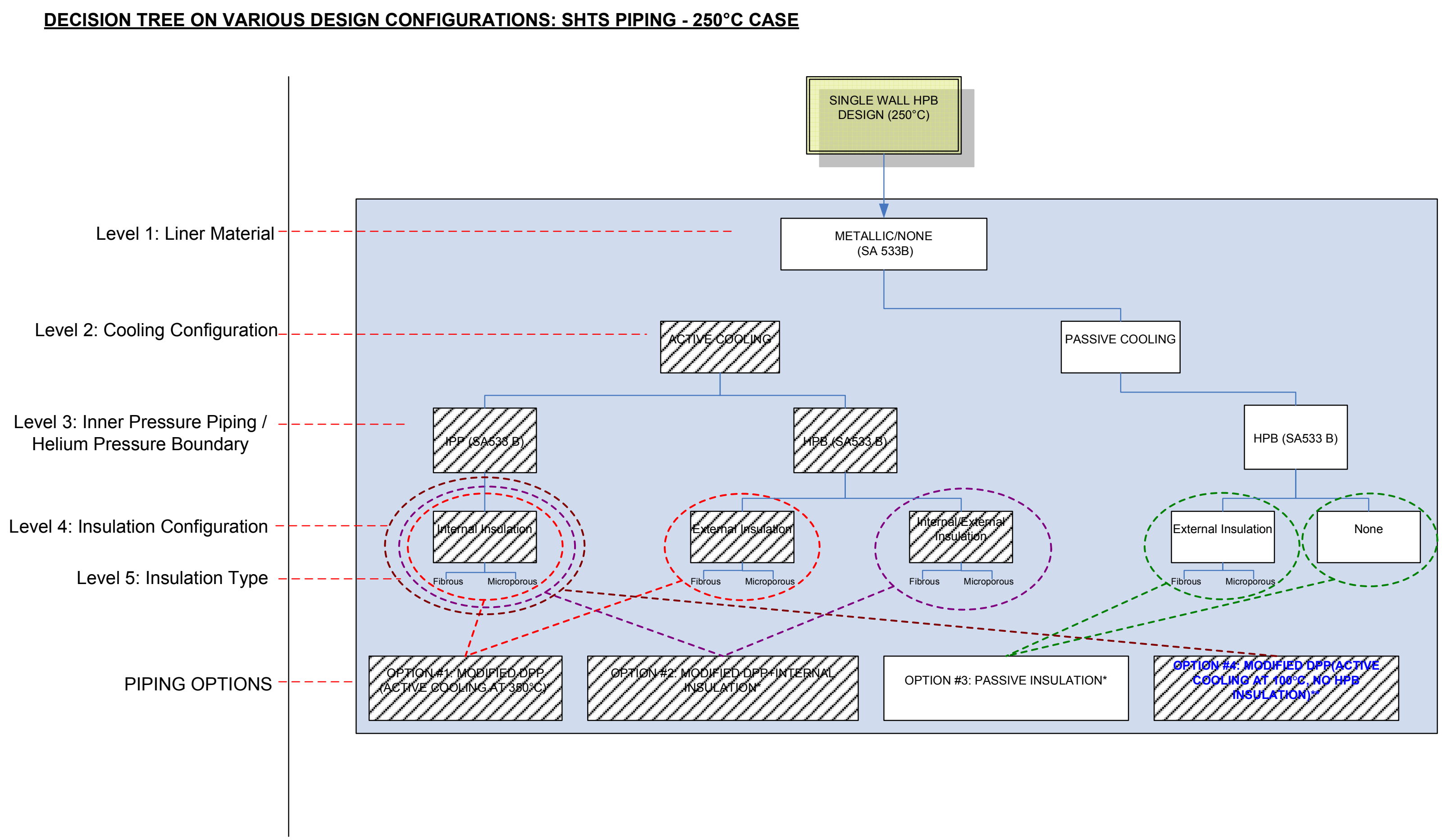

Figure 3-7: Design Options for Low Temperature SHTS Piping Sections (~250°C)

3.2 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 [3].

3.3 Technology Development Road Map

3.3.1 Overview

The TDRM for HTS piping provides a listing of the Maturation Tasks that are necessary to advance the status of technology to succeeding 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 A; associated maturations tasks are described below.

3.4 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 and low temperature piping sections. Additionally, it is necessary to determine the effects of helium 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 [1] as well as in Section 17 of the NGNP TDRM Report [5].

3.5 Core Outlet Connection Technology Development

The Core Outlet Connection (COC) is an element of the HTS piping and its functions and design have been discussed in detail in the NGNP Conceptual Design Study: Composites R&D Technical Issues [6].

The DPP COC will be tested as part of the DPP testing program 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: Composites R&D Technical Issues [6]. 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.

3.6 References

[1] NGNP: Intermediate Heat Exchanger Development and Trade Studies, NGNP-NHS-HTS-RPT-M-0004, Rev. 0, July 2009

[2] NGNP-06-RPT-001, Rev0, May 2007 – NGNP and Hydrogen Production Preconceptual Design Report, "Section 6: Heat Transport System"

[3] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

[4] Metallic Component Schedule Risk and Cost Uncertainty Assessment report

[5] NGNP-CTF MTECH-TDRM-017, Rev 0, December 2008 – NGNP TDRM Report: Integrated Schedule & Cost Estimate

[6] NGNP-NHS TI-COMP, Rev 0, Oct 2008 - NGNP Conceptual Design Study: Composites R&D Technical Issues

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750℃-800℃

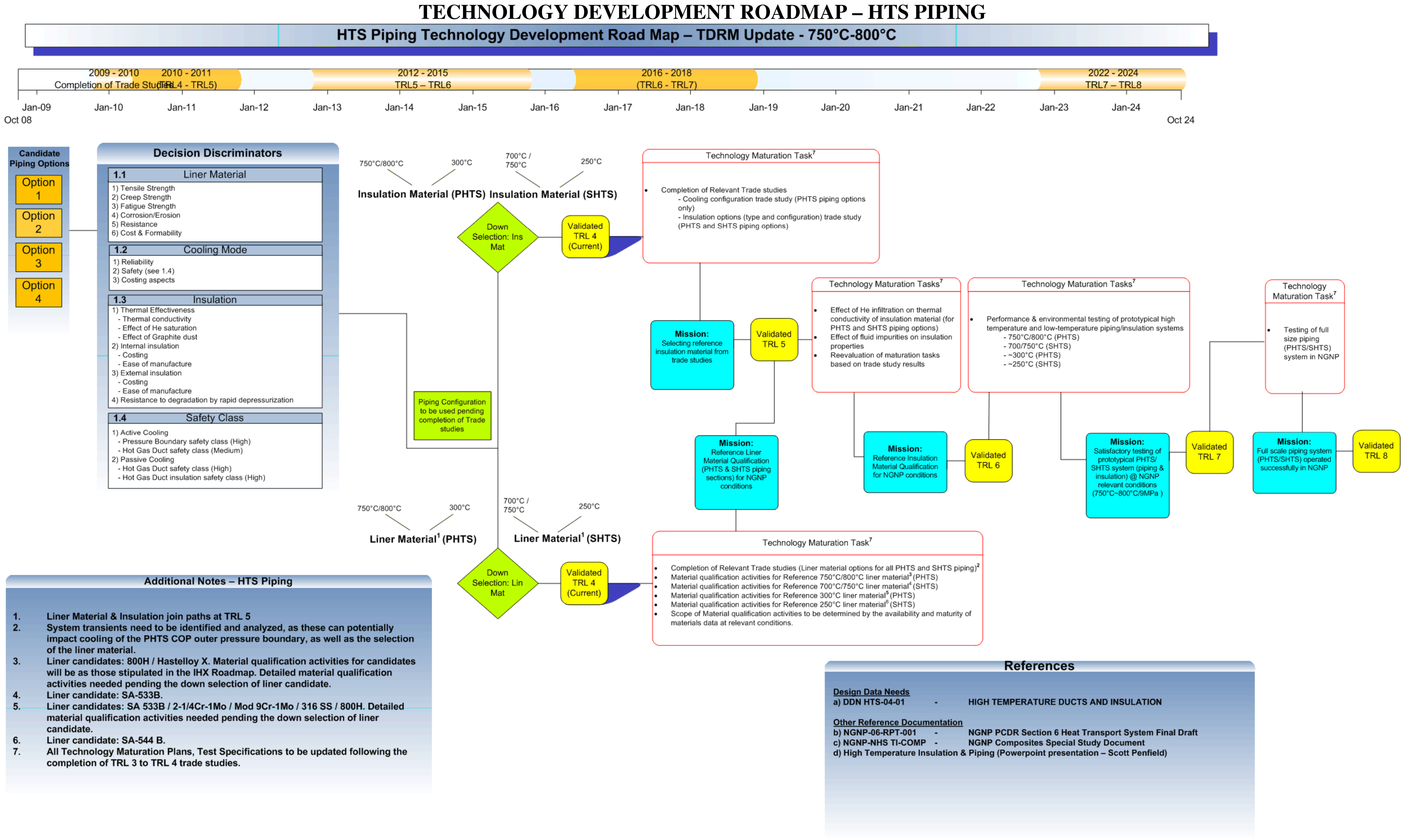

Figure A-1: TDRM for the HTS Piping

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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REQUIRED SPECIFICATIONS/TEST TO ACHIEVE NEXT TRL

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- Specification 1: PHTS High-Temperature [750°C and 800°C] Piping Cooling, Liner, and Insulation Options Trade Study *(WEC-TS-PIP$_{750}$-001)*
- Specification 2: PHTS Low-Temperature [~300°C] Piping Liner and Insulation Options Trade Study *(WEC-TS-PIP$_{750}$-002)*
- Specification 3: SHTS High-Temperature [700°C and 750°C] Piping Liner and Insulation Trade Study *(WEC-TS-PIP$_{750}$-003)*
- Specification 4: SHTS Low-Temperature [~250°C] Piping Liner and Insulation Trade Study *(WEC-TS-PIP$_{750}$-004)*

TRL 5 to TRL 6

- Specification 1: Effects of Helium Infiltration on Thermal Conductivity of Insulation Material *(WEC-TS-PIP$_{750}$-005)*
- Specification 2: The Effect of Fluid Impurities (C) on Insulation Properties *(WEC-TS-PIP$_{750}$-006)*
- Specification 3: Re-evaluation of Needed Maturation Tasks Based on Trade Study Results *(WEC-TS-PIP$_{750}$-007)*

TRL 6 to TRL 7:

- Specification 1: Performance and Environmental Testing of Prototypical High-Temperature and Low-Temperature Piping/Insulation System *(WEC-TS-PIP$_{750}$-008)*

TRL 7 to TRL 8:

- Specification 1: Testing of Full-Size PHTS Piping in NGNP *(WEC-TS-PIP$_{750}$-009)*

B1 TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 4 TO TRL 5

B1.1 TECHNOLOGY MATURATION PLAN SUMMARY

B1.1.1 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 four tasks involve conducting trade studies on cooling, liner and insulation options for the high- [750°C and 800°C] and low-temperature [~300°C] PHTS piping sections and the high- [700°C and 750°C] and low-temperature [~250°C] SHTS piping sections.

B1.1.2 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 [750°C and 800°C] Piping Cooling, Liner, and Insulation Options Trade Study
- PHTS Low-Temperature [~300°C] Liner and Insulation Options Trade Study
- SHTS High-Temperature [700°C and 750°C] Piping Liner and Insulation Trade Study
- SHTS Low-Temperature [~250°C] Piping Liner and Insulation Trade Study.

B1.1.3 Anticipated Schedule

It should be possible to complete the trade studies indicated by the bullets in B1.1.2 within a 6-month period after system operating conditions (steady state & transients) have been fully defined.

B1.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B1.2 Test Specifications

B1.2.1 PHTS High-temperature [750°C and 800°C] Piping Cooling, Liner and Insulation Options Trade Study (WEC-TS-PIP$_{750}$-001)

B1.2.1.1 Objectives

This Test Specification provides for trade studies to assess cooling, liner and insulation options for the PHTS piping sections operating at 750°C and 800°C (reactor to IHX). 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.

B1.2.1.2 Test Conditions

Test Configuration/Set-up

Not applicable

Test Duration

This activity should require approximately 6 months.

Proposed Test Location

The piping system designer should lead these studies. Refer to Section 12 of the document.

B1.2.1.3 Measured Parameters

Parameters to be considered in this study are as follows:

- Results of steady-state and transient analyses addressing normal operation and Licensing Basis Events (LBEs) that potentially impose bounding conditions on the PHTS piping (e.g., loss of secondary cooling (LOSC), loss of secondary pressure (LOSP)).
    - Maximum PHTS helium temperatures reached during bounding events.
    - Liner and pressure boundary temperatures for each liner/cooling/insulation combination during normal operation and for bounding events.
- Estimated relative cost and reliability of each liner/cooling/insulation combination.

B1.2.1.4 Data Requirements

Qualified and industry-accepted transient and heat transport codes and models shall be employed for all calculations.

B1.2.1.5 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 B1.2.1.6).
- Relative cost of each combination.
- Relative operational reliability estimate for each combination.
- Relative inspectability and maintainability.

B1.2.1.6 Test Deliverables

Task deliverables are as follows:

- Helium temperatures in reactor-to-IHX piping sections during normal operation and bounding events.
- Decision trees describing liner, cooling, and insulation options for reactor-to IHX piping sections.
- Analyses of the ability of liner/cooling/insulation combinations to achieve the temperature limits described in Section 3.1 (nominally 371°C for pressure retaining pipes and <100°C at the external surface of these pipes) during normal operation
- Analyses of the ability of liner/cooling/insulation combinations to achieve the temperature limits described in Section 3.1 during bounding events.
- Cost and reliability assessment of each liner/cooling/insulation combination.
- Recommendation as to preferred design for each piping section.

B1.2.1.7 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 B1.1.3 and B1.1.4. The risk that satisfactory design options for high-temperature PHTS piping cannot be achieved is minimal.

B1.2.2 PHTS Low-temperature [~300℃] Piping Liner and Insulation Options Trade Study (WEC-TS-PIP$_{750}$-002)

B1.2.2.1 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 ~300°C (IHX 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.

B1.2.2.2 Test Conditions

Test Configuration/Set-up

Not applicable

Test Duration

The trade study should require no more than 6 months.

Proposed Test Location

The piping system designer should lead these studies. Refer to Section 12 of the document.

B1.2.2.3 Measured Parameters

Parameters to be considered in this study are as follows:

- Results of steady-state and transient analyses addressing normal operation and Licensing Basis Events (LBEs) that potentially impose bounding conditions on the PHTS piping (e.g., loss of secondary cooling (LOSC), loss of secondary pressure (LOSP)).
  - Maximum helium temperatures reached during bounding events.
  - Liner and pressure boundary temperatures for each liner/insulation combination during normal operation and for bounding events.
- Estimated relative cost and reliability of each liner/insulation combination.

B1.2.2.4 Data Requirements

Qualified and industry-accepted transient and heat transport codes and models shall be employed for all calculations.

B1.2.2.5 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 B1.2.2.6).
- Relative cost of each combination.
- Relative operational reliability estimate for each combination.
- Relative inspectability and maintainability.

B1.2.2.6 Test Deliverables

Task deliverables are as follows:

- Helium temperatures in IHX to circulator and circulator-to-reactor piping sections during normal operation and bounding events.
- Decision trees describing liner and insulation options for IHX to circulator and circulator-to-reactor piping sections.
- Analyses of the ability of liner/insulation combinations to achieve the temperature limits described in Section 3.1 (nominally 371°C for pressure retaining pipes and <100°C at the external surface of these pipes) during normal operation.
- Analyses of the ability of liner/insulation combinations to achieve the temperature limits described in Section 3.1 during bounding events.
- Other options (e.g., alternate materials) for assuring the integrity of the pressure vessel piping during bounding transients.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for the low-temperature piping sections.

B1.2.2.7 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 B1.1.3 and B1.1.4. The risk that satisfactory design options for low-temperature PHTS piping cannot be achieved is minimal. However, materials different from those presently specified may be needed in some instances.

B1.2.3 SHTS High-temperature [700°C and 750°C] Piping Liner and Insulation Options Trade Study (WEC-TS-PIP$_{750}$-003)

B1.2.3.1 Objectives

This Test Specification provides for trade studies to assess liner and insulation options for the SHTS piping sections operating at 700°C and 750°C (IHX to the steam generator or to another process system). 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.

B1.2.3.2 Test Conditions

Test Configuration/Set-up

Not applicable

Test Duration

The trade study should require no more than 6 months.

Proposed Test Location

The piping system designer should lead these studies. Refer to Section 12 of the document.

B1.2.3.3 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.
- Liner and pressure boundary (HPB) temperatures for each liner/insulation combination during bounding transients.
- Estimated relative cost and reliability of each liner/ insulation combination.

B1.2.3.4 Data Requirements

Qualified and industry-accepted transient and heat transport codes and models shall be employed for all calculations.

B1.2.3.5 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 B1.2.3.6).
- Relative cost of each combination.
- Relative operational reliability estimate for each combination.
- Relative inspectability and maintainability.

B1.2.3.6 Test Deliverables

Task deliverables are as follows:

- Helium temperatures in IHX to steam generator or other process system during normal operation and bounding events.
- Decision trees describing liner and insulation options for the IHX to steam generator or process system piping.

- 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 3.1.
- Analyses of the ability of liner/insulation combinations to achieve the temperature limits described in Section 3.1 during bounding events.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for each piping section.

B1.2.3.7 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 B1.1.3 and B1.1.4. The risk that satisfactory design options for high-temperature SHTS piping cannot be achieved is minimal.

B1.2.4 SHTS Low-Temperature [~250°C] Piping Liner and Insulation Options Trade Study (WEC-TS-PIP_{750}-004)

B1.2.4.1 Objectives

This Test Specification provides for trade studies to assess liner and insulation options for the SHTS piping sections operating at ~250°C (steam generator or other process system to circulator) and from the circulator to the secondary inlet of the IHX. 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.

B1.2.4.2 Test Conditions

Test Configuration/Set-up

Not applicable

Test Duration

The trade study should require no more than 6 months.

Proposed Test Location

The piping system designer should lead these studies. Refer to Section 12 of the document.

B1.2.4.3 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.
- Liner and pressure boundary (HPB) temperatures for each liner/insulation combination during bounding transients.
- Estimated relative cost and reliability of each liner/ insulation combination.

B1.2.4.4 Data Requirements

Qualified and industry-accepted transient and heat transport codes and models shall be employed for all calculations.

B1.2.4.5 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 B1.2.4.6).
- Relative cost of each combination.
- Relative reliability estimate for each combination.
- Relative inspectability and maintainability.

B1.2.4.6 Test Deliverables

Task deliverables are as follows:

- Helium temperatures in the piping from the steam generator or other process system to the circulator and from the circulator to the IHX secondary inlet during normal operation and bounding events.
- Decision trees describing liner and insulation options for the piping sections from the steam generator/process system to the circulator and from the circulator to the IHX secondary inlet.
- 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 3.1.
- Cost and reliability assessment of each liner/insulation combination.
- Recommendation as to preferred design for each piping section.

B1.2.4.7 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 B1.1.3 and B1.1.4. The risk that satisfactory design options for low-temperature SHTS piping cannot be achieved is minimal.

B2 TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 5 TO TRL 6

B2.1 TECHNOLOGY MATURATION PLAN SUMMARY

B2.1.1 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 helium (pure helium and helium with controlled impurities such as moisture) and circulating solids such as carbon dust on the thermal conductivity of insulation options. Additionally, the trade studies noted above under B1.2 may result in the need for other maturation tasks and a Test Specification is included to cover the development of such tasks if necessary.

B2.1.2 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 Helium Infiltration on Thermal Conductivity of Insulation Material
- The Effects of Solid Circulating Impurities (C dust) on Insulation Properties
- Re-evaluation of Needed Maturation Tasks Based on Trade Study Results

B2.1.3 Anticipated Schedule

The helium 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 helium 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.

B2.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B2.2 Test Specifications

B2.2.1 Effects of Helium Infiltration on Thermal Conductivity of Insulation Material (WEC-TS-PIP$_{750}$-005)

B2.2.1.1 Objectives

Work conducted under this Test Specification will provide data on the effects of helium infiltration and fluid impurities on the thermal conductivity of insulation materials. The Test Specification responds to DDN HTS-04-01.

B2.2.1.2 Test Conditions

Test Configuration/Set-up

These activities require the following:

- Equipment/facilities for exposing insulation materials (both fibrous and microporous) to helium at pressures to 9 MPa and temperatures to 850°C
- Provisions for temperature and pressure (including cycling) control and measurement
- Provision for the introduction and control of trace impurities typical of those projected for the PHTS and SHTS
- Equipment for measurement of thermal conductivity of insulation materials at pressures to 9 MPa and temperatures to 850°C

Test Duration

Test equipment set-up and testing of the insulation should require no more than 18 months.

Proposed Test Location

Insulation manufacturers, universities, and National Laboratories are candidates to conduct these studies. Refer to Section 12 of the document.

B2.2.1.3 Measured Parameters

Parameters to be measured and controlled in this study are as follows.

- Helium temperature
- Helium pressure
- Helium impurity levels
- Duration of exposure
- Thermal conductivity.

B2.2.1.4 Data Requirements

Data shall be acquired employing industry accepted techniques and standards and appropriate QA.

B2.2.1.5 Test Evaluation Criteria

Evaluation criteria include reproducibility of results in multiple tests and agreement of results with existing data.

B2.2.1.6 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

B2.2.1.7 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 B2.1.3 and B2.1.4.

The risk that insulation of satisfactory thermal conductivity for HTS piping insulation will not be available is small.

B2.2.2 The Effect of Solid Impurities (C) on Insulation Properties (WEC-TS-PIP$_{750}$-006)

B2.2.2.1 Objectives

Work conducted under this Test Specification will provide data on the effects of solid impurities (graphite dust) in the testing fluid on the thermal conductivity of insulation materials. The Test Specification responds to DDN HTS-04-01.

B2.2.2.2 Test Conditions

Test Configuration/Set-up

These activities require the following.

- Equipment/facilities for exposing insulation materials (both fibrous and microporous) to helium with controlled levels of solid impurities at pressures to 9 MPa and temperatures to 850°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 850°C

Test Duration

Test equipment set-up and testing of the insulation should require 18-to 24 months.

Proposed Test Location

Insulation manufacturers, universities, and National Laboratories are candidates for this work. Refer to Section 12 of the document.

B2.2.2.3 Measured Parameters

Parameters to be measured and controlled in this study are as follows.

- Helium temperature
- Helium pressure
- Helium impurity levels
- Duration of exposure

- Thermal conductivity

B2.2.2.4 Data Requirements

Data shall be required employing industry accepted techniques and standards and appropriate QA.

B2.2.2.5 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 solid (C) impurities.

B2.2.2.6 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).

B2.2.2.7 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 B2.1.3 and B2.1.4. The risk that insulation of satisfactory thermal conductivity for HTS piping will not be available is small.

B2.2.3 Re-evaluation of Needed Maturation Tasks Based on Trade Study Results (WEC-TS-PIP$_{750}$-007)

B2.2.3.1 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 B1.2.1 to B1.2.4.

B2.2.3.2 Test Conditions

Test Configuration/Set-up

Not applicable

Test Duration

Re-evaluation of needs based on the results of Test Specifications B1.2.1 through B1.2.4 should require no more than three months.

Proposed Test Location

The piping system designer should lead the re-evaluation. Refer to Section 12 of the document.

B2.2.3.3 Measured Parameters

N/A

B2.2.3.4 Data Requirements

N/A

B2.2.3.5 Test Evaluation Criteria

N/A

B2.2.3.6 Test Deliverables

The task deliverable is to provide recommendation for additional maturation tasks, if needed, for advancing the technology of HTS piping from TRL 5 to TRL 6.

B2.2.3.7 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 B2.1.3 and B2.1.4. There is no risk associated with Test Specification B1.2.3.

B3 TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 6 TO TRL 7

B3.1 TECHNOLOGY MATURATION PLAN SUMMARY

B3.1.1 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 6 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 B3.2).

B3.1.2 Scope

The maturation task necessary to advance the maturity of the technology of the HTS piping from TRL 6 to TRL 7 is as shown below.

- 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 below. The objectives and scope of this maturation task should be reviewed in the course of the piping trade studies outlined in Section B1.

B3.1.3 Anticipated Schedule

The work described by the Test Specification in this Technology Maturation Plan will be accomplished during the period FY 2016 through FY 2018.

B3.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B3.2 Test Specifications

B3.2.1 Performance and Environmental Testing of Prototypical High-Temperature and Low-Temperature Piping/Insulation System (WEC-TS-PIP$_{750}$-008)

B3.2.1.1 Objectives

The objectives of testing the HTS prototypical piping/insulation system are:

- To demonstrate the performance of the HTS piping system, including
    - Limited heat losses at enveloping conditions
    - Required surface temperatures of the Hot Gas Duct and Helium Pressure Boundary
    - Pressure drop through the 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 gaseous and solid impurities on insulation material (with special reference made to reduction reactions that may take place over time, thereby increasing the insulation thermal conductivity and 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 varies, since the threshold conditions of each piping section differ throughout the PHTS and SHTS loops.

Table B-1 summarizes the applicability of these objectives to the various piping sections. For the purpose of the HTS piping, only a single maturation plan detailing all piping tasks is given and should be evaluated against Table B-1..

Table B-1: Applicability of Maturation Plan Objectives to HTS Piping Sections

Objectives	PHTS		SHTS	
	750°C-800°C	~300°C	700°C-750°C	~250°C
TMP (TRL5-TRL7)				
a) Performance				
- Limited heat losses	☑	☑	☑	☑
- Required surface temperatures	☑	☑	☑	☑
- Pressure drop	☑	☑	☑	☑
- Flow induced vibrations	☑	☑	☑	☑
b) Environmental behavior				
- Depressurization (insulation subsystem)	☑	☑	☑	☑
- Impurities (reduction reactions on insulation)	☑	☑	☑	n/a
- Thermal fatigue (liner in subsystem)	☑	☑	☑	n/a, liner may not be needed

B3.2.1.2 Test Conditions

System Requirements

Subsystem and system requirements include the following:

- Size limitation: TBD
- Certain interface design requirements: TBD
- Testing fluid – Helium with controlled gaseous and solid impurities
- Temperature threshold – see test requirements
- Pressure threshold – see test requirements
- Mass flow threshold – see test requirements

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 helium temperatures
  - HGD, HPB, insulation, and testing temperatures for active cooling
  - Insulation, HPB, and testing temperatures for passive cooling
- Measurement of mass flows
- Measurement of helium compositional changes (controlled impurities) over time

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 = 200°C to 800°C[1]
ii. Pressure = 9MPa
iii. Pressure Δ[2] = A_O pressure > A_I pressure (magnitude tbd)
iv. Mass flow = tbd
v. helium 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. Depressurizing 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 800°C max[3])
      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
4. Effect of various impurities on insulation properties if liner joint integrity is compromised
5. Thermal Conductivity
6. Required surface temperatures vs. actual surface temperatures (HPB & HGD surfaces)
7. Percentage of specific elements (determined by levels of gaseous and solid impurities) as added over time to internal insulation or liner at a certain depth
8. HGD Interfacing to be addressed as a separate SSC at a later stage

Tests Duration

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

Facility Requirements

[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

The following facilities will be required:

1. Prototypical piping testing facility (TBD)
2. Facilities for testing sampled helium composition
3. Facilities required for metallographic analysis (or other analysis means) of insulation material and liner material & joints after testing

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 12 of the document.

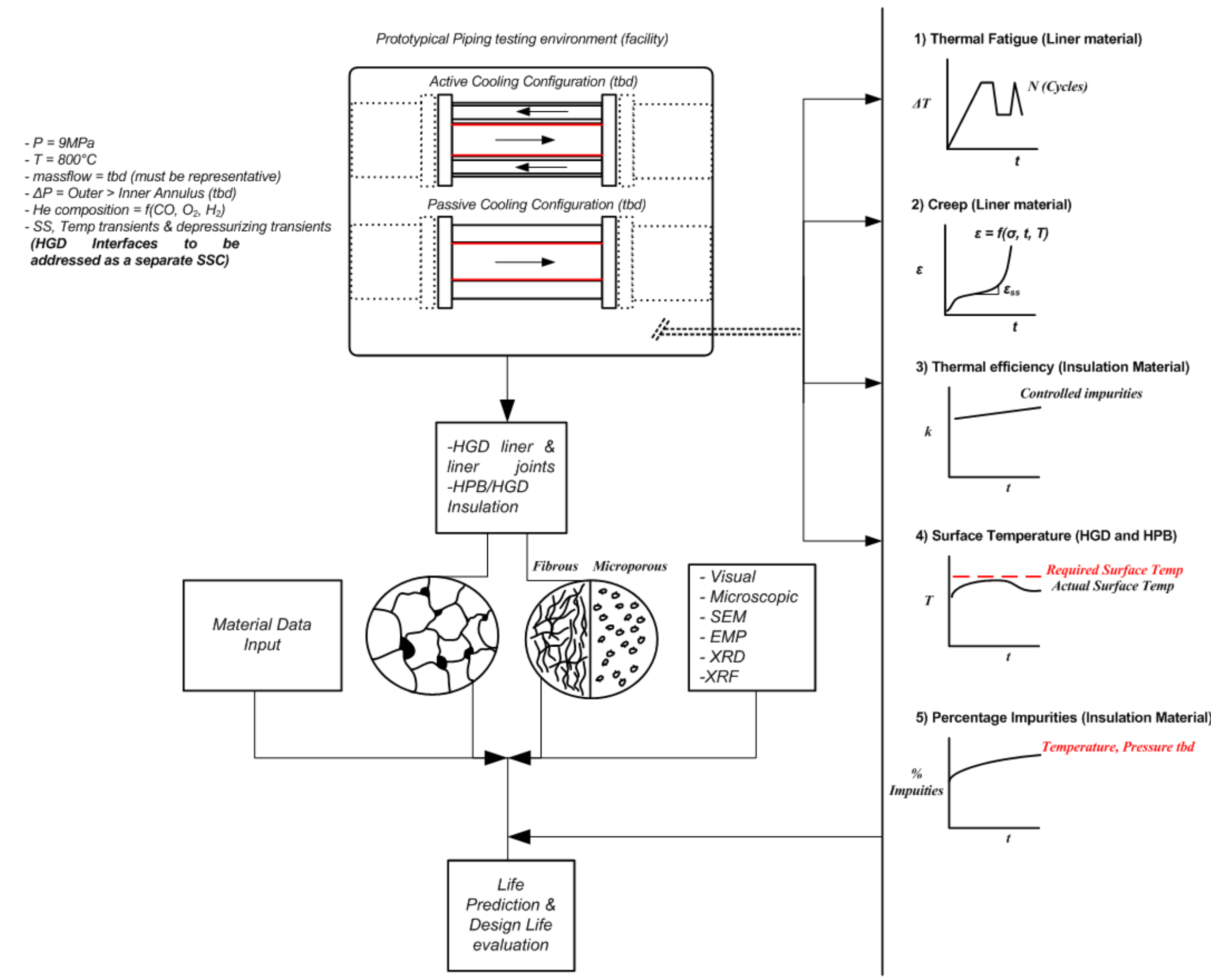

Figure B-1: Proposed setup and relevant parameters in testing the prototypical HTS piping (active and passive cooling configurations noted pending the down selection of design options)

B3.2.1.3 Measured Parameters

The following parameters will be measured:

- Temperatures
- Pressures
- Gaseous and solid impurity levels in the He
- Thermal fatigue and creep 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.

B3.2.1.4 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 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.

B3.2.1.5 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 at enveloping conditions.

- Satisfactory values of thermal conductivity for insulation material (local) after exposure to certain impurities for a predetermined time.

B3.2.1.6 Test Deliverables

Deliverables are as follows.

- Test Data for all areas as indicated in section B3.2.1.3
- Documentation containing test requirements, performance verification criteria, and test results verified against stress/strain models of the HTS piping and material properties.

B3.2.1.7 Cost, Schedule, and Risk

Cost and schedule for the overall Technology Maturation Plan for advancing technology for HTS piping from TRL 6 to TRL 7 is addressed in Sections B3.1.3 and B3.1.4.

Depending on the failure modes of the HTS prototypical piping sections, new liner material candidates might need to be evaluated or slight modifications to the selected piping/insulation configuration will need to be implemented.

B4 TECHNOLOGY MATURATION PLAN FOR HTS PIPING - TRL 7 TO TRL 8

B4.1 TECHNOLOGY MATURATION PLAN SUMMARY

B4.1.1 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 B4.2).

B4.1.2 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.

- Testing of Full-Sized HTS Piping in the NGNP

This task will be described in the test specification given below..

B4.1.3 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.

B4.1.4 Overall Cost

Cost and schedule for the overall maturation plan with associated specifications are addressed in Section 12 of this document.

B4.2 Test Specifications

B4.2.1 Specification of testing of Full-Sized HTS Piping in the NGNP (WEC-TS-PIP$_{750}$-009)

B4.2.1.1 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-TDI-TDR-RPT-G-00011 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 4: Steam Generator

APPROVALS

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Scott Penfield (Technology Insights)	July 14, 2009

BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
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4 PCS STEAM GENERATOR

4.1 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 for 750°C-800°C Reactor Outlet Temperature (ROT) operation in a steam-only application are listed in Table 4-1, however these will be adapted to the specific requirements of the steam and power user, as applicable.

Table 4-1: Typical Steam Generator Performance Parameters

Parameter	Typical of 750°C-800°C ROT
Thermal Power, MWt	520
Hot Side	
Fluid	Helium
Inlet Press, MPa	8.8
Inlet Temp, °C	700 - 750
Flow Rate, kg/s	203
Outlet Temp, °C	210
Outlet Press, MPa	8.7
Design Temp, °C	[TBD]
Design Press, MPa	>14.0
Cold Side	
Fluid	Water
Superheater Outlet Press, MPa	16.88
Superheater Outlet Temp, °C	567
Main Steam Flow, kg/s	186.34
Feedwater Temp, °C	164
Feedwater Press, MPa	19.04
Design Temp, °C	<300

4.2 Design/Technology 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.

Candidate SG technologies are identified in Section 4.2.1. Decision discriminators leading to a final design selection are discussed in Section 4.2.2. The PCDR reference SG used as a surrogate in the development of this report is described in Section 4.2.3. 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.

4.2.1 Candidate Technologies

Candidate technologies include the following:

Large Diameter 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.

Small Diameter Modular Helical Coil Shell & Tube Heat Exchanger

The HTR-10 plant in China utilises a small diameter modular helical coil shell and tube heat exchanger that forms the basis for the High Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) commercial plant currently in the design phase.

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).

4.2.2 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 or for indirect process energy applications in which the thermal energy present in the steam is transferred to a third circuit. This arrangement facilitates stringent control of feedwater quality and is consistent with a once-through boiling configuration.
- Cleaning requirements and provisions for tube cleaning
- In-service monitoring of tube condition as to provide for detection, access to and isolation of 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.

4.2.3 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 [2]. 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.

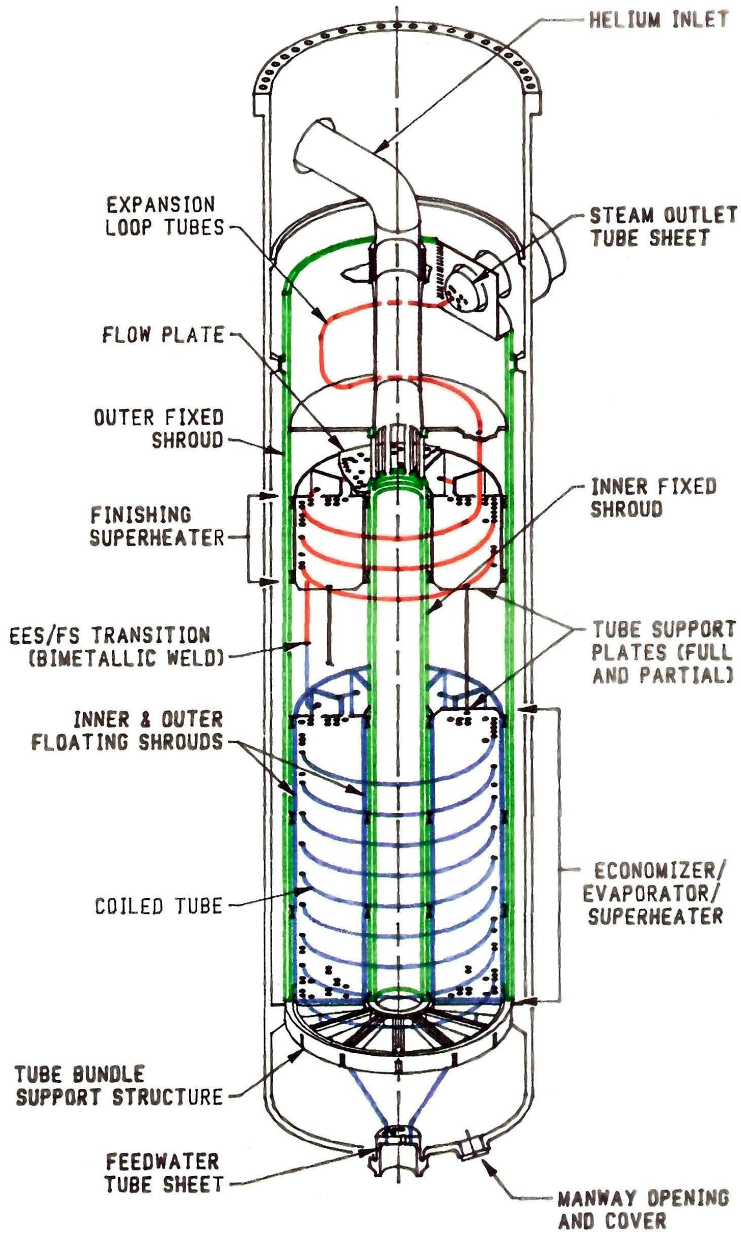

Figure 4-1: Steam Generator (PCS-SG-001)

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.

4.2.4 Down Selection Task

A trade study is required to further compare the large and small diameter helical-coil, serpentine-tube and other SG concepts in terms of the decision discriminators summarized in Section 4.2.2.

4.3 TRL Status

The TRL status of the Steam Generator has been assessed and it is concluded that the present status is TRL 6. It is acknowledged that a lower NGNP ROT of 750°C-800°C will most likely reduce the risk of using established materials in the SG design such as Alloy 800H and 2-1/4 Cr. The development needs for the NGNP SG outlined in this document will however stay the same and be refined at the completion of associated conceptual design trade studies. The associated rating sheet is provided in [1].

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.

4.4 Technology Development Road Map Summary

The Steam Generator Technology Development Road Map is provided as part of Appendix A. The associated maturation tasks are summarized in Section 4.5.

As already noted, a key prerequisite to advancing the SG from the present level of TRL 6 to succeedingly higher levels 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 4-2.

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.

4.5 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, Sections III and VIII)
- Essential analysis tools available
- Need to reassemble/refresh the technology base for the NGNP application. Application of the technology is dormant and a focused effort should be endeavored to retrieve, review and

document the relevant databases (this could be completed during the first year of conceptual design of the SG).

- Confirmation of performance
- Demonstration of steam generator fabrication technology

The Steam Generator maturation tasks are summarized below.

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 [2] and listed in Table 4-2. Some DDNs listed in Table 4-2 are sensitive to SG configuration while others are generic to the helium and water/steam operational environment. A majority of the DDNs in Table 4-2 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 4-2 are required to establish or confirm SG features.

Maturation Tasks 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 4-2 identified as being associated with the transition between TRL 7 and TRL 8.

Table 4-2: Design Data Needs

DDN #	Design Data Need	Category	TRL 6->7	TRL 7->8	Expected Outcome	Recommended Performer
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 Possible testing in CTC
PCS-01-05	Large Helical Coil Fabrication Test[1]	Fabrication		X	Verification of design assumptions and assembly process for large diameter helical bundle	Designer/fabricator

[1] PCS-01-05 should be applicable to all helical wound Steam Generators (Large and small diameter)

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 Possible testing in CTC
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 Possible testing in CTC
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 (FIV) Testing of Helical Bundle	Performance		X	Establish FIV characteristics of tube bundle	Designer/fabricator Possible testing in CTC
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 Possible testing in CTC
PCS-01-17	Tubing Inspection Methods and Equipment	Design		X	Demonstrate acceptable methods and equipment	Designer/fabricator
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-01-19	Testing of Scale Prototype SG in CTC	Integrated system performance	X		Demonstrate acceptable performance of SG in a simulated PCS loop	Designer/fabricator/system designer Possible testing in CTC

4.6 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

[2] NGNP-08-RPT-001, Revision 0, May 2007 - NGNP and Hydrogen Production Preconceptual Design Report, "Section 8: Power Conversion System".

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750℃-800℃

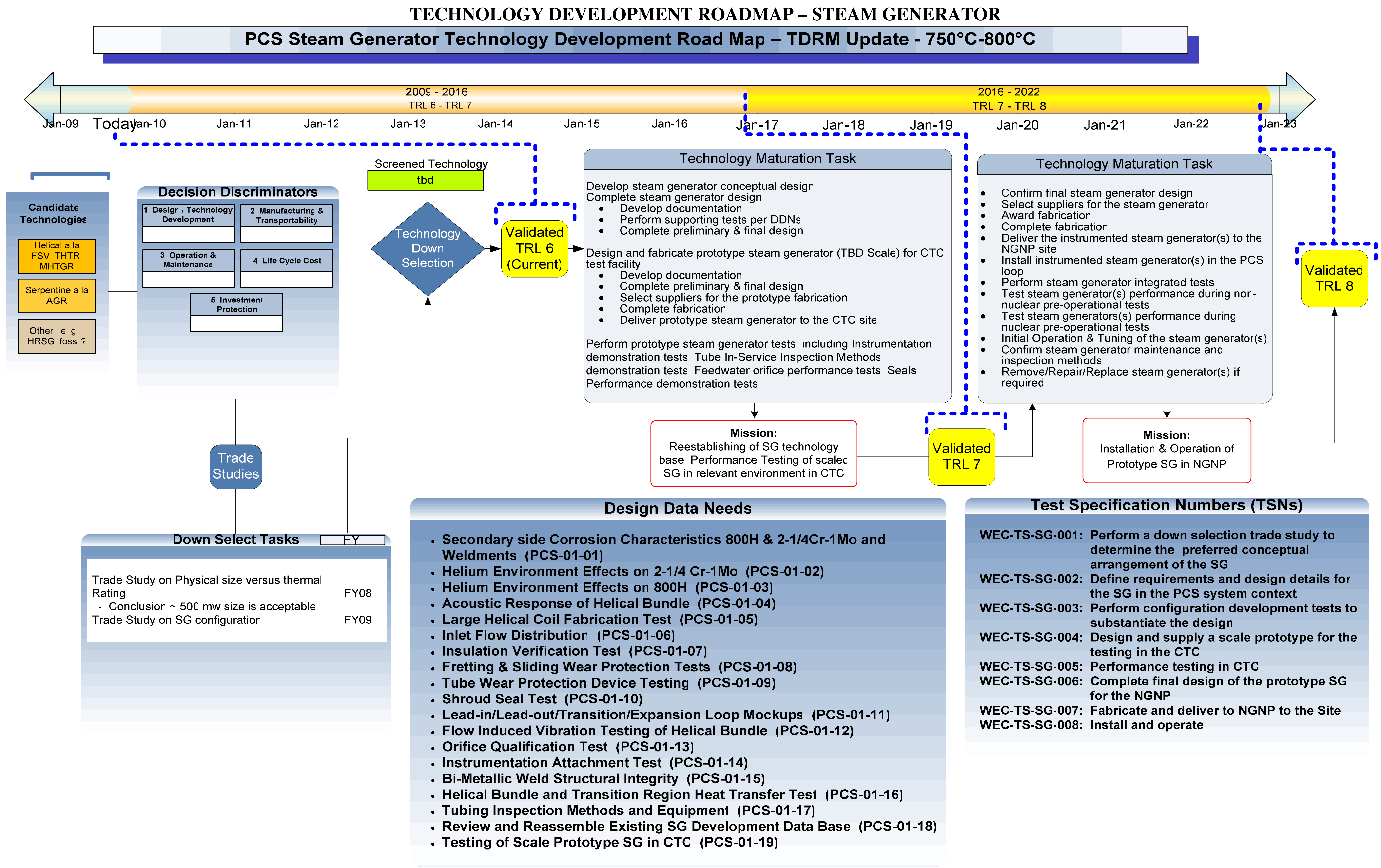

Figure A-1: TDRM for the PCS Steam Generator

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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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 CTC
- Conduct performance testing in CTC

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

B1 TECHNOLOGY MATURATION PLAN FOR STEAM GENERATOR (TRL 6 TO TRL 7)

B1.1 TECHNOLOGY MATURATION PLAN SUMMARY

B1.1.1 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.

B1.1.2 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 large diameter helical arrangement of heat transfer surface
  - Alternate 1 is serpentine arrangement of heat transfer surface
  - Alternate 2 is small diameter helical 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 CTC test facility
  - CTC 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 CTC 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 CTC:

- The CTC will provide a source of high temperature helium consistent with the NGNP plant operating parameters.
- The CTC 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.

B1.1.3 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 7 years.

B1.1.4 OVERALL COSTS

To be determined.

B1.2 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.

B2 TECHNOLOGY MATURATION PLAN FOR STEAM GENERATOR (TRL 7 TO TRL 8)

B2.1 TECHNOLOGY MATURATION PLAN SUMMARY

B2.1.1 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.

B2.1.2 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

B2.1.3 ANTICIPATED SCHEDULE

Dependent on overall NGNP schedule. Typically this work would have a 40 to 50 month span.

B2.1.4 OVERALL COST

To be determined.

B2.2 TEST SPECIFICATIONS

To be determined during conceptual design phase.

NGNP-TDI-TDR-RPT-G-00012 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 5: Fuel Elements

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5 FUEL ELEMENTS

5.1 Functions and Operating Requirements

5.1.1 Description and Function of the Fuel Elements

The PBMR fuel pebbles are as described in detail in section 5 of the NGNP PCDR [2]. 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 [2].

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 [2]. These DDNs[1] address Fuel irradiation and heating tests as well as graphite irradiation tests, and can be subdivided into 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)

[1] The change in NGNP ROT from 950°C down to 800°C-750°C does not invalidate the DDNs, however the specific parameters stated in the DDNs need to be brought in line with the adjusted qualification envelope.

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 520°C (800°C-280°C) or 470°C (750°C-280°C) for the 500MWt NGNP reactor.

5.1.2 Operational Requirements

For the 750–800°C case, the recent NGNP Reactor Parametric Conceptual Design Study [3] refined the maximum fuel temperature to 1002°C (750°C ROT) - 1065°C (800°C ROT) during normal operation and the peak maximum temperature to 1640°C (750°C ROT) - 1665°C (800°C ROT)°C during a DLOFC event.

Table 5-1: Fuel Qualification Envelope for the DPP and the NGNP

Parameter	PBMR-DPP Qualification Envelope	PBMR-NGNP (750°C ROT)	PBMR-NGNP (800°C ROT)
Normal Operations Maximum Temperature (sphere centre)	1250°C	1122°C	1185°C
DLOFC Peak Maximum Temperature	Up to 1800°C	Up to 1800°C	Up to 1800°C
Fast neutron flux (n)	2.7×10^{21} cm^{-2}	2.7×10^{21} cm^{-2}	2.7×10^{21} cm^{-2}
Burn-up	1119000 MWd/tU	1119000 MWd/tU	1119000 MWd/tU

When defining irradiation and heating tests, temperature uncertainties need to be taken into account. Currently, the magnitudes of these uncertainties are assumed to be as large as 120°C (as per DPP) until the temperature uncertainties have been refined after the PBMR DPP Software Verification and Validation is completed.

The PBMR-DPP fuel qualification program will advance the fuel for the NGNP from TRL 7 to TRL 8, satisfying the requirements of the 3 DDNs. The NGNP will operate its fuel system within the envelope of the fuel qualification program of the DPP and consequently no additional testing will be required in order to qualify the PBMR-based NGNP fuel.

5.2 Design/Technology Selection Status

5.2.1 Candidate Technologies

PBMR fuel is based on the established and proven German pebble design.

5.2.2 Decision Discriminators

The pebble fuel is the only TRISO fuel capable of supporting on-line refueling which is a strategic advantage of the PBMR.

Readiness 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.

5.2.3 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*

5.2.4 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.

5.2.5 Down Selection Task

N/a.

5.3 TRL Status

Evaluations of the status of the current technology for pebble fuel resulted in a TRL 7 [1]. The generic definition for this selection level states:

"Subsystem integrated into a system and demonstrated in a relevant environment".

The specific definition (related to the NGNP pebble fuel program) TRL level 7 states:

"Pebble bed reactors have been built and operated in similar environment to NGNP. Commitments made for fuel irradiation tests in Dutch Petten, HFR and Russian IVV-2M reactors. Commitments made for source materials for sphere matrix, which duplicate materials proven in German program".

The TRL sheets explaining the underlying bases for the current TRL selection are provided in the latest update of the TRL/DRL Report [1]

5.4 Technology Development Road Map Summary

5.4.1 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 7 to 8 (taking into account that the NGNP will now operate the fuel system within the envelope of the fuel qualification program of the DPP). 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 2010, whilst irradiation on production PBMR fuel will commence in FY 2012.

5.4.2 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 fluence for PBMR-DPP under normal conditions is specified at 2.72 ± 0.2 x 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 7 to TRL 8. The NGNP will operate its fuel system within the envelope of the fuel qualification program of the DPP. The PBMR DPP production fuel irradiation program 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
- Fuel spheres are irradiated to a maximum center temperature of 1250 °C
- The fast neutron fluence for PBMR DPP under normal conditions is specified at 2.72 $\pm$ 0.2 x 10^{21} cm^{-2}.
- Non-destructive PIE and Küfa heat-up tests at 1600 °C and 1800 °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 x 10^{21} cm^{-2}. These tests are not to determine for the first 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.

Additional irradiation testing (over and above the PBMR DPP Fuel Qualification Plan) will not be necessary to advance the PBMR-based NGNP fuel from TRL 7 to TRL 8. The NGNP will operate its fuel system within the envelope of the fuel qualification program of the DPP and consequently no additional testing will be required in order to qualify the PBMR-based NGNP fuel.

The technology development road map of the Fuel is shown in Appendix A.

5.5 Technology Maturation Plan Summary (TRL 7 to TRL 8)

PBMR DPP fuel qualification tests are deemed sufficient to develop the current TRL 7 to a TRL 8 for the PBMR-based NGNP Fuel.

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[2].

No additional PBMR-NGNP fuel qualification tests are required to progress the PBMR-NGNP fuel from TRL 7 to TRL 8

5.6 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

[2] NGNP-01-RPT-01: NGNP and Hydrogen Production Pre-Conceptual Design Report; Westinghouse Electric Company, May 2007

[3] NGNP-NHS 90-PAR, NGNP Conceptual Design Study: Reactor Parametric Study, Westinghouse Electric Company LLC, August 2008

2 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.

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750℃-800℃

TECHNOLOGY DEVELOPMENT ROADMAP –FUEL ELEMENTS

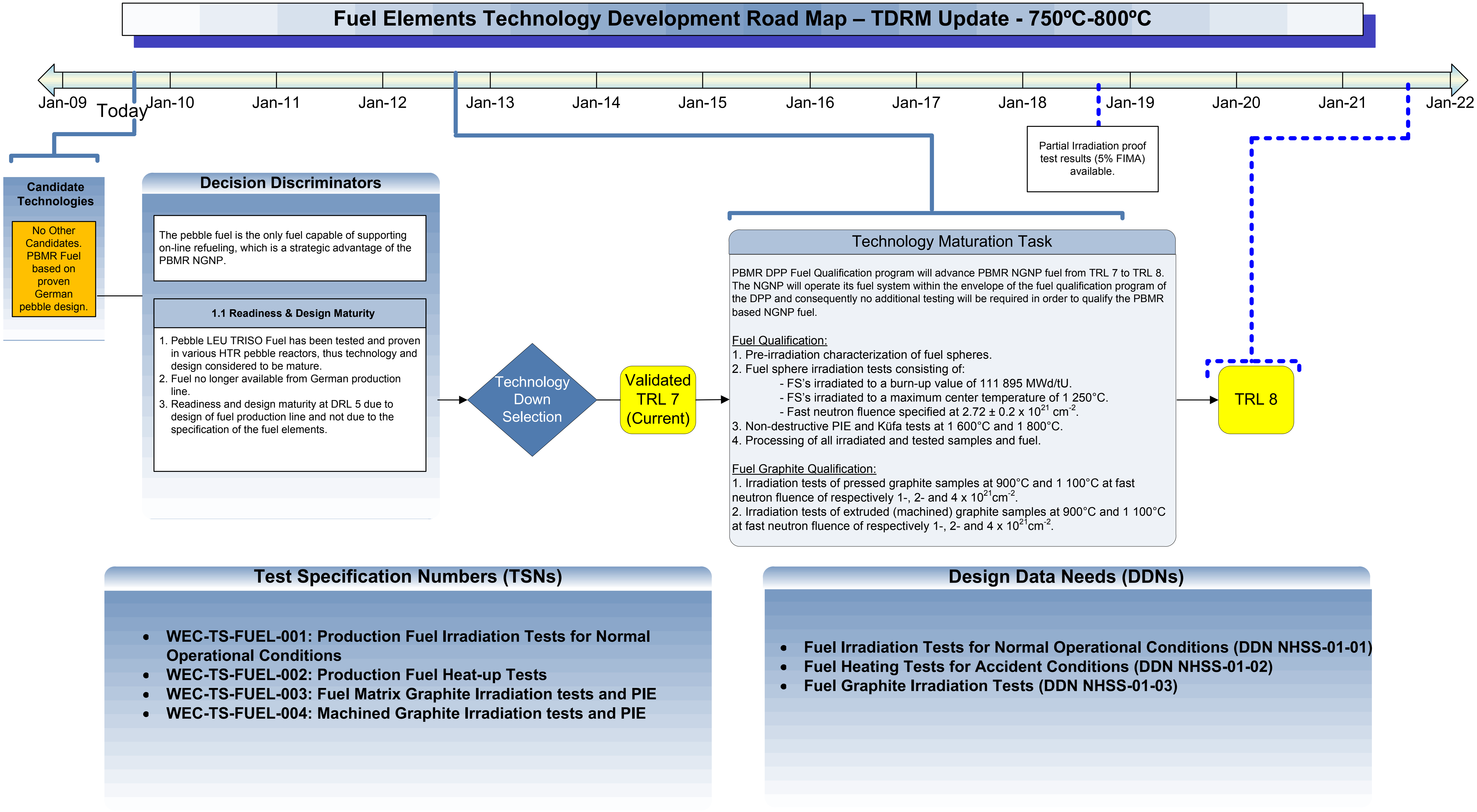

Figure A-1: **TDRM for Fuel Elements**

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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Section **Title** **Page**

REQUIRED SPECIFICATIONS/TESTS TO ACHIEVE NEXT TRL

TRL 7 to TRL 8:

B1.2.1: Production Fuel Irradiation Tests for DPP Normal Operational Conditions (WEC-TS-FUEL-001)
B1.2.2: Production Fuel Heat-up Tests at 1600°C and 1800°C (WEC-TS-FUEL-002)
B1.2.3: Fuel Matrix Graphite Irradiation Tests and PIE (WEC-TS-FUEL-003)
B1.2.4: Machined Graphite Irradiation Tests and PIE (WEC-TS-FUEL-004)

B1 TECHNOLOGY MATURATION PLAN FOR FUEL - TRL 7 TO TRL 8

B1.1 TECHNOLOGY MATURATION PLAN SUMMARY

B1.1.1 Objectives

The purpose of the TMP is to give more information regarding the activities to advance PBMR NGNP fuel from TRL 7 to TRL 8. The PBMR NGNP fuel operational envelope falls within the PBMR DPP fuel envelope, thus the irradiation and post irradiation examination (PIE) tests to be performed on the PBMR DPP fuel are considered adequate to also advance the PBMR NGNP fuel to TRL 8. The PBMR DPP- and PBMR 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 objective is to supplement the German LEU-TRISO fuel performance statistical database to show that the PBMR DPP and 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.

B1.1.2 Scope

In order to advance the maturity of the PBMR NGNP fuel element technology from a TRL 7 to TRL 8, the following tasks needs to be performed as per the PBMR DPP fuel qualification program:

- Production fuel irradiation including pre-irradiation characterization and PIE.
- Fuel graphite irradiation, including pre-irradiation characterization and PIE.

The following test specifications have been developed to satisfy the requirements of the two above tasks:

- B1.2.1: Production Fuel Irradiation Tests for Normal Operational Conditions (WEC-TS-FUEL-001)
- B1.2.2: Production Fuel Heat-Up Tests for Accident Conditions (WEC-TS-FUEL-002)

- B1.2.3: Fuel matrix Graphite Irradiation Tests and PIE (WEC-TS-FUEL-003)
- B1.2.4: Machined Graphite Irradiation Tests and PIE (WEC-TS-FUEL-004)

B1.1.3 Anticipated Schedule

The anticipated work for the production irradiation tests is set to start in FY 2013 for the machined graphite and FY 2016 for the production fuel and matrix graphite. The partial proof test results should be available at the end of FY2018 and the full proof test results should be available during FY2021.

B1.1.4 Overall Cost

Costs not provided due to business confidentiality reasons.

B1.2 TEST SPECIFICATIONS

B1.2.1 Production Fuel Irradiation Tests for Normal Operational Conditions (WEC-TS-FUEL-001)

B1.2.1.1 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.

B1.2.1.2 Test Conditions

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)

Table B 1: DPP Design Requirements – Production Fuel Irradiation Tests

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})	2.72×10^{21}	1.7×10^{21}	3.63×10^{21}
Average discharge burn-up (MWd/t / % FIMA)	91012 / 9.44	48200 / 5	111895 / 11.61
Normal operation temperature (C) (sphere surface temperature)[3]	1068	1200 constant	900 / 1150 cycles
Maximum power per fuel sphere (kW)[4]	2.76	As required	3

Test Duration

The duration of this activity can be subdivided into the following activities:

- Irradiation planning & Preparation ca 260 calendar days
- Irradiation of Production Fuel ca 1045 calendar days
- PIE and Analysis ca 130 calendar days

Proposed Test Location

Production fuel to be irradiated and tested at the INM facility.

B1.2.1.3 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

B1.2.1.4 Data Requirements

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

[3] The surface temperatures specified in the test aim to achieve the required centre temperatures as required and quoted elsewhere in this document.
[4] This parameter will only be finalized when the initial start-up strategy has been defined to include start-up enrichment, power ascension rate, duration, etc.

B1.2.1.5 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.

B1.2.1.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph B1.2.1.3

B1.2.1.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

B1.2.2 Production Fuel Heat-up Tests (WEC-TS-FUEL-002)

B1.2.2.1 Objectives

The objective of the post-irradiation 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 fuel performance will be used to evaluate fuel integrity for PBMR NGNP use.

B1.2.2.2 Test Conditions

Test Configuration/Set-up

Fuel spheres that have completed the irradiation profile for partial- and nominal irradiation proof testing are required for this test.

Fuel spheres are to be subjected to heating tests at 1600 °C and at 1800 °C for ca 100 hours respectively.

Table B 2: DPP Design Requirements – Production Fuel Heat Up Tests

Parameter	DPP Design Requirements	Nominal Partial Proof Test Heating Target	Nominal Proof Test Heating Target
DLOFC (C)	1592	1600 / 1800	1600 / 1800
PLOFC (C)	1319	N/A	1350

Test Duration

The heat up tests consists of the following subsections:

- Physical heating test: ca 130 days
- PIE and analysis of heated spheres: ca 130 days

Proposed Test Location

At the same test station where irradiation was performed.

B1.2.2.3 Measured Parameters

Upon deconsolidation, the following measurements will be performed:

- Optical Ceramography
- Fission product inventory measurements

B1.2.2.4 Data Requirements

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

B1.2.2.5 Test Evaluation Criteria

Results to be evaluated against current NGNP DLOFC temperature requirements.

B1.2.2.6 Test Deliverables

Deliverables for this test specification shall include:

Report on all the measured parameters listed in paragraph B1.2.2.3. Of particular interest will be the measurement of particle failure fraction, which is related to the free uranium content.

B1.2.2.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

B1.2.3 Fuel Matrix Graphite Irradiation Tests and PIE (WEC-TS-FUEL-003)

B1.2.3.1 Objectives

To acquire relevant material data pertaining to irradiation behaviour of the fuel matrix graphite over the fluence-temperature regime for PBMR fuel (DPP and NGNP) as part of PBMR fuel qualification. Data can be used for validation for PBMR NGNP DDNs.

B1.2.3.2 Test Conditions

Test Configuration/Set-up

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

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

Proposed Test Location

The IVV-2M Russian will be used to test the fuel matrix graphite.

B1.2.3.3 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 sample preparation, 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.

B1.2.3.4 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.

B1.2.3.5 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.

B1.2.3.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph B1.2.3.3.

B1.2.3.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

B1.2.4 Machined Graphite Irradiation Tests and PIE (WEC-TS-FUEL-004)

B1.2.4.1 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 and PBMR NGNP, as part of PBMR fuel qualification. Data can be used for validation for PBMR NGNP DDNs.

B1.2.4.2 Test Conditions

Test Configuration/Set-up

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.

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

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

Proposed Test Location

The IVV-2M Russian will be used to test the machined graphite spheres.

B1.2.4.3 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 sample preparation, 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.

B1.2.4.4 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.

B1.2.4.5 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.

B1.2.4.6 Test Deliverables

Deliverables for this test specification shall include:

- Report on all the measured parameters listed in paragraph B1.2.4.3.

B1.2.4.7 Cost, Schedule, and Risk

Costs not provided due to business confidentiality reasons.

NGNP-TDI-TDR-RPT-G-00013 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 6: Core Structure Ceramics

APPROVALS

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BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
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6 CORE STRUCTURE CERAMICS

6.1 Functions and Operating Requirements

6.1.1 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 6-1 illustrates the probable position for these different components as part of the PBMR CSC.

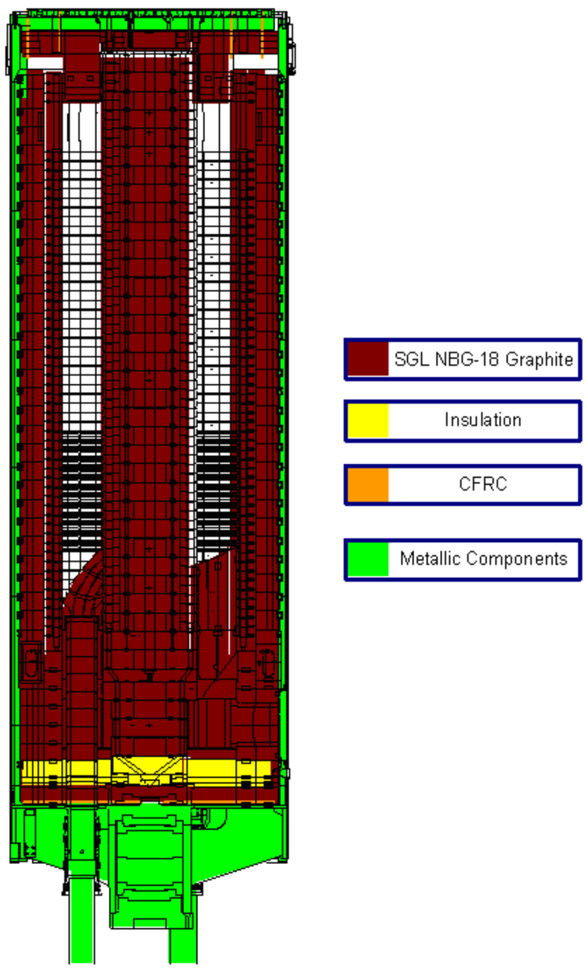


Figure 6-1: Probable location of different materials for the CSC

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 6-2:.

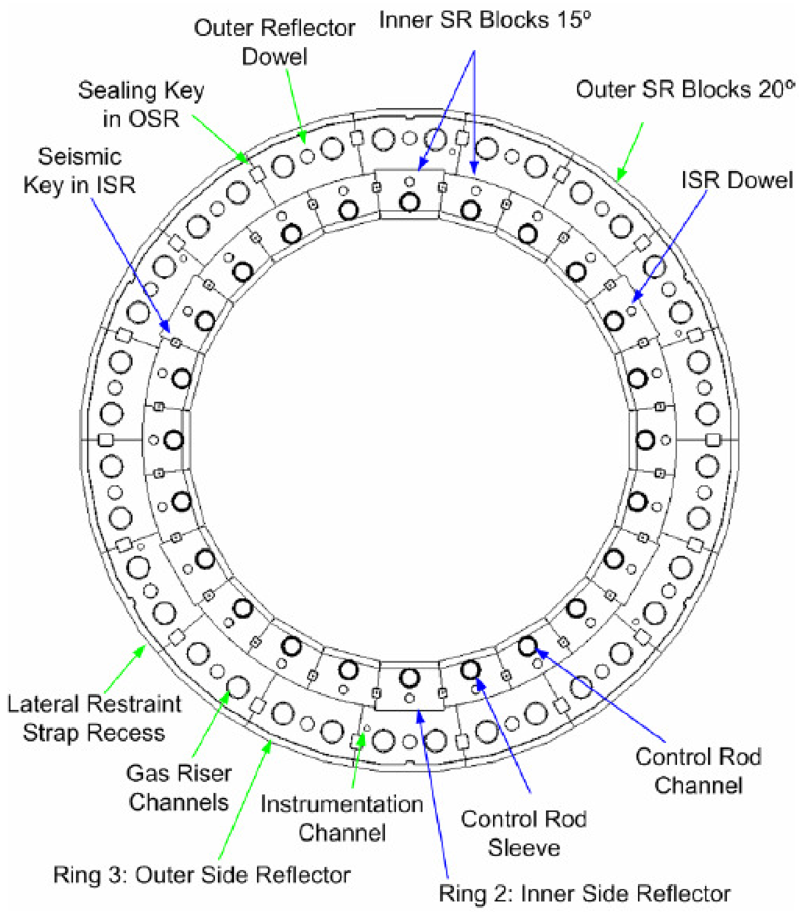


Figure 6-2: Side reflector

Top reflector structure

The Top Reflector (TR) is suspended from the Core Barrel top plate by means of tie-rods, manufactured from Carbon Fiber Reinforced Carbon (CFRC). 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 6-3: indicates this sub-assembly.

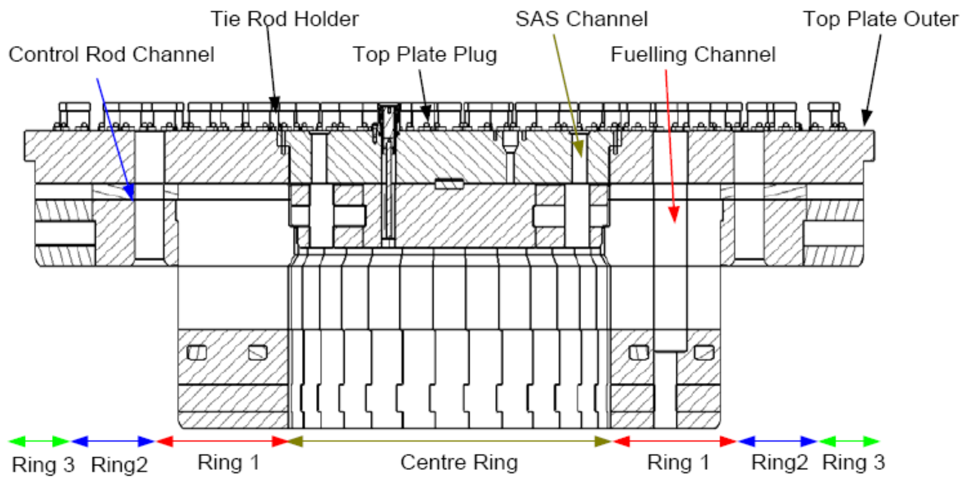


Figure 6-3: Top reflector

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 6-4:.

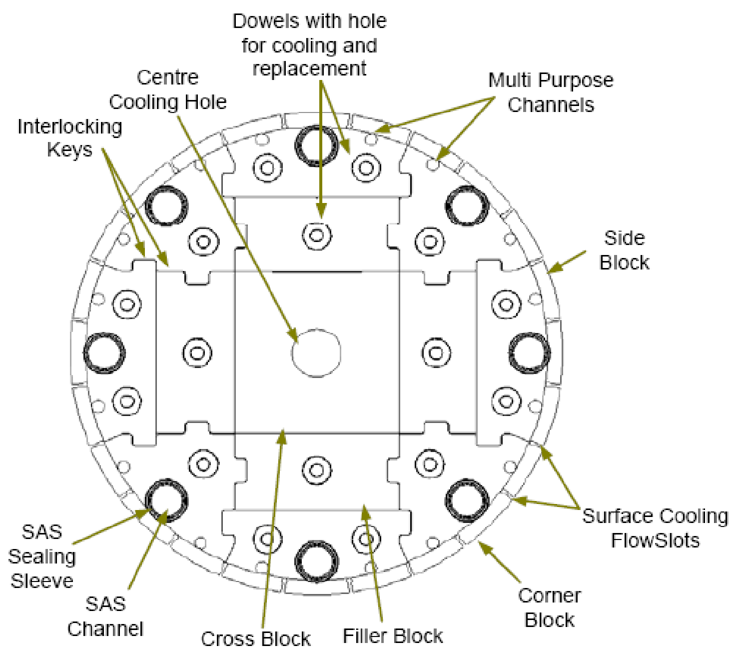


Figure 6-4: Central Reflector

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 6-5:) 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.

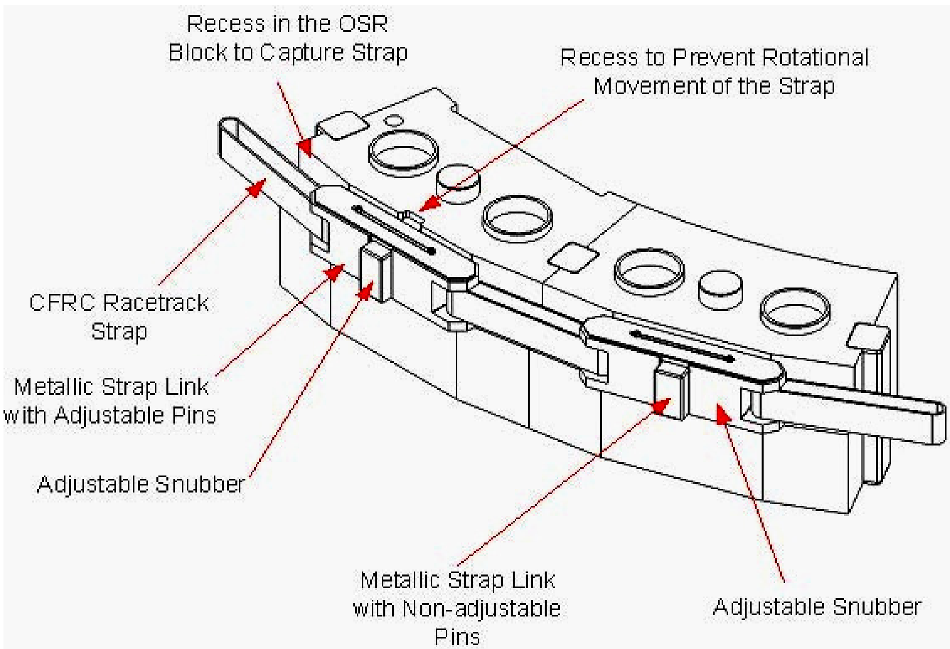


Figure 6-5: Lateral restrain strap

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 6-6: indicates the tie rod geometry.

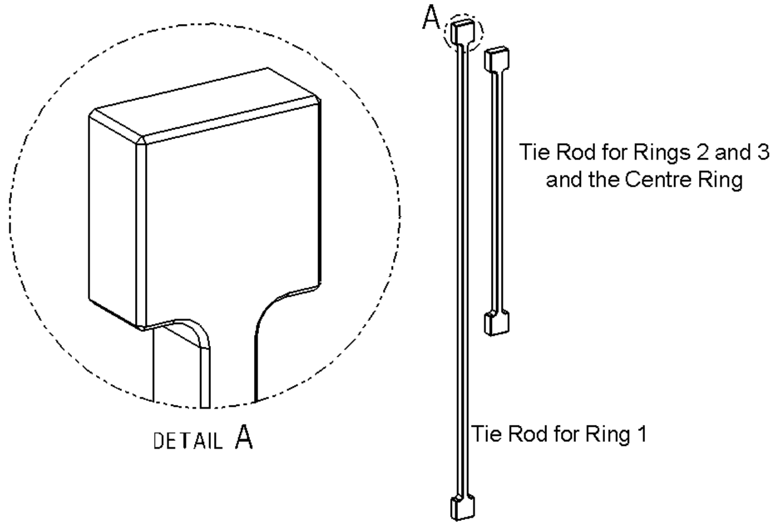


Figure 6-6: Tie rod geometry

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. The basis for this document is a design that requires only Baked Carbon Insulation due to the reduced outlet temperature.

6.1.2 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 Replaceable Reflector Parts.

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.

6.1.3 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 channeled 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 750°C-800°C
- Nominal Reactor Inlet Temperature of 280°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

6.2 Design/Technology 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.

6.2.1 Candidate Technologies

Not applicable to the NGNP CSC.

6.2.2 Decision Discriminators

Not applicable to the NGNP CSC.

6.2.3 Reference Design

Not applicable to the NGNP CSC.

6.2.4 Down Selection Task

Not applicable to the NGNP CSC.

6.3 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 6-1. A copy of the original TRL rating sheet can be found in [1].

Table 6-1: 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.

6.4 Technology Development Road Map Summary

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.

These additional tests can be performed in independent laboratories and does not necessarily create any input to the CTC. The technology development road map of the CSC is shown in Appendix A.

6.5 Technology Maturation Plan Summary

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.

6.6 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP –750℃-800℃

TECHNOLOGY DEVELOPMENT ROADMAP – CORE STRUCTURE CERAMICS

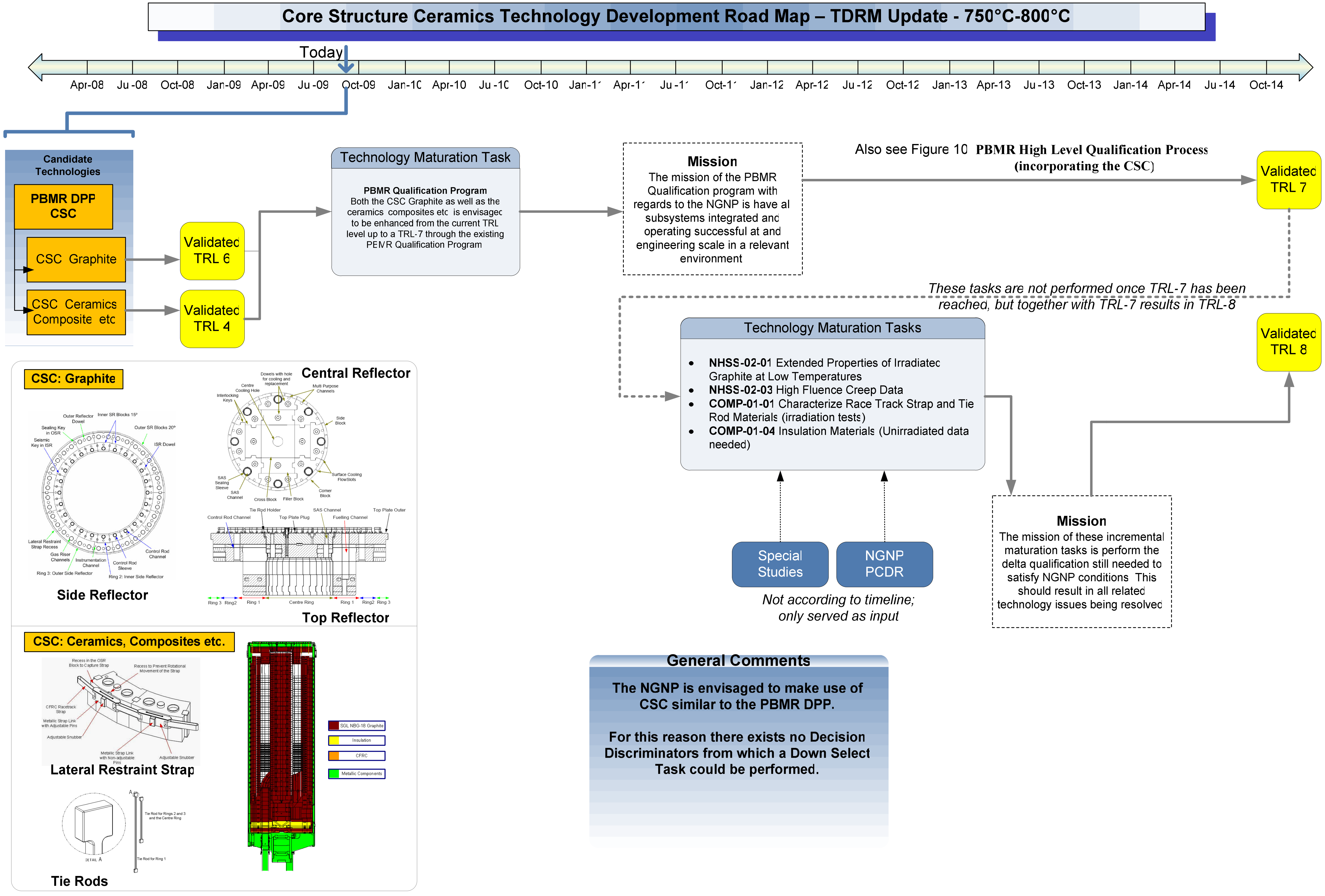


Figure A-1: TDRM for Core Structure Ceramics

APPENDIX B: TECHNOLOGY MATURATION PLAN –750°C-800°C

TABLE OF CONTENTS

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: Characterize effect of Irradiation on Race Track Strap and Tie-Rod Materials (WEC-TS-CSC-004)

B1 TECHNOLOGY MATURATION PLAN FOR CSC (CURRENT TRL TO TRL 7)

B1.1 Technology Maturation Plan Summary (Current TRL to TRL 7)

B1.1.1 Objectives

The PBMR NGNP Core Structure Ceramics (CSC) comprise the non-metallic components enclosed within the core barrel and its underlying support structure. These components are subdivided into the graphite and other (consisting of the hard ceramics and composites) and are envisaged to be identical to those of the PBMR DPP. These subsystems have been reviewed and rated in terms of DRL and TRL as indicated in [1].

The completion of the PBMR DPP program would ensure the equivalent TRL/DLR levels of 8 for the DPP operating conditions. We however degrade this to level 7 for the NGNP application as the operating conditions of the NGNP differ from the DPP.

In order to advance these systems from the determined TRL/DRL levels up to the required NGNP level of TRL-8 the identified maturation tasks need to be performed. These maturation tasks consist of the qualification process as per PBMR DPP, expanded for the NGNP operating conditions.

B1.1.2 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 B 1: provides an extract from the complete list of PBMR qualification and development tests due to business confidentiality reasons.

Table B 1: Extract from PBMR Equipment Qualification Test List

Test ID	CSC TQC Test Catalogue Extract[1]
CSC-QT-1	Graphite Material Characterization - Virgin Material Properties
CSC-QT-3	Graphite Material Characterization - Irradiated Material Properties
CSC-QT-4	Graphite Wear Characterization
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
CSC-QT-14	Tie Rod Ultimate Load Tests

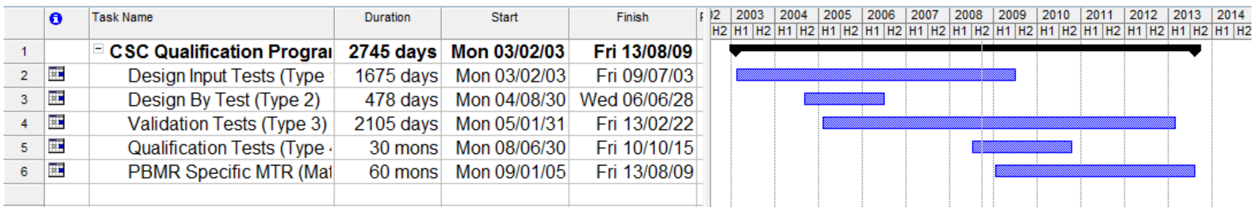
[1] This table represent 12 of 71 tests over the entire CSC qualification process.

CSC-QT-25	Integrated Insulation Mechanical Test
CSC-QT-32	CIL Core connection HTF Tests
CSC-QT-36	CFRC Material Characterization - Virgin Material Properties
CSC-QT-41	Insulation Characterization

B1.1.3 Anticipated Schedule

PBMR Schedule

The PBMR CSC material qualification testing is currently underway with a expected completion date (excluding irradiation tests) 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. Figure B 2 provides an extract from the current CSC Engineering schedule.



	Task Name	Duration	Start	Finish
1	**CSC Qualification Progra**	**2745 days**	**Mon 03/02/03**	**Fri 13/08/09**
2	Design Input Tests (Type	1675 days	Mon 03/02/03	Fri 09/07/03
3	Design By Test (Type 2)	478 days	Mon 04/08/30	Wed 06/06/28
4	Validation Tests (Type 3)	2105 days	Mon 05/01/31	Fri 13/02/22
5	Qualification Tests (Type	30 mons	Mon 08/06/30	Fri 10/10/15
6	PBMR Specific MTR (Mat	60 mons	Mon 09/01/05	Fri 13/08/09

Figure B 1: PBMR CSC Qualification Schedule

B1.1.4 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 identified DDN's. The PBMR related costs is omitted due to business confidentially reasons.

B1.2 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.

B1.2.1 SSC Test Specifications #1: PBMR Relevant (WEC-TS-CSC-001)

A simplified version of the development and deployment lifecycle for the PBMR DPP CSC and how it relates to the higher level qualification lifecycle process is indicated in Figure B 2. The TRL levels as determined from the technology readiness review are shown on the figure as well.

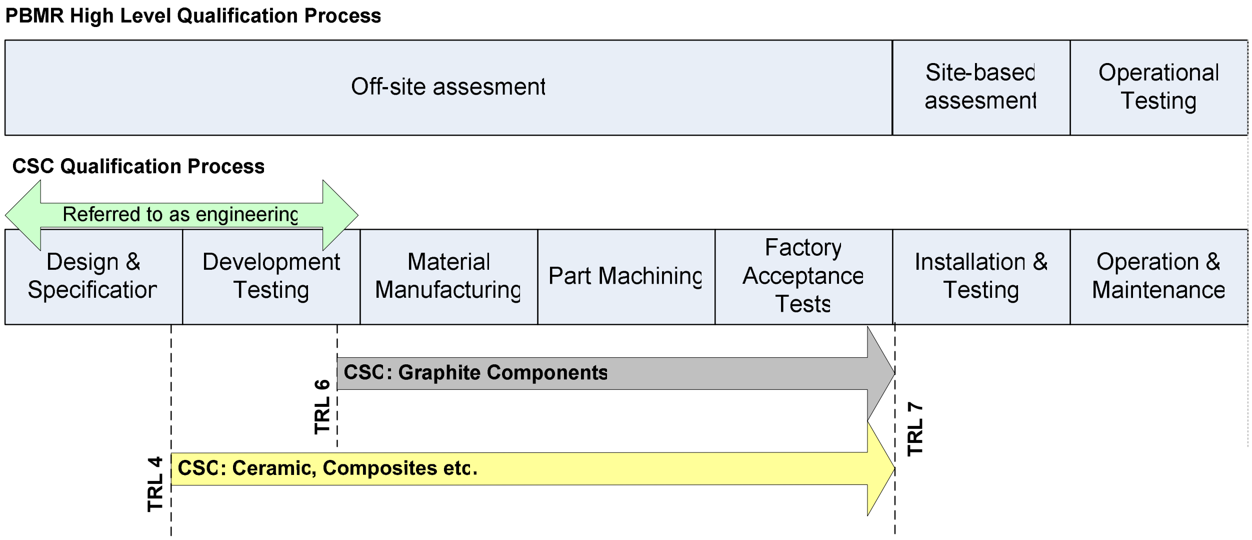


Figure B 2: PBMR High Level Qualification Process (incorporating the CSC)

For the purpose of managing the DPP CSC Testing, each test is allocated to one of 4 Test Types, depending on how that data produced is to be used. These Test Types are as follows:

- Type 1 – Design Inputs: Design input data (i.e. material properties) are obtained from these tests.
- Type 2 – Design By Test: Test substituted for calculation (for proof of strength) as allowed in PBMR's design methodology.
- Type 3 – Verification Test: Test used to provide validation of the analyses or methodologies employed while completing design (As per the requirements in NQA-1).
- Type 4 – Qualification Test: Qualification of the completed designs is demonstrated by these tests. Only qualification tests have acceptance criteria.

For the DPP, the completion of this testing must match the overall project schedule. To ensure that the testing is scheduled appropriately, we employ the following rules:

- Type 1 and Type 2 tests relating to a piece of equipment are completed prior to the release of the equipment for manufacture.
- Type 3 and Type 4 tests are completed prior to installation of the equipment in the plant.

Any deviations from these rules is managed on a case-by-case basis with client and regulatory acceptance where required.

These tests are all initiated as part of a qualification program logic. Testing is completed for design inputs or verification and related to the functions that the equipment must perform.

The following tests represent an extract from the PBMR CSC development and qualifications tests. This list includes a sample of PBMR DPP testing over the entire qualification process of the CSC as well as summary information regarding these tests. The tests are managed through detailed specifications. Annexure B-1 indicates a typical Test Requirement Specification as documented for the bottom reflector insulation integrated test.

B1.2.1.1 CSC-QT-1: Graphite Material Characterization - Virgin Material Properties

Material input data is generated by means of the material characterization 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: Design Input

B1.2.1.2 CSC-QT-3: Graphite Material Characterization - Irradiated Material Properties

The characterization 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 PBMR standard for graphite design 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: Design Input

Note: This will not be completed prior to manufacture of the CSC due to the long term nature of the tests. Sufficient data will be available to support initial operation prior to loading fuel into the DPP.

B1.2.1.3 CSC-QT-4: Graphite Wear Characterization

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: Design Input

B1.2.1.4 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: Design by Test and Qualification

B1.2.1.5 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: Design Verification

B1.2.1.6 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: Design Verification

B1.2.1.7 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: Design by Test

B1.2.1.8 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: Design by Test and Qualification

B1.2.1.9 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. Not that this test specifically targets the use of Fused Quartz insulation and may be removed due removal of these parts form the design due to reduce outlet temperature requirements. Considering this possible design change is beyond the scope of this assessment.

Qualification Life Cycle Phase: Off-site
Test Type: Qualification

B1.2.1.10 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: Qualification

B1.2.1.11 CSC-QT-36: CFRC Material Characterization - Virgin Material Properties

Material input data is generated by means of the material characterization 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: Design Input

B1.2.1.12 CSC-QT-41: Insulation Characterization

Material input data is generated by means of the material characterization 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: Design Input

B2 TECHNOLOGY MATURATION PLAN FOR CSC (TRL 7 TO TRL 8)

B2.1 Technology Maturation Plan Summary (TRL 7 to TRL 8)

B2.1.1 Objectives

The PBMR NGNP Core Structure Ceramics (CSC) comprise the non-metallic components enclosed within the core barrel and its underlying support structure. 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 have been reviewed and rated in terms of TRL as indicated in [1].

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 tasks that need to be performed due to the identified DDN's.

B2.1.2 Scope

The NGNP related TRL advancement consists of addressing the additional DDN's as identified for the NGNP relevant conditions. These DDNs 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 B 3 indicate these incremental requirements by means of comparison between the NGNP and PBMR DPP fluence-temperature conditions envelope.

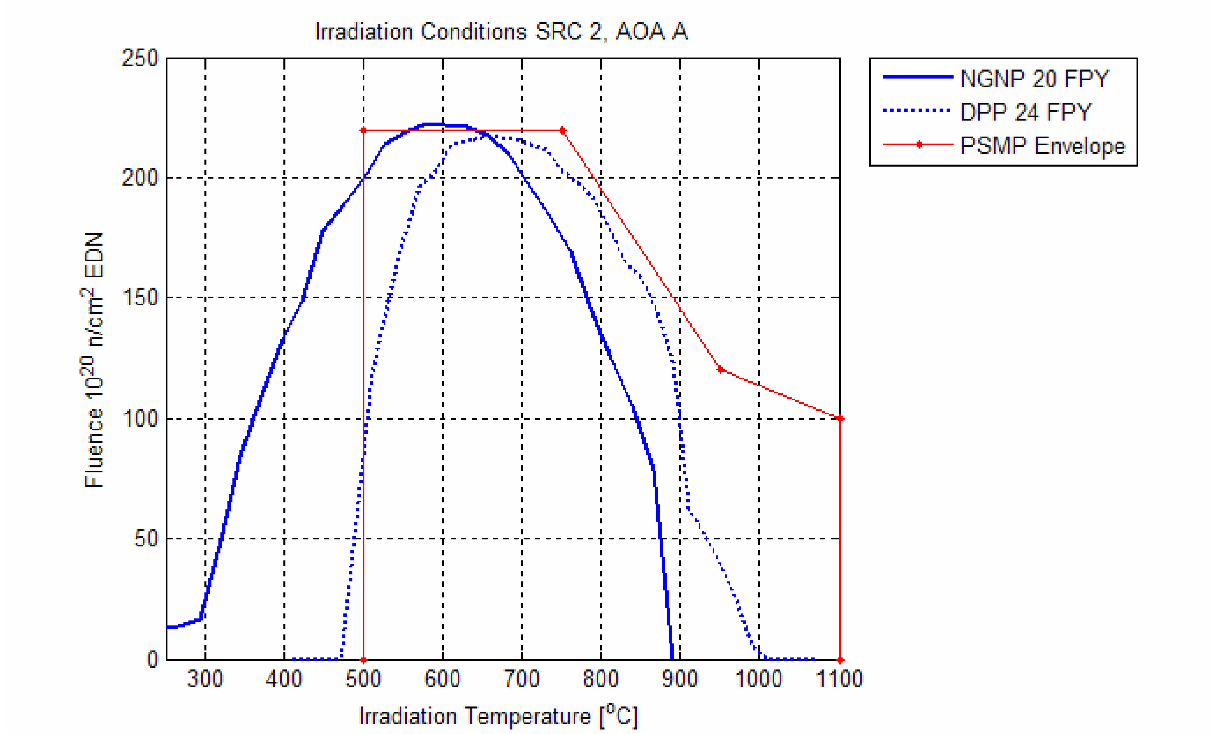


Figure B 3: Irradiation Requirements for the NGNP Reflector Graphite

The following should be noted regarding Figure B 3:

- 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 Class 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. The estimates shown in Figure B 3, are based on scaling of results from previous NGNP analyses based on the higher (950^{o}C) outlet temperature. It is estimated that the NGNP envelope will fit in the DPP envelope in the high temperature region if the outlet temperature is reduced.

As can been seen in Figure B 3, there are parts of the PBMR NGNP operating envelope that are not presently addressed by the PSMP. These parts are in the low-temperature operating range, below about 500 ºC. This corresponds to the lower reactor inlet 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

- COMP-01-01 Characterize Race Track Strap and Tie Rod Materials (Irradiation Tests)

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 at the start of this Appendix.

B2.1.3 Anticipated Schedule

B2.1.3.1 NGNP Schedule (for incremental DDN)

The NGNP schedule consists of the incremental tasks that need to be performed. As shown in the schedule of Figure B 4, 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 FY2012. 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.

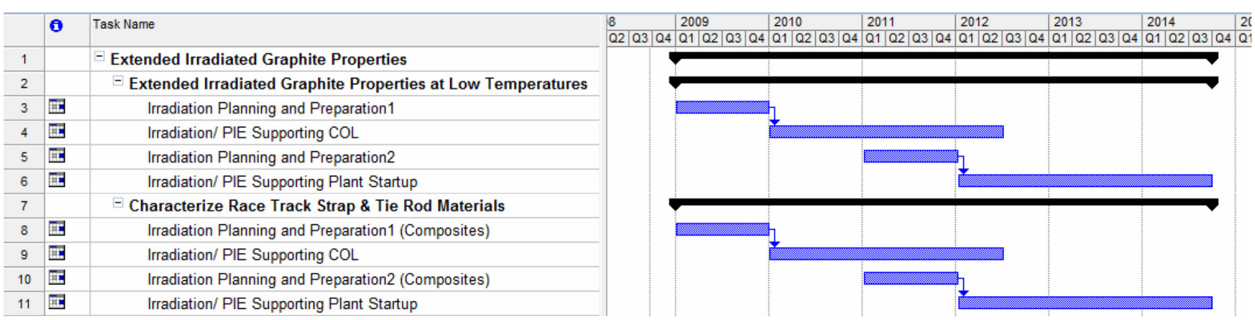


Figure B 4: NGNP Incremental Graphite Qualification Schedule

B2.1.4 Overall Cost

B2.1.4.1 Current NGNP cost related information:

The estimated costs of the R&D activities supporting the Reflector Graphite qualification program are shown in Table B 2. 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 B 2: 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

B2.2 Test Specifications (TRL 7 to TRL 8)

In order to advance the TRL rating of the CSC to the required TRL-8, assuming completion of the PBMR activities as described in the previous section, two additional tasks need to be performed. These incremental tasks are defined in the additional DDNs. The following test specifications provide details of the incremental testing (to meet the DDNs) in order to advance the CSC from a TRL-7 to a TRL-8.

B2.2.1 SSC Test Specification #2: Extended properties of irradiated graphite at low temperatures (WEC-TS-CSC-002)

B2.2.1.1 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.

B2.2.1.2 Test Conditions

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.

Test Duration

Typical test activities include sample preparation, pre-irradiation characterization, 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 (B1.1.3) could be regarded as the time necessary to complete these tests.

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.

B2.2.1.3 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 and agreed set of standards (or procedures) to ensure that the data is compatibly with the PBMR dataset that it extends.

Table B 3: 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.

B2.2.1.4 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

B2.2.1.5 Test Evaluation Criteria

The extended irradiation tests do not have acceptance criteria.

The test conditions however need to be to be determined within the specified accuracies and the quality of work during PIE must be of a high standard.

B2.2.1.6 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.

B2.2.1.7 Cost, Schedule, and Risk

The anticipated schedule and cost for these irradiation tests are captured in section B1.1.3 & B1.1.4. 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.

B2.2.2 SSC Test Specification #3: Characterize effect of Irradiation on Race Track Strap and Tie-Rod Materials (WEC-TS-CSC-004)

B2.2.2.1 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.

B2.2.2.2 Test Conditions

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 $1.4x10^{21}n/cm^2$ (E>0.1 MeV) in increments of 0.5 dpa (carbon) at irradiation temperatures of 600ºC and 800ºC is required. Note that the selected fluence levels may have to be increased to ensure measurable changes in the material.

Test Duration

Typical test activities include sample preparation, pre-irradiation characterization, 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 (B1.1.3) could be regarded as the time necessary to complete these tests.

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.

B2.2.2.3 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)

B2.2.2.4 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

B2.2.2.5 Test Evaluation Criteria

The CFRC irradiation tests do not have acceptance criteria.

The test conditions however need to be to be determined within the specified accuracies and the quality of work during PIE must be of a high standard.

B2.2.2.6 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.

B2.2.2.7 Cost, Schedule, and Risk

The anticipated schedule and cost for these irradiation tests are captured in section B1.1.3 & B1.1.4. 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.

ANNEXURE B-1: 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: 1. Page 17, Table 1, Heading: Test conditions – The initial load was changed from 35kN to 18kN. 2. Page 5, Section 1 and Page 17, Section 4: Sections were updated to refer to Test Requirement Specification and not to duplicate information. 3. Added: “This length can be modified to accommodate the design of the test setup.” Under the heading: Test Description on page 10. 4. Page 10, Table 1, Heading: Test description the symbols β and α were changed around in the sentences where used. 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. 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 **AN-43**	**Tie Rod Qualification tests - Bottom interface**
Test Objectives:	The objectives of this test are to: • determine the maximum tensile load of a standard full size CFRC tie-rod under ideal loading conditions with the authentic bottom interface • determine the maximum tensile load of a standard full size CFRC tie-rod under non-ideal loading conditions with the authentic bottom interface The ideal loading conditions represents the CFRC tie-rod when installed, within the allowed installation tolerances. 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.

Test Requirement Specification Sheet	
Test Description:	The tests will be carried out in air at room temperature. 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. Two different bottom interfaces exist namely : • CFRC tie-rod to graphite block, with CFRC plate insert (Ring 1) • CFRC tie rod to graphite block, without CFRC plate insert (Ring 2) Both of these interfaces will be tested separately. 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. 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. 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. 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. 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. Next the angular misalignment of the tie rod must be done by: Moving one side of the tie-rod in the X-direction to obtain angle β Next moving one side of the tie-rod in the Y-direction to obtain angle α This misalignment can also be done in 1 (one) movement in the resultant direction. 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. Measure and record the angles between the tie rods and the interfacing material after installation in the X-Y plane. The graphite blocks, parts and all CFRC parts shall be changed for each test in order to have a repeatable test result.

Test Requirement Specification Sheet

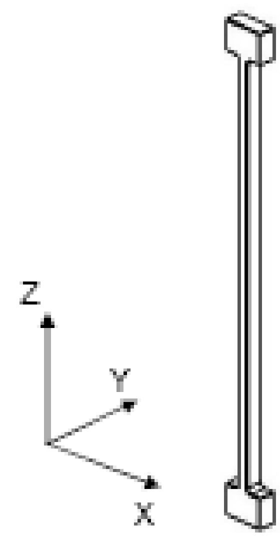


Figure 1: Reference Axis for CFRC Tie-Rod

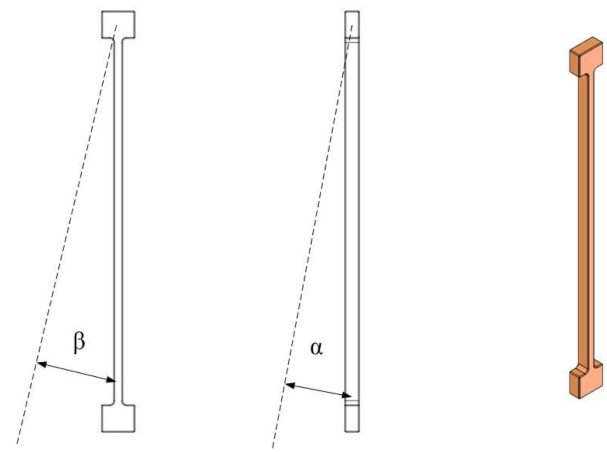


Figure 2: Angles and Displacements to Obtain Non-Ideal Loading Conditions

Test Requirement Specification Sheet

- **CFRC tie-rod to graphite block, with CFRC plate insert (Ring 1)**

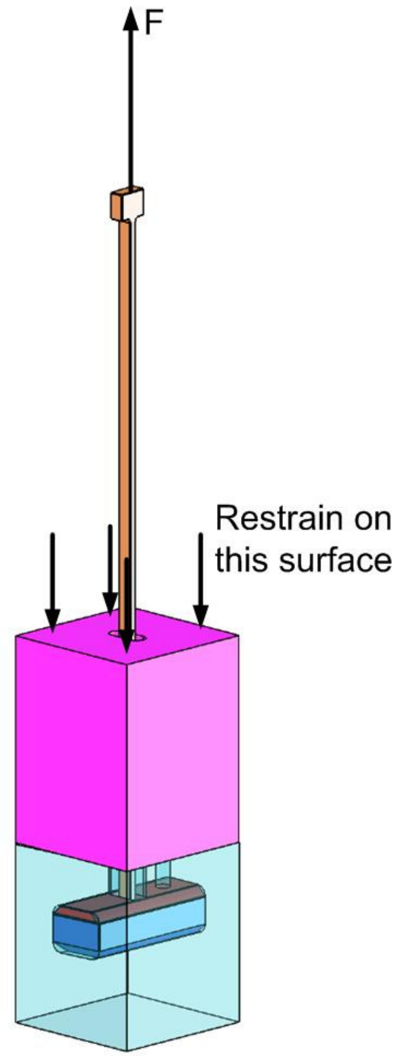


Figure 3: CFRC Tie-Rod to Graphite Block, with CFRC Plate Insert

Test Requirement Specification Sheet

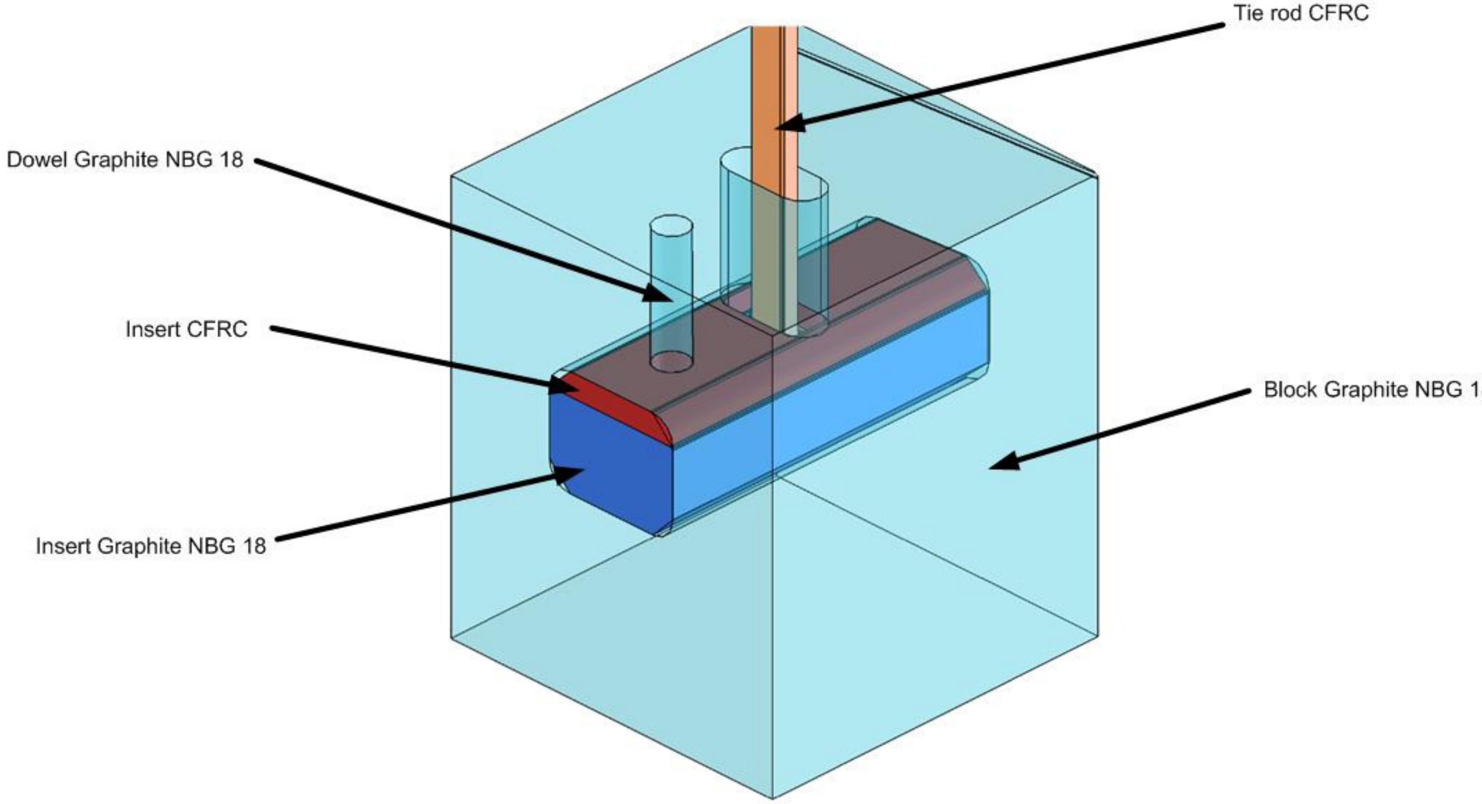


Figure 4: CFRC Tie-Rod to Graphite Block, with CFRC Plate Insert

Test Requirement Specification Sheet

- **CFRC tie rod to graphite block, without CFRC plate insert (Ring 2)**

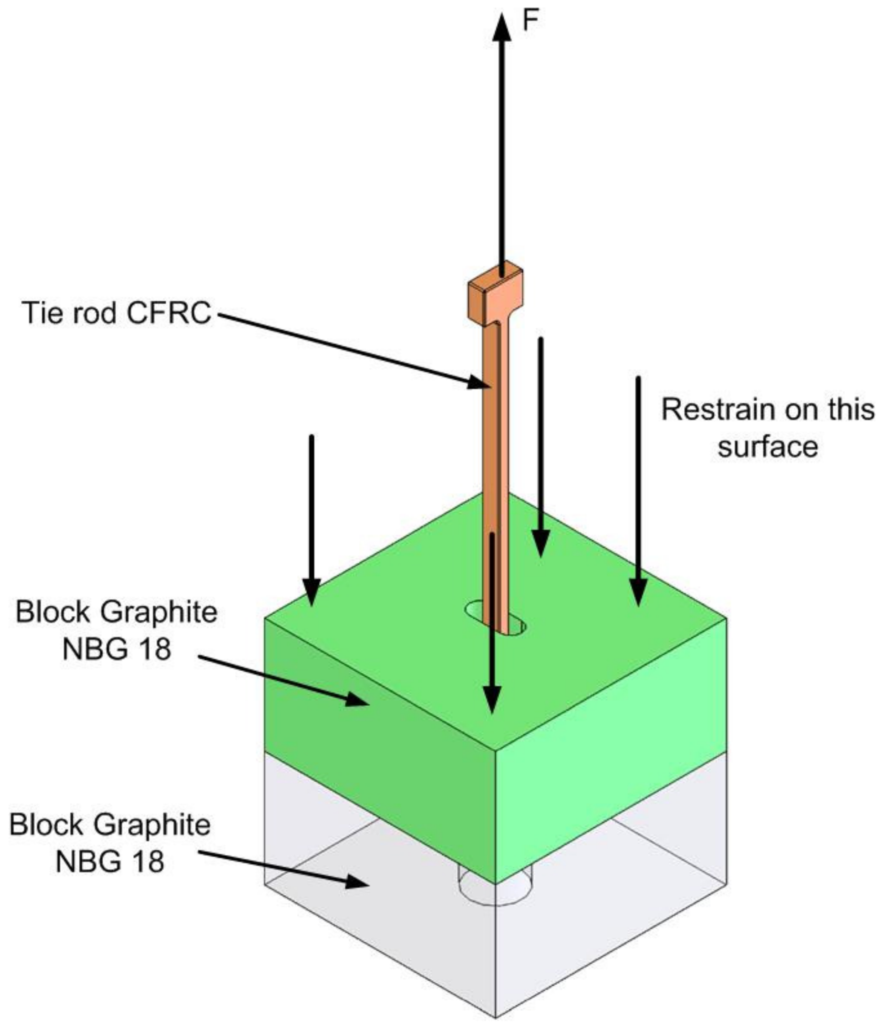


Figure 5: CFRC Tie Rod to Graphite Block, without CFRC Plate Insert

Test Requirement Specification Sheet

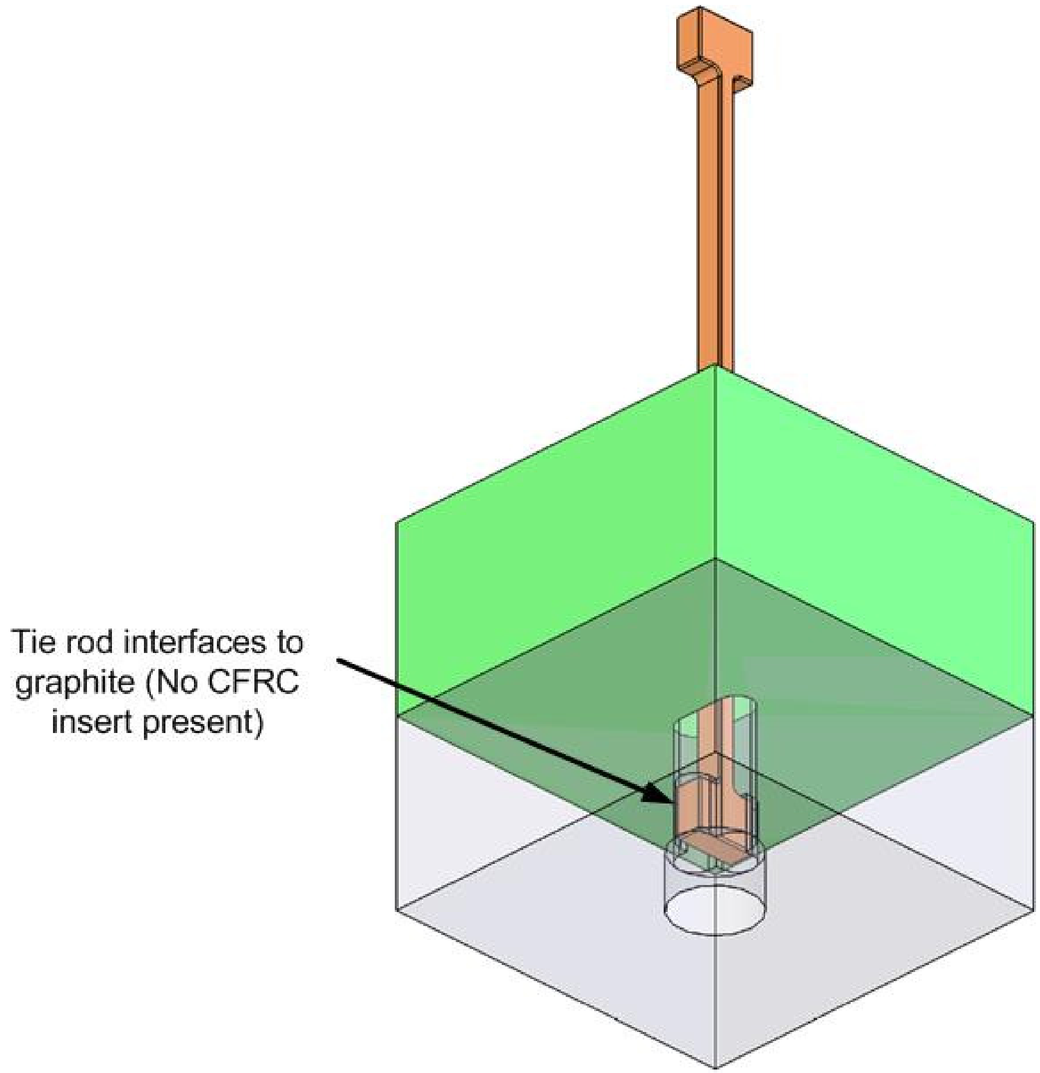


Figure 6: CFRC Tie Rod to Graphite Block, without CFRC Plate Insert

Test Requirement Specification Sheet	
Test Scope:	There are 2 different test configurations and for each the amount of tested are: • for ideal loading conditions at least 6 specimens • for non-ideal loading conditions at least 6 specimens This means that a total of at least 24 specimens shall be tested. 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:
	• Tie-rod tensile force
	• Tie-rod elongation (ΔHead distance sufficient)
	• Misalignment angles:
	  • α or distance ΔY
	  • β or distance ΔX
	• Atmosphere
	• 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:
	• Initial-load (tensile force) to simulate normal operation approximately 18 kN
	• Misalignment angles:
	  • $\alpha < 0.5°$ between the top and bottom of the tie-rod in the Y-direction
	  • $\beta < 0.5°$ between the top and bottom of the tie-rod in the X-direction
	• Atmosphere and Temperature will be air at room temperature
	• Ultimate tensile load under ideal conditions will be < 100 kN (TBD) approximately
	• 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 Test design report 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-TDI-TDR-RPT-G-00014 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 7: Reserve Shutdown System

APPROVALS

Function	Printed Name and Signature	Date
Author	Name: Pieter Coetzer Company: Pebble Bed Modular Reactor (Pty) Ltd	September 18, 2009
Reviewer	Name: Chris Bothma Company: Pebble Bed Modular Reactor (Pty) Ltd	September 18, 2009
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Roger Young (Pebble Bed Modular Reactor (Pty) Ltd)	July 13, 2009

BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
N/A		

REVISION HISTORY

RECORD OF CHANGES

Revision No.	Revision Made by	Description	Date
A	Pieter Coetzer	First Draft of 750℃-800℃ TDRM Update for review	July 13, 2009
0	Pieter Coetzer	Approved Document	July 30, 2009
0A	Werner Koekemoer	Editorial changes	August 31, 2009
1	Roger Young	Document for release to BEA	September 18, 2009

DOCUMENT TRACEABILITY

Created to Support the Following Document(s)	Document Number	Revision
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7 RESERVE SHUTDOWN SYSTEM

7.1 Functions and Operating Requirements

7.1.1 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 and pressures amenable to the valves and other components wetted by gas flow [2].

A schematic layout of the RSS is shown in Figure 7-1.

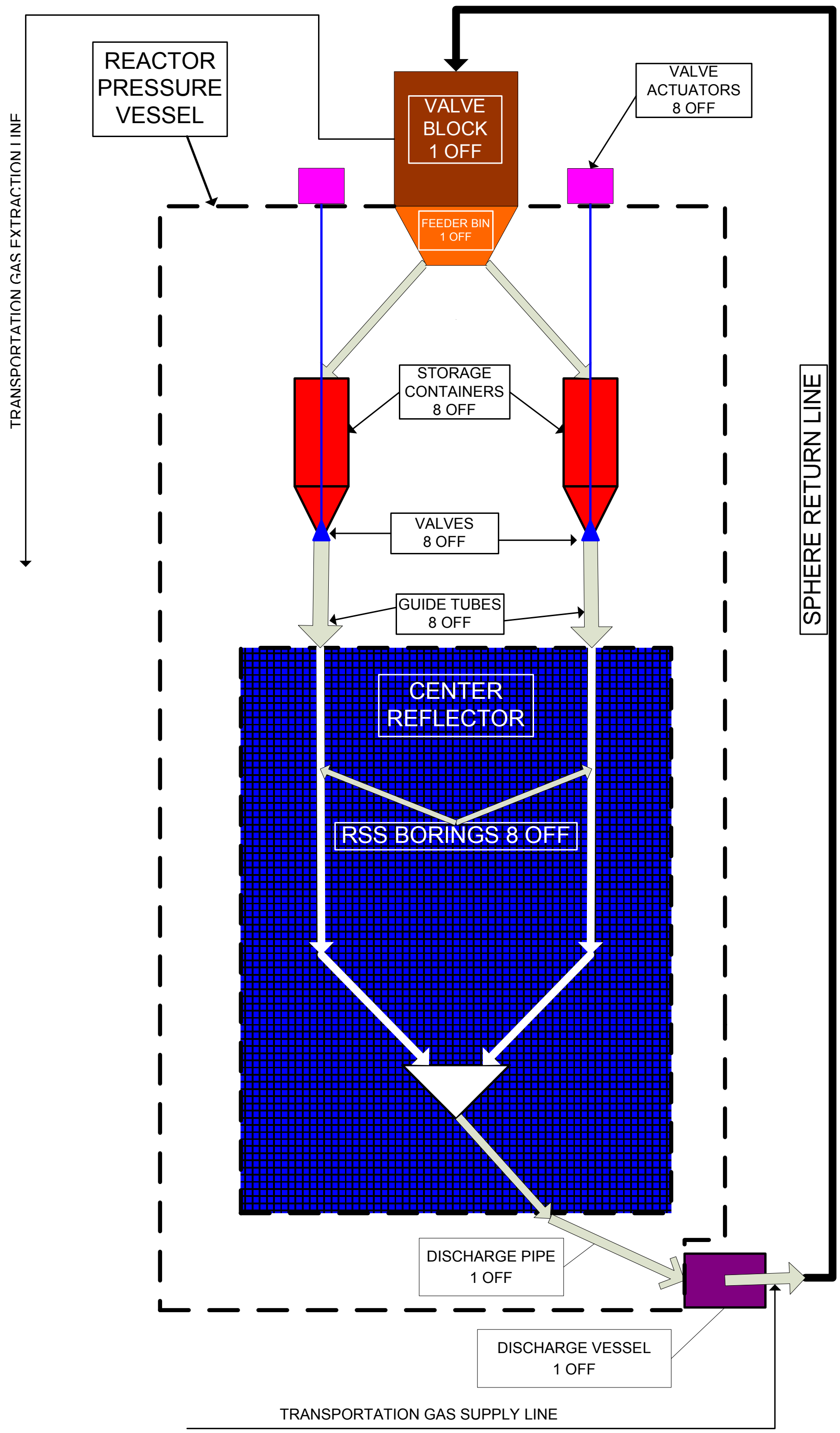

Figure 7-1: Reserve Shutdown System Schematic Layout

7.1.2 Helium Test Facility

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 [3]. The test set-up will simulate the steady state environment of the PBMR RSS during normal, abnormal and shutdown conditions.

Figure 7-2 shows a photo of a section of the HTF during construction. Figure 7-3 shows part of the RSS test setup during installation.

Figure 7-2: The HTF (Left) and its Main Loop (Right)

Figure 7-3: Part of the RSS during installation

7.1.3 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.

7.1.4 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

7.1.5 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 280˚C and 750˚C-800˚C and a reactor power level of 500MWt. The change in operating conditions between DPP and NGNP 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.

7.2 Design/Technology 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 most likely 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.

7.2.1 Candidate Technologies

N/A

7.2.2 Decision Discriminators

N/A

7.2.3 Reference Design

The PBMR RSS will serve as the reference design for the NGNP.

7.2.4 Down Selection Task

N/A

7.3 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.

If the NGNP Requirements are enveloped by / aligned with 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, 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 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.

Initial assessments indicate that the RSS in the NGNP with lower operating conditions (750°C-800°C ROT, 280°C RIT) will be enveloped by the DPP design and operating parameters, thus no design or technology changes are anticipated from the DPP design. The NGNP RSS is assessed to be at TRL 6 as per the DPP RSS.

The TRL rating sheet for the RSS is shown in [1].

7.4 Technology Development Road Map Summary

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.

Upon reaching a validated TRL 8 for the DPP RSS, the NGNP RSS can also be advanced to a validated TRL 8 if the NGNP requirements are enveloped by / aligned with the DPP. If analyses have indicated that additional delta testing is indeed required for the NGNP RSS (notably SAS validation), 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 A.

7.5 Technology Maturation Plan Summary

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 [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 SAS

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 possible 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.

7.6 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels
[2] 016956, Rev 5, PBMR Technical Description
[3] HTF-000000-225, System Operational Description
[4] 066776, Rev A - Qualification Life Cycle Strategy

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750°C-800°C

TECHNOLOGY DEVELOPMENT ROADMAP – RESERVE SHUTDOWN SYSTEM

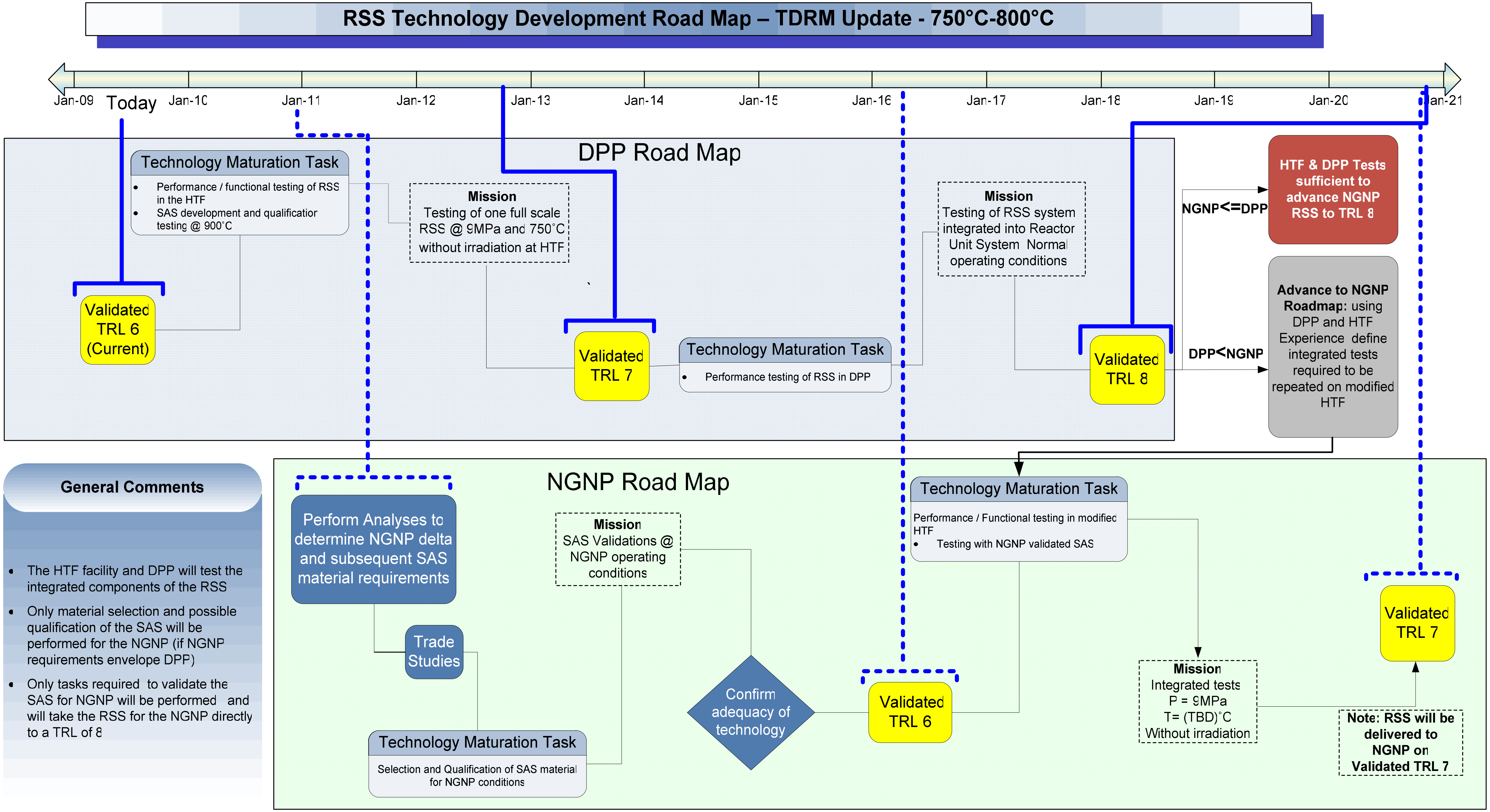

Figure A-1: TDRM for RSS

APPENDIX B: TECHNOLOGY MATURATION PLAN – 750°C-800°C

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B1 TECHNOLOGY MATURATION PLAN FOR RSS (TRL 6 TO TRL 8)

B1.1 Technology Maturation Plan Summary (TRL 6 to TRL 8)

B1.1.1 Objectives

The objective of the technology maturation plan is to mature the RSS technology from its current TRL of 6 to a TRL of 8 in order to qualify the technology ready for use in the DPP reactor.

B1.1.2 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 B 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 [1].

Table B 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

B1.1.3 Anticipated Schedule

The testing is expected to last at least three years which will be followed by continuous lifecycle testing (availability, reliability, etc.).

B1.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

B1.2 TEST SPECIFICATIONS

B1.2.1 Typical RSS Test Specification

A typical test specification used to mature the RSS technology to a TRL of 7 is given below:

B1.2.1.1 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.

B1.2.1.2 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 the test. 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 B 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 B 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

B1.2.1.3 Measured Parameters

During the test runs the instruments listed in Table B 3 were logged on the data historian.

Table B 4: List of Instruments used for Data Capturing.

Instrument No.	Position/Description	Units	Range	Class	Accuracy	Sample
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

B1.2.1.4 Test Deliverables

No data analysis was requested. The data was only packaged and presented in graphed form as requested in the Test Specification.

NGNP-TDI-TDR-RPT-G-00015 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 8: Reactivity Control System

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BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
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REVISION HISTORY

RECORD OF CHANGES

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A	Ruttie Nel	Technology Maturation Plan Update for 750°C-800°C	July 17, 2009
0	Ruttie Nel	Approved Document	July 31, 2009
0A	Werner Koekemoer	Editorial changes	August 31, 2009
1	Ruttie Nel	Document for release to BEA	September 18, 2009

DOCUMENT TRACEABILITY

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8 REACTIVITY CONTROL SYSTEM

8.1 Functions and Operating Requirements

8.1.1 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 side reflector whereas the shutdown rods are fully inserted into the bottom part of the side 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 (a portion of the reactor inlet 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 bottom reflector in the unlikely event of a rod becoming disengaged from the link chain and dropping to the bottom of the boring.

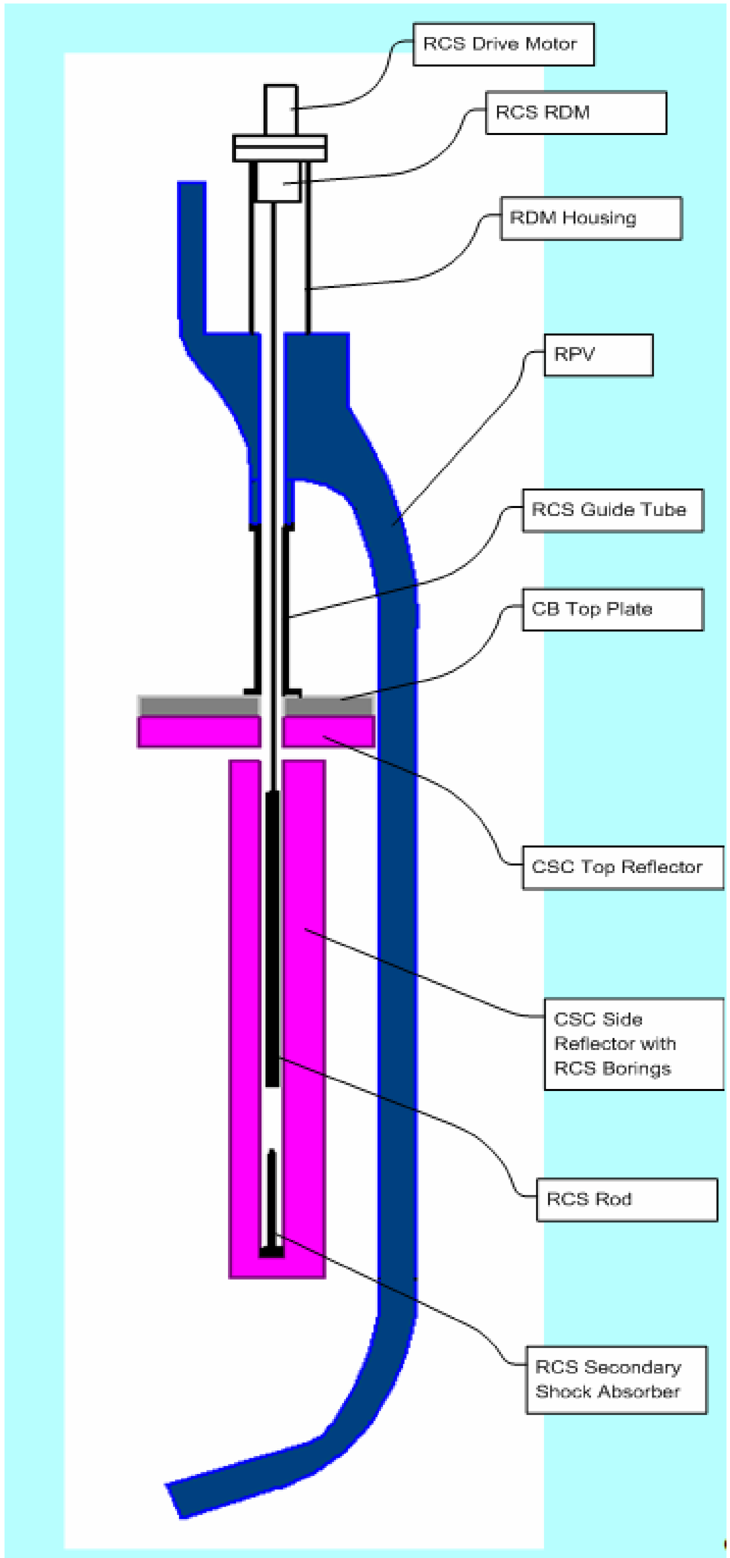

Figure 8-1: Layout and position of the Reactivity Control System

8.1.2 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 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 utilized 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 utilized in a specific part of the RCS test set-up to simulate the different conditions in the PBMR.

Figure 8-2: Photo of the HTF tower where the RCS test setup is located

8.1.3 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 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).

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.

8.1.4 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).

8.1.5 Operating Conditions

The DPP reactor operates at a power level of 400MWt with the DPP RCS subjected to reactor core inlet and outlet temperatures of 500°C and 900°C respectively. The NGNP nominal operating conditions are:

- Nominal outlet temperature of 750°C-800°C.
- Nominal inlet temperature of 280°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.

The RCS operating conditions for the NGNP (at ROT of 750°C-800°C) are expected to be as follows:

- 600°C maximum normal operating temperature – based on PBMR DPP temperatures minus 100°C.
- For DBA temperatures up to 900°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 [TBD].

All parameters are initial estimates and will be better defined during conceptual design.

8.2 Design/Technology 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 testing or possible development in some materials of the RCS, as the RCS operating environments in the NGNP could potentially be at higher fluence levels and a longer operating life.

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 may need to be considered for this component, with potential candidate materials already having been identified.

8.2.1 Candidate Technologies

The candidate technologies currently under consideration for the DPP RCS 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)

8.2.2 Decision Discriminators

Design / Technology development

The primary decision discriminators are the fluence and operating life 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 to 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.

8.2.3 Reference Design

The PBMR DPP RCS will serve as the reference design for the NGNP.

8.2.4 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.

8.3 TRL Status

The DPP 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 PBMR RCS is based on the THTR design, but with modifications to the electric motor, gearbox and secondary shock absorber. The DPP RCS will reach a TRL of 7 when HTF development tests are completed in a relevant environment and a TRL of 8 when qualification tests on representative RCS hardware as well as DPP testing have been completed.

If the NGNP Requirements are enveloped by / aligned with the DPP, these development and qualification tests will be sufficient to advance the NGNP RCS to a TRL of 8. If the NGNP requirements are not enveloped by the DPP (thus, the environment of DPP does not cover the material qualification limits of the control rod cladding), further material qualification may be required for the NGNP application in an upgraded / revised HTF to bring the NGNP RCS from a possible TRL of 6 to a TRL of 7. The NGNP will then receive the RCS at a TRL of 7 and will be advanced to a TRL 8 during commissioning in the NGNP. 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.

Initial assessments indicate that the RCS in the NGNP with lower operating conditions (750-800°C ROT, 280°C RIT, excluding higher fluence levels and lifetime) will be enveloped by the DPP design and operating parameters, thus no design or technology changes are anticipated from the DPP design. The NGNP RCS is assessed to be at TRL 6 as per the DPP RCS.

8.4 Technology Development Road Map Summary

The RCS technology development roadmap shows the maturation tasks necessary to advance the RCS from its current TRL status to a TRL status of 8. The roadmap is divided into a DPP and a NGNP section.

Upon reaching a validated TRL 8 for the DPP RCS, the NGNP RCS can also be advanced to a validated TRL 8 if the NGNP requirements are enveloped by / aligned with the DPP. If analyses have indicated that additional delta testing is indeed required for the NGNP RCS (notably qualification of control rod cladding material), experience from the DPP RCS (then already at a TRL 8) will be fed into the NGNP RCS maturation tasks to help advance the NGNP RCS from its current TRL 6 to a TRL of 8.

Since the RCS that is being developed for the 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.

The technology development road map is shown in Appendix A.

8.5 Technology Maturation Plan Summary

Before 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 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 DPP RCS from its current TRL to a TRL Rating 7; and
- Tasks to be performed to qualify the materials used for the control rod 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.
- Tasks to be performed to verify the functional operation of the NGNP RCS, to advance to a TRL Rating of 7

The maturation plans and test specifications described in Appendix B are those required to take the DPP RCS to TRL 7 while operation in the DPP will advance the RCS to TRL 8 and it will be assumed in the interim that this is adequate to advance the NGNP RCS to TRL 8, thus the plans only describe the step from TRL 7 to TRL 8.

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

Tasks to be performed to qualify the materials and extended operating period used for the control rods in the NGNP

Since the specific requirements of the materials and lifetime 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 and modified HALT tests to ensure that the functional requirements of the RCS are still fulfilled for the new operating conditions. Tasks required for qualification of the materials and integrated testing of the NGNP RCS could include, but are not limited to, the following:

1) Modeling is required of the Inner Side Reflector (ISR) to determine the fluences experienced by the control rods and chains for the NGNP application.
2) A modeling study to verify the temperatures of the RCS control rods and chains need to be performed for the NGNP design. Depending on the outcome of this study (if the temperatures are higher than in the DPP) the following tasks need to be performed:
    a) A review of the adequacy of the Alloy 800H material for the control rods is required for the NGNP application

b) A study to determine qualification testing for the components of the RCS, needed for the NGNP design. These include tests that need to be repeated in the HTF, possibly at higher temperatures. This could include:

   i) SCRAM tests.

   ii) Rod temperature distribution (thermal bending) tests.

3) Irradiation testing at the temperatures that is required in the NGNP.

4) Material characterization of the selected material in and outside a Helium environment.

5) Structural ageing tests of selected material due to radiation, Helium and elevated temperatures.

6) HALT tests to simulate the extended lifetime of the control rods in the NGNP.

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750°C-800°C

TECHNOLOGY DEVELOPMENT ROADMAP – REACTIVITY CONTROL SYSTEM

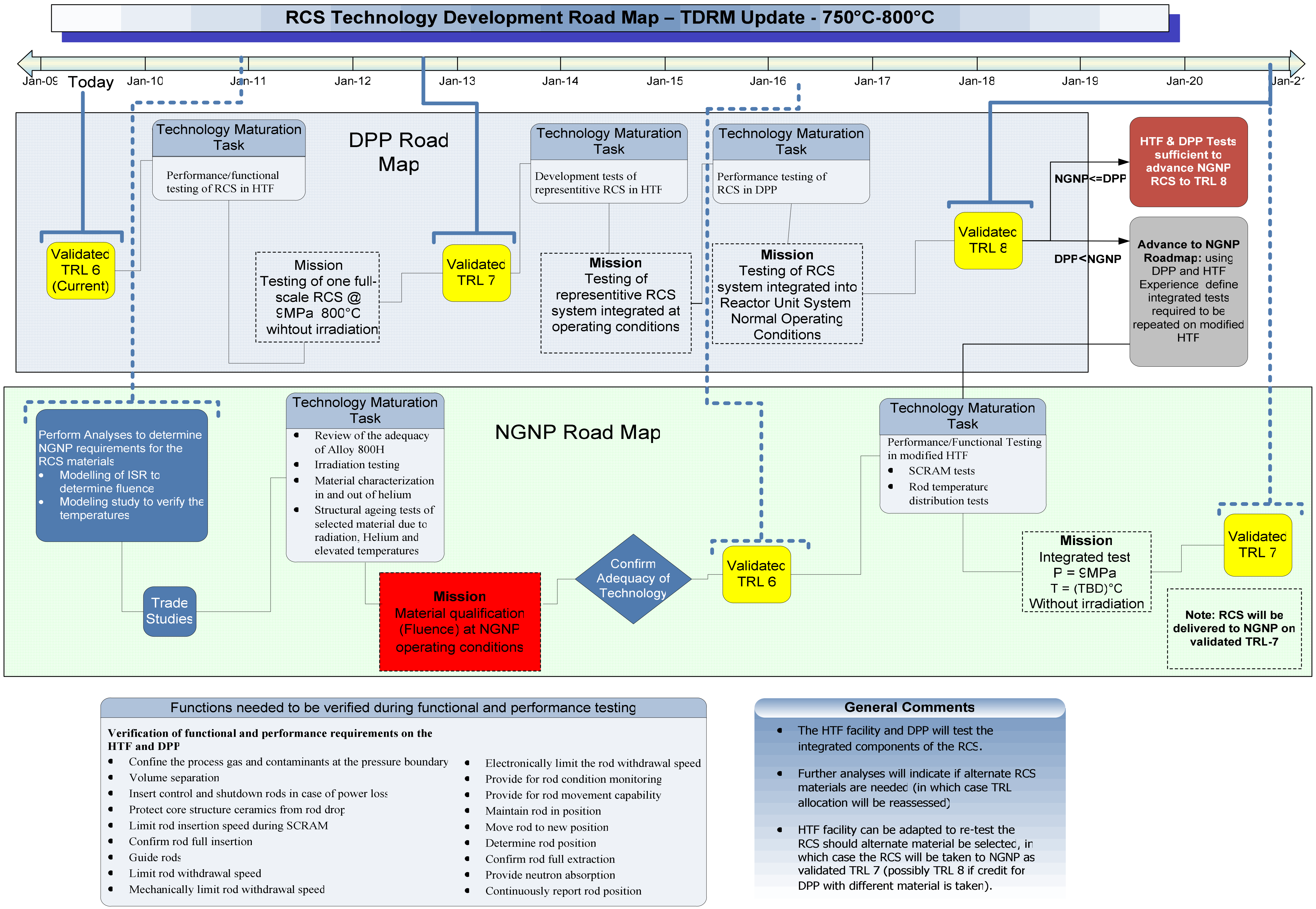

Figure A-1: TDRM for RCS

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750℃-800℃

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B1 TECHNOLOGY MATURATION PLAN FOR CCS (TRL 6 TO TRL 7)

B1.1 TECHNOLOGY MATURATION PLAN SUMMARY

B1.1.1 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.

B1.1.2 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 B-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 B1.2.1.

Table B-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	Analysis
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	Analysis
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
Prototype production dry run	Inspection	Manufacturing Inspection
Control rod SCRAM simulation	Test	Functional Assessment
FAT inspection of the prototype without	Test	Manufacturing Inspection

Qualification Test	Verification Method	Qualification Activity
shroud		
Process Qualification of RCS Component Manufacture and Quality Surveillance	Inspection	Manufacturing Inspection
RCS motor functional acceptance testing and characterization	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

B1.1.3 Anticipated Schedule

The testing is expected to last at least three years which will be followed by continuous lifecycle testing (availability, reliability, etc.).

B1.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

B1.2 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.

B1.2.1 RCS Test Specification #1: Control Rod SCRAM (WEC-TS-RCS-001)

B1.2.1.1 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.

B1.2.1.2 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

B1.2.1.2.1 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.

B1.2.1.2.2 Proposed Test Location

The tests will be performed in the RCS test setup in the HTF in South Africa.

B1.2.1.3 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.

B1.2.1.4 Data Requirements

All measurements shall be for reference only.

B1.2.1.5 Test Evaluation Criteria

The 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.

B1.2.1.6 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.

B2 TECHNOLOGY MATURATION PLAN FOR CCS (TRL 7 TO TRL 8)

B2.1 TECHNOLOGY MATURATION PLAN SUMMARY

B2.1.1 Objectives

The objective of the maturation plan is to advance the RCS from a TRL Rating of 7 to a TRL Rating of 8. The plan is an overview of possible tests aimed at verifying certain critical functions of the RCS prior to it being installed and commissioned in the PBMR DPP.

B2.1.2 Background

Currently the RCS that is being tested at the HTF is currently not fully representative of the RCS that will be installed in the DPP. The current RCS unit under test will need to be modified or a complete new RCS need to be manufactured and tests at operating conditions need to be performed.

B2.1.3Scope

Depending on the outcome of the current RCS tests and after an evaluation of the differences between the RCS unit under test and the final DPP RCS, an updated test program will be compiled. The following tests have been identified as possible tests for an updated RCS:

- SCRAM test
- RCS functionality (movement speed, position control, etc)
- Lifetime testing

B2.1.4 Anticipated Schedule

The testing is expected to last at one to two years which will be followed by continuous lifecycle testing (availability, reliability, etc.).

B2.1.5 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

B2.2 TEST SPECIFICATIONS

B2.2.1 Test Objectives

The objective of the tests will be to complete the development testing cycle of the RCS before it is installed in the DPP.

B2.2.2Test Parameters

Tests will be performed at the DPP operating conditions.

B2.2.3 Hardware Configuration

The configuration of the RCS that will be tested will be identical to the DPP RCS.

NGNP-TDI-TDR-RPT-G-00016 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 9: Core Conditioning System

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BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
N/A		

REVISION HISTORY

RECORD OF CHANGES

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A	Carel Wilken	First Draft of 750°C-800°C TDRM for review	July 13, 2009
0	Carel Wilken	Approved Document	July 30, 2009
0A	Werner Koekemoer	Editorial changes	August 31, 2009
1	Carel Wilken	Document for release to BEA	September 18, 2009

DOCUMENT TRACEABILITY

Created to Support the Following Document(s)	Document Number	Revision
N/A		

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9 CORE CONDITIONING SYSTEM

9.1 Functions 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 9.1 along with a simplified gas flow path through the reactor unit.

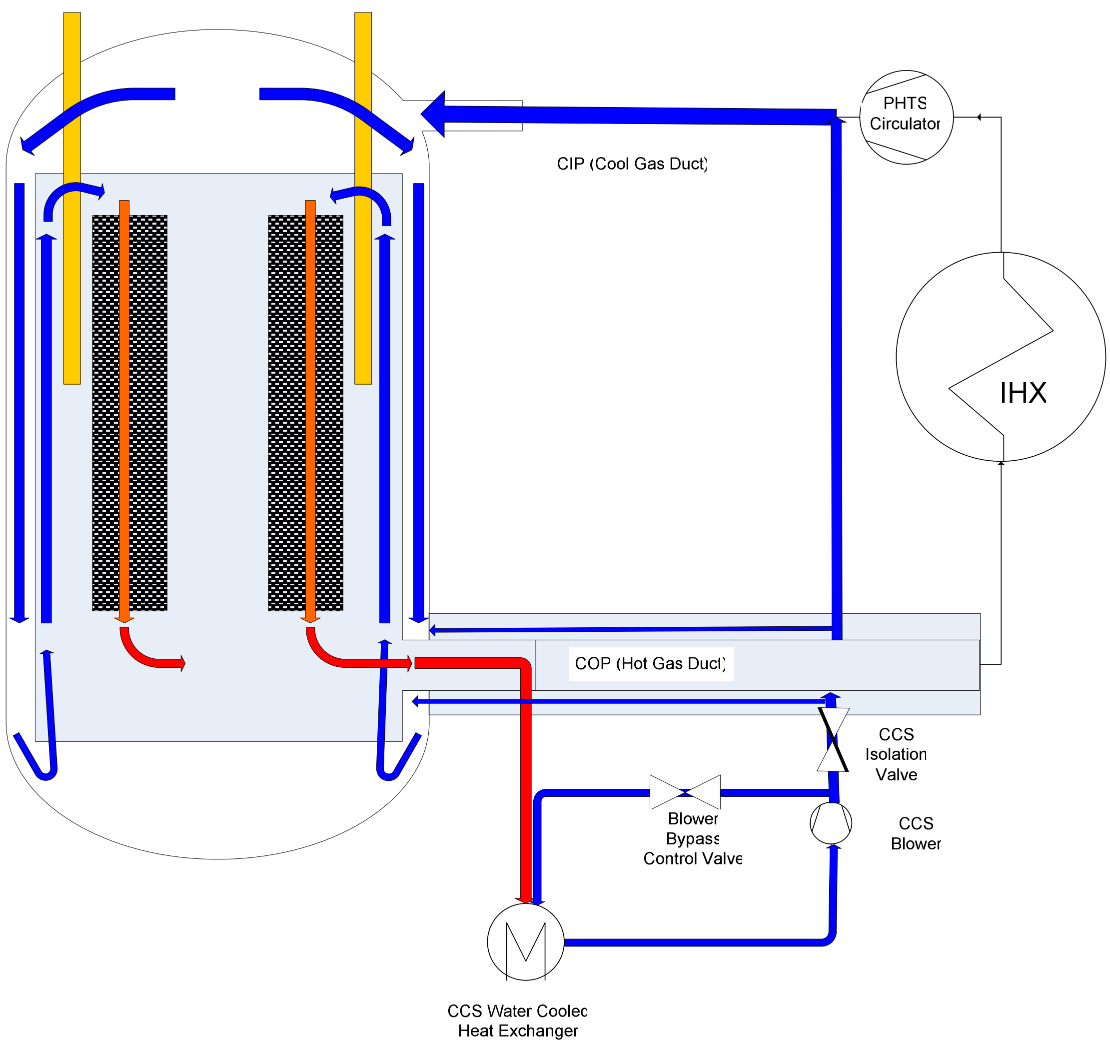

Figure 9.1: Process Flow Diagram of the CCS for a 750°C-800℃ NGNP ROT

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 CCS 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.

9.1.1 Operating Modes & States

The CCS operational states as mapped to the NGNP Modes and States are detailed in Table 9-1.

Table 9-1: 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

9.1.2 Operating Conditions

The steady-state operating conditions of the CCS at a ROT of 750°C–800°C are expected to be as shown in Table 9-2. These estimated steady-state conditions are preliminary and updated steady state estimates will be given as part of the following updated TDRM report. The actual steady-state conditions for the NGNP CCS will only be determined through dynamic modeling as part of conceptual design.

Table 9-2: 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	800	280	3	10**	Max. 35**	Higher temp operation after trip
Depressurized Forced Cooling	101.3	800	280	1.6	1.9	5.13	Start of DFC
Maintenance cooling	101.3	250	90	1.6	1.9	2	Maintenance

Notes: ** Short durations only.

9.1.3 Components

Components[1] of the CCS are:

- **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 9-2. 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

- **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 9-2.

Helium side

Design pressure	Min: 1 kPa	Max: 9700 kPa
Design temperature	Min: 18 °C	Max: 850 °C

[1] All design values provided here are conservative estimates and will be defined during conceptual design

Water side

Design pressure	Min: 100 kPa	Max: 300 kPa
Design temperature	Min: 18 °C	Max: 41 °C

- **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

- **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.

- **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).

- **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: 850 °C

Pressure boundary

Design pressure	Min: 1 kPa	Max: 9700 kPa
Design temperature	Min: 18 °C	Max: 371 °C

9.2 TRL Status

The status of technology for the CCS was evaluated [1] 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).
- 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.
- 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).

9.3 Technology Development Road Map Summary

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 (with the exception of EMBs and CBs). 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 A while the maturation tasks are described below.

9.4 Technology Maturation Plan Summary

In the section below the tasks needed to advance the technology of the CCS system from a validated TRL 6 to a validated TRL 8 are described. Various tests will be done on the individual components of the CCS (inclusive of extensive development of EMB and CB technologies). 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.

Maturation Tasks from 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.

The development and validation of EMB and CB technologies also forms part of the maturation tasks needed to advance the CCS blower technology from a validated TRL 6 to a TRL 7. It is conceivable that single effects tests will be able to address this development needed. The detail of these tests will however be defined in detailed maturation plans with the following series of TDRM updates.

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.

Hot Gas Ducts:

See Hot Gas Ducts technology development road map.

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.

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. This will verify that each component of the CCS subsystem performs within its specifications.
- 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.

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.

9.5 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750℃-800℃

TECHNOLOGY DEVELOPMENT ROADMAP – CORE CONDITIONING SYSTEM

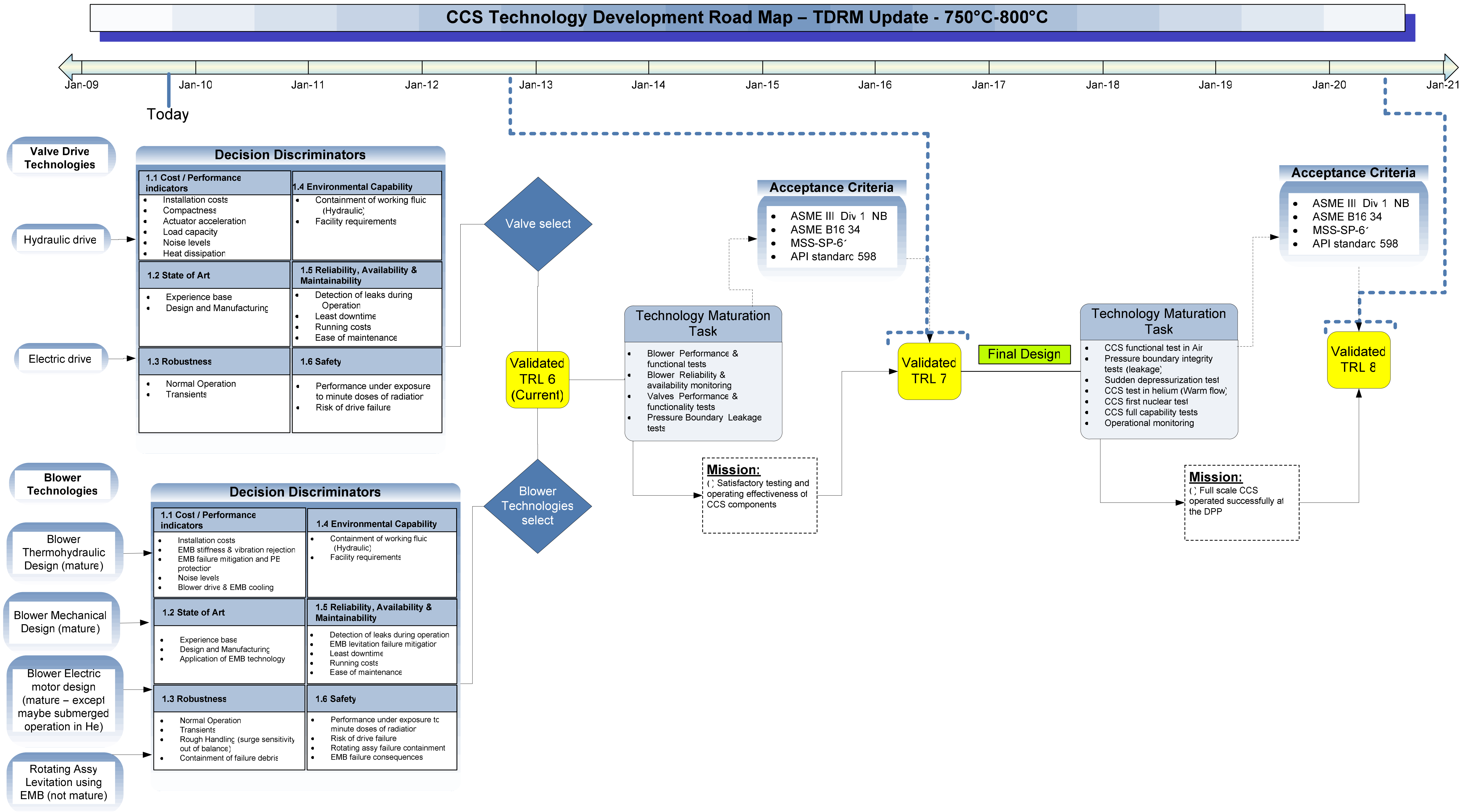

Figure A-1: TDRM for CCS

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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B1 TECHNOLOGY MATURATION PLAN FOR CCS (TRL 6 TO TRL 7)

B1.1 TECHNOLOGY MATURATION PLAN SUMMARY

B1.1.1 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.

B1.1.2 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.

B1.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan can be accomplished during the period FY 2010 through FY 2012. Work specified in the two test specifications can be conducted in parallel and each has an expected duration of three years.

B1.1.4 Overall Cost

The PBMR related costs are omitted due to business confidentiality reasons.

B1.2 TEST SPECIFICATIONS

The tests defined in the following test specifications have been identified to advance from TRL6 to TRL 7:

- Specification 1: CCS Valves development test specification (WEC-TS-CCS-001)
- Specification 2: CCS Blower development test specification (WEC-TS-CCS-002)

B1.2.1 CCS Test Specification #1: CCS Valve development test (WEC-TS-CCS-001)

B1.2.1.1 Objectives

The objectives of the test include:

a) Verification of the performance parameters for the valve, including:

- Valve response times.
- Internal leak rate at the maximum operating pressure as a function of time/usage.
- External leak rate at the maximum operating pressure as a function of time/usage.

b) Assessment of the position feedback and control of the valves.
c) Assessment of sealing performance of valve seats after a predetermined number of cycles.
d) Determination of key inputs for maintenance procedures.
e) Quantification of the endurance of valve components in a helium environment.

Note: The valves, on which the development tests will be performed, will be selected based on the criticality of the valve function as determined by failure analysis on the CCS.

B1.2.1.2 Test Conditions

The valve tests will be conducted using helium as working fluid. Tests will be performed with the helium in the temperature range of between 25 °C and 350 °C, and pressure range from ambient pressure to 10 MPag. Valve functionality may be verified at lower test pressures prior to final testing. Such verification may be performed using compressed air if it is more practical. Pressure differential across the valve should not exceed 1MPa during testing

Note: Tests up to 350°C at 9MPa in a helium atmosphere has been conducted on similar valves to the CCS valves at the University of Stellenbosch

Test Configuration/Set-up

The following equipment would be needed for the test:

a) The prototype valves 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/s from the prototype valve inlet before and after the test.
c) Pressure and temperature gauges and/or transducers.
d) Electrical and C&I system which includes a Data Acquisition Unit (DAU).

The following facilities will be required for the test:

a) High pressure air supply at a minimum of 7MPag supply pressure (if required).
b) High pressure helium supply at a minimum of 12MPag supply pressure.
c) Two pressure vessels rated at minimum 10MPag for helium blow-down tests. The test valve will be mounted in line between the two pressure vessels. Vessel capacity will be determined at a later stage.
d) Three phase electrical supply rated at 20 kW.
e) An overhead crane with 10 tons capacity covering the test area.

Test Duration

The test is estimated to run for a minimum of time period of three years.

Proposed Test Location

The Helium Test facility (HTF) at Pelindaba is the preferred site for the test

B1.2.1.3 Measured Parameters

Parameters for valve performance as specified in the valve specification and requirement.

The measured parameters should at least include the following parameters over the pressure and temperature ranges tested:

a) Response parameters
b) Flow coefficient
c) Leak flow versus usage
d) Failure frequency over the test time, if possible

B1.2.1.4 Data Requirements

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

B1.2.1.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the valve specifications and requirements.

The measured valve parameters must also conform to the requirements of the specified standards for the NGNP plant where applicable, including, but not limited to, the following standards:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

B1.2.1.6 Test Deliverables

A test report will be compiled containing the following, for each valve tested, where applicable:

- Description of test equipment and calibration status
- Definition of test software used
- Data recorded
- Description of type of observations
- Interpreted results and conclusions
- Recommendations with respect to any deviations noted
- Key inputs to maintenance procedures
- Unresolved anomalies

B1.2.1.7 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 three years. There is a medium risk associated with the test due to the high working pressures.

B1.2.2CCS Test Specification #2: CCS Blower development test (WEC-TS-CCS-002)

B1.2.2.1 Objectives

The objectives of the test include:

a) Verification of the performance parameters of the blower, including:

- Determination of availability of the blower.
- Determination of the reliability of the blower
- Assessment of blower performance deterioration over time
- Assessment of blower response to rough handling and transient conditions.

b) Assessment of the performance of the electromagnetic bearings, in particular:

- Deterioration of performance over time

- EMB failure modes, if failures do occur
- Assessment of EMB performance under low pressure conditions (less than 90kPa abs)

c) Verification of the endurance of the blower, including metal parts, in a helium environment.
d) Determination of key inputs for maintenance procedures.

B1.2.2.2 Test Conditions

The blower shall be connected in the main loop of the HTF. Operation and testing shall be in the pressures range 80kPa abs to 9MPag and temperatures up to 140 °C with helium as a test medium.

Test Configuration/Set-up

The blower acts as a circulator of the helium in the main loops.

Test Duration

The duration of the test and monitoring is estimated to be three years.

Proposed Test Location

The Helium Test facility (HTF) at Pelindaba is the preferred site for the test.

B1.2.2.3 Measured Parameters

Parameters for blower and EMB performance as specified in the blower system specification and requirement

The measured parameters should at least include the following parameters over the pressure and temperature ranges tested:

a) Blower thermodynamic performance (mass flow and efficiency versus pressure ratio at a range of blower speeds)
b) Blower and EMB cooling water conditions
c) Blower and EMB power consumption
d) EMB performance (vibration spectra, shaft proximity, stability), in particular at low pressures
e) Availability and downtime
f) Failure modes identified

B1.2.2.4 Data Requirements

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

B1.2.2.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower specification and requirements.

The measured blower parameters must also conform to the requirements of the specified standards for the NGNP plant where applicable, including, but not limited to, the following standards:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

B1.2.2.6 Test Deliverables

A test report will be compiled containing the following:

- Description of test equipment and calibration status
- Definition of test software used
- Data recorded
- Description of type of observations
- Interpreted results and conclusions
- Recommendations with respect to any deviations noted
- Unresolved anomalies
- Inputs to the final design of the blower system .

B1.2.2.7 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.

B2 TECHNOLOGY MATURATION PLAN FOR CCS (TRL 7 TO TRL 8)

B2.1 TECHNOLOGY MATURATION PLAN SUMMARY

B2.1.1 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.

B2.1.2 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 CCS blower tests at operational temperature.

B2.1.3 Anticipated Schedule

Due to the fact that these tests are performed as part of the DPP commissioning test, it should be remembered that the test schedule is dependent on the DPP commissioning test schedule. The fact that work specified in the three test specifications cannot be conducted in parallel, will also impact on test schedules.

It is expected that the work described by the Test Specifications in this Technology Maturation Plan can be accomplished in two years

B2.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality reasons.

B2.2 TEST SPECIFICATIONS

The following specifications/ tests have been identified to advance from TRL7 to TRL 8:

- Specification 3: Cold CCS integrated functional testing (WEC-TS-CCS-003)
- Specification 4: CCS blower at operational temperatures (WEC-TS-CCS-004)
- Specification 5: Hot (Nuclear) CCS integrated functional testing (WEC-TS-CCS-005)

B2.2.1 CCS Test Specification #3: Cold CCS integrated functional Test (WEC-TS-CCS-003)

B2.2.1.1 Objectives

The objectives of the test include verification of the following at unheated conditions:

a) Integrated CCS functionality while operating in unheated air/nitrogen
b) CCS process flow
c) CCS pressure boundary integrity
d) Verification of a), b) and c) for helium as working fluid

B2.2.1.2 Test Conditions

CCS functional testing will be conducted at pressures up to 6MPag and ambient temperature. When confidence has been built that the CCS is fully functional in air/nitrogen, the same tests may be repeated with helium as a working fluid.

Test Configuration/Set-up

The CCS will be fully integrated into the DPP, including all C&I as specified for the DPP.

Test Duration

The test duration is expected to be one year.

Proposed Test Location

The test will be performed at the PBMR DPP power plant at Koeberg, Cape Town.

B2.2.1.3 Measured Parameters

All parameters for CCS performance as specified in the CCS specification and requirements applicable to ambient performance

The measured parameters should at least include the following parameters over the pressure and temperature ranges tested:

a) CCS gas and cooling water flow rate, leakage rate, pressure losses
b) CCS transient and transition times

c) Power consumption
d) Noise and vibration spectra
e) Availability and downtime
f) Failure modes identified, if any

B2.2.1.4 Data Requirements

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

B2.2.1.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower and valve specifications and requirements.

The measured integrated system parameters must also conform to the requirements of the specified standards for the NGNP plant, including, but not limited to, the following standards:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

B2.2.1.6 Test Deliverables

A test report will be compiled after the tests containing the following:

- Description of test equipment and calibration status
- Definition of test software used
- Data recorded
- Description of type of observations
- Interpreted results and conclusions
- Recommendations with respect to any deviations noted
- Unresolved anomalies
- Inputs to the qualification of the CCS system .

B2.2.1.7 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.

B2.2.2CCS Test Specification #4: CCS Blower Test at Operational Temperatures (WEC-TS-CCS-004)

B2.2.2.1 Objectives

The objectives of the test include:

a) Confirmation of the blower maps at various temperatures and pressures.
b) Logging additional operating time on all CCS subsystems with the objective of additional verification of reliability and availability data

It must be noted that there is a DPP requirement to perform verification of the CCS blower maps at the blower supplier facility by means of a factory acceptance test (FAT). For that reason this test will only serve as final confirmation of the blower maps.

In addition it must be noted that the PLICS operation is only performed with nitrogen as working fluid, therefore the additional confirmation is only applicable to the nitrogen blower map. It is reasonable to assume that the helium map will conform to requirements if it is confirmed that the nitrogen map conforms to requirements.

B2.2.2.2 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 300°C using the primary loop initial clean-up system heaters with nitrogen 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 300kPa. The CCS heat exchanger is emptied of water 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 commissioning and qualification at elevated temperatures.

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.

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)

Proposed Test Location

The PBMR DPP at Koeberg, Cape Town.

B2.2.2.3 Measured Parameters

In order to confirm the blower map the following blower thermodynamic parameters will be recorded:

a) Blower speed
b) Blower mass flow rate
c) Blower inlet and outlet temperature
d) Blower inlet pressure and pressure rise
e) Blower power consumption

In addition CCS and CCS subsystems operating time and downtime will be logged.

B2.2.2.4 Data Requirements

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

B2.2.2.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower specification and requirements.

The measured integrated system parameters must also conform to the requirements of the specified standards for the NGNP plant, including, but not limited to, the following standards:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

B2.2.2.6 Test Deliverables

A test report shall be compiled after the test containing the following:

- Description of test equipment and calibration status
- Definition of test software used
- Data recorded
- Blower maps for nitrogen operation over the selected test conditions
- Interpreted results and conclusions
- Recommendations with respect to any deviations noted
- Unresolved anomalies
- Inputs to the qualification of the CCS system

B2.2.2.7 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.

B2.2.3 CCS Test Specification #3: Hot (Nuclear) CCS Integrated Test (WEC-TS-CCS-005)

B2.2.3.1 Objectives

The objectives of the test include verification of the following up to design conditions:

a) Integrated CCS functional performance in Helium
b) Initial integrated CCS first nuclear test performance
c) Integrated CCS full capability performance
d) Initial operational monitoring of the CCS with the objective of additional verification of reliability and availability data

B2.2.3.2 Test Conditions

CCS functional testing will proceed with helium in the pressure ranges 100kPag-6 MPag and elevated CCS inlet temperatures up to 500°C.

CCS full capacity testing shall be conducted with the CCS connected to the PBMR DPP reactor operating at temperatures of 900 °C and 9MPag pressure.

Test Configuration/Set-up

The CCS shall be fully integrated into the DPP, including all C&I as specified for the DPP.

Test Duration

The test duration is expected to be at least one year

Proposed Test Location

The test will be performed at the PBMR DPP power plant at Koeberg, Cape Town.

B2.2.3.3 Measured Parameters

All parameters for CCS performance as specified in the CCS specification and requirements applicable to ambient performance

The measured parameters should at least include the following parameters over the pressure and temperature ranges tested:

a) CCS gas and cooling water flow rate, leakage rate, pressure losses
b) CCS transient and transition times
c) Power consumption
d) Noise and vibration spectra
e) Availability and downtime
f) Failure modes identified, if any

B2.2.3.4 Data Requirements

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

B2.2.3.5 Test Evaluation Criteria

All measured parameters shall meet the design requirements as listed in the blower specification and requirements.

The measured integrated system parameters must also conform to the requirements of the specified standards for the NGNP plant, including, but not limited to, the following standards:

- ASME III, Div 1, NB
- ASME B16.34
- MSS-SP-61
- API standard 598

B2.2.3.6 Test Deliverables

A test report will be compiled after the tests containing the following:

- Description of test equipment and calibration status
- Definition of test software used
- Data recorded
- Description of type of observations
- Interpreted results and conclusions
- Recommendations with respect to any deviations noted
- Unresolved anomalies
- Inputs to the qualification of the CCS system

B2.2.3.7 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.

NGNP-TDI-TDR-RPT-G-00017 **September 2009**
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 10: Reactor Cavity Cooling System

APPROVALS

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A	Tertius Baard	First draft of 750°C-800°C TDRM for review	July 13, 2009
0	Tertius Baard	Approved Document	July 30, 2009
0A	Werner Koekemoer	Editorial changes	August 31, 2009
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10 REACTOR CAVITY COOLING SYSTEM

10.1 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 10-1 and Figure 10-2 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).

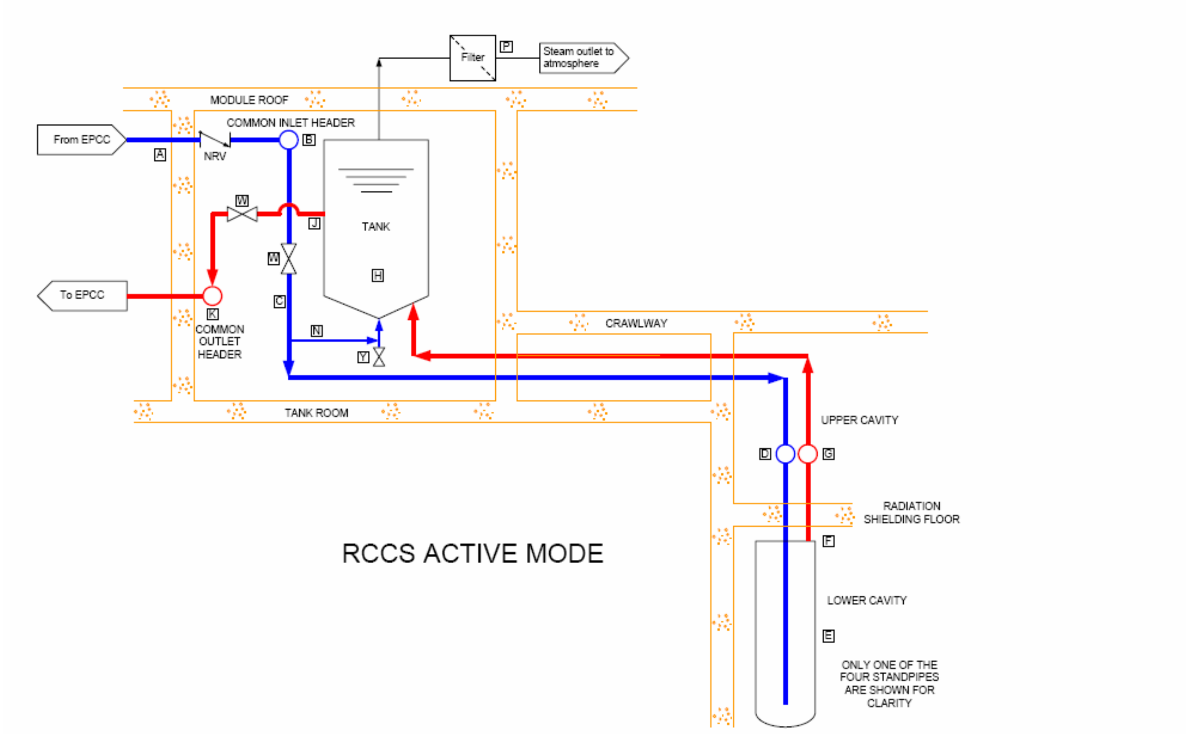


Figure 10-1: Flow direction of the water in the RCCS during active operation

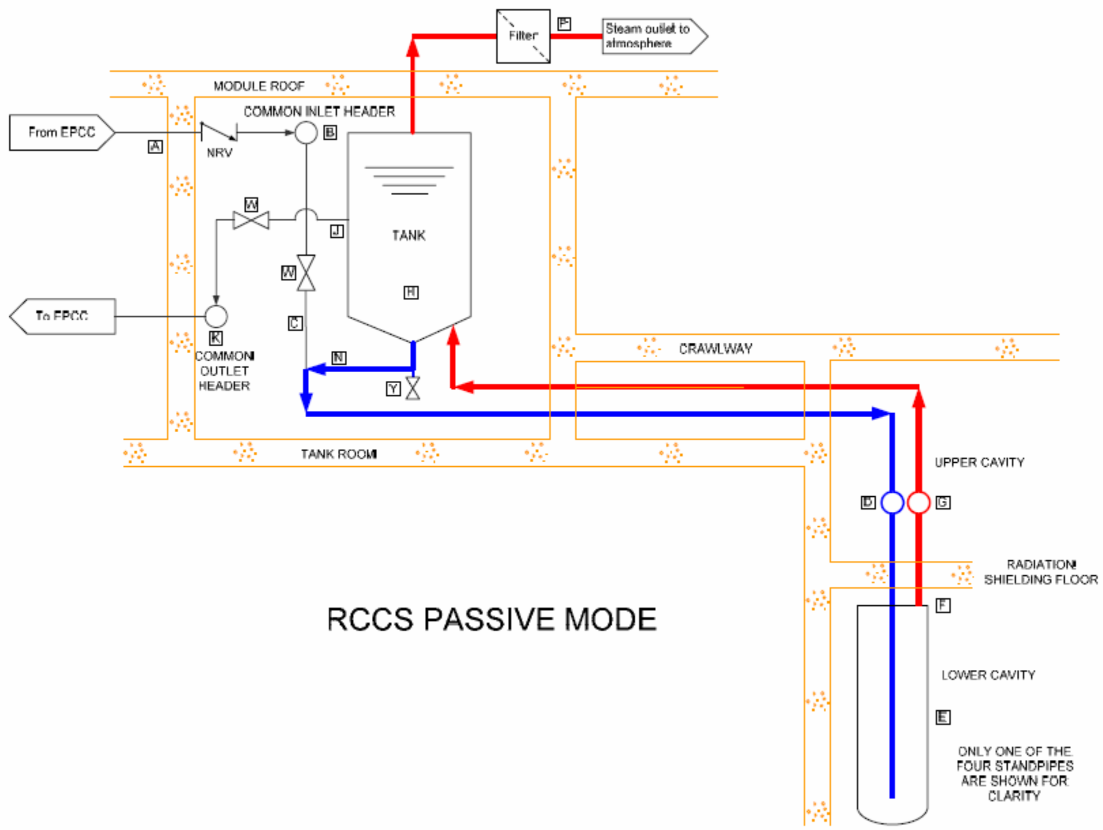


Figure 10-2: Flow directions of the water in the RCCS during passive operation

Figure 10-3 shows the general layout of the RCCS, while Figure 10-4 and Figure 10-5 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.

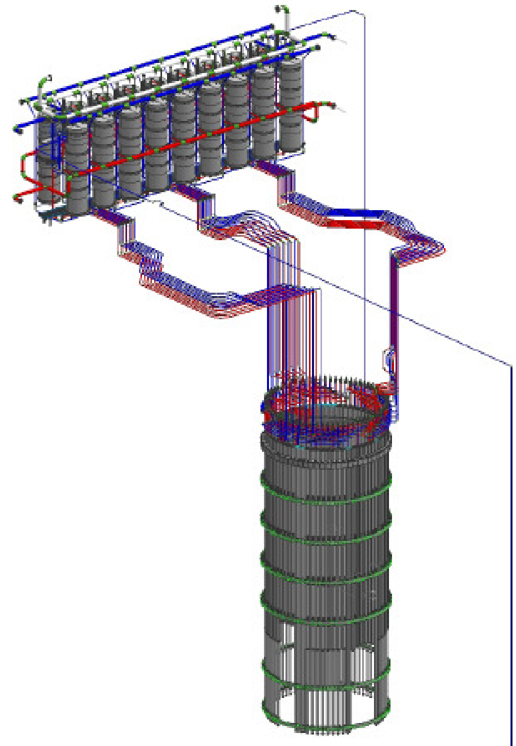


Figure 10-3: General arrangement of RCCS components

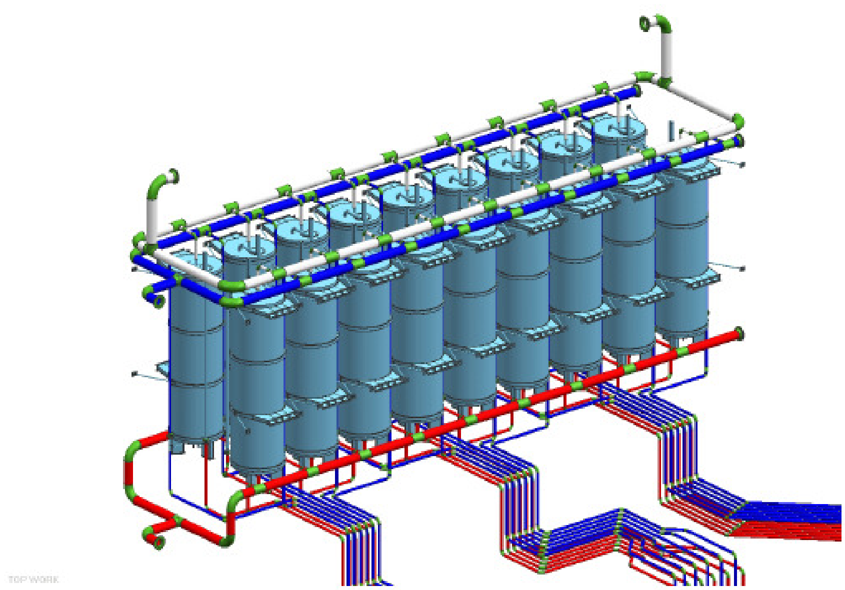
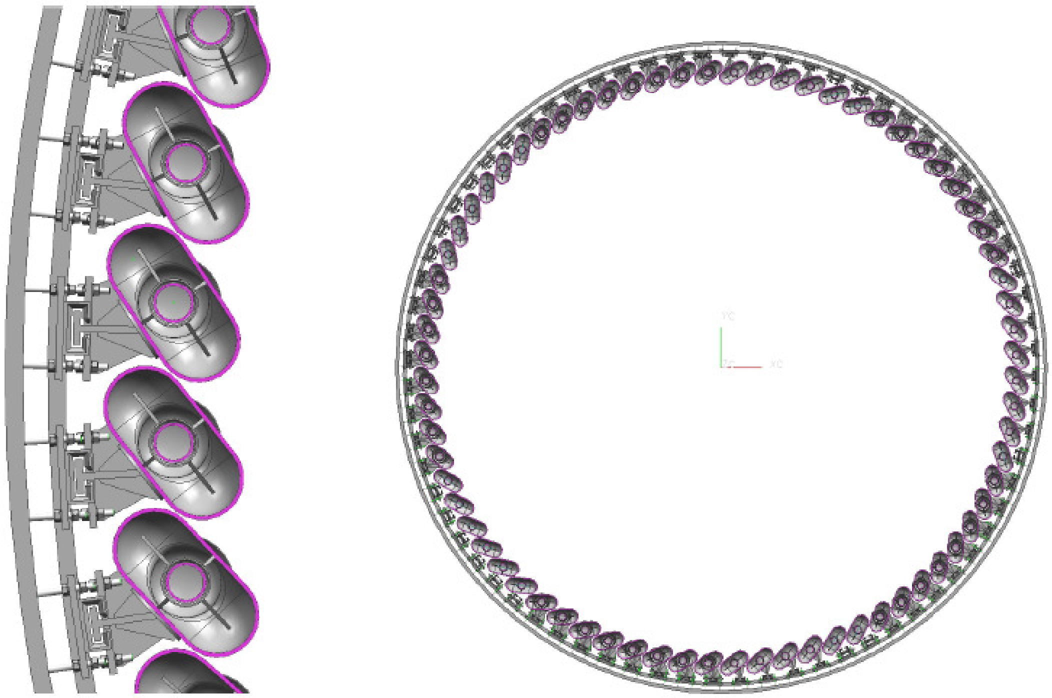


Figure 10-4: Arrangement of water storage tanks.

Top header is for steam release; second from top is the water inlet header. Bottom header returns water to the EPCC



(a) **(b)**

Figure 10-5: 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°C. 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°C and an outlet temperature of approximately 22°C.

10.2 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 (apart from interrogating existing V&V of the software codes). An alternative design utilizing heat pipes is being evaluated for future plants, though the DPP design remains the basis for the PBMR NGNP.

10.2.1 Candidate Technologies – RCCS

N/A

10.2.2 Decision Discriminators

N/A

10.2.3 Reference Design

N/A

10.2.4 Alternatives for Further Evaluation

N/A

10.2.5 Down Select Task

N/A

10.3 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 latest revision of the NGNP-DRL &TRL Report. [1]

10.4 Technology Development Road Map Summary

10.4.1 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.

The technology development road map is shown in Appendix A.

10.5 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.

The following section will show the Technology Maturation Plan required to progress this technology from a TRL 6 to a TRL 8.

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 analysis input, modeling methodology, boundary conditions and empirical correlations 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.

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

Maturation Tasks from TRL 7 to TRL 8

To move from a TRL 7 to a TRL 8, the TRL definition requires:

- 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.

The RCCS will be TRL 8 when tested on the DPP.

[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 ensures that the model of the RCCS used in the code is valid.

10.6 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750°C-800°C

TECHNOLOGY DEVELOPMENT ROADMAP – REACTOR CAVITY COOLING SYSTEM

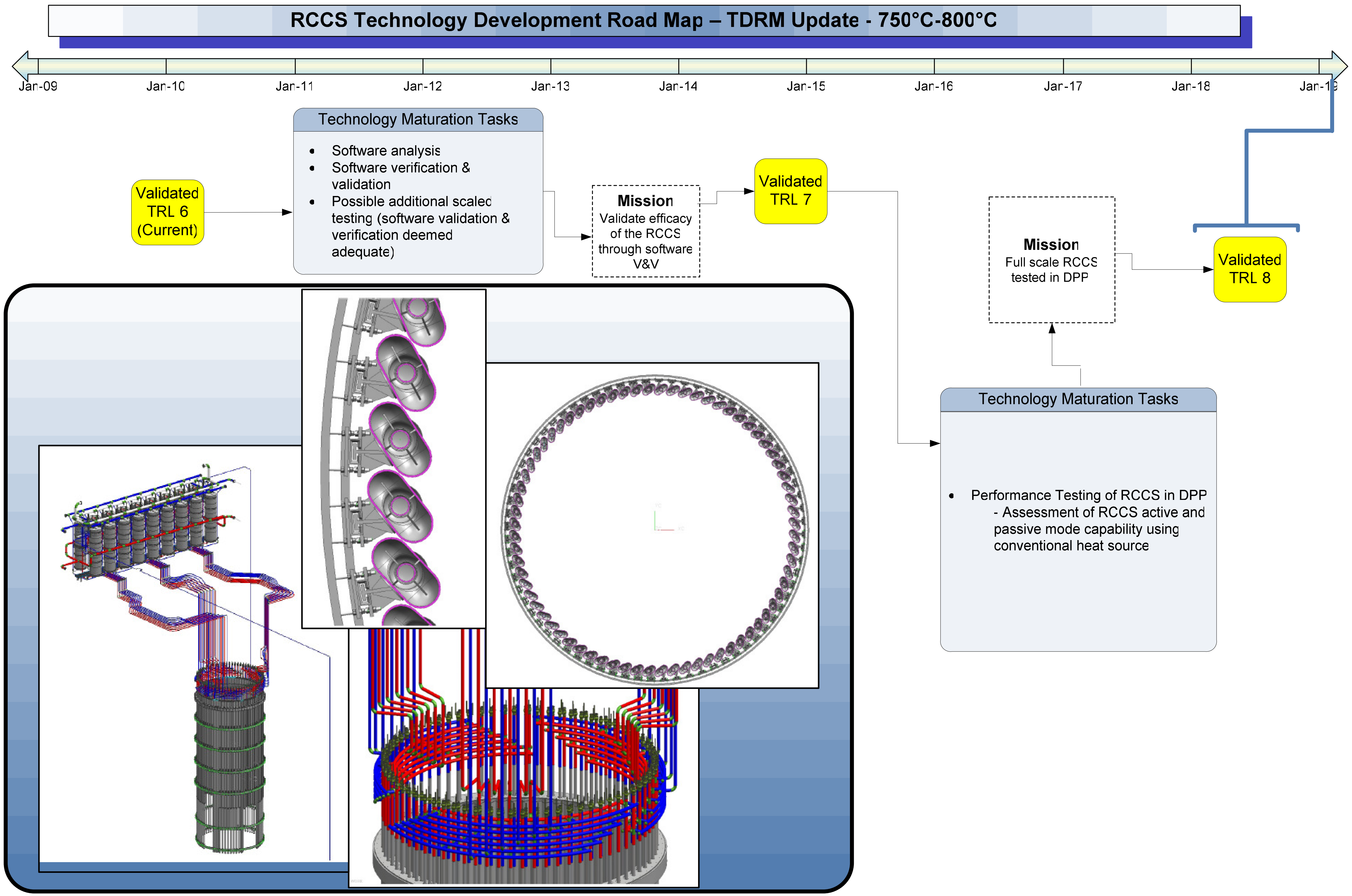


Figure A-1: TDRM for RCCS

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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REQUIRED SPECIFICATIONS/TESTS 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:

- Active and passive mode tests, using a conventional heat source.

B1 RCCS TECHNOLOGY MATURATION PLAN (TRL 6 TO TRL 7)

B1.1 Technology Maturation Plan Summary

B1.1.1 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.

B1.1.2 Scope

Only if it is decided to perform physical tests, the scope of the tests will be defined.

B1.1.3 Anticipated Schedule

The analysis of the RCCS could be accomplished during the period FY2010 through FY2012.

B1.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

B1.2 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.

B2 RCCS TECHNOLOGY MATURATION PLAN (TRL 7 TO TRL 8)

B2.1 Technology Maturation Plan Summary

B2.1.1 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. Note that the qualification strategy for the RCCS is currently under development. Therefore the tests identified below are preliminary only. As the design matures, more details will become available.

B2.1.2 Scope

The testing deemed necessary for technology maturation to TRL 8 are listed in Table B 1.

Table B 1: Compliance tests (summary)

Description	Test Compliance
Assess the active functioning of the RCCS (WEC-TS-RCCS-001)	Heat flux absorbed during active operation.
Assess the passive functioning of the RCCS (WEC-TS-RCCS-002).	Heat flux absorbed during passive operation.

B2.1.3 Anticipated Schedule

The work described by the Test Specifications in this Technology Maturation Plan could be accomplished during the period FY2016 through FY2019.

B2.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

B2.2 Test Specifications

B2.2.1 RCCS Test Specification #1 (WEC-TS-RCCS-001)

B2.2.1.1 Objectives

Assess the active functioning of the RCCS.

B2.2.1.2 Test Conditions

The test will be performed by introducing a conventional heat source to the system, prior to nuclear fuel load. The RCCS will be operated in active mode.

Test Configuration/Set-up

RCCS fully installed in the DPP. The system will be instrumented to suit the test.

Test Duration

Between FY2016 through FY2019.

Proposed Test Location

PBMR DPP.

B2.2.1.3 Measured Parameters

A preliminary list of variables to be measured:

- Heat source thermal power
- RCCS stand pipe water temperature (in/out)
- RCCS stand pipe water flow rate
- Cavity concrete temperature

B2.2.1.4 Data Requirements

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

B2.2.1.5 Test Evaluation Criteria

The heat flux absorbed by the system for the imposed temperature, pressure and flow conditions.

B2.2.1.6 Test Deliverables

Time based plots for all parameters

B2.2.1.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality.

B2.2.2 RCCS Test Specification #2 (WEC-TS-RCCS-002)

B2.2.2.1 Objectives

Assess the passive functioning of the RCCS.

B2.2.2.2 Test Conditions

The test will be performed by introducing a conventional heat source to the system, prior to nuclear fuel load. The RCCS will be operated in passive mode.

Test Configuration/Set-up

RCCS fully installed in the DPP. The system will be instrumented to suit the test, including thermocouples in the concrete behind the standpipes.

Test Duration

Between FY2016 through FY2019.

Proposed Test Location

PBMR DPP.

B2.2.2.3 Measured Parameters

A preliminary list of variables to be measured:

- Heat source thermal power
- RCCS stand pipe water temperature (in/out)
- RCCS stand pipe water flow rate
- Water level in tanks
- Cavity concrete temperature

B2.2.2.4 Data Requirements

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

B2.2.2.5 Test Evaluation Criteria

The heat flux absorbed by the system for the imposed temperature, pressure and flow conditions.

B2.2.2.6 Test Deliverables

Time based plots for all parameters

B2.2.2.7 Cost, Schedule, and Risk

The PBMR related cost is omitted due to business confidentiality.

NGNP-TDI-TDR-RPT-G-00018 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C

Section 11: Fuel Handling and Storage System

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11 FUEL HANDLING AND STORAGE SYSTEM

11.1 Functions and Operating Requirements

11.1.1 Description

The Fuel Handling and Storage System (FHSS) is a support system to the Main Power System (MPS) of the PBMR DPP. The primary purpose of the FHSS is to circulate the spherical fuel elements through the reactor core while the reactor is operating at power. When the selected burn-up is reached, spent fuel is removed from the circulation loop and stored in intermediate storage tanks. The spent fuel is then replaced by fresh fuel, which is introduced into the circulation loop.

The FHSS transports, handles and stores various types of fuel, damaged fuel and contaminated graphite dust. It is therefore subject to the Fundamental Safety Functions (FSFs) of the PBMR.

The FHSS is designed as a multi-function system with a number of its own support systems, and controlled by the FHSS Control System, which selects the appropriate subsystems to carry out the required functions. The main FHSS subsystems follow:

- Sphere Conveying Subsystem (FSCS)
- Gas Conveying Subsystem (FGCS)
- Sphere Replenishment Subsystem (FSRS)
- Auxiliary Gas Subsystem (FAGS)
- Sphere Storage Subsystem (FSSS)

The burn-up of the fuel spheres are measured by the Burn-up Measurement System (BUMS) which is part of the FSCS. This is an on-line fuel measurement instrument intended to enable the FHSS to discriminate between the different types and states of irradiated fuel and graphite spheres. There are three BUMS units in the DPP, one for each measurement block. Each BUMS measurement unit operates as a gamma spectrometer, incorporating a high-resolution Hyper-pure Germanium (HpGe) gamma detector and uses automated, computer processing of the measured gamma spectra to perform its functions. A BUMS calibration source is installed which can be moved to the measurement position when required to calibrate the BUMS measurement unit.

The physical layout of the FHSS occupies the following building spaces:

- A space below the Reactor Pressure Vessel (RPV) where the three Core Unloading Devices (CUDs) are situated.
- A vertical shaft along which the pneumatic sphere lifting lines run.
- A sloping floor above the RPV, known as the helix-floor, where sphere management stations and burn-up measurement stations are situated.

- A space divided onto cells, on the side of the building, where the Spent Fuel, Used Fuel and Graphite vessels are situated.
- A space above the helix-floor, where the fresh fuel and graphite replenishment equipment, as well as the BUMS/Activity Measurement System (AMS) support equipment is situated.

The FHSS layout configuration is shown in Figure 11-1.

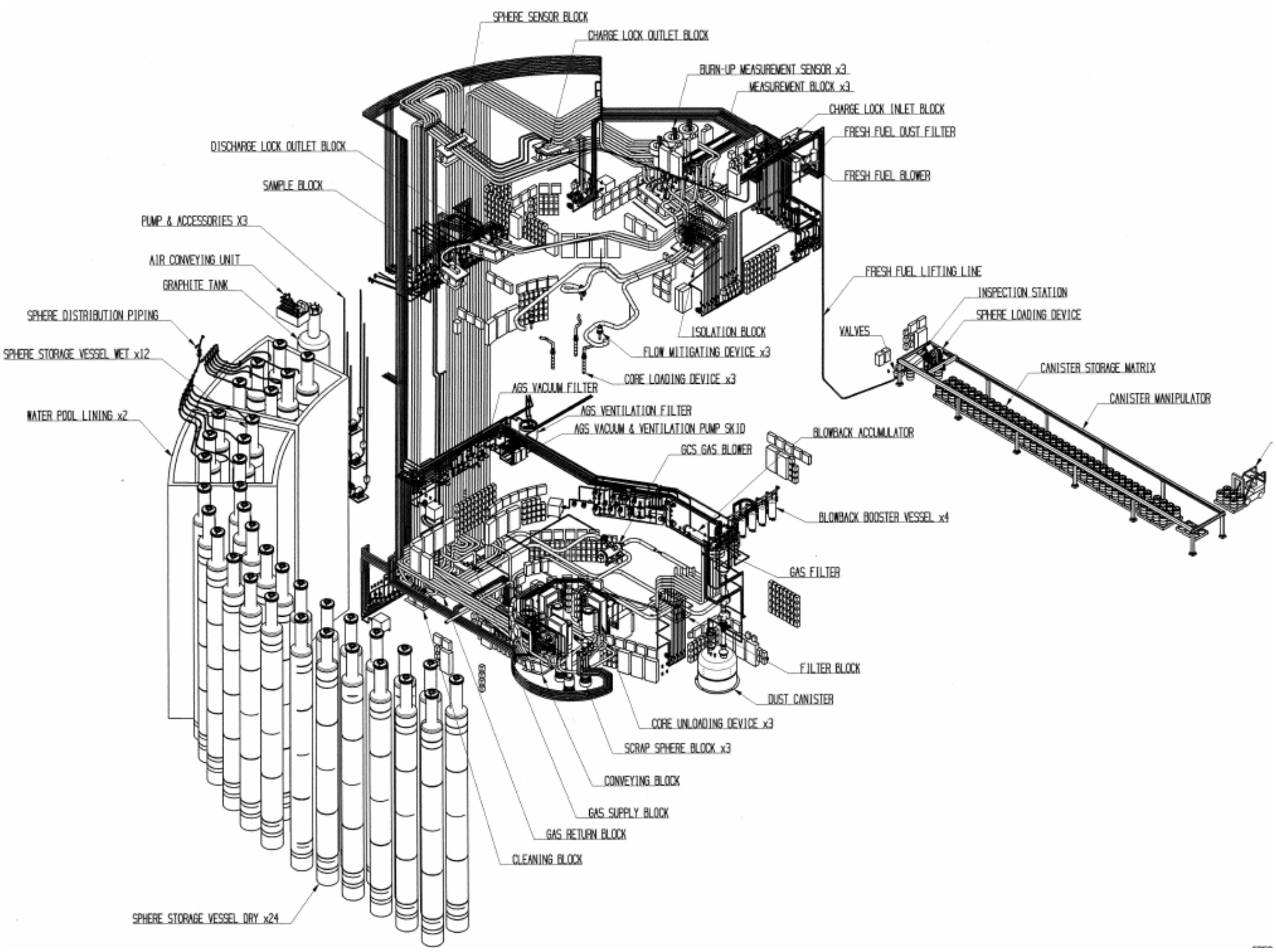

Figure 11-1: Layout of the Fuel Handling and Storage System.

11.1.2 FHSS in the Helium Test Facility (HTF)

All major components of the FHSS (except the sub-systems FSSS, FSRS and the BUMS) will be accommodated in the HTF in the form of the Fuel Handling System(FHS) test set-up – see Figure 11-2. The test set-up will simulate the steady state environment of the FHSS during normal conditions.

FHSS tests are executed at different facilities of the HTF, listed below:

- Tower (FHS test loop) - Temperatures, pressure and flow rates are adjustable channels to create representative environments.
- DTL (Dust Test Loop; planned facility)
- ATL (Air Test Loop)
- HTF –Laboratory (Planned test facility)
- Blow down Facility(Planned test facility)
- SPU (Shaft Penetration Unit)

Important tests to support the FHSS development are highlighted below:

Tower

The FHS Loop at the HTF was designed with similarity with the FHSS at the DPP in mind. It has been developed with the following test purposes in mind:

1. Sphere movement studies
2. Process simulations (similarity)
3. Pressure & Temperature tests
4. Reliability studies
5. CUD & insert functionalities
6. Gas flow tests

HTF - Laboratory

Characterization of valve inserts. The laboratory enables pressure, temperature & gas flow tests to be carried out on all inserts including pressure differential studies on sphere handling inserts. This facility is aimed at tests that require high pressures as well as temperature. It is a general-purpose test section to evaluate and test control valves and other diverse components. helium gas is supplied to emulate the component conditions.

DTL

The purpose of proposed tests is to characterize dust with regard to filtering, transport and component susceptibility to it. These tests are required to verify the assumption that pulsejet cleaning will be an efficient method for regeneration of filters; to determine the gas velocities required for blowing pipes clean; and to establish the manner in which valve block inserts are susceptible to dust. During these tests other information will also be gathered to assist with design of the FHSS filter. The scope of the tests will at present be limited to providing preliminary design information, as the experiments are conducted in air & nitrogen. Testing in helium will be undertaken in the HTF.

ATL

The ATL is a test facility to pneumatically convey spheres using air. With the new modification, a number of spheres can be inserted and left to be circulated as many times as is deemed necessary for a specific test.

The main focus of the ATL will be to characterize the pneumatic gas brake concept, sphere conveying, which will include hover tests whereby drag coefficients can be determined, and the interaction between the spheres and the pipes, which includes sphere wear studies. Additionally, the Sphere Counter will be characterized and tested in the ATL for basic operation, repeatability and secondary recognition.

Blow down Facility

This test section will be used to test the Double Seat Isolation valve (DSI) and Flow Restricting Indexer (FRI) for operational abilities during blow down. The DSI's ability to close and seal in the case of a pipe burst is to be demonstrated at various pressure differential settings, at this facility. The ability to open the DSI with maximum pressure difference across the valve will also be demonstrated.

The pressure difference over time measurement in helium across the FRI is also to be quantified for a pipe burst simulation.

Figure 11-2: Photo of the HTF tower where the FHSS test setup is located.

11.1.3 Functions

The main functions of the FHSS are to perform the following:

- Replacing the graphite spheres with fresh fuel spheres intermixed with graphite spheres during initial start-up.
- Gradually changing the start-up core composition of graphite and fuel to a fuel only composition, and then to a core consisting of fuel to be used in the equilibrium state.
- Loading and unloading the fuel into and from the reactor core while the reactor is operating at power.
- Loading of the core of the reactor with graphite spheres after a complete unload.
- Discharging spent fuel to spent fuel vessels.
- Loading of fresh fuel to compensate for spent fuel discharges.
- Removing broken or damaged spheres, or spheres worn down to minimum diameter.

The simplified process flow diagram of the FHSS is shown in Figure 11-3.

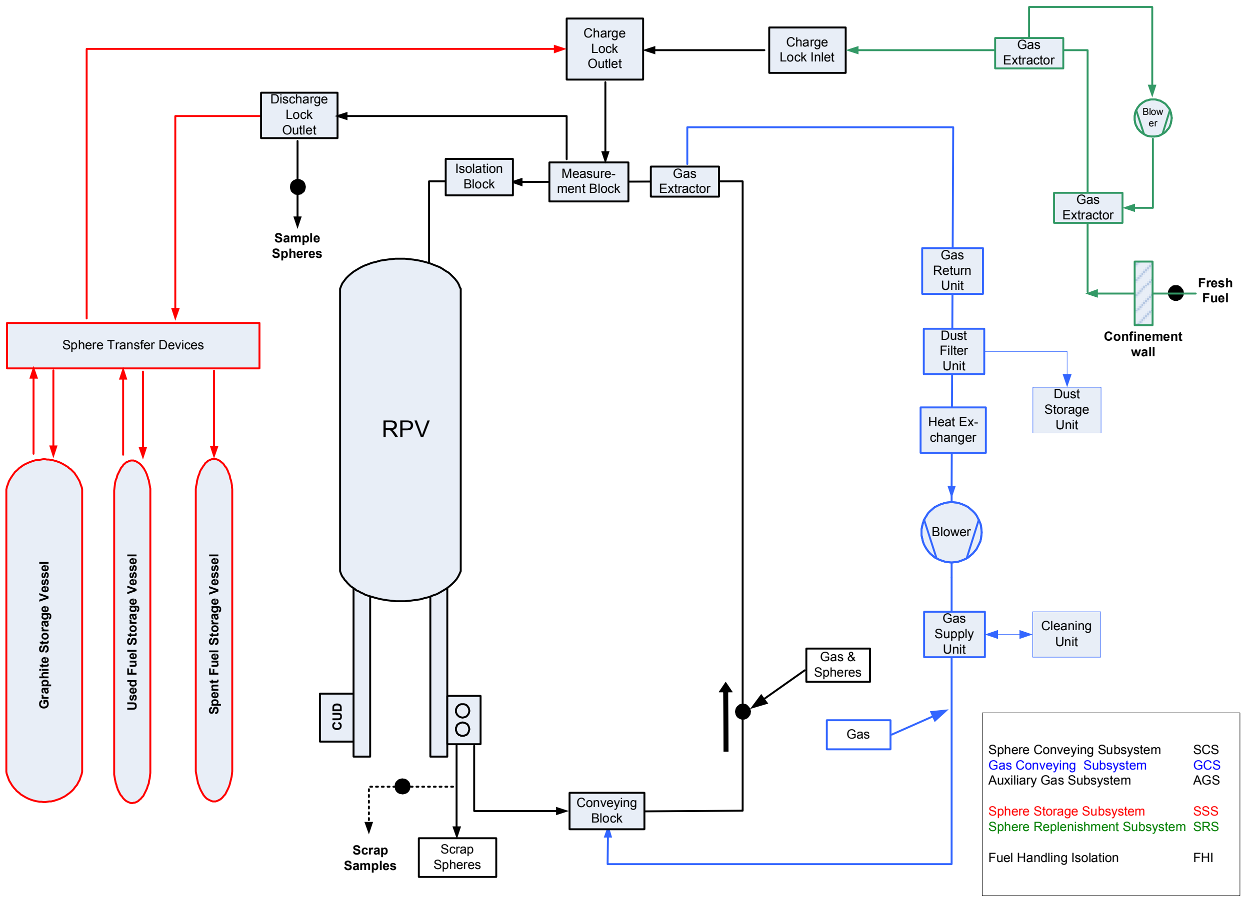

Figure 11-3: The simplified process flow diagram of the FHSS.

11.1.4 Interfaces

The FHSS interfaces with the following high level systems:

- Security System
- Infrastructure System
- Helium Services System
- Helium Leak Detect & Monitoring System
- Fuel System
- Primary Loop Initial Clean-up System (PLICS) Vacuum System
- Maintenance & Logistic System
- Plant Operating System
- Cooling System
- Reactor Unit
- Business Management System

11.1.5 Operating Conditions

The FHSS will be isolated from the reactor during normal operation. The nominal operating conditions are:

Table 11-1: Nominal Operating Conditions for the FHSS

Parameter	Design Value	Operating Value
FSCS Pressure	9,7 MPa	1 to 9 MPa
FSSS Pressure	1,2 MPa	0,1 to 1 Mpa
FSCS Temperature	300 ˚C	250 ˚C
FSSS Temperature	450 ˚C	150 to 300˚C
Sphere flowrate	5000/FPD	2900/FPD
Spent Fuel flowrate	810 SF/FPD	484 SF/FPD
Fresh Fuel flowrate	4000/day	484 FF/FPD
Used Fuel flowrate	1000/hr	1000/hr

11.2 Design/Technology Selection Status

The PBMR DPP FHSS technology will be used in the NGNP. The PBMR DPP FHSS is nearing the completion of its basic design phase while development tests are also being performed. Most of the component tests are executed at the HTF, but have not been completed. Components of the BUMS have been demonstrated as a Proof of Concept followed by demonstration test and although a radioactive source was used, the exact environment as it will be utilized in the plant has not been tested.

The THTR (Thorium High-Temperature Reactor in Germany) design was used as the technology basis to develop the FHSS components as far as possible, however the THTR operated at a lower pressure, hence design modifications had to be implemented on certain components. Important components were identified and will be tested at the different HTF facilities. No radioactive materials are tested at the HTF facility and therefore the integrated FHSS will only be tested in the DPP plant.

11.2.1 Candidate Technologies

- N/A

11.2.2 Decision Discriminators

Design / Technology development

Not all components designed for the DPP had been used in the THTR and the technology or application thereof must still be proven.

The performance of the BUMS to discriminate between different fuel burn-up levels, is based on the existing technology as demonstrated at experimental scale. This performance determines the maximum circulation rate of the FHSS.

The reliability of the sphere counter is important for the control of the system and the monitoring of fuel movement throughout the life cycle of the plant. Digital processing is used and the functioning to reliably count and measure the velocity of normal and damaged spheres must still be tested.

The application of ceramic bearings in the helium environment must still be tested for reliability.

Long term behaviour of the valve stem penetration seals have to be proved at the higher DPP pressures.

11.2.3 Reference Design

The PBMR DPP FHSS will serve as the reference design for the NGNP. The system design is dependent on the performance requirements, which at this stage is assumed not to change.

11.2.4 Alternatives for further evaluation

- N/A

11.2.5 Down Selection Task

- N/A

11.3 TRL Status

The NGNP FHSS is currently rated at a Technology Readiness Level (TRL) of 5, mainly due to the BUMS being assessed at a TRL of 5 [1]. The rest of the FHSS TRL will be 6, based on the fact that operating experience exists for fuel handling and storage systems in other gas-cooled, graphite moderated reactor applications and certain component tests will be completed at the HTF. (The FSSS design is a new design, but does not pose a technology risk). The applicable TRL sheets are attached in the newest revision of the TRL/DRL Report.

Since the NGNP will operate at 500MWt, instead of 400MWt as in the case of the PBMR DPP, it is currently anticipated that the FHSS will be required to circulate 25 percent more spheres/FPD. Preconceptual comparative assessments show that this is within the current DPP performance requirements; however the complete implications of the adjusted operating points will only be determined during NGNP conceptual design. This may have design implications, but no technology maturity implication is expected.

11.4 Technology Development Road Map Summary

The FHSS that is being developed for the PBMR DPP will be used in the NGNP. The FHSS for the PBMR DPP is at a TRL rating of 5 due to specific component tests not being completed or being tested in an integrated system.

Component tests will be completed at the HTF simulating the relevant pressure and temperature. Integrated system tests will only be completed at the DPP after fuel load.

11.5 Technology Maturation Plan Summary (Current TRL 5 to TRL 8)

The PBMR DPP FHSS is currently at a TRL rating of 5 due to the TRL rating of BUMS and specific component tests not being completed or being tested in an integrated system. The rest of the FHSS will reach a TRL rating of 6 after development and qualification tests have been completed at the HTF. No integrated system tests will be conducted prior to tests at the DPP. After completion of commissioning tests at the DPP the FHSS will reach a TRL rating of 8.

The DPP FHSS technology development roadmap will be sufficient to advance the NGNP FHSS to TRL 8 when it is confirmed that the NGNP requirements for FHSS corresponds with that of DPP. However, this can only be done once more analyses have been performed to determine the NGNP requirements implication for the FHSS.

11.5.1 Maturation plan summary for the PBMR DPP FHSS

The maturation plan of the FHSS for the PBMR DPP consists of a number of qualification actions that are aimed at validating certain functions of the FHSS. The qualification activities can be classified as one of the following, depending on the requirements of the specific function:

- Functional Assessment (tests or analysis)
- Environmental Assessment or
- Seismic Assessment
- Manufacturing & Inspection

Each of the functions can be verified by means of design, analysis, testing, inspection or a combination hereof. The high level functions and requirements of the FHSS can only be verified when the system is integrated with the rest of the plant. These requirements are further decomposed to the lower levels systems and/or components. The test facilities at the HTF are used to test components and to prove that their requirements can be met.

The FHS test loop has been designed to simulate the FHSS environment in order to test major components in a representative subsystem. The HTF environment simulates pressure and temperature, but not radiation. After completion of these tests at the HTF, the TRL of 6 will be attained for the specific components. Seismic influence on components will be analyzed and only tested at approved facilities by exception.

All components and subsystems of the FHSS will be integrated at the DPP for the first time. The commissioning tests will be executed, first at operating temperature and pressure, but without fuel. After completion of these commissioning tests at the DPP, the TRL of 7 will be attained for the system, although no irradiated fuel will be handled.

The FHSS integrated system will be tested in its operational environment during commissioning of the DPP after fuel has been loaded into the reactor and the DPP has reached operational temperature and pressure. After completion of these commissioning tests at the DPP, the TRL of 8 will be attained for the system.

The DPP FHSS technology development roadmap will be sufficient to advance the NGNP FHSS to TRL 8 when it is confirmed that the NGNP requirements for FHSS corresponds with that of DPP. However, this can only be done once more analyses have been performed to determine the NGNP requirements implication for the FHSS.

11.5.2 Tasks to be performed to qualify the components

BUMS

The functional components of the BUMS that will be utilized have been tested on a representative radioactive source and processing of the data was successful. The design to integrate the different components and integration of the BUMS with the measurement blocks are outstanding. Testing of the three units of the BUMS, integrated in the FHSS, will only be done when fuel is loaded into the reactor during commissioning.

Sphere Sensor

The basic functioning of the sphere sensor has been proven, to detect a passing sphere and use the signals to determine sphere transportation velocity. Outstanding tests to be completed at the HTF are:

- Functioning with damaged fuel spheres
- Digital signal processing upgrade and testing
- Functioning at elevated temperatures
- Resolution capability for a train of spheres

Ceramic Bearings

THTR used conventional bearings whereas DPP will utilize ceramic bearings. All units under test at the HTF will initially use conventional bearings that will be replaced regularly. Final testing of the units under tests at the HTF will be with the specified bearings for DPP in a dust environment.

Dust Filter

This task may be classified as a design activity, therefore not affecting the FHSS TRL rating, since existing technology is used in a unique application.

The application of filter elements to collect graphite dust generated in the FHSS must still be proven. Although the application the filters are well known in industry, the collection of irradiated graphite dust, the use of helium as process gas and the removal of the dust and the filters have not been tested. The following tests are planned.

- Pulse-jet cleaning of filter elements (HTF DTL)
- Fluidization of dust (HTF DTL)
- Operation of solenoid valve in helium and dust environment (HTF DTL)
- Integrated system tests (DPP)

11.6 References

[1] NGNP-TRL & DRL REPORT, Rev 2, April 2009 - Next Generation Nuclear Plant – Report on Technology Readiness Levels and Design Readiness Levels

APPENDIX A: TECHNOLOGY DEVELOPMENT ROADMAP – 750℃-800℃

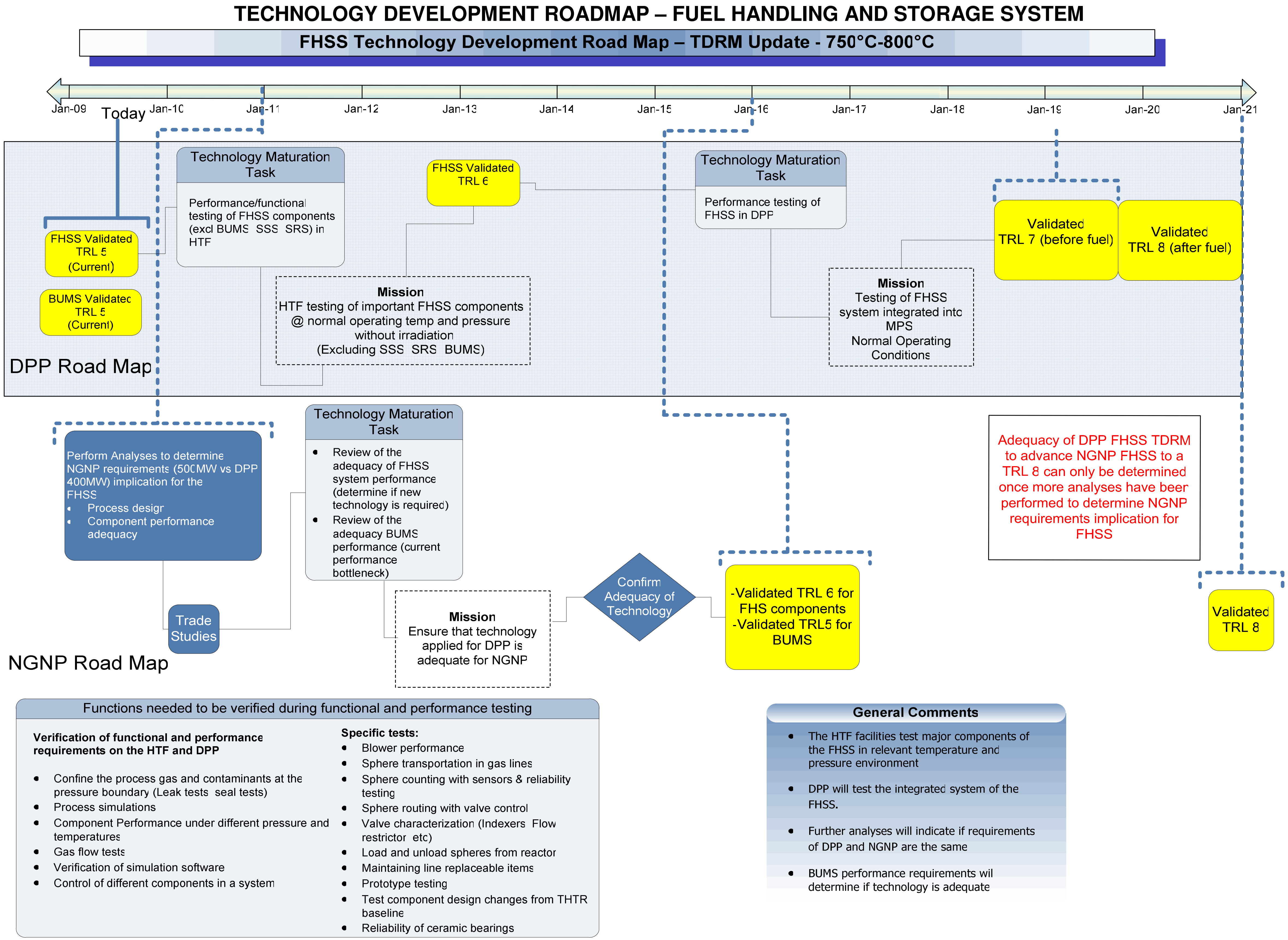

Figure A-1: TDRM for FHSS

APPENDIX B: TECHNOLOGY MATURATION PLAN - 750°C-800°C

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B1 TECHNOLOGY MATURATION PLAN FOR PBMR DPP FHSS (TRL 5 TO TRL 8)

B1.1 Technology Maturation Plan Summary (TRL 5 to TRL 8)

B1.1.1 Objectives

The objective of the maturation plan is to advance the FHSS from a TRL rating of 5 to a TRL rating of 8. The plan proposes a number of tests aimed at verifying certain critical functions of the FHSS prior to it being operated with fuel in the PBMR DPP.

B1.1.2 Scope

The high level qualification process for the FHSS consist of assessments carried out over three stages; off-site, site-based (during installation, integration and plant commissioning) and operational. For the FHSS, installation & commissioning assessments will take place during the site-based stage of the DPP.

The qualification of the FHSS will focus on hardware/components and processes performance. System processes can only be executed when the complete system is integrated at the DPP. With reference to the TDRM, the different TRL levels will be reached as follows:

- TRL 6 – testing of major components in HTF facilities (normal temperature and pressure)
- TRL 7 – testing of integrated system and process parameters in DPP before fuel load
- TRL 8 – testing of integrated system and process parameters in DPP after fuel load (normal temperature and pressure and radiation environment)

The FHSS components are grouped in the following categories to execute qualification.

- Valve blocks and piping – Off-site qualification; design analysis and standard design codes.
- Active Valves and standard equipment – Off-site qualification, standard design codes.
- First Of A Kind Equipment (FOAKE) – Testing, Analysis, off-site qualification except where facilities do not exist or radiation environment is required. The BUMS will only be tested when integrated in the rest of the FHSS at the DPP.

The tests that have been defined in support of the verification of the functions that needs to be performed for the FHSS are listed in Table B 1 and Table B 2. These are not individual tests (or test specifications), but rather a general outline of the tests.

Table B 1: Activities that need to be performed to verify FHSS component functions Off-site.

Qualification Test	Verification Method	Qualification Activity
HTF process simulations		
Load Fuel	Test	Functional assessment
Unload Fuel	Test	Functional assessment
Fuel Sphere Circulation	Analysis	Functional assessment
Gas flow thermo hydraulic simulation	Analysis	Functional assessment
Gas flow for sphere transportation	Test	Functional assessment
Fuel Sphere routing control	Test	Functional assessment
Remove broken or damaged spheres from core	Test	Functional assessment
Major Component testing at HTF facilities		
Blower performance	Test	Functional assessment
Sphere Counter	Test	Functional assessment
Core Loading Device		
Sphere movement control via valve inserts in Distribution block	Test	Functional assessment
Valve insert functionality • Flow Restricting Indexer • Double Seat Isolation Valve • Indexer • Diverter	Test	Functional assessment
Shaft penetrations leak test (leakage and reliability	Test	Functional assessment
Component characterization under all operating conditions	Test	Functional assessment
Components of Dust Filter system	Test	Functional assessment
Reliability testing of ceramic bearings	Test	Functional Assessment
Simultaneous Control of components to execute continuous processes	Test	Functional Assessment
Maintenance simulations	Test	Functional Assessment
Environmental Assessment		
Accident conditions for active valves	Test	Functional Assessment
FOAKE equipment, pipes and pressure vessels	Analysis	Seismic Assessment (depending on classification)
DPP Component Procurement		
Manufacturing DPP hardware	Inspection	Manufacturing & Inspection
Factory Acceptance Testing of FHSS component assembly for DPP	Test	Manufacturing & Inspection
Hardware in the Loop integration	Inspection & Test	Manufacturing & Inspection

Table B 2: Summary of activities that need to be performed to verify FHSS functions at the DPP.

Qualification Test	Verification Method	Qualification Activity
DPP Installation		
Hardware installation inspection of the FHSS assemblies for DPP	Inspection	Manufacturing & Inspection
Hardware in the Loop integration	Inspection & Test	Manufacturing & Inspection
BUMS validation with calibration source	Test	Functional Assessment
Process (Main functions)		
Replace graphite with fresh fuel	Test	Functional Assessment
Load and Unload Fuel (circulate fuel)	Test	Functional Assessment
Validate BUMS performance after measurement of sample sphere	Test	Functional Assessment
Discharge spent fuel (includes BUMS)	Test	Functional Assessment
Remove broken /damaged spheres	Test	Functional Assessment
DPP Operation		
In service inspections of components	Inspection	Reliability Assessment
Performance and ageing monitoring during operation	Inspection	Reliability Assessment

B1.1.3 Anticipated Schedule

The off-site testing is expected to last at least three years which will be followed by installation and testing, as well as continuous lifecycle testing (availability, reliability, etc.) at the DPP.

B1.1.4 Overall Cost

The PBMR related cost is omitted due to business confidentiality.

B1.2 Test Specifications

Test requirements for the execution of all qualification activities will be to PMBR Quality Assurance Procedure PRC0023. As part of the execution, a test specification will be required with the following information as a minimum:

- Objectives
- Test Conditions
- Parameters to be measured
- Data requirements
- Test Evaluation Criteria
- Test Deliverables

Table B 3 summarizes the objectives of the activities listed in Table B 4.

Table B 3: Objectives of FHSS Qualification activities.

Qualification Test	**Qualification Activity**
HTF process simulations	
Load Fuel	Loading of spheres with the FHS into a representative reactor core. • Emulate operation of long buffer (large number of spheres) above indexer isolation valve block • Verify control logic • Characterize sphere flow from the FRI to the FHS vessel • Characterize compression brake • Characterize leak flow effects
Unload Fuel	Unloading of spheres with the FHS from representative reactor core. • Emulate various circulation rates with CUD • Vary pneumatic sphere lift velocities to investigate buffer level variation • Verify control logic
Fuel sphere transportation (Circulate fuel)	The performance of the design will be characterised for all expected plant processes that can be emulated on the HTF. The following shall be demonstrated/investigated: • The amount of mechanical damage to spheres during circulation will be investigated. • Brake characterisation & effectivity for various sphere sizes & weights, along with the influences of gas speeds, pressures and temperatures. • Leak rates after extended operation while varying circulation rates, Pressure cycles and Temperatures The control system of the HTF FHS loop will be used to demonstrate the ability to index a sphere into the simulated core for each released from the Distribution block into the large buffer simulating storage. This is, however a limited demonstration as the functionality of the BUMS and the FSSS functionalities are not incorporated on the HTF. .
Gas flow for sphere transportation	Gas flow characteristics of the FHS will be recorded during various functions to verify Thermo Hydraulic simulations

Qualification Test	**Qualification Activity**
Gas flow thermo hydraulic simulation	Analysis of the FHSS temperature and pressure conditions during all modes of operation will be simulated based on results of the HTF FHS simulation
Fuel Sphere routing control	Control of FHS equipment is tested during system test to load fuel, unload fuel and circulate fuel
Remove broken or damaged spheres from core	This function will be tested with CUD functional tests. Damaged spheres will be loaded in the simulated core for removal by the CUD
Dislodge broken or damaged spheres from sphere pipes	Emulate unblocking of spheres in pneumatic conveying lines. The capability of backflow ability for sphere dislodgement shall be demonstrated by introducing partial and severely damaged spheres into the circulation loop during circulation tests at the HTF. 1. Monitor effect on blower 2. Evaluate Gas Block trim valve integrated operation 3. Evaluate 3 Way valve block operation
Major Component testing at HTF facilities	
Blower performance	Blower tests at the HTF shall include the following: • C&I evaluations of blower capacity. • Trip tests and protection simulations. • Temperature measurement of the HTF blower to measure the removal of induced heat. • Continuous monitoring for all FHS Loop operations
Sphere Counter	Functioning and reliability of the sphere sensor will be tested: • Single sphere detection characterization • Multiple sphere (pocket) detection characterization • Multiple sphere (consecutive) detection characterization Instrument loops

Qualification Test	Qualification Activity
Core Loading Device (CLD)	Functional tests of the CLD will include the following: • Sphere damage evaluation • Evaluate CLD thermal behaviour • Integrated functioning with CLD Sphere Counter • Bed formation characteristics are to be studied
Core Unloading Device (CUD)	Tests on the CUD at the HTF will demonstrate the following: • Handling of scrap, extraction & singulisation of spheres. • Durability of the ceramic bearings, singuliser plate, spindle and the pressure boundary from the RPV • Scrap management and performance at various rates. • Cooling gas injection at temperature into scrap as well as abrasion rate of singuliser plate surface. • Demonstration of ability to dislodge spheres. • Ability of the Kartoffel Kiste (Potato Box) to handle abnormal amounts of scrap. • Stationary seal leakage characterization
Sphere movement control via valve inserts in Distribution block	Verify integrated functional operation of the distribution block together with the Auxiliary Gas services - Evaluate extended performance (effect of leak past FRI, effect of continuous dust pocket cleaning, typical transport time of spheres in block)

Qualification Test	Qualification Activity
Valve insert functionality and characterization • Flow Restricting Indexer(FRI) • Double Seat Isolation Valve(DSI) • Indexer • Diverter	• The ability of the DSI to seal in case of a pipe burst is to be demonstrated in this test. • Demonstrate the capability to close the DSI against pipe break flow conditions, for various starting conditions, measure the torque (spring action). Also demonstrate the ability to open DSI with maximum pressure differential across the valve <u>Indexing characteristics of the Indexer and FRI.</u> • Indexer & FRI ability to hold and control buffers as well as the related sphere damage & graphite abrasion rates. • Diverter functionality on simulated command from C&I influenced by an artificial BUMS readout can be demonstrated. • Gas brake performance to be demonstrated as well as conveying gas injection & extraction. • All applicable valves to be tested as part of sphere circulation tests, including cleaning modes. • MUV functionality demonstration. Logistic evaluation for its exchange within 32 hours.
Shaft penetrations leak test (leakage and reliability	Leakage rate will be monitored during a cycling test to test reliability of the sealing mechanism of the shaft penetration during operational conditions
Component characterization under all operating conditions in Helium	Refer components tests
Components of Dust Filter system	The functionality of certain components of the Dust filter system will be tested • Pulse-jet cleaning of filter elements (HTF) • Fluidization of dust (HTF facilities) • Operation of solenoid valve in helium and dust environment (HTF)
Reliability testing of ceramic bearings	Bearing reliability tests in simulated operating conditions
Simultaneous Control of components to execute continuous processes	• Evaluate automation algorithms • Emulate the balancing of the make-up gas flow in the gas supply, leak flow and gas return • Emulate the balancing of the conveying gas in the conveying lines, brake gas supply and gas return
Maintenance simulations	Execution of maintenance tasks identified for tasks requiring special equipment, especially where there is potential radiation risk.

Qualification Test	Qualification Activity
Environmental Assessment	
Accident conditions for active valves	Equipment will be tested under simulated seismic conditions
FOAKE equipment, pipes and pressure vessels	Analysis to simulate seismic conditions
DPP Component Procurement	
Manufacturing DPP hardware	Manufacture and inspection to Quality control plans, requirements based on the component classification
Factory Acceptance Testing of FHSS component assembly for DPP	Acceptance test on components prior to delivery
Hardware in the Loop integration	Components or subsystem hardware and software integration tests. For example: the integration of the BUMS in a subsystem can be tested off-site.

NGNP-TDI-TDR-RPT-G-00019 September 2009
Revision 1

NEXT GENERATION NUCLEAR PLANT

Technology Development Roadmapping Report - Steam Production at 750℃-800℃

Section 12: Integrated Schedule and Cost Estimate

APPROVALS

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SUMMARY AND CONCLUSIONS

This section of the Technology Development Roadmapping (TDRM) report documents the integrated test schedule and cost estimate for the critical SSCs identified in the 750°C - 800°C TDRMs. The technology development included herein supports process steam and/or cogeneration applications with the steam generator located in either the primary or secondary loops. It also supports intermediate temperature direct heat applications, such as reforming and ammonia production that require an Intermediate Heat Exchanger (IHX). It excludes the process coupling heat exchanger for direct heat applications, which will be application specific. The technology development related to hydrogen production still forms part of the overall NGNP objective. However, considering the 750 ° - 800 °C WEC NGNP development path for Critical SSCs, hydrogen production is omitted.

The cost and schedule of the NGNP progresses continuously as the project develops and is coupled to uncertainties associated with technology advancements, evolving test plans and schedules and also timely availability of resources. Therefore this document presents the following:

- Integrated 750°C - 800°C TDRM test schedule.
- Costs for 750°C - 800°C WEC NGNP, notably for IHX (Alloy 800H and Hastelloy X) and Heat Transport System (HTS) Piping.

Concerning the IHX and HTS Piping, cost estimates are provided up to a TRL rating of 5. Estimates for higher TRL advancements can only be provided when additional design information of aforementioned SSCs becomes available. As with the other SCCs, more design information is required to develop reliable cost estimates (notably PHTS Circulator and Steam Generator). Trade studies need to be done to verify and determine the specific combinations of sub-components that will be used in most of the SSCs.

The bases for all estimates given are noted in Appendix B of this document.

12.1 INTEGRATED TEST SCHEDULE

12.1.1 Introduction

In this section the integrated schedule for the Technology Development Road Maps (TDRMs) addressing the critical SSCs for the 750°C - 800°C WEC NGNP development path is provided. The integrated test schedule portrays the TDRM schedule including an assumed 30 month period allocated for high level Heat Transport Small Scale Test (HTSST) [12-1] Engineering, Construction and Commissioning (ECC).

The following Critical SSCs are included in the TDRM schedule:

- PHTS Circulator
- IHX
- HTS Piping
- Power Conversion System Steam Generator
- Fuel Elements
- Core Structure Ceramics
- Reserve Shutdown System
- Reactivity Control System
- Core Conditioning System
- Reactor Cavity Cooling System
- Fuel Handling and Storage System

The technology development included in the schedule provided herein supports process steam and/or cogeneration applications with the steam generator located in either the primary or secondary loops. It also supports intermediate temperature direct heat applications, such as reforming and ammonia production, excluding the process coupling heat exchanger, which will be application specific. The technology development related to hydrogen production still forms part of the overall NGNP objective. However, considering the 750 ° - 800 °C WEC NGNP development path for Critical SSCs, hydrogen production is omitted.

All of the Test Specifications and their test duration dates, as stated in Sections 1 to 11 of this document [12-2] are indicated in the TDRM Schedule Section of the Integrated Test Schedule.

This schedule is given in Appendix A and is bounded by:

- The HTSST schedule showing an operational date of 2012.
- The WEC Next Generation Nuclear Plant (NGNP) Demonstration Plant schedule showing a NGNP startup date of 2021.

The simplified schedule of the 750°C - 800°C TDRMs, including the proposed HTSST ECC period is depicted in the graphs given in paragraph 12.1.4.

12.1.2 Road to HTSST

The need for a Heat Transport Small Scale Test (HTSST) surfaced from the Component Test Capability (CTC - previously known as the Component Test Facility (CTF) [12-3]) Preconceptual Design that addressed the CTC Mission Need. The HTSST loop will be used to facilitate High Temperature Reactor (HTR) heat transfer technology development as a forerunner to larger-scale heat transfer testing loops.

From the NGNP CTF Test Loop Preconceptual Design Report [12-3], the Technology Development Loop (TDL) originated from a collection of tests that requires a certain volume flow rate in a helium environment of 950°C and 9.0 MPa. The TDL size was driven by the IHX test requirements basing the TDL design mass flow on the mass flow required for multi-module (3 x 1.2 MW) heat transfer testing for the IHX.

Since the release of the CTF PCDR [12-3], a Statement of Work (SOW) for Heat Transport Small Scale Testing has been issued by Battelle Energy Alliance (BEA) [12-1]. This SOW has been followed-up by a Technical and Functional Requirements Document [12-4] describing the need for an HTSST as follows:

"To provide a small-scale testing loop capability for heat transport system components thereby making provision to advance the technology maturation of these components in an environment representative of High Temperature Reactors at minimum schedule and cost."

The priority for TRL advancement lies in IHX testing. The envisaged HTSST will be capable of addressing most of the identified IHX test specifications, which makes it highly attractive for immediate development.

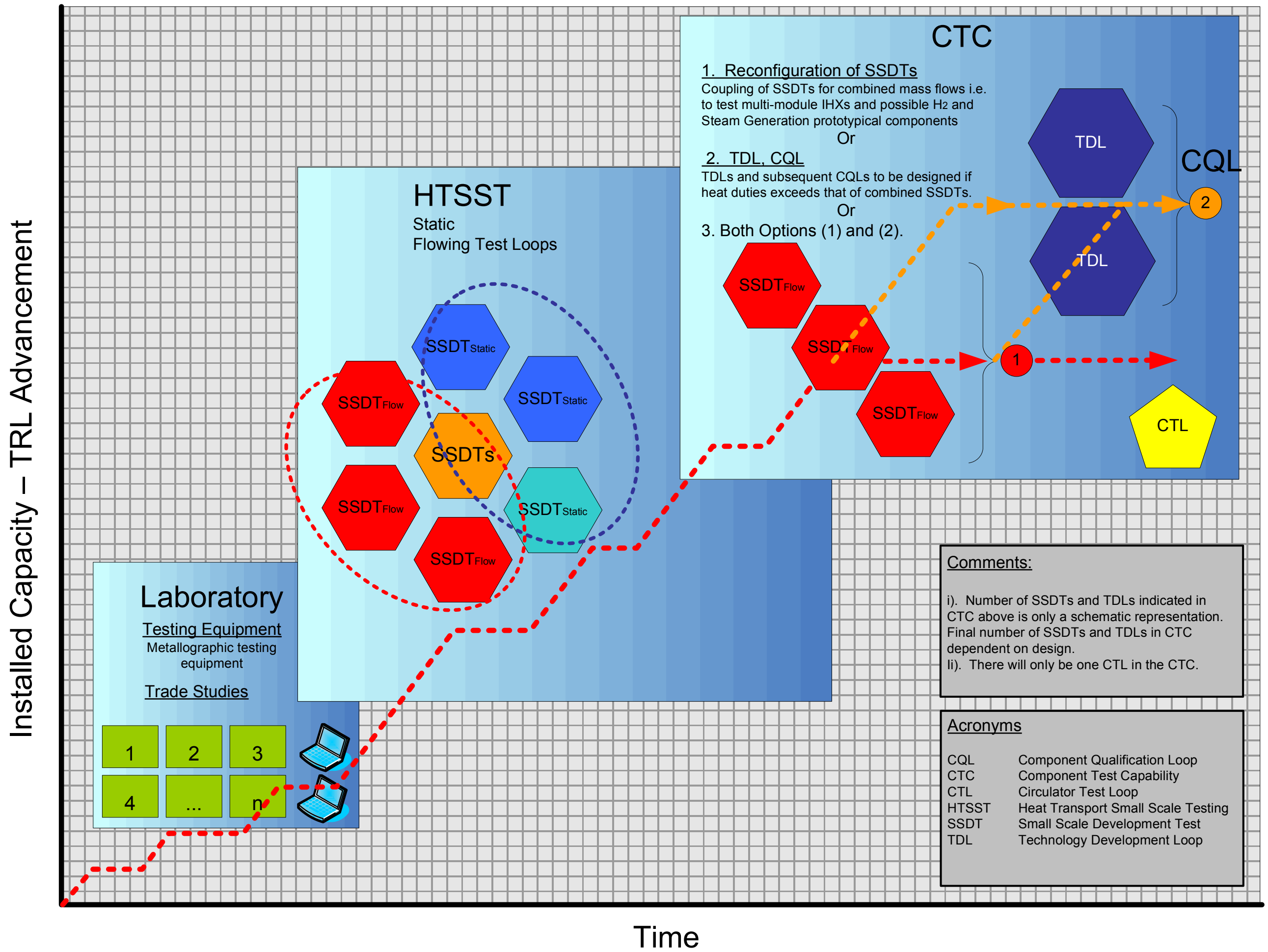


Figure 1: Schematic of Envisaged Installed Capacity *vs.* Time.

The Westinghouse NGNP team proposed different SSDTs to operate within the HTSST, i.e. static testing with NGNP representative environments without helium mass flow and testing where helium mass flow is required within the same NGNP representative environments.

At writing, static tests will be handled by equipment equivalent to the proposed SSDT1 and SSDT2 whereas loop tests will be handled by equipment equivalent to the proposed SSDT3. All SSDTs comprise modularized systems of the HTSST as schematically presented in Figure 1.

12.1.3 Integrated Test Schedule

The integrated 750°C - 800°C TDRM Test Schedule is given in Appendix A and includes High Level HTSST Engineering, Construction and Commissioning (ECC).

12.1.3.1 750°C - 800°C TDRM Schedule

The 750°C - 800°C TDRM schedule identifies the test durations of the following critical SSCs:

- PHTS Circulator
- IHX
- HTS Piping
- Power Conversion System Steam Generator
- Fuel Elements
- Core Structure Ceramics
- Reserve Shutdown System
- Reactivity Control System
- Core Conditioning System
- Reactor Cavity Cooling System
- Fuel Handling and Storage System

The 950°C TDRM schedule [12-5], made the assumption that all testing activities would start in October 2008, while the 750°C - 800°C TDRM schedule as presented in Appendix A, assumes a starting date of October 2009 (excluding HTSST related testing activities). The 750°C - 800°C TDRM schedule is constrained by the HTSST and NGNP start-up dates.

The following assumptions are to be noted:

- Heat Transport Small Scale Testing (HTSST) is assumed to start in October 2012. This implies an HTSST ECC commencement date of January 2010 if the project lifecycle spans 30 months.
- NGNP Initial Operation Date is October 2021
- The designs of heat exchanger elements[1] are assumed to be complete three months prior to the start of IHX module tests i.e. July 2012.
- Re-engineering and re-configuration of SSDTs entail the engineering, construction and commissioning of the hot gas duct network connecting 2 or 3 available SSDTs for combined mass flow testing, i.e. to test multi-module IHXs and possible H_2 and Steam Generator prototypical components. This will typically be done after completion of tests conducted in singular SSDTs (flowing).

The HTSST will primarily be responsible for all major TRL advancements of all NGNP heat transport SSCs. Appendix A shows the 750ºC – 800°C test specifications for NGNP SSCs relevant to the envisaged HTSST. In general, static and flowing Small Scale Development Tests (SSDTs) make up the HTSST.

The SSDTs are envisaged to incorporate separate and multiple effects tests with a thermal heat duty of less than 2 MW at temperatures up to 950ºC and pressures up to 9 MPa. The SSDTs

[1] As defined in the 750°C - 800°C IHX TDRM report.

are more sophisticated than laboratory-scale tests but may also be utilized for laboratory testing. By and large, the SSDTs will advance Technology Readiness Levels of scaled heat transport components from levels of 3 to 6. All SSDTs are to operate within the HTSST.

The HTSST test schedule will be used as input to the Test Loops' conceptual designs and will be updated as the Test Loops' designs develop.

Schedules for each of the SSCs are given in the next paragraph.

12.1.4 High Level Schedules for the 750°C - 800°C Critical SSCs

Bar chart schedules including test durations of laboratory tests, trade studies and HTSST-related tests for each of the critical SSCs are given below. These graphs form a high level summary of the integrated schedule given in Appendix A. The graphs include the following:

- Test Specification Numbers on the Ordinate axis.
- Time on the Abscissa axis (spanning from Oct 2009 to Oct 2022.)
- Test duration for each test, as given in the 750°C - 800°C TDRMs.
- HTSST ECC duration of 30 months, which has been assumed for these schedules.
- TRL goals, which are given on each of the Test Duration bars.
- Summary description of tests, given next to each of the test durations on the bar charts.
- The NGNP start-up date, indicated as October 2021.

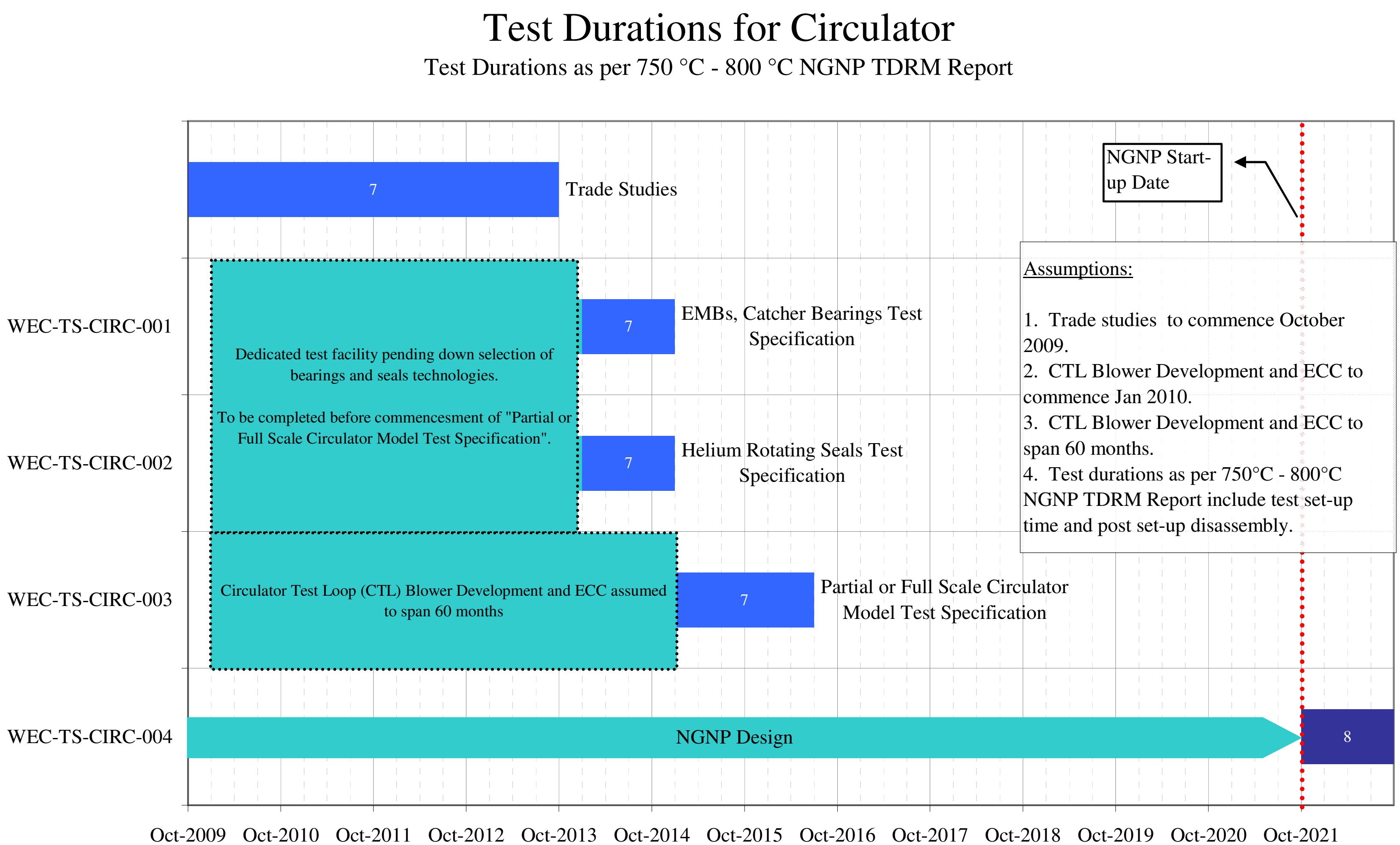


Figure 2: Circulator Test Duration Schedule

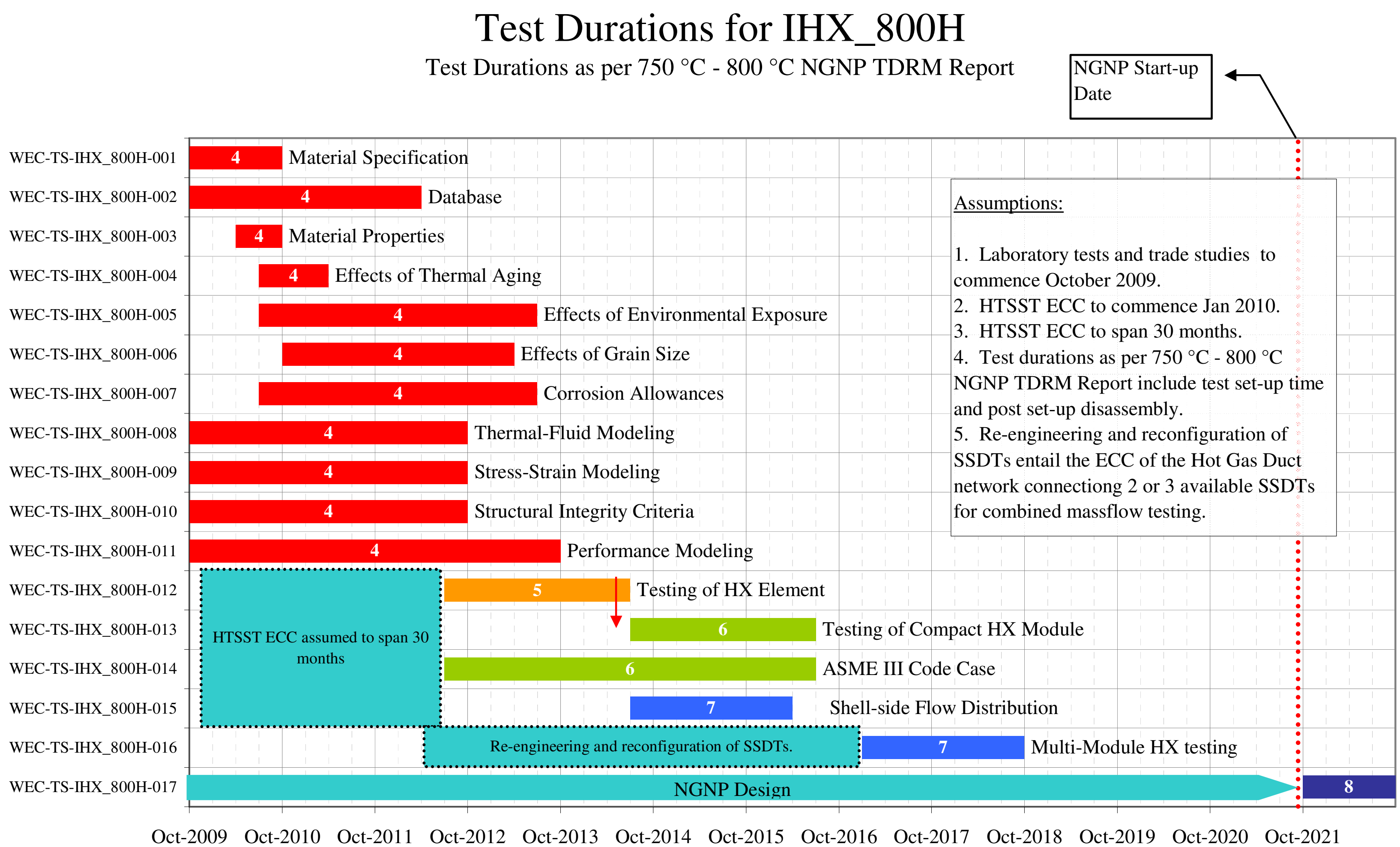


Figure 3: IHX 800H Test Duration Schedule.

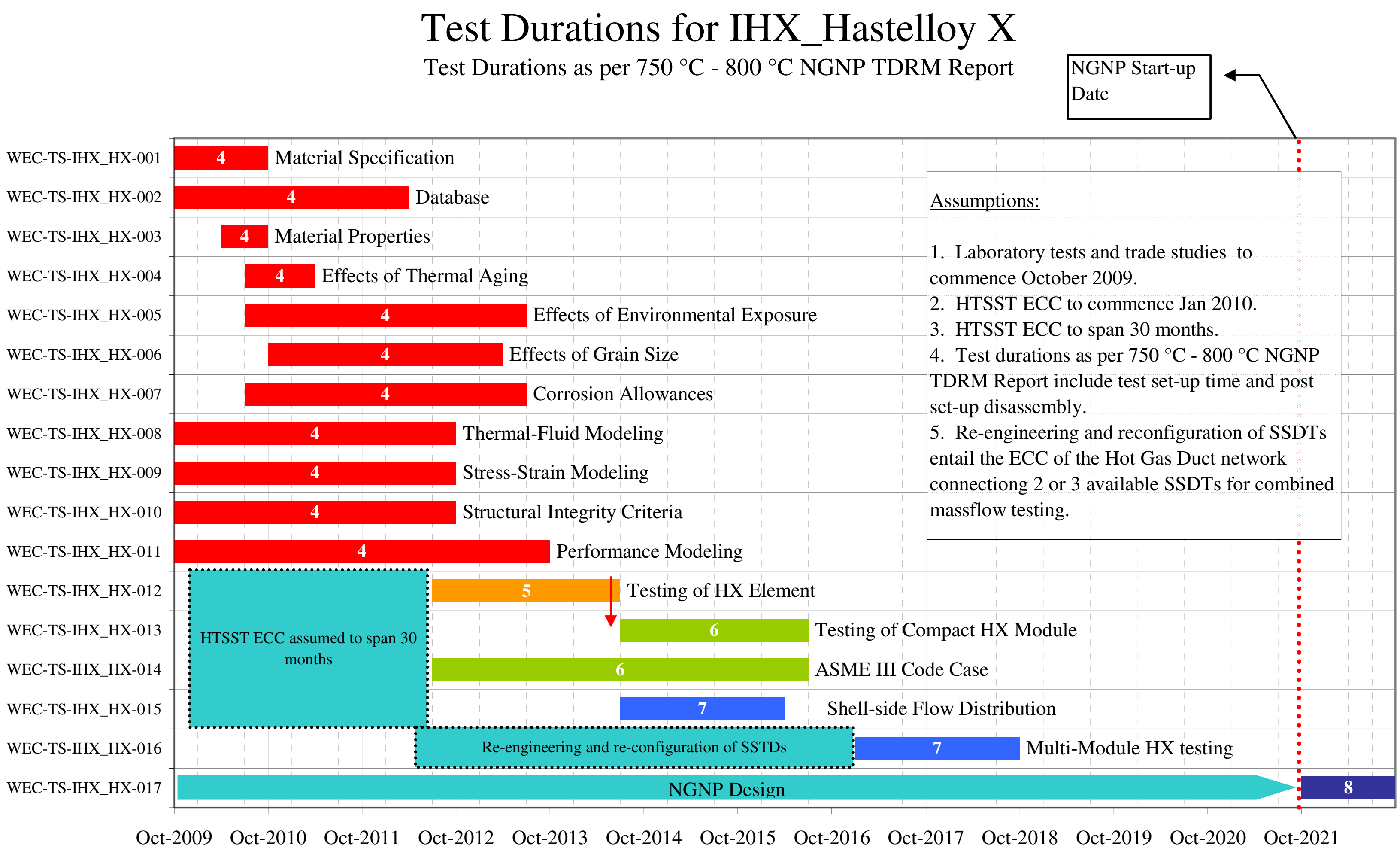


Figure 4: IHX Hastelloy Test Duration Schedule.

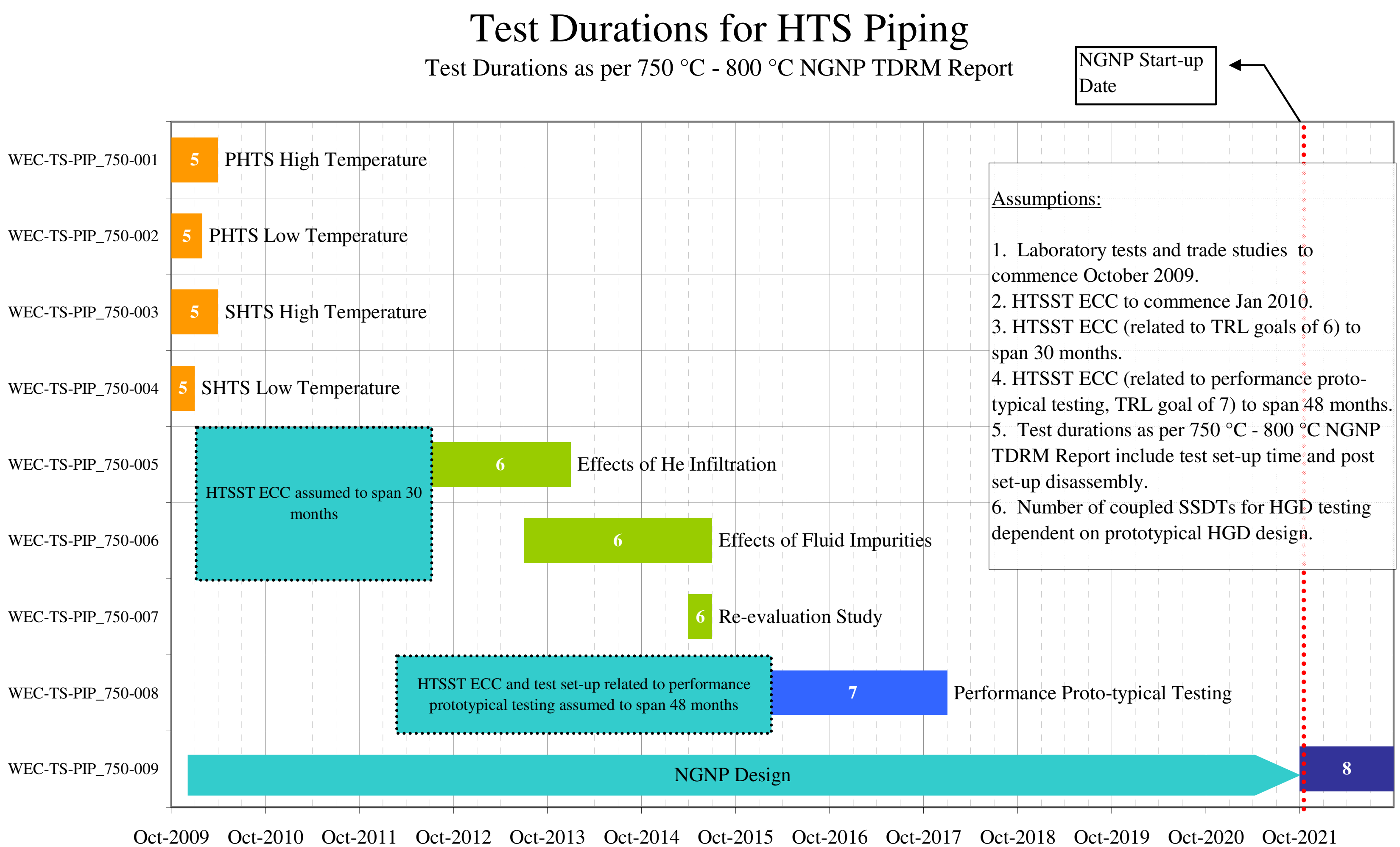


Figure 5: Heat Transport Piping Test Duration Schedule.

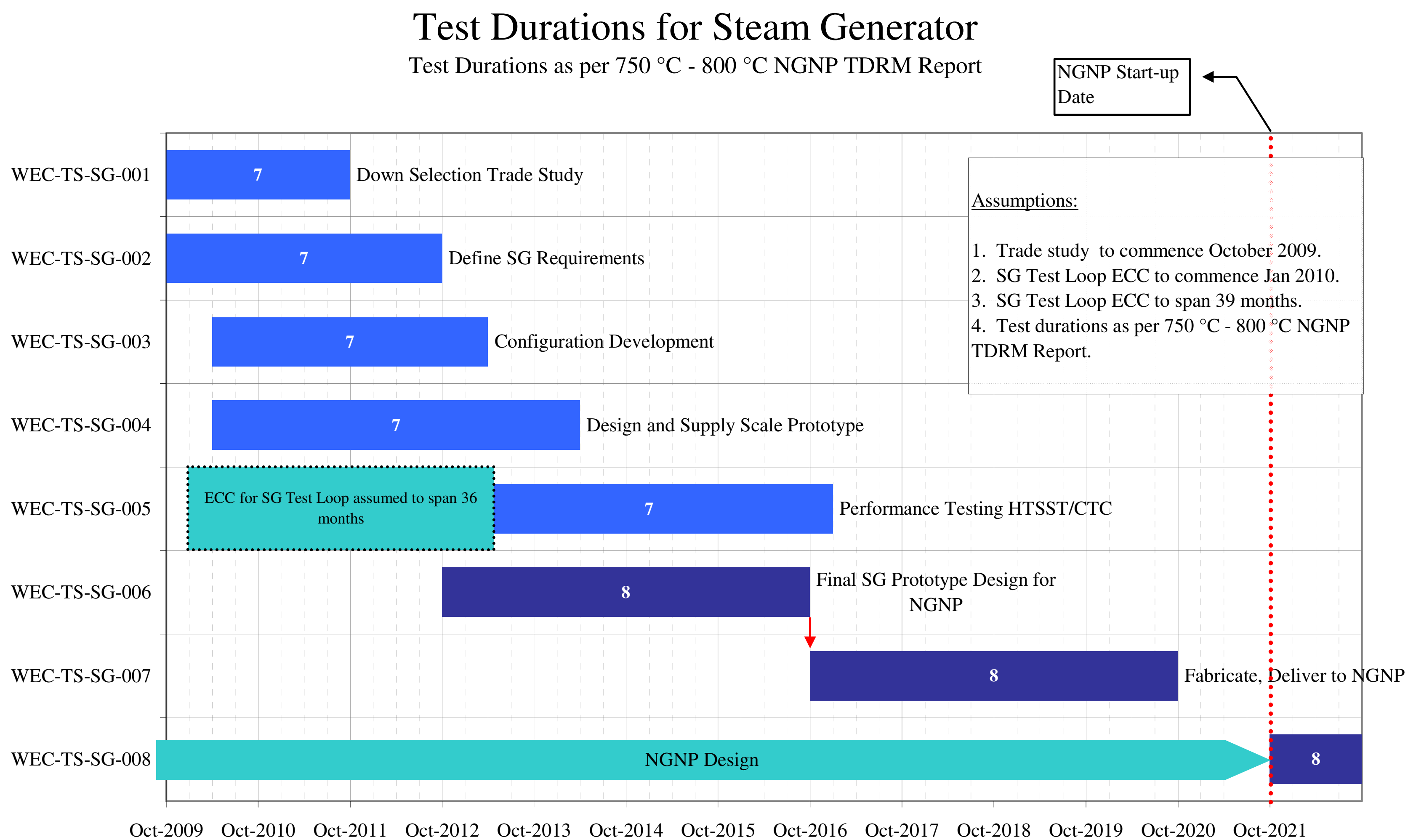


Figure 6: Steam Generator Test Duration Schedule.

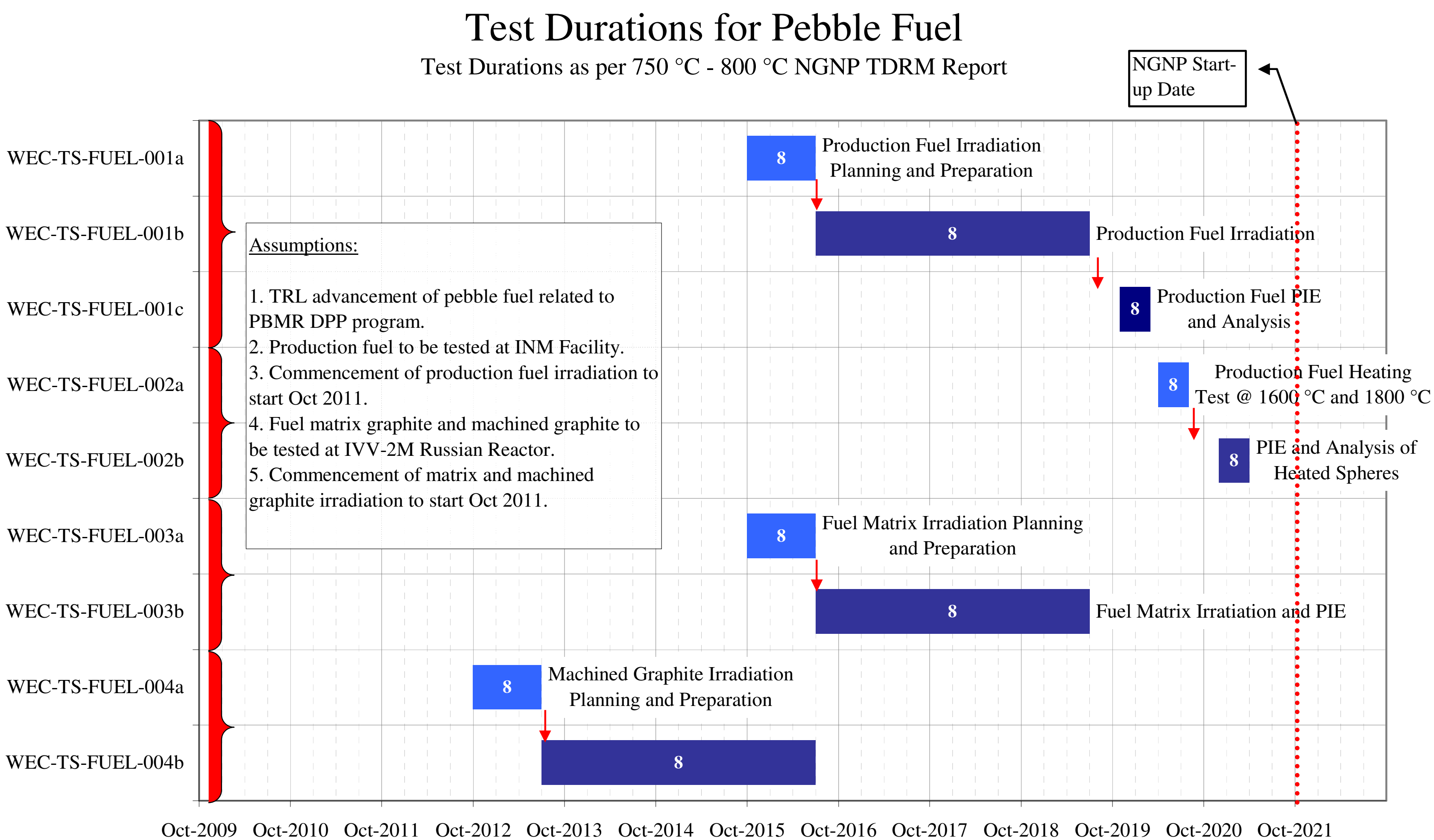


Figure 7: Fuel Test Duration Schedule.

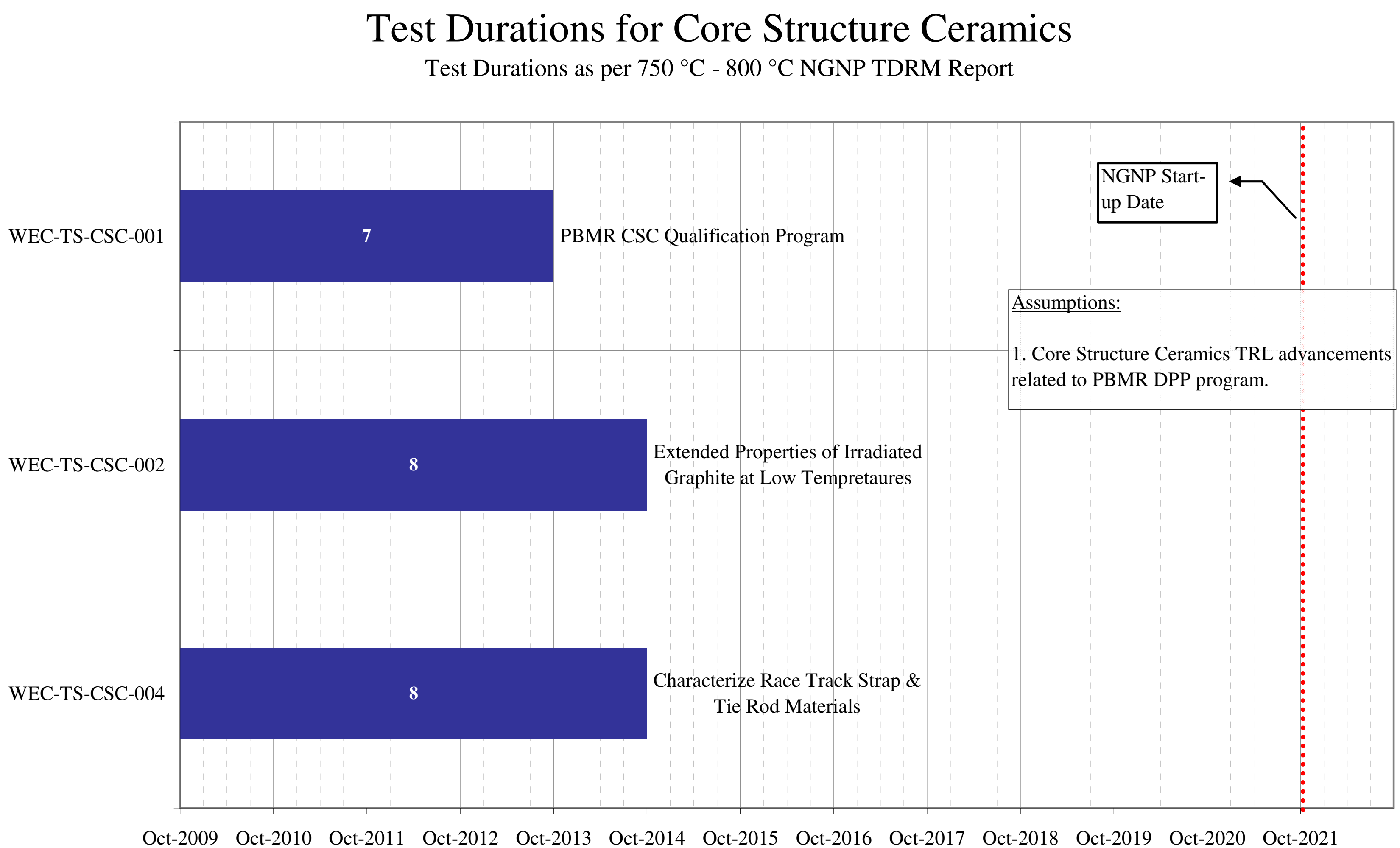


Figure 8: Core Structure Ceramics Test Duration Schedule.

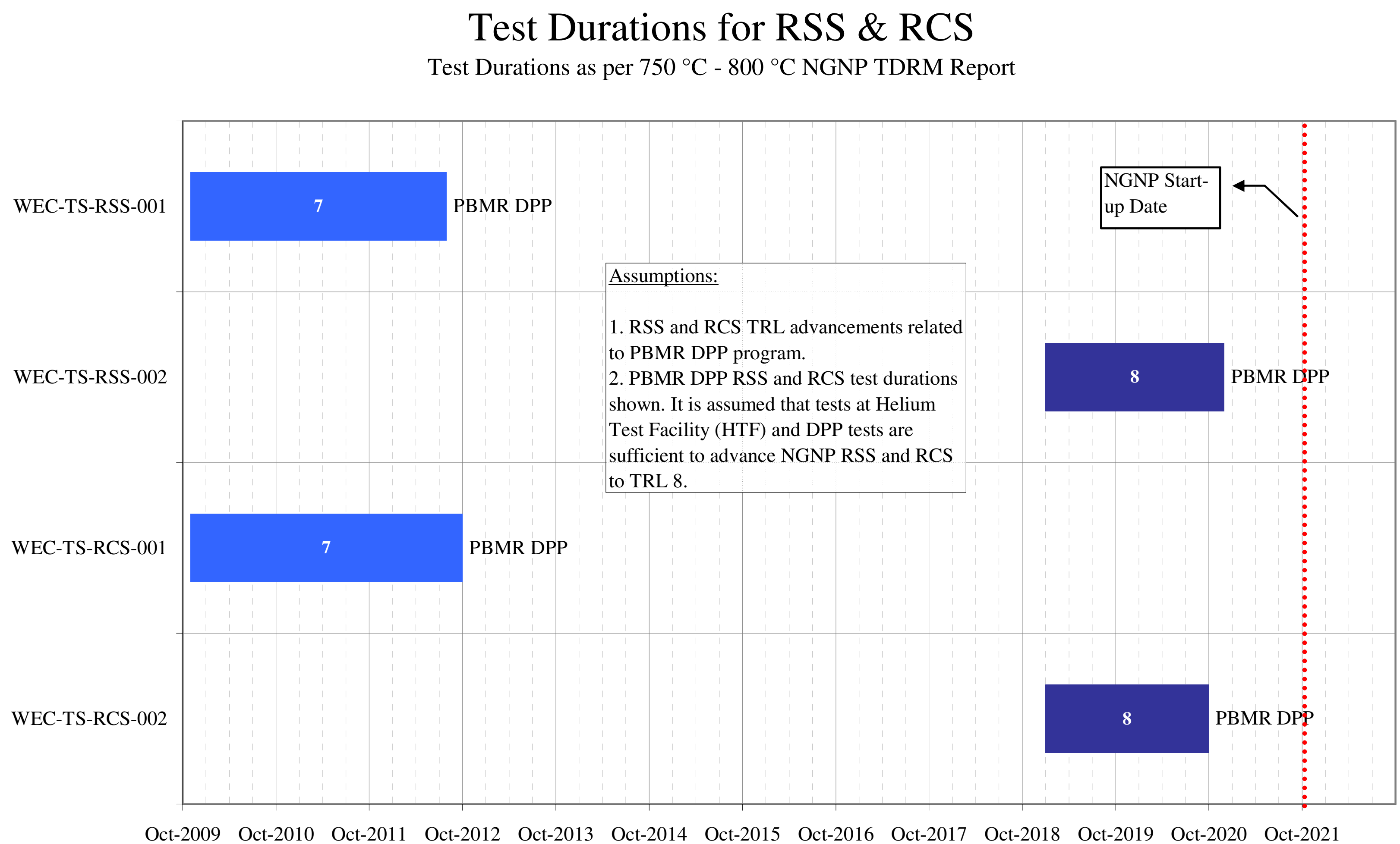


Figure 9: RSS and RCS Test Duration Schedule.

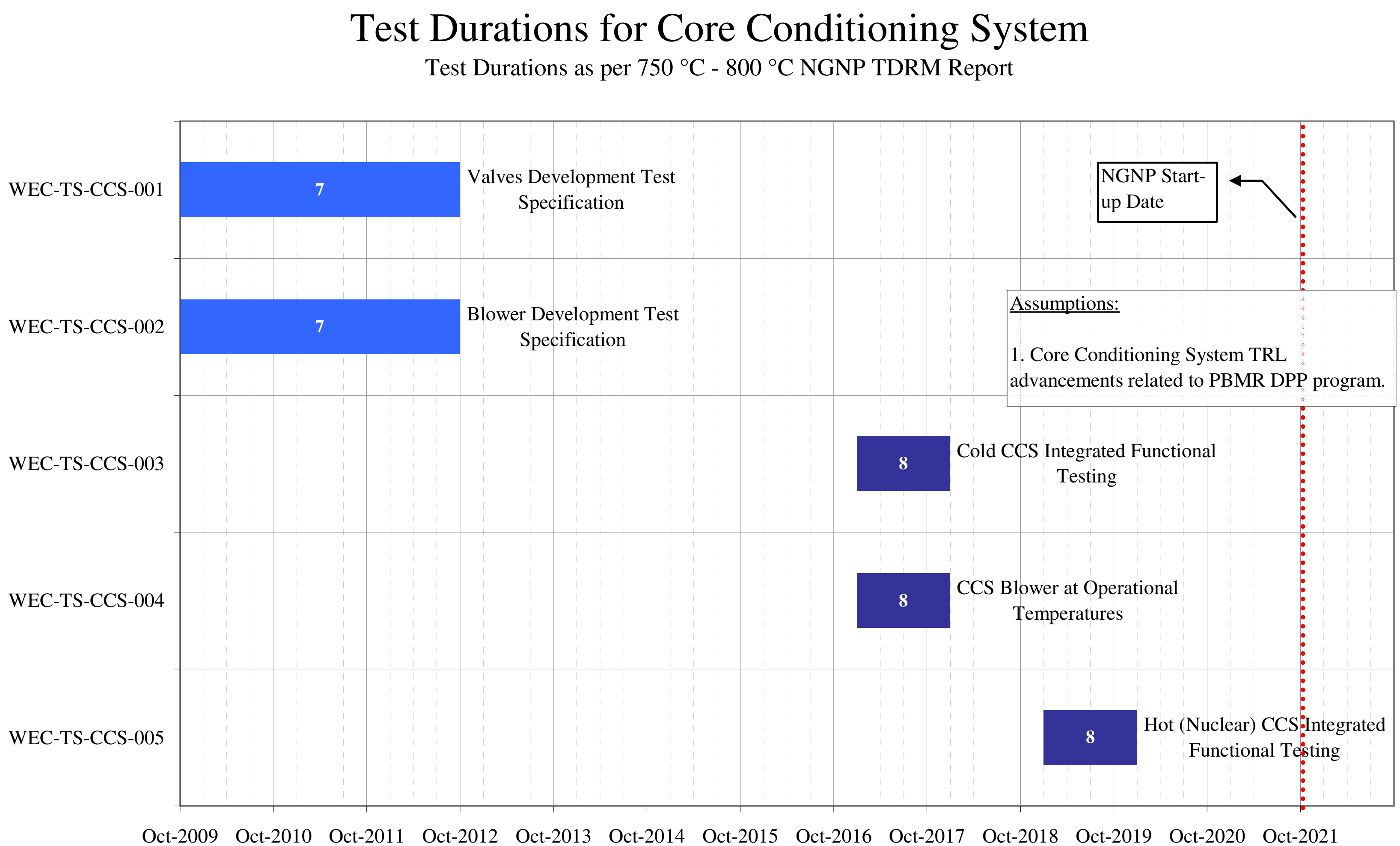


Figure 10: CCS Test Duration Schedule.

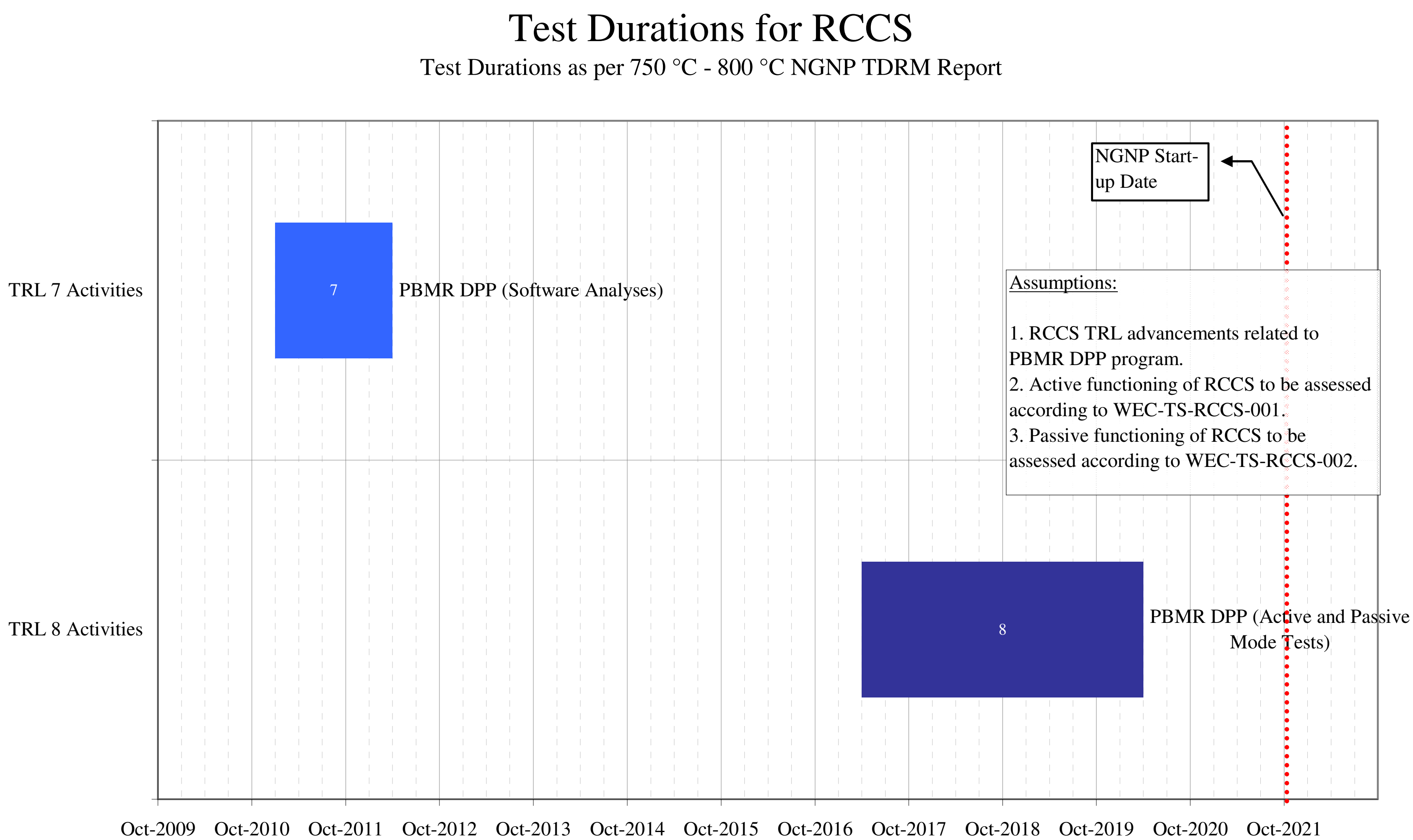


Figure 11: RCCS Test Duration Schedule.

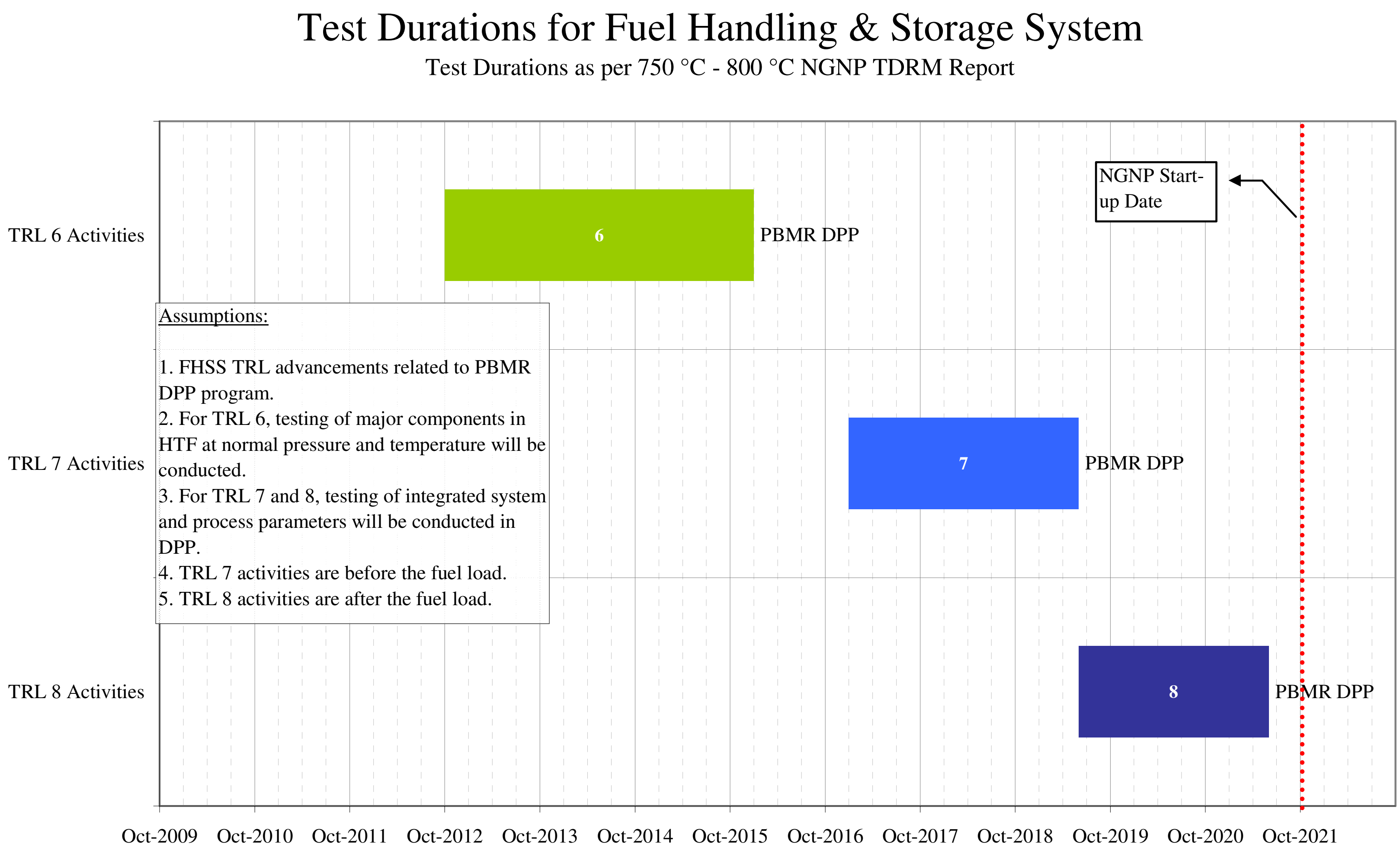


Figure 12: FHSS Test Duration Schedule.

12.1.5 Conclusion

Pending further schedule enhancements and optimization, the number of loops required in the HTSST will be confirmed as part of the Test Loops' conceptual designs. The number of loops required for the CTC (inclusive of TDLs and CQLs) can only be determined when testing requirements have been fixed for other critical SSCs, notably the Steam Generator and Hydrogen Production. Also, the heat duties of these proto-typical designs would determine the path henceforth i.e. to either combine test loops within HTSST to provide for larger mass flow or to start anew with the CTC that will contain larger test loops than those in HTSST.

Considering the 750ºC – 800°C NGNP Development Path the following is foreseen:

- The number of SSDT resources (i.e. amount of SSDTs for passive conditions and amount of SSDTs for flowing conditions) needs to be finalized, which is dependent on the urgency of completing tests within a certain time frame. The number of proposed SSDTs will be determined during the design phase upon addressing the HTSST Technical and Functional requirements [12-4].
- Initial estimates (engineering judgment) indicate that two static Westinghouse proposed SSDTs and three proposed SSDT3s be needed for a start. This number could easily be expanded in time if required.
- Some of the tests are long-term environmental tests i.e. the IHX-related Corrosion Allowance tests. Exposure of samples in a helium environment could be done in the HTSST (or then the proposed SSDT3).
- The amount of samples per proposed SSDT (1 and 2) is dependent on the outcome of the design as well as the requirements applicable to the restriction of number of samples per sample stack.
- It is suggested that the SSDT3s be dedicated to component-specific tests as follows.
    - One proposed SSDT3 will be dedicated for IHX tests.
    - A second proposed SSDT3 will be dedicated for Hot Gas Duct tests.
    - A third proposed SSDT3 will be dedicated for "Other" tests i.e. Blower Development tests and PHTS Backflow Prevention Valves confirmatory tests.
- A fourth proposed SSDT3 could be justified for component specific tests like the Steam Generator Helical Bundle and Transition Region Heat Transfer Test where the infrastructure provided within the proposed SSDT3 could be used to characterize the water-side heat transfer coefficient (in a 1- or 2-tube test).
- Independent from the number considered, all proposed SSDT components need to be preserved after tests and made available for analysis.
- One CTL will be required to test the circulator as well as some of the piping sections and the mixing chamber.

At completion of the HTSST conceptual design, where the optimum construction and commissioning schedule will be determined, the TDRM Schedules will be updated accordingly.

12.2 COST ESTIMATE

12.2.1 Introduction

Cost estimates are provided for certain test specifications of critical Systems, Structures and Components (SSCs) in this document. These SSCs entail the IHX and the HTS Piping systems. For the purpose of this document, estimates have been provided only up to a **TRL rating of 5**, due to the high uncertainty that exists in estimating the costs for higher TRL advancements. 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 (PHTS Circulator and Steam Generator), more design information is also required in order to develop reliable cost estimates. Trade studies need to be done to progress the designs and to verify and determine the specific combinations of sub-components that will be used. There is enough time as per the modified schedule to perform the trade study before the advancement of the TRL and before possible testing in the HTSST will be performed.

Where cost information was not available, the WEC NGNP PCDR costs [12-6] were used as basis including the following:

- Fuel Elements
- Core Structures Ceramics
- Reserve Shutdown System
- Reactivity Control System
- Core Conditioning System
- Reactor Cavity Cooling System

The bulk of estimated costs provided are based on input received from contributors and institutions conducting similar work in industry. Table 2 through Table 8 of this document captures the estimates made for the identified SSCs as well as possible test locations and facilities that were identified and are involved with similar testing programs. The compositions of the estimates made for each test specification are captured in individual specification estimates in Appendix B. The bases used in these sheets will be elaborated upon here after.

12.2.2 Assumptions and Bases of Cost Estimates

The following assumptions and bases are applicable to the estimates shown in Appendix B.

12.2.2.1 Applicability to Schedule

The cost estimates stated in Table 2 through Table 8 are based on November 2008 dollar values. No escalation for future years has been incorporated.

12.2.2.2 TRL Advancements

For the purpose of this document, estimates have only been provided up to a TRL rating of 5 due to the high uncertainty that exists in estimating the costs for higher TRL advancements. Estimates for higher TRL advancements can only be provided when additional design information (preliminary or final) is available and the initial technology development has progressed to a more mature point.

12.2.2.3 Contingencies and Uncertainties

Contingencies for the proposed estimates given involve a 10 percent adjustment on resource, testing, materials and other applicable costs stated.

In the 950°C TDRM report, certain IHXB's materials-related testing costs were fractioned to those of IHXA. For the 750°C - 800°C TDRM report, dedicated sample quantities are recommended for each of the tests where applicable i.e. IHX 800H, IHX Hastelloy X and HTS Piping for TRL goals equal to and less than 5.

The confidence level of the cost estimates at present is +120%/-:60%, which corresponds to an accuracy level of Class 4 as noted in [12-7].

12.2.2.4 General

Other bases for the estimates relating to resources used, testing estimates as well as materials are stated in Appendix B. Aspects lacking an estimate basis will only be updated when additional preliminary or final plant design information is available. Until this information is readily available, only an allowance for certain identified tasks without a basis can be given.

12.2.3 Summary Cost: 750°C – 800°C TDRMs

Table 1 shows the sum of cost estimates distributed along a timeline starting in FY2009 and ending in FY2021. The start dates and durations of the tasks correspond to those noted in the 750°C – 800°C TDRMs. These test commencement dates and durations are also depicted in the bar charts in paragraph 12.1.4. Comments and assumptions applicable to the values shown are given below Table 1.

Table 1: Summary of Costs: 750°C – 800°C NGNP TDRM

Summary costs: 750°C - 800°C TDRMs

SSC [1], [2]	FY2010	FY2011	FY2012	FY2013	FY2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	Total
Circulator [3]	$112,500	$112,500	$112,500	$112,500	$0	$0	$0	$0	$0	$0	$0	$0	**$450,000**
IHX 800H[4]	$3,569,506	$3,605,010	$2,574,492	$946,194	$75,000	$0	$0	$0	$0	$0	$0	$0	**$10,770,202**
IHX Hastelloy X[4]	$3,569,506	$3,605,010	$2,574,492	$946,194	$75,000	$0	$0	$0	$0	$0	$0	$0	**$10,770,202**
Piping[4]	$668,800	$0	$66,667	$322,917	$291,667	$274,350	$0	$0	$0	$0	$0	$0	**$1,624,400**
Steam Generator	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$0	$0	$0	**$22,500,000**
Fuel		$5,000,000	$6,500,000	$6,500,000	$6,500,000	$5,500,000	$3,500,000	$3,500,000	$3,500,000	$4,500,000	$0	$0	**$45,000,000**
CSC	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$0	$0	$0	$0	$0	$0	$0	**$5,000,000**
RSS	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**
RCS	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**
CCS	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**
RCCS	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**
FHSS	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**
TOTAL ($)	**$7,850,806**	**$12,217,510**	**$12,753,659**	**$11,381,611**	**$10,366,667**	**$8,274,350**	**$6,000,000**	**$6,000,000**	**$6,000,000**	**$4,500,000**	**$0**	**$0**	**$85,344,602**

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

[2] Costing of RSS, RCS, CCS, RCCS and FHSS is related to PBMR DPP and are not included.

[3] Considering the Circulator and the Steam Generator, concept design needs to be progressed further before sensible estimations can be made.

[4] Estimates have been provided only up to a TRL rating of 5.

12.2.4 750°C – 800°C TDRM Cost Estimate (Facilities Description and Total Cost Included)

Table 2 to Table 8 show the 750°C – 800°C TDRM cost estimates for each test specification with associated details regarding possible facilities that have the capabilities of conducting the relevant testing. Costing assumptions have also been listed at the end of the table. Detailed bases for each of the individual test specifications estimates are given in the specification cost estimate sheets shown in Appendix B.

Due to the large number of possible facilities that can conduct work similar to that stated in the test specifications (notably materials qualification actions), only the facility capability is noted in aforementioned tables and not the facility availability. Facilities have been identified in the following areas:

1. Laboratories – These facilities are most common and widely available. Work associated with these facilities involves aspects relating to material qualification.
2. Heat Transport Small Scale Testing (HTSST) – Specialized testing on scaled units is required here and can in general be conducted by the relevant supplier or in small scale development test loops.
3. CTC Testing – Testing of partial- or full-scale units at relevant temperatures and pressures.

Table 2: 750°C – 800°C TDRM Circulator Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	Circulator						**$450,000**
	Trade studies to select reference design	n/a	7	Supplier / Design Authority	48 Months	FY 2010 - FY 2013	$450,000
	EMBs, Catcher bearings Test Specification	WEC-TS-CIRC-001	7	EMBs Supplier Test Facility	12 Months	FY 2014 - FY 2015	[-]
	Helium Rotating seals Test Specification	WEC-TS-CIRC-002	7	Rotating Seal Supplier Test Facility	12 Months	FY 2014 - FY 2015	[-]
	Partial or Full scale circulator Model Test Specification	WEC-TS-CIRC-003	7	CTC/Supplier Site	18 Months	FY 2015 - FY 2016	[-]
	Prototype circulator Test Specification	WEC-TS-CIRC-004	8	NGNP Site	24 Months	FY 2022 - FY 2024	[-]

Comments:

Additional design information is required to conduct sensible cost estimates. Trade studies still have to be completed for the Circulator to verify and determine the specific combinations of sub-components that will be used.

Table 3: 750°C – 800°C TDRM IHX Alloy 800H Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	IHX 800H						**$10,770,202**
	Alloy 800H Material Specification and Procurement	WEC-TS-IHX_800H-001	4	INL, ORNL	12 Months	FY 2010 - FY 2011	$70,400
	Database for Brazed and Diffusion Bonded Alloy 800H	WEC-TS-IHX_800H-002	4	INL, ORNL, ANL, CHE designers/manufacturers	30 Months	FY 2010 - FY 2012	$3,891,066
	Alloy 800H High Temperature Material Properties	WEC-TS-IHX_800H-003	4	INL, ORNL, CSIR	6 Months	FY 2010	$603,004
	Effects of Thermal Aging and Environment on Alloy 800H Properties	WEC-TS-IHX_800H-004	4	INL, ORNL	9 Motnhs	FY 2010 - FY 2011	$831,914
	Effects of Environmental Exposure on Alloy 800H Braze and Diffusion Bonded Joints	WEC-TS-IHX_800H-005	4	INL, ORNL	36 Months	FY 2010 - FY 2013	$2,029,112
	Effects of Grain Size and Section Thickness on Alloy 800H Properties	WEC-TS-IHX_800H-006	4	INL, ORNL, ANL, LANL, SNL, BNL, CSIR	30 Months	FY 2011 - FY 2013	$831,581
	Corrosion Allowances for Alloy 800H	WEC-TS-IHX_800H-007	4	INL, ORNL, FZJ, Saclay	36 Months	FY 2010 - FY 2013	$1,892,374
	Thermal/Fluid Modeling Methods for IHX B	WEC-TS-IHX_800H-008	4	CHE designer/supplier, INL, ORNL, ANL	36 Months	FY 2010 - FY 2012	$105,188
	Methods for Stress/Strain Modling of IHX B	WEC-TS-IHX_800H-009	4	CHE designer/supplier, INL, ORNL, ANL	36 Months	FY 2010 - FY 2012	$105,188
	Criteria for Structural Intergrity of IHX B	WEC-TS-IHX_800H-010	4	CHE designer/supplier, INL, ORNL, ANL	36 Months	FY 2010 - FY 2012	$105,188
	Performance Modeling Methods for IHX B	WEC-TS-IHX_800H-011	4	CHE designer/supplier, INL, ORNL, ANL	48 Months	FY 2010 - FY 2013	$105,188
	Specification of testing of element of Compact Heat Exchanger	WEC-TS-IHX_800H-012	5	CHE designer/manufacturer (Heatric, Brayton Energy)	24 Months	FY 2012 - FY2014	$200,000
	Specification of testing of compact heat exchanger module (~1.2MW)	WEC-TS-IHX_800H-013	6	CTC	24 Months	FY 2014 - FY 2016	[-]
	ASME Section III Code Case for Compact Heat Exchanger Designs	WEC-TS-IHX_800H-014	6	CHE supplier/design authority, INL, ORNL, ANL, LANL	48 Months	FY 2012 - FY 2016	[-]
	Shell-side Flow Distribution and Bypass Leakage Testing	WEC-TS-IHX_800H-015	7	CTC	24 Months	FY 2014 - FY 2016	[-]
	Multi-module Heat Transfer Testing	WEC-TS-IHX_800H-016	7	CTC	24 Months	FY 2017 - FY 2018	[-]
	Specification of testing of a full scale compact heat exchanger	WEC-TS-IHXB_800H-017	8	NGNP	24 Months	FY 2022 - FY 2024	[-]

Table 4: 750°C – 800°C TDRM IHX Alloy Hastelloy Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	IHX Hastelloy X						**$10,770,202**
	Alloy Hastelloy X Material Specification and Procurement	WEC-TS-IHX_HX-001	4	INL, ORNL	12 Months	FY 2010 - FY 2011	$70,400
	Database for Brazed and Diffusion Bonded Alloy Hastelloy X	WEC-TS-IHX_HX-002	4	INL, ORNL, ANL, CHE designers/manufacturers	30 Months	FY 2010 - FY 2012	$3,891,066
	Alloy Hastelloy X High Temperature Material Properties	WEC-TS-IHX_HX-003	4	INL, ORNL, CSIR	6 Months	FY 2010	$603,004
	Effects of Thermal Aging and Environment on Alloy Hastelloy X Properties	WEC-TS-IHX_HX-004	4	INL, ORNL	9 Motnhs	FY 2010 - FY 2011	$831,914
	Effects of Environmental Exposure on Alloy Hastelloy X Braze and Diffusion Bonded Joints	WEC-TS-IHX_HX-005	4	INL, ORNL	36 Months	FY 2010 - FY 2013	$2,029,112
	Effects of Grain Size and Section Thickness on Alloy Hastelloy X Properties	WEC-TS-IHX_HX-006	4	INL, ORNL, ANL, LANL, SNL, BNL, CSIR	30 Months	FY 2011 - FY 2013	$831,581
	Corrosion Allowances for Alloy Hastelloy X	WEC-TS-IHX_HX-007	4	INL, ORNL, FZJ, Saclay	36 Months	FY 2010 - FY 2013	$1,892,374
	Thermal/Fluid Modeling Methods for IHX	WEC-TS-IHX_HX-008	4	CHE designer/supplier, INL, ORNL, ANL	36 Months	FY 2010 - FY 2012	$105,188
	Methods for Stress/Strain Modling of IHX	WEC-TS-IHX_HX-009	4	CHE designer/supplier, INL, ORNL, ANL	36 Months	FY 2010 - FY 2012	$105,188
	Criteria for Structural Intergrity of IHX	WEC-TS-IHX_HX-010	4	CHE designer/supplier, INL, ORNL, ANL	36 Months	FY 2010 - FY 2012	$105,188
	Performance Modeling Methods for IHX	WEC-TS-IHX_HX-011	4	CHE designer/supplier, INL, ORNL, ANL	48 Months	FY 2010 - FY 2013	$105,188
	Specification of testing of element of Compact Heat Exchanger	WEC-TS-IHX_HX-012	5	CHE designer/manufacturer (Heatric, Brayton Energy)	24 Months	FY 2012 - FY2014	$200,000
	Specification of testing of compact heat exchanger module (~1.2MW)	WEC-TS-IHX_HX-013	6	CTC	24 Months	FY 2014 - FY 2016	[-]
	ASME Section III Code Case for Compact Heat Exchanger Designs	WEC-TS-IHX_HX-014	6	CHE supplier/design authority, INL, ORNL, ANL, LANL	48 Months	FY 2012 - FY 2016	[-]
	Shell-side Flow Distribution and Bypass Leakage Testing	WEC-TS-IHX_HX-015	7	CTC	24 Months	FY 2014 - FY 2016	[-]
	Multi-module Heat Transfer Testing	WEC-TS-IHX_HX-016	7	CTC	24 Months	FY 2017 - FY 2018	[-]
	Specification of testing of a full scale compact heat exchanger	WEC-TS-IHX_HX-017	8	NGNP	24 Months	FY 2022 - FY 2024	[-]

Table 5: 750°C – 800°C TDRM HTS Piping Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	HTS Piping						**$1,624,400**
	PHTS high-temperature [750°C and 800°C] piping cooling, liner and insulation options trade study	WEC-TS-PIP$_{750}$-001	5	Piping System Designer	6 Months	FY 2010	$211,200
	PHTS low-temperature [~300°C] piping liner and insulation options trade study	WEC-TS-PIP$_{750}$-002	5	Piping System Designer	3 Months	FY 2010	$140,800
	SHTS high-temperature[700°C and 750°C] piping liner and insualtion study	WEC-TS-PIP$_{750}$-003	5	Piping System Designer	6 Months	FY 2010	$211,200
	SHTS low-temperature [~250°C] piping liner and insulation trade study	WEC-TS-PIP$_{750}$-004	5	Piping System Designer	3 Months	FY 2010	$105,600
	Effects of He infiltration on thermal conductivity of insulation material	WEC-TS-PIP$_{750}$-005	6	Insulation Manufacturers, INL, ORNL, ANL	18 Months	FY 2012 - FY 2014	$400,000
	The effect of fluid impurities on insulation properties	WEC-TS-PIP$_{750}$-006	6	Insulation Manufacturers, INL, ORNL, ANL	24 Months	FY 2013 - FY 2015	$450,000
	Re-evaluation of needed maturation tasks based on Trade studies	WEC-TS-PIP$_{750}$-007	6	Piping System Designer	3 Months	FY 2015	$105,600
	Performance & environmental testing of prototypical high-temp and low-temp piping/insulation system	WEC-TS-PIP$_{750}$-008	7	CTC	24 Months	FY 2016 - FY 2018	[-]
	Testing of full sie PHTS piping in NGNP	WEC-TS-PIP$_{750}$-009	8	NGNP	24 Months	FY 2022 - FY 2024	[-]

Table 6: 750°C – 800°C TDRM Steam Generator Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	Steam Generator						**$22,500,000**
	Perform a down selection trade study to determine the preferred conceptual arrangement of the SG	WEC-TS-SG-001	7	TBD	24 Months	FY 2010 - FY2011	[-]
	Define requirements and design details for the SG in the PCS system context	WEC-TS-SG-002	7	TBD	36 Months	FY 2010 - FY2012	[-]
	Perform configuration development tests to substantiate the design	WEC-TS-SG-003	7	TBD	36 Months	FY 2010 - FY2013	[-]
	Design and supply a scale prototype for the testing in the CTC	WEC-TS-SG-004	7	TBD	48 Months	FY 2010 - FY2014	[-]
	Performance testing in CTC	WEC-TS-SG-005	7	CTC	45 Months	FY 2013 - FY2017	[-]
	Complete final design of the prototype SG for the NGNP	WEC-TS-SG-006	8	TBD	48 Months	FY 2012 - FY2016	[-]
	Fabricate and deliver to NGNP to the Site	WEC-TS-SG-007	8	TBD	48 Months	FY 2017 - FY2020	[-]
	Install and operate	WEC-TS-SG-008	8	NGNP	24 Months	FY 2022 - FY2024	[-]

Comments:

NGNP PCDR Report - Section 16 estimate given - Concept design of plant needs to be progressed before sensible cost estimates can be given [12-6].

Table 7: 750°C – 800°C TDRM Fuel Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	Fuel						**$45,000,000**
	Production Fuel Irradiation Tests for Normal Operational Conditions	WEC-TS-FUEL-001	8	INM Facility	52 Months	FY 2016 - 2020	[-]
	Production Fuel Heat-up Tests	WEC-TS-FUEL-002	8	INM Facility	12 Months	FY 2019 - 2020	[-]
	Fuel Matrix Graphite Irradiation tests and PIE	WEC-TS-FUEL-003	8	IVV-2M Russian Reactor	45 Months	FY 2016 - 2019	[-]
	Machined Graphite Irradiation tests and PIE	WEC-TS-FUEL-004	8	IVV-2M Russian Reactor	45 Months	FY 2013 - 2016	[-]

Comments:

NGNP PCDR Report - Section 16 estimate given [12-6].

Table 8: 750°C – 800°C TDRM CSC Cost Estimates

SSC	Test Specification	Test Specification Number	TRL Goal	Facility/Supporting Organizations	Duration	Fiscal Year/s	Total ($)
	CSC						**$5,000,000**
	PBMR Relevant	WEC-TS-CSC-001	7		48 Months	FY 2010 - FY 2013	[-]
	Extended Properties of Irradiated Graphite at Low Temperatures	WEC-TS-CSC-002	8	National Laboratory / University	60 Months	FY 2010 - FY 2014	[-]
	Characterize Race Track Strap and Tie Rod Material	WEC-TS-CSC-004	8	National Laboratory / University	60 Months	FY 2010 - FY 2014	[-]

Comments:

NGNP PCDR Report - Section 16 estimate given [12-6].

12.2.5 Conclusion – Cost Estimates

Cost estimates have been provided for certain critical SSCs, notably IHX (800H and Hastelloy X) and HTS Piping. Estimates have only been provided up to a TRL rating of 5. Estimates for higher TRL advancements can only be provided when additional preliminary or final design information of the NGNP associated components are available.

For some of the SSCs, more design information is required in order to develop reliable cost estimates, notably the PHTS Circulator and Steam Generator. Trade studies need to be done to verify and determine the specific combinations of sub-components that will be used in the aforementioned SSCs.

The bases for the estimates given have also been noted in Appendix A of this document.

REFERENCES

[12-1] "Heat Transport Small Scale Testing," Statement of Work, Project No. 23843, Document ID: SOW-7342, Revision 1.

[12-2] "NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C," NGNP-TDI-TDR-RPT-G-00008 … 00018.

[12-3] "NGNP-CTF-MTECH-TLDR. NGNP CTF Test Loop Pre-Conceptual Design Report", dated December 2008.

[12-4] "Technical and Functional Requirements - Heat Transport Small Scale Testing Loop**,"** NGNP-TDI-GEN-FRD-G-00021, dated July 2009.

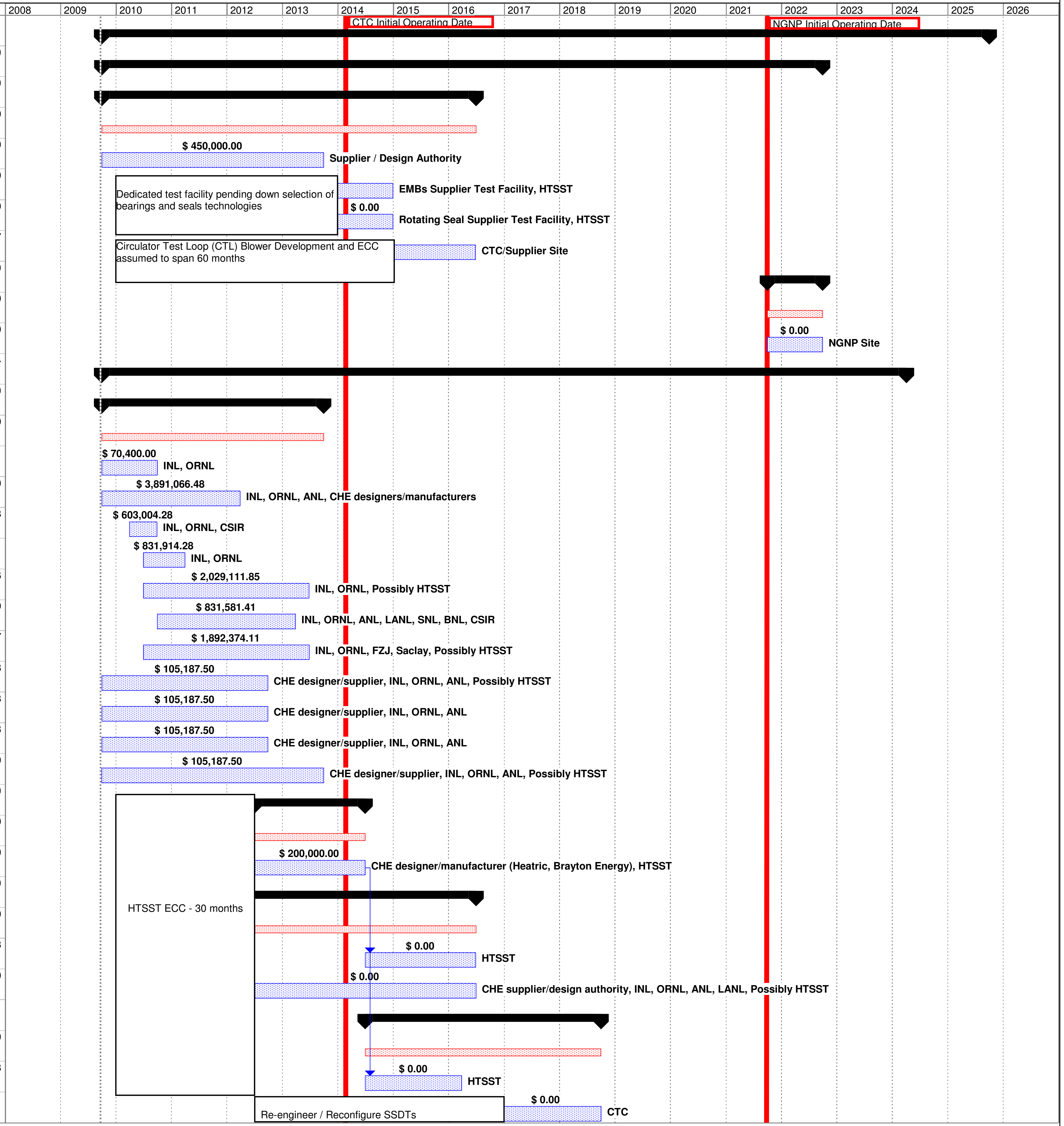
[12-5] "NGNP Technology Development Roadmapping Report," NGNP-CTF MTECH-TDRM, dated December 2008.

[12-6] "NGNP Preconceptual Design Report, Section 16: Technology Development," NGNP-16-RPT-001.

[12-7] AACE International Recommended Practice No. 17R-97 TCM Framework; 7.3-Cost Estimating and Budgeting (as supplied by BEA).

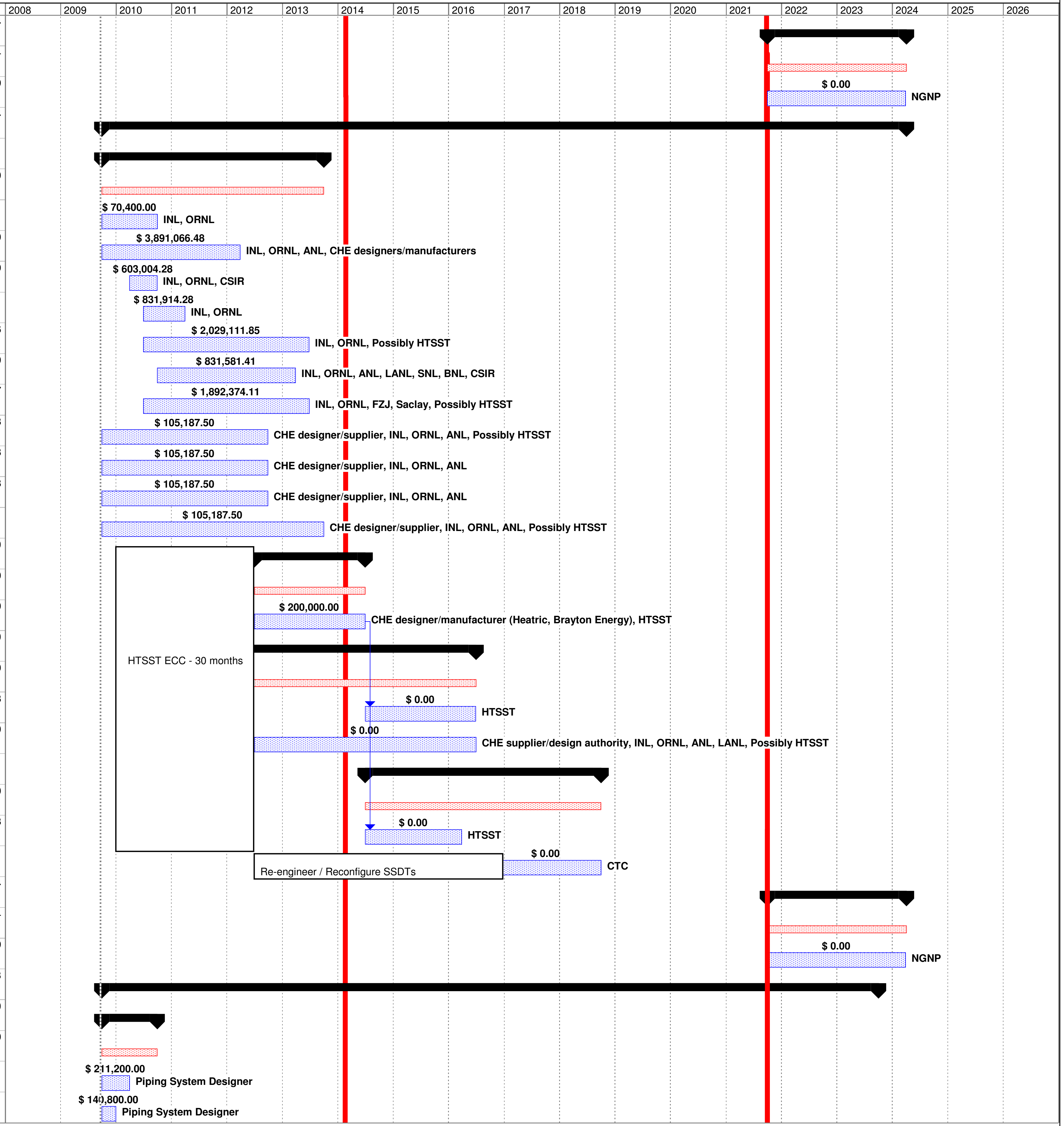
12.3 APPENDIX A: 750°C – 800°C INTEGRATED SCHEDULE

ID	Notes	Task Name	Start	Finish
1	**Test Spec Number**	**750C - 800C TDRM Schedule**	**Wed 09/09/30**	**Wed 25/10/01**
2		**PHTS Circulator**	**Thu 09/10/01**	**Fri 22/09/30**
3		**TRL 6 - TRL 7**	**Thu 09/10/01**	**Thu 16/06/30**
4		Original Schedule in TDRM	Thu 09/10/01	Thu 16/06/30
5		Trade Studies	Thu 09/10/01	Mon 13/09/30
6	WEC-TS-CIRC-001	Electro Magnetic Bearings, and Catcher Bearings Test Specification	Wed 14/01/01	Tue 14/12/30
7	WEC-TS-CIRC-002	Helium Rotating Seals Test Specification	Wed 14/01/01	Tue 14/12/30
8	WEC-TS-CIRC-003	Partial or Full Scale Circulator Model Test Specification	Thu 15/01/01	Mon 16/06/27
9		**TRL 7 - TRL 8**	**Fri 21/10/01**	**Fri 22/09/30**
10		Original Schedule in TDRM	Fri 21/10/01	Fri 22/09/30
11	WEC-TS-CIRC-004	Prototype Circulator Test Specification	Fri 21/10/01	Fri 22/09/30
12		**IHX - Alloy 800H**	**Wed 09/09/30**	**Thu 24/04/04**
13		**TRL 3 - TRL 4**	**Wed 09/09/30**	**Mon 13/09/30**
14		Original Schedule in TDRM	Thu 09/10/01	Mon 13/09/30
15	WEC-TS-IHX_800H-001	Alloy 800H Material Specification and Procurement	Thu 09/10/01	Fri 10/10/01
16	WEC-TS-IHX_800H-002	Database for Brazed and Diffusion Bonded Alloy 800H	Thu 09/10/01	Fri 12/03/30
17	WEC-TS-IHX_800H-003	Alloy 800H High Temperature Material Properties	Thu 10/04/01	Tue 10/09/28
18	WEC-TS-IHX_800H-004	Effects of Thermal Aging and Environment on Alloy 800H Properties	Thu 10/07/01	Thu 11/03/31
19	WEC-TS-IHX_800H-005	Effects of Environmental Exposure on Alloy 800H Braze and Diffusion Bonded Joints	Thu 10/07/01	Wed 13/06/26
20	WEC-TS-IHX_800H-006	Effects of Grain Size and Section Thickness on Alloy 800H Properties	Fri 10/10/01	Fri 13/03/29
21	WEC-TS-IHX_800H-007	Corrosion Allowances for Alloy 800H	Thu 10/07/01	Thu 13/06/27
22	WEC-TS-IHX_800H-008	Thermal/Fluid Modeling Methods for the Compact IHX	Thu 09/10/01	Fri 12/09/28
23	WEC-TS-IHX_800H-009	Methods for Stress/Strain Modling of the Compact IHX	Thu 09/10/01	Fri 12/09/28
24	WEC-TS-IHX_800H-010	Criteria for Structural Intergrity of the Compact IHX	Thu 09/10/01	Fri 12/09/28
25	WEC-TS-IHX_800H-011	Performance Modeling Methods for the Compact IHX	Wed 09/09/30	Mon 13/09/30
26		**TRL 4 - TRL 5**	**Sun 12/07/01**	**Mon 14/06/30**
27		Original Schedule in TDRM	Sun 12/07/01	Mon 14/06/30
28	WEC-TS-IHX_800H-012	Specification of Testing of Compact Heat Exchanger Element	Sun 12/07/01	Mon 14/06/30
29		**TRL 5 - TRL 6**	**Mon 10/09/27**	**Thu 16/06/30**
30		Original Schedule in TDRM	Mon 10/09/27	Thu 16/06/30
31	WEC-TS-IHX_800H-013	Specification of Testing of Integrated Compact Heat Exchanger Module (1.2 MW)	Tue 14/07/01	Tue 16/06/28
32	WEC-TS-IHX_800H-014	ASME Section III Code Cases for Metallic Compact Heat Exchanger Designs	Sun 12/07/01	Thu 16/06/30
33		**TRL 6 - TRL 7**	**Tue 14/07/01**	**Mon 18/10/01**
34		Original Schedule in TDRM	Tue 14/07/01	Sun 18/09/30
35	WEC-TS-IHX_800H-015	Shell-Side Flow Distribution and Bypass Leakage Testing	Tue 14/07/01	Mon 16/03/28
36	WEC-TS-IHX_800H-016	Multi-Module Heat Transfer Testing	Mon 16/10/03	Mon 18/10/01



Project: 750C-800C TDRM Schedule Date: Fri 09/09/18	Task	Progress	Summary	External Tasks	Deadline
	Split	Milestone	Project Summary	External Milestone	

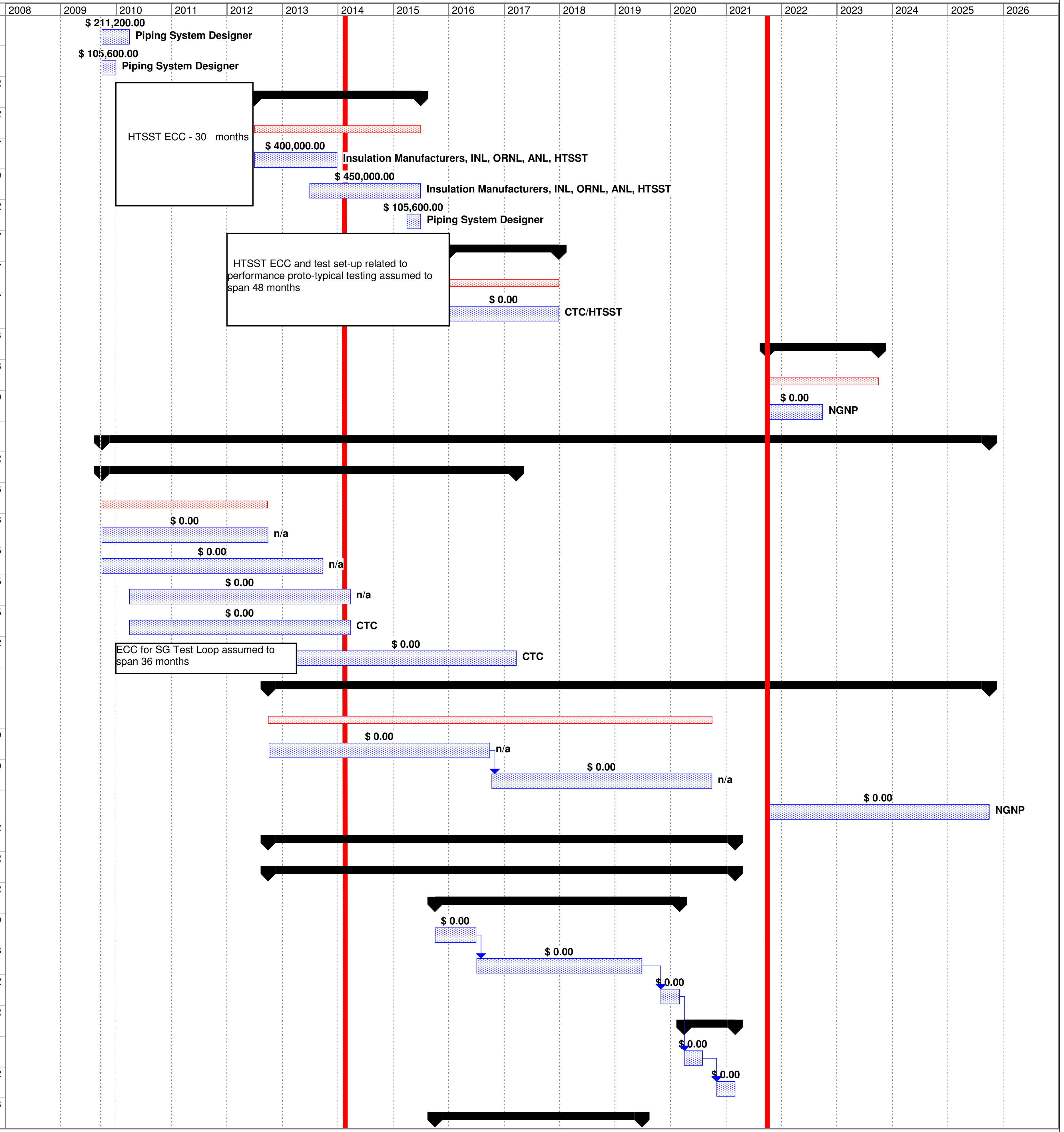
ID	Notes	Task Name	Start	Finish
37		**TRL 7 - TRL 8**	**Fri 21/10/01**	**Thu 24/04/04**
38		Original Schedule in TDRM	Fri 21/10/01	Thu 24/04/04
39	WEC-TS-IHX_800H-017	Specification of Testing of a Full Size Compact Heat Exchanger	Fri 21/10/01	Fri 24/03/29
40		**IHX - Hastelloy X**	**Thu 09/10/01**	**Thu 24/04/04**
41		**TRL 3 - TRL 4**	**Thu 09/10/01**	**Tue 13/10/01**
42		Original Schedule in TDRM	Thu 09/10/01	Mon 13/09/30
43	WEC-TS-IHX_HX-001	Hastelloy X Material Specification and Procurement	Thu 09/10/01	Fri 10/10/01
44	WEC-TS-IHX_HX-002	Database for Brazed and Diffusion Bonded Hastelloy X	Thu 09/10/01	Fri 12/03/30
45	WEC-TS-IHX_HX-003	Hastelloy X High Temperature Material Properties	Thu 10/04/01	Wed 10/09/29
46	WEC-TS-IHX_HX-004	Effects of Thermal Aging and Environment on Hastelloy X Properties	Thu 10/07/01	Thu 11/03/31
47	WEC-TS-IHX_HX-005	Effects of Environmental Exposure on Hastelloy X Braze and Diffusion Bonded Joints	Thu 10/07/01	Wed 13/06/26
48	WEC-TS-IHX_HX-006	Effects of Grain Size and Section Thickness on Hastelloy X Properties	Fri 10/10/01	Fri 13/03/29
49	WEC-TS-IHX_HX-007	Corrosion Allowances for Hastelloy X	Thu 10/07/01	Thu 13/06/27
50	WEC-TS-IHX_HX-008	Thermal/Fluid Modeling Methods for the Compact IHX	Thu 09/10/01	Fri 12/09/28
51	WEC-TS-IHX_HX-009	Methods for Stress/Strain Modling of the Compact IHX	Thu 09/10/01	Fri 12/09/28
52	WEC-TS-IHX_HX-010	Criteria for Structural Intergrity of the Compact IHX	Thu 09/10/01	Fri 12/09/28
53	WEC-TS-IHX_HX-011	Performance Modeling Methods for the Compact IHX	Thu 09/10/01	Tue 13/10/01
54		**TRL 4 - TRL 5**	**Sun 12/07/01**	**Mon 14/06/30**
55		Original Schedule in TDRM	Sun 12/07/01	Mon 14/06/30
56	WEC-TS-IHX_HX-012	Specification of Testing of Compact Heat Exchanger Element	Sun 12/07/01	Mon 14/06/30
57		**TRL 5 - TRL 6**	**Mon 10/09/27**	**Thu 16/06/30**
58		Original Schedule in TDRM	Mon 10/09/27	Thu 16/06/30
59	WEC-TS-IHX_HX-013	Specification of Testing of Integrated Compact Heat Exchanger Module (1.2 MW)	Tue 14/07/01	Tue 16/06/28
60	WEC-TS-IHX_HX-014	ASME Section III Code Cases for Metallic Compact Heat Exchanger Designs	Sun 12/07/01	Thu 16/06/30
61		**TRL 6 - TRL 7**	**Tue 14/07/01**	**Mon 18/10/01**
62		Original Schedule in TDRM	Tue 14/07/01	Sun 18/09/30
63	WEC-TS-IHX_HX-015	Shell-Side Flow Distribution and Bypass Leakage Testing	Tue 14/07/01	Mon 16/03/28
64	WEC-TS-IHX_HX-016	Multi-Module Heat Transfer Testing	Mon 16/10/03	Mon 18/10/01
65		**TRL 7 - TRL 8**	**Fri 21/10/01**	**Thu 24/04/04**
66		Original Schedule in TDRM	Fri 21/10/01	Thu 24/04/04
67	WEC-TS-IHX_HX-017	Specification of Testing of a Full Size Compact Heat Exchanger	Fri 21/10/01	Fri 24/03/29
68		**Piping**	**Thu 09/10/01**	**Tue 23/10/03**
69		**TRL 4 - TRL5**	**Thu 09/10/01**	**Thu 10/09/30**
70		Original Schedule in TDRM	Thu 09/10/01	Thu 10/09/30
71	WEC-TS-PIP750-001	PHTS High-temperature [750°C and 800°C] Piping Cooling, Liner and Insulation Options Trade Study	Thu 09/10/01	Thu 10/04/01
72	WEC-TS-PIP750-002	PHTS Low-temperature [~280°C] Piping Liner and Insulation Options Trade Study	Thu 09/10/01	Fri 10/01/01



Project: 750C-800C TDRM Schedule
Date: Fri 09/09/18

Task		Progress		Summary		External Tasks		Deadline	
Split		Milestone		Project Summary		External Milestone			

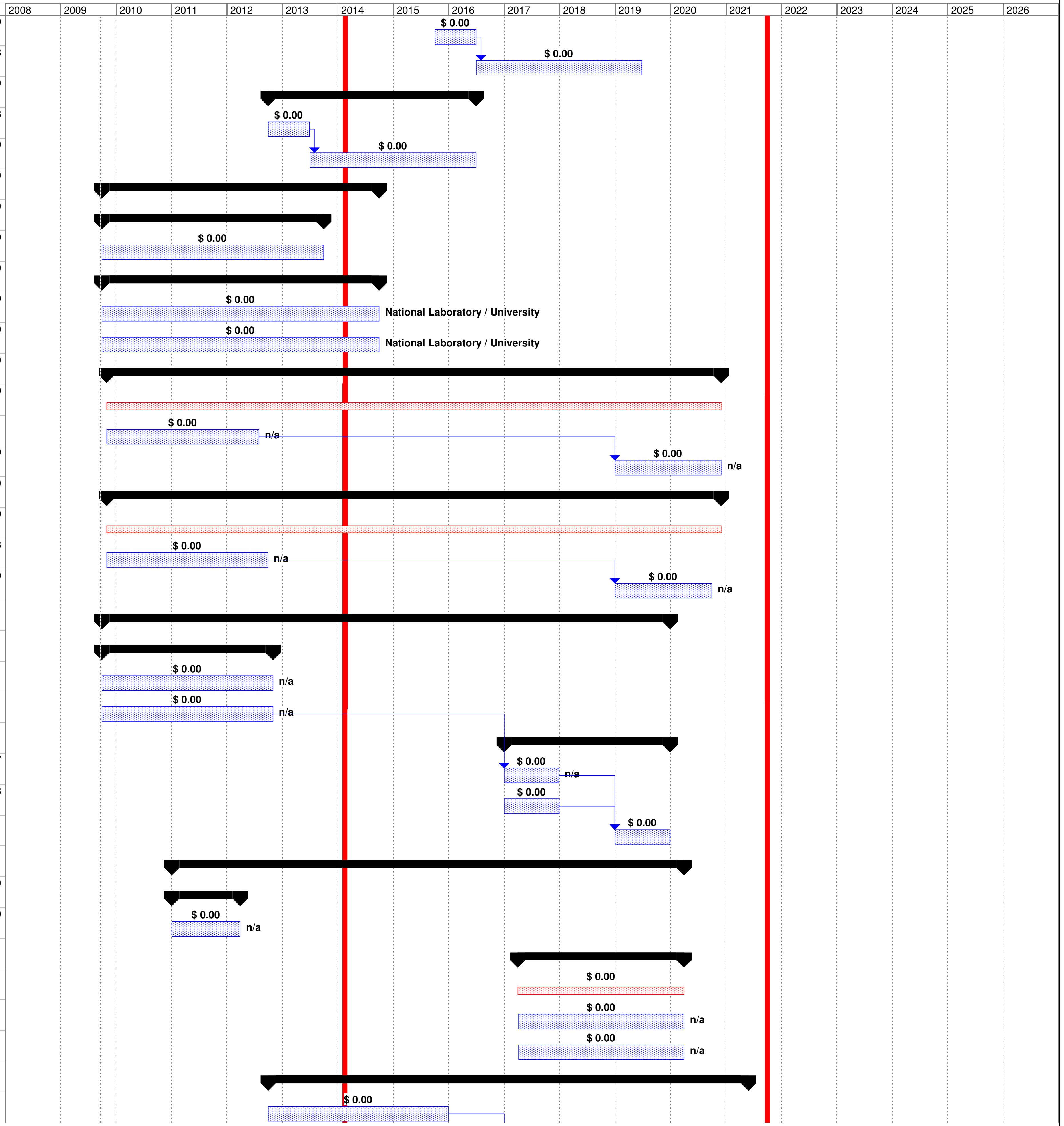
ID	Notes	Task Name	Start	Finish
73	WEC-TS-PIP750-003	SHTS High-temperature [700°C and 750°C] Piping Liner and Insualtion Options Trade Study	Thu 09/10/01	Thu 10/04/01
74	WEC-TS-PIP750-004	SHTS Low-temperature [~220°C] Piping Liner and Insulation Trade Study	Thu 09/10/01	Fri 10/01/01
75		**TRL 5 - TRL 6**	**Sun 12/07/01**	**Thu 15/07/02**
76		Original Schedule in TDRM	Sun 12/07/01	Thu 15/07/02
77	WEC-TS-PIP750-005	Effects of Helium Infiltration on Thermal Conductivity of Insulation Material	Sun 12/07/01	Fri 13/12/27
78	WEC-TS-PIP750-006	The Effect of Solid Impurities (C) on Insulation Properties	Mon 13/07/01	Tue 15/06/30
79	WEC-TS-PIP750-007	Re-evaluation of Needed Maturation Tasks Based on Trade Study Results	Wed 15/04/01	Thu 15/07/02
80		**TRL 6 - TRL 7**	**Fri 16/01/01**	**Wed 17/12/27**
81		Original Schedule in TDRM	Fri 16/01/01	Wed 17/12/27
82	WEC-TS-PIP750-008	Performance and Environmental Testing of Prototypical High-Temperature and Low-Temperature Piping/Insulation System	Fri 16/01/01	Wed 17/12/27
83		**TRL 7 - TRL 8**	**Fri 21/10/01**	**Tue 23/10/03**
84		Original Schedule in TDRM	Fri 21/10/01	Tue 23/10/03
85	WEC-TS-PIP750-009	Specification of Testing of Full Sized HTS Piping in NGNP	Fri 21/10/01	Fri 22/09/30
86		**Steam Generator**	**Thu 09/10/01**	**Wed 25/10/01**
87		**TRL 6 - TRL 7**	**Thu 09/10/01**	**Wed 17/03/22**
88		Original Schedule in TDRM	Thu 09/10/01	Wed 12/09/26
89		Down Selection Trade Study: Determine the Preferred Conceptual Arrangement of the Steam Generator	Thu 09/10/01	Fri 12/09/28
90		Define Requirements and Design Details for the SG in the PCS System Context	Thu 09/10/01	Wed 13/09/25
91		Perform Configuration Development Tests to Substantiate the Design	Thu 10/04/01	Tue 14/03/25
92		Design and Supply a Scale Prototype for the Testing in the CTC/HTSST	Thu 10/04/01	Tue 14/03/25
93		Performance Testing in CTC/HTSST	Mon 13/04/01	Wed 17/03/22
94		**TRL 7 - TRL 8**	**Mon 12/10/01**	**Wed 25/10/01**
95		Original Schedule in TDRM	Mon 12/10/01	Thu 20/10/01
96		Complete Final Design of the Prototype SG for the NGNP	Fri 12/10/05	Thu 16/09/29
97		Fabricate and Deliver SG to NGNP Site	Tue 16/10/11	Wed 20/09/30
98		Install and Operate SG in NGNP	Fri 21/10/01	Wed 25/10/01
99		**Fuel Elements**	**Mon 12/10/01**	**Tue 21/03/02**
100		**TRL 7 - TRL 8**	**Mon 12/10/01**	**Tue 21/03/02**
101	**WEC-TS-FUEL-001**	**Production Fuel Irradiation Tests for DPP Normal Operational Conditions**	**Mon 15/10/05**	**Mon 20/03/02**
102		Irradiation Planning & Preparation	Mon 15/10/05	Thu 16/06/30
103		Irradiation of Pre-Production Fuel	Tue 16/07/05	Fri 19/06/28
104		PIE and Analysis	Wed 19/10/30	Mon 20/03/02
105	**WEC-TS-FUEL-002**	**Production Fuel Heat-up Tests at 1600°C and 1800°C.**	**Wed 20/04/01**	**Tue 21/03/02**
106		Physical Heating Test	Wed 20/04/01	Fri 20/07/31
107		PIE and Analysis of Heated Spheres	Mon 20/11/02	Tue 21/03/02
108	**WEC-TS-FUEL-003**	**Fuel Matrix Graphite Irradiation tests and PIE**	**Mon 15/10/05**	**Fri 19/06/28**



Project: 750C-800C TDRM Schedule
Date: Fri 09/09/18

Task		Progress		Summary		External Tasks		Deadline	
Split		Milestone		Project Summary		External Milestone			

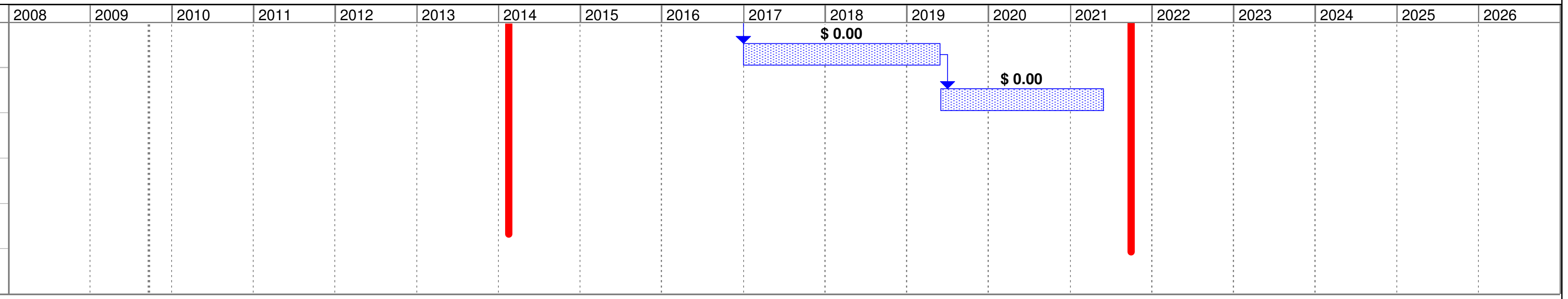
ID	Notes	Task Name	Start	Finish
109		Irradiation Planning & Preparation	Mon 15/10/05	Thu 16/06/08
110		Irradiation and PIE	Fri 16/07/01	Fri 19/06/28
111	**WEC-TS-FUEL-004**	**Machined Graphite Irradiation Tests and PIE**	**Mon 12/10/01**	**Thu 16/06/30**
112		Irradiation Planning & Preparation	Mon 12/10/01	Fri 13/06/28
113		Irradiation and PIE	Wed 13/07/03	Thu 16/06/30
114		**Core Structure Ceramics**	**Thu 09/10/01**	**Tue 14/09/30**
115		**TRL 6 - TRL 7**	**Thu 09/10/01**	**Mon 13/09/30**
116	WEC-TS-CSC-001	PBMR CSC Qualification Program	Thu 09/10/01	Mon 13/09/30
117		**TRL 7 - TRL 8**	**Thu 09/10/01**	**Tue 14/09/30**
118	WEC-TS-CSC-002	Extended Properties of Irradiated Graphite at Low Temperatures	Thu 09/10/01	Tue 14/09/30
119	WEC-TS-CSC-004	Characterize Race Track Strap and Tie Rod Material	Thu 09/10/01	Tue 14/09/30
120		**Reserve Shutdown System**	**Mon 09/11/02**	**Mon 20/11/30**
121		Original Schedule in TDRM	Mon 09/11/02	Mon 20/11/30
122		TRL 6 - TRL 7	Mon 09/11/02	Tue 12/07/31
123		TRL 7 - TRL 8	Tue 19/01/01	Mon 20/11/30
124		**Reactivity Control System**	**Mon 09/11/02**	**Mon 20/11/30**
125		Original Schedule in TDRM	Mon 09/11/02	Mon 20/11/30
126		TRL 6 - TRL 7	Mon 09/11/02	Fri 12/09/28
127		TRL 7 - TRL 8	Tue 19/01/01	Wed 20/09/30
128		**Core Conditioning System**	**Thu 09/10/01**	**Tue 19/12/31**
129		**TRL 6 - TRL 7**	**Thu 09/10/01**	**Wed 12/10/31**
130	WEC-TS-CCS-001	Valves development Test Specification	Thu 09/10/01	Wed 12/10/31
131	WEC-TS-CCS-002	Blower development Test Specification	Thu 09/10/01	Wed 12/10/31
132		**TRL 7 - TR8**	**Mon 17/01/02**	**Tue 19/12/31**
133	WEC-TS-CCS-003	Cold CCS Integrated Functional Testing	Mon 17/01/02	Wed 17/12/27
134	WEC-TS-CCS-004	CCS Blower at Operational Temperaures	Mon 17/01/02	Thu 17/12/28
135	WEC-TS-CCS-005	Hot (Nuclear) CCS Integrated Functional Testing	Tue 19/01/01	Tue 19/12/31
136		**Reactor Cavity Cooling System**	**Wed 11/01/05**	**Tue 20/03/31**
137		**TRL 6 - TRL 7**	**Wed 11/01/05**	**Fri 12/03/30**
138		Software Analysis	Wed 11/01/05	Fri 12/03/30
139		**TRL 7 - TRL 8**	**Sun 17/04/02**	**Tue 20/03/31**
140		Original Schedule in TDRM	Sun 17/04/02	Tue 20/03/31
141	WEC-TS-RCCS-001	Assess the Active Functioning of the RCCS	Thu 17/04/06	Tue 20/03/31
142	WEC-TS-RCCS-002	Assess the Passive Functioning of the RCCS	Thu 17/04/06	Tue 20/03/31
143		**Fuel Handling & Storage System**	**Mon 12/10/01**	**Mon 21/05/31**
144		TRL 5 - TRL 6	Mon 12/10/01	Thu 15/12/31



Project: 750C-800C TDRM Schedule
Date: Fri 09/09/18

Task		Progress		Summary		External Tasks		Deadline	
Split		Milestone		Project Summary		External Milestone			

ID	Notes	Task Name	Start	Finish
145		TRL 6 - TRL 7	Mon 17/01/02	Fri 19/05/31
146		TRL 7 - TRL 8	Mon 19/06/03	Mon 21/05/31



Project: 750C-800C TDRM Schedule Date: Fri 09/09/18	Task		Progress		Summary		External Tasks		Deadline
	Split		Milestone		Project Summary		External Milestone		

12.4 APPENDIX B: DETAILED COST ESTIMATION SHEETS

Table 9: Costs related to test specification WEC-TS-IHX_800H-001

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-001	Alloy 800H Material Specifications and Procurement	Finalize material specifications, develop procurement requirements, procure 1 to 2 heats of Alloy 800H	No test equipment / facility is needed except for existing conventional test machines (e.g. tensile test machine) for confirming that 800H material procured meets specification.

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Time needed Hours	Time needed Days	Time needed Weeks	Time needed Months	Total ($)	Assumptions/Bases
Alloy 800H procurement specification	Engineer	200	N/A	8	5	8		64,000	Based on time needed to compile procurement specification, inspection during procurement production (production/rolling/sampling) as well as compiling report.

Cost Summary

Total ($)	**64,000**
10% contingency ($)	**6,400**
Grand total ($)	**70,400**

Table 10: Costs related to test specification WEC-TS-IHX_800H-002

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-002	Database for Brazed and Diffusion Bonded Alloy 800H	Demonstrate that Alloy 800H can be brazed, diffusion bonded and that joint properties are appropriate for use in compact heat exchangers.	Activities require equipment and facilities for brazing and diffusion bonding, microscopical examination and mechanical property testing.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Weld design/Compiling W-BR-DB specification	Engineer	200		8	5	4	3		96,000	Assuming 1 month needed per joining method to compile specification (W/BR/DB).
Welding of joints (W/BR/DB)	Coded welder	100		8	5	46			184,000	549 samples to be joined. Due to large uncertainty of the time needed to establish diffusion bonded specimens, assume that 12 samples/week are to be joined (irrespective of joining method).
Conducting testing: Joint properties	Lab. Technician	80	n/a	8	5	61			195,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	61			488,000	Assuming that 9 samples/week are tested (due to large time uncertainty for fatigue testing).
Total 1 ($)									**963,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. [2] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding, pre-testing) [3]										
Cutting, polishing	549		640	351,360					351,360	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	549		400	219,600					219,600	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist/Engineering input at $200/hour.
Chemistry profile in joints	549		400	219,600					219,600	
Thermal Physical Mechanical properties of W/BR/DB joints										
Elastic properties [4]	18	7,200	350	6,300	n/a	n/a	n/a	6,000	19,500	$350 / specimen at 950℃ (+- 30℃).
Tensile Properties [5]	45	18,000	350	15,750	n/a	n/a	n/a	6,000	39,750	$350 / specimen at 950℃ (+- 30℃).
Fatigue Strength (LCF)	135	54,000	720	97,200	66,000	n/a	n/a	12,000	229,200	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour thereafter / specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	135	54,000	800	108,000	66,000	n/a	n/a	12,000	240,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles / specimen at 950℃ (+- 30℃).
Creep strength	144	57,600	3,500	504,000	n/a	n/a	n/a	6,000	567,600	Creep strength to 1000℃ for 10,000 h - $3500 / specimen.
Fracture toughness: CTOD	27	10,800	1,000	27,000	n/a	n/a	n/a	6,000	43,800	Fracture toughness: CTOD - $1000 at 650℃ / specimen.
Fracture toughness: Kc	27	10,800	560	15,120	n/a	n/a	n/a	6,000	31,920	Fracture toughness: Kc - $560 at 650℃ / specimen.
Thermal conductivity	18	7,200	95	1,710	n/a	n/a	n/a	6,000	14,910	Thermal conductivity to 1000℃: $95 / specimen.
Metallography/Optical/SEM (post-welding,post-testing) [6]										
Cutting, polishing, etching sample	549		640	351,360					351,360	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	549		400	219,600					219,600	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**219,600**		**2,136,600**	**132,000**	**0**	**0**	**60,000**	**2,548,200**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy 800H samples [7]	n/a	n/a	25,933	25,933	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**25,933**	

Table 10 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-002	Database for Brazed and Diffusion Bonded Alloy 800H	Demonstrate that Alloy 800H can be brazed, diffusion bonded and that joint properties are appropriate for use in compact heat exchangers.	Activities require equipment and facilities for brazing and diffusion bonding, microscopical examination and mechanical property testing.

Cost Summary

Total ($)	**3,537,333**
10% contingency ($)	**353,733**
Grand total ($)	**3,891,066**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Assuming that all the joined samples are to be checked for joint integrity after joining.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Optical/SEM work to be conducted for tensile, fatigue (HCF & LCF) and creep.
[7] Refer to 'material cost' sheet for material costing aspects.

W = Welding
BR = Brazing
DB = Diffusion Bonding

Table 11: Costs related to test specification WEC-TS-IHX_800H-003

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-003	Alloy 800H High Temperature Material Properties	Demonstrate that procured Alloy 800H will have thermal, physical and mechanical properties appropriate for use in compact heat exchangers.	N/A

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Conducting testing	Laboratory Technician	80	n/a	8	5	21			67,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	21			168,000	
Total 1 ($)									**235,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. [2] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis [3]	Reporting	Total ($)	Assumptions/Bases
Thermal Physical Mechanical properties										
Elastic properties [4]	2	800	350	700	n/a	n/a	n/a	6,000	7,500	$350 per specimen at 950℃ (+- 30℃).
Tensile Properties [5]	5	2,000	350	1,750	n/a	n/a	n/a	6,000	9,750	$350 per specimen at 950℃ (+- 30℃).
Fatigue Strength (LCF)	15	6,000	720	10,800	66,000	n/a	3,000	12,000	97,800	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour there after / specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	15	6,000	800	12,000	66,000	n/a	3,000	12,000	99,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles / specimen at 950℃ (+- 30℃).
Creep strength	16	6,400	3,500	56,000	n/a	n/a	n/a	6,000	68,400	Creep strength to 1000℃ for 10,000 h - $3500 / specimen.
Fracture toughness: CTOD	3	1,200	1,000	3,000	n/a	n/a	600	6,000	10,800	Fracture toughness: CTOD - $1000 at 650℃ / specimen.
Fracture toughness: Kc	3	1,200	560	1,680	n/a	n/a	600	6,000	9,480	Fracture toughness: Kc - $560 at 650℃ / specimen.
Thermal conductivity	2	800	95	190	n/a	n/a	400	6,000	7,390	Thermal conductivity to 1000℃: - $95 / specimen.
Total 2 ($)		**24,400**		**86,120**	**132,000**	**0**	**7,600**	**60,000**	**310,120**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy 800H samples [6]	n/a	n/a	2,866	2,866	Costing based on material price of $35/kg.
Total 3 ($)				**2,866**	

Cost Summary

Total ($)	**548,186**
10% contingency ($)	**54,819**
Grand total ($)	**603,004**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Post test analyses includes possible optical and scanning electron microscopy work and is based engineer/scientist tariff of $200/hour.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Refer to 'material cost' sheet for material costing aspects.

Table 12: Costs related to test specification WEC-TS-IHX_800H-004

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-004	Effects of Thermal Aging and Environment on Alloy 800H properties	Agree to except existing databases on the effects of thermal aging and environmental exposure on the thermal, physical and mechanical properties of Alloy 800H	N/A

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Welding of joints (W/BR/DB)	Coded welder	n/a	n/a	n/a	n/a	n/a			0	
Oversee & Manage: Thermal exposure of samples - 10,000h	Laboratory Technician	100	n/a	100					10,000	Thermal exposure monitored by lab technician every 100h (100 intervals).
Conducting testing: Alloy properties	Laboratory Technician	80	n/a	8	5	21			67,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	21			168,000	
Total 1 ($)									**245,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. [2] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding, pre-testing) [3]										
Cutting, polishing sample	61	n/a	640	39,040		n/a	n/a	n/a	39,040	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	61	n/a	400	24,400		n/a	n/a	6,000	30,400	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Chemistry profile in joints	61	n/a	400	24,400		n/a	n/a	6,000	30,400	
Thermal Physical Mechanical properties of Alloy 800H and W/BR/DB joints										
Elastic properties [4]	2	800	350	700	n/a	n/a	n/a	6,000	7,500	$350 / specimen at 950°C (+- 30°C).
Tensile Properties [5]	5	2,000	350	1,750	n/a	n/a	n/a	6,000	9,750	$350 / specimen at 950°C (+- 30°C).
Fatigue Strength (LCF)	15	6,000	720	10,800	66,000	n/a	n/a	12,000	94,800	Fatigue strength LCF to 1000°C - $720 up to 80 000 cycles + $20/hour there after / specimen at 950°C (+- 30°C).
Fatigue strength (HCF)	15	6,000	800	12,000	66,000	n/a	n/a	12,000	96,000	Fatigue strength HCF to 1000°C - $800 up to 1000 000 cycles / specimen at 950°C (+- 30°C).
Creep strength	16	6,400	3,500	56,000	n/a	n/a	n/a	6,000	68,400	Creep strength to 1000°C for 10,000 h - $3500 / specimen.
Fracture toughness: CTOD	3	1,200	1,000	3,000	n/a	n/a	n/a	6,000	10,200	Fracture toughness: CTOD - $1000 at 650°C / specimen.
Fracture toughness: Kc	3	1,200	560	1,680	n/a	n/a	n/a	6,000	8,880	Fracture toughness: Kc - $560 at 650°C / specimen.
Thermal conductivity	2	800	95	190	n/a	n/a	n/a	6,000	6,990	Thermal conductivity to 1000°C: - $95 / specimen.
Metallography/SEM (post-welding, post-testing) [6]										
Cutting, polishing, etching sample	61	n/a	640	39,040		n/a	n/a	n/a	39,040	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	61	n/a	400	24,400		n/a	n/a	6,000	30,400	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**24,400**		**237,400**	**132,000**	**0**	**0**	**78,000**	**471,800**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy 800H samples [7]	n/a	n/a	2,866	2,866	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**2,866**	

Table 12 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-004	Effects of Thermal Aging and Environment on Alloy 800H properties	Agree to except existing databases on the effects of thermal aging and environmental exposure on the thermal, physical and mechanical properties of Alloy 800H	N/A

Other

Additional requirements	Unit price ($)	Quantity	Total ($)	Assumptions/Bases
Capital cost - furnaces for thermal aging	3,000	3	9,000	Furnace with required capability sized at 180mm x 180mm x 250mm.
Contingencies (power consumption, element replacement)	900	1	900	Furnace contingencies make up 10% of total capital cost for furnaces.
Helium gas for regulating environment	120	156	18,720	156 50kg x He cylinders to be utilized. One cylinder a week for each furnace (52 weeks in total). He gas cost inclusive of impurity gases.
Sampling gas analyses	150	52	7,800	Sampling of furnace testing environment done once a week by external institution. Collective sampling from 3 furnaces add up to $150/week.
Total 4 ($)			**36,420**	

Cost Summary

Total ($)	**756,286**
10% contingency ($)	**75,629**
Grand total ($)	**831,914**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Assuming that all samples to be checked for joint consistency after joining.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Optical/SEM work to be conducted for tensile, fatigue (HCF, LCF), creep.
[7] Refer to 'material cost' sheet for material costing aspects.

Table 13: Costs related to test specification WEC-TS-IHX_800H-005

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-005	Effects of Environmental Exposure on Alloy 800H Joints	Determine response of the properties of welded, brazed and diffusion bonded Alloy 800H to exposures in NGNP helium environments	Facility will be needed for exposure of specimens of welded, brazed and diffusion bonded Alloy 800H to helium environments representative of NGNP. Equipment will also be needed for conducting tensile, creep, fatigue and fracture toughness tests. Instruments will be needed for post-test characterization.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Welding of joints (W/BR/DB)	Coded welder	100	n/a	8	5	46			184,000	549 samples to be joined. Assume 12 samples/week. Based on metallic IHX A (see adjustment factor).
Oversee & Manage: Thermal exposure of samples - 10,000h	Laboratory Technician	100	n/a	100					10,000	Thermal exposure monitored by lab technician every 100h (100 intervals). Based on metallic IHX A (see adjustment factor).
Conducting testing: Alloy/Joint properties	Laboratory Technician	80	n/a	8	5	61			195,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	61			488,000	
Total 1 ($)									**877,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding, pre-testing) [3]										
Cutting, polishing sample	183	n/a	640	117,120		n/a	n/a	n/a	117,120	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	183	n/a	400	73,200		n/a	n/a	500	73,200	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Chemistry profile in joints	183	n/a	400	73,200		n/a	n/a	500	73,200	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Thermal Physical Mechanical properties of Alloy 800H and W/BR/DB joints										
Elastic properties [4]	6	2,400	350	2,100	n/a	n/a	n/a	500	5,000	$350 per specimen at 950℃ (+- 30℃).
Tensile Properties [5]	15	6,000	350	5,250	n/a	n/a	n/a	500	11,750	$350 per specimen at 950℃ (+- 30℃).
Fatigue Strength (LCF)	45	18,000	720	32,400	66,000	n/a	n/a	1,000	117,400	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour there after per specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	45	18,000	800	36,000	66,000	n/a	n/a	1,000	121,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles per specimen at 950℃ (+- 30℃).
Creep strength	48	19,200	3,500	168,000	n/a	n/a	n/a	500	187,700	Creep strength to 1000℃ for 10,000 h - $3500 per specimen. Based on metallic IHX A (see adjustment factor).
Fracture toughness: CTOD	9	3,600	1,000	9,000	n/a	n/a	n/a	500	13,100	Fracture toughness: CTOD - $1000 at 650℃ per specimen. Based on metallic IHX A (see adjustment factor).
Fracture toughness: Kc	9	3,600	560	5,040	n/a	n/a	n/a	500	9,140	Fracture toughness: Kc - $560 at 650℃ per specimen. Based on metallic IHX A (see adjustment factor).
Thermal conductivity	6	2,400	100	600	n/a	n/a	n/a	500	3,500	Thermal conductivity to 1000℃: - $95 per specimen. Based on metallic IHX A (see adjustment factor).
Metallography/SEM (post-welding, post-testing) [6]										
Cutting, polishing, etching sample	183	n/a	640	117,120		n/a	n/a	n/a	117,120	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	183	n/a	400	73,200		n/a	n/a	500	73,200	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**73,200**		**712,230**	**132,000**	**0**	**0**	**6,500**	**922,430**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy 800H samples [7]	n/a	n/a	8,597	8,597	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**8,597**	

Table 13 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-005	Effects of Environmental Exposure on Alloy 800H Joints	Determine response of the properties of welded, brazed and diffusion bonded Alloy 800H to exposures in NGNP helium environments	Facility will be needed for exposure of specimens of welded, brazed and diffusion bonded Alloy 800H to helium environments representative of NGNP. Equipment will also be needed for conducting tensile, creep, fatigue and fracture toughness tests. Instruments will be needed for post-test characterization.

Other

Additional requirements	Unit price ($)	Quantity		Total ($)	Assumptions/Bases
Capital cost - furnaces for thermal aging	3,000	3		9,000	Furnace with required capability sized at 180mm x 180mm x 250mm.
Contingencies (power consumption, element replacement)	900	1		900	Furnace contingencies make up 10% of total capital cost for furnaces.
Helium gas for regulating environment	120	156		18,720	156 x 50kg He cylinders to be utilized. One cylinder a week for each furnace. He gas cost inclusive of impurity gases.
Sampling gas analyses	150	52		7,800	Sampling of furnace testing environment done once a week by external institution. Collective sampling from 3 furnaces add up to $150/week.
Total 4 ($)				**36,420**	

Cost Summary

Total ($)	**1,844,647**
10% contingency ($)	**184,465**
Grand total ($)	**2,029,112**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Assuming that all samples to be checked for joint consistency after joining.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Optical/SEM work to be conducted for tensile, fatigue (HCF, LCF), creep.
[7] Refer to 'material cost' sheet for material costing aspects.

Table 14: Costs related to test specification WEC-TS-IHX_800H-006

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-006	Effects of Grain Size and Section Thickness on Alloy 800H	Demonstrate that slight changes in grain size as well as the section thickness of Alloy 800H has little effect in overall properties of material.	Conduct of this work requires equipment or facilities for creep and fatigue measurement and for metallographic determination of grain size.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Conducting testing: Alloy 800H properties	Laboratory Technician	80	n/a	8	5	16			51,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	16			128,000	
Total 1 ($)									**179,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Thermal Physical Mechanical properties of Alloy 800H										
Fatigue Strength (LCF)	45	18,000	720	32,400	66,000	n/a	n/a	1,000	117,400	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour there after / specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	45	18,000	800	36,000	66,000	n/a	n/a	1,000	121,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles / specimen at 950℃ (+- 30℃).
Creep strength	48	19,200	3,500	168,000	n/a	n/a	n/a	500	187,700	Creep strength to 1000℃ for 10,000 h - $3500 / specimen.
Metallography/SEM (post-testing) [3]										
Cutting, polishing, etching sample	138		640	88,320		n/a	n/a	n/a	88,320	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	138		400	55,200		n/a	n/a	500	55,200	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**55,200**		**379,920**	**132,000**	**0**	**0**	**3,000**	**569,620**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy 800H samples [4]	n/a	n/a	7,163	7,163	Costing based on material price of $35/kg. Number of samples only relevant to fatigue testing and creep testing.
Total 3 ($)				**7,163**	

Cost Summary

Total ($)	**755,983**
10% contingency ($)	**75,598**
Grand total ($)	**831,581**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Optical/SEM work to be conducted for fatigue and creep samples.
[4] Refer to 'material cost' sheet for material costing aspects.

Table 15: Costs related to test specification WEC-TS-IHX_800H-007

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-007	Corrosion Allowances for Alloy 800H	Demonstrate satisfactory corrosion allowances for Alloy 800H and welded/bonded sections	Facility for exposure in a helium environment with low levels of controlled and measured CO, CO2, H2, H2O and CH4 for up to 10 000 hours, will be required. Metallographic and SEM equipment required for determination of thickness of oxides and depths of internal oxidation, alloy element depletion and carburization / decarburization.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Action	Hours	Duration Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Welding of joints (W/BR/DB)	Coded welder	100	n/a	8	5	12			48,000	135 samples to be joined. Assume 12 samples/week. Based on metallic IHX A (see adjustment factor).
Oversee & Manage: Thermal exposure of samples - 10,000h	Laboratory Technician	100	n/a	100					10,000	Thermal exposure monitored by lab technician every 100h (100 intervals).
Oversee & Manage	Engineer	200	n/a	8	5	20			160,000	
Total 1 ($)									**218,000**	

Testing (All costs in $)

Task requirement	Samples	Prep. [1] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding) [2]										
Cutting, polishing sample	162	n/a	640	103,680		n/a	n/a	n/a	103,680	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	162	n/a	400	64,800		n/a	n/a	500	64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Chemistry profile in joints	162	n/a	400	64,800		n/a	n/a	500	64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Thermal Physical Mechanical properties of Alloy 800H and W/BR/DB joints										
n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
Metallography/SEM (post-testing)										
Cutting, polishing, etching sample	162	n/a	640	103,680		n/a	n/a	n/a	103,680	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	162	n/a	400	64,800		n/a	n/a	500	64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Depth of internal oxidation	162	n/a	400	64,800				500	65,300	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Depth of depletion of alloy elements (Cr)	162	n/a	400	64,800				500	65,300	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Depth affected bycarburization/ decarburization	162	n/a	400	64,800					64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**0**		**596,160**	**0**	**0**	**0**	**2,500**	**597,160**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy 800H samples [3]	n/a	n/a	8,590	8,590	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**8,590**	

Other

Additional requirements	Unit price ($)	Quantity	Total ($)	Assumptions/Bases
Capital cost - furnaces for thermal aging	3,000	3	9,000	Furnace with required capability sized at 180mm x 180mm x 250mm.
Contingencies (power consumption, element replacement)	900	1	900	Furnace contingencies make up 10% of total capital cost for furnaces.
Helium gas for regulating environment	120	156	18,720	156 x 50kg He cylinders to be utilized. One cylinder a week for each furnace. He gas cost inclusive of impurity gases.
Sampling gas analyses	150	52	7,800	Sampling of furnace testing environment done once a week by external institution. Collective sampling from 3 furnaces add up to $150/week.
Total 4 ($)			**36,420**	

Table 15 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-007	Corrosion Allowances for Alloy 800H	Demonstrate satisfactory corrosion allowances for Alloy 800H and welded/bonded sections	Facility for exposure in a helium environment with low levels of controlled and measured CO, CO2, H2, H2O and CH4 for up to 10 000 hours, will be required. Metallographic and SEM equipment required for determination of thickness of oxides and depths of internal oxidation, alloy element depletion and carburization / decarburization.

Cost Summary

Total ($) (Primary side He effects)	**860,170**
Secondary side He effects ($)	**860,170**
Total (Primary and secondary effects) ($)	**1,720,340**
10% contingency ($)	**172,034**
Grand total ($)	**1,892,374**

[1] Basis for preparation costs - $400/sample.
[2] Assuming that all joined samples to be checked for joint consistency after joining.
[3] Refer to 'material cost' sheet for material costing aspects.

Table 16: Costs related to test specification WEC-TS-IHX_800H-008

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-008	Thermal/Fluid Modeling Methods for the Compact IHX	Develop thermal models for the compact IHX	Models will be applied to the results obtained under DDN HTS-01-17.

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Model generation giving results for mechanical, physical and thermal performance prediction	Group of thermal fluid/modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech - Duration and cost is greatly dependant on the data supplied by suppliers (transfer coefficients). Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 17: Costs related to test specification WEC-TS-IHX_800H-009

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-009	Methods for Stress-Strain Modeling of the compact IHX	Develop structural modelling methods for predictive operation for the compact IHX	Models will be applied to the results obtained under DDN HTS-01-17.

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Structural model generation giving results for predictive operation for IHX B	Group of modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech Industria. Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 18: Costs related to test specification WEC-TS-IHX_800H-010

Critical SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-010	Criteria for Structural Integrity of the Compact IHX	Establish criteria for structural integrity of compact heat exchangers	N/A

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Structural integrity models of CHE's	Group of modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech Industrial. Duration and cost is greatly dependant on the data supplied by suppliers (transfer coefficients). Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 19: Costs related to test specification WEC-TS-IHX_800H-011

Crit SSC	Specification number	Specification	Description	Comments
IHX_800H	WEC-TS-IHX-011	Performance Modeling Methods for the IHX	Develop performance models for predictive operation for compact heat exchangers	N/A

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Performance models for IHX	Group of modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech Industrial. Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 20: Material Costs

Material cost details based on preferred number of samples to be tested - Alloy 800H (@ $35/kg)

Test Reference		IHX_800H.2		IHX_800H.3		IHX_800H.4		IHX_800H.5		IHX_800H.6		IHX_800H.7		Grand Total ($)
Sample amount		549		61		61		183		138		162		
	Per sample cost - 800H ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	
Elastic Properties	**0.7875**	18	14.175	2	1.575	2	1.575	6	4.725	0	0	0	0	
Tensile Properties	**0.7875**	45	35.4375	5	3.9375	5	3.9375	15	11.8125	0	0	0	0	
Fatigue strength (LCF)	**78.75**	135	10631.25	15	1181.25	15	1181.25	45	3543.75	45	3543.75	54	4252.5	
Fatigue strength (HCF)	**78.75**	135	10631.25	15	1181.25	15	1181.25	45	3543.75	45	3543.75	54	4252.5	
Creep strength	**1.575**	144	226.8	16	25.2	16	25.2	48	75.6	48	75.6	54	85.05	
Fracture toughness: CTOD	**78.75**	27	2126.25	3	236.25	3	236.25	9	708.75	0	0	0	0	
Fracture toughness: Kc	**78.75**	27	2126.25	3	236.25	3	236.25	9	708.75	0	0	0	0	
Thermal conductivity	**7.875**	18	141.75	2	15.75	2	15.75	6	47.25	0	0	0	0	
Total ($)	**326**		**25933**		**2866**		**2866**		**8597**		**7163**		**8590**	**56015**

Table 21: Costs related to test specification WEC-TS-IHX_HX-001

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-001	Alloy Hastelloy X Material Specifications and Procurement	Finalize material specifications, develop procurement requirements, procure 1 to 2 heats of Alloy Hastelloy X	No test equipment / facility is needed except for existing conventional test machines (e.g. tensile test machine) for confirming that Hastelloy X material procured meets specification.

Resources

Tasks required	Action to be performed by	Tariff ($)		Time needed				Total ($)	Assumptions/Bases
		Hour	Action	Hours	Days	Weeks	Months		
Alloy Hastelloy X procurement specification	Engineer	200	N/A	8	5	8		64,000	Based on time needed to compile procurement specification, inspection during procurement production (production/rolling/sampling) as well as compiling report.

Cost Summary

Total ($)	**64,000**
10% contingency ($)	**6,400**
Grand total ($)	**70,400**

Table 22: Costs related to test specification WEC-TS-IHX_HX-002

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-002	Database for Brazed and Diffusion Bonded Alloy Hastelloy X	Demonstrate that Alloy Hastelloy X can be brazed, diffusion bonded and that joint properties are appropriate for use in compact heat exchangers.	Activities require equipment and facilities for brazing and diffusion bonding, microscopical examination and mechanical property testing.

Resources

Resource requirement	Action to be performed by	Tariff ($)		Duration					Total ($)	Assumptions/Bases
		Hour	Action	Hours	Days	Weeks	Months	Years		
Weld design/Compiling W-BR-DB specification	Engineer	200		8	5	4	3		96,000	Assuming 1 month needed per joining method to compile specification (W/BR/DB).
Welding of joints (W/BR/DB)	Coded welder	100		8	5	46			184,000	549 samples to be joined. Due to large uncertainty of the time needed to establish diffusion bonded specimens, assume that 12 samples/week are to be joined (irrespective of joining method).
Conducting testing: Joint properties	Lab. Technician	80	n/a	8	5	61			195,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	61			488,000	Assuming that 9 samples/week are tested (due to large time uncertainty for fatigue testing).
Total 1 ($)									**963,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. [2] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding, pre-testing) [3]										
Cutting, polishing	549		640	351,360					351,360	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	549		400	219,600					219,600	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist/Engineering input at $200/hour.
Chemistry profile in joints	549		400	219,600					219,600	
Thermal Physical Mechanical properties of W/BR/DB joints										
Elastic properties [4]	18	7,200	350	6,300	n/a	n/a	n/a	6,000	19,500	$350 / specimen at 950℃ (+- 30℃).
Tensile Properties [5]	45	18,000	350	15,750	n/a	n/a	n/a	6,000	39,750	$350 / specimen at 950℃ (+- 30℃).
Fatigue Strength (LCF)	135	54,000	720	97,200	66,000	n/a	n/a	12,000	229,200	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour thereafter / specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	135	54,000	800	108,000	66,000	n/a	n/a	12,000	240,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles / specimen at 950℃ (+- 30℃).
Creep strength	144	57,600	3,500	504,000	n/a	n/a	n/a	6,000	567,600	Creep strength to 1000℃ for 10,000 h - $3500 / specimen.
Fracture toughness: CTOD	27	10,800	1,000	27,000	n/a	n/a	n/a	6,000	43,800	Fracture toughness: CTOD - $1000 at 650℃ / specimen.
Fracture toughness: Kc	27	10,800	560	15,120	n/a	n/a	n/a	6,000	31,920	Fracture toughness: Kc - $560 at 650℃ / specimen.
Thermal conductivity	18	7,200	95	1,710	n/a	n/a	n/a	6,000	14,910	Thermal conductivity to 1000℃: $95 / specimen.
Metallography/Optical/SEM (post-welding,post-testing) [6]										
Cutting, polishing, etching sample	549		640	351,360					351,360	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	549		400	219,600					219,600	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**219,600**		**2,136,600**	**132,000**	**0**	**0**	**60,000**	**2,548,200**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy Hastelloy X samples [7]	n/a	n/a	25,933	25,933	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**25,933**	

Table 22 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-002	Database for Brazed and Diffusion Bonded Alloy Hastelloy X	Demonstrate that Alloy Hastelloy X can be brazed, diffusion bonded and that joint properties are appropriate for use in compact heat exchangers.	Activities require equipment and facilities for brazing and diffusion bonding, microscopical examination and mechanical property testing.

Cost Summary

Total ($)	**3,537,333**
10% contingency ($)	**353,733**
Grand total ($)	**3,891,066**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Assuming that all the joined samples are to be checked for joint integrity after joining.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Optical/SEM work to be conducted for tensile, fatigue (HCF & LCF) and creep.
[7] Refer to 'material cost' sheet for material costing aspects.

W = Welding
BR = Brazing
DB = Diffusion Bonding

Table 23: Costs related to test specification WEC-TS-IHX_HX-003

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-003	Alloy Hastelloy X High Temperature Material Properties	Demonstrate that procured Alloy Hastelloy X will have thermal, physical and mechanical properties appropriate for use in compact heat exchangers.	N/A

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Conducting testing	Laboratory Technician	80	n/a	8	5	21			67,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	21			168,000	
Total 1 ($)									**235,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. [2] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis [3]	Reporting	Total ($)	Assumptions/Bases
Thermal Physical Mechanical properties										
Elastic properties [4]	2	800	350	700	n/a	n/a	n/a	6,000	7,500	$350 per specimen at 950℃ (+- 30℃).
Tensile Properties [5]	5	2,000	350	1,750	n/a	n/a	n/a	6,000	9,750	$350 per specimen at 950℃ (+- 30℃).
Fatigue Strength (LCF)	15	6,000	720	10,800	66,000	n/a	3,000	12,000	97,800	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour there after / specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	15	6,000	800	12,000	66,000	n/a	3,000	12,000	99,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles / specimen at 950℃ (+- 30℃).
Creep strength	16	6,400	3,500	56,000	n/a	n/a	n/a	6,000	68,400	Creep strength to 1000℃ for 10,000 h - $3500 / specimen.
Fracture toughness: CTOD	3	1,200	1,000	3,000	n/a	n/a	600	6,000	10,800	Fracture toughness: CTOD - $1000 at 650℃ / specimen.
Fracture toughness: Kc	3	1,200	560	1,680	n/a	n/a	600	6,000	9,480	Fracture toughness: Kc - $560 at 650℃ / specimen.
Thermal conductivity	2	800	95	190	n/a	n/a	400	6,000	7,390	Thermal conductivity to 1000℃: - $95 / specimen.
Total 2 ($)		**24,400**		**86,120**	**132,000**	**0**	**7,600**	**60,000**	**310,120**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy Hastelloy X samples [6]	n/a	n/a	2,866	2,866	Costing based on material price of $35/kg.
Total 3 ($)				**2,866**	

Cost Summary

Total ($)	**548,186**
10% contingency ($)	**54,819**
Grand total ($)	**603,004**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Post test analyses includes possible optical and scanning electron microscopy work and is based engineer/scientist tariff of $200/hour.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Refer to 'material cost' sheet for material costing aspects.

Table 24: Costs related to test specification WEC-TS-IHX_HX-004

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-004	Effects of Thermal Aging and Environment on Alloy Hastelloy X properties	Agree to except existing databases on the effects of thermal aging and environmental exposure on the thermal, physical and mechanical properties of Alloy Hastelloy X	N/A

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Action	Hours	Duration Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Welding of joints (W/BR/DB)	Coded welder	n/a	n/a	n/a	n/a	n/a			0	
Oversee & Manage: Thermal exposure of samples - 10,000h	Laboratory Technician	100	n/a	100					10,000	Thermal exposure monitored by lab technician every 100h (100 intervals).
Conducting testing: Alloy properties	Laboratory Technician	80	n/a	8	5	21			67,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	21			168,000	
Total 1 ($)									**245,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. [2] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding, pre-testing) [3]										
Cutting, polishing sample	61	n/a	640	39,040		n/a	n/a	n/a	39,040	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	61	n/a	400	24,400		n/a	n/a	6,000	30,400	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Chemistry profile in joints	61	n/a	400	24,400		n/a	n/a	6,000	30,400	
Thermal Physical Mechanical properties of Alloy Hastelloy X and W/BR/DB joints										
Elastic properties [4]	2	800	350	700	n/a	n/a	n/a	6,000	7,500	$350 / specimen at 950°C (+- 30°C).
Tensile Properties [5]	5	2,000	350	1,750	n/a	n/a	n/a	6,000	9,750	$350 / specimen at 950°C (+- 30°C).
Fatigue Strength (LCF)	15	6,000	720	10,800	66,000	n/a	n/a	12,000	94,800	Fatigue strength LCF to 1000°C - $720 up to 80 000 cycles + $20/hour there after / specimen at 950°C (+- 30°C).
Fatigue strength (HCF)	15	6,000	800	12,000	66,000	n/a	n/a	12,000	96,000	Fatigue strength HCF to 1000°C - $800 up to 1000 000 cycles / specimen at 950°C (+- 30°C).
Creep strength	16	6,400	3,500	56,000	n/a	n/a	n/a	6,000	68,400	Creep strength to 1000°C for 10,000 h - $3500 / specimen.
Fracture toughness: CTOD	3	1,200	1,000	3,000	n/a	n/a	n/a	6,000	10,200	Fracture toughness: CTOD - $1000 at 650°C / specimen.
Fracture toughness: Kc	3	1,200	560	1,680	n/a	n/a	n/a	6,000	8,880	Fracture toughness: Kc - $560 at 650°C / specimen.
Thermal conductivity	2	800	95	190	n/a	n/a	n/a	6,000	6,990	Thermal conductivity to 1000°C: - $95 / specimen.
Metallography/SEM (post-welding, post-testing) [6]										
Cutting, polishing, etching sample	61	n/a	640	39,040		n/a	n/a	n/a	39,040	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	61	n/a	400	24,400		n/a	n/a	6,000	30,400	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**24,400**		**237,400**	**132,000**	**0**	**0**	**78,000**	**471,800**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy Hastelloy X samples [7]	n/a	n/a	2,866	2,866	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**2,866**	

Table 24 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-004	Effects of Thermal Aging and Environment on Alloy Hastelloy X properties	Agree to except existing databases on the effects of thermal aging and environmental exposure on the thermal, physical and mechanical properties of Alloy Hastelloy X	N/A

Other

Additional requirements	Unit price ($)	Quantity	Total ($)	Assumptions/Bases
Capital cost - furnaces for thermal aging	3,000	3	9,000	Furnace with required capability sized at 180mm x 180mm x 250mm.
Contingencies (power consumption, element replacement)	900	1	900	Furnace contingencies make up 10% of total capital cost for furnaces.
Helium gas for regulating environment	120	156	18,720	156 x 50kg x He cylinders to be utilized. One cylinder a week for each furnace (52 weeks in total). He gas cost inclusive of impurity gases.
Sampling gas analyses	150	52	7,800	Sampling of furnace testing environment done once a week by external institution. Collective sampling from 3 furnaces add up to $150/week.
Total 4 ($)			**36,420**	

Cost Summary

Total ($)	**756,286**
10% contingency ($)	**75,629**
Grand total ($)	**831,914**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Assuming that all samples to be checked for joint consistency after joining.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Optical/SEM work to be conducted for tensile, fatigue (HCF, LCF), creep.
[7] Refer to 'material cost' sheet for material costing aspects.

Table 25: Costs related to test specification WEC-TS-IHX_HX-005

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-005	Effects of Environmental Exposure on Alloy Hastelloy X Joints	Determine response of the properties of welded, brazed and diffusion bonded Alloy Hastelloy X to exposures in NGNP helium environments	Facility will be needed for exposure of specimens of welded, brazed and diffusion bonded Alloy Hastelloy X to helium environments representative of NGNP. Equipment will also be needed for conducting tensile, creep, fatigue and fracture toughness tests. Instruments will be needed for post-test characterization.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Welding of joints (W/BR/DB)	Coded welder	100	n/a	8	5	46			184,000	549 samples to be joined. Assume 12 samples/week. Based on metallic IHX A (see adjustment factor).
Oversee & Manage: Thermal exposure of samples - 10,000h	Laboratory Technician	100	n/a	100					10,000	Thermal exposure monitored by lab technician every 100h (100 intervals). Based on metallic IHX A (see adjustment factor).
Conducting testing: Alloy/Joint properties	Laboratory Technician	80	n/a	8	5	61			195,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	61			488,000	
Total 1 ($)									**877,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding, pre-testing) [3]										
Cutting, polishing sample	183	n/a	640	117,120		n/a	n/a	n/a	117,120	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	183	n/a	400	73,200		n/a	n/a	500	73,200	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Chemistry profile in joints	183	n/a	400	73,200		n/a	n/a	500	73,200	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Thermal Physical Mechanical properties of Alloy Hastelloy X and W/BR/DB joints										
Elastic properties [4]	6	2,400	350	2,100	n/a	n/a	n/a	500	5,000	$350 per specimen at 950℃ (+- 30℃).
Tensile Properties [5]	15	6,000	350	5,250	n/a	n/a	n/a	500	11,750	$350 per specimen at 950℃ (+- 30℃).
Fatigue Strength (LCF)	45	18,000	720	32,400	66,000	n/a	n/a	1,000	117,400	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour there after per specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	45	18,000	800	36,000	66,000	n/a	n/a	1,000	121,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles per specimen at 950℃ (+- 30℃).
Creep strength	48	19,200	3,500	168,000	n/a	n/a	n/a	500	187,700	Creep strength to 1000℃ for 10,000 h - $3500 per specimen. Based on metallic IHX A (see adjustment factor).
Fracture toughness: CTOD	9	3,600	1,000	9,000	n/a	n/a	n/a	500	13,100	Fracture toughness: CTOD - $1000 at 650℃ per specimen. Based on metallic IHX A (see adjustment factor).
Fracture toughness: Kc	9	3,600	560	5,040	n/a	n/a	n/a	500	9,140	Fracture toughness: Kc - $560 at 650℃ per specimen. Based on metallic IHX A (see adjustment factor).
Thermal conductivity	6	2,400	100	600	n/a	n/a	n/a	500	3,500	Thermal conductivity to 1000℃: - $95 per specimen. Based on metallic IHX A (see adjustment factor).
Metallography/SEM (post-welding, post-testing) [6]										
Cutting, polishing, etching sample	183	n/a	640	117,120		n/a	n/a	n/a	**117,120**	Laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	183	n/a	400	73,200		n/a	n/a	500	73,200	Inclusive of 1) Analyses cost (operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**73,200**		**712,230**	**132,000**	**0**	**0**	**6,500**	**922,430**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy Hastelloy X samples [7]	n/a	n/a	8,597	8,597	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**8,597**	

Table 25 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-005	Effects of Environmental Exposure on Alloy Hastelloy X Joints	Determine response of the properties of welded, brazed and diffusion bonded Alloy Hastelloy X to exposures in NGNP helium environments	Facility will be needed for exposure of specimens of welded, brazed and diffusion bonded Alloy Hastelloy X to helium environments representative of NGNP. Equipment will also be needed for conducting tensile, creep, fatigue and fracture toughness tests. Instruments will be needed for post-test characterization.

Other

Additional requirements	Unit price ($)	Quantity	Total ($)	Assumptions/Bases
Capital cost - furnaces for thermal aging	3,000	3	9,000	Furnace with required capability sized at 180mm x 180mm x 250mm.
Contingencies (power consumption, element replacement)	900	1	900	Furnace contingencies make up 10% of total capital cost for furnaces.
Helium gas for regulating environment	120	156	18,720	156 x 50kg He cylinders to be utilized. One cylinder a week for each furnace. He gas cost inclusive of impurity gases.
Sampling gas analyses	150	52	7,800	Sampling of furnace testing environment done once a week by external institution. Collective sampling from 3 furnaces add up to $150/week.
Total 4 ($)			**36,420**	

Cost Summary

Total ($)	**1,844,647**
10% contingency ($)	**184,465**
Grand total ($)	**2,029,112**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Assuming that all samples to be checked for joint consistency after joining.
[4] Determination by way of mechanical testing not advised. Determination should be based on natural vibrational methods.
[5] Tensile properties (yield strength, tensile strength, elongation, and RA).
[6] Optical/SEM work to be conducted for tensile, fatigue (HCF, LCF), creep.
[7] Refer to 'material cost' sheet for material costing aspects.

Table 26: Costs related to test specification WEC-TS-IHX_HX-006

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-006	Effects of Grain Size and Section Thickness on Alloy Hastelloy X	Demonstrate that slight changes in grain size as well as the section thickness of Alloy Hastelloy X has little effect in overall properties of material.	Conduct of this work requires equipment or facilities for creep and fatigue measurement and for metallographic determination of grain size.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Conducting testing: Alloy Hastelloy X properties	Laboratory Technician	80	n/a	8	5	16			51,200	Testing will require resources in the form of 1 engineer ($200/hour) as well as 1 laboratory technician (80$/hour).
Oversee & Manage	Engineer	200	n/a	8	5	16			128,000	
Total 1 ($)									**179,200**	

Testing (All costs in $)

Task requirement	Samples [1]	Prep. (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Thermal Physical Mechanical properties of Alloy Hastelloy X										
Fatigue Strength (LCF)	45	18,000	720	32,400	66,000	n/a	n/a	1,000	117,400	Fatigue strength LCF to 1000℃ - $720 up to 80 000 cycles + $20/hour there after / specimen at 950℃ (+- 30℃).
Fatigue strength (HCF)	45	18,000	800	36,000	66,000	n/a	n/a	1,000	121,000	Fatigue strength HCF to 1000℃ - $800 up to 1000 000 cycles / specimen at 950℃ (+- 30℃).
Creep strength	48	19,200	3,500	168,000	n/a	n/a	n/a	500	187,700	Creep strength to 1000℃ for 10,000 h - $3500 / specimen.
Metallography/SEM (post-testing) [3]										
Cutting, polishing, etching sample	138		640	88,320		n/a	n/a	n/a	88,320	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	138		400	55,200		n/a	n/a	500	55,200	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**55,200**		**379,920**	**132,000**	**0**	**0**	**3,000**	**569,620**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy Hastelloy X samples [4]	n/a	n/a	7,163	7,163	Costing based on material price of $35/kg. Number of samples only relevant to fatigue testing and creep testing.
Total 3 ($)				**7,163**	

Cost Summary

Total ($)	**755,983**
10% contingency ($)	**75,598**
Grand total ($)	**831,581**

[1] See preferred number of samples to be used in 'sample' sheet.
[2] Basis for preparation costs - $400/sample.
[3] Optical/SEM work to be conducted for fatigue and creep samples.
[4] Refer to 'material cost' sheet for material costing aspects.

Table 27: Costs related to test specification WEC-TS-IHX_HX-007

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-007	Corrosion Allowances for Alloy Hastelloy X	Demonstrate satisfactory corrosion allowances for Alloy Hastelloy X and welded/bonded sections	Facility for exposure in a helium environment with low levels of controlled and measured CO, CO2, H2, H2O and CH4 for up to 10 000 hours, will be required. Metallographic and SEM equipment required for determination of thickness of oxides and depths of internal oxidation, alloy element depletion and carburization / decarburization.

Resources

Resource requirement	Action to be performed by	Tariff ($) Hour	Tariff ($) Action	Duration Hours	Duration Days	Duration Weeks	Duration Months	Duration Years	Total ($)	Assumptions/Bases
Welding of joints (W/BR/DB)	Coded welder	100	n/a	8	5	12			48,000	135 samples to be joined. Assume 12 samples/week. Based on metallic IHX A (see adjustment factor).
Oversee & Manage: Thermal exposure of samples - 10,000h	Laboratory Technician	100	n/a	100					10,000	Thermal exposure monitored by lab technician every 100h (100 intervals).
Oversee & Manage	Engineer	200	n/a	8	5	20			160,000	
Total 1 ($)									**218,000**	

Testing (All costs in $)

Task requirement	Samples	Prep. [1] (Machining)	Test cost/ sample	Testing Costs	Eq. setup	Post test sample prep	Post test analysis	Reporting	Total ($)	Assumptions/Bases
Metallography (post welding/bonding) [2]										
Cutting, polishing sample	162	n/a	640	103,680		n/a	n/a	n/a	103,680	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of metallurgy	162	n/a	400	64,800		n/a	n/a	500	64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Chemistry profile in joints	162	n/a	400	64,800		n/a	n/a	500	64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Thermal Physical Mechanical properties of Alloy Hastelloy X and W/BR/DB joints										
n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
Metallography/SEM (post-testing)										
Cutting, polishing, etching sample	162	n/a	640	103,680		n/a	n/a	n/a	103,680	Taking into account that laboratory technician will need 8 hours for sample preparation at $80/hour.
Observation of sample/metallurgy	162	n/a	400	64,800		n/a	n/a	500	64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Depth of internal oxidation	162	n/a	400	64,800				500	65,300	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Depth of depletion of alloy elements (Cr)	162	n/a	400	64,800				500	65,300	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Depth affected bycarburization/ decarburization	162	n/a	400	64,800					64,800	Inclusive of 1) Analyses cost (inclusive of operator and machine costs) at $200/hour and 2) Scientist or Engineering input at $200/hour.
Total 2 ($)		**0**		**596,160**	**0**	**0**	**0**	**2,500**	**597,160**	

Materials (All costs in $)

Materials requirement	Samples	Material cost/sample	Material cost	Total ($)	Assumptions/Bases
Alloy Hastelloy X samples [3]	n/a	n/a	8,590	8,590	Costing based on material price of $35/kg. This does not allow for the cost/development for the weld/braze alloy.
Total 3 ($)				**8,590**	

Other

Additional requirements	Unit price ($)	Quantity	Total ($)	Assumptions/Bases
Capital cost - furnaces for thermal aging	3,000	3	9,000	Furnace with required capability sized at 180mm x 180mm x 250mm.
Contingencies (power consumption, element replacement)	900	1	900	Furnace contingencies make up 10% of total capital cost for furnaces.
Helium gas for regulating environment	120	156	18,720	156 x 50kg He cylinders to be utilized. One cylinder a week for each furnace. He gas cost inclusive of impurity gases.
Sampling gas analyses	150	52	7,800	Sampling of furnace testing environment done once a week by external institution. Collective sampling from 3 furnaces add up to $150/week.
Total 4 ($)			**36,420**	

Table 27 (Continued)

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-007	Corrosion Allowances for Alloy Hastelloy X	Demonstrate satisfactory corrosion allowances for Alloy Hastelloy X and welded/bonded sections	Facility for exposure in a helium environment with low levels of controlled and measured CO, CO2, H2, H2O and CH4 for up to 10 000 hours, will be required. Metallographic and SEM equipment required for determination of thickness of oxides and depths of internal oxidation, alloy element depletion and carburization / decarburization.

Cost Summary

Total ($) (Primary side He effects)	**860,170**
Secondary side He effects ($)	**860,170**
Total (Primary and secondary effects) ($)	**1,720,340**
10% contingency ($)	**172,034**
Grand total ($)	**1,892,374**

[1] Basis for preparation costs - $400/sample.
[2] Assuming that all joined samples to be checked for joint consistency after joining.
[3] Refer to 'material cost' sheet for material costing aspects.

Table 28: Costs related to test specification WEC-TS-IHX_HX-008

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-008	Thermal/Fluid Modeling Methods for the Compact IHX	Develop thermal models for the compact IHX	Models will be applied to the results obtained under DDN HTS-01-17.

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Model generation giving results for mechanical, physical and thermal performance prediction	Group of thermal fluid/modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech - Duration and cost is greatly dependant on the data supplied by suppliers (transfer coefficients). Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 29: Costs related to test specification WEC-TS-IHX_HX-009

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-009	Methods for Stress-Strain Modeling of the compact IHX	Develop structural modelling methods for predictive operation for the compact IHX	Models will be applied to the results obtained under DDN HTS-01-17.

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Structural model generation giving results for predictive operation for IHX B	Group of modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech Industria. Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 30: Costs related to test specification WEC-TS-IHX_HX-010

Critical SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-010	Criteria for Structural Integrity of the Compact IHX	Establish criteria for structural integrity of compact heat exchangers	N/A

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Structural integrity models of CHE's	Group of modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech Industrial. Duration and cost is greatly dependant on the data supplied by suppliers (transfer coefficients). Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 31: Costs related to test specification WEC-TS-IHX_HX-011

Crit SSC	Specification number	Specification	Description	Comments
IHX_Hastelloy X	WEC-TS-IHX-011	Performance Modeling Methods for the IHX	Develop performance models for predictive operation for compact heat exchangers	N/A

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Tariff ($) Year	Time needed Hours	Days	Weeks	Months	Years	Total ($)	Assumptions/Bases
Performance models for IHX	Group of modeling specialists		42,500					3	127,500	1) Estmation made by M-Tech Industrial. Duration of 3 years for work.

Cost Summary

Total ($)	**127,500**	
10% contingency ($)	**12,750**	
Subtotal ($)	**140,250**	
Minus 25%	**35,063**	Test specificaions WEC-TS-IHX-008 to WEC-TS-IHX-011 are generic, thus the reduction in cost.
Grand total ($)	**105,188**	

Table 32: Material Costs

Material cost details based on preferred number of samples to be tested - Alloy Hastelloy X (@ $35/kg)														
Test Reference		IHX_HX.2		IHX_HX.3		IHX_HX.4		IHX_HX.5		IHX_HX.6		IHX_HX.7		Grand Total ($)
Sample amount		549		61		61		183		138		162		
	Per sample cost - Hastelloy X ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	Samples	Mat.cost ($)	
Elastic Properties	**0.7875**	18	14.175	2	1.575	2	1.575	6	4.725	0	0	0	0	
Tensile Properties	**0.7875**	45	35.4375	5	3.9375	5	3.9375	15	11.8125	0	0	0	0	
Fatigue strength (LCF)	**78.75**	135	10631.25	15	1181.25	15	1181.25	45	3543.75	45	3543.75	54	4252.5	
Fatigue strength (HCF)	**78.75**	135	10631.25	15	1181.25	15	1181.25	45	3543.75	45	3543.75	54	4252.5	
Creep strength	**1.575**	144	226.8	16	25.2	16	25.2	48	75.6	48	75.6	54	85.05	
Fracture toughness: CTOD	**78.75**	27	2126.25	3	236.25	3	236.25	9	708.75	0	0	0	0	
Fracture toughness: Kc	**78.75**	27	2126.25	3	236.25	3	236.25	9	708.75	0	0	0	0	
Thermal conductivity	**7.875**	18	141.75	2	15.75	2	15.75	6	47.25	0	0	0	0	
Total ($)	**326**		**25933**		**2866**		**2866**		**8597**		**7163**		**8590**	**56015**

Table 33: Costs related to test specification WEC-TS-PIP$_{750}$-001

Critical SSC	Specification number	Specification	Description	Comments
HTS Piping	WEC-TS-PIP-001	PHTS High temperature trade study	Assess design options for high temperature PHTS piping	N/A

Resources

Tasks required	Action to be performed by	Tariff ($) Hour	Action	Time needed Hours	Days	Weeks	Months	Total ($)	Assumptions/Bases
Evaluate and identify candidate design options from trade studies	Engineer	200	N/A	8	5	4	6	192,000	Based on need for one engineer for duration of 6 months. Includes reporting.

Cost Summary

Total ($)	**192,000**
10% contingency ($)	**19,200**
Grand total ($)	**211,200**

Table 34: Costs related to test specification WEC-TS-PIP$_{750}$-002

Crit SSC	Specification number	Description	Comments	
HTS Piping	WEC-TS-PIP-002	Assess design options for low temperature PHTS piping	N/A	

Tasks required	Action to be performed by	Tariff ($) Hour	Action	Hours	Days	Weeks	Months	Total ($)	Assumptions/Bases
Evaluate and identify candidate design options from trade studies	Engineer	200	N/A	8	5	4	4	128,000	Based on need for one engineer for duration of 4 months. Includes reporting.

Total ($)	**128,000**
10% contingency ($)	**12,800**
Grand total ($)	**140,800**

Table 35: Costs related to test specification WEC-TS-PIP$_{750}$-003

Crit SSC	Specification number	Description	Comments	
HTS Piping	WEC-TS-PIP-003	Assess design options for high temperature SHTS piping	N/A	

Tasks required	Action to be performed by	Tariff ($) Hour	Action	Hours	Days	Weeks	Months	Total ($)	Assumptions/Bases
Evaluate and identify candidate design options from trade studies	Engineer	200	N/A	8	5	4	6	192,000	Based on need for one engineer for duration of 6 months. Includes reporting.

Total ($)	**192,000**
10% contingency ($)	**19,200**
Grand total ($)	**211,200**

Table 36: Costs related to test specification WEC-TS-PIP$_{750}$-004

Crit SSC	Specification number	Description	Comments	
HTS Piping	WEC-TS-PIP-004	Assess design options for low temperature SHTS piping	N/A	

Tasks required	Action to be performed by	Tariff ($) Hour	Action	Hours	Days	Weeks	Months	Total ($)	Assumptions/Bases
Evaluate and identify candidate design options from trade studies	Engineer	200	N/A	8	5	4	3	96,000	Based on need for one engineer for duration of 3 months. Includes reporting.

Total ($)	**96,000**
10% contingency ($)	**9,600**
Grand total ($)	**105,600**