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NGNP and Hydrogen Production Preconceptual Design Report

SPECIAL STUDY 20.3: HIGH TEMPERATURE PROCESS HEAT TRANSFER AND TRANSPORT

Revision 0

APPROVALS

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ACRONYMS

AGATA	European Advanced Gas Turbine for Automobiles
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
BOP	Balance of Plant
BNCS	ASME Board on Nuclear Codes and Standards
C-C	Carbon/Carbon Composites
CFRC	Carbon Fiber Reinforced Carbon
CRBRP	Clinch River Breeder Reactor Plant
CTE	Coefficient of Thermal Expansion
DDN	Design Data Needs
DOE	US Department of Energy
dP	Pressure difference between primary and secondary or between the IHX internal channels and the exterior surfaces of the HX
DPP	Demonstration Power Plant
EOFY	End of Fiscal Year
ESR	Electro-slag Re-melting
FEA	Finite Element Analysis
GA	General Atomic
GIF	Generation IV International Forum
GS	Grain Size
GT	Gas Turbine
GTCC	Gas Turbine Combined Cycle
HPU	Hydrogen Production Unit
HT	High Temperature
HTE	High Temperature Electrolysis
HTGR	High Temperature Gas-Cooled Reactor
HTR	High Temperature Reactor (Germany)
HTR-10	High Temperature Test Reactor (Chinese)
HTS	Heat Transport System
HTTR	High Temperature Test Reactor (Japanese)
HX	Heat Exchanger
HyS	Hybrid Sulfur System for Hydrogen Production
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
ITRG	Independent Technology Review Group
JAEA	Japan Atomic Energy Agency
LCF	Low Cycle Fatigue
MIT	Massachusetts Institute of Technology
NERAC	Nuclear Energy Research Advisory Committee
NGNP	Next Generation Nuclear Plant
ORNL	Oak Ridge National Laboratory
PBMR	Pebble Bed Modular Reactor
PCHE	Printed Circuit Heat Exchanger

PCHX	Process Coupling Heat Exchanger
PCS	Power Conversion System
PHTS	Primary Heat Transport System
PPMP	Preliminary Project Management Plan for the NGNP
PWHT	Post Weld Heat Treatment
PSR	Primary Surface Reaction Type of HX Design
R&D	Research and Development
RBSN	Reaction Bonded Silicon Nitride
RCC-MR	French Design Code
RPV	Reactor Pressure Vessel
SHTS	Secondary Heat Transport System
S-I	Sulfur Iodine System for Hydrogen Production
USC	Ultra-Supercritical Fossil R&D Boiler Program
VHTR	Very High Temperature Gas-Cooled Reactor
VIM	Vacuum Induction Melting

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20.3 HIGH TEMPERATURE PROCESS HEAT TRANSFER AND TRANSPORT

SUMMARY AND CONCLUSIONS

This report documents the NGNP Special Study on high temperature process heat transfer and transport. The objective of this study was to select a reference configuration for the NGNP Heat Transport System (HTS). The selection of a reference HTS configuration is, by necessity, accomplished in close coordination with the NGNP special studies addressing the Power Conversion System (PCS) and Hydrogen Production Unit (HPU).

In accomplishing the study objective, the first step was to obtain necessary study inputs. Included in such inputs are commercial applications, along with their respective performance requirements. Support for the development and commercialization of these applications is the ultimate purpose of the NGNP demonstration. Closely related are NGNP demonstration objectives, which derive from the needs of the supported commercial applications. Also related, at a more detail level, are key functional requirements that must be fulfilled by the HTS. Finally, criteria for screening of HTS options and selection of a reference HTS configuration were developed from a consideration of all of the above.

In addition to these external inputs, two key inputs were obtained from companion NGNP special studies. These are the PCS options to be considered in conjunction with the HPU, and the minimum size and range of potential sizes of the HPU itself.

The NGNP Heat Transport System special study includes two important sub-studies that have a significant bearing on HTS configuration options. The first is an evaluation of prospective Secondary Heat Transport System (SHTS) working fluids. The second is a specific evaluation of design and materials readiness for the Intermediate Heat Exchanger (IHX), a key HTS component. Note that the Process Coupling Heat Exchanger (PCHX), which transfers thermal energy to the PCS, is common to all HTS configuration options and, as such, was not directly assessed in this special study.

With the above elements in hand, a number of specific HTS configuration options were evaluated and a recommendation provided.

Study Inputs and Evaluation Criteria

Three hydrogen production options were considered in establishing the commercial performance requirements to be supported by the NGNP. The first is the Hybrid Sulfur (HyS) process, which is the present basis for the Pebble Bed Modular Reactor (PBMR) Process Heat Plant (PHP) for hydrogen production. The other processes, the Sulfur-Iodine (S-I) cycle and High Temperature Electrolysis (HTE), have not yet been specifically optimized for the PBMR PHP. The principal requirements influencing the HTS configuration are process temperature and thermal power. Common to all three applications is a requirement for high temperatures within the process, ranging from 900ºC to 925ºC. The corresponding reactor outlet temperature is 950ºC in all cases. In both the HyS and S-I commercial applications, all of the energy produced in the reactor is routed via the IHX to the process and/or power conversion section. In the case of HTE, only a small fraction (~10%) of the total reactor energy is needed as heat in the process.

Electric generation applications of high temperature gas cooled reactors (HTGRs) either have been demonstrated or will be demonstrated through the South African Demonstration Power Plant (DPP). In this context, the principal mission of the NGNP must be to demonstrate and support commercial process heat applications of the HTGR, notably including hydrogen production. If this mission is to be fulfilled, there are three critical corollary objectives that must be attained:

1. **Intermediate Heat Exchanger (IHX) -** Demonstration of a reliable IHX with acceptable performance and lifetime is viewed as one of the most important technical barriers to commercial high-temperature process heat applications and a critical objective of the NGNP demonstration.

2. **Hydrogen Production Unit (HPU) -** A critical incremental contribution of the NGNP will be demonstration of the integration of one or more HPUs with a nuclear heat source. This will provide the basis for confirming the design and licensing of future commercial plants. Note that a unique differentiating requirement for the NGNP is providing the flexibility to demonstrate multiple processes.

3. **Licensing/Design Certification** - Demonstration of the licensing process as it pertains to process heat applications, specifically including hydrogen production, is viewed as being particularly important in support of commercial process heat applications. In all likelihood, such demonstration is a prerequisite for private sector investment in follow-on commercial plants.

For each of these three critical objectives, it is essential that the NGNP provide an adequate basis for the deployment of commercial plants without the need for further demonstration.

Functional requirements provide further inputs. Key HTS functions include:

- Transport and transfer of thermal energy from the reactor to the HPU and PCS during normal operation and to alternate heat sinks during other operating modes and transients.
- Control of radionuclides (e.g., integrity of pressure boundaries, tritium transport)
- Protection of the Nuclear Heat Source (NHS) from process-related hazards

Based on all of the above inputs, evaluation criteria for selection of the NGNP HTS configuration were selected and are summarized in Table 1

The category of Readiness refers to the ability of the selected HTS to support NGNP objectives within the specified schedule which calls for startup within the 2016 to 2018 timeframe. In addition to the overt criterion relating to the ability to meet the NGNP timeline, which is highly weighted, two additional readiness criteria are identified. The first relates to R&D requirements and their associated costs and risk. Such R&D requirements can be thought of as an indirect measure of the likelihood of attaining NGNP goals in a timely manner. Also related is the ability of the vendor/supplier/regulatory infrastructure to support NGNP

Table 1 HTS Evaluation Criteria

Attribute	Importance
• **Readiness**	
➢ **Ability to meet NGNP timeline (startup: 2016-2018)**	**High**
➢ NGNP R&D Requirements/Cost/Risk	Med
➢ Vendor/Supplier Infrastructure Development	Med
• **Support of Commercial Applications**	
➢ **Adequately demonstrates commercial process heat applications**	**High**
➢ **NHS commonality with commercial products**	**High**
➢ **Can serve as process heat prototype for design certification**	**High**
➢ Flexibility for demonstrating advanced applications	Med
➢ Flexibility for ultimate NGNP conversion to full-scale H2 production	Med
• **Performance**	
➢ **Ability to meet operational performance goals**	**High**
➢ Overall Plant Efficiency	Low
➢ Operability	Med
➢ Availability	Low
• **Cost**	
➢ **NGNP Capital Cost**	**High**
➢ NGNP Operating Cost	Low

requirements. To the extent that such infrastructure is not in place, or cannot be put in place in a timely manner, the risk to the NGNP objectives and schedule are increased. Since there is some overlap, the latter two criteria are given a medium weighting.

As stated above, the demonstration of commercial process heat applications is the principal mission of the NGNP. This is reflected in the high importance weighting of the first three criteria in this category. The third criterion, support of commercial process heat plant design certification, is viewed as particularly important.

In the category of Performance, the ability to meet operational performance goals (e.g., the provision of thermal energy to the process at required temperatures and thermal capacities with high reliability) is considered essential to the mission of the NGNP. Overall plant efficiency and availability are rated low, in recognition that compromises may be required to provide the flexibility for testing of multiple hydrogen production options, and that availability will be impacted by both testing requirements and equipment change out as different HPU options are tested. Operability is rated as medium in importance, recognizing that such operability will be optimized through experience gained with the NGNP.

The capital cost of the NGNP is given a high weighting, recognizing that the difficulty of obtaining public and congressional support for the NGNP Project will increase with capital cost. Operating costs are given a low weighting, again anticipating the expected impacts of testing and equipment change out.

Input Options

Power Conversion System Options

Power conversion system options were evaluated in a separate NGNP special study. Reference configurations were identified for the direct Brayton cycle, GTCC and Rankine cycle options.

The reference direct Brayton cycle is a single shaft recuperated and intercooled configuration, as shown in Figure 1. The reference GTCC incorporates a recuperated Brayton topping cycle with a single stage of compression and a bottoming Rankine cycle, as shown in Figure 2. A representative Rankine cycle was selected, as shown in Figure 3.

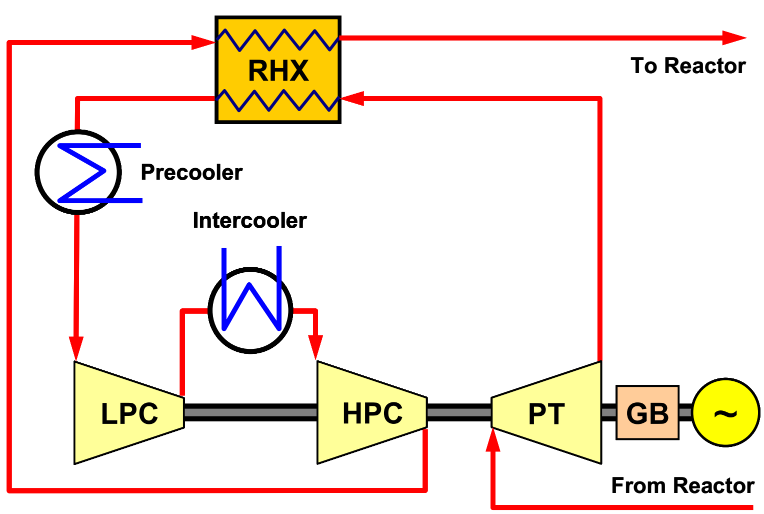


Figure 1 Reference Direct Brayton Cycle

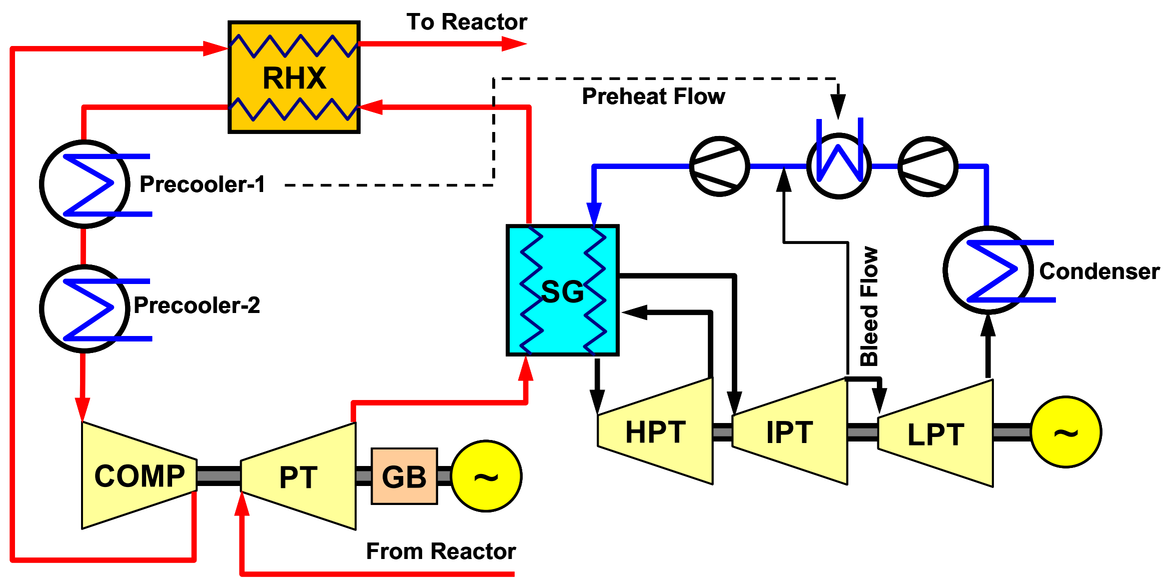


Figure 2 Reference GTCC

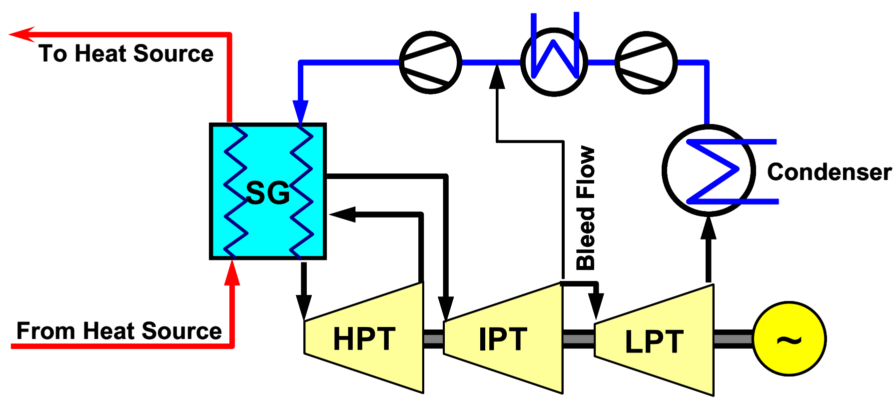


Figure 3 Representative Rankine Cycle

H2 Production Unit Size

The range of sizes potentially required for the hydrogen production unit (HPU) was evaluated in a separate NGNP special study. As a result of that study, the minimum size that would allow scale up of the most critical components to commercial size for the applications evaluated was determined to be ~5 MWt. An alternate approach to HPU sizing would be demonstration of a single train of a commercial HPU. For this option, it was determined that approximately 50 MWt would be required. It is further noted that the thermal rating of the high temperature PCHX for the HyS process is approximately 200 MWt.

SHTS Working Fluid Options

Four candidate SHTS working fluids were analyzed and compared as part of the overall NGNP Heat Transport System special study. Fluids evaluated included helium, carbon dioxide

(CO_2), which is used in British gas-cooled reactors, liquid salts and liquid metals. In terms of performance, the key differentiating characteristics among candidate fluids are the fluid state (gas or liquid), volumetric heat capacity and thermal conductivity. Other factors being equal, pumping power requirements will be higher for a gas than for an incompressible liquid. Volumetric heat capacity is a measure of the thermal energy that can be carried per unit volume. Higher volumetric heat capacity implies reduced pumping power requirements and/or smaller pipes or ducts. Thermal conductivity is an important determinant of heat exchanger size.

Beyond these performance characteristics, a major design consideration is the adequacy of obtainable and developed compatible materials. This concern raises issues of economics and of requirements for further development. Other issues related to the fluid selection include operational considerations (implications for duty cycle, availability, reliability & investment protection), economics and regulatory/licensing implications.

As a first step in the selection process, liquid metal was eliminated from further consideration. There are potential liquid metal candidates having melting and boiling temperatures suitable for coupling with high temperature process applications. However, there is no experience with these liquid metals in the temperature range of interest, and input from ORNL suggests that compatibility with materials at high temperatures is problematical. Above 600°C corrosion becomes a major issue.

The remaining candidates, Helium, CO_2 and Liquid Salts (LS) were compared on the basis of the attributes summarized in Table 2.

The most significant factors and bases for a tradeoff decision are summarized as follows:

- LS has a much higher volumetric heat capacity ($\rho \cdot C_P$) than helium or CO_2, and this implies reduced piping diameters and lower SHTS pumping power requirements, on the order of 1/5th that for helium. The volumetric heat capacity of CO_2 is about twice that of helium, with a corresponding reduction in pumping power requirements at equivalent temperatures and pressures.
- LS has a much higher thermal conductivity than helium or CO_2, which translates to higher heat transfer coefficients and reduced log-mean temperature difference (LMTD) requirements that can be taken advantage of in terms of either lower reactor outlet temperature for a given process temperature or higher process temperatures for increased efficiency and smaller heat exchangers. The thermal conductivity of CO_2 is only about 1/6 that of helium, implying significantly larger and more expensive heat exchangers with CO_2.
- Experience with CO_2 and LS heat transport fluids has not extended to the temperature range of the NGNP SHTS.

Table 2 Summary of SHTS Working Fluid Evaluation Results

Item	Helium	CO_2	LS
Design Compatibility	+	-	- -
Influence on Major Components			
Heat Exchangers	+	-	+/-
Circulators/Pumps	-	+	++
Piping and Insulation	++	+	- -
Valves and Seals	- -	-	+
System Integration	+	-	- -
System Operation	+	-	- -
Availability and Reliability	+	-	- -
Safety & Licensing	+/-	-	+/-
Economic Considerations	+/-	+/-	+
R&D	+	-	- -

- There is a requirement for an alternate heat source of undetermined size for startup of a LS heat transport circuit, and to avoid freeze-up there needs to be a drain, storage and vent system for LS.
- The LS heat transport pressure-retaining pipes will have to operate at LS temperatures, unless an internal insulating system can be devised - this implies a new piping material. Therefore, insulation to limit heat loss will be external to the pipe. On the other hand, heat losses will be reduced with LS, due to the smaller required pipe sizes. With helium or CO_2, internal insulation is possible and the pipe can run nearer to external ambient temperature. Helium and CO_2 working fluids are compatible with an optional configuration of coaxial Secondary Heat Transport System (SHTS) transport pipes.
- LS is not compatible with conventional shell and tube PCHXs that have the process fluid and catalyst on the inside of the tubes. For a given heat delivery, the flow rate on the LS side would be much smaller than that on the process side, leading to issues with shell side flow distribution. With compact heat exchangers, there is a lower limit to the size of flow passages, below which plugging can be a concern, and this limit is more likely encountered in the smaller passages of HXs with LS.
- With LS as the SHTS working fluid, any detectible leak in the IHX or PCHX will require immediate shut-down for repairs, while continued operation is feasible with small leaks in the IHX of an all-helium heat transport system. With CO_2, leaks would also require

immediate shutdown for repair; however, the consequences of leaks are unlikely to be as severe as those with LS.

- R&D will be required for any of the three SHTS working fluid candidates. Of the three, helium has the fewest R&D requirements. Assuming that metallic heat exchangers are determined to be feasible, CO_2 would have modest incremental R&D needs relative to helium. The LS alternative will almost certainly require a ceramic/CFRC IHX, and has unique R&D needs in the areas of piping materials compatibility, piping insulation design, high-temperature pumps and pump and valve seals. LS R&D requirements are not compatible with the present schedule for the NGNP.

The conclusion of this evaluation was that helium should be selected as the SHTS working fluid for the NGNP and that the PCHX should be located as close to the IHX as possible. There should be continued following of LS heat transport system development with a view to future distributed process heat applications (e.g., energy parks), where longer distance high-temperature process energy transport is mandatory. As noted in the preceding section addressing study inputs, a differentiating requirement of the NGNP is to provide flexibility for demonstrating various energy utilization options. If future demonstration of LS thermal energy transport in the NGNP environment is desired, an option is to replace the PCHX with a secondary IHX and to add a tertiary LS loop to transport energy to a more distant location.

IHX Readiness Assessment

In the Study Inputs and Evaluation Criteria, summarized above, the IHX was identified as a critical demonstration objective of the NGNP. It was recognized early in the planning process that the technical barriers associated with the IHX also have the potential to drive the NGNP schedule and significantly influence decisions regarding the overall configuration of the HTS.

For these reasons, a supporting assessment was undertaken to evaluate IHX design options and issues, identify and evaluate potential metallic and ceramic IHX fabrication materials and to determine the status of applicable codes and standards. For identified shortcomings of the technology base, Design Data Needs (DDNs) and associated R&D implications for the NGNP were determined and overall conclusions and recommendations were developed regarding the readiness of the materials for the IHX.

Assessment Inputs

High-temperature components, and specifically the IHX, featured prominently in the review by the Independent Technology Review Group (ITRG) in 2004. The ITRG review was undertaken to provide a critical review of the proposed NGNP project and identify areas of R&D that needed attention. The implications of the ITRG review for the IHX are summarized as follows:

- The reactor outlet temperature for the NGNP should not exceed 950ºC, based in part on IHX materials considerations.
- Non-replaceable metallic components designed for the full plant lifetime (60 years) should be limited to ~900ºC. Metallic components operating at

temperatures higher than ~900ºC, notably including high-temperature sections of the IHX, are likely to have reduced lifetimes and should be designed for replacement.[1]

- Time-dependent deformation for Class 1 pressure boundary components should be "insignificant", as defined by the ASME Code.
- The IHX should be designed to minimize stresses imposed on the metallic alloy due to the low margin of allowable creep stress associated with available metallic alloys operating in the 900-950ºC temperature range.
- Metallic materials should be limited to alloys listed in ASME Section II for Section III or Section VIII service.

Based on the requirements of commercial applications, the ITRG recommendations, above, and input from the separate NGNP Special Study on the HPU, the key assumptions and parameters used in the assessment of IHX designs and materials are as follows:

- Nominal 950ºC reactor outlet temperature (ROT)
- Nominal 900ºC secondary IHX outlet temperature
- He in primary and secondary loops
- Primary loop pressure - 9 MPa
- Primary to secondary loop delta P - essentially pressure balanced
- Order for IHX component by end of fiscal year (EOFY) 2012
- Design life for replaceable components greater than or equal to 10 years with a target of 20 years (depending on size, design and other factors)
- Target operating capacity - 95%

IHX Design Considerations

Both conventional shell-and-tube and compact heat exchangers were considered in this assessment. The most significant issues with shell-and-tube HXs are their size and weight. A 10MWt prototype IHX for the German process heat program was fabricated in the 1980s, satisfied all specified parameters and operated in excess of 900ºC ; however, the unit weighed about 135 tons. A corresponding unit for an indirect cycle 400-500MWt NGNP would be too large to be considered a viable option. Compact heat exchangers typically provide at least an order of magnitude improvement in surface compactness (m^2/m^3) and heat transfer compactness (MWt/m^3) relative to shell-and-tube heat exchangers.

A summary of design tradeoffs for the evaluated heat exchanger designs is provided in Table 3. Taking into account these tradeoffs, the Printed Circuit Heat Exchanger (PCHE) has been selected on a preliminary basis for the NGNP IHX pre-conceptual design. The shell & tube

[1] Based on the present assessment, it is recommended that non-replaceable components be limited to ~850ºC.

HX was eliminated as not being commercially viable for a large IHX. The PCHE was judged to be more robust than other compact designs with a solid basis of commercial experience, albeit at lower temperatures. Tradeoffs include: (1) More difficult inspection and maintenance, and (2) Need to establish design basis for Code acceptance. Additional discussion regarding materials and code issues is given later.

Table 3 Summary of Design Tradeoffs for Evaluated HX Types

Metric	Shell & Tube	Plate-Fin & Prime Surface	PCHE
Compactness (m^2/m^3 & MW/m^3)	Poor	Best	Good
Cost (tons/MWt)	Poor: (13.5 tons/MWt) Unlikely to be commercially viable	Best: Most compact, least materials	Good: (0.2 tons/MWt) Estimated to be ~1/68 that of S&T
Experience Base	HTTR, German PNP Development	Conventional GT recuperators	PBMR DPP Recuperator, other commercial products
Robustness	Best: Simple cylindrical geometry, stress minimized in HT area	Worst: Thin foils; stressed welds in pressure boundary; stress risers in pressure boundary welds; Small material and weld defects more significant	Good: Thicker plates; local debonding does not immediately affect pressure boundary; potential for higher transient thermal stresses vs. P-F
Inspection and Maintenance	Design facilitates inspection and plugging of individual tubes	Inspection and maintenance difficult or impractical below module level	Inspection and maintenance difficult or impractical below module level
HX Integration	Headers and HX-vessel integration demonstrated	More difficult HX integration with multiple series/parallel modules	More difficult HX integration with multiple series/parallel modules
Code Basis for Design	Existing Sect VIII Code basis for tubular geometries	No existing Code basis	No existing Code basis

Metallic Materials Assessment

A large number of metallic alloys that could be potentially useful for VHTR IHX fabrication were evaluated as a part of the NGNP Materials Program. Most of the alloys evaluated are not ASME Code materials and some are specialty alloys that may not be generally available in multiple forms. Most of the alloys evaluated also had a limited database and are not considered mature (those that have been used in multiple high temperature applications for many years). Some of the alloys evaluated were ASME Code materials, have reasonably large databases and have been used for multiple high temperature applications. Most of the alloys evaluated had no existing database for high temperature impure helium exposure.

From this larger database, the subset of alloys presently included in the ASME Code was selected for further detailed evaluation against the specific requirements of the NGNP IHX. The final conclusion of this evaluation was that if maximum mechanical properties are required at high temperature for the IHX design, Alloy 617 is the best IHX alloy option. There are unverified indications that the more restrictive chemistry of the Alloy 617CCA specification developed through the USC Program may result in improved properties relative to the standard Alloy 617 specification. This should be verified. If slightly less tensile and creep strength could be tolerated at high temperature in the IHX design, Alloy 230 may become the best IHX alloy option on the basis of lower Co content and superior resistance to helium impurities.

Existing metallic materials can be applied in the temperature regime of the NGNP IHX, albeit with significant limitations:

- Will require designs based on very low stresses during normal long-term operation
- Transient-related stresses will be more significant in compact IHXs (needs further evaluation)
- Likely need to replace IHX core multiple times over 60-year design life of plant

Ceramic Materials Assessment

Present metallic materials are likely not the optimum long-term solution for commercial process heat plants operating in the NGNP temperature range. For this reason, ceramic and composite materials were also evaluated.

The primary issues associated with a ceramic IHX are very high cost (for SiC or Si_3N_4), lack of standardization, lack of ASME Code acceptance, lack of a design basis, and the scale-up requirements for the NGNP application. For composites, fabrication technology and the establishment of a leak tight pressure boundary are additional concerns. Virtually all experts in this area agree that a ceramic or composite IHX is not a viable option for the timeframe of the NGNP initial deployment.

However, the limitations of metallic materials provide significant incentives for the development of ceramic heat exchangers for the IHX, as well as for the Process Coupling Heat Exchanger (PCHX), which poses additional challenges related to the process environment. It is viable to include this type of HX in a prototype testing program or to include a ceramic prototype in a side helium stream in the NGNP. This would facilitate the development of a specification, procurement for testing purposes and comparative testing with alloy prototype IHX units in a controlled loop. It is recommended that SiC or Si_3N_4 be used as the base ceramic for this application. While composite materials also appear to have promise, issues associated with fabrication and leakage must be solved before they can be considered viable for this application.

Codes and Standards Readiness

The availability and applicability of industrial codes and standards (e.g., ASME) was assessed as part of the overall assessment of materials readiness. Metal alloys that could potentially be used to construct the IHX are not currently a part of the ASME Nuclear Code, Section III. A significant effort will be required to resolve this issue because a reliable database potentially useful for a code case based on three well-documented heats of material is not available. There is no existing ASME Code basis (Section III or other) for the application of ceramics in pressure boundary applications. There is no existing ASME Section III design basis for either a conventional tube-and-shell IHX or less-conventional plate-type IHX, such as the PCHE. The most expedient approach for the NGNP IHX appears to be development of an application-specific design basis and submittal of a Section III code case associated with Subsection NH. A significant effort will also be required to resolve this issue, because an openly available design basis is not available in a format suitable for a code case. If a plate-type IHX is selected, testing of prototype IHX units would be needed to support the code case design basis for the specific IHX design selected.

The IHX for the NGNP should be contained in a Class 1 pressure boundary from an ASME Code consideration and to minimize pressure-induced stresses in the unit, because of the low metallic materials margin at 900-950ºC. A pressure boundary will be needed if a plate type HX is used, which under current rules is not a Code vessel. The pressure boundary size would be greatly reduced if a plate-type HX unit is used for the NGNP IHX. The pressure vessel(s) should be designed using ASME Section III, Subsection NB design rules (no creep) and should be insulated and cooled as required.

Design Data Needs and R&D Program

Based on the above, Design Data Needs (DDNs) were identified for the IHX and associated materials. These DDNs can be generally identified with the following categories:

- Material properties data relevant to the selected alloy (presumably either Alloy 617 or 230, depending on the high temperature strength and creep requirements for the IHX design). This data would support the materials part of the directed IHX ASME Section III Code Case
- Design methods and design basis information, based on detailed analysis, that would support the design part of the directed Code Case
- Verification of IHX performance and structural adequacy. Fulfillment of this DDN is likely to require testing of prototype IHX units that are procured following detailed discussions and a detailed procurement specification for the IHX design selected (presumably a plate-type HX concept).

Conclusions and Recommendations

- The reactor outlet temperature for the NGNP should not exceed 950ºC, based in part on IHX materials considerations.

- As a result of this assessment, it is concluded that non-replaceable metallic components designed for the full plant lifetime (60 years) should be limited to ~850ºC versus 900ºC, as earlier recommended by the ITRG. Metallic components operating at temperatures higher than ~850ºC, notably including high-temperature sections of the IHX, are likely to have reduced lifetimes and should be designed for replacement.

- For large IHXs, such as would be used in indirect cycle architectures, the above suggests consideration of a 2-Section IHX concept (Figure 4) in which the sections operating at the highest temperatures are separated from those operating at lower temperatures.

- Time-dependent deformation for Class 1 pressure boundary components should be "insignificant", as defined by the ASME Code.

- The IHX should be designed to minimize stresses imposed on the metallic alloy due to the low margin of allowable creep stress associated with available metallic alloys operating in the 900-950ºC temperature range
- Metallic materials should be limited to alloys listed in ASME Section II for Section III or Section VIII service.
- A metallic plate-type HX development program should be pursued for the NGNP IHX in conjunction with an appropriate design and materials development program.
- Alloys 617 or 230 are recommended for IHX construction depending on the stress and creep requirements of the design.
- NGNP-specific code cases should be developed to provide an ASME design and fabrication material basis for the NGNP IHX.
- While ceramic materials hold significant future promise, their selection for the initial NGNP IHX would pose an unacceptable risk to the NGNP schedule. Nevertheless, their potential for resolving the high-temperature issues associated with metals justifies an aggressive parallel development path.

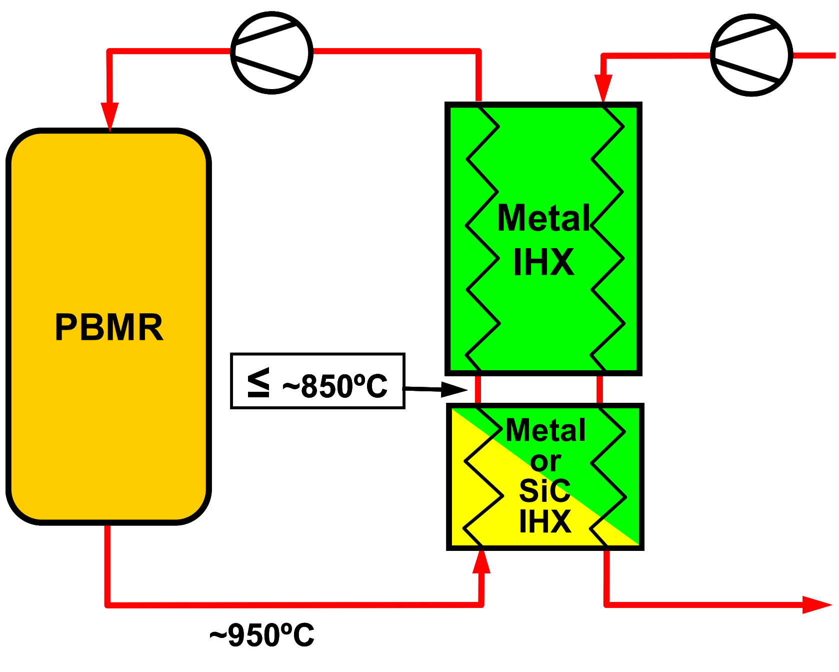


Figure 4 2-Section IHX Concept

HTS Configuration Options

A range of HTS configurations were evaluated as candidates for the NGNP preconceptual design. As shown in Figure 5, the HTS options can be generally categorized in terms of the integration of the PCS relative to the primary coolant circuit and the process coupling.

In direct PCS configuration options, the power conversion turbomachinery is located within the primary helium loop itself. In indirect PCS configuration options, the power conversion turbomachinery is isolated from the primary circuit by an intermediate heat exchanger (IHX). Indirect PCS configuration options are further categorized by whether the PCS is independently coupled to the secondary heat transport system (SHTS) circuit or integrated with the process itself. In the latter, all or part of the PCS coupling is located in the process streams beyond the process coupling heat exchanger (PCHX). This is prototypical of proposed commercial applications, including the PBMR PHP for hydrogen production via the HyS process.

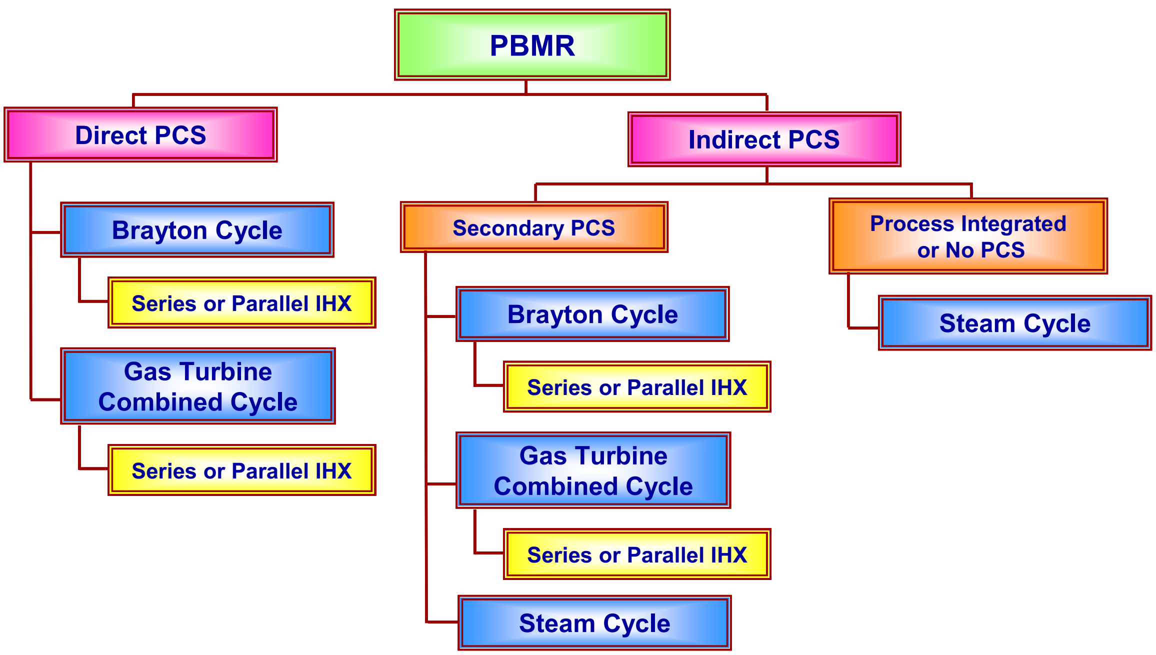


Figure 5 Process Heat/PCS Configuration Hierarchy

The following seven candidate HTS configurations were evaluated against the criteria of Table 1.

Option 1: Primary Brayton Cycle or GTCC, Series IHX
Option 2: Primary Brayton Cycle or GTCC, Parallel IHX
Option 3: Secondary Brayton Cycle or GTCC, Series PCHX
Option 4: Secondary Brayton Cycle or GTCC, Parallel PCHX

Option 5: Bottoming Steam Cycle, Series IHX
Option 6: Secondary Steam Cycle, Series PCHX
Option 7: PCS Integrated with Process

In the course of the evaluation, it became evident that the Brayton cycle versus Gas-Turbine Combined Cycle (GTCC) tradeoff was primarily an issue of optimization, based on overall efficiency and cost. On that basis, the Brayton and GTCC alternatives were considered to be sub-options of Options 1-4.

Important differentiating factors in the evaluation are summarized as follows:

- The principal demonstration objective of the NGNP has been identified as high-temperature process heat applications, notably hydrogen production. There is an incentive to reduce technical risks not directly associated with this objective. It is further noted that support for commercial electrical generation applications will be provided by the PBMR Demonstration Power Plant in South Africa.
- Establishing the technology basis for the IHX is a key NGNP demonstration objective and a prerequisite for leading commercial applications. The indirect cycle architectures of Options 3, 4, 6 and 7 definitively address the IHX issue at commercial scale.
- The NGNP must provide an adequate basis for licensing/design certification of follow-on commercial plants. This is also considered a prerequisite for commercial applications. The Nuclear Heat Source of the indirect cycle architectures of Options 3, 4, 6 and 7 is prototypical of proposed commercial applications and would provide an optimum basis for licensing/design certification of follow-on commercial plants. It is not clear that Options 1, 2 or 5 would provide an adequate basis for the licensing of commercial plants.
- The Rankine PCS of Options 5, 6 and 7 provides maximum flexibility for demonstrating HPUs of varying size and provides an option for the ultimate conversion of the NGNP to a commercial hydrogen production facility. The characteristics of the Rankine cycle further avoid operational pressure transients that would result from a Brayton or GTCC PCS, whether located in the primary or secondary loop. Such transients may not be compatible with a metallic IHX at the temperatures of interest.

Conclusions and Recommendations

As a result of this evaluation, it is recommended that Option 6, Secondary Steam Cycle Series PCHX (Figure 6), be selected as the initial basis for the NGNP preconceptual design. As noted above, the application of a full-size IHX best represents and supports commercial designs, and provides the optimum basis for licensing/design certification of the nuclear heat source for commercial process heat applications. The Rankine cycle, which is also applied in the corresponding commercial designs, provides maximum flexibility for HPU demonstration and avoids technical risks not associated with the primary NGNP mission.

The IHX should be of a metallic plate-type design, with subdivision of the IHX into two stages by temperature. The lower temperature part would be designed as a lifetime component, while the higher temperature part would be designed for ease of replacement. An aggressive parallel ceramic IHX development path is recommended with the objective of replacing the higher temperature part of the IHX, when available.

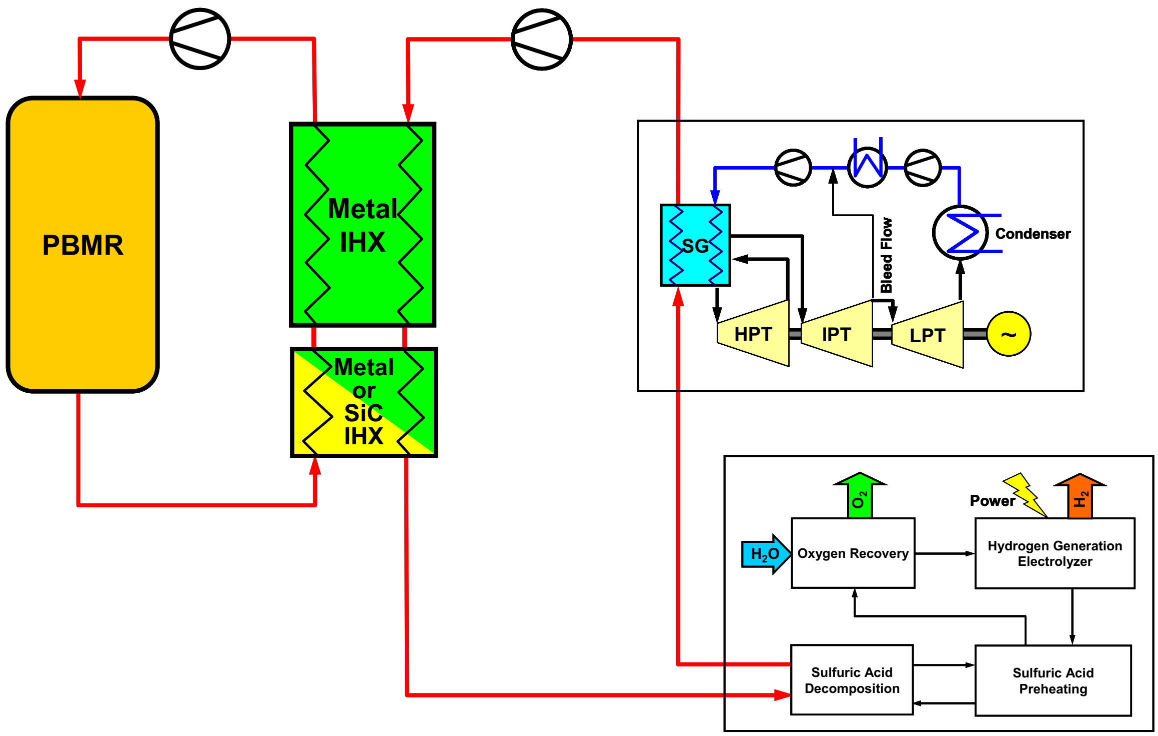


Figure 6 Recommended HTS Configuration

INTRODUCTION

This report documents the NGNP Special Study on high temperature process heat transfer and transport.

Objective and Scope

The objective of this study is to select a reference configuration for the NGNP Heat Transport System (HTS). The selection of a reference HTS configuration is, by necessity, accomplished in close coordination with the NGNP special studies addressing the Power Conversion System and Hydrogen Production Unit.

In accomplishing the study objective, the first step was to obtain necessary study inputs. Included in such inputs are commercial applications, along with their respective performance requirements. Support for the development and commercialization of these applications is the ultimate purpose of the NGNP demonstration. Closely related are NGNP demonstration objectives, which derive from the needs of the supported commercial applications. Also related, at a more detail level, are key functional requirements that must be fulfilled by the HTS. Finally, criteria for screening of HTS options and selection of a reference HTS configuration are developed from a consideration of all of the above.

In addition to these external inputs, two key inputs are obtained from companion NGNP special studies. These are the Power Conversion System (PCS) options to be considered in conjunction with the Hydrogen Production Unit (HPU), and the minimum size and range of potential sizes of the HPU itself.

The NGNP Heat Transport System special study includes two important sub-studies that have a significant bearing on HTS configuration options. The first is an evaluation of prospective Secondary Heat Transport System (SHTS) working fluids. The second is a specific evaluation of design and materials readiness for the IHX, a key HTS component. Note that the process coupling heat exchanger (PCHX), which transfers thermal energy to the PCS, is common to all HTS configuration options and, as such, is not directly assessed in this special study.

With the above elements in hand, a number of specific HTS configuration options are evaluated and a recommendation is provided.

Organization of Report

The organization of this report follows the logic of the study that is outlined above. Study inputs, both from external sources and companion special studies, are described in Section 20.3.1. The evaluation of HTS working fluid options is documented in Section 20.3.2. The readiness of designs and materials for the IHX is documented in Section 20.3.3. The evaluation of specific HTS configuration options and the recommended HTS configuration are provided in Section 20.3.4.

20.3.1 STUDY INPUTS

In this section, external inputs that influence the selection of the HTS configuration are first identified, and evaluated in Section 20.3.1.4, to develop screening criteria. Additional inputs from the parallel NGNP special studies addressing the Power Conversion System and Hydrogen Production Unit are summarized in Sections 20.3.1.5 and 20.3.1.6.

20.3.1.1 Commercial Applications and Performance Requirements

Commercial applications of the PBMR include both electricity production and process heat. The principal product for electricity production is the Multi-Module Power Plant (MMP). The MMP incorporates a direct Brayton cycle, and is the follow-on commercial version of the Demonstration Power Plant (DPP) that is presently in the initial stages of construction in South Africa. Consideration is also being given to gas turbine combined cycle (GTCC) options that are being addressed in a separate NGNP special study for power conversion system options.

A number of process heat applications are being evaluated for process heat plant versions of the PBMR (PBMR PHP). Among such applications are steam-methane reforming, process steam and hydrogen production. For the latter, the leading PBMR candidate is the Hybrid Sulfur (HyS) process, conceptually depicted in Figure 20.3.1-1 [Ref. 20.3.1-1]. Alternative hydrogen production concepts being evaluated by PBMR include the sulfur-iodine (S-I) process [Ref. 20.3.1-2] and high temperature electrolysis (HTE) process [Ref. 20.3.1-3]. Note that the S-I and HTE applications have not yet been specifically optimized for the PBMR PHP.

Key commercial application parameters for the Reactor/IHX and high-temperature Process Coupling Heat Exchanger (PCHX) for the three hydrogen production processes are summarized in Table 20.3.1-1. Common to all three applications is a requirement for high temperatures within the process, ranging from 900ºC to 925ºC. The corresponding reactor outlet temperature is 950ºC in all cases. In both the HyS and S-I applications, all of the energy produced in the reactor is routed via the IHX to the process and/or power conversion section. In the case of HTE, only a small fraction (~10%) of the total reactor energy is needed as heat in the process. For this reason, the configuration of [Ref. 20.3.1-3] comprises a small IHX operating in parallel with a direct Brayton cycle power conversion system.

20.3.1.2 Key NGNP HTS Demonstration Objectives

Electric generation applications of high temperature gas cooled reactors (HTGRs) either have been demonstrated or will be demonstrated through the South African DPP. Rankine cycle applications have been adequately demonstrated in earlier HTGRs, including Peach Bottom, AVR, Fort St. Vrain and THTR. The DPP, under construction in South Africa [Ref. 20.3.1-4], will provide a commercial scale demonstration of the direct Brayton cycle for electricity generation.

In this context, the principal mission of the NGNP must be to demonstrate and support commercial process heat applications of the HTGR, notably including hydrogen production. If

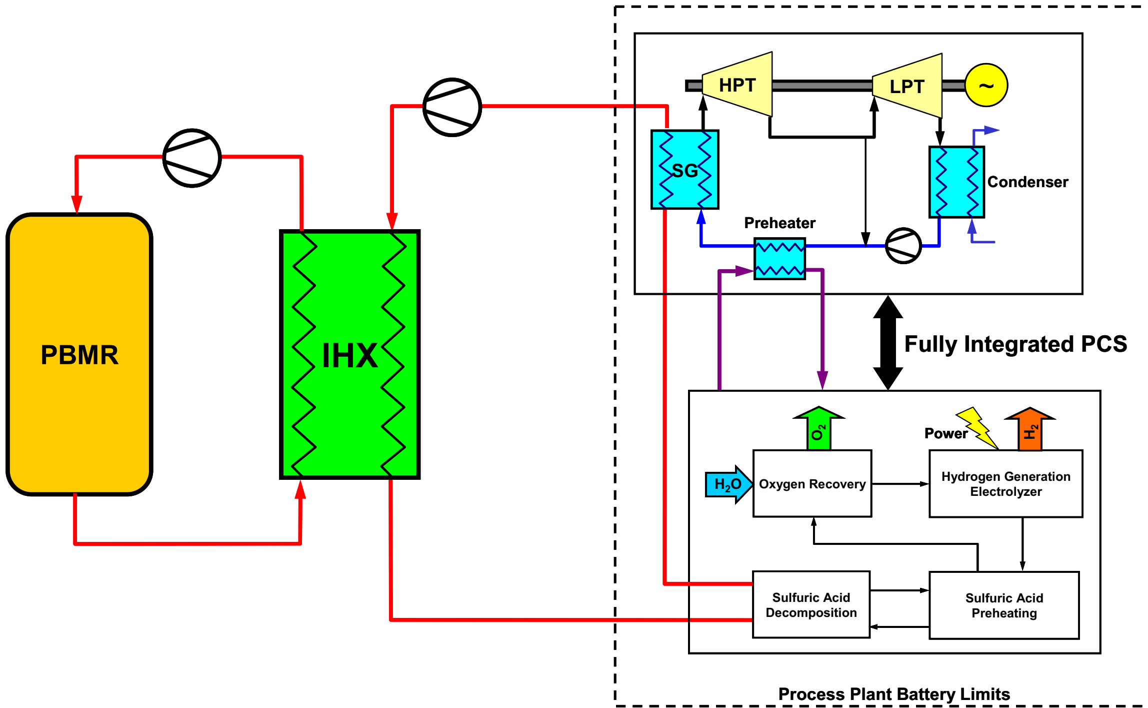


Figure 20.3.1-1 PBMR PHP for Hydrogen Production via HyS

Table 20.3.1-1 Key Commercial Application Parameters for Hydrogen Production

Application	HyS	S-I	HTE
Reactor/IHX			
Core Outlet Temperature, C	950	950	950
IHX Secondary Outlet Temperature, C	900	925	917
Fraction of Energy via IHX, %	100	100	10
High Temp PCHX			
High Temp PCHX	H_2SO_4 Decomposer	H_2SO_4 Vaporizer/ Decomposer	Steam Generator and Superheater
Fraction of Energy via PCHX, %	36	100	10
Process Pressure, MPa	8.8	7.0	5
Process Side Outlet Temp, ºC	872	900	772

this mission is to be fulfilled, there are three critical corollary objectives that must be attained. These relate to the IHX, the hydrogen production unit and licensing.

20.3.1.2.1 IHX

With the exception of HTE, the commercial process heat configurations revealed to date require all of the thermal energy produced in the reactor to be routed via the IHX. At the temperatures required in leading hydrogen production processes, available metallic materials are marginal at peak IHX temperatures for commercially acceptable lifetimes. If metallic options are found not to be acceptable, ceramic or carbon fiber reinforced carbon (CFRC) materials may offer acceptable options, but would require significant development, and would likely be incompatible with the present NGNP schedule. Further, it is unlikely that conventional shell and tube heat exchangers would be technically or economically acceptable for commercial process heat applications due to their size and weight. The alternative is development of compact heat exchangers, which would provide an order of magnitude improvement in performance. In summary, the demonstration of a reliable IHX with acceptable performance and lifetime is viewed as one of the most important barriers to commercial process heat applications and a critical objective of the NGNP demonstration.

20.3.1.2.2 Hydrogen Production Unit

The hydrogen production unit (HPU), including the process coupling heat exchanger (PHCX) represents a second critical demonstration objective of the NGNP. Candidate HPUs, based on the HyS, S-I and HTE processes are presently being developed through the Nuclear Hydrogen Initiative (NHI). For the HyS and S-I options, the PCHX is also under development.

The critical incremental contribution of the NGNP will be demonstration of the integration of one or more of these HPUs with a nuclear heat source. This will provide the basis for confirming the design and for licensing of future commercial plants. Note that a unique differentiating requirement for the NGNP is providing the flexibility to demonstrate multiple processes.

20.3.1.2.3 Licensing

A third critical contribution of the NGNP will be demonstration of the licensing process as it pertains to process heat applications, specifically including hydrogen production. This objective is viewed as being particularly important in support of commercial process heat applications and, in all likelihood, a prerequisite for private sector investment.

20.3.1.2.4 Other Demonstration Objectives

In addition to the three critical objectives already noted, demonstration via the NGNP will provide additional confidence regarding a number of important process heat related technologies. Examples include piping and insulation, primary and secondary circulators and secondary heat transport system isolation valves, if required.

20.3.1.3 Key HTS Functional Requirements

Heat transport system (HTS) functional requirements provide another input to the HTS configuration selection process. HTS functions and requirements were addressed in a recent study of nuclear hydrogen production applications [Ref. 20.3.1-5]. As depicted in Figure 20.3.1-2, functional requirements are imposed on the HTS by both the nuclear reactor and hydrogen production plant, in addition to overall plant requirements, which apply to the plant as a whole. Representative functions and requirements are provided in Table 20.3.1-2 and Table 20.3.1-3.

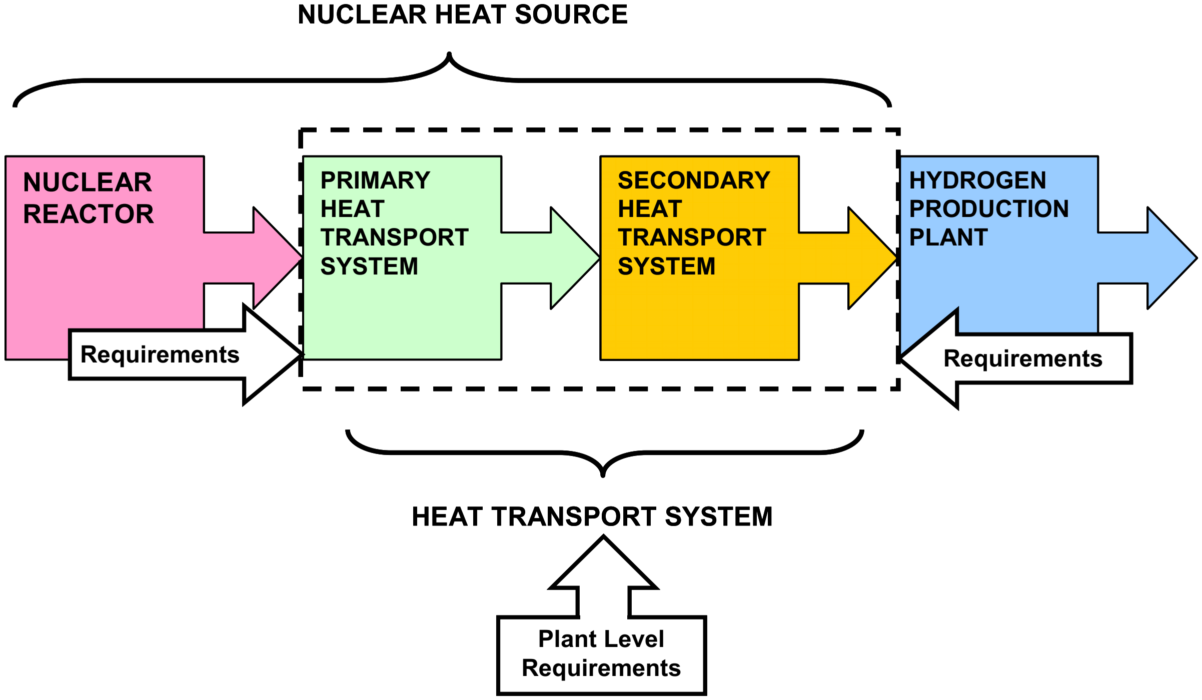


Figure 20.3.1-2 Sources of HTS Functional Requirements

Table 20.3.1-2 Representative HTS Functions and Requirements

- During normal operation, transport and transfer thermal energy from the reactor to the process and power conversion system (PCS), as applicable

  Requirements:

  - Application-specific requirements: See Table 20.3.1-1
  - Design life: 60 years (limited life components to be replaceable)

- During other normal (e.g., starting up/shutting down) and off-normal (e.g., loss of process load) operational states, transport and transfer thermal energy from the reactor to an ultimate heat sink

  Requirements:

  - Duty Cycle: See Table 20.3.1-3

- Maintain control of radionuclides

  Requirements:

  - IHX leakage requirements
  - Tritium-related requirements

- Protect Nuclear Heat Source from process-related hazards

  Requirements:

  - Distance from IHX to process plant
  - Mitigating features

Table 20.3.1-3 Comparison of Generation Plant and H_2 Plant Design Duty Cycles

Events	Number of Events Per Power Unit	
	Generating HTGR	Hydrogen Plant HTGR
Start-up from cold conditions	240	240
Shutdown to cold conditions	240	240
Normal load following cycles(1)	22,000	Not Applicable
Frequency control	800,000	Not Applicable
Load reject to house load	100	[25]
Rapid load ramp	1500 up / 1500 down	[500] down
Step load changes	3000(1)	[500] down

(1) Total number, up or down.

Functions that are unique to process heat applications include those related to control of radionuclides in the path to the process via the HTS, and the potential needed to mitigate the consequences of process related hazards on the nuclear heat source. In considering Table 20.3.1-3, it can be seen that the duty cycle for a representative process heat application, such as hydrogen production, is likely to be less demanding than a corresponding electric application, which is governed by electric grid requirements.

20.3.1.4 Screening Criteria

Taking into consideration the inputs of Section 20.3.1.1 through Section 20.3.1.3, screening criteria have been developed for the HTS selection process and are provided in Table 20.3.1-4.

The category of Readiness refers to the ability of the selected HTS to support NGNP objectives within the specified schedule which calls for startup within the 2016 to 2018 timeframe. In addition to the overt criterion relating to the ability to meet the NGNP timeline, which is highly weighted, two additional readiness criteria are identified. The first relates to R&D requirements and their associated costs and risk. Such R&D requirements can be thought of as an indirect measure of the likelihood of attaining NGNP goals in a timely manner. Also related is the ability of the vendor/supplier infrastructure to support NGNP requirements. To the extent that such infrastructure is not in place, or cannot be put in place in a timely manner, the risk to the NGNP objectives and schedule are increased. Since there is some overlap, the latter two criteria are given a medium weighting.

As stated in Section 20.3.1.2, the demonstration of commercial process heat applications is the principal mission of the NGNP. This is reflected in the high importance weighting of the

Table 20.3.1-4 HTS Screening Criteria

Attribute	Importance
• **Readiness**	
➢ **Ability to meet NGNP timeline (startup: 2016-2018)**	**High**
➢ NGNP R&D Requirements/Cost/Risk	Med
➢ Vendor/Supplier Infrastructure Development	Med
• **Support of Commercial Applications**	
➢ **Adequately demonstrates commercial process heat applications**	**High**
➢ **NHS commonality with commercial products**	**High**
➢ **Can serve as process heat prototype for design certification**	**High**
➢ Flexibility for demonstrating advanced applications	Med
➢ Flexibility for ultimate NGNP conversion to full-scale H2 production	Med
• **Performance**	
➢ **Ability to meet operational performance goals**	**High**
➢ Overall Plant Efficiency	Low
➢ Operability	Med
➢ Availability	Low
• **Cost**	
➢ **NGNP Capital Cost**	**High**
➢ NGNP Operating Cost	Low

first three criteria in this category. The third criterion, support of commercial process heat plant design certification, is viewed as particularly important.

In the category of Performance, the ability to meet operational performance goals (e.g., the provision of thermal energy to the process at required temperatures and thermal capacities with high reliability) is considered essential to the mission of the NGNP. Overall plant efficiency and availability are rated low, in recognition that compromises may be required to provide the flexibility for testing of multiple hydrogen production options, and that availability will be impacted by both testing requirements and equipment change out as different HPU options are tested. Operability is rated as medium in importance, recognizing that such operability will be optimized through experience gained with the NGNP.

The capital cost of the NGNP is given a high weighting, recognizing that the difficulty of obtaining public and congressional support for the NGNP Project will increase with capital cost. Operating costs are given a low weighting, again anticipating the expected impacts of testing and equipment change out.

20.3.1.5 Power Conversion System Options

Power conversion system options were evaluated in a separate NGNP special study (20.4). As a result of this study, reference configurations were identified for the direct Brayton cycle, GTCC and Rankine cycle options.

The reference direct Brayton cycle is a single shaft recuperated and intercooled configuration, as shown in Figure 20.3.1-3. The reference GTCC incorporates a recuperated Brayton topping cycle with a single stage of compression and a bottoming Rankine cycle, as shown in Figure 20.3.1-4. A representative Rankine cycle was selected, as shown in Figure 20.3.1-5.

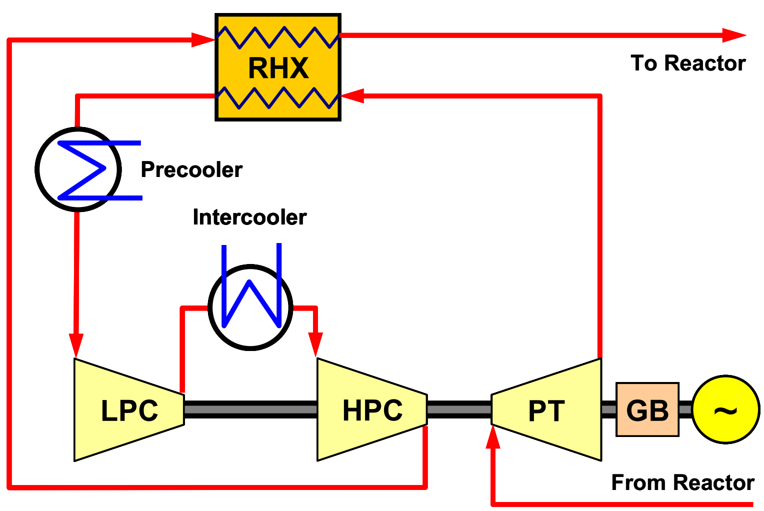


Figure 20.3.1-3 Reference Direct Brayton Cycle

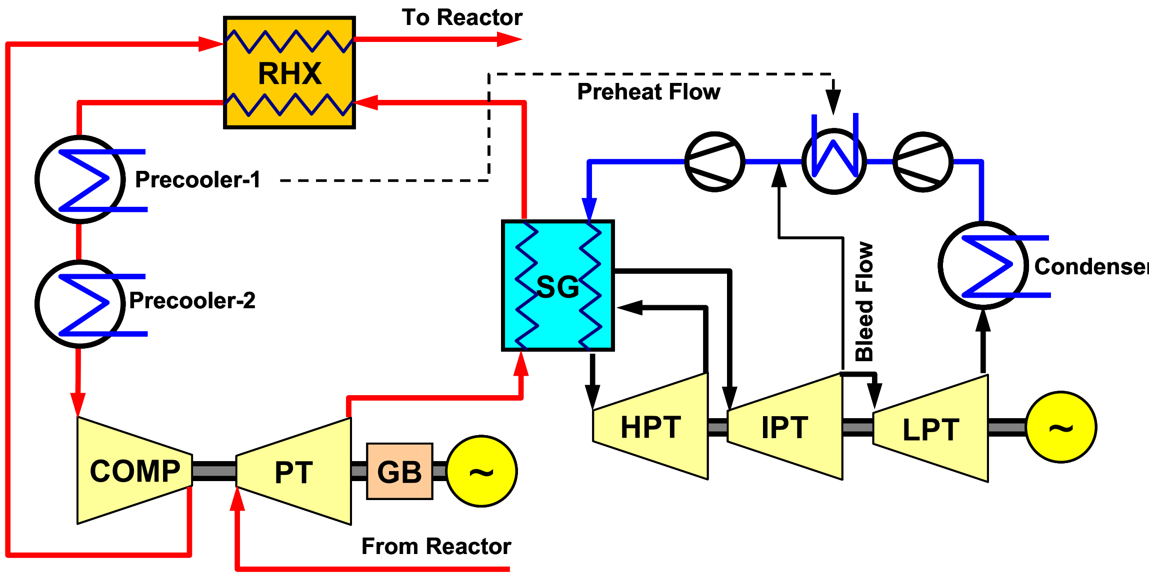


Figure 20.3.1-4 Reference GTCC

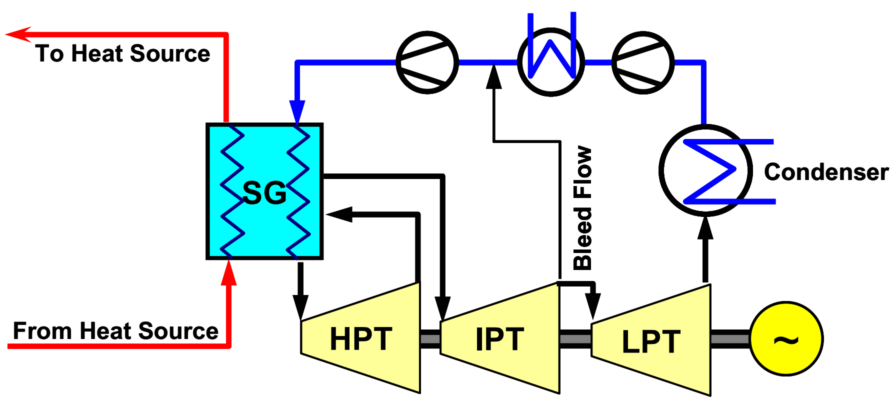


Figure 20.3.1-5 Representative Rankine Cycle

20.3.1.6 H2 Production Unit Size

The range of sizes potentially required for the hydrogen production unit (HPU) was evaluated in a separate NGNP special study (20.6). As a result of that study, the minimum size that would allow scale up of the most critical components to commercial size for the applications evaluated was determined to be ~5 MWt. An alternate approach to HPU sizing would be demonstration of a single train of a commercial HPU. For this option, it was determined that approximately 50 MWt would be required. It is further noted that the thermal rating of the high temperature PCHX for the HyS process is approximately 200 MWt.

20.3.1.7 References for Section 20.3.1

20.3.1-1 Lahoda, E.J., et.al., "Estimated Costs for the Improved HyS Flowsheet", HTR2006, October 2006.

20.3.1-2 H2-MHR Conceptual Design Report: SI-Based Plant (GA-A25401), General Atomics, April 2006.

20.3.1-3 H2-MHR Conceptual Design Report: HTE-Based Plant (GA-A25402), General Atomics, April 2006.

20.3.1-4 "Technical Description of the PBMR Demonstration Power Plant", Pebble Bed Modular Reactor Pty. Ltd Document 016956, Rev 4, February 14, 2006.

20.3.1-5 "High Temperature Gas-Cooled Reactors for the Production of Hydrogen: Establishment of the Quantified Technical Requirements for Hydrogen Production that will Support the Water-Splitting Processes at Very High Temperatures", EPRI, Palo Alto, CA: 2004. 1009687.

20.3.2 EVALUATION OF SHTS WORKING FLUID OPTIONS

The working fluid for the Primary Heat Transport System (PHTS) is defined to be the reactor helium coolant, which for the NGNP is helium. For the Secondary Heat Transport System (SHTS), there is an option to consider alternate heat transport fluids, each having advantages and disadvantages for the NGNP and corresponding commercial process heat plants. Specifically proposed have been carbon dioxide (CO_2), which is used in British gas cooled reactors, liquid salts and liquid metals. Candidate SHTS fluids have been analyzed and compared as part of the overall NGNP Heat Transport System special study. A key difference among candidate fluids is a wide variation in volumetric heat capacity, and this significantly affects performance. A major design consideration is adequacy of obtainable and developed compatible materials. This concern raises issues of economics and of requirements for further development. Other design issues related to the fluid selection are operational (implications for duty cycle, availability, reliability & investment protection), component size and parasitic consumption of power for pumping.

20.3.2.1 Functions

PBMR PHP applications require transport of high temperature thermal energy from nuclear heat source to point of use. This reference separation distance is presently 100m for the study of PHP configurations with SMR [Ref. 20.3.2-1].

The functions of the Secondary Heat Transport System (SHTS) are the following:

- Principal Functions
  - ➢ During operational modes in which the thermal energy produced in the nuclear reactor is utilized in the process, transport thermal energy produced in the reactor from the IHX to the Process Coupling Heat Exchanger (PCHX)
  - ➢ Contain the secondary fluid during all operational modes
- Potential Function
  - ➢ For designated events within the duty cycle, transport reactor heat (reduced power or decay heat) to an alternate heat sink, either in the Secondary Heat Transport System (SHTS) or the process. [Note: The scope of this function is to be determined.]
- Ancillary Functions
  - ➢ Minimize energy losses (regenerative and to the environment)
  - ➢ Support personnel and investment protection goals
  - ➢ Support reliability and economic goals

Candidates

Table 20.3.2-1 identifies the candidate Secondary Heat Transport System (SHTS) fluids and provides general comments on each.

Table 20.3.2-1 Candidate SHTS Coolants

Helium ➢ NGNP primary coolant ➢ Extensive experience base with HTGRs ➢ Chemically inert ➢ Highest conductivity of candidate gases → Smaller heat exchangers
CO_2 ➢ Experience base with Magnox/Advanced Gas Reactors to 650ºC (British) ➢ Increased volumetric heat capacity → Reduced pumping power vs. helium
Liquid Salt (LS) ➢ Prior nuclear experience at high temperatures (to ~700ºC) • Molten Salt Reactor Experiment/Molten Salt Breeder Reactor (MSRE/MSBR) • Aircraft Reactor Experiment/Aircraft Reactor Test (ARE/ART) ➢ Industrial experience, but with different compounds in baths vs. loops ➢ Feasibility established ➢ Temperature range of applicability bounded by melting/boiling points
Liquid Metal ➢ No experience in temperature range of interest ➢ Materials compatibility at high temperatures problematical per ORNL ➢ Temperature range of applicability bounded by melting/boiling point

20.3.2.2 Initial Screening

As a first step in comparing Helium, CO_2, Liquid Salt (LS) and Liquid Metal coolant options, the choice of liquid metal was eliminated from further consideration. There are possible liquid metal candidates having melting and boiling temperatures useable for coupling with high temperature process applications, these being

- Lead
- Bismuth
- Lithium
- Combinations of the above

However, there is no experience with these liquid metals in the temperature range of interest, and ORNL input suggests that compatibility with materials at high temperatures is problematical. Above 600°C corrosion becomes a major issue [Ref. 20.3.2-2].

20.3.2.3 Thermophysical Properties

Table 20.3.2-2 provides relevant thermophysical properties of candidate SHTS working fluids. Of the candidate liquid salts, only three have been characterized to the extent that meaningful comparisons can be made. Two of these three well-characterized salts incorporate beryllium, which is both expensive and toxic. The two beryllium-based salts were developed for primary coolant applications, wherein nuclear properties are an important consideration. By contrast, FLiNaK, which was developed for SHTS applications, is relatively inexpensive and less toxic.

The thermophysical properties of greatest influence in the working fluid selection are the melting point, the volumetric heat capacity and the thermal conductivity. The melting point establishes the lower end of the feasible operating range for the liquid salts. The volumetric heat capacity is a measure of the energy carried in a given volume of fluid. This, in turn, is a key determinant of the required pipe size and the energy required for pumping. The thermal conductivity is a key factor in the sizing of heat exchangers.

In terms of gases, the principal thermophysical tradeoff between helium and CO_2 relates to thermal conductivity on one hand and volumetric heat capacity on the other. The higher conductivity of helium implies smaller and less expensive heat exchangers, while the higher volumetric heat capacity of CO_2 would be manifested in smaller pipes and reduced pumping power requirements. Relative to these gases, the high volumetric heat capacity and thermal conductivity of the liquid salts imply substantial advantages in terms of reduced heat exchanger and pipe sizes. The high volumetric heat capacity of liquid salts and the fact that they are incompressible fluids would result in low pumping power requirements compared to the gases.

20.3.2.4 Evaluation

Helium, CO_2 and Liquid Salts (LS) were compared with respect to the following attributes and considerations. The details of these comparisons are provided in the subsections that follow.

- Design Compatibility
- Influence on Major Components
  - Heat Exchangers
  - Circulators/Pumps
  - Piping and Insulation
  - Valves and Seals
- System Integration
- System Operation
- Availability and Reliability

Table 20.3.2-2 Helium and Candidate Liquid Salts

Property	Helium	CO_2	$(LiF)_2 \cdot BeF_2$ (FLiBe)	NaF-KF-LiF (11.5-42-46.5) (FLiNaK)	$NaF \cdot BeF_2$ (57 – 43)	$KF\text{-}ZrF_4$ & $RbF\text{-}ZrF_4$	Alkali Fluroborates (Mix Req'd)
T_{melt}, C	NA	NA	459	455	340	380 - 410	TBD
T_{boil}, C	NA	NA	1430			ZrF_4 family recommended for consideration by ORNL. Individual salts investigated by ONRL. Mixtures not well characterized. Melt range is estimate for various mixtures.	Fluroborates recommended for consideration by ORNL. $NaF\text{-}NaBF_4$ was reference secondary coolant for MSBR (700C), but V.P too high > 700C. Mixtures may be suitable.
ρ, kg/m^3 (7MPa/9MPa)	4.3/5.5 (@500C) 2.6/3.4 (@1000C)	47.6/61.1 (@500C) 34.0/43.5 (@800C)	2036 (@500C) 1792 (@1000C)	2078 (@500C) 1785 (@1000C)	2010 (@700C)		
C_p, J/(kg·K)	5200	1190 (@500C) 1270 (@800C)	2380	1889	2230		
ρC_p, kJ/(m^3·K) (avg. 500-1000C)	17.9 @7MPa 23.1 @9MPa	40.8 @7MPa 52.3 @9MPa (avg. 500-800C)	4555	3649	4270		
k, W/(m·K)	0.368 (avg. 500-1000C)	0.066 (avg. 500-800C)	1	4.5	0.87		
η, (Pa·s) x 10^3	0.039 (@500C) 0.055 (@1000C)	0.035 (@500C) 0.044 (@800C)	23 (@500C) 2.2 (@1000C)	13 (@500C) 1.7 (@1000C)			
Comments		NIST data not provided above 800C	Well characterized; Used in MSRE; Expensive, Toxic	Well characterized; Reference for MSBR secondary; Inexpensive	Well characterized; Expensive; Toxic		

- Safety & Licensing
- Economic Considerations
- R&D

20.3.2.4.1 Design Compatibility

As suggested earlier, the relatively high melting point of candidate liquid salt working fluids represents a significant constraint on SHTS design options. As an example, the reference PBMR PHP configuration for hydrogen production via the HyS process is shown in Figure 20.3.2-1. At a return temperature of 290ºC, this design would be incompatible with the use of liquid salt. Figure 20.3.2-2 depicts an alternate PBMR PHP coupling for the HyS process. While this latter coupling would be compatible with liquid salt SHTS working fluids, the high secondary return temperature would be problematical for helium or CO_2 in terms of both pumping power and feasibility issues associated with the gas circulator. Further, integration of the hydrogen production unit and power conversion system for maximum efficiency would be more difficult with separation of the process heat and steam coupling.

20.3.2.4.2 Influence on Major Components

The selection of the SHTS working fluid has significant implications for major components of the heat transport system, including the IHX, PCHX and those components of the SHTS that are in contact with the working fluid. These implications are summarized as follows:

20.3.2.4.2.1 Heat Exchangers

In selecting the SHTS working fluid, there are a number of significant tradeoffs associated with both the IHX and process coupling heat exchanger (PCHX) (Table 20.3.2-3). In the case of helium or CO_2, the SHTS must be operated at high-pressure to avoid excessive pumping energy requirements. With liquid salt (LS), the non-compressible nature of the fluid allows flexibility in selecting operating pressure and pressure differences can be staged between the primary loop and the process. However, this assumes that the pressure difference is within the design capability of the heat exchangers.

In the case of helium, a metallic IHX may be feasible, albeit marginal. It is not clear, however, whether a metallic IHX is feasible for CO_2. A ceramic or carbon fiber reinforced carbon (CFRC) heat exchanger will almost certainly be required for LS, based on materials compatibility at the operating temperatures in question. A related issue is the transition between metal and ceramic in the manifold region of the heat exchanger.

Assuming that a suitable heat exchanger can be constructed, the very high heat temperature coefficient on the LS side would allow a lower reactor outlet temperature (ROT) for a given process temperature or, alternatively, an increased process temperature for a given ROT. For a given duty, a LS heat exchanger would tend to be smaller, and less expensive. A more subtle difference is illustrated by the inset figure of Table 20.3.2-3. Because the cross-section of the channels within the heat exchanger would be much smaller with liquid salt, the manifold section of the heat exchanger would be much smaller and the heat exchanger would operate more nearly in counter flow than the alternatives with gaseous SHTS working fluids. Another subtle

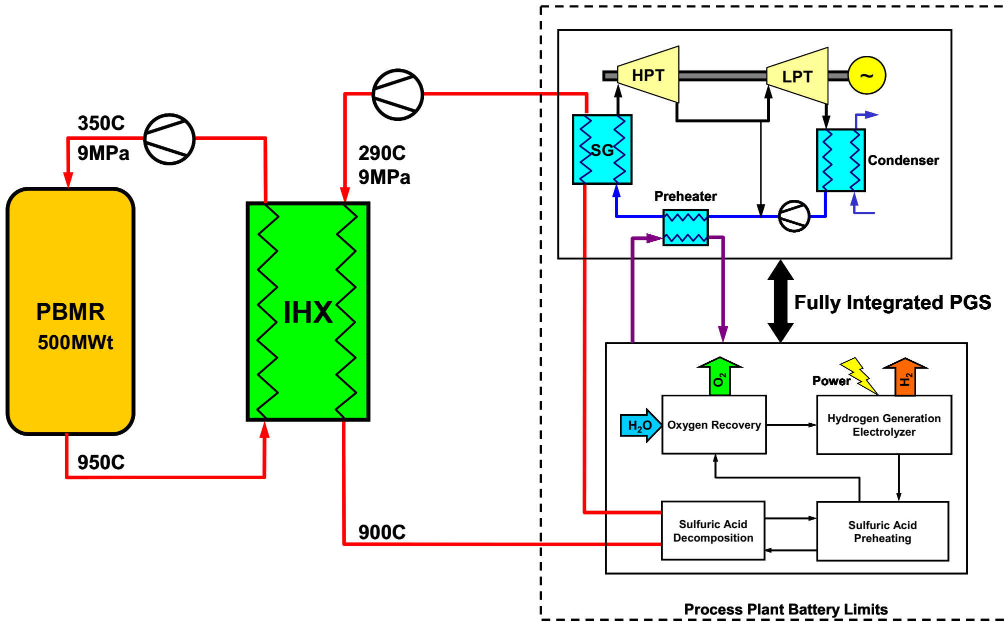


Figure 20.3.2-1 Reference PBMR PHP for H_2 via HyS Process

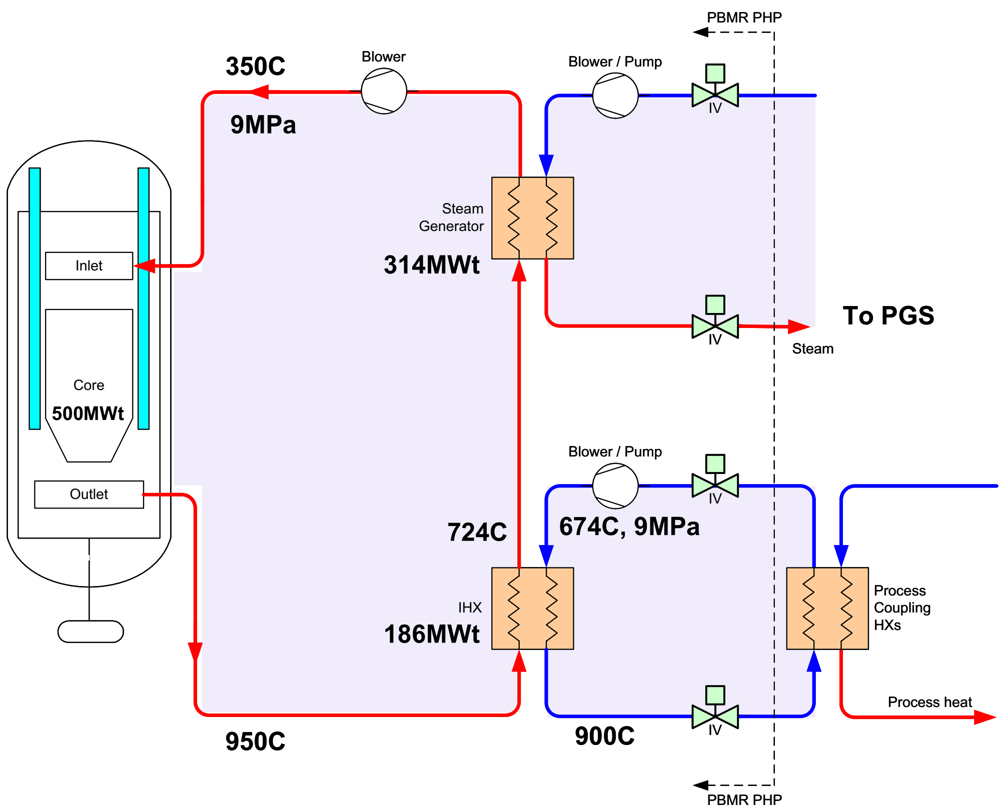
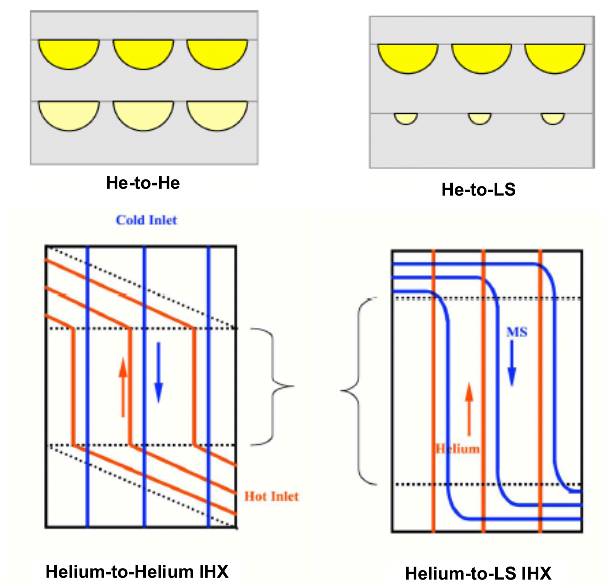


Figure 20.3.2-2 Alternate HyS Process Coupling

Table 20.3.2-3 Heat Exchangers

Helium	CO_2	Liquid Salt
• High SHTS pressure required for efficient heat transport ➢ Consistent with IHX pressure balancing ➢ Implies high dP across PCHX • Comparable heat transport characteristics on both sides of IHX ➢ Compatible with shell & tube PCHX • Manifolding more difficult in compact HXs (see inset figure) • Metallic HXs feasible, albeit marginal	• High SHTS pressure required for efficient heat transport ➢ Consistent with IHX pressure balancing ➢ Implies high dP across PCHX • Secondary heat transfer coefficient will govern HX sizing ➢ HX will be larger, more expensive ➢ Compatible with shell & tube PCHX • Manifolding more difficult in compact HXs (see inset figure) • Metallic HX feasibility questionable	• Flexible operating pressure, established by cover gas ➢ Can stage pressure differences between primary loop and process • Potential to operate with lower LMTD ➢ Reduce ROT for given process temperature, or ➢ Allow increased process temperature for given ROT • Mismatch in heat transport characteristics ➢ HT coefficient, volumetric heat capacity much higher on LS side ➢ Primary heat transfer coefficient will govern HX sizing ➢ Simplifies manifolding in compact HXs (see inset figure) ➢ Flow area needs to be much smaller on LS side – Fewer, smaller channels – Concern with plugging of small channels in compact HX designs • Likely to require ceramic/CFRC HXs ➢ Metal to ceramic/CFRC interfaces an issue • May not be compatible with tube & shell PCHX designs ➢ Flow area outside of tubes is too large for LS ➢ Would need new PCHX design • For given duty, HX will be smaller, much less expensive
		
Overall: Advantage for helium/disadvantage for CO_2/LS with available technology. Future advantage for LS with compact ceramic/CRFC HXs		

difference is that the volumetric flow of LS would be much smaller than that of the helium in the primary loop, and possibly the process fluid. In the case of the PCHX, it may be difficult to configure a shell and tube heat exchanger with LS on the outside of the tubes.

Overall, it is concluded that there is an advantage for helium and a modest disadvantage for CO_2 with available technology. It is unlikely that heat exchangers can be constructed for a LS working fluid at the temperatures of the NGNP using present materials. When ceramic and/or CFRC heat exchangers become available, LS would have a significant advantage.

20.3.2.4.2.2 Circulators/Pumps

Trade-offs related to circulators and pumps are summarized in Table 20.3.2-4. Circulators have been developed for both helium and CO_2 nuclear applications at temperatures up to approximately 350ºC. Above that level, incremental R&D would be required. CO_2 pumping power requirements would be on the order of half those of helium for equivalent temperature and pressure, due to its higher volumetric heat capacity (ρC_p). This is the principal incentive for its consideration. Pumping power requirements would be far less for LS, on the order of 1/5 that of helium [Ref. 20.3.2-3]. Such pumps have been demonstrated in prior applications, such as the Molten Salt Reactor Experiment (MSRE).

Overall, pumping energy requirements represent an advantage for CO_2 vs. helium, and a large advantage for LS.

20.3.2.4.2.3 Piping and Insulation

Trade-offs related to piping and insulation are summarized in Table 20.3.2-5. Piping and insulation for helium applications are well-developed and have been demonstrated in several operating plants. For CO_2 applications, piping and insulation have been applied at temperatures up to approximately 650ºC. With CO_2, the piping is likely to be somewhat smaller than that with helium.

In concept, a LS working fluid would allow pipes to be reduced to approximately 1/5 of the size required for helium [Ref. 20.3.2-3]. In practice, however, there is no known practical wetted insulation system for LS, and this implies that the SHTS piping would have to operate at or near the LS temperature. At 900ºC, it is unlikely that metallic materials would be adequate and an alternative material, such as CFRC, would have to be selected.

Overall, the availability of established technology is a major advantage for helium, while reduced pipe -size would be a modest advantage for CO_2. The lack of an internal insulation system is a feasibility issue for LS.

20.3.2.4.2.4 Valves and Seals

Trade-offs related to valves and seals are summarized in Table 20.3.2-6. In the case of both helium and CO_2, SHTS valves would be both very large and would have to operate at high temperature. Experience shows that helium valves and seals are particularly difficult. In this respect, CO_2 would have a modest advantage relative to helium.

Table 20.3.2-4 Circulators/Pumps

Helium	CO_2	Liquid Salt
• Highest pumping power • R&D issues with temperatures above ~350C	• Pumping power lower than helium, but much greater than LS • R&D issues with temperatures above ~350C	• Pumping power much less than for gases • Pumps demonstrated in earlier LS applications
Overall: Advantage for CO_2 vs. helium. Large advantage for LS		

Table 20.3.2-5 Piping and Insulation

Helium	CO_2	Liquid Salt

• Internal insulation typically used to reduce pressure boundary temperature, reduce energy losses
• Potential to use coaxial ducts for hot/cold legs
• Piping systems demonstrated, including in nuclear applications
• Similar systems used in PBMR DPP
• However, internal cooling applied in DPP would be more difficult in PHP and involve increased energy losses
	• As with helium except that piping and valves may be somewhat smaller	• Pipe size ~ 1/5 that of He pipe
		• No known practical LS wetted insulation system
		  ➢ Implies pressure boundary must operate at or near LS temperature
		  ➢ Eliminates or makes more difficult potential for coaxial heat transport
		• Suggests CFRC pressure boundary
		  ➢ Metallic materials may not be adequate at 900ºC
		• External insulation will be required to reduce energy losses

Overall: Established technology a major advantage for helium, reduced pipe size a modest advantage for CO_2. Lack of internal insulation system a feasibility issue for LS.		

Table 20.3.2-6 Valves & Seals

Helium	CO_2	Liquid Salt
• Very large valves required ➢ Size and potential for leakage problematical for SHTS isolation valves, if required • Leak-tight seals difficult ➢ Welded seals typical for pressure boundary ➢ Non-welded seals have been demonstrated for internal components	• Large valves required ➢ Size and potential for leakage problematical for SHTS isolation valves, if required ➢ Pipe diameters may be reduced relative to helium • Leak-tight seals less difficult than with helium	• Small valves required • Mechanical closure valves have not yet been developed ➢ In early applications, LS tended to clean surface to condition that promoted self-welding ➢ Freeze valves were used in some early applications; effective, but slow ➢ Newer material alternatives make feasibility likely; however qualification required to 900ºC • No mechanical seals used in prior designs ➢ Newer material alternatives make feasibility likely; however qualification required to 900ºC
Overall: Significant R&D issue for helium/CO_2 If SHTS isolation valves required. LS would require much smaller valves/seals.		

LS valves and seals would be significantly smaller than their gas working fluid counterparts. Regulating valves have been previously demonstrated in MSRE and other experiments. However, at 900ºC, the maximum temperature of the NGNP SHTS is significantly higher than in these earlier applications.

At this time, it is not clear that SHTS isolation valves would be required for the NGNP. If required, such valves would represent a significant R&D issue for helium or CO_2.

20.3.2.4.3 System Integration

Trade-offs related to system integration are summarized in Table 20.3.2-7. As previously noted, the freezing point of liquid salts places constraints on SHTS design options. However, the use of LS, in conjunction with ceramic/CFRC or other heat exchangers which are not limited by creep effects, would allow staging of the pressure from the primary loop to the process. For efficient heat transport, both helium and CO_2 would need to operate at relatively high-pressure, and most of the pressure drop would have to be taken across the PCHX.

Helium provides the most flexibility with respect to biasing the differential pressure across the IHX. In the case of both CO_2 and LS, the IHX pressure differential must be biased toward the SHTS. In the case of the PCHX, it is not clear as to which direction the pressure differential would be biased. There are potentially significant consequences of leakage in either direction.

Overall, helium provides the most flexibility for system integration with available technology. Leakage bias and the consequences of leaks are a disadvantage for CO_2 and a feasibility issue for LS.

20.3.2.4.4 System Operation

Trade-offs related to system operation are summarized in Table 20.3.2-8. There is significant operational experience with helium in earlier HTGRs. There is also significant experience with CO_2 in British gas-cooled reactors, albeit at lower temperatures. The selection of LS as the SHTS working fluid poses significant operational issues. The LS must be heated to a liquid state prior to introduction to the SHTS during startup. Separate provisions will be required to preheat the SHTS components in contact with the LS, in order to avoid thermal shock. For any event in which the temperature of the LS would drop below the freezing point, provisions must be made to drain the LS from all SHTS components.

Overall, operational experience at high temperature is an advantage for helium. The freezing of LS implies significant operational issues with startup, shut down and response to certain transients.

20.3.2.4.5 Availability and Reliability

Trade-offs related to availability and reliability are summarized in Table 20.3.2-9. The consequences of leaks in either the IHX or PCHX are a distinguishing characteristic. With

Table 20.3.2-7 System Integration

Helium	CO_2	Liquid Salt
• Pressure differential from primary to process must largely be taken across PCHX • Leakage biases: ➢ More flexible for IHX ➢ PCHX biased toward process	• Pressure differential from primary to process must largely be taken across PCHX • Leakage biases: ➢ IHX must be biased toward SHTS ➢ PCHX biased toward process	• Flexibility to stage primary to process pressure differential • Leakage biases: ➢ IHX leakage must be biased toward LS side of IHX ➢ PCHX leakage bias: – If toward LS side, need to evaluate consequences of process gas ingress – If toward LS side, implies high dP across IHX – If toward process side, must assess consequences of salt contamination
Overall: Leakage bias and consequences a disadvantage for CO_2; feasibility issue for LS.		

Table 20.3.2-8 System Operation

Helium	CO_2	Liquid Salt
• Significant operational experience with helium heat transport; no major issues	• Significant operational experience with CO_2 heat transport at lower temperatures; no major issues	• Startup/Shutdown ➢ Salt must be heated to liquid state and introduced to SHTS as part of startup ➢ LS must be drained for cold shutdown ➢ Temperature must be maintained above minimum level for hot standby ➢ Alternate heat source required for above • Steady State/Transients ➢ No unusual issues anticipated with steady state operation ➢ Transients resulting in shutdown addressed above
Overall: Freezing of LS implies significant operational issues with startup, shutdown and response to certain transients. Operational experience with helium at high temperatures an advantage.		

Table 20.3.2-9 Availability/Reliability

Helium	CO_2	Liquid Salt
• Continued operation with small HX leaks may be possible • Difficulty in locating/repairing leaks a problem with compact HXs	• Must be shut down when any leak is detected • Difficulty in locating/repairing leaks a problem with compact HXs	• Must be shut down when any leak is detected • Difficulty in locating/repairing leaks a problem with compact HXs
Overall: Consequences of leaks a disadvantage of CO_2, major disadvantage of LS.		

helium, continued operation may be possible with small leaks that are within technical specification limits. With CO_2 or LS, the plant must be shut down for repairs upon detection of any leaks.

Overall, the consequences of leaks represent a disadvantage for CO_2, and a major disadvantage for LS.

20.3.2.4.6 Safety & Licensing

Trade-offs related to safety and licensing are summarized in Table 20.3.2-10. As with availability and reliability, the consequences of leaks are a distinguishing characteristic among the candidate working fluids. An advantage of LS is the flexibility to move the process to a greater distance from the reactor.

20.3.2.4.7 Economic Considerations

Trade-offs related to economic considerations are summarized in Table 20.3.2-11. Relative to helium, it is not clear whether the reduced pumping energy requirements potentially obtained with CO_2 offset the larger and more expensive heat exchangers that would be required. With LS, the IHX, PCHX and other main SHTS components would tend to be smaller and less expensive. These reductions would be offset by additional auxiliary systems required for LS melting, injection, withdrawal and temperature control. Overall there may be a capital cost advantage for LS, and such advantage would increase with the distance between the IHX and PCHX. Operating costs may be higher or lower for LS, with key tradeoffs being associated with lower pumping energy vs. higher maintenance costs.

20.3.2.4.8 R&D Requirements

Trade-offs related to R&D requirements are summarized in Table 20.3.2-12. Of the SHTS working fluid options, helium would require the least R&D support. Incremental R&D for CO_2 largely relates to materials compatibility at the high temperatures of the NGNP. In particular, the feasibility of a metallic IHX needs to be verified. With LS, an advanced material will almost certainly be required for the IHX. For any of the options incorporating ceramic/CFRC heat exchangers, R&D would be required to develop the ceramic to metal transitions at the interfaces between the heat exchangers and the ducts.

As earlier noted, piping and insulation is a key LS issue that would have to be resolved through R&D. Overall, R&D requirements for CO_2 would be somewhat greater than for helium if metallic heat exchangers are feasible. The application of LS would require several major R&D initiatives.

Table 20.3.2-10 Safety/Licensing

Helium	CO_2	Liquid Salt
• Requires process to be close to reactor	• Requires process to be close to reactor • Consequences of CO_2 ingress into primary loop may have to be addressed	• Flexibility for moving process farther from reactor • Consequences of salt ingress into primary loop may have to be addressed
Overall: Potential for SHTS leaks into primary system a disadvantage for CO_2, potentially a major issue for LS. LS would allow greater distance between reactor and process.		

Table 20.3.2-11 Economics

Helium	CO_2	Liquid Salt
• Base for comparison	• Tradeoff of larger heat exchangers (IHX, PCHX) vs. reduced pumping costs ➢ Further evaluation required to determine net impact	• Capital cost likely to be lower ➢ IHX, PCHX, main SHTS components will be smaller, less expensive ➢ However, an offset will be additional auxiliary systems required for melting, LS temperature control ➢ Capital cost advantage will increase with distance between IHX and PCHX • Operating costs may be higher or lower ➢ Lower pumping costs (distance a key parameter) ➢ Higher maintenance costs
Overall: Potentially significant capital cost advantage for LS, but operating cost tradeoffs uncertain.		

Table 20.3.2-12 R&D Requirements

Helium	CO_2	Liquid Salt
• IHX ➢ Potential exists to use a metallic IHX • IHX core to metal transitions ➢ Applies to ceramic/CFRC IHX • Isolation valves • PCHX	• IHX ➢ Material compatibility an issue for metallic HXs • IHX core to metal transitions ➢ Applies to ceramic/CFRC IHX • Isolation valves • PCHX	• IHX ➢ Will almost certainly require ceramic/CFRC IHX • IHX core to metal transitions ➢ Applies to ceramic/CFRC IHX • Isolation valves • SHTS piping and insulation • PCHX • Pump and seals
Overall: R&D somewhat greater for CO_2 if metallic HXs are feasible. LS requires major R&D initiative.		

Table 20.3.2-13 Summary of SHTS Working Fluid Evaluation Results

Item	Helium	CO_2	LS
Design Compatibility	+	-	- -
Influence on Major Components			
Heat Exchangers	+	-	+/-
Circulators/Pumps	-	+	++
Piping and Insulation	++	+	- -
Valves and Seals	- -	-	+
System Integration	+	-	- -
System Operation	+	-	- -
Availability and Reliability	+	-	- -
Safety & Licensing	+/-	-	+/-
Economic Considerations	+/-	+/-	+
R&D	+	-	- -

20.3.2.5 Evaluation and Recommendation

A qualitative summary of the SHTS working fluid evaluation results is provided in Table 20.3.2-13. The most significant factors and bases for a tradeoff decision are summarized as follows:

- LS has a much higher volumetric heat capacity ($\rho \bullet C_P$) than helium or CO_2, and this implies reduced piping diameters and lower SHTS pumping power requirements, on the order of 1/5th that for helium. The volumetric heat capacity of CO_2 is about twice that of helium, with a corresponding reduction in pumping power requirements at equivalent temperatures and pressures.
- LS has a much higher thermal conductivity than helium or CO_2, which translates to higher heat transfer coefficients and reduced log-mean temperature difference (LMTD) requirements that can be taken advantage of in terms of either lower reactor outlet temperature for a given process temperature or higher process temperatures for increased efficiency and smaller heat exchangers. The thermal conductivity of CO_2 is only about 1/6 that of helium, implying significantly larger and more expensive heat exchangers with CO_2.

- Experience with CO_2 and LS heat transport fluids has not extended to the temperature range of the NGNP SHTS.
- There is a requirement for an alternate heat source of undetermined size for startup of a LS heat transport circuit, and to avoid freeze-up there needs to be a drain, storage and vent system for LS.
- The LS heat transport pressure-retaining pipes will have to operate at LS temperatures, unless an internal insulating system can be devised - this implies a new piping material. Therefore, insulation to limit heat loss will be external to the pipe. On the other hand, heat losses will be reduced with LS, due to the smaller required pipe sizes. With helium or CO_2, internal insulation is possible and the pipe can run nearer to external ambient temperature. Helium and CO_2 working fluids are compatible with an optional configuration of coaxial Secondary Heat Transport System (SHTS) transport pipes.
- LS is not compatible with conventional shell and tube PCHXs that have the process fluid and catalyst on the inside of the tubes. For a given heat delivery, the flow rate on the LS side would be much smaller than that on the process side, leading to issues with shell side flow distribution. With compact heat exchangers, there is a lower limit to the size of flow passages, below which plugging can be a concern, and this limit is more likely encountered in the smaller passages of HXs with LS.
- With LS as the SHTS working fluid, any detectible leak in the IHX or PCHX will require immediate shut-down for repairs, while continued operation is feasible with small leaks in the IHX of an all-helium heat transport system. With CO_2, leaks would also require immediate shutdown for repair; however, the consequences of leaks are unlikely to be as severe as those with LS.
- R&D will be required for any of the three SHTS working fluid candidates. Of the three, helium has the fewest R&D requirements. Assuming that metallic heat exchangers are determined to be feasible, CO_2 would have modest incremental R&D needs relative to helium. The LS alternative will almost certainly require a ceramic/CFRC IHX, and has unique R&D needs in the areas of piping materials compatibility, piping insulation design, high-temperature pumps and pump and valve seals. LS R&D requirements are not compatible with the present schedule for the NGNP.

The conclusion of this evaluation is that helium should be selected as the SHTS working fluid for the NGNP and that the PCHX should be located as close to the IHX as possible. There should be continued following of LS heat transport system development with a view to future distributed process heat applications (e.g., energy parks), where longer distance high-temperature process energy transport is mandatory. As noted in Section 20.3.1.2.2, a differentiating requirement of the NGNP is to provide flexibility for demonstrating various energy utilization options. If future demonstration of LS thermal energy transport in the NGNP environment is desired, an option is to replace the PCHX with a secondary IHX and to add a tertiary LS loop to transport energy to a more distant location.

20.3.2.6 References for Section 20.3.2

20.3.2-1 Smith, C., Beck, S. and Galyean, B., "An Engineering Analysis for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor", INL/EXT-05-00137 Rev 0, INL, March 2005.

20.3.2-2 "Liquid Salt for Secondary Heat Transport Applications", Record of Meeting at ORNL, November 8, 2005 Technology Insights, 21 Nov 2005.

20.3.2-3 du Toit, B. and van Ravenswaay, J., "The Impact of Separation Distance between Reactor and Process on the Choice of Secondary Heat Transport Coolant for High Temperature Process Heat Applications" (I00000153), Proceedings HTR2006, Johannesburg, South Africa, October 1-4, 2006.

20.3.3 IHX READINESS ASSESSMENT

20.3.3.1 Introduction

The NGNP reference concepts are helium-cooled, graphite-moderated, thermal neutron spectrum reactors with a design goal outlet helium temperature of 950°C (see Section 20.3.3.4, Assessment Input Requirements). The NGNP is expected to produce both electricity and hydrogen. Depending upon the selected Heat Transport System architecture, the thermal energy for hydrogen production and, potentially, electrical production will be transferred by an intermediate heat exchanger (IHX).

The basic technology for the NGNP was established in earlier high temperature gas-cooled reactor (HTGR) demonstration plants (DRAGON, Peach Bottom, AVR, Fort St. Vrain, and THTR). Presently, a prototype commercial HTGR for electricity generation, the Pebble Bed Modular Reactor (PBMR) Demonstration Power Plant (DPP), is being deployed in South Africa. Furthermore, the Japanese High Temperature Test Reactor (HTTR) and Chinese HTR-10 test reactors are demonstrating the feasibility of some of the planned components and materials.

The proposed high operating temperatures in the NGNP place significant constraints on the choice of materials selected for the IHX. The main focus of this section is the materials readiness issues associated with the IHX.

20.3.3.1.1 Purpose

The purpose of this section is to document the results of an IHX materials assessment performed to support a pre-conceptual design study for the NGNP. This assessment includes an evaluation of IHX design issues, potential metallic and ceramic IHX fabrication materials, applicable codes and standards, Design Data Needs (DDNs) and associated R&D implications for the NGNP and, finally, appropriate conclusions and recommendations.

20.3.3.1.2 Scope

The scope of this assessment includes evaluation of the following issues associated with the IHX:

- The likelihood of achieving a He/He IHX design with an inlet temperature up to 950ºC for procurement by 2012, using available mature metallic alloys at high operating capacity factor (>95%)
- Projected lifetimes under various conditions
- IHX designs (tube and shell vs. compact)
- The pros and cons regarding application to the NGNP
- The candidate metallic materials for the IHX with respect to applicability and adequacy for the proposed service
- Significant gaps in the knowledge base for the application of these materials
- The availability and/or applicability of codes and standards that could be used for IHX materials procurement, design, fabrication and testing

- Significant gaps in materials property databases, design methods and codes and standards
- An approach to resolution where codes and standards are found to be unavailable or inadequate (identified in terms of DDNs)
- Required R&D programs to address gaps and needs
- The design options for routing reactor thermal energy to the IHX
- Alternate IHX materials (e.g., composites, ceramics) and associated pros and cons
- Implications for the NGNP pre-conceptual design
- Conclusions and recommendations

20.3.3.1.3 Outline

The outline for the remainder of this assessment is as follows:

- ITRG Recommendations
- Definition of "High Temperature" for Metallic Materials
- Assessment Input Requirements
- IHX Design Considerations
- Metallic Materials Assessment
- Ceramic Materials Assessment
- Codes and Standards Readiness
- Design Data Needs and R&D
- Implications for NGNP Preconceptual Design
- Final Conclusions and Recommendations
- References

20.3.3.2 Independent Technology Review Group Recommendations Associated with the IHX

The Independent Technology Review Group (ITRG) performed their review from November 2003 through April 2004. The purpose of the ITRG review was to provide a critical review of the proposed NGNP project and identify areas of R&D that needed attention. As stated in the report, the ITRG observations and recommendations focus on overall design features and important technology uncertainties of a very-high-temperature nuclear system concept for the NGNP.

The ITRG report entitled *Design Features and Technology Uncertainties for the Next Generation Nuclear Plan*t was issued on June 30, 2004 by the INL [Ref. 20.3.3-1]. An analysis of the materials-related risk issues noted in this report and comments associated with these risk issues are given below. The NGNP Program response was originally stated in Revision 3 of the NGNP Materials Program Plan, Section 20.3.1.4 [Ref. 20.3.3-2].

20.3.3.2.1 Upper Temperature Limit

Technical Observation: The originally specified NGNP gas outlet temperature of 1000°C is beyond the current capability of metallic materials. The requirement of a gas outlet temperature of 1000°C will result in operating temperatures for metallic core components (core barrel, upper shroud, control rod drive assemblies), and IHX components that will approach 1200°C in some cases. Metallic materials that are capable of withstanding this temperature for the anticipated plant life will not be available on the NGNP schedule, if they can be developed at all. Nonmetallic materials capable of this temperature will require a development program that cannot support the NGNP schedule.

Associated Risk: The requirement for a gas outlet temperature of 1000°C represents a significant risk that ITRG judges cannot be resolved consistent with the schedule for the NGNP.

Recommendation: It is recommended that the required gas outlet temperature be reduced such that metallic components are not exposed to more than 900°C for the base NGNP design. Raising the gas outlet temperature to 950°C may be considered but at the potential expense of a reduced life (<60 year) for key components (e.g., the IHX).

NGNP Materials Program Response: This recommendation was implemented and the NGNP materials program now focuses on a reactor outlet temperature for the NGNP of 950°C maximum.

20.3.3.2.2 Pressure Boundary Time-Dependent Deformation

Technical Observation: Several of the NGNP concepts that were reviewed require many of the irreplaceable Class I boundary components (pressure vessel, piping, etc.) to operate at temperature and stress combinations that will result in significant time-dependent deformation (creep) during the component life. While there is allowance (ASME Code Case) for the inclusion of time-dependent deformation in pressure vessel designs, this has not been a part of commercial nuclear pressure vessel and piping systems in the past and represents a very significant departure from current practice. Moreover, it is likely that creep as well as fatigue-related time-dependent deformation will be present. Creep-fatigue interaction represents the most complex form of high temperature behavior, often requiring component-specific design rules. In addition, the regulatory infrastructure does not have experience with including significant time-dependent deformation in the licensing and safety evaluation process.

Associated Risk: The allowance of time-dependent deformation in the non-replaceable Class I boundary represents an unacceptable risk for the NGNP program.

Recommendation: The ITRG recommends that time-dependent deformation be limited to "insignificant," as defined by the ASME Code, during the life of non-replaceable (60-year life) components for the NGNP. Time-dependent deformation for replaceable Class I components (portions of the IHX, interface heat exchanger for the hydrogen system, etc.) can be allowed, but only with the addition of significant additional levels of inspection and monitoring. However, the fraction of the Class I boundary that experiences significant creep deformation must be limited as much as possible.

NGNP Materials Program Response: The program agrees with this recommendation and this philosophy is currently reflected in materials design approaches.

20.3.3.2.3 ASME Codes and Standards

Technical Observation: Several of the NGNP concepts require either that existing materials be qualified for Section III service or that entirely new materials be developed. In addition, some of the NGNP designs allow for creep deformation in the Class I boundary.

Associated Risk: The risk is associated with the time that will be necessary for the qualification of existing or new materials for use in the Class I boundary. In addition, there will be risk associated with the allowance of creep deformation as a part of the Class I boundary design, both technical and regulatory. It is the judgment of the ITRG that the development and qualification of new materials for Section III, Class I service cannot be achieved in the time frame for the NGNP. Further, it is our judgment that the qualification of existing materials for Class I service where creep deformation is allowed represents an unacceptable risk for the program.

Recommendation: The ITRG recommends that the NGNP non-replaceable Class I boundary components be constructed using materials that are currently qualified for Class I service or that can be qualified without an appreciable data gathering program. The ITRG further recommends that qualification of new materials be limited to those that are either currently listed in Section II for Section VIII service or for which a database currently exists.

NGNP Materials Program Response: The materials development program agrees with these recommendations assuming that an aggressive schedule for plant construction is an overriding consideration; however, as noted in the discussion above, the use of SA-508/533 LWR RPV steel for the NGNP RPV will cause limitations on the design of the plant which will need to be addressed. The other important issue involves a Nuclear Energy Research Advisory Committee (NERAC) recommendation to design a prototype VHTR plant with lesser initial capabilities but with the ability to upgrade the capabilities of the plant over time. This could be more easily accomplished if the Class I boundaries were fabricated with a more advanced alloy because the Class I boundary components are not easily replaceable and the materials used for these components establish long term limitations on possible higher power, higher temperature plant operation that may represent a desirable modification in the future. While the higher alloy content steel 9Cr- 1MoV is included in ASME Section III, Subsection NH for Class I service, it is not necessarily adequately qualified for the full ranges of time and temperature of service that the plants may require. It may be possible to address these issues with design changes over time but this approach represents a tradeoff of reduced initial risk versus potential additional long term risk associated with possible long term plant upgrades.

20.3.3.2.4 Corrosion and Oxidation

Technical Observation: High-temperature operation of metallic components for times up to 60 years will result in the possibility of corrosion damage. This damage will most likely be associated with coolant contamination within the primary system or air oxidation on external surfaces. In addition, the development of oxidized surfaces may affect the overall thermal resistance of the system as a result of changes in emissivity.

Associated Risk: The risk is associated with potential changes in material properties as a result of corrosion-induced embrittlement.

Recommendation: This risk is judged to be minimal, assuming that adequate coolant contaminant control is exercised.

NGNP Materials Program Response: The materials development program does not consider this risk to be minimal because it is currently unclear how effective coolant contamination control measures will be. Therefore, the program is planning to perform adequate testing to characterize changes that take place from corrosion induced embrittlement. However, it is now clear, based on a subsequent literature review, that this issue has not been a significant problem with VHTR plants that have operated in the past. These plants may not be representative of the NGNP design; however, the results noted from the review are encouraging. The program also believes that continued R&D in this area will be useful during licensing discussions with the NRC if questions arise concerning this issue. The new issue of particular concern for NGNP is the impact of impure helium corrosion on the very thin sections that may be required within compact heat exchangers, if they are used to minimize system cost.

20.3.3.2.5 Microstructural Stability

Technical Observation: The exposure of metallic materials to high temperature for long periods of time may result in microstructural changes in pressure boundary materials that result in a degradation of material properties.

Associated Risk: The risk is associated with embrittlement of materials. However, with an adequate monitoring and inspection program, this risk is judged to be acceptable.

Recommendation: The ITRG recommends that the development program conducted for the NGNP include tests to identify thermal aging issues. Special consideration should be given to welds and heat-affected zones.

NGNP Materials Program Response: The materials development program agrees with this recommendation and investigation of these issues have been integrated into the program.

20.3.3.2.6 Advanced Materials Development

Technical Observation: Operation at a gas outlet temperature of 1000°C will require use of nonmetallic materials in core structural applications and will require development of new materials for heat exchanger designs.

Associated Risk: The risk is associated with the time it will take for the development and qualification of new materials. It is judged that sufficient new material development and qualification cannot be achieved in time to support the NGNP construction permit application (2009).

Recommendation: The ITRG recommends that NGNP materials be limited to those currently qualified or that can be qualified with minimal effort. As discussed in earlier sections, this will require that the gas outlet temperature be reduced.

NGNP Materials Program Response: The materials development program agrees with this recommendation. This is the reason that the program has selected only the most mature high temperature metallic alloys, RPV materials, and non-metallic materials for qualification within the NGNP. No inherently new materials are being developed, though small variations to existing materials are being evaluated, including graphites from currently available coke sources, controlled chemistry variations of high temperature alloys, like Alloy 617, and minor architecture and processing variations of C-C composite already developed for other applications.

20.3.3.2.7 Summary Observations Regarding ITRG Report

The recommendations and discussion noted above have the following implications with regard to the IHX:

- The reactor outlet temperature for the NGNP should not exceed 950ºC, based in part on IHX materials considerations.
- Non-replaceable metallic components designed for the full plant lifetime (60 years) should be limited to ~900ºC. Metallic components operating at temperatures higher than ~900ºC, notably including high-temperature sections of the IHX, are likely to have reduced lifetimes and should be designed for replacement.[2]
- Time-dependent deformation for Class 1 pressure boundary components should be "insignificant", as defined by the ASME Code.
- The IHX should be designed to minimize stresses imposed on the metallic alloy due to the low margin of allowable creep stress associated with available metallic alloys operating in the 900-950ºC temperature range.
- Metallic materials should be limited to alloys listed in ASME Section II for Section III or Section VIII service.

20.3.3.3 Definition of "High Temperature" for Metallic Materials

For the purposes of this assessment, a "high temperature" for metallic materials is defined as that which would necessitate the design to account for creep effects.

- Creep is plastic deformation in a material that occurs over a period of time at a stress below the elastic limit
- Creep normally occurs in three stages called Stage 1, 2 and 3 creep
- Stage 3 creep is also called tertiary creep
- Stage 2 creep is normally linear and Stages 1 and 3 are normally defined by various non-linear functions depending on the material and creep model used
- Design basis is given in ASME Section III, Subsection NH; and Section VIII, Div. 1 and 2

[2] Based on the present assessment, it is recommended that non-replaceable components be limited to ~850ºC.

- For ferritic alloys, creep effects normally start about 400-500C
- For Ni-base alloys, creep effects normally start about 500-700C

20.3.3.4 Assessment Input Requirements

Assessment requirements for this evaluation are given below:

- Nominal 950ºC reactor outlet temperature (ROT)/ 350ºC reactor inlet temperature (RIT)
- Nominal 900ºC secondary IHX outlet temperature
- Maximum 300ºC secondary inlet temperature for indirect cycle with all reactor heat output to IHX
- Maximum 450ºC (likely but TBD) secondary inlet temperature for other designs
- He in primary and secondary loops
- Primary loop pressure - 9 MPa
- Primary to secondary loop delta P - essentially pressure balanced with slight positive pressure on secondary side
- Order for IHX component by end of fiscal year (EOFY) 2012
- Design life greater than or equal to 10 years with a target of 20 years (depending on size, design and other factors)
- Target operating capacity - 95%

20.3.3.5 IHX Design Considerations

Several different potential plant design configurations for the NGNP with either direct or indirect power conversion cycles and integrated IHX designs were proposed and evaluated by [Ref. 20.3.3-3]. These configurations included IHX designs in parallel or in series with the NGNP power conversion system. In the serial designs, the total primary system flow from the reactor outlet passes through the IHX where approximately 50 MWt is transferred to the intermediate loop to drive the hydrogen production process. In these designs, heat is extracted from the primary fluid at the highest possible temperature (the reactor outlet temperature) for delivery to the hydrogen production process, while the power conversion system receives a slightly lower temperature fluid. In the parallel flow designs, the flow from the reactor outlet is split with a small fraction of the flow (approximately 10%) going to the IHX to drive the hydrogen production process, while the majority of the flow is delivered to the power conversion system for electrical power production. In these designs, both the hydrogen production process and the power conversion system receive the highest possible temperature fluid. Harvego [Ref. 20.3.3-4] has discussed the possible configurations for the design of an IHX for the NGNP and established the pros and cons of each configuration. Based on the design, he also established the flow rates, temperature distributions through the loops, and other IHX requirements.

The purpose of the IHX in the NGNP is to transfer heat from the nuclear reactor to the process heat facilities and, in some arrangements, to the electrical plant. One of the process heat facilities being considered is a hydrogen production plant. Due to safety concerns, the hydrogen production facility cannot be integrated into the nuclear power production plant and the heat generated in the reactor may need to be transported over significant distances to the hydrogen production plant [Ref. 20.3.3-5]. The IHX must be robust enough to effectively transfer the heat from the reactor outlet helium at 950°C to the secondary system. The hydrogen production facility requires a minimum temperature of 800°C for the thermo-chemical production of hydrogen (e.g., HyS or S-I cycles) and about 700°C for high temperature electrolysis of water [Ref. 20.3.3-1]. Therefore, the components of the heat transport system will be subjected to elevated temperatures for long times where adequate and reliable performance of materials is critical. This section addresses several of the key issues relating to IHX materials readiness, codes and standards readiness, design data needs, further research and development on materials and implications on the NGNP preconceptual design

Both conventional shell-and-tube and compact heat exchangers are considered in this assessment. Shell and tube exchangers are generally built of cylindrical tubes (in either straight or helical configurations) in a cylindrical shell with the tube bundle axis parallel to that of the shell. One fluid flows inside the tubes and the other flows across and/or along the outsides of the tubes in a counterflow arrangement for maximum effectiveness. The major components of this exchanger are the tubes, shell, front-end head, rear-end head, baffles and tube-sheets. Shell and tube heat exchangers can be very efficient heat transfer devices; however, the most significant issues with this type of HX are their size and weight. A 10MWt prototype IHX for the German process heat program was fabricated in the 1980s, satisfied all specified parameters and operated in excess of 900ºC ; however, the unit weighed about 135 tons. A corresponding unit for an indirect cycle 400-500MWt NGNP would be too large to be considered a viable option. Design rules for shell and tube HXs and associated pressure vessels are given in ASME Section VIII, Division 1, Part UHX. Alternative rules that permit higher design stresses are given in Section VIII, Division 2. Examples of shell and tube HXs are given in Figure 20.3.3-1 and Figure 20.3.3-2 [Ref. 20.3.3-6].

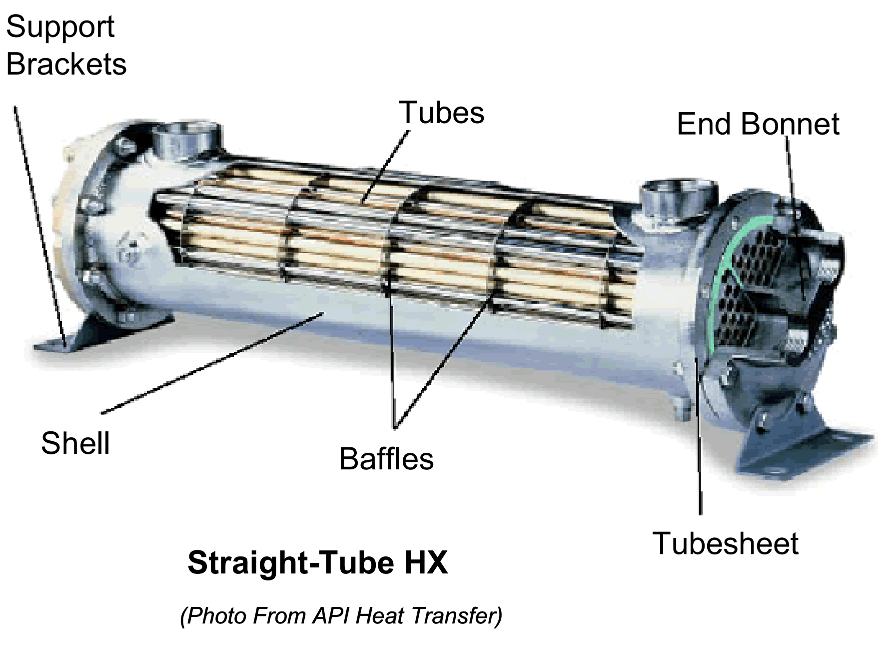
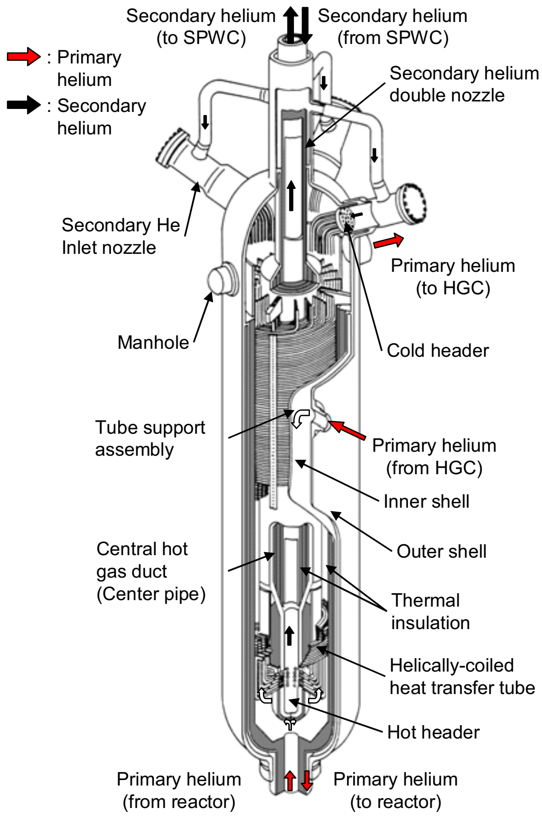


Figure 20.3.3-1 Example of Tube and Shell Heat Exchanger with Straight Tubes



Key IHX Parameters

Type		Vertical, helically coiled, counter flow
Primary / Secondary coolant		Helium / Helium
Thermal Rating		10MW
Coolant mass flow rate	Primary	15t/h / 12t/h*
	Secondary	14t/h / 12t/h*
Coolant temperature	Primary	(Inlet) 850 / 950°C* (Outlet) 390ºC
	Secondary	(Inlet) 300ºC (Outlet) 775 / 860°C *
Heat transfer tubes	Number	96
	O. D.	31.8mm
	Thickness	3.5mm
	Material	Hastelloy XR
Shell outer diameter		2.0m
Total height		11.0m
Material	Shell	2 1/4Cr-1Mo steel
	Hot header	Hastelloy XR
	Tubes	Hastelloy XR

*** Rated operation ／High temperature test operation**

Figure 20.3.3-2 Example of Tube and Shell Heat Exchanger with Helical Tubes

More recently, compact heat exchangers have been developed that provide for increased performance relative to their weight and volume. Compact heat exchangers typically provide at least an order of magnitude improvement in surface compactness (m^2/m^3) and heat transfer compactness (MWt/m^3) relative to shell and tube heat exchangers (Figure 20.3.3-3) [Ref. 20.3.3-7]. A common design feature to achieve such compactness is small channel size.

Included among compact heat exchangers are plate-fin (Figure 20.3.3-4 [Ref. 20.3.3-8] and Figure 20.3.3-5), primary surface (Figure 20.3.3-6 [Ref. 20.3.3-9]) and etched-plate (Figure 20.3.3-7, Figure 20.3.3-8) designs. In plate-fin heat exchangers, the primary and secondary fluids are separated by plates that are seal welded at the edges (Figure 20.3.3-4). Thin corrugated sections comprising fins are typically incorporated between the plates and brazed to the plates on one or both sides. The plate-fin assemblies are stacked to form the complete heat exchanger (Figure 20.3.3-5).

Primary surface heat exchangers are distinguished from plate-fin designs in that the corrugated fins themselves separate the primary and secondary fluids (Figure 20.3.3-6).

The most advanced example of etched plate heat exchangers is the Printed Circuit Heat Exchanger (PCHE) developed by the Heatric Division of Meggitt (UK) Ltd [Ref. 20.3.3-10, Ref. 20.3.3-11, Ref. 20.3.3-12]. The PCHE consists of metal plates on the surface of which millimeter-size semicircular channels are chemically etched. Subsequently, the plates are diffusion bonded together to fabricate an HX core. Flow distributors are integrated into the plates or welded outside the core, depending on the design. Several PCHE concepts have been developed by Heatric and a plate-type configuration, illustrated in Figure 20.3.3-7 and Figure 20.3.3-8, has been selected for present analysis. In this configuration, flow distributors are integrated within the plates. Between the inlet and outlet flow distribution regions, the flow is purely counter-flow.

The internal configuration of a PCHE is information proprietary to Heatric. Each PCHE is a custom built heat exchanger in that the PCHE technology allows variation of configuration parameters (channel diameter, plate thickness, channel angles, and so on) to fit the specified task. The PCHE unit size is limited to about 60 MWt/unit [Ref. 20.3.3-12]. This unit size actually represents several sub-units of about 1.5 m x 0.6 m (maximum) on plate dimension and 0.6 m (maximum) on stack height that have been connected by headers [Ref. 20.3.3-13]. The weight/MWt for the tube and shell HX and the PCHE is about 13.5 tons/MWt and 0.2 tons/MWt, respectively [Ref. 20.3.3-12]. This represents a factor of about 68X for weight, a factor estimated to be about 100X for volume compared to a tube and shell HX/PCHE. Assuming approximately equal primary and secondary pressures, a pressure vessel used with a plate type HX could, if properly designed, act to reduce ΔP and, hence, steady state stress to near zero by enclosing the HX in a pressurized environment. Another factor that favors the PCHE is that the size of leaks that are likely to occur between the primary and secondary sides would be about 2 orders of magnitude less for the PCHE compared to the tube and shell. This results because the most likely leak from a PCHE would be from a semicircular passage with a radius of 0.6 mm versus a round tube with a diameter of about 15mm [Ref. 20.3.3-12]. Disadvantages of this design are (1) the susceptibility to very high thermally induced stresses during transients, particularly at the semi-circular channel corners, (2) inspection, (3) repair and (4) the lack of an ASME design basis.

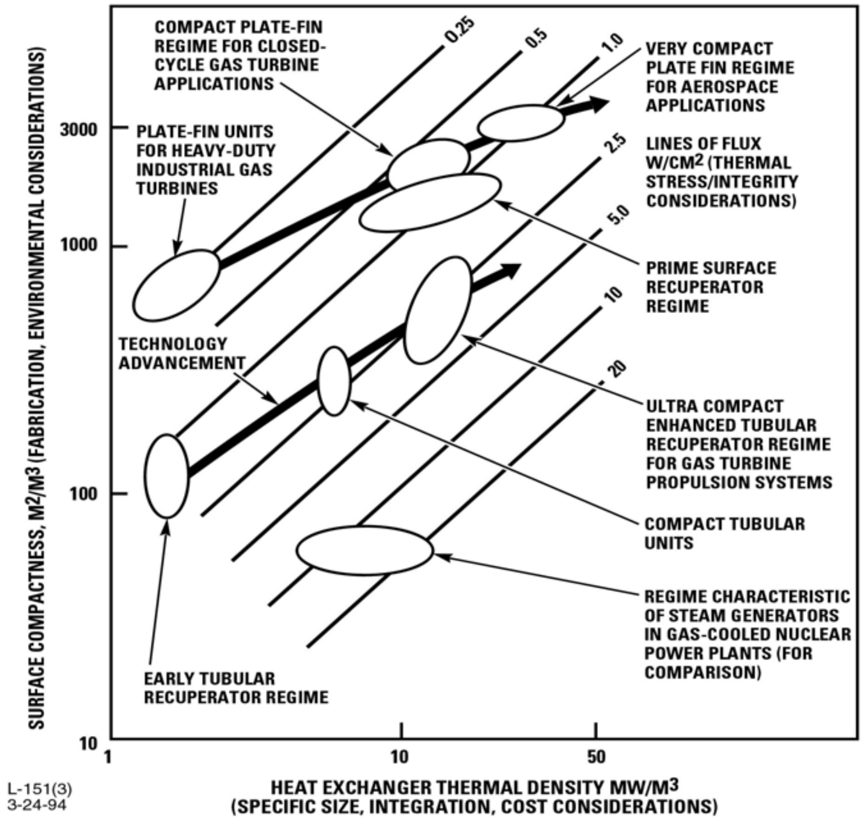


Figure 20.3.3-3 Compact Heat Exchanger Performance

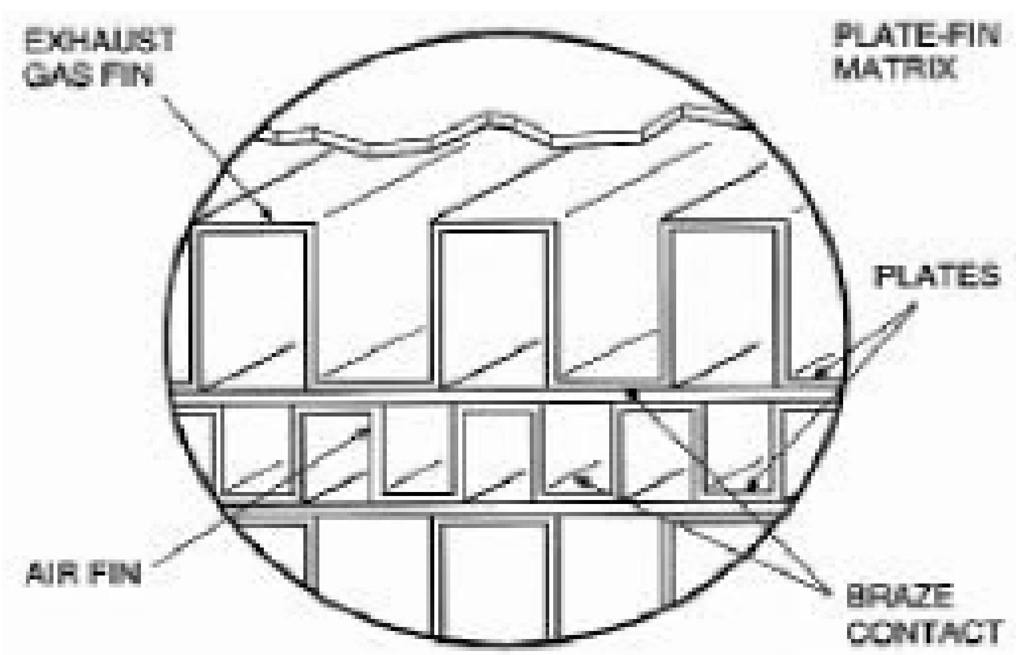


Figure 20.3.3-4 Brazed Plate-Fin Recuperator Cross-Section

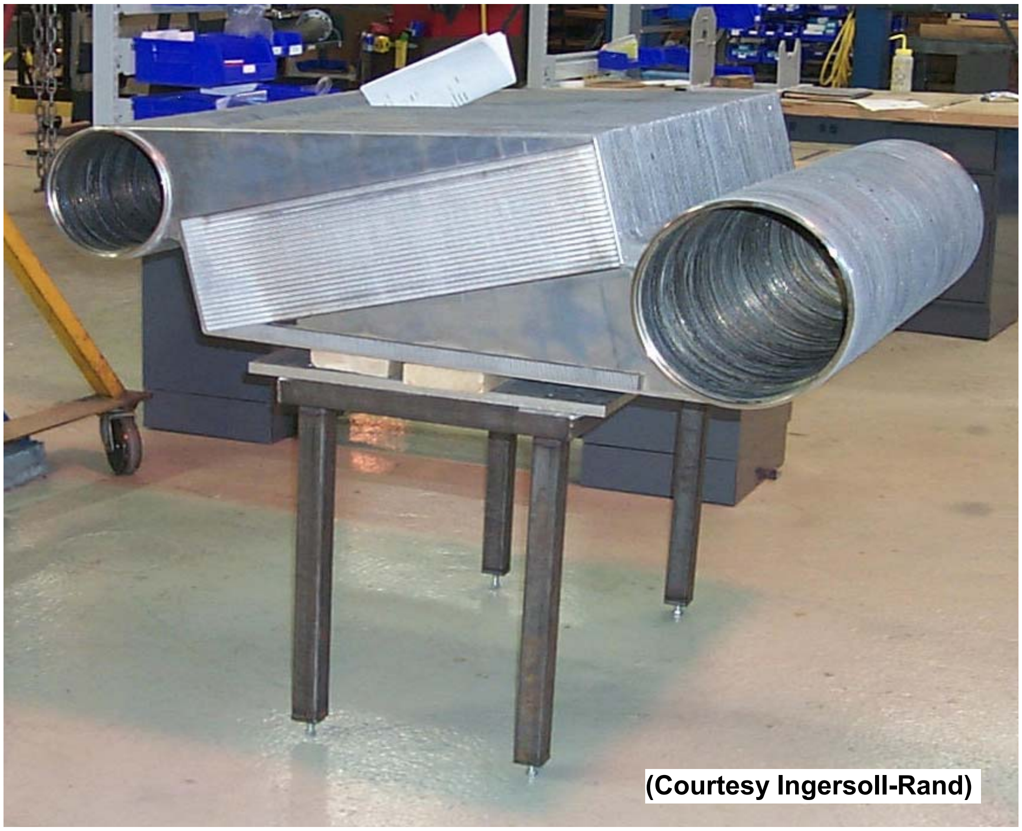


Figure 20.3.3-5 Plate-Fin Recuperator Assembly

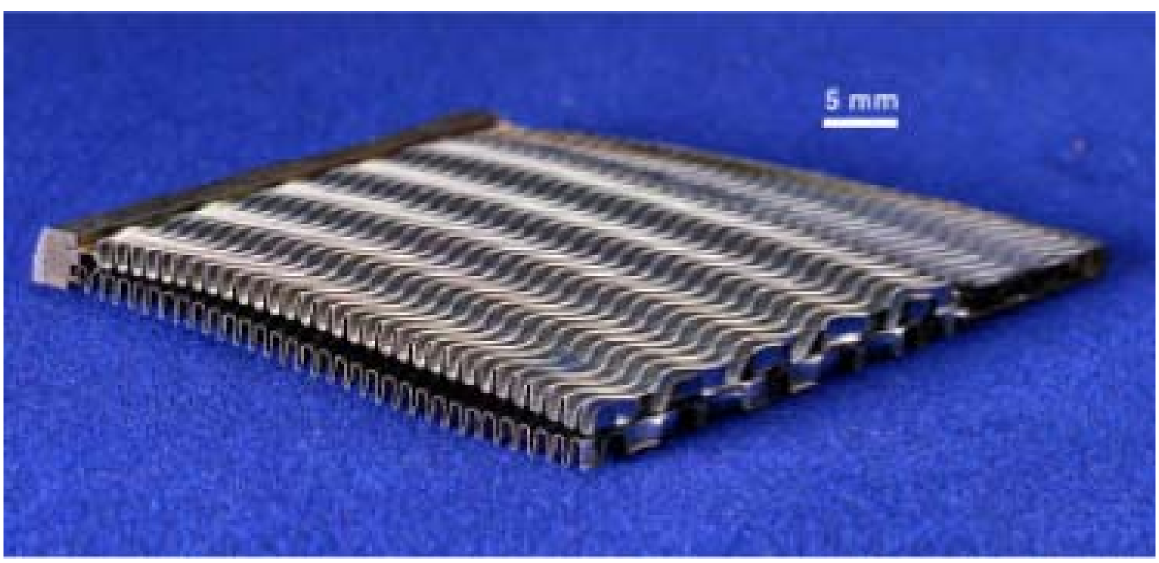


Figure 20.3.3-6 Corrugated Foil Pattern for Primary Surface Recuperator

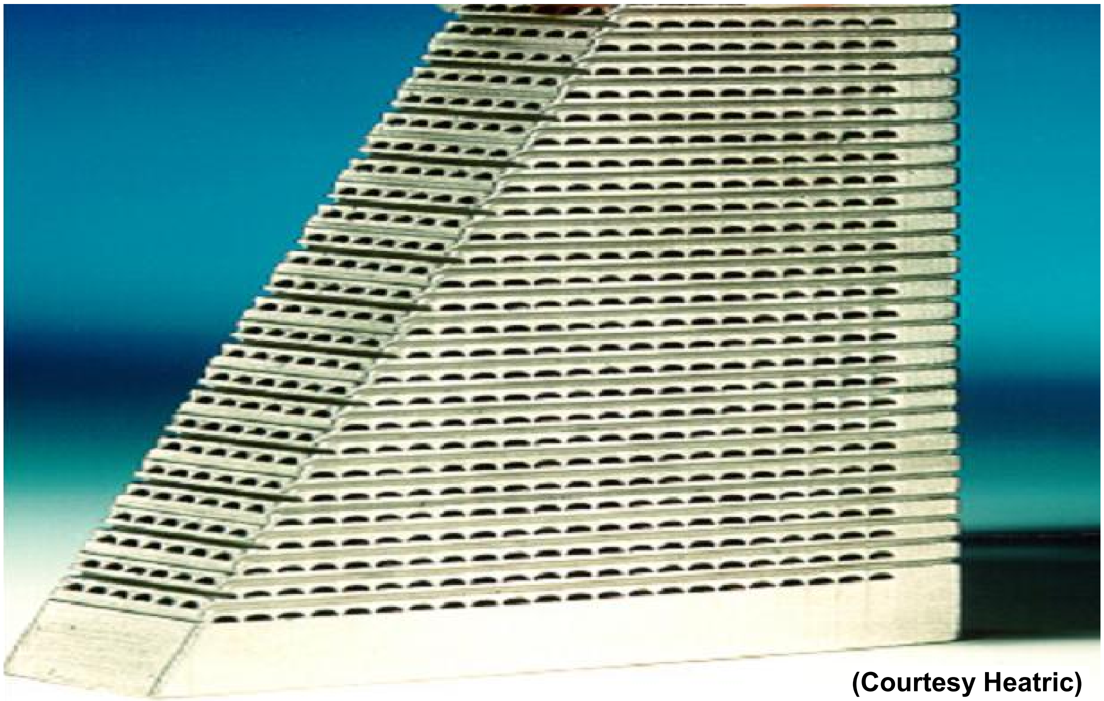


Figure 20.3.3-7 Cross-section through Heatric PCHE

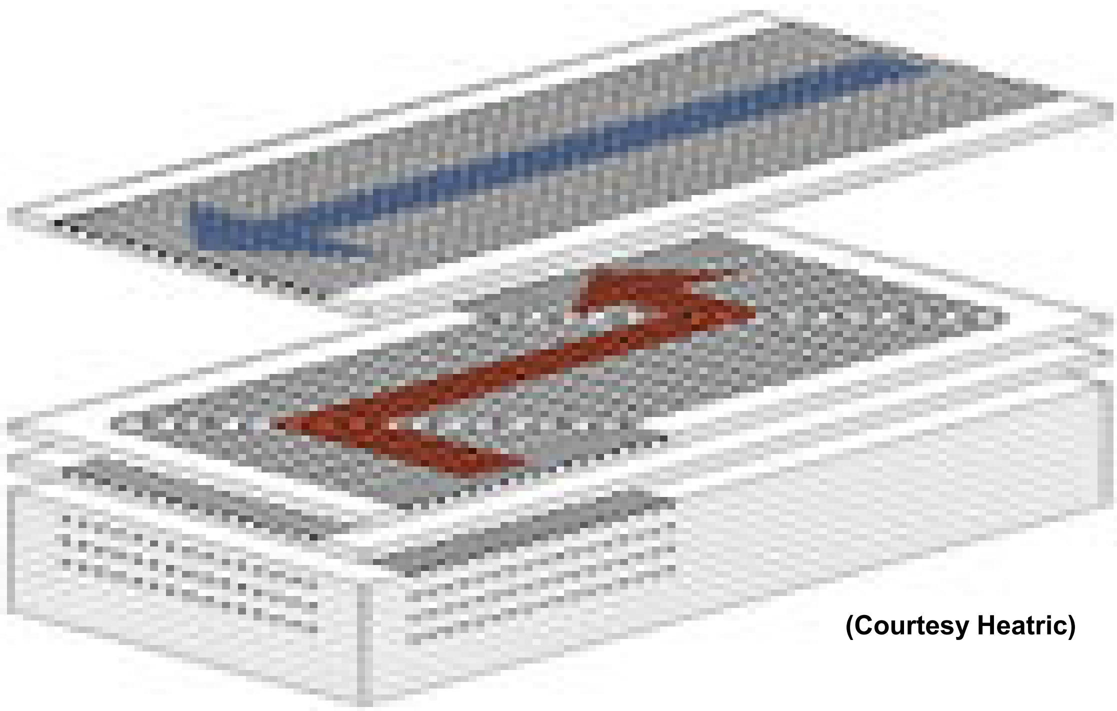


Figure 20.3.3-8 Flow Path through PCHE

Table 20.3.3-1 Summary of Design Tradeoffs for Evaluated HX Types

Metric	Shell & Tube	Plate-Fin & Prime Surface	PCHE
Compactness (m^2/m^3 & MW/m^3)	Poor	Best	Good
Cost (tons/MWt)	Poor: (13.5 tons/MWt) Unlikely to be commercially viable	Best: Most compact, least materials	Good: (0.2 tons/MWt) Estimated to be ~1/68 that of S&T
Experience Base	HTTR, German PNP Development	Conventional GT recuperators	PBMR DPP Recuperator, other commercial products
Robustness	Best: Simple cylindrical geometry, stress minimized in HT area	Worst: Thin foils; stressed welds in pressure boundary; stress risers in pressure boundary welds; Small material and weld defects more significant	Good: Thicker plates; local debonding does not immediately affect pressure boundary; potential for higher transient thermal stresses vs. P-F
Inspection and Maintenance	Design facilitates inspection and plugging of individual tubes	Inspection and maintenance difficult or impractical below module level	Inspection and maintenance difficult or impractical below module level
HX Integration	Headers and HX-vessel integration demonstrated	More difficult HX integration with multiple series/parallel modules	More difficult HX integration with multiple series/parallel modules
Code Basis for Design	Existing Sect VIII Code basis for tubular geometries	No existing Code basis	No existing Code basis

A summary of design tradeoffs related to the heat exchangers discussed above is provided in Table 20.3.3-1 . Taking into account these tradeoffs, the PCHE has been selected on a preliminary basis for the NGNP IHX pre-conceptual design. The shell & tube HX was eliminated as not being commercially viable for a large IHX. The PCHE was judged to be more robust than other compact designs with a solid basis of commercial experience, albeit at lower temperatures. Tradeoffs include: (1) More difficult inspection and maintenance, and (2) Need to establish design basis for Code acceptance. Additional discussion regarding materials and code issues is given in other sections.

20.3.3.6 Metallic Materials Assessment

The following factors have the most impact on the selection of metallic alloys for application to the IHX:

- ASME Code acceptance (Section III preferably or Section VIII)
- Adequate data base for the temperature region of the IHX
- The data base must include mechanical properties of small grain size samples and diffusion bonds if a plate type heat exchanger (HX) is selected
- Must be able to be easily welded and/or diffusion bonded (plate type HX)
- Must be able to be formed, machined or etched if a plate type HX is selected
- Adequate creep rupture and mechanical properties in the region of 850-950C

- Must be commercially available in large quantities at reasonable cost
- Must be available in multiple forms such as plate, tubing, forgings, etc.
- Must be able to fabricate into thin sheets if a plate type HX is used
- Must have reasonably stable properties during exposure to high temperatures for long time periods (thermal ageing)
- Must be able to resist the corrosion effects of an impure He environment at high temperature
- Must have reasonably stable and predictable mechanical and corrosion properties and microstructure over multiple heats within the ASTM/ASME chemical specification range for the alloy
- Should be a part of an ASME Code basis for the design of the HX

20.3.3.6.1 Evaluation of Specific High Temperature Alloys

A large number of alloys that could be potentially useful for VHTR IHX fabrication are shown in Table 20.3.3-2 and were originally evaluated as a part of the NGNP Materials Program [Ref. 20.3.3-13]. Most of the alloys noted are not ASME Code materials and some are specialty alloys and may not generally be available in multiple forms. Most of the alloys noted also have a limited database and are not considered mature alloys (those that have been used in multiple high temperature applications for many years). Some of the alloys noted are ASME Code materials, have reasonably large databases and have been used for multiple high temperature applications. Most of the alloys have no database for high temperature impure Helium exposure. Selected mechanical properties of several alloys from these tables that are listed in the ASME Code are given in Table 20.3.3-3.

Haynes 214 is not discussed in this report because it is not an ASME Code material; however, this alloy has a stress rupture strength at 980ºC for 10,000 hours slightly less than Hastelloy X and has the highest resistance to oxidation compared to all other metallic alloys due to the formation of an adherent Al_2O_3 surface film. Only Alloy 617 (among the alloys evaluated) forms this type of oxide film at high temperatures, but it is less adherent than the film formed on Haynes 214. The other alloys discussed form films that are primarily Cr_2O_3, which are less stable at high temperature in air but have adequate resistance in high temperature exposure to impure helium.

Other cobalt based alloys such as Haynes 188 were not considered even though they have excellent high temperature mechanical properties for reasons that will be discussed later.

20.3.3.6.1.1 Haynes 556

Haynes 556 alloy is an iron-nickel-chromium-cobalt alloy that has excellent high temperature mechanical properties and resistance to sulfidizing, carburizing and chlorine bearing environments. This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and is a solid solution high temperature alloy that contains about 31% iron and about

Table 20.3.3-2 Alloys Considered for NGNP High Temperature Applications

Nominal Composition	UNS Number	Common Name	Existing Data Max Temp (°C)	Helium Experience
Ni-16Cr-3Fe-4.5Al-Y		Haynes 214	1040	
63Ni-25Cr-9.5Fe-2.1Al	N06025	VDM 602CA	1200	
Ni-25Cr-20Co-Cb-Ti-Al		Inconel 740	815	
60Ni-22Cr-9Mo-3.5Cb	N06625	Inconel 625		
53Ni-22Cr-14W-Co-Fe-Mo	N06230	Haynes 230	Section VIII, Div 1-982	
Ni-22Cr-9Mo-18Fe	N06002	Hastelloy X	Section VIII, Div1-899	Yes
Ni-22Cr-9Mo-18Fe		Hastelloy XR	1000	Yes
46Ni-27Cr-23Fe-2.75Si	N06095	Nicrofer 45		
45Ni-22Cr-12Co-9Mo	N06617	Inconel 617	Section VIII, Div 1-982	Yes
Ni-23Cr-6W		Inconel 618E	1000	
Ni-33Fe-25Cr	N08120	HR-120	Section VIII, Div 1-899	
35Ni-19Cr-1 1/4Si	N08330	RA330	Section VIII, Div 1-899	
33Ni-42Fe-21Cr	N08810	Incoloy 800H	Section III, Div 1-760	Yes
33Ni-42Fe-21Cr	N08811	800HT	Section VIII, Div 1-899	
21Ni-30Fe-22Cr-18Co-3Mo-3W	R30556	Haynes 556	Section VIII, Div 1-899	
18Cr-8Ni	S30409	304H SS	870	Yes
16Cr-12Ni-2Mo	S31609	316H SS	870	Yes
16Cr-12Ni-2Mo		316FR	700	
18Cr-10Ni-Cb	S34709	347H SS	870	
18Cr-10Ni-Cb		347HFG	760	
18Cr-9Ni-3Cu-Cb-N		Super 304	1000	
15Cr-15Ni-6MnCb-Mo-V	S21500	Esshete 1250	900	
20Cr-25Ni-Cb		NF 709	1000	
23Cr-11.5Ni-N-B-Ce		NAR-AH-4	1000	
Ni-20Cr-Al-Ti-Y_2O_3	NO7754	Inconel MA 754	1093	
Ni-30Cr-Al-Ti-Y_2O_3		Inconel MA 754	1093	
Fe-20Cr-4.5Al-Y_2O_3	S67956	Incoloy MA956	1100	

Table 20.3.3-3 Refined Alloy List Based on Listing in ASME Code Section II

Alloys	UNS No	Max Allowable Code Stress at 899C (MPa)	Max Code Allowable Temperature (C)	Ultimate Tensile Strength at 870C (Mpa)	Yield Strength at 870C (Mpa)	10000 hour rupture strength at 870C (Mpa)	10000 hour rupture strength at 980C (Mpa)	Stress for 1% Creep in 10000 hours at 980C	Stress Rupture Life (Hours), 980C at 14MPa
Haynes 556	R30556	12	899	330	195	34	13	11	7500
Haynes 230	N06230	10.4	982	385	225	39	7.6	NA	5000
Hastelloy X	N06002	8.3	899	255	180	27	10	7	2100
Inconel 617	N06617	12.4	982	275	205	36	15	10	10000
HR-120	N08120	9.7	899	325	185	40	13	8	10000
RA-330	N08330	3.3	899	NA	110	12	4	1	130
Incoloy 800H	N08810	5.9	899	110	110	24	NA	NA	920
Incoloy 800HT	N08811	6.3	899	110	110	24	8	NA	NA

20% nickel. Haynes 556 is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 900ºC. This alloy has a very high resistance to gas carburizing environments but has not been tested for resistance to an impure helium environment at high temperatures. This alloy is less mature compared to Alloys 617, 230, X and 800H.

20.3.3.6.1.2 Haynes 230

Haynes 230 alloy is a nickel-chromium-tungsten alloy that has excellent high temperature mechanical properties and outstanding oxidization resistance. This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and is a solid solution high temperature alloy that contains about 57% nickel, about 22% chromium and about 14% tungsten. This alloy has excellent stability and resistance to grain coarsening following long time exposure at high temperatures and has a very low thermal expansion coefficient. This alloy does not precipitate embrittling second phases during high temperature exposure. Haynes 230is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 982ºC. This alloy is very mature compared to Alloys 556, HR-120 and RA-330, and is slightly less mature compared to Alloys 617 and 800H. The French are currently performing an extensive evaluation of this alloy for application to the ANTARES VHTR IHX design.

20.3.3.6.1.3 Hastelloy X and XR

Alloy X is a nickel-chromium-iron-molybdenum alloy that has moderately good high temperature mechanical properties and outstanding oxidization resistance. This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and is a solid solution high temperature alloy that contains about 47% nickel, about 22% chromium, about 18% iron and about 9% molybdenum.. This alloy can precipitate embrittling second phases during high temperature exposure above 700ºC. Alloy X is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 900ºC . This alloy is very mature compared to Alloys 556, HR-120 and RA-330 and is slightly less mature compared to Alloys 617 and 800H. The Japanese conducted an extensive evaluation of Alloy X for application to the IHX of the HTTR demonstration that was subsequently constructed in Japan. In doing so, they developed an XR compositional variant of this alloy specifically designed to resist the oxidizing and carburizing effects of impure helium at high temperatures.

20.3.3.6.1.4 Inconel 617 and 617CCA

Alloy 617 is a nickel-chromium-cobalt-molybdenum alloy that has the highest high-temperature mechanical properties (compared to the other alloys evaluated) and outstanding oxidization resistance. This alloy was originally developed to optimize resistance to high temperature creep. This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and is a solid solution high temperature alloy that contains about 44% nickel, about 22% chromium, about 13% cobalt and about 9% molybdenum. This alloy has excellent stability and resistance to grain coarsening following long time exposure at high temperatures and has a low thermal expansion coefficient. This alloy does not precipitate embrittling second phases during high temperature exposure; however, the alloy does show some loss of fracture toughness as a function of aging time at high temperatures. Alloy 617 is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 982ºC. This alloy is the most mature of the alloys evaluated, with the exception of Alloy 800H, which has comparable maturity. The French are currently performing an extensive evaluation of this alloy for application to the ANTARES VHTR IHX design. Variability in high temperature mechanical properties for different heats of this alloy has been an issue in the past. This is due in part to the long history of this alloy, significant changes that have taken place over the years in melting practice and the relatively wide chemical specification range for this alloy. This variability has been extensively addressed by the Ultrasupercritical (USC) Fossil Boiler R&D Program funded by the DOE. The USC program has developed a compositional variant to this alloy (Alloy 617 CCA) that produces more consistent mechanical properties at high temperature. An attempt to develop an alternate compositional variant (Alloy 617C) of this alloy for VHTR applications was made by the NGNP Materials Program; however, this alternate specification has not proven to be viable to date.

20.3.3.6.1.5 Haynes HR-120

Haynes HR-120 is an iron-nickel-chromium alloy that has excellent high temperature mechanical properties and resistance to sulfidizing, carburizing and oxidizing environments.

This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and is a solid solution high temperature alloy that contains about 33% iron, about 37% nickel and about 25% chromium. HR-120 is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 900ºC . This alloy has a good resistance to gas carburizing environments but has not been tested for resistance to an impure helium environment at high temperatures. This alloy is less mature compared to Alloys 617, 230, X and 800H.

20.3.3.6.1.6 Haynes RA-330

Haynes RA-330 is an iron-nickel-chromium alloy that has poor high temperature mechanical properties and fair resistance to sulfidizing, carburizing and oxidizing environments. This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and is a solid solution high temperature alloy that contains about 48% iron, about 35% nickel and about 18% chromium. RA-330 is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 900ºC . This alloy has not been tested for resistance to an impure helium environment at high temperatures. This alloy is less mature than Alloys 617, 230, X and 800H.

20.3.3.6.1.7 Alloy 800H

Alloy 800H is an iron-nickel-chromium alloy that has fair high temperature mechanical properties and fair resistance to sulfidizing, carburizing and oxidizing environments. This alloy has excellent forming and welding characteristics and, due to good ductility, can also be formed by cold working. This alloy is furnished in the solution heat treated condition and must be solution annealed at about 1093ºC in order to obtain a stable austenitic structure. This alloy is a solid solution high temperature alloy that contains about 43% iron, about 33% nickel and about 22% chromium. 800H is available in a wide variety of product forms and specifications and is covered by ASME Section VIII, Division 1 up to 982ºC. It is the only alloy in the group that is listed for use in ASME Section III, Subsection NH for a maximum temperature up to 760ºC. This alloy has been tested for resistance to an impure helium environment at high temperatures. This alloy is the most mature of the alloys evaluated, with the exception of Alloy 617, which has comparable maturity.

20.3.3.6.2 Further Evaluation of Alloys

Further evaluation of the properties of these alloys was made. The results of this evaluation are given in Table 20.3.3-4 and Table 20.3.3-5.

Table 20.3.3-4 Selected Properties of Alloys Evaluated

Alloys	UNS No	Max Allowable Code Stress at 899C (MPa)	Max Code Allowable Temperature (C)	Ultimate Tensile Strength at 870C (Mpa)	Yield Strength at 870C (Mpa)	10000 hour rupture strength at 870C (Mpa)	10000 hour rupture strength at 980C (Mpa)	Stress for 1% Creep in 10000 hours at 980C	Stress Rupture Life (Hours), 980C at 14MPa
Haynes 556	R30556	12	899	330	195	34	13	11	7500
Haynes 230	N06230	10.4	982	385	225	39	7.6	NA	5000
Hastelloy X	N06002	8.3	899	255	180	27	10	7	2100
Inconel 617	N06617	12.4	982	275	205	36	15	10	10000
HR-120	N08120	9.7	899	325	185	40	13	8	10000
RA-330	N08330	3.3	899	NA	110	12	4	1	130
Incoloy 800H	N08810	5.9	899	110	110	24	NA	NA	920
Incoloy 800HT	N08811	6.3	899	110	110	24	8	NA	NA

Table 20.3.3-5 Selected Properties of Alloys Evaluated

Alloys	Incipient Melting Point	Thermal Conductivity at 900C (W/m)xK	He Corrosion Data Base	Welding	Typical ASTM Grain Size	Relative Cost-$Alloy/$304SS	Available	% of RT Tensile Strength following Aging at 982C for 1000 hours	Mils of Penetration after 55 Hours in Ar-5%H2-1% CH4
Haynes 556	1329	27.2	No	Readily Weldable	5-6	8.5	Sheet, Plate, Round Bar	32 (16000 hours)	NA
Haynes 230	1302	26.4	Yes	Readily Weldable	5-6	NA	All	37 (b)	NA
Hastelloy X	1260	27.2	Yes	Some Welding Problems	5-6	4.8-5.6	Sheet, Plate, Round Bar	12 (a)	NA
Inconel 617	1332	26.7	Yes	Readily Weldable	1-4	NA	All	39 ©	NA
HR-120	1302	26.2	No	Readily Weldable	3-6	3.5	Sheet, Plate, Round Bar	99	25
RA-330	1343	NA	No	NA	4-6	2.6-3.0	NA	NA	35
Incoloy 800H	1302	NA	Yes	Readily Weldable	2-4	2.6-3.0	All	NA	30
Incoloy 800HT	1302	NA	Yes	Readily Weldable	2-4	2.6-3.0	All	NA	NA

(a) % of Impact Strength Retained (compared to RT) following aging for 16000 hours at 871C
(b) 32 % elongation retained following 8000 hour exposure at 982C and 36% impact strength after 16000 hours at 982C
c 39% of impact strength following 12000 exposure at 760C

Alloys 230 and 617 have the highest ASME Code temperature rating (982ºC). The four alloys with the highest maximum allowable Code stress at 900ºC are Alloys 617, 556, 230 and HR-120 (12.4, 12, 10.4 and 9.7 MPa, respectively). The two alloys Code-rated for service at 982ºC (Alloys 617 and 230) have Code allowable stresses of only 5 and 3.1 MPa, respectively. Therefore there is little design margin at this temperature. The four alloys with the highest maximum allowable Code stress at 900ºC (Alloys 617, 556, 230 and HR-120) also have the highest 10,000 hour rupture strength at 980ºC (15, 13, 7.6 and 13 MPa, respectively). The ranking of these alloys by stress rupture life (hours) at 14 MPa at 980ºC are Alloys 617/HR-120 (Rank 1), Alloy 556 (Rank 2) and Alloy 230 (Rank 3) The incipient melting point and thermal conductivities of these alloys are similar. Hastelloy X precipitates detrimental second phases following long term high temperature exposure; the other alloys have good long term stability except HR-120 which may also be susceptible under some conditions. All of these alloys are readily available in multiple forms. Therefore, based on these criteria, the alloys would rank overall: Alloy 617, HR-120, Alloy 556, Alloy 230 and Hastelloy X. Alloys RA-330 and Alloy 800H are not considered viable for the IHX due to somewhat inferior high temperature strength.

The Japanese selected Hastelloy XR for fabrication of the heat transfer tubes and hot headers for use in a helical tube and shell IHX for the HTTR. Hastelloy XR is a refined chemistry specification of Hastelloy X that was developed over several years, primarily to resist the corrosion effects of high temperature impure helium used in the HTTR. In this application, Hastelloy XR has a design temperature rating of about 950ºC (1000ºC maximum allowable temperature) and a design pressure rating of 0.29MPa (absolute). Total weight of Hastelloy XR used for the 10MWt IHX of the HTTR was about 20 tons (20,000kg) with the weight of each ingot about 3 tons. The Japanese evaluated other alloys, including Alloy 617, prior to the development of Hastelloy XR. The HTTR represents the most recent actual application of resources for the design, materials and fabrication of an IHX for a VHTR and, therefore, needs to be seriously considered. The creep rupture life to failure for Alloys 617, 230, 800H and Hastelloy X is compared in Figure 20.3.3-9.

Alloys 617 and 556 have the highest Co content among the four alloys. The high Co content is undesirable for the IHX application because surface layers (oxides) that form on the IHX surface in the primary loop could become dislodged and form Co-60 by neutron activation following circulation in the reactor. This could result in a maintenance problem for equipment that became contaminated. The high W content in Alloy 230 is also undesirable for the same reasons. Iron, nickel and chromium also could potentially become activated; however, these activation products would produce fewer problems. In general, Alloy 617 is the most resistant of the alloys to surface oxidation. HR-120 and Alloy 556 contain significant quantities of iron; Hastelloy X also contains significant iron. The corrosion of alloys with significant iron content has not been investigated (except Hastelloy X and XR) for the effects of impure helium corrosion.

The ASTM standard specification range for these alloys and their compositional variants are given in Table 20.3.3-6.

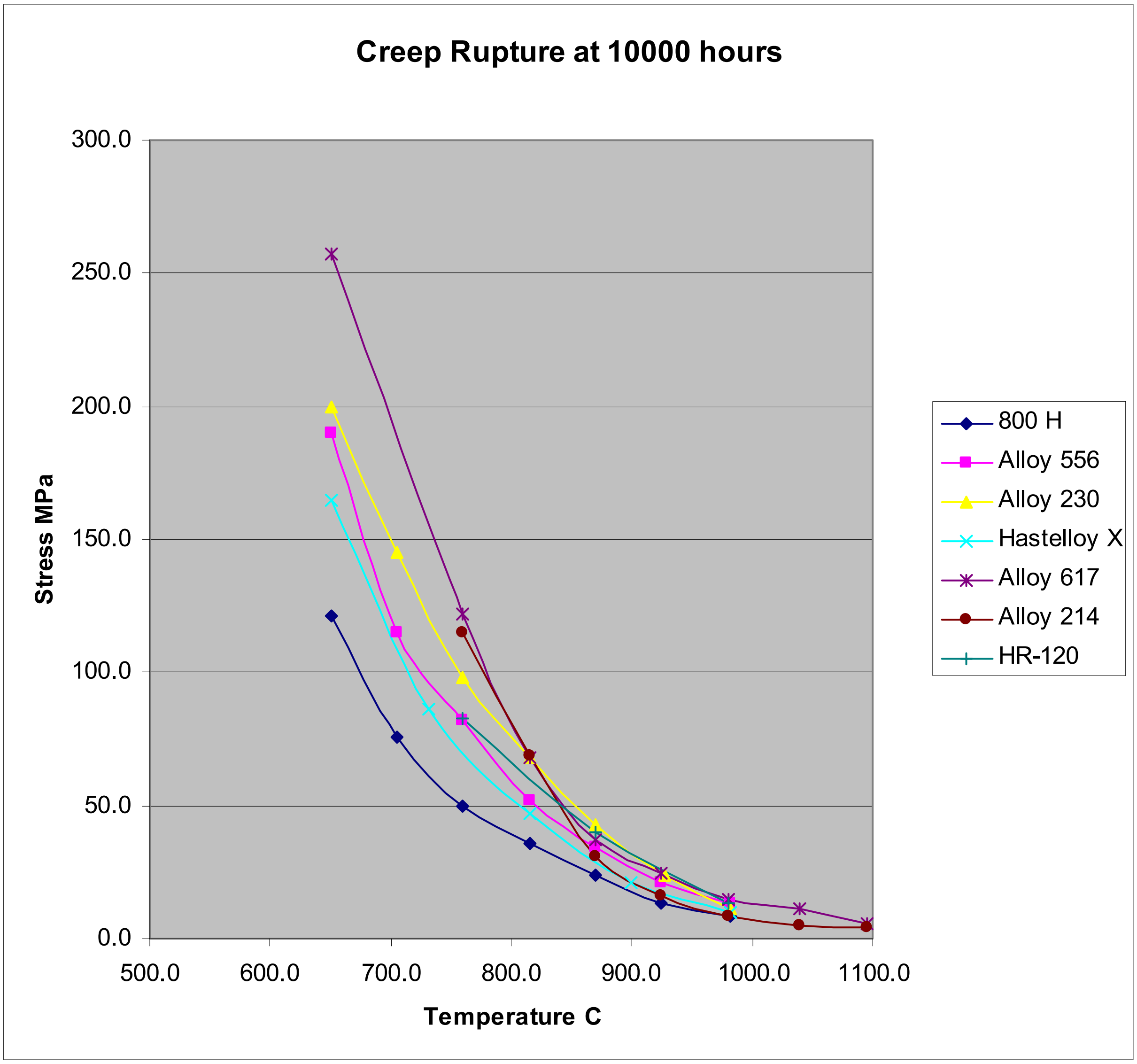


Figure 20.3.3-9 Comparison of Creep Rupture Life to Failure for Alloys Evaluated

Table 20.3.3-6 ASTM Specification Range for Alloys Evaluated

Heat	Ni	Cr	Co	Mo	Fe	Mn	Al	C	Cu	Si	S	Ti	B	N	P	W	Ta	La	Zr	Cb	Y
617 min	44.5	20	10	8	0	0	0.8	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
617 max	Bal	24	15	10	3	1	1.5	0.2	0.5	1	0	0.6	0	0	0	0	0	0	0	0	0
617C min	44.5	22	13	9	0	0	1.2	0.1	0	0	0	0.4	0	0	0	0	0	0	0	0	0
617C max	Bal	24	15	10	1	1	1.4	0.1	0.2	0.3	0	0.6	0	0	0	0	0	0	0	0	0
Haynes 230 (nomimal)	57*	22	5*	2	3*	0.5	0.3	0.1	0	0.4	0	0	.015*	0	0	14	0	0.02	0	0	0
HX min	Bal	20.5	0.5	8	17	0	0	0.1	0	0	0	0	0	0	0	0.2	0	0	0	0	0
HX max	Bal	23	2.5	10	20	1	0	0.2	0	1	0	0	0	0	0	1	0	0	0	0	0
XR min	Bal	20.5	0	8	17	0.8	0	0.1	0	0.3	-	0	0	0	0	0.2	0	0	0	0	0
XR max	Bal	23	2.5	10	20	1	0.1	0.2	0.5	0.5	0	0	0	0	0	1	0	0	0	0	0
800H min	30	19	0	0	Bal	-	0.2	0.1	0	0	0	0.2	0	0	0	0	0	0	0	0	0
800H max	35	23	0	0	Bal	0.2	0.6	0.1	0.8	1	0	0.6	0	0	0	0	0	0	0	0	0
617 CCA Min	Bal	21	11	8	0	0	0.8	0.1	0	0	0	0.3	0	0	0	0	0	0	0	0	0
617 CCA Max	Bal	23	13	10	1.5	0.3	1.3	0.1	0.1	0.3	0	0.5	0	0.1	0	0	0	0	0	0	0
Alloy 556 (nominal)	20	22	18	3	Bal	1	0.2	0.1	0	0.4	0	0	0	0.2	0	2.5	0.6	0.02	0.02	0	0
HR-120 (nominal)	37	25	3*	2.5*	Bal	0.7	0.1	0.05	0	0.6	0	0	0.004	0.2	0	2.5*	0	0	0	0.7	0
Haynes 214 (nominal)	Bal	16	0	0	3	0.5	4.5	0.05	0	.2*	0	0	.01*	0	0	0	0	0	.1*	0	0.01
*=Maximum																					

As previously noted, Alloy 617 contains the widest specification range for the primary elements. The wide specification range has resulted in heats of Alloy 617 being produced that did not have uniform properties, and this is considered undesirable for the IHX application.

The Alloy 617C controlled material specification [Ref. 20.3.3-15] was developed for VHTR materials applications, based on the analysis of mechanical properties and chemical compositions of historical data from various heats. The intent of the controlled specification was to tighten the ASTM specification to produce a more predictable material for testing, as opposed to optimizing the corrosion properties of Alloy 617 in high temperature impure helium. The current recommended melting practice (solution anneal at a minimum temperature of 1150^{0}C for a time commensurate with section size followed by water quench; melting practice is VIM+ESR and heat analysis should be checked after ESR) was not uniformly followed in older Alloy 617 heats. It is not clear at this point if the Alloy 617C material can be reliably formed into plates, due to various issues with hot working revealed in the small laboratory heats produced to date.

Given this result, the Alloy 617CCA specification developed previously as a part of the USC program for high temperature applications for fossil power is currently being investigated. It is known that this material can be hot formed. Alloy 617 CCA is being extensively examined by the USC Program and, to date, the results are favorable. Creep rupture data for Alloy 617 compared to Alloy 617CCA is given in Figure 20.3.3-10 and Figure 20.3.3-11. (Note that in Figure 20.3.3-10 the arrows indicate samples that were removed from testing without failure.)

The effects of heat to heat variation and environmental effects on Alloy 617 produced and tested in 1984 are given in Figure 20.3.3-12 and Figure 20.3.3-13. High temperature creep data obtained for Alloy 230 compared to Hastelloy X and Alloy 617 is given in Figure 20.3.3-14 and Figure 20.3.3-15 [Ref. 20.3.3-16] (red stars indicate French Alloy 230 data; other data are from INCO and Haynes). A comparison of average creep-to-rupture data for Alloys 617 and 230 is plotted in Figure 20.3.3-16. Major sources of creep data for Alloy 617 are summarized in Table 20.3.3-7 and Table 20.3.3-8 [Ref. 20.3.3-17].

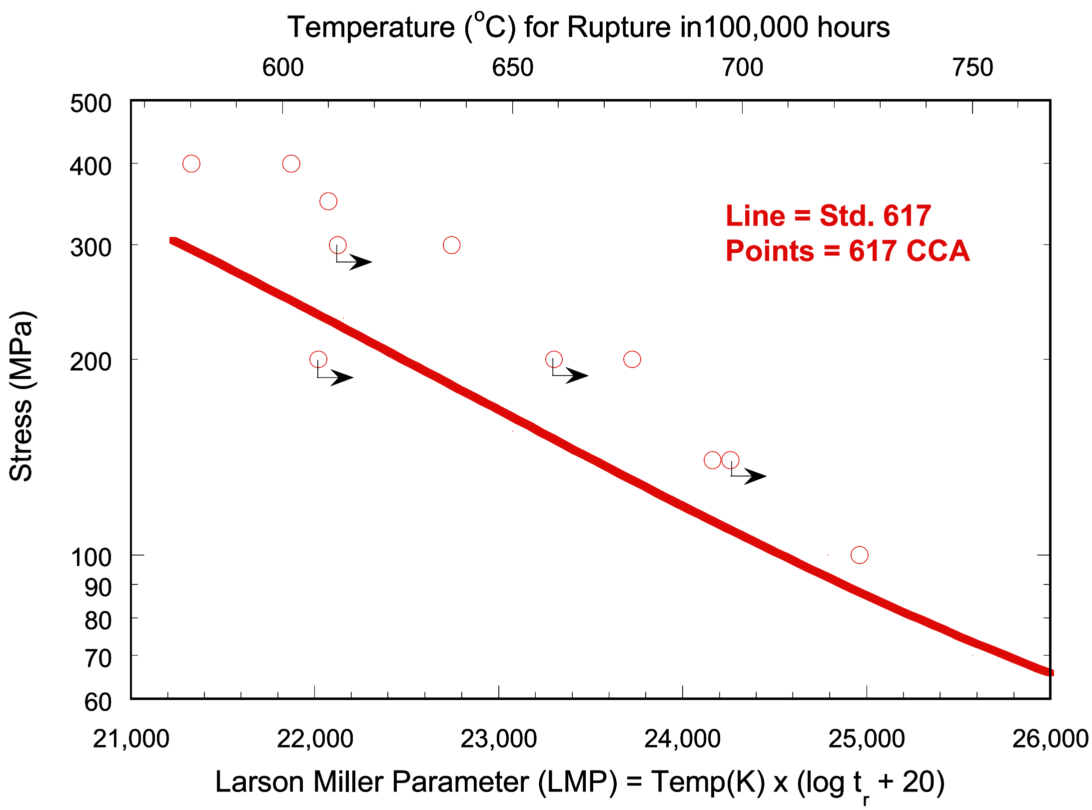


Figure 20.3.3-10 Creep Rupture Data That Compares Alloy 617 and 617CCA

The Alloy 617 CCA has slightly higher creep rupture properties compared to standard Alloy 617.

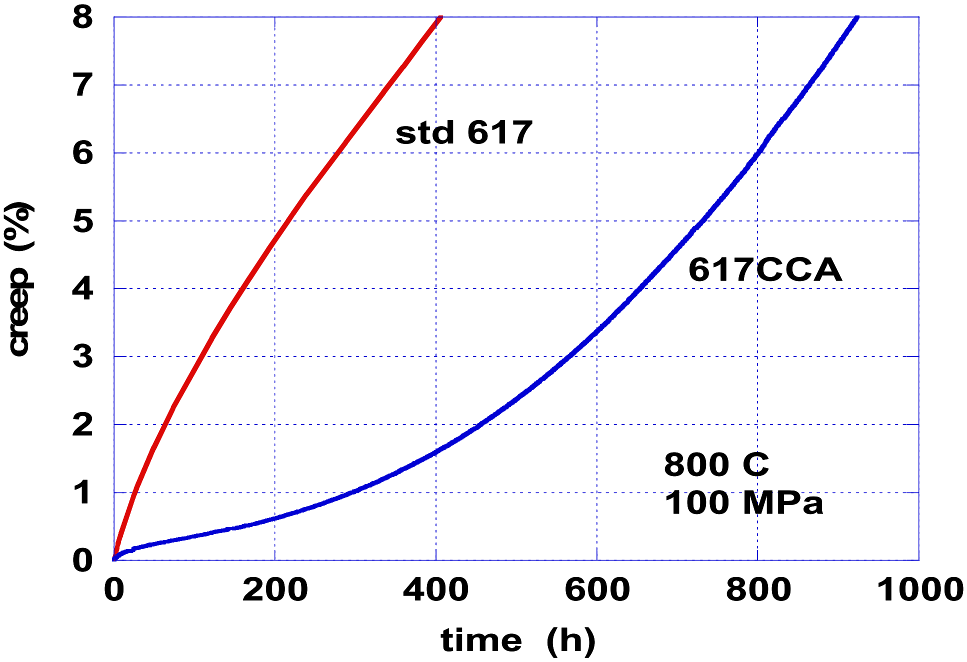


Figure 20.3.3-11 Creep Rupture Data That Compares Alloy 617 and 617CCA

The Alloy 617 CCA has slightly higher creep rupture properties compared to standard Alloy 617.

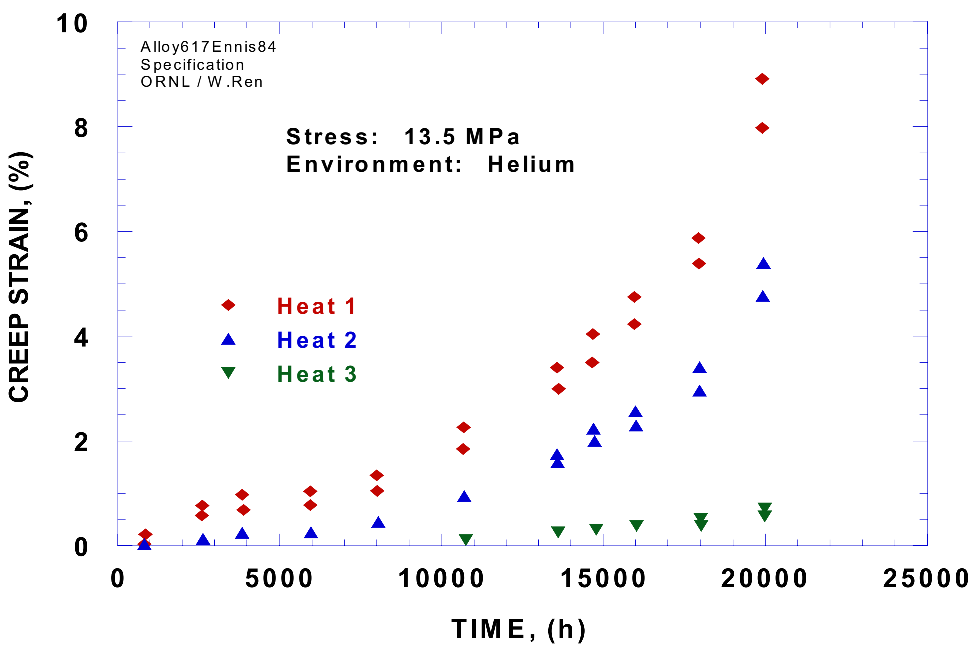


Figure 20.3.3-12 Creep Strain vs. Time for 3 Alloy 617 Heats in Helium at 13.5MPa Stress

Note the heat to heat variation in the creep properties. Heat 3 has the most favorable creep properties and had a high Al content of 1.35% [Ref. 20.3.3-18].

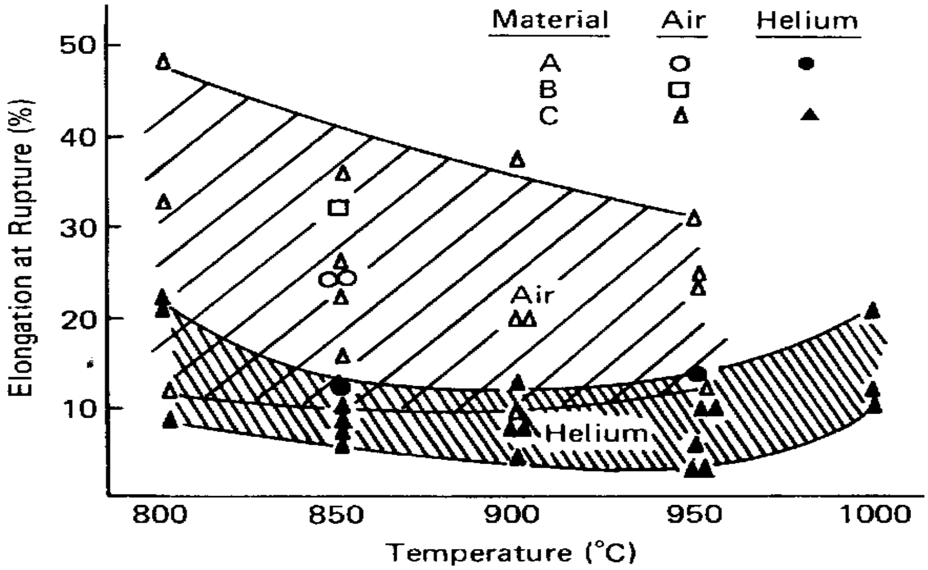


Figure 20.3.3-13 Elongation at Rupture vs. Temperature for 3 Alloy 617 Heats in Air and Impure Helium

Specimens tested in air show more favorable properties and specimens tested in impure helium show effects of corrosion [Ref. 20.3.3-19].

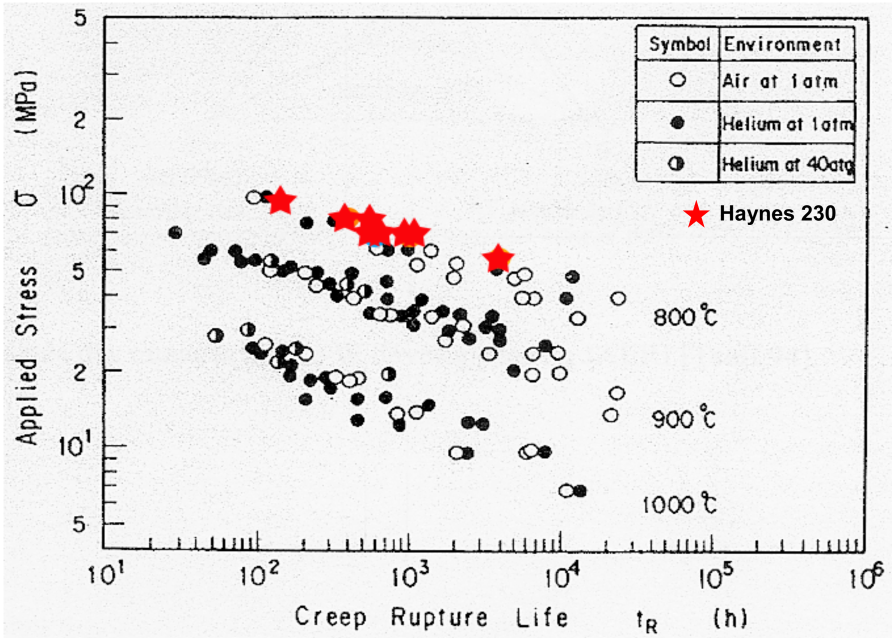


Figure 20.3.3-14 Recent Alloy 230 High Temperature Creep Rupture Life Data Compared to Hastelloy XR

There is no significant difference in properties for times and temperatures tested [Ref. 20.3.3-16]

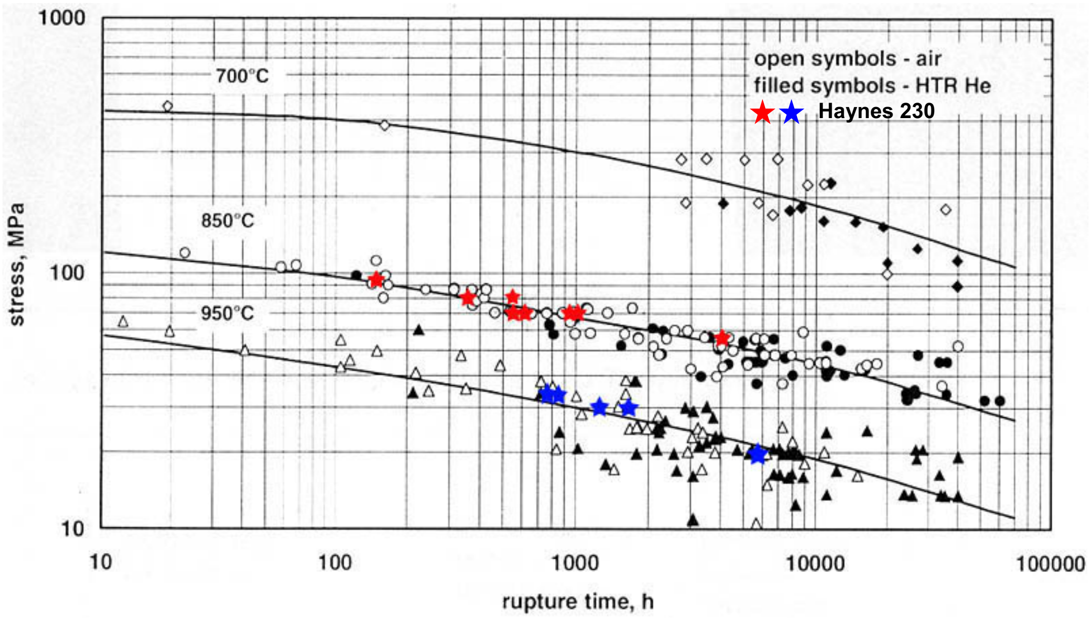


Figure 20.3.3-15 Recent Alloy 230 High-Temperature Creep Rupture Life Data vs. Alloy 617

There is no significant difference in properties for times and temperatures tested [Ref. 20.3.3-16]

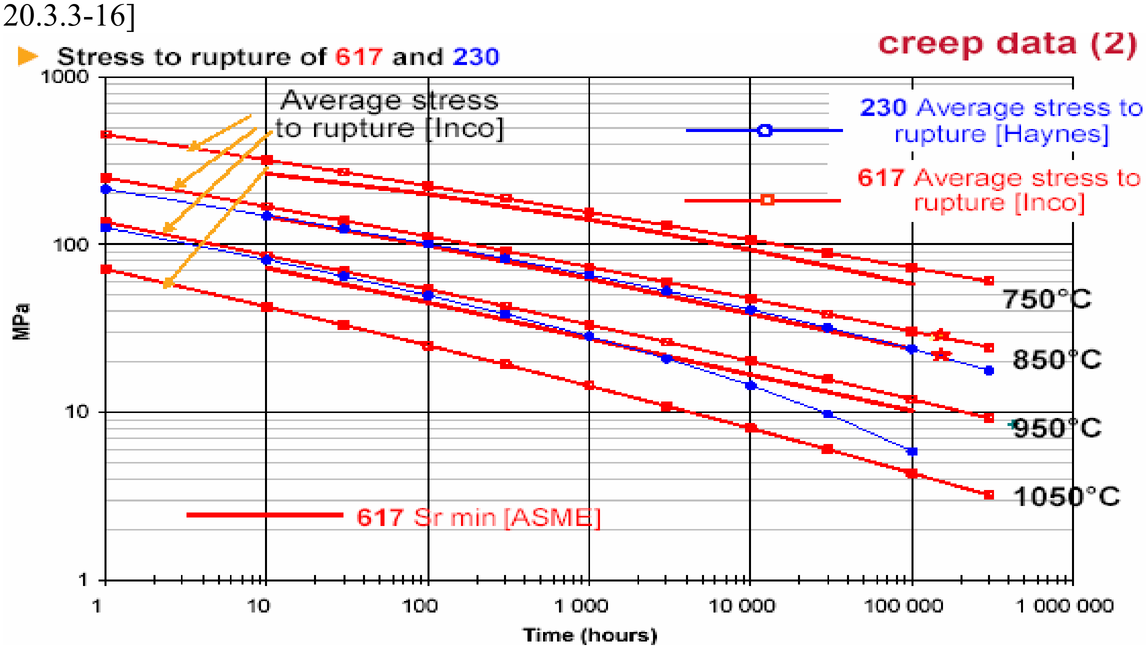


Figure 20.3.3-16 Average Alloy 230 and 617 INCO and Haynes Creep Rupture Data at High Temperatures for Long Times

Alloy 230 creep properties are similar to Alloy 617 except at high temperatures and long times where Alloy 617 shows superior properties.

Table 20.3.3-7 Major Sources of Creep Data for Alloy 617

Source	# of Tests	Temp. Range	Max Duration	Min Stress
ORNL-HTGR	51	593 - 871°C	34,231 h	21 MPa
GE-HTGR	36	750 - 1100°C	28,920 h	9.6 MPa
Huntington Alloy	249	593 – 1093°C	40,126 h	6.2 MPa
German HTGR	294	800 – 1000°C	~20,000 h	8.2 MPa

Table 20.3.3-8 Known Creep Data for Alloy 617 at about 950ºC

Source	# Tests	# Tests> 500 Hours	Max Duration Hours	Min Stress MPa	Min Creep Rate (%/Hr)
Kihara	8	0	2115	24.5	1.70E-03
Baldwin	13	3	28920	20.7	4.50E-05
Huntington Alloy	35	0	4788	13.8	1.50E-05
Schubert	62	6	~20000	13.9	1.00E-04
Schneider	22	??	??	30.6	2.00E-04
Osthoff	18	0	1000	8.2	4.00E-05
Ennis	19	6	~20000	12.7	??
Cook	9	2	6116	19.8	1.70E-03
	Total	Total	Max	Min	Min
	186	17	28920	8.2	1.50E-05

The next area that needs to be examined is the influence of helium coolant on the chemical compatibility of structural materials that are planned for use in the NGNP. Helium, because of its chemical inertness and attractive thermal properties, is used as a primary coolant in VHTRs. However, the primary coolant in an operating VHTR is expected to be contaminated by small amounts of gaseous impurities such as H_2, H_2O, CH_4, CO, CO_2 and O_2 from a variety of sources, such as reactions of ingressed water and oil with core graphite, and outgassing of reactor materials. These impurities are projected to be at ppm levels in the helium coolant, but the upper bound would strongly depend on the level of purification used for the helium supply and the leak tightness of the reactor system.

Corrosion of structural alloys by these gaseous impurities at elevated temperatures can be significant. Past studies have shown that the corrosion of heat resistant materials such as austenitic stainless steels, Alloy 800H and Alloy 617 may involve oxidation, carburization, and decarburization, depending on the exposure temperature, carbon activity in the gas phase, and the alloy composition. Further, the corrosion process is dynamic in the sense that it is dictated by the exposure time, gas chemistry variations, integrity of the corrosion product scales, and presence of particulates in the gas phase.

The helium coolant in an operating VHTR makes a complete circuit from the graphite core to the heat exchangers or gas turbines and back to the core in several seconds. It is reported that the gas components in the coolant, via reaction with the graphite in the core and, to a limited extent, with themselves, will reach a steady state under this dynamic flow condition and may approach an equilibrium state with respect to the core [Ref. 20.3.3-20]. Equilibrium between the surfaces of metallic components and the gaseous impurities in the primary coolant helium is not expected to occur under these very fast flow conditions. Therefore, the carbon activity and oxygen partial pressure in the helium coolant, under such non-equilibrium conditions, will be determined by individual reactions that predominate in the gas mixture.

Although the gaseous impurities in a primary coolant environment may not be in equilibrium with themselves or with surfaces of metallic components, driving forces will exist for gas-metal interactions to occur. The extent to which these interactions will occur will be kinetically controlled, dictated by time, temperature, alloy chemistry and surface condition of the alloy. In such non-equilibrium conditions, potentials for gas-metal corrosion reactions may be determined through equilibrium thermodynamics by considering each individual chemical reaction that is possible between the metal and individual gaseous impurities.

From the structural materials standpoint, we are interested in reactions that can affect the corrosion loss and/or influence the mechanical integrity; reactions that can lead to processes such as oxidation, carburization, and decarburization are of interest. Carburization and decarburization processes are determined by the carbon activity in the gas mixture relative to that in the exposed metal surface. Similarly, the oxidation process is determined by the oxygen partial pressure in the environment relative to the stability of oxides of the constitutive elements that are present on the exposed metal surface. A detailed discussion on reactions between various gas species in helium and its influence on the thermodynamic activity of carbon and oxygen has been documented elsewhere [Ref. 20.3.3-13]. In summary form, the corrosion behavior is determined by comparing the potentials of oxygen and carbon in the gas with the stability of oxides and carbides in the alloy. The following gas reactions establish the oxygen partial pressure:

$$H_2O \leftrightarrow H_2 + 1/2O_2$$
$$CO + H_2 \leftrightarrow C + H_2O$$

Carbon and oxygen partial pressures are coupled by the reaction:

$$CO \leftrightarrow C + 1/2O_2$$

There is a critical value of partial pressure of CO (p*CO) that represents CO pressure in equilibrium with metal, oxide and carbide. Several photomicrographs that show the effects of impure helium exposure for 813 hours at 950ºC on Hastelloy X, Alloy 800H and Alloy 617 are shown in Figure 20.3.3-17, Figure 20.3.3-18 and Figure 20.3.3-19. These results are shown in summary form in Figure 20.3.3-20.

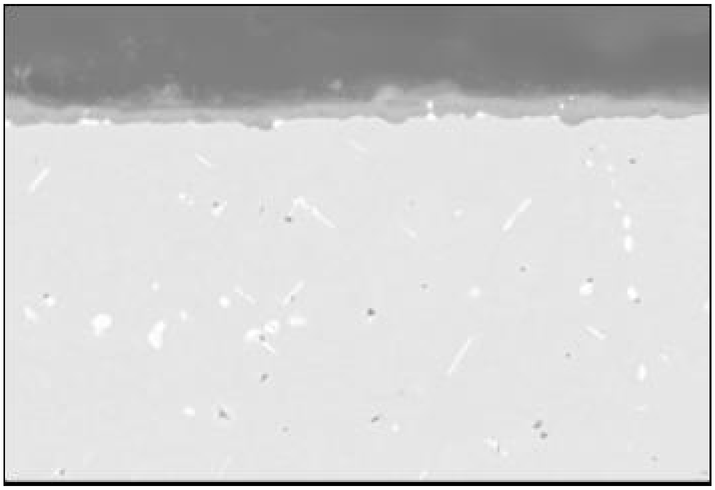


Figure 20.3.3-17 Hastelloy X Exposure with Relatively Little Cr Oxide Formation

Cr_2O_3 /Cr-Mn spinel is the layer between the alloy (white) and the mounting (dark grey), [10μm], [Ref. 20.3.3-21].

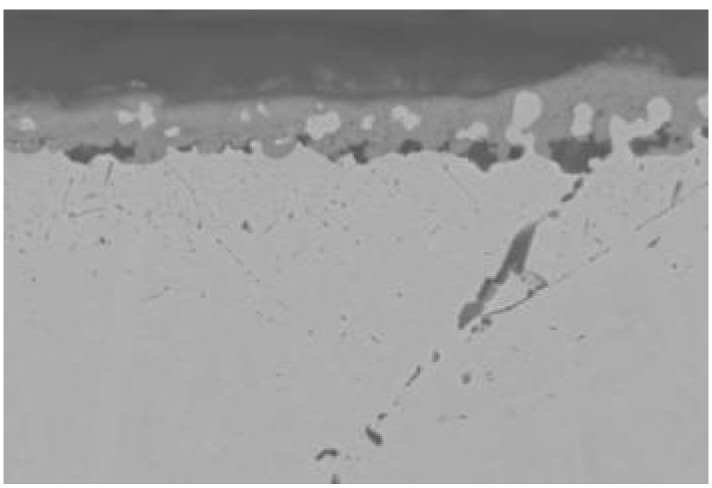


Figure 20.3.3-18 Alloy 800H Exposure with Relatively Greater Cr Oxide and Ti Oxide Formation and Some Internal Oxidation of Al

Oxide is the layer between the alloy (white) and the mounting (dark grey), [10μm], [Ref. 20.3.3-21].

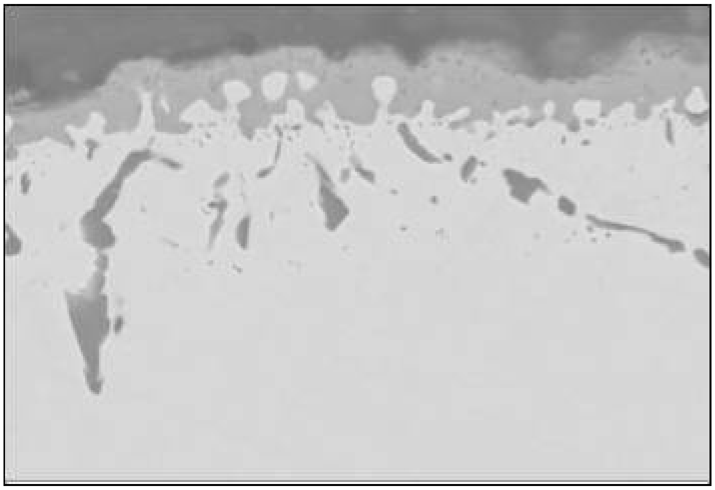


Figure 20.3.3-19 Alloy 617 Exposure with Cr Oxide and Ti Oxide Formation Similar to Alloy 800H and Some Internal Oxidation of Al

Oxide is the layer between the alloy (white) and the mounting (dark grey), [10µm], [Ref. 20.3.3-21].

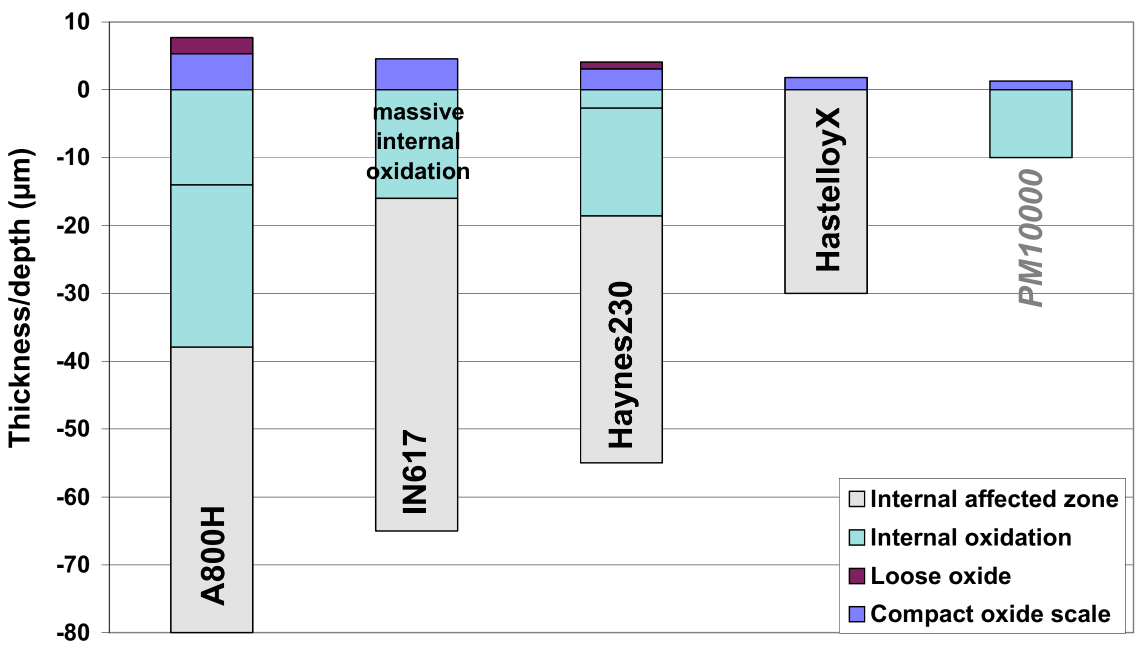


Figure 20.3.3-20 Summary of French He Test Data at 950ºC and 813 Hours

In summary, the internal oxidation of Alloys 617 and 230 are related to the Ti and Al contents. As shown in Figure 20.3.3-20 [Ref. 20.3.3-21], Alloy 230 is more corrosion resistant than Alloy 617. Hastelloy XR revealed stable corrosion characteristics relative to the conventional Hastelloy X even at 1000°C up to 20,000h in stimulated HTGR helium. This is due to the improvement of the stability of surface oxide film which consists of $MnCr_2O_4$ and Cr_2O_3 layers.

Detailed discussions of high temperature mechanical property regarding Alloys 617, 230, X and XR is given in [Ref. 20.3.3-22].

Initial conclusions regarding the refined list of alloys are given below:

- Alloy 617 has more retained strength and creep resistance at the temperatures of interest
- Hastelloy X and XR are the more resistant alloys to impure He corrosion at high temperatures
- Alloy 556 has the highest resistance to gas carburization of any of the alloys evaluated
- Alloy 230 has slightly less strength and creep resistance (compared to Alloy 617 at long times and high temperatures) but it shows (based on French testing) more resistance to impure He corrosion at high temperatures
- Alloys HR-120 and Alloy 556 have very high retained strength and creep resistance at high temperatures, but they are 1/3 Fe and no one has studied these materials in high temperature impure He. However, they have several similarities to Hastelloy X (31-33% Fe versus 20-23% for Hastelloy, low or no Al and Ti) and therefore may perform well in impure He. These materials are the most immature of the four alloys and this would result in a longer R&D program
- Hastelloy X has considerably less retained strength and creep resistance at high temperature
- Incoloy 800H and 800HT creep properties are inferior to the other alloys in the IHX temperatures of interest; however, 800H is the only current ASME Section III alloy in the group
- All of the other alloys that have been seriously evaluated are currently ASME Section VIII usage only, which is limited to non-nuclear applications
- This indicates that there is a serious problem with the lack of usable ASME Section III alloys for the IHX application. This will be discussed in detail in the next section.
- It is therefore concluded that if a new ASME Section III Code Case will need to be written for this application (discussed later), Alloys 617 and 230 should be considered the best available metallic alloys for this application if high retained strength and creep resistance at high temperature is a major factor and a relatively shorter R&D Program is a major consideration.
- If the IHX design selected could tolerate a lower high temperature strength and creep resistance, then Hastelloy X or XR should be considered.
- Hastelloy XR would require the transfer of the Japanese data base to be seriously considered (an agreement with the ASME for data base transfer has now been established but the extent of the information transfer would require further investigation).
- If the length of the R&D Program is not a major factor, Alloy 556 should be seriously considered.

20.3.3.6.3 Other Considerations

Low cycle fatigue properties need to be considered to assess the influence of thermal cycling during startup, shutdown and power changes. Thermal expansion associated with constraint (plate type HX design) will translate into thermal stress and therefore limit the fatigue life of the IHX. If a PCHE is selected, the alloy sheets would need to be capable of channel etching and diffusion bonding. It is known that this process can be performed for Alloy 617 and is being developed for Alloy 230 by Heatric. It is currently unknown whether HR-120, Alloy 556 and Hastelloy X could be processed in this manner. The development of Alloy 617 centered on the desire for maximum creep strength at elevated temperatures. Solution anneal temperatures were normally selected to obtain coarse grain material which optimizes creep strength. Smith and Yates [Ref. 20.3.3-23] performed a development program to optimize both low cycle fatigue (LCF) properties and creep properties on Alloy 617. It was shown that by using closely controlled thermo-mechanical processing a fine grain size (GS) alloy can be produced that possesses very good fatigue resistance with no loss in creep resistance. The best LCF properties were for Alloy 617 with a GS of 9.5. A peak alternating stress of 80MPa resulted in failure at 980ºC following 100,000 cycles. There is no equivalent LCF data available for Alloy 556. HR-120 has poor LCF properties at high temperature. Alloy 230 has excellent LCF strength. Hastelloy X and XR have inferior LCF properties compared to Alloy 230. A detailed discussion of LCF for Alloys 617, 230 and X is given in Natesan et al, 2006.

The mean coefficient of thermal expansion for the alloys noted below between room temperature and 1000ºC is given below in mm/(m·ºC):

- Alloy 617: 11.6 (100ºC) - 16.3 (1000ºC)
- Hastelloy X: 13.8 (100ºC) - 16.6 (1000ºC)
- Alloy 230: 11.8 (100ºC) - 16.1 (1000ºC)
- HR-120: 14.3 (100ºC) - 17.8 (1000ºC)
- Alloy 556: 14.3 (100ºC) - 17.1 (1000ºC)

20.3.3.6.4 Final Recommendations

The final conclusion of this evaluation is that if maximum mechanical properties are required at high temperature for the IHX design, Alloy 617 is the best IHX alloy option. There are unverified indications that the more restrictive chemistry of the Alloy 617CCA specification developed through the USC Program may result in improved properties relative to the standard Alloy 617 specification. This should be verified. If slightly less tensile and creep strength could be tolerated at high temperature in the IHX design, Alloy 230 may become the best IHX alloy option on the basis of lower Co content and superior resistance to helium impurities.

Existing metallic materials can be applied in the temperature regime of the NGNP IHX, albeit with significant limitations:

- Will require designs based on very low stresses during normal long-term operation
- Transient-related stresses will be more significant in compact IHXs (needs further evaluation)

- Likely need to replace IHX core multiple times over 60-year design life of plant

Present metallic materials are likely not the optimum long-term solution for commercial process heat plants operating in the NGNP temperature range.

20.3.3.7 Ceramics Materials Assessment

Structural ceramics such as silicon carbide (SiC) and silicon nitride (Si_3N_4) have outstanding high temperature strength, plus they have higher thermal conductivity and lower thermal expansion than metals. These attributes make them attractive candidates for the NGNP IHX operating in the range 850 -1000ºC. Recuperators and heat exchangers made of ceramics are being developed for turbine, automotive, and fuel cell applications. OxyCube™ is a ceramic heat exchanger design developed at ORNL based on gel technology that does not require the joining of ceramic layers during fabrication. . Heat exchanger units have been fabricated from a monolithic sodium zirconium phosphate ceramic in collaboration with industry for fuel cell applications and can withstand temperatures up to 1200ºC [Ref. 20.3.3-24]. ORNL also has developed a ceramic regenerator made of cordierite, a magnesium aluminum silicate ($2MgO{\cdot}2Al_2O_3{\cdot}5SiO_2$) to capture exhaust heat for automotive applications [Ref. 20.3.3-24]. The cordierite material is also expected to withstand temperatures up to 1200ºC. Monolithic SiC, Si_3N_4 and SiC/SiC composites are being considered for gas turbine applications at temperatures beyond the capability of nickel based superalloys (alloys discussed above). However, the technical barriers to achieving high performance and large scale use of structural ceramics include inherently low fracture toughness, poor impact resistance and water vapor corrosion at high temperatures and pressures. Use of ceramics for the NGNP IHX would require an extensive, long term material qualification effort in terms of defining heat exchanger designs, characterizing mechanical properties and aging effects, evaluating environmental behavior and standardization of the material used. All of the above would be necessary to codify the material for use in the NGNP IHX design. Based on the available literature and the timeframe for construction of the NGNP, it is unlikely that ceramic materials could be used in the initial IHX of the NGNP. However, testing of prototype ceramic heat exchanger components could be performed in conjunction with the NGNP for potential application in the future and/or replacement of NGNP IHX components, when required.

20.3.3.7.1 Historical Background

The interest in ceramic components for recuperators developed in the early 1970s, when ceramics were being considered for components in engines and turbochargers. The oil crisis had driven up the cost of petroleum-based fuels, and it was thought that the prices would continue to rise. Therefore, the aluminum, steel, and glass industries considered coal as an alternative energy source because it was relatively cheap and abundant. At the same time, they investigated methods for capturing waste heat and returning it to the high-temperature process streams. Researchers found that the waste energy was difficult to recover because the streams (at temperatures up to 1650ºC) fouled surfaces with particulate buildup, and, at the high preheat temperatures (>1100ºC), they were corrosive to metal alloys. Ceramics were investigated because, unlike metal alloys, ceramics have sufficient high-temperature strength and oxidation resistance to preheat air up to 1100ºC. However, because the cost of oil dropped in the 1980s, research into ceramic recuperators gradually ceased [Ref. 20.3.3-25].

The early research for the development of ceramics for large, industrial recuperators provides information for the current assessment of ceramic recuperators for microturbines and other applications such as the NGNP IHX. Some of the results of those early investigations are summarized in [Ref. 20.3.3-26]. The materials used and the flow configurations were given, as indicated in the following examples:

- GTE used cordierite in a finned-plate design, in which the fins and plates were staked and bonded. The result is a crossflow matrix, although the system becomes counterflow when staged.
- Midland-Ross used cordierite in a heat wheel with a segmented-matrix configuration.
- Garrett-Air Research (formerly AlliedSignal, now Honeywell) used reaction-bonded Si_3N_4 (RBSN) and SiC in a tube-in-shell exchanger that is crossflow as a single unit but counterflow when staged.
- Solar Turbines, Inc. used sintered SiC for its tube-in-shell design with an axial counterflow configuration. Other materials used were phosphate-bonded SiC, alumina chromia, and magnesia chromia.

The following reports summarize the early high-temperature ceramics research:

- Ceramic Heat Recuperators for Industrial Heat Recovery [Ref. 20.3.3-27], which states that cordierite was selected for its "ease of fabrication, relatively low thermal expansion, good thermal shock resistance and good corrosion resistance"
- Technology Assessment of Ceramic Joining Applicable to Heat Exchangers [Ref. 20.3.3-28], which investigates joining of ceramics
- Economic Application, Design Analysis, and Material Availability for Ceramic Heat Exchangers [Ref. 20.3.3-29], which states that demonstration of performance and durability of ceramic heat exchangers must be shown before they can be considered for industrial production furnaces
- Ceramic Heat Exchanger Technology Development [Ref. 20.3.3-30], which describes the use of siliconized SiC materials
- Ceramic Heat Exchanger Design Methodology [Ref. 20.3.3-31], which lists the available materials and their vendors (sintered α-SiC from Carborundum; reaction-bonded SiC from Carborundum, Coors, Norton, and Refel; sintered SiC and sintered Si_3N_4 from Kyocera; and nitride-bonded SiC, reaction-bonded Si_3N_4, and hot-pressed Si_3N_4 from Norton)
- Design Methodology Needs for Fiber-Reinforced Ceramic Heat Exchangers [Ref.3-32], which distinguishes between design of the ceramic material and design with the ceramic material.

It should be noted that most of the companies that investigated these large-size ceramic recuperators are no longer in the field, and several of the companies that manufactured the ceramic materials have also left the business. In both cases, even though new companies replaced the old ones, there are fewer companies in this area now than there were in the 1970s and 80s. Because there are fewer companies and because many of the investigators have retired, the availability of experienced researchers who could work on ceramic HXs will be affected.

20.3.3.7.2 Examples of Ceramic Recuperators for Small Turbines

A plate-fin ceramic recuperator for a 60-kW turbogenerator was fabricated as part of the European Advanced Gas Turbine for Automobiles (AGATA) program to develop a gas turbine hybrid vehicle [Ref. 20.3.3-33]. The authors claim that the plate-fin design is flexible and that the fin height and geometry can be varied. Cordierite and SiC were investigated extensively. Cordierite was chosen because its safety coefficient (ratio of the mechanical strength to the induced stress) was higher. Although the mechanical strength of SiC is much higher, the induced thermal stress for cordierite is very low because its Young's modulus and coefficient of thermal expansion are lower. This recuperator is shown in Figure 20.3.3-21 [Ref. 20.3.3-34].

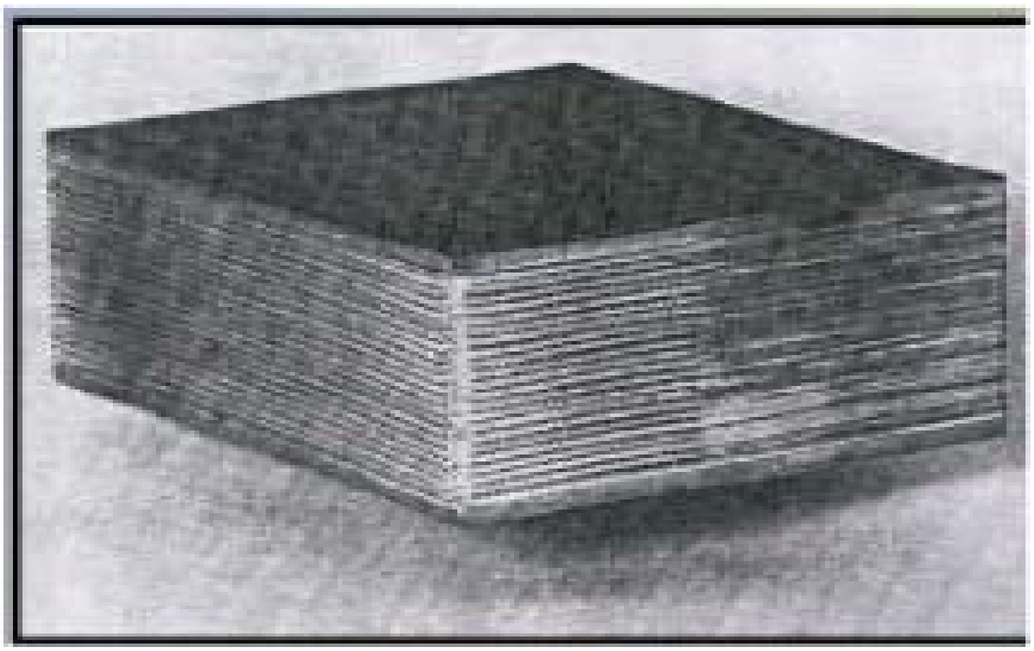


Figure 20.3.3-21 AGATA Cordierite Plate Type HX

The GTE industrial ceramic recuperator is a product that has survived the period of intensive development and continues to be used today. GTE developed modular crossflow ceramic recuperators (see Figure 20.3.3-22) in three sizes: 10 in (cube), 12-in (cube) and 12x12x18 in, rated at up to 0.4 MWt, respectively, for industrial applications. These recuperators used exhaust gas at ~1320ºC to heat incoming air to 705ºC. The best longevity of the recuperator was obtained when the exhaust gas temperature was less than 1100ºC. Although individual units are crossflow, they can be arranged to simulate counterflow, which would increase their effectiveness. Two points about the GTE recuperators should be noted. The first is that the material of construction is cordierite. The second is that many of these recuperators are still in operation. Based on practical experience, the following observations have theoretical validity [Ref. 20.3.3-25]:

- Conductivity of the material is not important for heat transfer
- Pressure drops must be small
- Leaks should be constant so they can be designed for
- The design for metallic recuperators cannot be translated to ceramic materials
- Manifolding to attain counterflow for high effectiveness is difficult
- Thermal shock and creep resistance are the determinant properties.

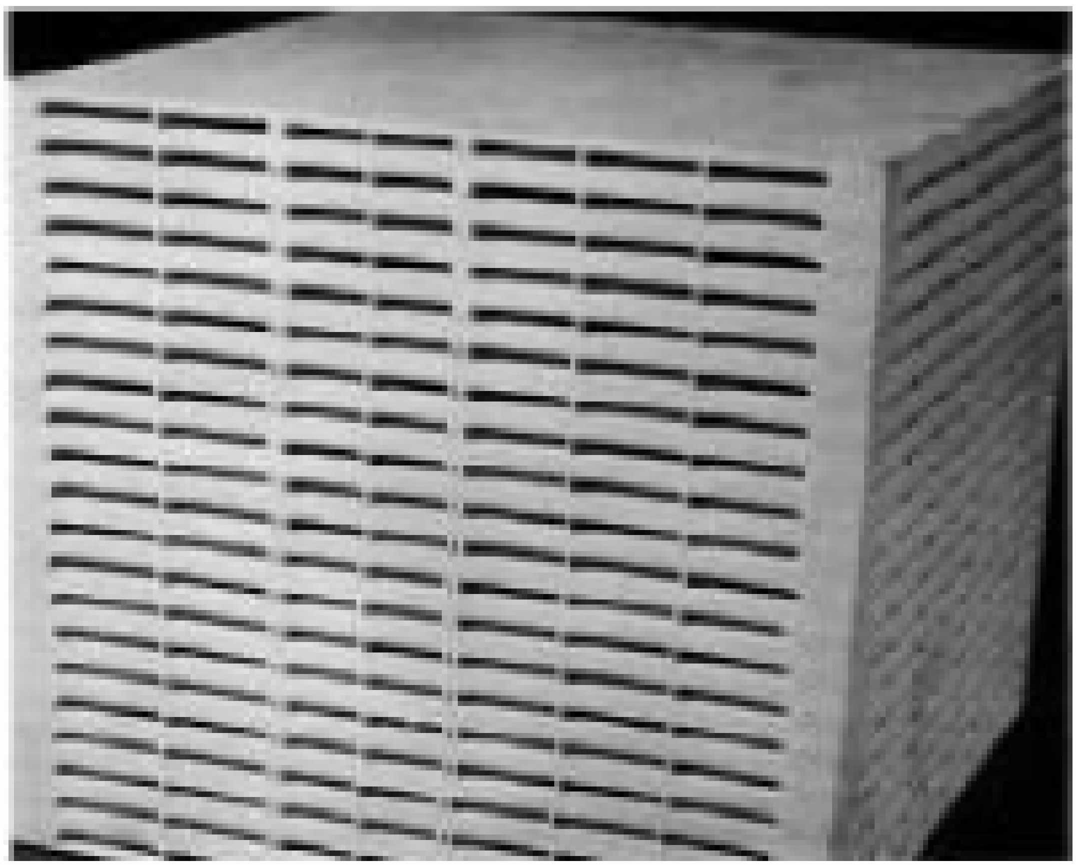


Figure 20.3.3-22 GTE Ceramic Recuperator Matrix

20.3.3.7.3 Materials Selection

In order to fabricate ceramic recuperators, two critical decisions must be made. The first is the selection of the ceramic material and the second is the selection of the construction method. A review of the activities in ceramic recuperation shows that no one material has been used consistently. This is not unexpected, because no one material meets all of the required specifications, which include the following [Ref. 20.3.3-25]:

- Low thermal expansion,
- High thermal-shock resistance,
- Good corrosion and oxidation resistance,
- High thermal strength,

- Good creep resistance,
- Ease of fabrication, and
- Low cost.

During the most active periods of research into ceramic recuperators, the following materials were used: cordierite, Si_3N_4, and SiC (both reaction-bonded and sintered), nitride-bonded SiC, phosphate-bonded SiC, alumina chromia, and magnesia chromia. Some of these materials are no longer considered for high-temperature operations. Of these materials, silicon nitride and cordierite are likely candidates for further development, but both have their drawbacks. In addition, new materials, such as low-thermal-expansion materials or high-thermal-conductivity carbon foam, developed recently at ORNL, should be evaluated.

Silicon Nitride: Silicon nitride has been investigated most extensively (for at least two decades) and has been found suitable for use at high temperatures. Si_3N_4 has excellent creep resistance: its creep lifetimes at stresses and temperatures typical of operating conditions have exceeded 10,000 hours, which is superior to those of nickel-based superalloys. However, it is difficult to fabricate and is very expensive. DOE, through the Ceramic Technology Project, has funded several studies to develop Si_3N_4 with desirable properties for high-temperature structural ceramic applications. Norton produced NT164 Si_3N_4, Kyocera produced SN282, and AlliedSignal Ceramic Components produced AS800. The material properties of AS800 are typical:

- Maximum operating temperature: 1400ºC,
- Room-temperature flexural strength: 715 MPa,
- Weibull modulus: 20-30,
- Fracture toughness: 8 $MPa \cdot m^{1/2}$,
- Thermal conductivity: 65 W/(m·K),
- Density: 3.3 g/cm^3,
- Elastic modulus: 310 GPa, and
- The mean coefficient of thermal expansion (CTE) (20-1000ºC): $3.9X10^{-6}$/ºC.

Although Si_3N_4 has excellent material properties, it is very expensive; the powder alone costs nearly $40/lb and its processing is complex. A less-expensive form is reaction-bonded silicon nitride (RBSN), made from cheap Si powder.

Silicon Carbide: Silicon carbide has been investigated most extensively and has been found suitable for use at high temperatures. It has extraordinary resistance to very corrosive environments and is one of a small group of materials that shows little or no effects from exposure to all portions of the S-I cycle. Hot pressed high purity SiC is a very expensive material; however, siliconized SiC is less expensive. The material properties are given below:

- Maximum operating temperature: 1650ºC
- Room-temperature flexural strength: 446-459 MPa (442MPa at 1000ºC)
- Weibull modulus: 12.3
- Fracture toughness: 4.6 $MPa \cdot m^{1/2}$,(Room Temperature); 6.4 $MPa \cdot m^{1/2}$ (1000ºC)

- Thermal conductivity: 490 W/mK (high purity); 82-90 W/mK (sintered)
- Density: 3.14-3.18 g/cm^3
- Elastic modulus: 406 GPa; 378 GPa (1000ºC)
- Mean coefficient of thermal expansion (CTE) (20-1000ºC): 4-4.73X10^{-6}/ºC
- Tensile strength (500^{0}C) 280MPa; 240MPa (1000ºC)

Cordierite: Cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$) was the material used in many of the earlier ceramic recuperators for microturbines (Coors and AGATA). It is the material used in the compact GTE recuperator, which is the only one in industrial application for more than a decade. It is used now as the support for the catalytic combustors in automobiles. Its CTE is low, similar to that of Si3N4, and it has excellent oxidation resistance and low density. Its major benefits are its low cost and relative ease of fabrication. However, it may not be applicable at temperatures beyond 900^{o}C (near its glass transition temperature), although the GTE recuperators apparently operate at higher temperatures. The latter point is a strong argument for investigating this material to find its maximum operating temperature. The properties of this material are quite variable depending on processing and composition.

20.3.3.7.4 Fabrication Methods

Materials selection and fabricability are closely related. Two heat exchanger designs that have been used in the fabrication of compact recuperators for microturbines are the fin-plate and the primary surface types. These are similar in concept to their metallic counterparts, discussed earlier in Section 20.3.3.5. As with metallic heat exchangers, the tube-and-shell method would be unsuitable because the surface area would be excessive. Theoretically, the prime surface approach may seem a better method, because of the poor conductivity of the ceramic fins in the plate-fin approach. However, the plate-fin design may be easier to fabricate and less costly with ceramic materials. [Ref. 20.3.3-25]

The fabrication method has to be amenable to high-volume production. An extrusion process, which is typically difficult in ceramic processing, may have to be developed. However, a continuous-batch operation would suffice. Scale up to high-volume production will follow later.

Honeywell Composites, Inc. (HCI), formerly Lanxide, has been investigating the fabrication of thin-sheet ceramic recuperators based on paper-making technology. The thin-sheet recuperator is made from alumina (Al_2O_3) particulates in an Al_2O_3 matrix and is designed for counterflow operation. A prototype recuperator has been fabricated and is being tested. Like cordierite, there is concern about permeability of the material in thin sections.

20.3.3.7.5 NHI Ceramic Heat Exchanger Initiatives

Ceramic heat exchangers are currently being developed through the DOE Nuclear Hydrogen Initiative (NHI) that is being coordinated through the University of Nevada, Las Vegas. The present focus is on process coupling heat exchangers, rather than IHXs.

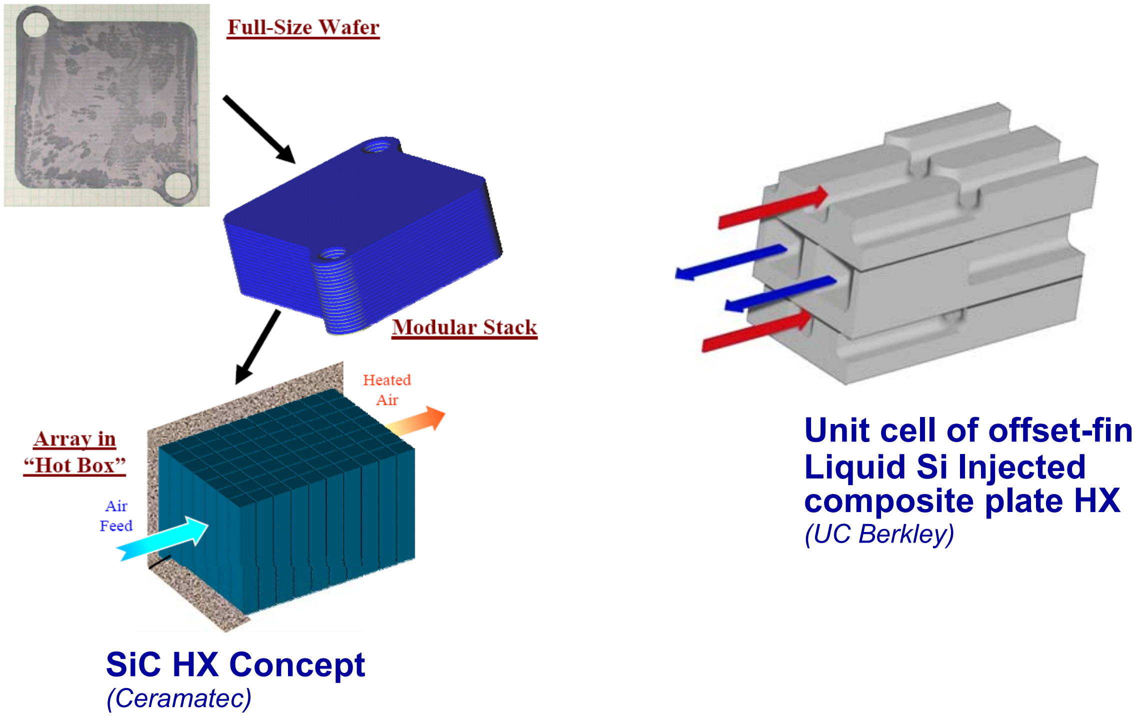


Figure 20.3.3-23 Representative NHI Ceramic Heat Exchanger Concepts

Two representative NHI design concepts are illustrated in Figure 20.3.3-23. The SiC heat exchanger concept being developed by Ceramatec comprises a plate-fin architecture that is built up from tape-cast ceramic layers. The liquid silicon injected (LSI) composite plate concept, being developed by the University of California-Berkeley, is created by first producing a carbon fiber reinforced carbon (CFRC) structure and then injecting liquid silicon into the matrix to make the heat exchanger gas tight.

The ongoing NHI heat exchanger development activities will represent a key resource for the evaluation and development of ceramic heat exchangers for the NGNP and commercial applications in the future. It is intended that this program be closely followed.

20.3.3.7.6 Ceramic HX Summary

Currently there are no ceramic or composite materials listed in the ASME Code. The INL and ORNL preformed a study in 2006 to determine a time table for inclusion of these materials in the ASME Code with appropriate ASTM standards. It was determined that, except for nuclear grade graphite, there was inadequate information to determine a timetable for codification of ceramic or composite materials. This issue is currently the subject of discussion in relevant ASME subcommittees on a quarterly basis. Therefore, it is very unlikely that any ceramic or composites (except nuclear graphite) will become a Code material in the foreseeable future. The primary reasons for this are given below:

- Ceramics and composites are custom designed in most cases for specific applications and there are many categories with one ceramic or composite family
- The subcategories include multiple ways of powder manufacture, powder consolidation, fiber manufacture, ceramic processing, fabrication of finished components, etc.; there has been little standardization in this area to date
- Much of the work being performed is secret or proprietary; this has not facilitated standardization

The structural or critical materials used in a nuclear reactor or an associated critical system has in the past been fabricated from ASME Code materials with standardized validation testing, design procedures and manufacturing methods. Currently, this does not describe ceramics or composites. Significant progress has been made to produce more reliable ceramics and composites with useful mechanical properties; however, the engineering properties of any of the high temperature alloys discussed are far superior to any ceramic or composite in the temperature region of interest. Ceramics and composites are of interest because their mechanical properties remain essentially constant in the temperature regime from 900ºC to 1000ºC or above. These materials are only being considered for the nuclear industry for higher temperatures and extraordinary conditions of corrosion where there are no or few alternative materials and virtually all components that have been fabricated are prototypes or developmental.

It is possible to design a one-of-a-kind system, including heat exchangers, such as the Sulfur Iodine (S-I) hydrogen production process being developed through the Nuclear Hydrogen Initiative (NHI). However, there is little similarity between this program and what would be required to design and manufacture a ceramic IHX as a licensed nuclear component within the NGNP schedule requirements.

The primary issues associated with a ceramic IHX are very high cost (for SiC or Si_3N_4), lack of standardization, lack of ASME Code acceptance, lack of a design basis, and the scale-up requirements for this application. Therefore, virtually all experts in this area agree that a ceramic or composite IHX is not a viable option for the timeframe of the NGNP initial deployment.

However, the limitations of metallic materials provide significant incentives for the development of ceramic heat exchangers for the IHX, as well as for the Process Coupling Heat Exchanger (PCHX), which poses additional challenges related to the process environment. It is viable to include this type of HX in a prototype testing program that will be discussed later, or to include a ceramic prototype in a side helium stream in the NGNP. This would facilitate the development of a specification, procurement for testing purposes and comparative testing with alloy prototype IHX units in a controlled loop. It is recommended that SiC or Si_3N_4 be used as the base ceramic for this application. There is a large experience base with Cordierite and this material is relatively inexpensive; however, the material is inferior to SiC or Si_3N_4 in the area of high temperature properties and, therefore, it may not be worth the long term developmental investment for this application. Si_3N_4 probably has the best overall properties for this application; however, for combined corrosion resistance and mechanical properties, SiC is superior. While composite materials also appear to have promise, issues associated with fabrication and leakage must be solved before they can be considered viable for this application.

Based on a private communication with Dave Stinton, ORNL, he believes that it is possible to fabricate a prototype ceramic HX from any of the three ceramics noted using the OxyCube™ process. He also believes that the HX could be fabricated in a scaled up size that would be useful for testing using facilities at ORNL.

20.3.3.8 Codes and Standards Readiness

20.3.3.8.1 Historical Background

Prior to World War II, the design of pressure vessels was based on selecting the thickness such that the maximum design pressure-induced stress in simple geometries was less than one-fifth the ultimate tensile strength. As a war emergency measure, this nominal factor of safety of five was reduced to four. Based on the success of this step, the codes were revised to adopt this lower factor of safety and questions arose as to the practicality of reducing the safety factor further. However, as the design technology including material behavior advanced, concerns were raised as to the need to include additional failure modes in the design of some vessels. These two aspects led to the development of Section III in 1963 and Section VIII Division 2 in 1968. The major conceptual change in these documents was in design, a change so significant that it was termed "Design by Analysis" to distinguish it from the approach previously followed, "Design by Rules." By and large, the safety factors used in Design by Analysis were less conservative than those used in Design by Rules. In summary:

- The approach taken by Sections III and VIII Div. 2 is referred to as: Design by Analysis, indicating that it relies on explicit structural analysis to evaluate stress/strain states for design.
- The alternative approach of Section I and VIII Div. 1 uses simplified rules and is, therefore, referred to as Design by Rule.
- The Design-by-Analysis procedure, as outlined in the Code has the appearance of a linear elastic analysis. In fact the foundation of the methodology is Limit Load Analysis.

The basic intent of the code was to address the requirements for new construction while providing reasonable assurance of reliable operation. Therefore, the requirements were primarily addressed to the manufacturer, although an important role was assigned to the owner/user with respect to defining the operational conditions to be considered by the manufacturer. The means by which the owner/user fulfilled this assigned responsibility was the preparation of a design specification.

A significant ground rule for the Design-by-Analysis procedures was to permit the application of elastic stress analysis techniques, even though practically all of the criteria were developed based on consideration of elastic-plastic failure modes (plastic collapse and necking, fatigue, ratcheting, etc.), because material selection requirements were intended to assure ductile behavior. Although it was intended that the gross behavior of the structure remain elastic, it was recognized that localized plastic deformation was not necessarily harmful. Since most of the failure criteria addressed by the code are for plastic failure, the elastic analysis criteria are usually much more conservative than the elastic-plastic analysis criteria. The objective is to provide the designer with the option of satisfying less stringent rules at the expense of more detailed and rigorous analysis. Note that Section III has served as the model for almost all of the nuclear design codes developed in other countries.

With the prospect of the construction of liquid metal fast breeder reactors and high temperature gas-cooled reactors in the U.S. in the late 1960s and early 1970s, a need arose for the development of new Code rules applicable at "high temperatures," where ductile materials undergo thermal creep deformation that can lead to a new set of failure modes (creep rupture, creep-fatigue, creep ratcheting, etc.) not experienced at the low temperatures for which the Section III rules were originally developed. The high-temperature design rules were initially developed as a series of code cases (e.g., Code Case 1331, Code Case 1592, and Code Case N47), which ultimately culminated in Subsection NH of Section III. Subsection NH (Code Case N47) has served as a template for several other code cases for elevated temperature service. Code Case N-499 was developed to address the use of SA-533 Grade B, Class 1 plate and SA-508 Class 3 forgings and their weldments for limited elevated temperature service. Code Case N-201 was developed for core support structures in elevated temperature service. A draft code case for Alloy 617 was in the process of being developed by the Task Group on Very-High Temperature Design before the activity was terminated. The draft Code Case employs a unified constitutive model that does not differentiate between plastic and creep deformation at high temperature (>650°C).

20.3.3.8.2 ASME Board on Nuclear Codes and Standards (BNCS)

Basic information regarding the ASME BNCS and related Code activities is given below:

- Charter: To manage all ASME activities related to codes, standards, and accreditation programs directly applicable to nuclear facilities and technology.
- Code - A standard which has been adopted by governmental bodies, local, state, or federal, or which is cited in a contractual agreement, and which has the force of law.
- Code Case - Documents that clarify the intent of existing Code requirements or provide alternative requirements.
- Standard - A set of technical definitions and guidelines developed so that items can be manufactured uniformly and provide for safety and interchangeability.
- Guide - A suggested practice, process or method that is not mandatory and may be used as a whole or in part.

The BNCS provides procedural oversight of all nuclear codes and standards activities. The BNCS is composed of:

- Standards committees that establish consensus on technical issues
- Subcommittees that provide recommendations on technical issues in particular areas such as nuclear components to the standards committee
- Subgroups develop proposals in a particular area of specialty such as design. The Subgroups work with various other Working Groups, Technical Groups, and Project Task Groups to develop proposals

20.3.3.8.3 Basic ASME Code Definitions

Nuclear vessels and piping design criteria are governed by a combination of ASME Code and Nuclear Regulatory Commission (NRC) requirements. The main difference between low- and high-temperature requirements is not so much the effect of temperature, but the effect of time dependency that it introduces. In all other respects, the general design process is identical, and many of the notations used for low-temperature design are carried over to high-temperature applications.

The following six loading categories are defined in the ASME Code (ASME 2004).

- **Design Loadings:** The specified design parameters for the Design Loadings category equal or exceed those of the most severe combination of coincident pressure, temperature and applied loads specified under events that cause Service Level A loadings.
- **Service Level A Loadings (Normal operation):** These are loadings arising from system startup, operation in the design power range, hot standby, and system shutdown.
- **Service Level B Loadings (Upset conditions):** These are deviations from Service Level A loadings that are anticipated to occur at moderate frequency. The events that cause Service Level B loadings include transients which result from any single operator error or control malfunction, transients caused by a fault in a system component requiring its isolation from the system, and transients due to loss of load or power. These events include any abnormal incidents not resulting in a forced outage.
- **Service Level C Loadings (Emergency conditions):** These are deviations from Service Level A loadings that have a low probability of occurrence and would require shutdown for correction of the loadings or repair of damage in the system. The total number of postulated occurrences for such events may not exceed 25.
- **Level D Loadings (Faulted conditions):** These are the combinations of loadings associated with extremely low probability, namely, postulated events whose consequences are such that the integrity and operability of the nuclear energy system may be impaired to the extent that only consideration of public health and safety are involved.
- **Test Loadings:** Pressure loadings that occur during hydrostatic, pneumatic or leak testing. Other types of tests are classified as Service Level A or B loadings.

Safety factors are highest for Level A, followed in decreasing order by Levels B, C, and D.

20.3.3.8.4 Classification of Stresses

The basic premise behind classifying the stresses is that all stresses acting on a component made of ductile materials are not equal as far as the consequences of their presence are concerned. The stresses are characterized in the following three categories: primary stress, secondary stress, and peak stress [Ref. 20.3.3-35]:

- Primary stress (Pm, PL, and Pb) is any normal stress or a shear stress developed by an imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting, cannot be relieved by localized plastic deformation, and if not limited, can lead to excessive plastic deformation of the structure. Primary stress is an algebraic sum of general or local primary membrane stress (Pm or PL) and primary bending stress (Pb). Note that local primary membrane stress, PL, includes the general primary membrane stress, Pm. The primary stresses are generally based on linear elastic theory.

- Secondary stress (Q) is a normal or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure. The basic characteristic of a secondary stress is that it is self-limiting, because it can be relieved by small-localized plastic deformation that cannot cause large distortion of the structure. Failure from one application of a secondary stress is not expected. Not all deformation-controlled stress can be categorized as secondary stress. The code requires all deformation-controlled stress with high elastic follow-up to be treated as primary stress. Often, membrane components of thermal stresses are categorized as primary.
- Peak stress (F) is due to local discontinuities or local thermal stress including the effects of stress concentration. This stress is additive to the primary plus secondary stress. The basic characteristic of a peak stress is that it does not cause any noticeable distortion. The peak stress is objectionable only as a possible source of a fatigue crack or a brittle failure.

In summary:

- Primary stresses are intended to represent a sufficient condition to avoid structural failure. According to the bounding theorems of plasticity, ANY stress state, in equilibrium with the load, and not exceeding the yield stress, represents a lower bound on collapse and is therefore safe.
- A linear elastic analysis which does not exceed yield satisfies this criterion and, in an age when limit analysis was difficult to implement, a modified elastic route was adopted, based on an initial linear elastic analysis, followed by a procedure referred to as stress "linearization". These issues are no longer limiting factors today and very powerful analysis techniques are currently available.
- The ASME stress classification system is basically sound.
- The method of classification provided in the Code may be excessively conservative and, on occasions, wrong and misleading.
- A method with less conservatism is needed in order to enter more severe operating environments, as will be expected in future high-temperature applications.
- One such method, the Reference Stress technique, already exists and, with some adaptation, could be the basis for an alternative approach to very high temperature design.
- This approach is used in the UK and in other parts of Europe, but has not yet been incorporated into the ASME Code

20.3.3.8.5 ASME Section III, Subsection NB (Elastic Analysis)

In the ASME Code, structural integrity of a component below the creep range is assured by providing design margins against the following failure modes:

- Failure by plastic instability or necking,
- General structural collapse under a single application of limit load,
- Time-independent buckling,
- Incremental collapse or ratcheting under cyclic loading,
- Fatigue under cyclic loading, and
- Fast fracture.

The first two failure modes challenge the ability of the component to resist permanent distortion and/or plastic instability under a single application of the maximum anticipated load; the third failure mode is buckling of a slender component due to compressive loading; the next two failure modes challenge the ability of the component to survive a succession of the same and/or different loads; and the final failure mode challenges the defect tolerance of the component. Rules are given in the code to protect against these failure modes using either elastic or plastic analysis techniques.

The ASME Code requires that for normal operation and upset conditions (Service Level A and B loadings):

- $Pm \leq Sm$, where Sm is the minimum criterion among time independent stress components; Sm = minimum {1/3 Su or 2/3 Sy} where Su and Sy are the ultimate tensile and yield strengths, respectively at a given temperature

For upset conditions (Level B loading), the value of Sm, above, may be increased by 10%. For emergency conditions (Service Level C loading), the allowable general primary membrane stress intensity is:

- $Pm \leq$ max 1.2 Sm or Sy

For faulted conditions (Service Level D loading), the allowable general primary membrane stress intensity is:

- $Pm \leq 0.7$ Su or 2.4 Sm

The ASME Code requires that for normal operation and upset conditions (Service Levels A and B loadings):

- $P_L + Pb \leq KSm$ where $K \leq 1.5$ and represents the ratio between the loads to cause fully plastic section and initial yielding in the extreme fiber of the section. For shells and solid sections, K = 1.5.

For upset conditions (Level B loadings), the value of Sm may be increased by 10%. For emergency conditions (Service Level C loading), the allowable local primary membrane plus bending stress intensity is:

- $P_L + Pb \leq KSy$ or $1.2KSm$

For faulted conditions (Service Level D loading), the allowable local primary membrane plus bending stress intensity is:

- $P_L + Pb < 1.05Su$ or $3.6\ Sm$

A more comprehensive review of these issues is given in [Ref. 20.3.3-35].

20.3.3.8.6 ASME Section III, Subsection NH (Elastic/Inelastic Analysis)

Subsection NH of ASME B&PV Code, Section III, provides high-temperature design rules for construction of Class 1 components having metal temperatures exceeding those covered by the rules and stress limits of Subsection NB and Tables 2A, 2B, and 4 of Section II, Part D, Subpart 1. Table 20.3.3-9 lists the materials included in Subsection NH along with the maximum temperatures permitted.

Table 20.3.3-9 Subsection NH Materials and Maximum Allowable Times and Temperatures

Material	Temperature (°C)[a,c]	
	Primary Stress Limits and Ratcheting Rules	Fatigue Curves
304 stainless steel	816	704
316 stainless steel	816	704
2 1/4 Cr – 1 Mo steel	593[b]	593
Alloy 800 H	760	760
Modified 9 Cr – 1Mo steel (Grade 91)	593[b]	538

a. Allowable stresses extend to 300,000 h (34 years) unless otherwise noted.

b. Temperatures up to 649 °C are allowed for not more than 1000 h.

c. Alloy 718 is allowed up to a maximum temperature of 550 °C.

The first step in design for elevated temperature is to design the component for low-temperature operation. The first few steps in the design process are, therefore, identical with those used in low-temperature applications. Operation at elevated temperature introduces time-dependent failure modes. Thus, in addition to the six time-independent failure modes addressed previously, the following six time-dependent failure modes are considered in the high-temperature design:

- Creep rupture under sustained primary loading,
- Excessive creep deformation under sustained primary loading,
- Cyclic creep ratcheting due to steady primary and cyclic secondary loading,
- Creep-fatigue due to cyclic primary, secondary, and peak stresses,
- Creep crack growth and non-ductile fracture, and
- Creep buckling.

Rules are given in Subsection NH to protect against these failure modes using elastic and, in some cases, either elastic or elastic-plastic analysis techniques. To carry out high-temperature design, the following mechanical properties as functions of temperature are needed, from which the design allowables are derived after applying appropriate safety factors:

- Modulus of elasticity and Poisson's ratio (average),
- Yield strength Sy (average and minimum),
- Ultimate tensile strength Su (average and minimum),
- Stress-strain curves (average and minimum),
- Stress vs. creep rupture time for base metals and their weldments (average and minimum),
- Stress vs. time to 1% total strain (average),
- Stress vs. time to onset of tertiary creep (minimum),
- Constitutive equations for conducting time- and temperature-dependent stress-strain analysis (average),
- Isochronous stress-strain curves (average),
- Continuously cycling fatigue life as a function of strain range at a fast strain rate (average), and
- Creep-fatigue cyclic life involving cycles with various strain ranges and hold times (average).

Any loss or change in mechanical properties caused by thermal aging, decarburization, etc., with long-term high-temperature exposure in an environment should also be included in the database. The stress-strain curves and constitutive equations, included above, are needed for conducting inelastic stress-strain analyses. The rest of the items listed above are required for satisfying elastic as well as inelastic analysis limits.

In addition to the time-independent Sm, the code introduces a temperature and time-dependent quantity St to account for creep effects. For each specific time t and temperature T, St for the base metal is defined as the lesser of the following three stresses:

- 100% of the average stress required to obtain a total (elastic, plastic, primary creep, and secondary creep) strain of 1%;
- 80% of the minimum stress to cause initiation of tertiary creep; and
- 67% of the minimum stress to cause rupture.

A basic primary stress limit for high temperatures is Smt, which is the lesser of Sm and St, and is a function of both time and temperature. Note that the definition of St assumes that the material has a classical creep curve. However, some nickel alloys exhibit a non-classical creep curve with no clear primary creep or secondary creep regime. The above definition of St has to be revised for these materials. St and Sm curves are needed as a function of temperature for the determination of Smt. As shown in Figure 20.3.3-24, St is the time dependent stress intensity (1 hour to 300,000 hours), plotted versus temperature; Sm is the time independent stress intensity; Smt is the allowable stress intensity which is the lesser value of St or Sm for a specific temperature; therefore Smt is time dependent. Tensile and creep data are required to produce Sm and St Curves.

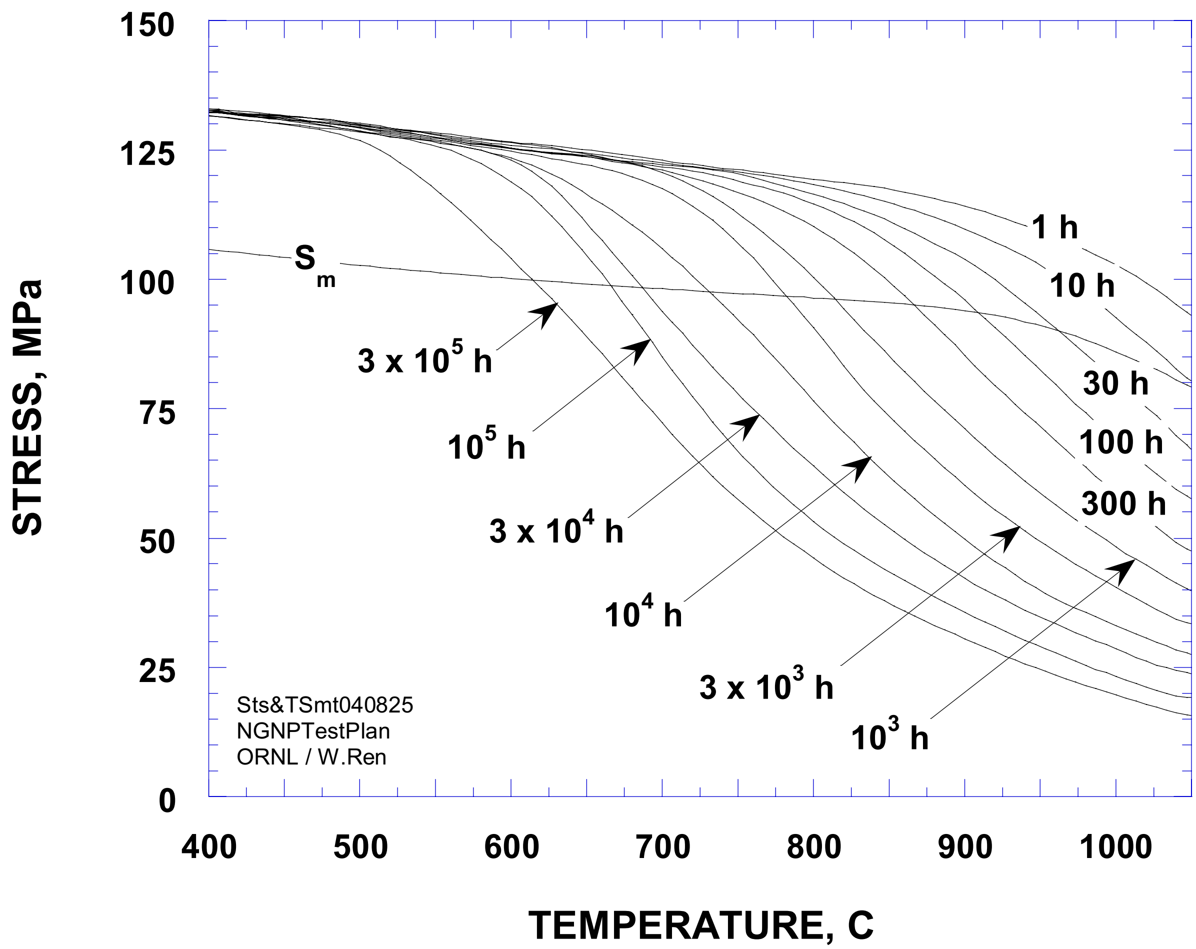


Figure 20.3.3-24 Typical Curves for Sm and St

20.3.3.8.7 ASME Section III, Subsection NH Design Issues

ASME Section III, Subsection NH applies above the temperature limits for Subsection NB allowable stresses [Ref. 20.3.3-36]. Subsection NB applies above temperature limits if creep effects are demonstrated to be not significant. As noted above, only 304 & 316 stainless steels, Alloy 800H, 2-1/4Cr-1Mo alloy pressure vessel steel and, recently, 9Cr-1Mo-V alloy pressure vessel steel are approved pressure boundary materials under NH. Alloy 718 is approved for bolting.

The ASME Subsection NH design condition evaluation is the same as for ASME Section VIII, Div 1, and with the same allowables. The ASME Subsection NH service condition allowable stress criteria are the same as ASME Subsection NB for time-independent Sm, but different and more conservative than ASME Section VIII, Div 1 for the time-dependent allowable, St. Evaluation of design conditions and all service conditions except Level D are based on a linear elastic material model. Time fraction summations are used to evaluate different stress, time and temperature conditions with time fractions summed over all service conditions. Time fraction is time in a specific condition divided by allowable time at that condition. Weld strength reduction factors are provided for permitted weld metal and properties, with the analysis based on parent metal properties. Strain limits and creep-fatigue damage rules can be satisfied using either elastic or inelastic analysis methods. Elastic analysis rules, originally envisioned as a simpler, more conservative and less costly screening method to satisfy strain limits and creep-fatigue, are actually considerably more complex than analogous ‘low” temperature rules in Subsection NB. Inelastic rules envisioned as a more costly and time consuming “gold standard” are conceptually simple but require sophisticated modeling of material behavior in the creep regime. Requirements for material modeling are only addressed in general terms. Strain limits, creep-fatigue and weld criteria are summarized below:

- **Strain Limits**
  - Accumulated averaged membrane strain, 1%; membrane plus linearized bending strain, 2%; total strain, 5%
  - Based on collective judgment and numerous rationale; no rigorous, failure-related basis

- **Strain Limits Using Elastic Analysis**
  - Based on elastic section of Bree Diagram**;** Simplest to use but most conservative
  - ASME T-1324, Test No. A-3 provides criteria for negligible creep with time fraction summation of creep damage less than 0.1, based on sustained stress 1.5 times minimum Sy and accumulated strain less than 0.2% based on sustained stress 1.25 times minimum Sy. This requires maximum primary stress over component lifetime to be considered with maximum secondary stress range over component lifetime.

- **Strain Limits Using Simplified Inelastic Analysis**
  - Based on extension of Bree analysis by O’Donnell & Porowski and, later, Sartory
  - Key is elastic core stress limit and subsequent deformation
  - Requires pressure induced membrane and bending and thermal induced membrane stresses to be classified as primary stresses

  - Requires maximum primary stress over lifetime be considered with maximum secondary stress range over whole life
  - More complex than analogous Subsection NB primary plus secondary stress limits

- **Creep-Fatigue (see Figure 20.3.3-25)-Major source of conservatism in NH**
  - Criteria: $\sum(n/Nd) + \sum(\Delta t/Td) \leq D$ where n is the number of cycles of a given strain range; Nd is the allowable number of cycles at that strain range; Δt is time at a stress level calculated from average properties; Td is the allowable time at the calculated stress level divided by a factor, K' = 0.67, as determined from plot of minimum stress to rupture versus time to rupture and D is a damage factor to account for combined effects of creep and fatigue. The limits of D for selected materials are given in Figure 20.3.3-25.
  - Rationale for conservatisms: K' = 0.67 is based on Eddystone piping failure and component test results; D for 9Cr-Mo-V due in part to environmental effects and in part to evaluation methodology and expectation that this would be revisited if material was used in practice.
  - Result: **Wall thickness may be limited by creep-fatigue rather than load controlled stress criteria**

- **Welds**
  - Weld strength reduction factors
  - Strain limits half that of parent material
  - Creep-fatigue limits: Nd, allowable number of cycles reduced by factor of two and Minimum parent metal creep rupture strength reduced by weld strength reduction factor
  - Weld geometry: Worst case weld geometry is used in the analysis; geometry must be confirmed by inspection

ASME Section III, Subsection NH issues are summarized below:

- Currently Subsection NH includes a very limited set of materials
- Subsection NH has never been used for design of a Section III structure
- Subsection NH rules are very conservative and difficult to use
- Subsection NH is only applicable at temperatures up to 760ºC
- Subsection NH has never been accepted by the NRC; the NRC has taken a neutral position until there is an applicable nuclear application
- ASME Section III, Subsection NB is easier to use and it is better to maintain the Class 1 boundary below the creep range, if possible
- Subsection NH is currently not useful for design of the IHX structures

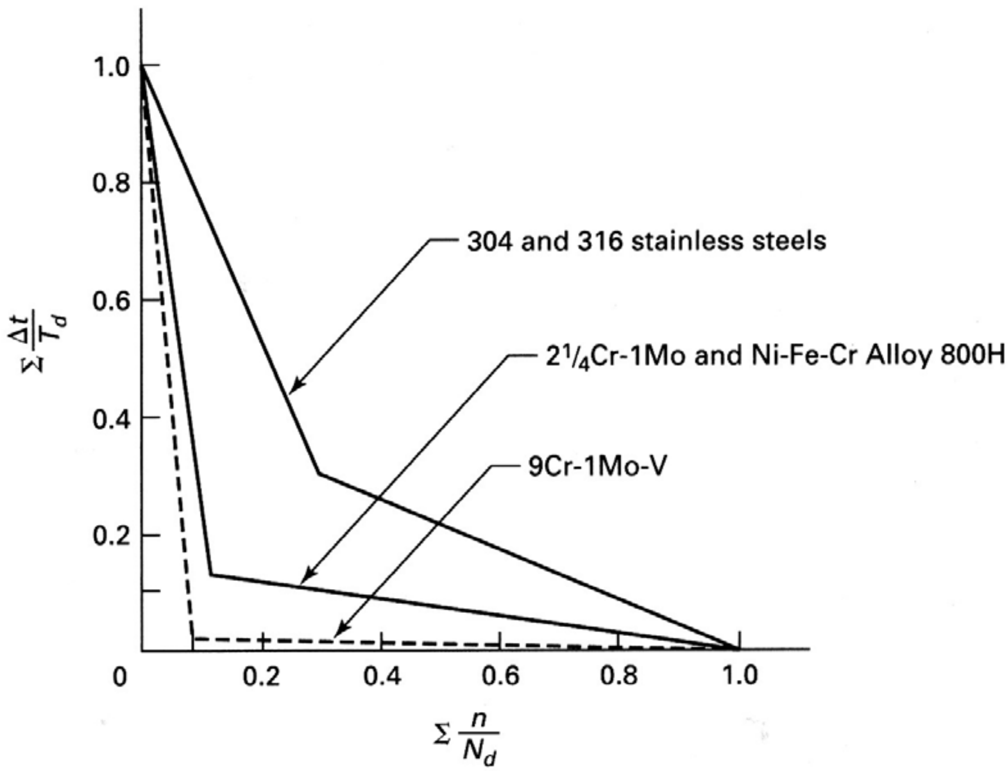


Figure 20.3.3-25 ASME Figure 20.3.T-1420-2 Creep-Fatigue Damage Envelope

20.3.3.8.8 ASME Section VIII Issues

ASME Section VIII Div 1 allows potentially useful materials for construction of the IHX (Alloy 800H-982ºC, maximum; Alloy 617- 982ºC, maximum; Hastelloy X- 898ºC, maximum and Alloy 230- 982ºC, maximum); however, Section VIII, Div 2 does not allow the use of these materials. Section VIII, Div 1 and Div 2 design rules are relatively easy to apply for tube and shell HXs and associated pressure vessels but not easy to apply for a plate type IHX. Basic design equations for plate type HXs are contained in Compact Heat Exchangers [Ref. 20.3.3-37] and Fundamentals of Heat Exchanger Design [Ref. 20.3.3-38]. ASME Section VIII does not contain specific design rules directly applicable to plate type HXs. It is not clear what design rules are currently being used to design Heatric plate type PCHE units, but the rules do not appear to be ASME-based.

Fatigue, environmental and aging issues are not currently addressed adequately in the ASME Code. The alloys listed and the maximum design temperatures in Section VIII are potentially useful for VHTR IHX applications; however, it is unlikely that the NRC would support IHX design and fabrication using Section VIII. Therefore, because metallic alloys that could potentially be used to construct the IHX are not currently a part of the ASME Nuclear Code, Section III, it is envisioned that a significant effort will be required to resolve this issue because a reliable database potentially useful for a code case based on three well-documented heats of material is not available.

Also, there is no existing ASME Section III design basis for either a conventional tube and shell IHX or less-conventional plate-type IHX. The most expedient approach for the NGNP IHX appears to be development of an application-specific design basis and submittal of a Section III code case associated with Subsection NH. A significant effort will also be required to resolve this issue because an openly available design basis is not available in a format suitable for a code case. Therefore, if a plate-type IHX is selected, testing of prototype IHX units would be needed to support the code case design basis for the specific IHX design selected.

20.3.3.8.9 DOE Initiative to Address ASME Code Issues

20.3.3.8.9.1 Funded Tasks

A three-year collaboration has been established between DOE and ASME that proposes to address twelve topics in support of an industrial stakeholder's application for licensing of the NGNP [Ref. 20.3.3-2]. Efforts to address the first five tasks are currently underway. The majority of these tasks are relevant to action items within ASME Section III, Subsection NH. The nature of the topics inherently includes significant overlap and, in some cases, parallel activities on the same issue. These tasks are summarized below.

Task 1: <u>Verification of Allowable Stresses</u>

Stress allowables for Alloy 800H include data for Alloy 800, and differences exist for stress allowables found in Subsection NH and RCC-MR for Grade 91. There are also discrepancies between material properties as implemented in allowable stress values in Subsection NH and Section II, Part D which should be in agreement. The review of stress allowables for base metal and weldments of Alloy 800H and extension of time-dependent allowables to 900°C (which would require data at least 25°C above the temperature at which allowables are set in order to achieve more reliable extrapolation to longer times) are desired, if possible. Similarly, review of stress allowables for Grade 91 Steel is desired.

The task will require formal access to and use rights of the various materials databases. The original database needs to be assembled and reviewed, including methods used to set the time-dependent allowables. Comparison of European and Japanese databases and the methods and procedures used by these sources to set allowable stresses are needed to provide guidance and comparison on how to set allowable stresses for ASME Section III, Subsection NH. For Alloy 800H, the U.S. database needs to include existing data produced up to 925°C, including both creep and stress rupture data. An updated compilation of the creep and rupture data for Grade 91 needs to be assembled, especially for up to 300 mm thick plate, forgings, and heavy wall piping. Consideration of post-weld heat-treatment (PWHT) effects needs to be made. Assessment of alternate procedures for describing creep and stress-rupture for conditions of concern to the NGNP, namely 60 year plant life, is also required; procedures developed by the

Pressure Vessel Research Council need to be considered as well. The current allowables need to be compared to the results of the reassessment, and a recommended course of action made with respect to ASME Section II-Part D and III-NH.

Task 2: Regulatory Safety Issues in Structural Design Criteria for ASME Section III, Subsection NH

The NRC licensing review of the Clinch River Breeder Reactor Plant (CRBRP) in the 1970's and 1980's identified a number of concerns, including but not limited to weldment safety evaluation, notch weakening and creep-fatigue evaluation. The major fundamental regulatory safety need was improvement of the criteria to prevent creep cracking. The need to build confidence in the regulatory community that the resulting designs will have adequate safety margins is critical. Compilation and storage of reports describing confirmatory program plans that were jointly developed by the NRC and the CRBRP are needed. A review of all the safety issues relevant to Subsection NH is required, including the generation of a historical record that includes a detailed description of how Subsection NH currently addresses these issues or not; further, identification of additional safety concerns within NH for application to very high temperature service is needed. The review will serve as a foundation to initiate communications with the NRC on these issues, and facilitate future consultation with the NRC in improving, developing, and confirming design and fabrication procedures, strain limits and material design curves.

Task 3: Improvement of ASME Section III, Subsection NH Rules for Negligible Creep and Creep-Fatigue of Grade 91 Steel

Significant differences in prediction of creep strain under monotonic loading exist between Subsection NH and RCC-MR. These differences are critical in satisfying the insignificant creep criteria and are likely due to extrapolation of data from 500-600ºC to lower temperatures applicable to the NGNP RPV, 370-450ºC. The current approaches available to define negligible creep need to be reviewed and their applicability verified for use with Grade 91 steel. Material data available in France and the U.S are needed. The methodology, data and additional tests required to support the definition of negligible creep conditions for Grade 91 steel need to be identified.

The damage envelopes for creep-fatigue are significantly different for Grade 91 steel in Subsection NH and RCC-MR codes. The differences have yet to be explained by scatter in data, variation between heats, whether the damage envelope is procedure dependent (e.g., definition of stress and creep damage during hold times), material softening, or other yet unidentified causes. Hence, a critical comparison of ASME Section III, Subsection NH and RCC-MR creep-fatigue procedures is needed.

Comparisons are desired on the basis of experimental test results available from Japan, France and the U.S.; particular attention is required in the definition of safety factors and creep-fatigue damage envelope procedures. Assessment of whether or not the material data presently available in nuclear codes are thought to be sufficient and valid is required, including recommended improvements to existing procedures and definition of a test program to validate the improved procedures.

Task 4: Updating of ASME Nuclear Code Case N-201

The scope of Code Case N-201 needs to be expanded to include materials with higher allowable temperatures, extend the temperature limits of current materials if possible, and to confirm whether the design methodology used is acceptable for design of core support structure components at the appropriate elevated temperatures. The maximum operating temperatures required for High-Temperature Gas-Cooled Reactor (HTGR) metallic core support structures must be identified in a review of data made available by AREVA, GA, PBMR, DOE and other available sources. Operating parameters including but not limited to temperature, pressure, time and environment need to be defined. Candidate materials need to be identified and prioritized for use as metallic core support structures within the defined operating parameters. The design methodology used, which is primarily based on ASME Section III, Subsection NH, needs to be critically reviewed for application to Generation IV reactors, specifically the NGNP. Recommendations for inclusion of new materials or extension of times and temperatures for current materials are required. If necessary, recommended changes and/or additions to design methodologies should be made. Note that Task 7 (not funded) closely parallels this portion of Task 4 - namely the evaluation of Subsection NH and Simplified Methods. Gap analysis on material data needs is required; including the definition of supplemental testing required to support determination of material design curves (e.g., creep rupture, creep-fatigue, etc.).

Task 5: Creep-Fatigue Procedures for Grade 91 Steel and Hastelloy XR

Tasks 3 and 7 include intentional parallel activity in evaluation of creep-fatigue procedures for Grade 91 (Task 3) and Alloys 617 and 230 (Task 7). The intent in this task is to compare procedures used on two different classes of alloys, and to develop modified or new procedures for application to universal creep-fatigue modeling and alloy specific procedures. The task will require that formal access to and use rights of the various materials databases be secured, followed by an evaluation of the state of existing data to determine if more data are necessary. Candidate database sources include Grade 91 steel data generated for the Japanese demonstration fast breeder reactor and Hastelloy XR used in the HTTR. Recently, agreement has been obtained between the ASME and JAEA to transfer the Hastelloy XR database.

Creep-fatigue criteria need to be summarized based on existing international nuclear codes, e.g. Subsection NH, RCC-MR, and Monju Design Codes. A comparison of creep-fatigue damage evaluation procedures is required, including assessment methods of strain range, initial stress and relaxation behavior, formulation of creep damage, strain rate and hold time effects, methods used in partitioning plastic, elastic, and creep strain, environment effects, and wave shape effects. A recommended testing program to generate required supplemental data needs and model verification are needed.

20.3.3.8.9.2 Unfunded Tasks

The seven task areas noted below are currently unfunded:

- Graphite and ceramic code development (Task 6)
- NH evaluation and simplified methods development (Task 7)
- Identification of testing needed to validate elevated temperature Section III, Subsection NH design procedures in support of the NGNP (Task 8)
- Address the lack of environmental and neutron fluence effects associated with ASME Section III (Task 9)
- ASME Code rules for the IHX (Task 10)
- Flaw assessment and leak before break ASME Section III rules in support of the NGNP (Task 11)
- Improved NDE methods (Task 12)

20.3.3.8.9.3 Project Organization

The current project organization is given in Figure 20.3.3-26.

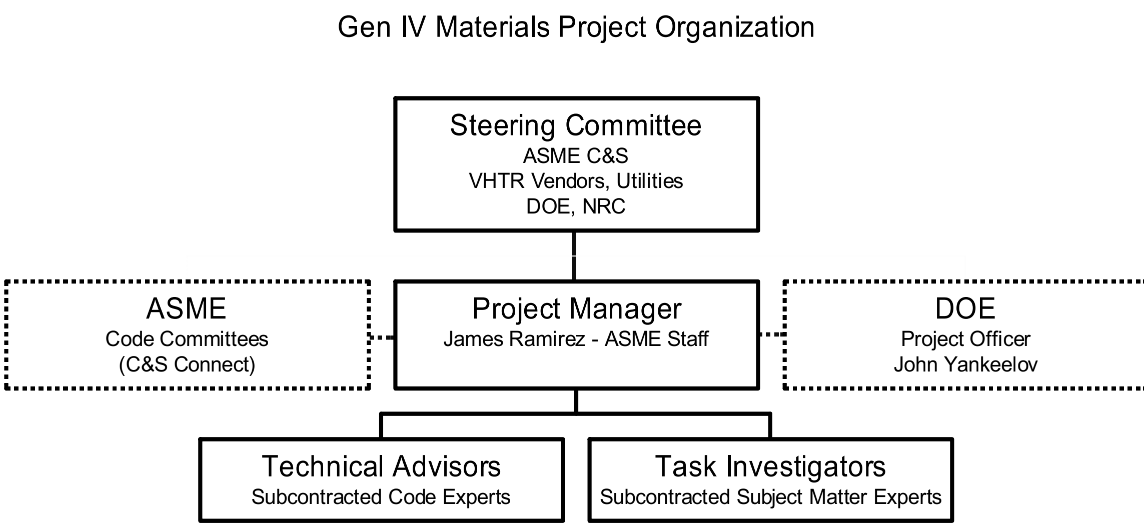


Figure 20.3.3-26 Current ASME/DOE Project Organization

The primary affiliated organizations for each of the funded tasks are given below:

- Task 1: University of Dayton Research Institute
- Task 2- O'Donnell Engineering
- Task 3- AREVA-Framatome ANP
- Task 4- Westinghouse Electric
- Task 5- Japan Atomic Energy Agency

The primary tasks that are of interest to the Code issues associated with the NGNP IHX are: Tasks 1, 2, 4 and 5 (funded tasks) and Tasks 7, 8, 9 and 10 (unfunded tasks).

20.3.3.8.10 ASME Draft Code Case for Alloy 617

A request to the ASME to establish high temperature design rules was made in the 1980s from the DOE and one of its contractors [Ref. 20.3.3-35]. Materials of potential interest included Alloys 800H, Hastelloy X and Alloy 617. An ad hoc task force of the ASME was established in 1983 to address the design of reactors operating at very high temperatures. The task force was organized under the Subgroup on Elevated Temperature Design of the Subcommittee on Design. The task group completed the draft code case in 1989 and submitted it to the subgroup which later approved the code case. No further work was done on the code case due to a lack of interest from the DOE and its contractor. The code case was patterned after Code Case N-47 and was limited to Alloy 617. The draft code case focused on this alloy because it was a leading materials candidate for high temperature designers and a significant high temperature data base was available with this alloy.

The code case focused on the failure modes addressed in Section III, Subsections NB and NH including non-ductile fracture. Non-ductile fracture was included because it was known that Alloy 617 showed a significant loss of fracture toughness after long term exposure to high temperatures (aging). Some of the design rules given in the draft code case were different from those given in Subsections NB and NH, and included somewhat unique behavior characteristics including: (1) a lack of a clear distinction between time dependent and time independent behavior, (2) high dependence of flow stress on strain rate, (3) softening as a function of time, temperature and strain. The draft code case specified that inelastic analysis above 649ºC must be based on unified constitutive equations which do not distinguish between time independent plasticity and time dependent creep. The draft code case prohibits cold worked material because Alloy 617 recrystallizes following high temperature exposure if it is in the cold worked condition.

Alloy 617 bolting is excluded from the draft code case, due to the loss of fracture toughness following aging.

The draft code case is based on a limited data base and minimal service experience. It was also determined following the publication of Shah, et al, 2003 that the draft code case for Alloy 617 had other deficiencies that were not easily resolved. These deficiencies included [Ref. 20.3.3-17]:

- Lack of test data that approach the low stresses and long durations required for the NGNP. The current data base was obtained by the application of higher stresses and these data would require significant extrapolation for an IHX-type component for the NGNP
- The existing database primarily uses power law creep as the deformation mechanism. There is uncertainty about whether this mechanism remains dominant at the significantly lower stresses and very long times envisioned for the IHX

- If a different deformation mechanism dominates at lower stresses, extrapolation of power law creep data to lower stresses could predict non-conservative (lower) creep rates by several orders of magnitude
- The existing data base was obtained primarily on relatively coarse grain material because this type of material favors greater creep resistance; however, if a compact plate type IHX is used for the NGNP a smaller grain size will be required because of fabrication using very thin sheets formed in a stack

Therefore, the basis of much of the draft code case data (isochronous stress-strain curves) will need to be reevaluated using small grain material. Testing should also include creep fatigue testing of weldments (including diffusion bond joints) and environmental effects. The grain size (GS) issue applies to the PCHE. Input from Heatric to MIT regarding a proposed experimental Alloy 617 heat exchanger provides some insights in this regard. For a plate thickness of 0.9mm, Heatric recommended a GS of ASTM 8 or finer. ASTM 8 has an average GS of 0.0254 mm which equals an average of 35 grains across the 0.9 mm thickness.

The current reference for Alloy 617 plate is ASTM GS 0 (0.405 mm) to ASTM GS 3 (0.143 mm). The range of grain size in the known Alloy 617 data base is 0.1 mm to 1 mm, based on references that actually reported the GS. It is a matter of opinion how large the GS should be for 0.9mm thick material but ASTM 6 (0.051mm) with 18 grains across the thickness or finer should probably be specified in order to mitigate crack propagation across the section. The Heatric guideline may be a little conservative, but it is indicative of their opinion on this issue.

20.3.3.8.11 Summary and Recommendations

Metal alloys that could potentially be used to construct the IHX (except for Alloy 800H) are not currently a part of the ASME Nuclear Code, Section III. A significant effort will be required to resolve this issue because a reliable database potentially useful for a code case based on three well-documented heats of material is not available. There is no existing ASME Code basis (Section III or other) for the application of ceramics in pressure boundary applications. There is no existing ASME Section III design basis for either a conventional tube-and-shell IHX or less-conventional plate-type IHX. The most expedient approach for the NGNP IHX appears to be development of an application-specific design basis and submittal of a Section III code case associated with Subsection NH. A significant effort will also be required to resolve this issue, because an openly available design basis is not available in a format suitable for a code case. If a plate-type IHX is selected, testing of prototype IHX units would be needed to support the code case design basis for the specific IHX design selected.

The IHX for the NGNP should be contained in a Class 1 pressure boundary from an ASME Code consideration and to minimize pressure-induced stresses in the unit, because of the low metallic materials margin at 900-950ºC. A pressure boundary will be needed if a plate type HX is used, which under current rules is not a Code vessel. The pressure boundary size would be greatly reduced if a plate-type HX unit is used for the NGNP IHX. The pressure vessel(s) should probably be designed using ASME Section III, Subsection NB design rules (no creep) and should be insulated and cooled as required.

The following recommendations are made:

- It is recommended that a plate-type HX development program be pursued for the NGNP IHX in conjunction with an appropriate design and materials development program, which will be discussed later in this report.
- It is recommended that revision of Subsection NH be a longer-term target; however, it is recognized that submittal of a code case of the type envisioned would have a significant impact on Subsection NH.
- It is recommended that a shorter-term target be focused on a code case specifically designed to provide an ASME design and fabrication material basis for the NGNP IHX.
- It is recommended that an R&D program be performed to obtain adequate test data to support the code case for the IHX alloy selected
- It is recommended that the Alloy 617 draft code case submitted in 1992 not be revised and updated
- It is recommended that one or more small (100-200kw) prototype plate-type HX units, including a ceramic unit, be procured and tested at an appropriate testing facility. A potential testing program is contained in Kesseli et al, 2006.
- It is recommended that detailed finite element analysis be performed on a plate-type HX grid for use as a design and evaluation tool. Some work in this area has been performed in the past; however, it is either not comprehensive or is proprietary (Heatric; Velocys; Brayton Engineering)

20.3.3.9 Design Data Needs and R&D Program

20.3.3.9.1 Introduction

Design Data Needs (DDNs) for the IHX and associated materials can be generally identified with the following categories:

- Material properties data relevant to the selected alloy (presumably either Alloy 617CCA or 230, depending on the high temperature strength and creep requirements for the IHX design). This data would support the materials part of the directed IHX ASME Section III Code Case
- Design methods and design basis information, based on detailed analysis, that would support the design part of the directed Code Case
- Verification of IHX performance and structural adequacy. Fulfillment of this DDN is likely to require testing of prototype IHX units that are procured following detailed discussions and a detailed procurement specification for the IHX design selected (presumably a plate-type HX concept)

IHX/materials DDNs and the R&D efforts to resolve them will be overviewed in this section of the report, based on the assumption that the prior recommendations are implemented and that Alloy 617 CCA or Alloy 230 is selected as the IHX fabrication material. Only a summary plan will be presented because a refined plan is dependent on several factors that will be discussed. A refined R&D plan can only be established following meetings with selected ASME Code experts. If a conventional tube and shell design is selected for the IHX, a design basis in ASME Section VIII, Div 1 has been established. However, ASME Code experts would need to evaluate the applicability of the Section VIII alloys and the specific design basis for the NGNP IHX.

If a plate-type IHX design is selected for the IHX, then the ASME experts would need to recommend the best approach that could used to implement a new design basis that is not currently a part of the ASME Code and recommend laboratory testing that would be needed to support the IHX alloy selected. These steps would only be partially effective until a final decision on IHX design and alloy is made. These decisions are needed before detailed Code planning and laboratory testing can be finalized.

The intent of Task 10 of the DOE/ASME initiative is to initiate these discussions; however, the implementation of Task 10 has been delayed due to funding issues. Prior to the selection of the reactor design and primary component suppliers, the intent of Task 10 is to:

- Determine how and where within ASME codes and standards the IHX and similar components should be addressed
- Address many technical questions to determine how the function of these components affects the plant from an engineering and safety perspective
- Consider all aspects of the potential IHX designs that could be used including materials, design fabrication, examination, testing, overpressure protection and in-service inspections that would be a part of the design or operation of the IHX
- Consider the design and location of the pressure boundary
- Discuss design criteria, including methods for evaluation of cyclic life, construction codes of record and designated pressure boundaries, qualification of materials and fabrication techniques for the intended service and environmental effects

Following the selection of the reactor design and primary component suppliers, the intent of Task 10 is to:

- Perform an evaluation of IHX design approaches with respect to past experience, including scoping analysis to identify critical design configurations and loading conditions
- Recommend changes or additions to current construction codes including ASME Section III, Subsection NB, NC, ND and NH, including their supporting code cases and Section VIII, Div 1 and 2

Therefore, there are two approaches that could be used to address the issues noted:

- Option 1- Jumpstart the process by establishing a study group to perform at least some of the activities noted above in a directed manner based on the actual design and materials decisions that have been made for the IHX and related containment systems

- Option 2 - Fund Task 10 based on ASME cost requirements and proceed down the path with the Task 10 study group, noted above

A primary issue for determining the path to follow is the time requirements for the initiation of final procurement of the IHX and related hardware, which is established as the end of fiscal year 2012. This allows about 6 years for completing this work, submitting a new code case and obtaining ASME approval of the code case. It is estimated that drafting and approval of the code case would take about 3 years after all decisions, additional data generation and analyses have been completed. This leaves about 3 years to finish the study group activities. This seems like a lot of time; however, considering the scope of the activities to be considered, three years is considered marginal. The following recommendations are made:

- It is recommended that Option 1 be implemented with appropriate ASME Code Committee representation and funded by the NGNP conceptual design contractors
- It is recommended that initial discussions in support of Option 1 be held with Bob Jetter (bjetter@sbcglobal.net), Chairman, ASME Section III, Subsection NH and Jim Ramirez (ramirezj@asme.org), ASME Task Group Manager. The purpose of these initial discussions would be to discuss more directed planning of the IHX issue to reduce the time required for the study group, draft a revised statement of intent for the study group and discuss potential Code experts that could be contracted to staff the study group. Based on a personal communication with Jim Ramirez, this appears to be an appropriate path forward.

20.3.3.9.2 Design Data Needs for Materials

Materials-related DDNs comprise those required to support a directed code case for the NGNP IHX material. All relevant Alloy 617 or Alloy 230 (assuming one of these alloys is selected) data should be collected or obtained from sources world-wide and evaluated. The evaluation should center on the quality of the data and whether the data is available in raw form. The data collected should include tensile test data, isochronous test data, low cycle fatigue test data, creep test data, environmental test data in impure He and aging data at various temperatures and times of interest to the IHX. It is recommended that the format established by ORNL for the Generation IV Materials Handbook [Ref. 20.3.3-39] be used. After the data has been collected and analyzed, a detailed R&D program can be established to obtain the missing information for a code case. In general, the R&D program is expected to include some or all of the following elements. For ASME code acceptance the following should be obtained from each of three heats of material.

20.3.3.9.2.1 Thermal Physical & Mechanical Properties DDNs

- Thermal Physical Properties
  - Thermal conductivity
  - Coefficient of thermal expansion
  - Chemical composition
- Mechanical Properties
  - Elastic constants (E, G, υ)

- Tensile stress-strain-time curves in strain control; temperature ranges to be determined per grade/alloy; various strain rates to be determined
- Yield & Ultimate Strength vs. temperature & strain rate; generation of Sy and Su at various temperature up to 1000ºC
- Uniform and total elongation vs. temperature & strain
- Fatigue Strength; Strain control, constant strain rate; LCF, various temperatures; Stress-strain-time history record of tests for cycles; Strain rate effect
- Creep Strength (some tests will continue for up to 100,000 hours and these results will not be a part of the original code case); Constant load or stress; Time to rupture; Strain at rupture; Stress-strain-time data, including behavior upon loading, primary, secondary, and tertiary deformation; generation of St, Sm, Smt at various times and temperatures up to 1000ºC
- Creep-Fatigue Strength; Strain controlled; Constant strain rate (except hold portion); Variation of hold-time effect; Variation of strain rate effect, effect of tensile vs. compressive vs. tension-compression hold; Stress-strain-time history record of tests for cycles at various temperatures up to 1000ºC
- Fracture Toughness at various temperatures up to 1000ºC
- Creep Crack Growth at various temperatures up to 1000ºC
- Fatigue Crack Growth at various temperatures up to 1000ºC

20.3.3.9.2.2 Weldability DDNs

The ability to weld Alloys 617 and 230 without unacceptable loss of strength and corrosion resistance needs to be developed and demonstrated. Adjust and select several weld filler materials to match strength with base metal.

- Fusion weld plate material
- Diffusion bond sheet material
- Conduct short term mechanical properties testing (tensile, creep, Charpy impact) at various temperatures up to 1000ºC on:
  - As-welded material
  - Aged in air (1,000 and 10,000 hours)
  - Aged in impure He (1,000 and 10,000 hours)
- Conduct optical, SEM, and TEM examination of material to evaluate microstructure, strength, and failure modes
  - Evaluate effect of grain size on above

20.3.3.9.2.3 Aging of Ni-based Alloys DDNs

- Aging effects on the short and long term properties at various temperatures up to 1000ºC
  - Short term properties: tensile, Charpy impact, hardness
  - Long term properties: fatigue, creep, creep-fatigue
  - Microstructural stability & evaluation

20.3.3.9.2.4 Exposure to Impure He at Elevated Temperatures up to 1000ºC DDNs

- Corrosion effects on the short and long term properties
- Short term properties: tensile, Charpy impact
- Long term properties: fatigue, creep, creep-fatigue
- Microstructural stability & evaluation

20.3.3.9.2.5 Grain Size Effects DDNs

It is important to identify the creep deformation mechanism that dominates at the low stress levels and long lifetimes of the IHX. An initial testing plan would involve a series of applied stresses that are likely to produce creep strains in each of the deformation mechanism regimes noted in Figure 20.3.3-27 and Figure 20.3.3-28 [Ref. 20.3.3-17].

These figures show possible test points for Alloy 617 at 850ºC and 950ºC; tests on Alloy 230 would be similar. In each case, three stresses are selected on each side of the mechanism transition point for material with a nominal grain size of 100 microns (solid squares). The lower stresses will likely produce creep rates consistent with Nabarro Herring creep while the higher stresses will be dominated by power law creep. By plotting the measured creep rates on a log-log scale (as seen in the figures) it is expected that the transition point will be easily identified as a change in slope between the two regimes. Tests at 900ºC would also be needed. By plotting lines of constant stress as a function of times and temperature, it will be possible to derive parameters for common creep extrapolation techniques. Separate parameters will be derived for each deformation mechanism, giving a physical basis for the extrapolation that is related to the material microstructure. These procedures may need to be varied to produce the desired results.

20.3.3.9.3 Design Basis Information DDNs

The data obtained from laboratory testing or prior data generation will be used to generate specific code-related information. It is assumed that a detailed finite element analysis (FEA) of the IHX will be required to obtain a portion of the design basis information. Further development of analysis methods may be required to support such an analysis. The remaining information for the code case will be obtained from existing design equations and models developed for the plate type IHX (if selected). If a tube and shell IHX is selected, it is assumed that only minimal design basis information (except that derived from lab testing on the alloy selected) will be required because of the existing design basis contained in ASME Section VIII; however, without further discussions (as noted previously) it is not totally clear if this design basis will be directly applicable for an ASME Section III code case.

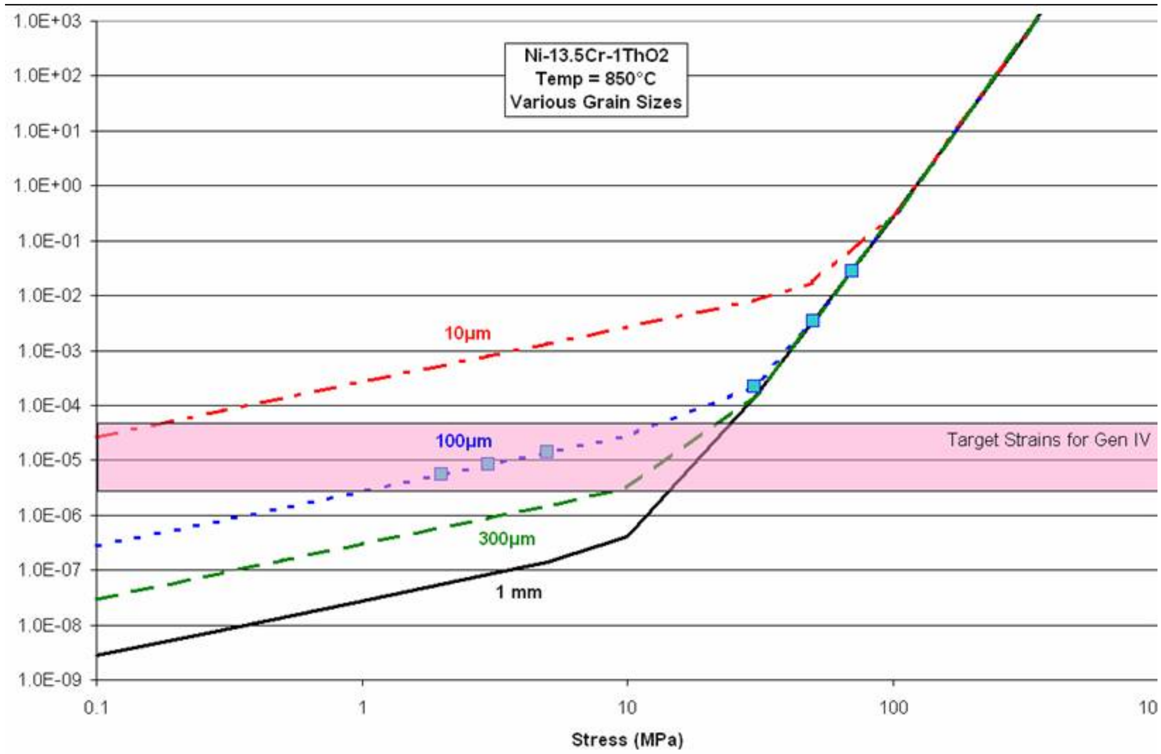


Figure 20.3.3-27 Planned Test Points for Alloy 617 at 850ºC

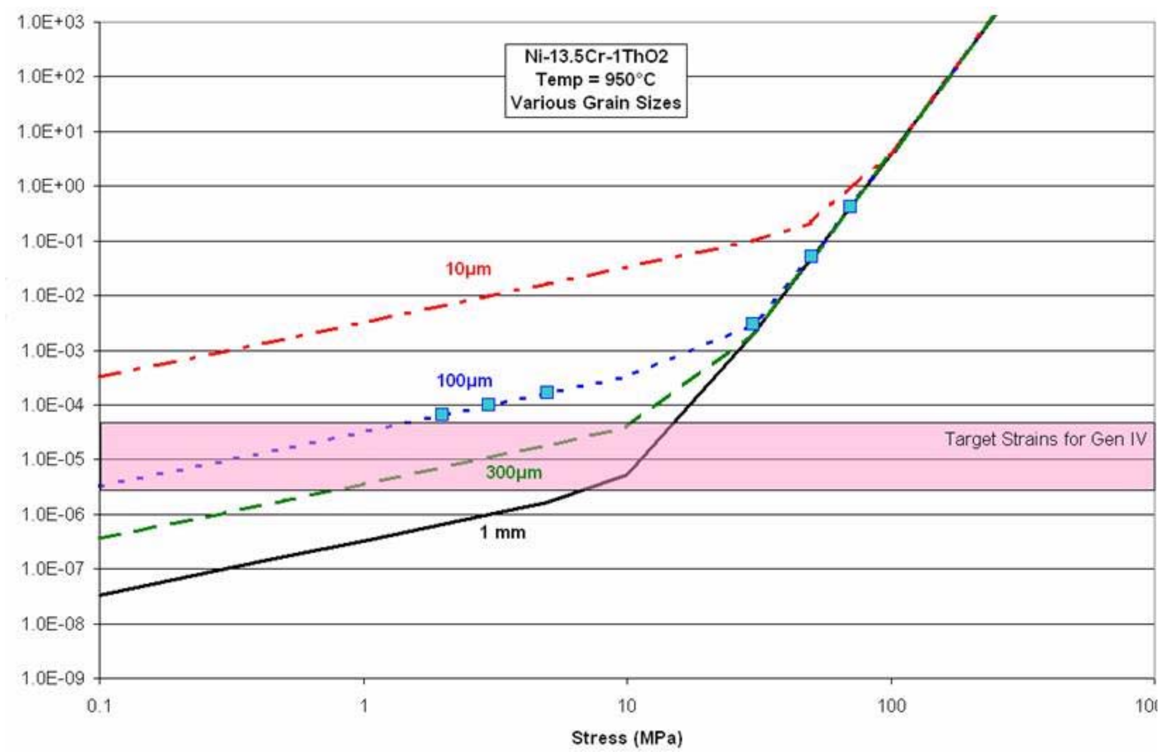


Figure 20.3.3-28 Planned Test Points for Alloy 617 at 950ºC

20.3.3.9.4 IHX Performance Verification DDNs

The development of directed materials and design code cases for the IHX is expected to require the verification of both performance and structural adequacy. Assuming selection of the recommended plate-type IHX, the required verification is expected to require experimental testing under various conditions expected in the NGNP. The objectives of the tests would be to validate models that are developed, to thoroughly understand the performance characteristics of these units under operational conditions and to establish models that will produce a reasonable estimate of unit life.

Tests could be performed in any facility suitable for this purpose; a preliminary test plan has been developed [Ref. 20.3.3-40]. The proposed IHX tests are based on the procedures and methodologies employed for military gas turbine recuperators, such as the advanced WR-21 engine developed by the U.S. and UK navies, and include stress and life model validation, durability testing, performance validation and materials testing. Four principal test objective categories are given below:

- IHX stress and life prediction model validation tests - accurate predictions of thermal profile throughout the core and structure, assures accuracy of the FEA stress maps
- IHX durability testing - the simulation of anticipated NGNP maneuvers, faults and failure modes
- IHX performance testing - steady state validation of thermal effectiveness and pressure loss
- Materials studies - evaluate long term exposure issues associated with He exposure, corrosion, velocity effects, erosion

20.3.3.10 Implications for the NGNP Pre-conceptual Design

The IHX is a key component for the NGNP, particularly if an indirect cycle configuration is used. Potential alloys that could be used to construct the IHX are not currently a part of the ASME Section III (nuclear code). A great deal of effort will be required to resolve this issue, because a reliable database potentially useful for a code case based on three well documented heats of material is not currently available for the alloys of interest. There is no existing ASME Section III design basis for either a conventional tube-and-shell or less-conventional plate type IHX. The approach to resolve this issue for the conventional IHX will not be clear until this issue is debated within the ASME. The resolution of utilizing a less conventional IHX design (which appears to have significant advantages for this application) appears to be the development of a formal design basis and submittal of a Section III code case associated with Subsection NH. A significant amount of effort will also be required to resolve this issue, because an openly available design basis is not currently available in a format suitable for a code case. Testing of prototype IHX units, if a plate type IHX is selected, is a prudent action that needs to be performed in support of the code case design basis for the specific IHX design selected. Testing should be performed on prototype units fabricated from both the metallic alloy selected and one or more ceramics that may have long term application for the IHX.

20.3.3.11 Final Conclusions and Recommendations

The following IHX-related recommendations, which are derived from the ITRG review of the NGNP, have been confirmed by the present assessment, except as noted:

- The reactor outlet temperature for the NGNP should not exceed 950ºC, based in part on IHX materials considerations.
- As a result of this assessment, it is concluded that non-replaceable metallic components designed for the full plant lifetime (60 years) should be limited to ~850ºC versus 900ºC, as recommended by the ITRG. Metallic components operating at temperatures higher than ~850ºC, notably including high-temperature sections of the IHX, are likely to have reduced lifetimes and should be designed for replacement.
- Time-dependent deformation for Class 1 pressure boundary components should be "insignificant", as defined by the ASME Code.
- The IHX should be designed to minimize stresses imposed on the metallic alloy due to the low margin of allowable creep stress associated with available metallic alloys operating in the 900-950ºC temperature range
- Metallic materials should be limited to alloys listed in ASME Section II for Section III or Section VIII service.

Tube-and-shell IHXs are evaluated to be economically infeasible for commercial HTGR process heat applications, due to their size and cost. On this basis, the NGNP IHX should be a compact design. Among the compact heat exchangers, plate-type HXs, such as the Heatric Printed Circuit Heat Exchanger (PCHE), are evaluated to be more robust than plate-fin and/or primary surface concepts. It is, therefore, recommended that a plate-type HX development program should be pursued for the NGNP IHX in conjunction with an appropriate design and materials development program. Creep will need to be carefully considered for any IHX design (not previously a part of nuclear construction in the US). In this regard, the IHX should be enclosed within a Class 1 pressure boundary that operates at temperatures below which creep becomes significant.

While ceramic materials hold significant future promise, their selection for the initial NGNP IHX would pose an unacceptable risk to the NGNP schedule. Nevertheless, their potential for resolving the high-temperature issues associated with metals justifies an aggressive parallel development path. The primary issues associated with a ceramic IHX are very high cost, lack of standardization, lack of ASME Code acceptance, lack of a design basis, lack of availability within existing industry and the scale-up requirements for the NGNP application.

A variety of Heat Transport System (HTS) configurations are possible, based around direct or indirect cycle architectures. The procurement cost for the IHX would be much greater for an indirect cycle compared to a direct cycle system. Note that a plate-type IHX would consist of multiple modules connected in series and/or parallel. For large IHXs, such as would be used in indirect cycle architectures, this suggests consideration of a 2-Section IHX concept

(Figure 20.3.3-29) in which the sections operating at the highest temperatures are separated from those operating at lower temperatures. The lower temperature sections would be designed as lifetime components, whereas the higher temperature sections would be designed to be replaceable, perhaps with a ceramic heat exchanger, when available. The impact of transients would have to be assessed for such designs.

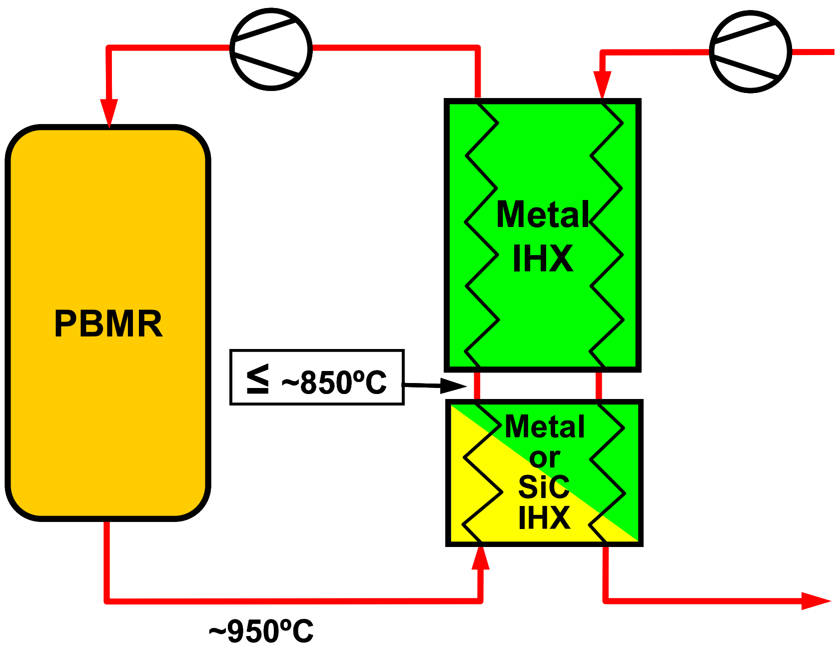


Figure 20.3.3-29 2-Section IHX Concept

The primary factors that have the most impact on the selection of metallic alloys for construction of the IHX include the following:

- ASME Code acceptance (Section III preferably or alternatively Section VIII)
- Adequate data base for the temperature region of the IHX
- The data base must include mechanical properties of small grain size samples and diffusion bonds if a plate type heat exchanger (HX) is selected
- The metallic alloy selected must be able to be easily welded and diffusion bonded (plate type HX)
- The metallic alloy selected must be formable, machinable or etchable if a plate type HX is selected
- The metallic alloy selected must have adequate creep rupture and mechanical properties in the region of 850-950C
- The metallic alloy selected must be commercially available in large quantities
- The metallic alloy selected must be available in multiple forms such as plate, tubing, forgings, etc
- The metallic alloy selected must be fabricable into thin sheets if a plate type HX is used

- The metallic alloy selected must have reasonably stable properties during exposure to high temperatures for long time periods (thermal ageing)
- The metallic alloy selected must be able to resist the corrosion effects of an impure He environment at high temperature
- The metallic alloy selected must have reasonably stable and predictable mechanical and corrosion properties and microstructure over multiple heats within the ASTM/ASME chemical specification range (or for a modified specification) for the alloy
- The metallic alloy selected should be a part of an ASME Code basis for the design of the HX

The Japanese used a conventional tube and shell IHX constructed of Hastelloy XR for the HTTR IHX. This is the most recent actual experience for a VHTR IHX. There are potentially a large number of very high temperature alloys that could be used for IHX construction; however, most are not ASME code materials or mature materials that have been used for multiple applications over many years. Alloys 617 or 230 are recommended for IHX construction depending on the stress and creep requirements of the design. Alloy 617 has been shown to have significant heat to heat variations in properties in the past and the specification for the alloy has been refined in the USC program to mitigate this issue. Ageing, particularly in the 700-750ºC range, can reduce some mechanical properties of either alloy. Long term exposure to impure He can cause corrosion to either alloy; however, it is believed that this can be controlled by an appropriate use of a He purification system. Grain size of these materials can affect high temperature properties and needs to be carefully considered.

Subsection NH is fundamentally sound, very conservative in several areas, has not been either accepted or rejected by the NRC, does not contain a good high temperature creep model for alloys such as 617, contains very limited materials not useful for the IHX and limits temperature to 760ºC. It is unclear how a new IHX code case would affect Subsection NH. It is recommended that the draft Alloy 617 code case submitted in 1992 not be revised. A new Section III code case should be submitted that is specific for the NGNP IHX.

ASME Section VIII contains materials useful for the design of the IHX, has a design basis for a tube and shell IHX and allows exposure temperatures up to 980ºC; however, this code is only applicable for non-nuclear applications. The approach that will be taken in the future by ASME to deal with the IHX issue is currently somewhat unclear. There is currently an initiative to address ASME issues regarding the NGNP; however, the IHX issue has not been addressed to date due to funding constraints.

The following additional recommendations are made:

- It is recommended that an R&D program be performed to obtain adequate test data to support the code case for the IHX alloy selected
- It is recommended that one or more small (100-200kW) prototype plate type HX units be procured for testing
- It is recommended that detailed finite element analysis be performed on a plate type HX grid for use as a design and evaluation tool

- It is recommended that an alternate approach (separate from DOE/ASME Task 10) be implemented with appropriate ASME Code Committee representation and funded by the NGNP conceptual design contractors
- It is recommended that initial discussions in support of the alternate approach be held with Bob Jetter (bjetter@sbcglobal.net), Chairman, ASME Section III, Subsection NH and Jim Ramirez (ramirezj@asme.org), ASME Task Group Manager and other experts as appropriate

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20.3.4 HTS CONFIGURATION OPTIONS

In this section, the Heat Transport System (HTS) configurations that were evaluated as candidates for the NGNP preconceptual design are identified and described. As shown in Figure 20.3.4-1, the HTS options can be generally categorized in terms of the integration of the Power Conversion System (PCS) relative to the primary coolant circuit and the process coupling.

In the direct PCS configuration options, the power conversion turbomachinery is located directly within the primary helium loop. In the indirect PCS configuration options, the power conversion turbomachinery is isolated from the primary circuit by an intermediate heat exchanger (IHX). Indirect PCS configuration options are further categorized by whether the PCS is independently coupled to the secondary heat transport system (SHTS) circuit or integrated with the process itself. In the latter, all or part of the PCS coupling is located in the process streams beyond the process coupling heat exchanger (PCHX).

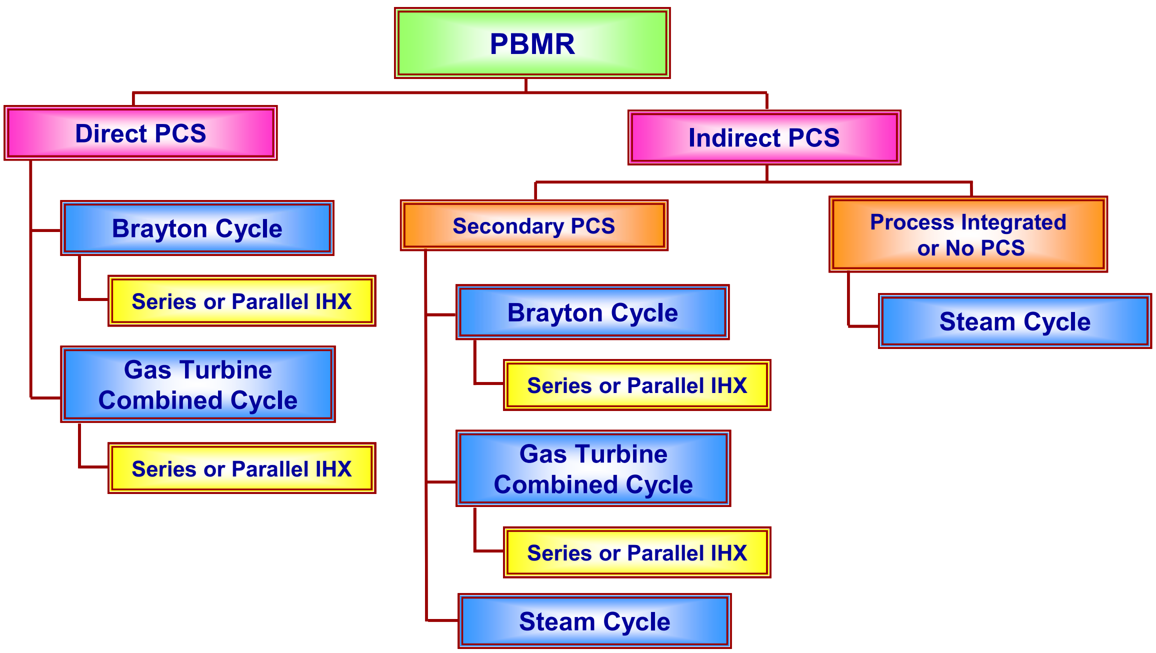

Figure 20.3.4-1 Process Heat/PCS Configuration Hierarchy

20.3.4.1 Direct Cycle PCS Options

In these direct cycle options, the PCS turbomachinery is located directly within the primary helium circuit. Helium circulation is provided by the gas turbine compressor.

20.3.4.1.1 Option 1: Primary Brayton Cycle/GTCC, Series IHX

In Option 1 (Figure 20.3.4-2, Table 20.3.4-1), thermal energy produced in the reactor is transferred to the SHTS and thence transported to the Hydrogen Production Unit (HPU) via a relatively small IHX that serves as a topping process to a direct Brayton cycle or, alternatively, to a Gas

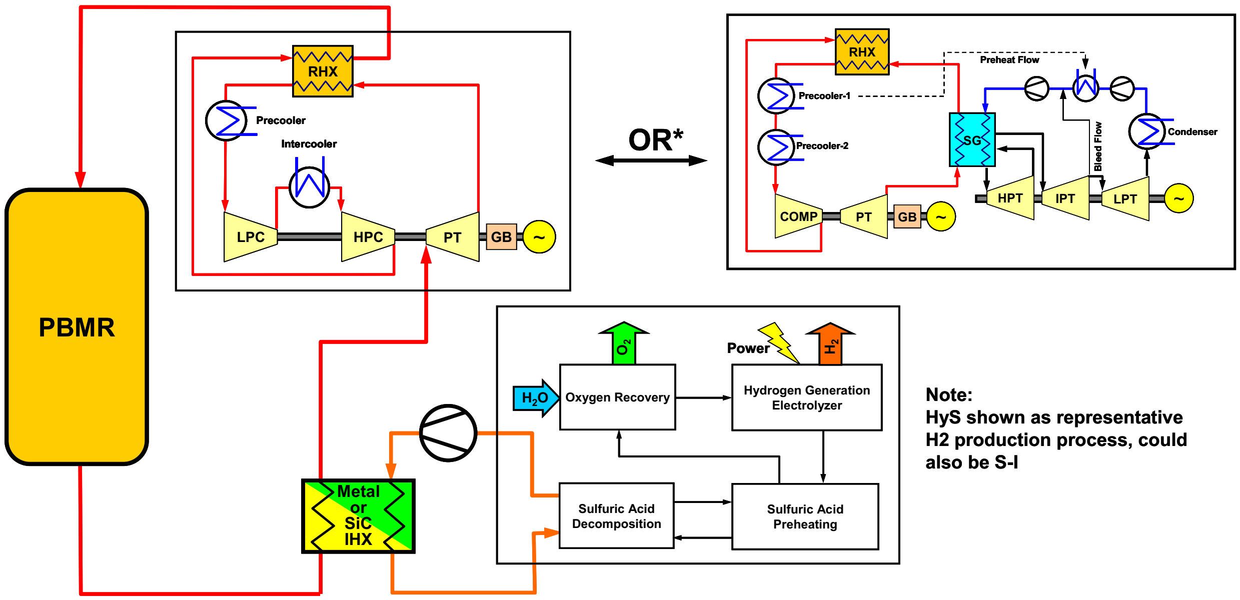

Figure 20.3.4-2 Option 1: Primary Brayton Cycle/GTCC, Series IHX

Table 20.3.4-1 Option 1: Primary Brayton Cycle/GTCC, Series IHX

Key Features • Small (≤ ~80MWt) topping IHX ➢ Designed for easy replacement, but more difficult than parallel (Option 2) ➢ Option to use liquid salt SHTS working fluid ➢ Option to operate without IHX • Direct Brayton or GTCC bottoming cycle ➢ Option to use 900ºC DPP PCS **Readiness** • Brayton cycle/GTCC based on DPP ➢ No R&D at 900ºC or modest R&D to 950ºC • Option to operate PCS without IHX installed • Significant primary/ secondary flow mismatch ➢ Primary side of IHX must be designed for full flow (potential issues with bypass/hot streaks) ➢ SHTS circulator temperature an issue **Support of Commercial Applications** • Low NHS commonality with commercial PHP ➢ May be inadequate as prototype for design certification of PHP commercial plants • GTCC variant supports deployment of AEP	**Performance** • Single PHTS flow path avoids operational issues with remixing of separate flows (Option 2) • PCS provides alternate heat sink (coolers) for off-normal events • Pressure transients associated with Brayton cycle transients must be considered **Cost** • Capital ➢ Along with Options 2 and 5, among lowest capital cost options ➢ Small IHX implies modest replacement capital cost • Operating ➢ Potential for good efficiency, high availability to maximize cost offsets via electric sales ➢ PCS maintenance higher with direct cycle

Turbine Combined Cycle (GTCC). The choice of a direct Brayton cycle or GTCC is a matter for further optimization, if required. The specific selection would be based on trade-offs between performance and cost, so as to optimize overall economics.

With Option 1, the size of the IHX would be limited by the performance characteristics of the Brayton cycle, which is very sensitive to turbine inlet temperature (TIT) (for details, see the PCS special study [Ref. 20.3.4-1]). At an IHX rating of 42 MW, the TIT would be close to that of the PBMR Demonstration Power Plant (DPP) (900ºC). At an IHX rating of 50 MW, the TIT would drop to ~890ºC.

With this configuration, the IHX may be designed for relatively easy removal and replacement. Operation without the IHX being installed is also a possibility. Note that, if the IHX is not installed, or the HPU is not in operation, the TIT would increase if the reactor is operated full capacity. For TITs above 900ºC, some turbine-related R&D may be required.

Since, in this configuration, all of the primary helium flow would be directed through the primary side of the IHX, there would be a significant primary/secondary flow mismatch. This factor leads to potential issues with bypass and/or hot streaks and tends to reduce commonality between the NGNP IHX and the corresponding commercial unit. Unless separate provisions for cooling are provided, the temperature of the helium returning to the IHX on the SHTS side would be relatively high. This would be a potential issue for the secondary circulator.

Option 1 would have relatively low commonality with commercial PBMR PHP applications, in which all of the thermal energy from the reactor is transferred via the IHX to the SHTS. While the anticipated modular nature of the IHX (assumed to be a compact heat exchanger) may allow technical extrapolations, it is questionable whether Option 1 would be sufficiently prototypical to support design certification of PBMR PHP commercial plants.

In terms of performance, the single primary system flow path avoids operational concerns with remixing of separate flows, an issue that will be seen with Option 2. The coolers which are located within the PCS can provide a heat sink for decay heat removal in the event of off-normal events. A significant issue with Brayton cycles is the pressure variations that would occur within the primary system during normal power maneuvering (inventory control) and upon collapse of the pressure ratio when the turbo-compressor unit is tripped. These events would impose significant pressure differentials relative to the SHTS, and represent an additional issue for metallic IHXs, for which pressure balanced operation will almost certainly be required.

Option 1, as well as Option 2, incorporate the least amount of PCS equipment and would, therefore, be among the lowest capital cost options. The relatively high efficiency of the direct Brayton cycle, along with the low parts count, which should be reflected in increased availability, are expected to maximize cost offsets via electric sales. Due to the potential for radionuclide contamination, PCS maintenance costs are expected to be higher.

20.3.4.1.2 Option 2: Primary Brayton Cycle/GTCC, Parallel IHX

Option 2 (Figure 20.3.4-3, Table 20.3.4-2) is similar to Option 1, except that the IHX is placed in parallel with the PCS. As with Option 1, the IHX will be relatively small. In this case, the size of the IHX is limited by process temperature requirements and the effects of reduced volumetric flow in the Brayton cycle, rather than by reduced TIT. Due both to its small size and parallel architecture, removal and replacement of the IHX should be relatively easy with this configuration.

In this parallel arrangement, the direct Brayton cycle will, by necessity, operate at 950ºC. This increased TIT will require a modest R&D effort in support of the turbomachinery, relative to the DPP. Branching of the reactor outlet helium flow introduces additional design requirements on the gas ducting and liner systems. Also with the parallel flow arrangement, provisions will be needed to remix the parallel streams that are potentially at different temperatures. A trim heat exchanger is conceptually shown in Figure 20.3.4-3 for that purpose.

Option 2 adds a primary helium circulator. Flow control between the two parallel branches requires integrated control of the turbine-generator and the circulator.

As is the case with Option 1, lack of commonality with commercial PBMR PHP designs raises concerns with respect to support of licensing and design certification of commercial applications.

Other characteristics of Option 2 are similar to Option 1.

20.3.4.2 Indirect Cycle PCS Options

In these indirect cycle PCS options, the PCS is independent of the process and is either located within or coupled to a secondary circuit. Primary helium circulation is provided by a motor driven gas circulator. In the case of the Brayton and GTCC options, the Brayton section of the PCS turbomachinery operates within the SHTS. In the case of Rankine cycles, the steam generator is placed either within the primary helium or SHTS circuit.

20.3.4.2.1 Option 3: Secondary Brayton Cycle/GTCC, Series PCHX

In Option 3 (Figure 20.3.4-4, Table 20.3.4-3), all of the thermal energy produced in the reactor is transferred to the SHTS via the IHX. Within the SHTS, the PCHX and PCS are placed in a series arrangement, and are likely to become located to minimize the extent of high temperature piping. As with Option 1, the size of the IHX is limited by efficiency impacts on the PCS that are associated with reduced TIT. In this case, the impacts are more significant, since the maximum temperature available within the SHTS is 900ºC. This tends to make selection of the GTCC alternative more likely to improve efficiency.

In this and similar configurations, the IHX represents the most significant challenge to readiness in terms of meeting the NGNP objectives within the reference schedule. On the other hand, this and similar indirect cycle configurations provide maximum commonality with

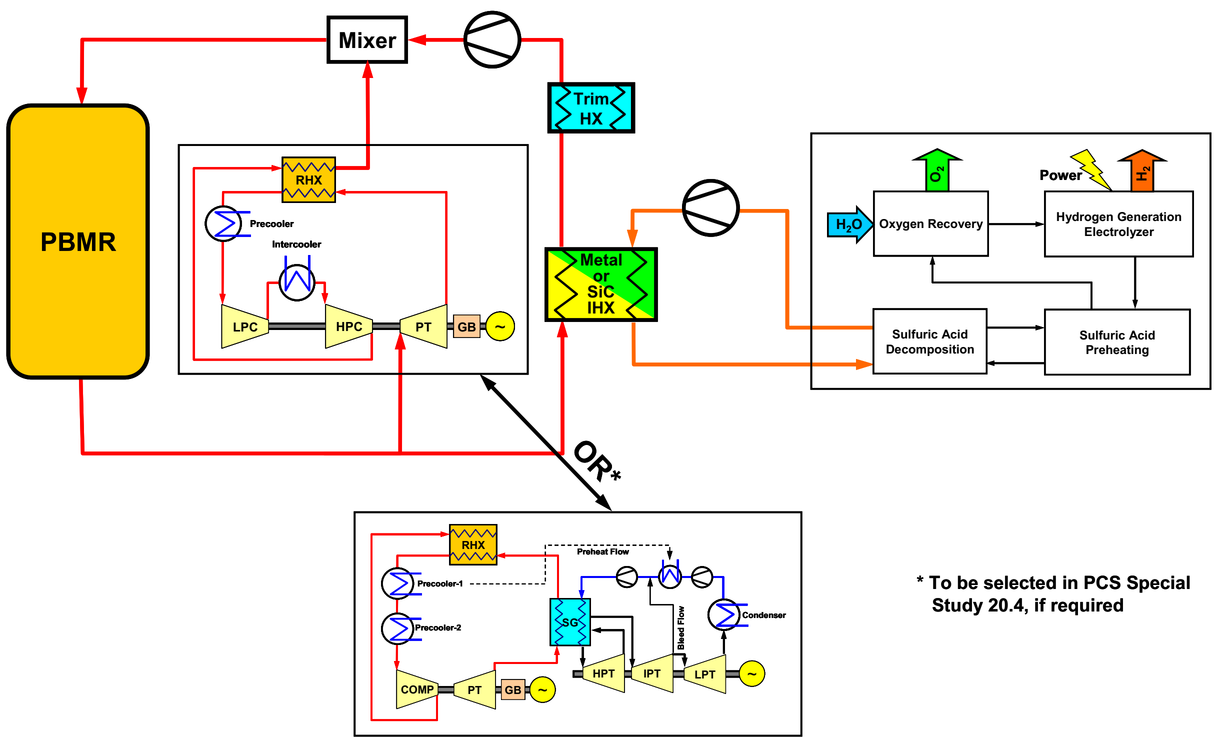

Figure 20.3.4-3 Option 2: Primary Brayton Cycle/GTCC, Parallel IHX

Table 20.3.4-2 Option 2: Primary Brayton Cycle/GTCC, Parallel IHX

<u>Key Features</u> • Small (≤ ~50MWt) parallel IHX ➢ Designed for easy replacement (easiest) ➢ Option to operate without IHX • Direct Brayton cycle or GTCC ➢ Requires 950ºC design basis **<u>Readiness</u>** • Brayton cycle/GTCC extrapolated from DPP ➢ Modest R&D at 950ºC • Option to operate PCS without IHX installed ➢ Facilitated by smaller, parallel PHTS piping • Requires provisions to control parallel flows, remix parallel streams that are potentially at different temperatures **<u>Support of Commercial Applications</u>** • Low NHS commonality with commercial PHP ➢ May be inadequate as prototype for design certification of PHP commercial plants • GTCC variant supports deployment of AEP	**<u>Performance</u>** • Parallel PHTS flow paths imply operational issues with remixing • PCS provides alternate heat sink (coolers) for off-normal events • Pressure transients associated with Brayton cycle transients must be considered **<u>Cost</u>** • Capital ➢ Along with Options 1 and 5, among lowest capital cost options ➢ Small IHX implies modest replacement capital cost • Operating ➢ Potential for good efficiency, good availability to maximize cost offsets via electric sales ➢ PCS maintenance higher with direct cycle

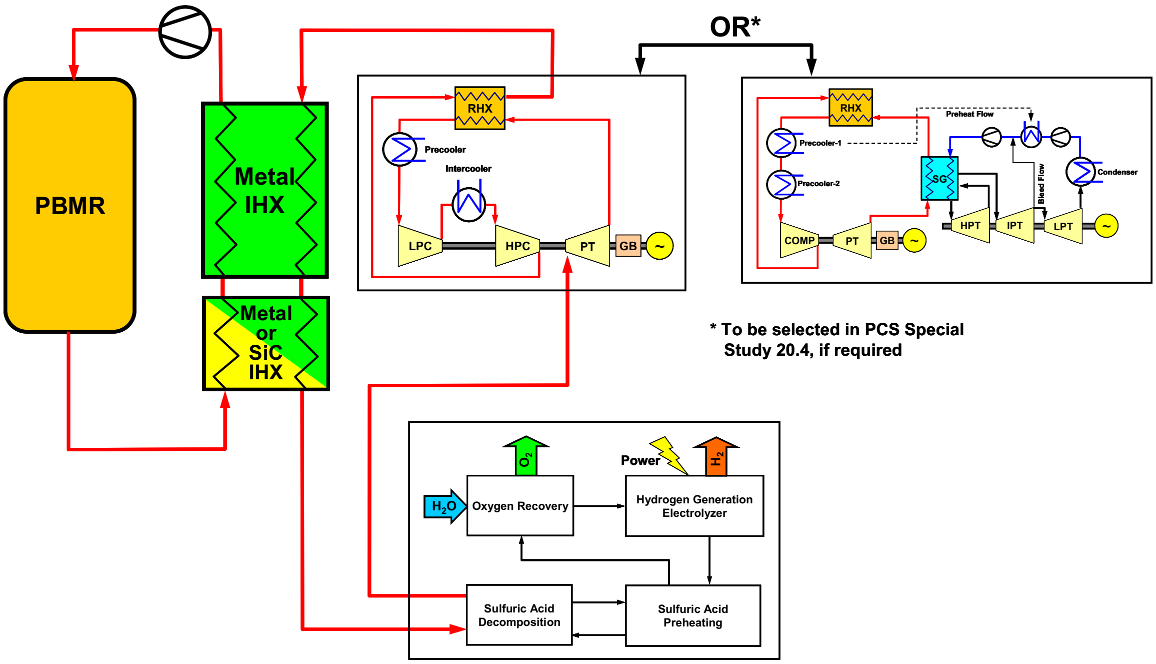

Figure 20.3.4-4 Option 3: Secondary Brayton Cycle/GTCC, Series PCHX

Table 20.3.4-3 Option 3: Secondary Brayton Cycle/GTCC, Series PCHX

Key Features
• Full-size IHX transfers all reactor heat to SHTS
• Small (≤ ~50MWt) PCHX as topping cycle
• Brayton cycle or GTCC bottoming cycle
  ➢ 850ºC PCS design basis
• PCHX/PCS likely need to be co-located
Readiness
• Brayton cycle/GTCC extrapolated from DPP
  ➢ No R&D to 900ºC
• Option to operate PCS without PCHX installed
• Large IHX poses greatest challenge to readiness
Support of Commercial Applications
• High NHS commonality with commercial PHP
  ➢ If successful, resolves IHX issue for commercial plants
  ➢ Adequate prototype for design certification of PHP commercial plants
• GTCC variant supports deployment of AEP
	Performance
	• PCS provides alternate heat sink (coolers) for off-normal events
	  ➢ Requires operational PHTS
	• Pressure transients associated with Brayton cycle transients must be considered
	• Significant availability risk associated with potential for IHX leaks
	Cost
	• Capital
	  ➢ High capital cost relative to direct PCS options
	  ➢ Large IHX implies potential for high replacement capital costs
	    – May be mitigated by selection of ceramic material and/or split section design
	• Operating
	  ➢ Lower efficiency, availability risk may reduce cost offsets via electric sales
	  ➢ Maintenance costs involve tradeoff of IHX/circulator vs. PCS

commercial PBMR PHP plants, and will provide an ideal basis for resolving both technical and licensing barriers to their deployment. In particular, Option 3, and similar options, will provide an adequate basis for design certification of PBMR PHP commercial plants.

As suggested in the IHX/materials readiness assessment (Section 20.3.3), it is proposed that the IHX be structured within two major sections. The highest temperature section would be designed for ease of replacement, while the lower temperature section, defined as being within the capability of current metallic materials, would be a plant lifetime component. In concept, the high temperature section could be replaced with a ceramic IHX section when available.

Analogous to Option 1, the entirety of the SHTS flow is routed through the PCHX to the PCS. This will result in a mismatch of flow between the SHTS and process sides of the PCHX.

In terms of performance, the PCS coolers provide a heat sink for removal of decay heat when the normal combined HPU and PCS heat transport paths are unavailable. However in indirect cycle configurations, such as Option 3, operation of the primary heat transport system (PHTS) is required. With the Brayton cycle located in the SHTS, pressure transients associated with both normal and off normal operations must be taken into account in the design of the IHX. Since the IHX must be installed and functional to operate the plant, the IHX represents a significant risk to overall plant availability. In concept, this risk can be mitigated somewhat by the potential to remove the high temperature IHX section and operate the plant at lower reactor outlet temperature.

Both initial capital and replacement costs are expected to be higher with the indirect cycle architecture. Moving the PCS to the SHTS will also impact efficiency, and thus reduce cost offsets via electric sales. Maintenance costs would involve a trade-off between the IHX and circulator of the indirect cycles vs. the PCS of the direct cycles.

20.3.4.2.2 Option 4: Secondary Brayton Cycle/GTCC, Parallel PCHX

In Option 4 (Figure 20.3.4-5, Table 20.3.4-4), the PCHX is placed in parallel with the Brayton section of the PCS within the SHTS. Since the PCS operates at higher temperature, its efficiency would be improved relative to Option 3. As with Option 2, the size of the IHX is limited by process temperature requirements and volumetric flow influences on the parallel Brayton cycle. With the parallel arrangement, the flow rates through the SHTS and process sides of the PCHX can be matched at the module level, allowing the PCHX to be more nearly representative of commercial PBMR PHP applications.

Other attributes of Option 4 are similar to those of Option 3.

20.3.4.2.3 Option 5: Bottoming Steam Cycle, Series IHX

In Option 5 (Figure 20.3.4-6, Table 20.3.4-5), thermal energy from the reactor is routed to a small-to medium-size IHX, which serves as a topping process to a bottoming steam generator, both located within the primary helium circuit. Helium circulation in the PHTS is provided by a gas circulator. As in Options 1 and 2, the design of the IHX is intended to

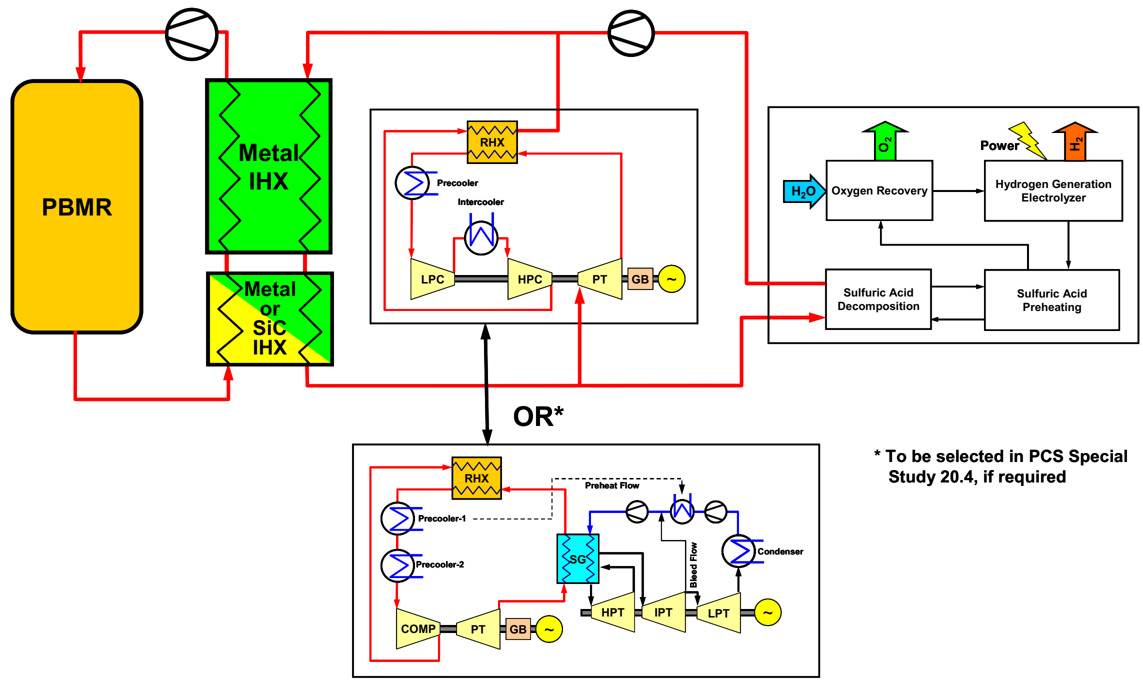

Figure 20.3.4-5 Option 4: Secondary Brayton Cycle/GTCC, Parallel PCHX

Table 20.3.4-4 Option 4: Secondary Brayton Cycle/GTCC, Parallel PCHX

Key Features • Full-size IHX transfers all reactor heat to SHTS • Small (≤ ~50MWt) parallel PCHX • Brayton or GTCC cycle ➢ Requires 900ºC design basis • PCHX/PCS likely to be co-located **Readiness** • Brayton cycle/GTCC extrapolated from DPP ➢ No R&D at 900ºC • Option to operate PCS without PCHX installed • Large IHX poses greatest challenge to readiness • Requires provisions to control parallel flows, remix parallel streams that are potentially at different temperatures **Support of Commercial Applications** • High NHS commonality with commercial PHP ➢ If successful, resolves IHX issue for commercial plants ➢ Adequate prototype for design certification of PHP commercial plants • GTCC variant supports deployment of AEP	**Performance** • PCS provides alternate heat sink (coolers) for off-normal events ➢ Requires operational PHTS • Parallel PHTS flow paths imply operational issues with remixing • Significant availability risk associated with potential for IHX leaks • Pressure transients associated with Brayton cycle transients must be considered **Cost** • Capital ➢ Higher capital cost relative to direct PCS options ➢ Large IHX implies potential for high replacement capital costs – May be mitigated by selection of ceramic material and/or split section design • Operating ➢ Lower efficiency, availability risk may reduce cost offsets via electric sales ➢ Maintenance costs involve tradeoff of IHX/circulator vs. PCS

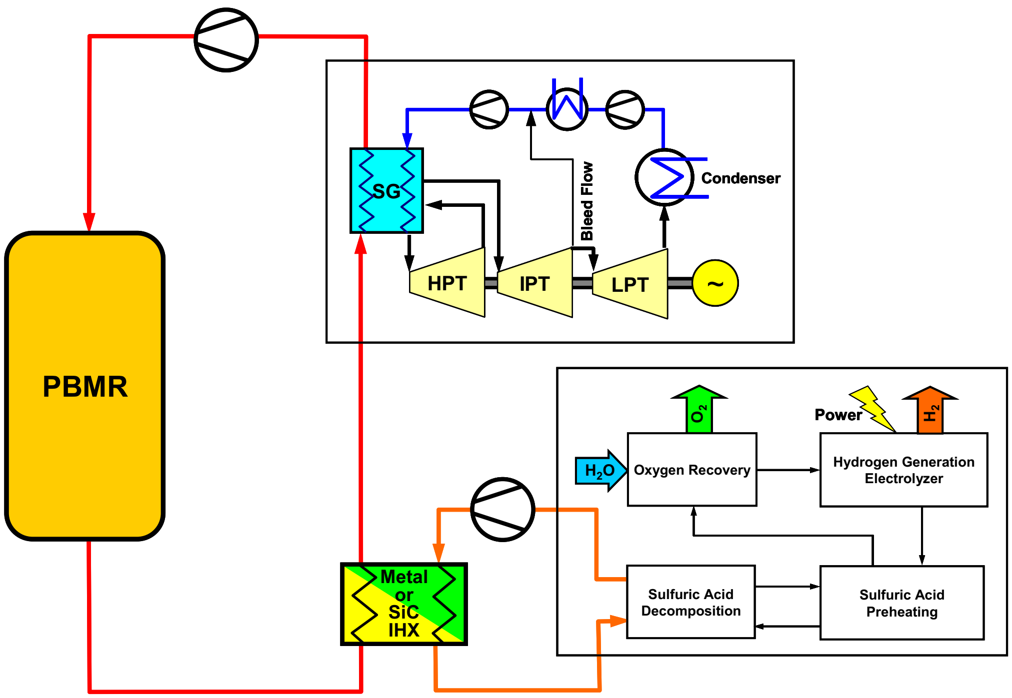

Figure 20.3.4-6 Option 5: Bottoming Steam Cycle, Series IHX

facilitate easy replacement and the potential to operate the PCS without the IHX in place. Since all of the primary helium flow is routed through the IHX, there is, as with Option 1, a mismatch in flow relative to the secondary side of the IHX.

A key advantage of the bottoming Rankine cycle is the flexibility to apply a larger fraction of the reactor thermal output to the HPU (up to ~200 MW), without significantly impacting the efficiency of the PCS (this advantage is further elaborated in the discussion related to Option 6). In prior HTGR applications, steam generators have been operated for extensive periods with reactor outlet temperatures up to 950ºC.

While there is a potential to demonstrate the HPU at larger scale than is possible with other options already described, there is low commonality with the commercial PBMR PHP nuclear heat source. For this reason, Option 5 is unlikely to represent an adequate prototype for licensing and design certification of commercial PBMR PHP plants.

In terms of performance, steam provided to the PCS is at temperatures and pressures consistent with modern steam plants, with efficiencies projected to exceed 40%. As already noted, the Rankine cycle is less sensitive to thermal inputs than the corresponding Brayton cycles. The condenser of the steam cycle can serve as an alternate heat sink for decay heat removal, provided that the PHTS is functional. With the steam generator located in the primary loop, the potential for water ingress must be considered as part of the design and licensing process. There are no SHTS pressure transients associated with the Rankine cycle.

Table 20.3.4-5 Option 5: Bottoming Steam Cycle, Series IHX

Key Features
• Small to medium (Up to ~200MWt) topping IHX
  ➢ Option to use liquid salt SHTS working fluid
  ➢ Option to operate without IHX
• Bottoming steam generator
  ➢ 700ºC-950ºC design basis, nominal depends on IHX rating
Readiness
• Conventional steam cycle, with steam generator based on earlier HTGRs → no R&D
• Option to operate steam cycle without IHX installed
• Significant mismatch between primary/ secondary flows
  ➢ Primary side of IHX must be designed for full flow (potential issues with bypass/hot streaks)
  ➢ Mismatch decreases as IHX power increases
  ➢ SHTS circulator temperature an issue
Support of Commercial Applications
• Larger engineering scale demonstrations of HyS/S-I feasible (up to ~100+ MWt)
  ➢ Possibly even larger with reductions of SC efficiency. Low NHS commonality with commercial HyS/SI
• Low NHS commonality with commercial PHP
  ➢ May be inadequate as prototype for design certification of PHP commercial plants
	Performance
	• PCS temperatures consistent with modern steam conditions
	  ➢ Steam cycle not as sensitive to thermal rating as GT cycles
	• Steam cycle provides alternate heat sink (coolers) for off-normal events
	  ➢ Requires operational PHTS
	• Potential for water ingress must be considered
	Cost
	• Capital
	  ➢ Along with Options 1 and 2, among the lowest capital cost options
	  ➢ Small IHX implies modest replacement capital cost
	• Operating
	  ➢ Potential for reasonable efficiency, high availability to maximize cost offsets via electric sales
	  ➢ PCS maintenance conventional

Option 5, along with Options 1 and 2, is among the lowest capital costs options. It offers reasonably good efficiency and the prospect for high availability, in enhancing the potential for cost offsets via electric sales. PCS maintenance would be conventional. As further discussed in conjunction with Option 6, there is also a potential for long-term conversion of the NGNP to commercial hydrogen production, after its demonstration mission has been completed.

20.3.4.2.4 Option 6: Secondary Steam Cycle, Series PCHX

In Option 6 (Figure 20.3.4-7, Table 20.3.4-6), all of the reactor thermal energy is transferred to the SHTS via the IHX. Within the SHTS, high temperature helium is first directed to the PCHX and, thence, to a bottoming steam cycle. Helium is circulated within the PHTS by a gas circulator. As with Options 3 and 4, it is proposed that the IHX be structured within two sections, a high-temperature section designed for easy replacement and a lower temperature section designed as a lifetime component. There is a potential to operate the plant at lower reactor outlet temperatures without the high temperature section of the IHX being installed.

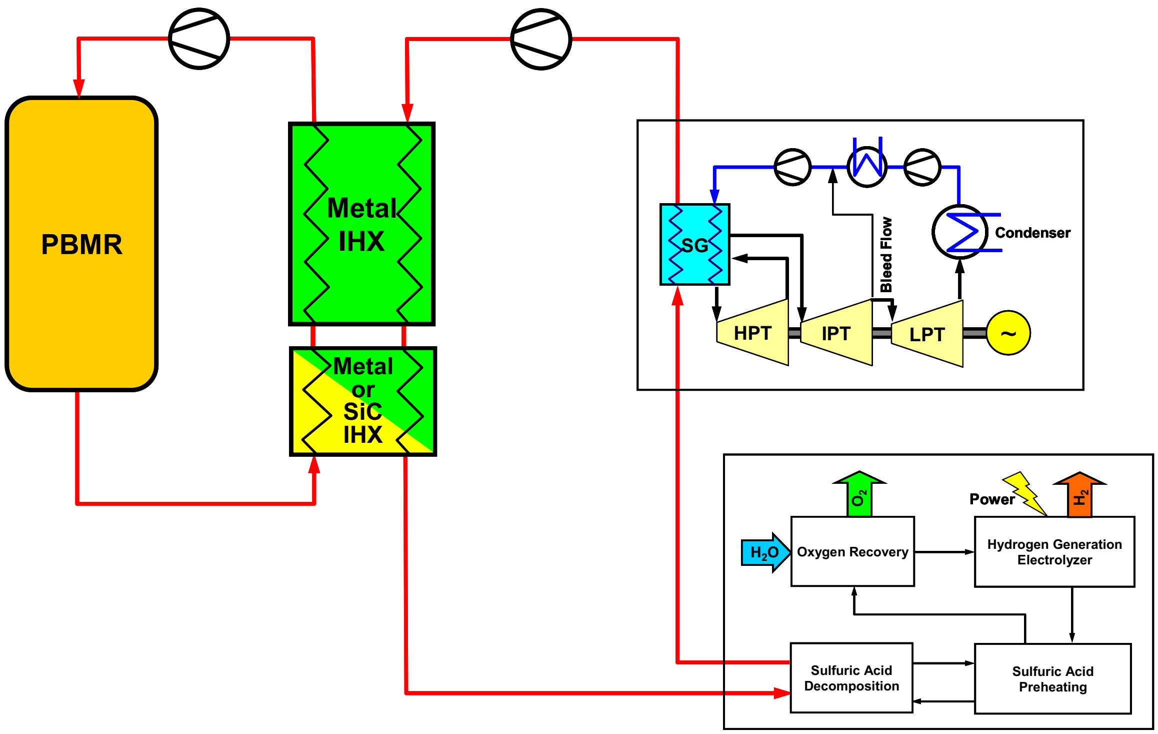

Figure 20.3.4-7 Option 6: Secondary Steam Cycle, Series PCHX

As with Options 3 and 4, the IHX represents the most significant challenge to readiness, in terms of meeting the reference NGNP schedule. As with those other options, the indirect configuration also most closely represents the commercial PBMR PHP nuclear heat source. If successful, it will resolve the IHX issue for commercial plants and provide an adequate basis in support of licensing and design certification of commercial plants.

As previously noted with Option 5, the Rankine bottoming cycle provides a great deal of flexibility with respect to the amount of thermal energy that can be routed to the HPU. A preliminary assessment was made, based upon Option 6, to illustrate this point. Figure 20.3.4-8 details the operating parameters for the plant when the HPU is not in operation. These parameters would be generally representative of HPU thermal power levels between 0 and 10 MW. Figure 20.3.4-9 illustrates the same Rankine cycle, operating at off-design conditions, with 200 MW directed to the HPU. Note that, while the helium temperature to the steam generator drops from 900ºC to 660ºC, the efficiency of the Rankine cycle decreases by only 6 percent. As further illustrated in Figure 20.3.4-11, the limit of the thermal power that can be withdrawn by the HPU, while still operating the Rankine cycle at high efficiency, is set by the pinch temperature within the steam generator. While 200 MW exceeds the levels contemplated for demonstration of the various hydrogen production processes, it does suggest that, after the NGNP completes its demonstration mission, there is a potential for converting the NGNP to commercial hydrogen production. While not specifically identified as an objective of the NGNP, such an option is consistent with the 60 year design life specified for the plant. This flexibility for longer term conversion of the NGNP to commercial production is also a potential with

Table 20.3.4-6 Option 6: Secondary Steam Cycle, Series PCHX

Key Features
• Full-size IHX transfers all reactor heat to SHTS
• Small to Medium PCHX as topping cycle
  ➢ Up to ~200MWt
• Steam generator as bottoming cycle
  ➢ 700ºC-900ºC design basis, nominal depends on PCHX rating
• PCHX/PCS likely to be co-located
Readiness
• Conventional steam cycle, with steam generator based on earlier HTGRs → no R&D
• Option to operate PCS without PCHX installed
• Large IHX poses greatest challenge to readiness
Support of Commercial Applications
• Larger engineering scale demonstrations of HyS/S-I feasible (up to ~100MWt)
  ➢ Possibly even larger with reductions of SC efficiency
• High NHS commonality with commercial PHP
  ➢ If successful, resolves IHX issue for commercial plants
  ➢ Adequate prototype for design certification of PHP commercial plants
	Performance
	• PCS temperatures consistent with modern steam conditions
	  ➢ Steam cycle not as sensitive to thermal rating as GT cycles
	• Steam cycle provides alternate heat sink for off-normal events
	  ➢ Requires operational PHTS and SHTS
	• Significant availability risk associated with potential for IHX leaks
	Cost
	• Capital
	  ➢ Large IHX implies potential for high replacement capital costs
	    – May be mitigated by selection of ceramic material and/or split section design
	• Operating
	  ➢ Lower efficiency, availability risk may reduce cost offsets via electric sales
	  ➢ Tradeoff of IHX/circulator vs. PCS maintenance costs

Option 5 and, with that option, an even greater thermal power level could be absorbed by the HPU.

The condenser section of the steam cycle can provide a continuous path for decay heat removal; however, with the steam generator being located in the SHTS, both the PHTS and SHTS must be operational.

As with Options 3 and 4, higher capital and operating costs and reduced efficiency are consequences of routing all of the thermal energy through the IHX. As noted above, however the efficiency impacts are modest over a wide range of HPU thermal power levels. These factors must be weighed against the ability of these indirect cycle options to better support commercial plant designs, in terms of risk mitigation and licensing/design certification.

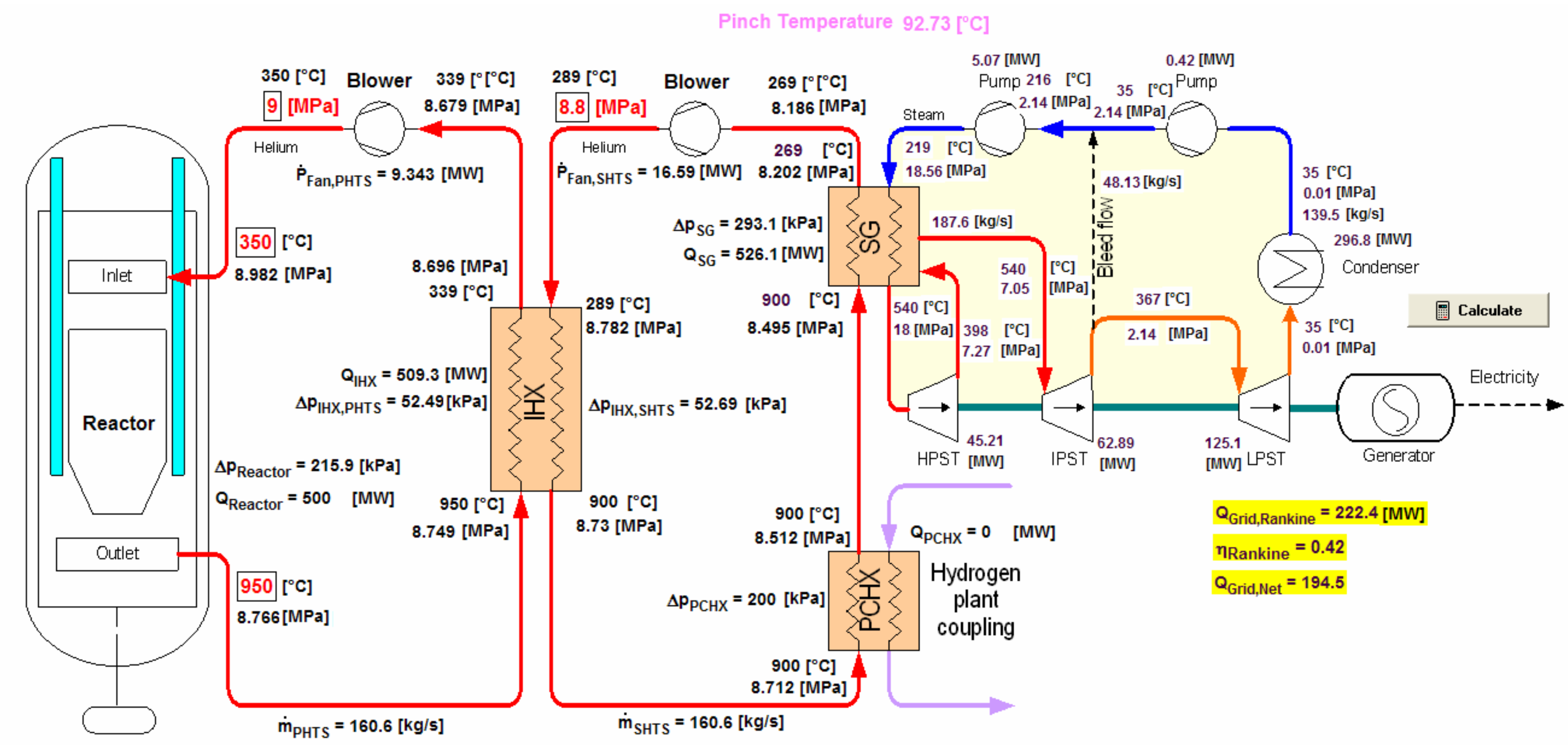

Figure 20.3.4-8 Cycle L: Rankine Cycle Parameters for 0-10 MW H_2 Plant Size

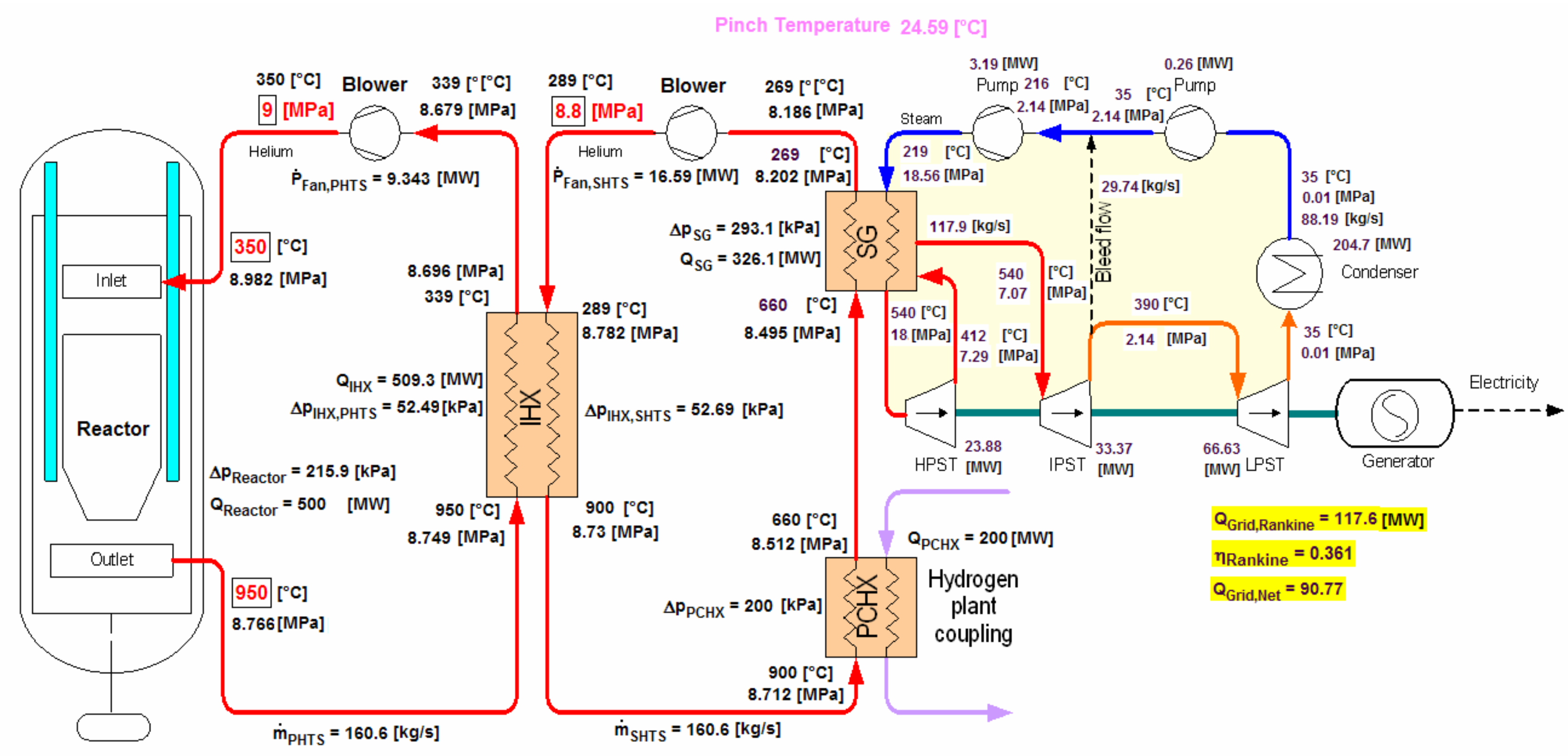

Figure 20.3.4-9 Cycle L: Rankine Cycle Parameters for 200 MW H_2 Plant Size

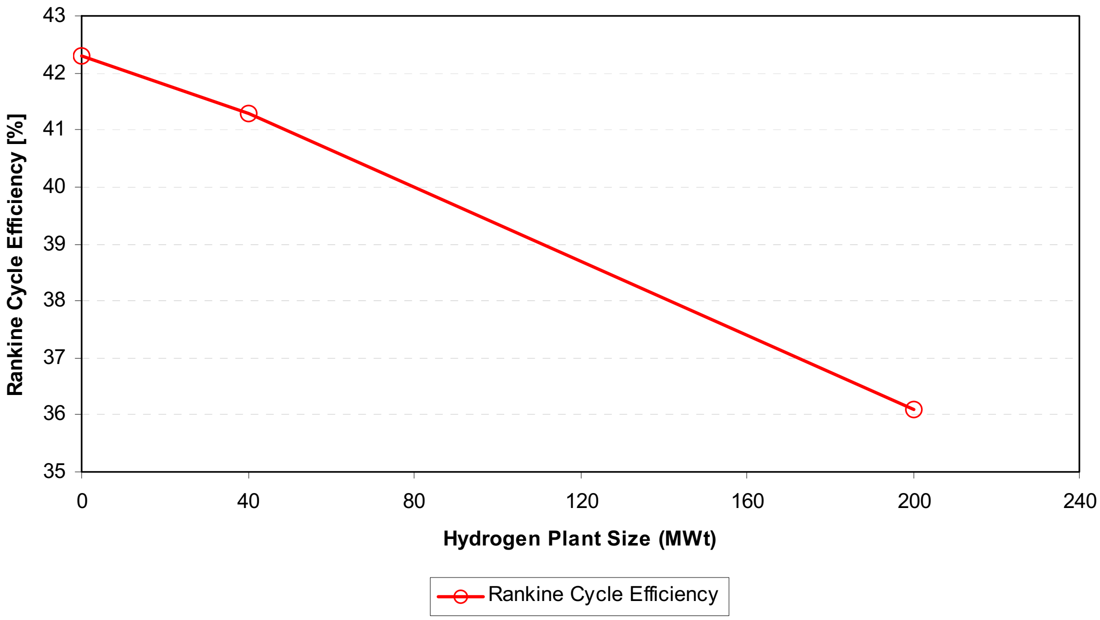

Figure 20.3.4-10 Cycle L: Influence of Hydrogen Plant Size

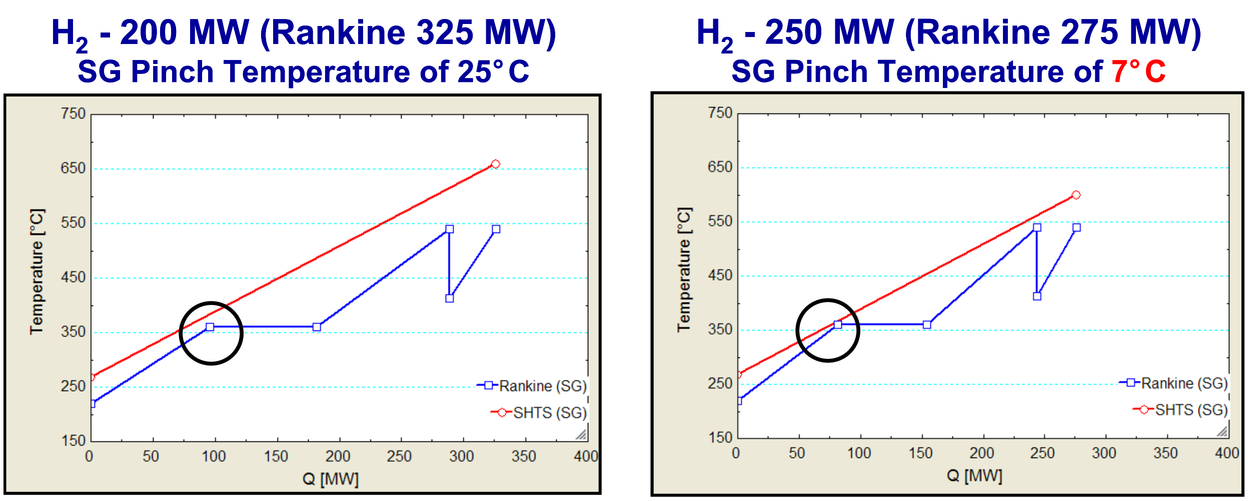

Figure 20.3.4-11 Pinch Temperature Allows H_2 Plant Sizes Up to ~200 MW

20.3.4.3 Integrated PCS/Process Options – Option 7

This final category includes those options for which there is no identified PCS or in which all or part of the PCS is coupled directly to the process.

Option 7, which is the reference PBMR PHP commercial process for hydrogen production via HyS (Figure 20.3.4-12, Table 20.3.4-7) is an example of such coupling.

In this particular configuration, all of the reactor thermal energy is transferred to the SHTS, where it is first routed to the PCHX. Approximately 200 MW is transferred to the PCHX. Thereafter, the remaining thermal energy is extracted in the bottoming steam generator before the SHTS helium returns to the IHX. There is additional coupling between the process and the steam cycle to enhance overall thermal efficiency. A large fraction of the electricity generated in the PCS is utilized in the electrolysis section of the HyS process.

The technical difficulties associated with the indirect coupling of Option 7 are generally in common with Options 3, 4 and 6. Obviously, Option 7 ideally represents and supports the commercial PBMR PHP HyS application. However, it is incompatible with the stated mission of the NGNP to demonstrate multiple options. If, however, a single reference hydrogen production process could be selected, full-scale demonstration, followed by long-term commercial operation of the NGNP may provide the most cost-effective path to commercialization.

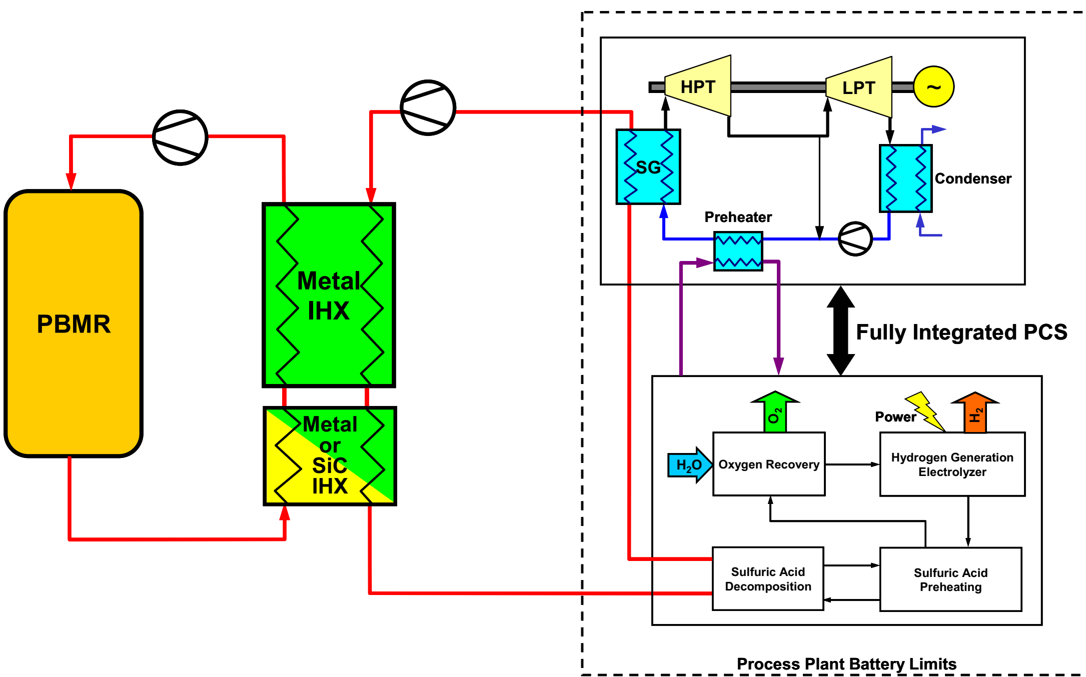

Figure 20.3.4-12 Option 7: PCS Integrated with Process

Table 20.3.4-7 Option 7: PCS Integrated with Process

Key Features
• Full-size IHX transfers all reactor heat to SHTS
• Full-size PCHX transfers all thermal energy to process
• Steam cycle-based PCS integrated with process
  ➢ Size/configuration is process dependent
Readiness
• Large IHX poses greatest challenge to readiness
• Requires process availability for operation
• Minimum flexibility for demonstration of multiple applications
  ➢ Requires reconfiguration of both process and PCS for individual applications
Support of Commercial Applications
• Not consistent with HTE architecture
• Up to full-scale demonstrations of PHP
• High NHS commonality with commercial PHP
  ➢ If successful, resolves IHX issue for commercial plants
  ➢ Best prototype for design certification of PHP commercial plants
	Performance
	• Prototypical of commercial applications
	• Provisions for alternate heat sink in SHTS or process are process dependent
	  ➢ Requires operational PHTS
	• Significant availability risk associated with potential for IHX leaks, process-related outages
	Cost
	• Capital
	  ➢ Added cost for multiple demonstrations
	  ➢ Large IHX implies potential for high replacement capital costs
	    – May be mitigated by selection of ceramic material and/or split section design
	• Operating
	  ➢ Low efficiency, availability likely to minimize cost offsets via electric sales
	  ➢ PCS maintenance costs moved to process

20.3.4.4 Evaluation and Recommendation

The Heat Transport System (HTS) configuration options described in Sections 4.1 through 4.3 were evaluated against the criteria identified in Section 20.3.1.4. The result of the evaluation is summarized in Table 20.3.4-8. As earlier described in Section 20.3.1.4, each attribute was assigned an importance rating of low, medium or high. In the semi-quantitative process of Table 20.3.4-8, these importance factors were associated with weighting factors of 1, 2 and 3, respectively. Each option was evaluated against each attribute on the basis of 1 to 10. For each attribute, the HTS configuration option which best met that criterion was assigned an evaluation value of 10. The option which least well met the evaluation criteria was assigned a score of 1. Other HTS configurations were assigned relative values between 1 and 10. The evaluation values were multiplied by the weighting factors to obtain a score for each attribute. These were added to obtain the total score for the respective configurations.

In considering Table 20.3.4-8, it can be seen that Options 1, 2 and 5 scored relatively high in the categories of readiness, performance and cost. This is consistent with the relative simplicity of those configurations in comparison with their indirect cycle counterparts, which incorporate a full-size IHX. On the other hand, Options 1 and 2 score relatively low in terms of support for the design and licensing of commercial PBMR PHP applications and ability to meet operational performance goals. These latter attributes are highly weighted, since they are the essence of the NGNP mission to serve as a launching pad for commercial nuclear hydrogen production and related process heat applications. It is worthy to note that the relatively higher score of Option 5 principally relates to the flexibility of the bottoming Rankine cycle to accommodate a wide range of hydrogen production unit (HPU) thermal ratings.

The scores of Options 3, 4 and 6 are relatively high in terms of support for commercial applications and the ability to meet operational performance goals. They are also highly rated in terms of their serving as a basis for supplier infrastructure development. Lower ratings are found in the areas of readiness and cost, which relate to the incorporation of a full-size IHX that would serve as a prototype for follow-on commercial applications. The higher score of Option 6, relative to Options 3 and 4, again relates to the flexibility provided by the Rankine cycle to accommodate a range of HPU sizes. The latter also provides near-optimum opportunity for ultimate conversion of the NGNP to a commercial production status.

The ratings of Option 7, which is essentially a commercial hydrogen production prototype, are at the extremes of the range. Obviously, if successful, such an option would be an ideal basis for launching a commercial industry. On the other hand, risk is maximized and flexibility is minimized with such an option. Only if a single optimum hydrogen production process can be selected in the near term would it be worthwhile considering this option further.

On balance, it is recommended that Option 6 (Figure 20.3.4-13) be selected as the basis for the NGNP preconceptual design. Consistent with the evaluation, it is concluded that the incorporation of a full-size IHX best represents and supports commercial designs, and provides the optimum basis for licensing/design certification of the nuclear heat source for commercial process heat applications.

Recognizing that direct Brayton cycle and related GTCC commercial applications will be adequately supported by the Demonstration Power Plant (DPP) in South Africa, Option 6 minimizes R&D and risk that is not directly associated with process heat and hydrogen production, the principal objectives of the NGNP. A specific example of the latter are pressure transients that would be imposed on the IHX by the Brayton cycle with Options 1 through 4.

Finally, the bottoming Rankine cycle provides the greatest flexibility for balancing the needs of the HPU demonstration and PCS. It also provides a clear path for conversion of the NGNP to commercial operation upon completion of its demonstration mission.

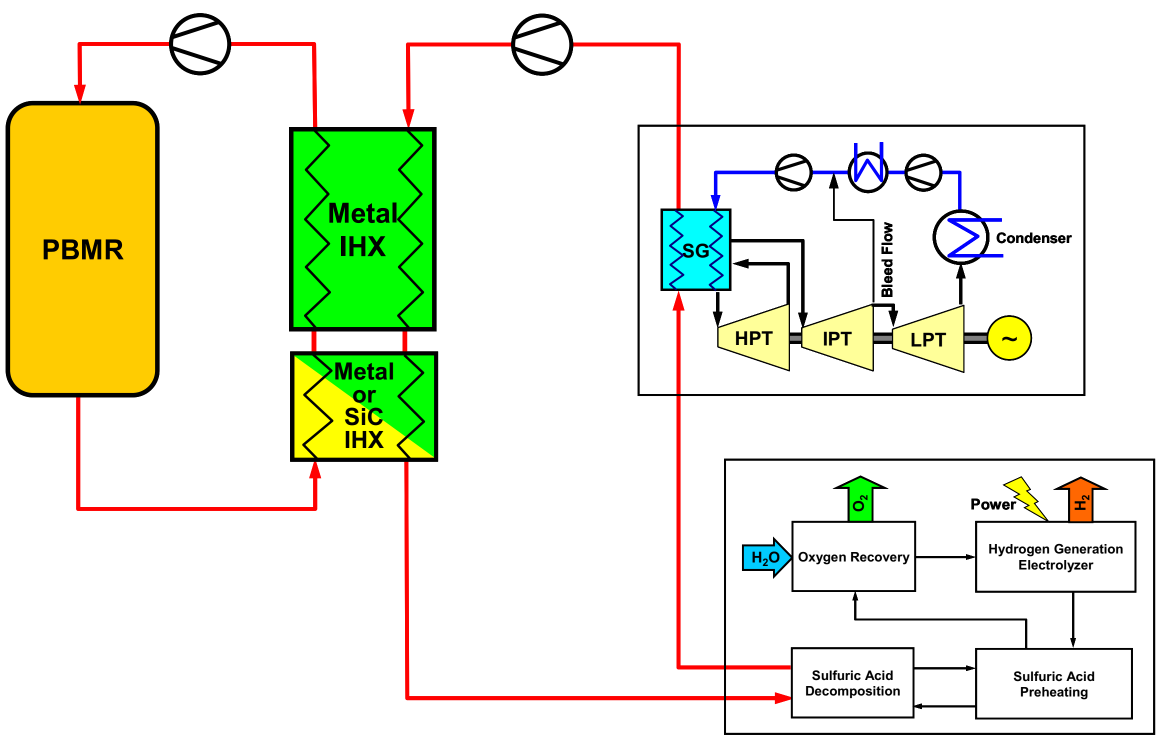

Figure 20.3.4-13 Recommended HTS Configuration: Option 6

20.3.4.5 References for Section 20.3.4

20.3.4-1 NGNP Special Study: Power Conversion System, Revision C – Draft, M-Tech Industrial (Pty) Ltd., 20 December 2006. [to be updated]

Table 20.3.4-8 Evaluation of HTS Configuration Options

Attribute	Importance	Assessment of Options													
		Option 1		Option 2		Option 3		Option 4		Option 5		Option 6		Option 7	
		Eval	Score	Eval	Score	Eval	Score	Eval	Score	Eval	Score	Eval	Score	Eval	Score
Readiness															
Ability to meet NGNP timeline (startup: 2016-2018)	High	8	24	8	24	5	15	5	15	10	30	7	21	1	3
NGNP R&D Requirements/Cost/Risk	Med	6	12	6	12	5	10	5	10	10	20	7	14	1	2
Supplier Infrastructure Development	Low	3	3	3	3	9	9	9	9	1	1	7	7	10	10
Support of Commercial Applications															
Adequately demonstrates commercial process heat	High	1	3	1	3	6	18	6	18	3	9	8	24	10	30
NHS commonality with commercial products	High	2	6	2	6	8	24	8	24	1	3	7	21	10	30
Can serve as process heat prototype for design certification	High	1	3	1	3	6	18	6	18	3	9	8	24	10	30
Flexibility for demonstrating multiple applications	Med	5	10	5	10	4	8	4	8	7	14	9	18	1	2
Flexibility for ultimate conversion to full-scale H2 production	Med	1	2	1	2	6	12	6	12	7	14	9	18	10	20
Performance															
Ability to meet operational performance goals	High	4	12	3	9	7	21	8	24	7	21	10	30	1	3
Efficiency	Low	7	7	8	8	5	5	6	6	8	8	1	1	10	10
Operability	Med	8	16	1	2	2	4	3	6	10	20	9	18	1	2
Availability	Low	8	8	8	8	5	5	6	6	10	10	7	7	1	1
Cost															
NGNP Capital Cost	High	8	24	9	27	6	18	6	18	10	30	7	21	1	3
NGNP Operating Cost	Low	8	8	9	9	6	6	7	7	10	10	8	8	1	1
Totals			138		126		173		181		199		232		147

REFERENCES

References are identified in individual sections.

BIBLIOGRAPHY

Bibliography items are identified in individual sections.

DEFINITIONS

None.

REQUIREMENTS

Requirements are addressed in Section 20.3.1.

LIST OF ASSUMPTIONS

Section 20.3.1: Study Inputs

1. The requirements for Sulfur-Iodine and High-Temperature Electrolysis inferred from sources referenced in Section 20.3.1.1 are representative of actual requirements.

Section 20.3.3: IHX Materials Readiness Assessment

1. Plate-type heat exchangers can be manufactured from high temperature alloys and associated manufacturing processes will not degrade materials properties to an unacceptable level.
2. An acceptable metallic alloy can be procured and qualified for the range of 900-950ºC with properties that are acceptable for plate-type heat exchangers (e.g., grain size, as-bonded characteristics).
3. Relevant ASME Code Cases can be developed for the NGNP-specific design and materials in a timeframe consistent with the NGNP schedule.
4. A metallic IHX with adequate life can be developed for the temperature range of 900-950ºC.

TECHNOLOGY DEVELOPMENT

Technology development requirements identified through this HTS Special Study were limited to those related to the IHX. The Design Data Needs for the IHX are presented in Section 20.3.3.9.

APPENDICES

The following appendices comprise the materials presented to BEA at the December 6-7, 2006 meetings in Stoughton, MA.

Appendix 20.3.1: Part 1 – Inputs and Criteria

Appendix 20.3.1: Part 2 – Power Conversion System Options

Appendix 20.3.1: Part 3 – HPU, IHX/Materials, SHTS Working Fluid

Appendix 20.3.1: Part 4 – Heat Transport System Options

APPENDIX 20.3.1: SPECIAL STUDY 20.3.1 SLIDES

PART 1 – INPUTS AND CRITERIA

SPECIAL STUDIES:
20.3 - HEAT TRANSPORT SYSTEM
20.4 - POWER CONVERSION SYSTEM

Part 1 – Inputs and Criteria

December 6, 2006

Outline

- **Objective and Scope**
- **Study Inputs**
  - Commercial applications and performance requirements
  - Key NGNP HTS demonstration objectives
  - Key HTS functional requirements
- **Screening Criteria**
- **H_2 Production Unit Size (20.7)**
- **Power Conversion System Options (20.4)**
- **IHX/High-Temperature Materials**
- **Secondary Working Fluid**
- **HTS Configuration Options**
- **Recommended HTS Configuration**

Objective

Select reference configurations for the Heat Transport System (HTS) and Power Conversion System (PCS) for the NGNP Preconceptual Design

HTS Configuration Study (20.3)
Scope

- **Identify and evaluate input requirements and/or criteria that would influence the HTS configuration**
  - From PBMR PHP commercial development activities
  - From NGNP Special Studies
    - *20.4 PCS Configuration Options*
    - *20.7 H2 plant size*
  - From INL/NGNP
- **Step 1: (the following in parallel)**
  - Identify candidate HTS and PCS configurations and conduct initial screening
  - Evaluate SHTS working fluid options and select reference
  - Readiness evaluation of IHX/high-temperature materials: select reference technology and materials
  - Develop criteria for evaluation and selection
- **Step 2: Evaluate and select reference HTS concept**

Outline

- **Objective and Scope**
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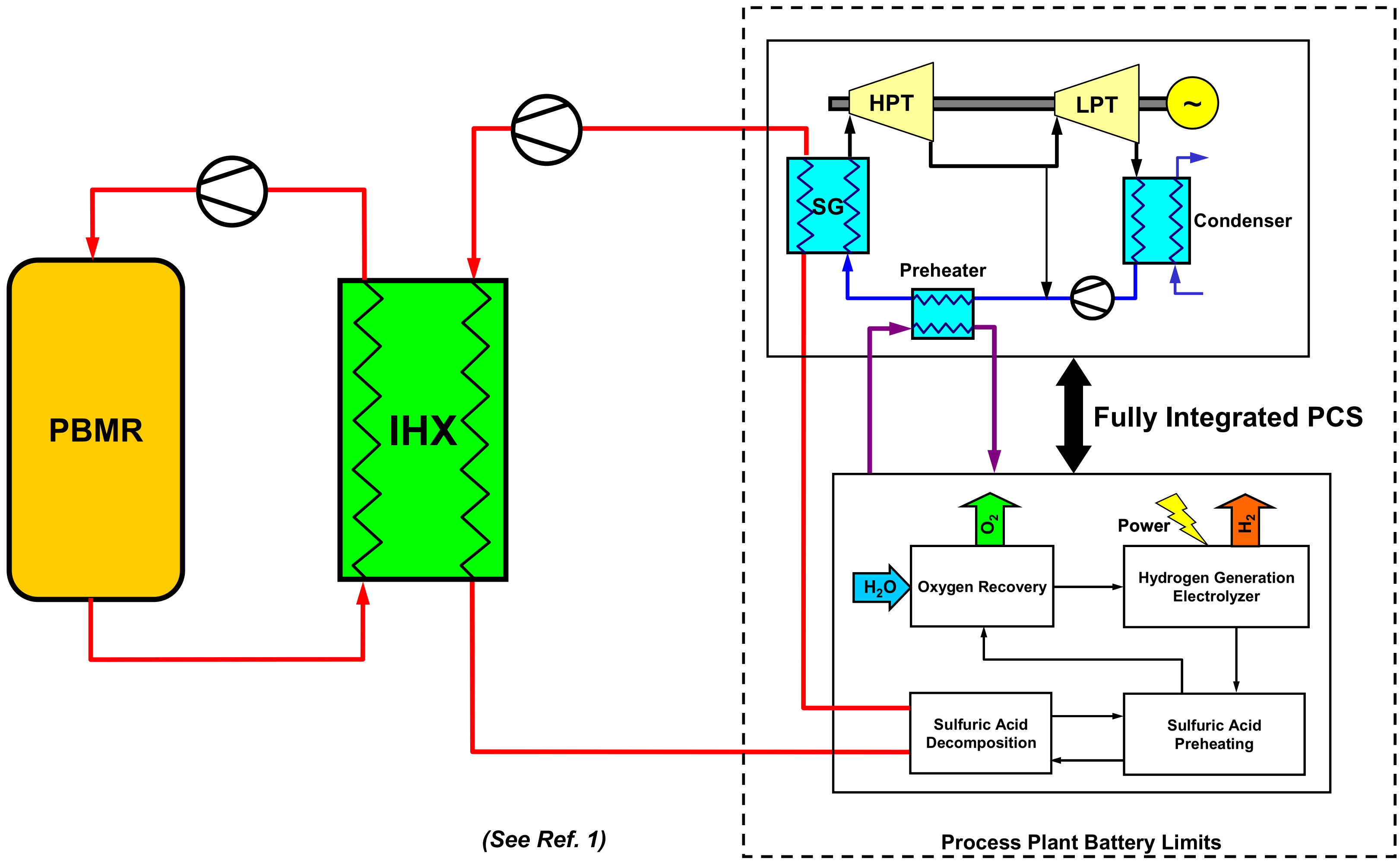
Prospective Commercial Applications

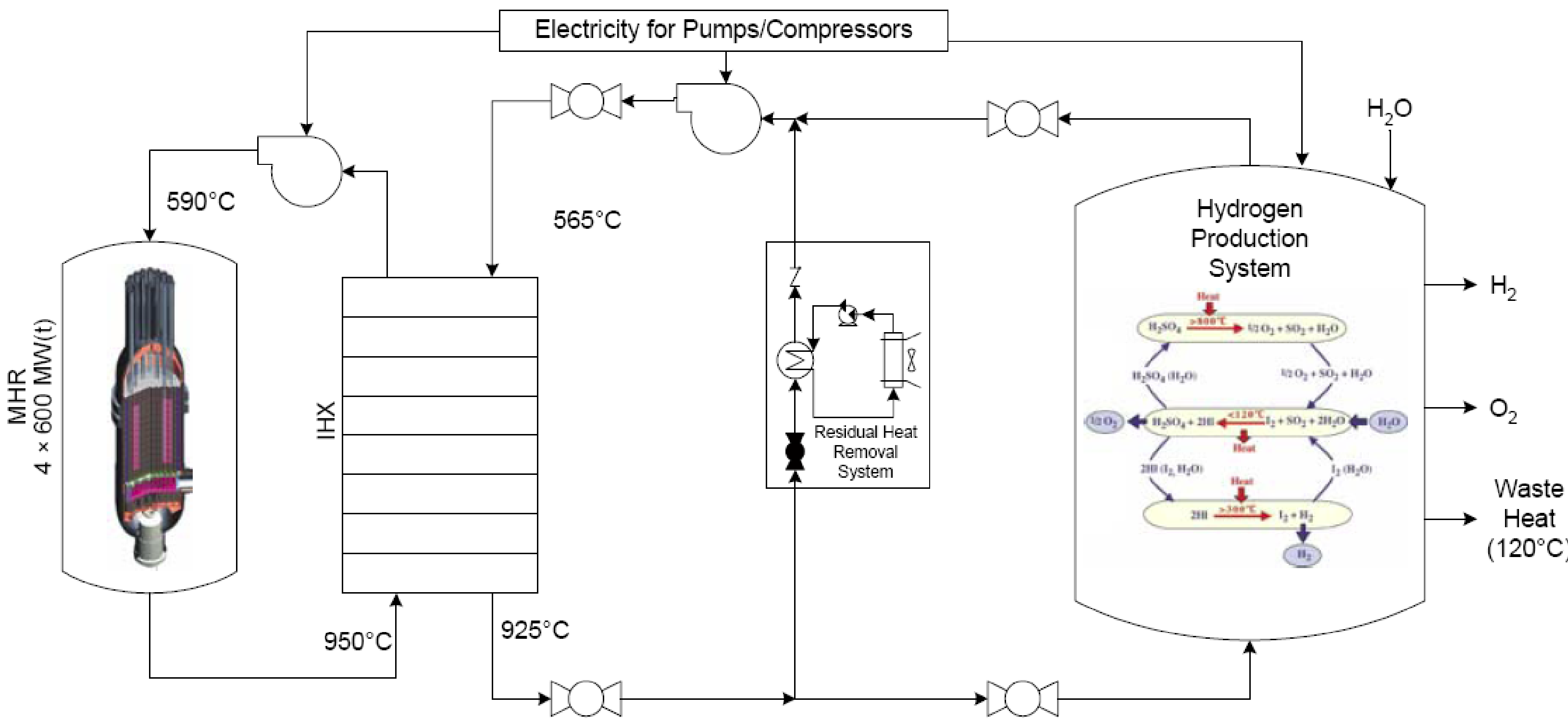
- **PBMR Electric Plant Applications**
  - Multi-Module Power Plant (MMP) – Brayton Cycle
    - *Commercial follow-on to Demonstration Power Plant (DPP)*
  - Advanced Electric Power Plant (AEP)
    - *Gas-turbine combined cycle power plant (GTCC) from 20.4*
- **Process Heat Applications**
  - H_2/Syngas via Steam-Methane Reforming (SMR)
  - H_2 via Hybrid Sulfur (HyS) Process (Ref.1)
  - H_2 via Sulfur-Iodine (S-I) Process (Ref. 2)
  - H_2 via High Temperature Electrolysis (HTE) (Ref. 3)

H_2 via Hybrid Sulfur (HyS) Cycle Commercial Plant Configuration



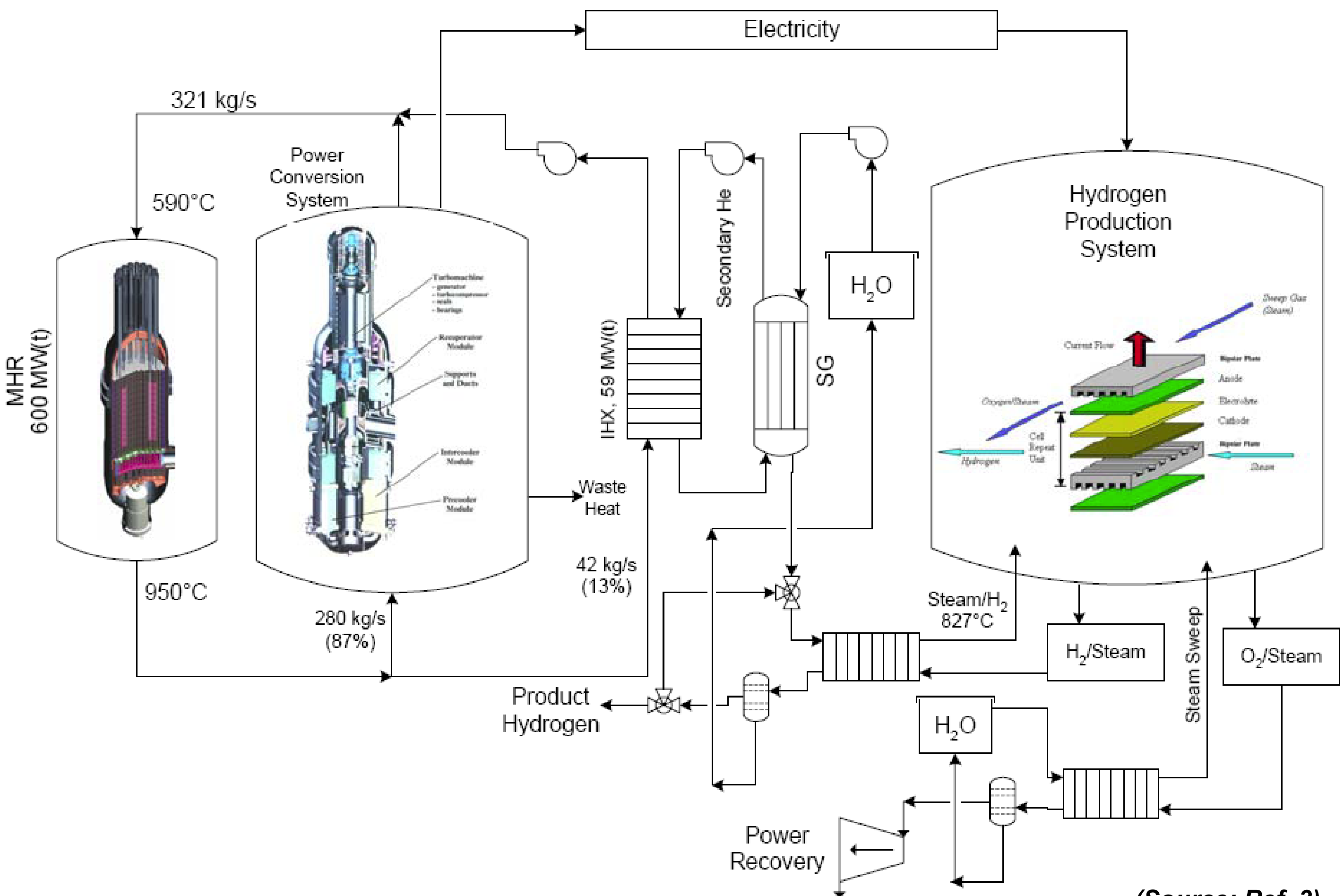
(See Ref. 1)

H_2 via Sulfur-Iodine Cycle



(Source: Ref. 2)

H_2 via High Temperature Electrolysis



(Source: Ref. 3)

Key Commercial Application Parameters

Application	HyS	S-I	HTE
Reactor/IHX			
Core Outlet Temperature, C	950	950	950
IHX Secondary Outlet Temperature, C	900	925	917
Fraction of Energy via IHX, %	100	100	10
High Temp PCHX			
High Temp PCHX	H_2SO_4 Decomposer	H_2SO_4 Vaporizer/ Decomposer	Steam Generator and Superheater
Fraction of Energy via PCHX, %	36	100	10
Process Pressure, MPa	8.8	7.0	5
Process Side Outlet Temp, ºC	872	900	772

Outline

- **Objective and Scope**
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Key HTS Demonstration Objectives: IHX

- **The IHX, which transfers thermal energy from the primary heat transport system (PHTS) to the secondary heat transport system (SHTS), is a common feature of commercial applications revealed to date**
  - With the exception of HTE, commercial configurations revealed to date depict all of the reactor thermal energy being routed via the IHX
  - HTE application requires a relatively small fraction of thermal energy, with the balance being provided as electricity
- **Available metallic materials are marginal at peak IHX temperatures for commercially acceptable lifetimes**
  - Ceramic or composite materials may offer acceptable options, but require significant development
- **The demonstration of an acceptable IHX solution is considered an key NGNP demonstration objective**

Key HTS Demonstration Objectives: H_2 Process

- **Integrated demonstration of candidate H_2 production processes (including the process coupling heat exchanger - PCHX) is an important NGNP objective**
  - Thermal requirements of the HTE process are modest
  - The recommended scale for demonstrating the HyS and S-I processes is addressed by a separate study (20.7)
- **A differentiating requirement of the NGNP versus commercial applications is providing the flexibility to demonstrate multiple processes**

Key HTS Demonstration Objectives: Licensing

- Basis for licensing/certification of commercial plants

Key HTS Demonstration Objectives:
Other HTS Components

- **Piping and insulation**
  - Designs developed and qualified for helium to 950ºC through prior HTGR programs + PBMR DPP
- **Circulators**
  - Prior HTGR experience supports operation to ~350ºC
  - PBMR DPP is developing potentially applicable technologies
    - *Magnetic bearings for Core Conditioning System circulator*
    - *Dry Gas Seals for Turbomachinery*
- **SHTS Isolation Valves (SIV)**
  - Need for SIVs to be assessed, based on functions and requirements of IHX heat transfer surface (separates PHTS/SHTS) and SHTS pressure boundary, plus licensing considerations

Outline

- **Objective and Scope**
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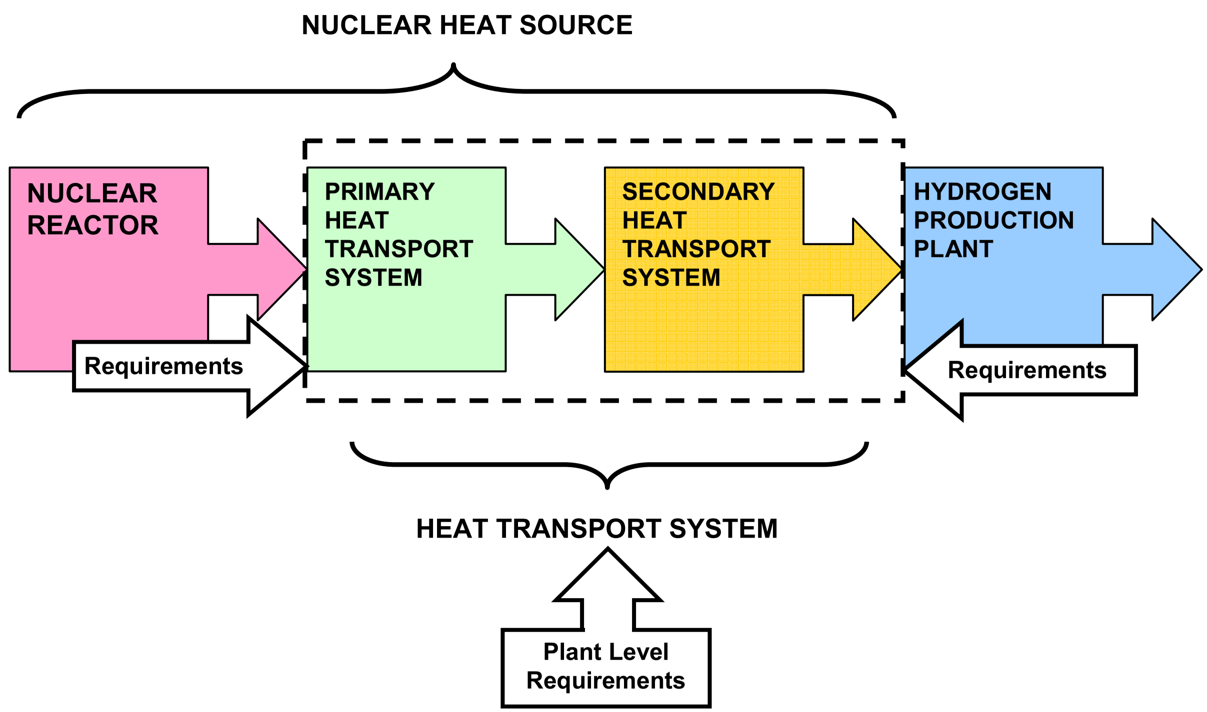
Sources of HTS Functional Requirements



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Representative HTS Functions & Requirements

- **During normal operation, transport and transfer thermal energy from the reactor to the process and power conversion system (PCS), as applicable**

  Requirements:
  - Application-specific requirements: See earlier table
  - Design life: 60 years (limited life components to be replaceable)

- **During other normal (e.g., starting up/shutting down) and off-normal (e.g., loss of process load) operational states, transport and transfer thermal energy from the reactor to an ultimate heat sink**

  Requirements:
  - Duty Cycle: See table that follows

- **Maintain control of radionuclides**

  Requirements:
  - IHX leakage requirements
  - Tritium-related requirements

- **Protect Nuclear Heat Source from process-related hazards**

  Requirements:
  - Distance from IHX to process plant
  - Mitigating features

Representative Plant Duty Cycle

Comparison of Generating Plant and Hydrogen Production Plant Design Duty Cycles

Events	Number of Events Per Power Unit	
	Generating HTGR	Hydrogen Plant HTGR
Start-up from cold conditions	240	240
Shutdown to cold conditions	240	240
Normal load following cycles(1)	22,000	Not Applicable
Frequency control	800,000	Not Applicable
Load reject to house load	100	[25]
Rapid load ramp	1500 up / 1500 down	[500] down
Step load changes	3000(1)	[500] down

(1) Total number, up or down.

(Source: Ref. 5)

Outline

- **Objective and Scope**
- **Study Inputs**
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Screening Criteria

Attribute	Importance
Readiness	
Ability to meet NGNP timeline (startup: 2016-2018)	**High**
NGNP R&D Requirements/Cost/Risk	Med
Vendor/Supplier Infrastructure Development	Med
Support of Commercial Applications	
Adequately demonstrates commercial process heat applications	**High**
NHS commonality with commercial products	**High**
Can serve as process heat prototype for design certification	**High**
Flexibility for demonstrating advanced applications	Med
Flexibility for ultimate NGNP conversion to full-scale H2 production	Med
Performance	
Ability to meet operational performance goals	**High**
Overall Plant Efficiency	Low
Operability	Med
Availability	Low
Cost	
NGNP Capital Cost	**High**
NGNP Operating Cost	Low

Part 1 References

1. Lahoda, E.J., et.al., "Estimated Costs for the Improved HyS Flowsheet", HTR2006, October 2006.
2. H2-MHR Conceptual Design Report: SI-Based Plant (GA-A25401), General Atomics, April 2006.
3. H2-MHR Conceptual Design Report: HTE-Based Plant (GA-A25402), General Atomics, April 2006.
4. Process Heat Plant-5: Steam Methane Reforming Process Flow Diagram (Prelim), Shaw December 2005.
5. "High Temperature Gas-Cooled Reactors for the Production of Hydrogen: Establishment of the Quantified Technical Requirements for Hydrogen Production that will Support the Water-Splitting Processes at Very High Temperatures", EPRI, Palo Alto, CA: 2004. 1009687.
6. Techno-economic Comparison of PCU's for the NGNP, PBMR, September 2005.

Outline

- **Objective and Scope**
- **Study Inputs**
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APPENDIX 20.3.1: SPECIAL STUDY 20.3.1 SLIDES

PART 2 – POWER CONVERSION SYSTEM OPTIONS

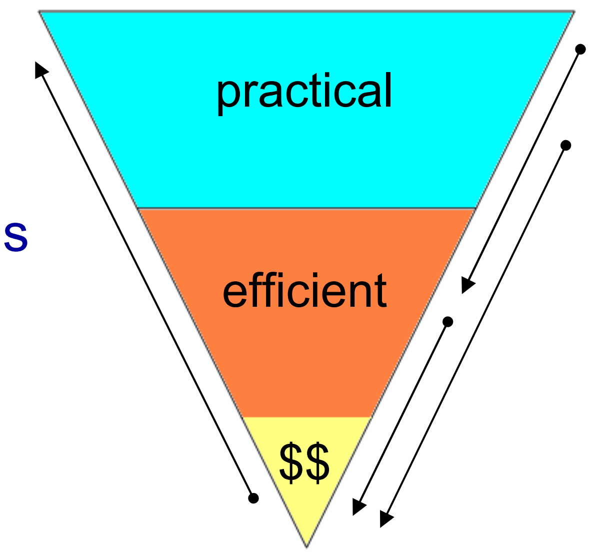
SPECIAL STUDIES:
20.3 - HEAT TRANSPORT SYSTEM
20.4 - POWER CONVERSION SYSTEM

Part 2 – Power Conversion System Options

December 6, 2006

Background

- **The choice of Power Conversion System (PCS) is a vital step in the Preconceptual Design of the NGNP**
- **The PCS directly influences**
  - Plant net efficiency
  - Practicality of the component designs
  - Plant flexibility
  - Plant cost
  - Potential technology growth

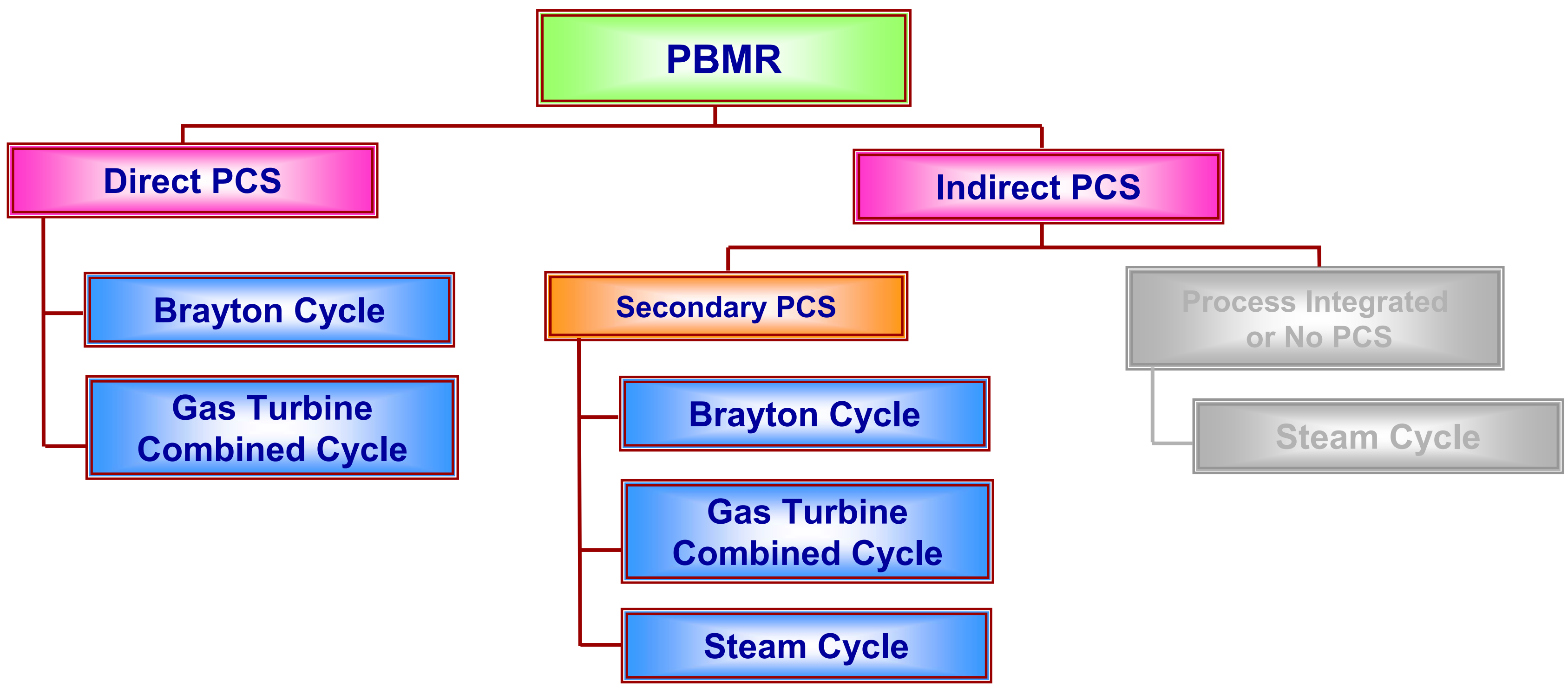


- **Identifying the optimum PCS is a complex problem which is influenced by a large number of interdependent variables**

Objective

- **Analyze and compare the performance of three PCS families being considered in conjunction with Heat Transport System (HTS) options**
  - Gas Turbine (Brayton) Cycles
  - Gas Turbine Combined Cycles (CCGT)
  - Rankine Cycles

PCS Options Investigated

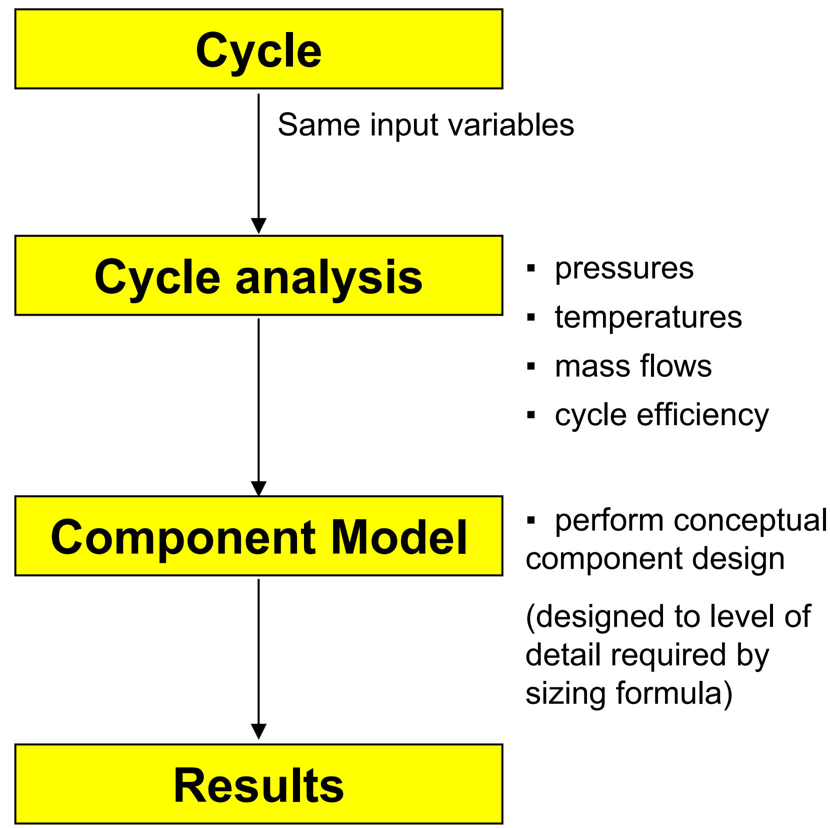


Part 2 Outline

- Introduction
- ➡ **Analysis Methodology**
- Evaluation
  - Brayton Cycles
  - GTCC
  - Rankine Cycles
- Cycle Trade-offs
- Summary

Analysis Methodology

- Integrated analysis approach
- Systematically compares various cycle configurations based on the same input parameters
- Evaluate the efficiency as a function of various design parameters



Influence of H_2 Production Unit

- **The size of the H_2 Production Unit (HPU) will be relatively small**
  - ~5 - 50MWt per 20.7
- **It is, therefore, assumed that the size of the HPU will not significantly influence the choice of the best cycle configuration within a given family (Brayton, GTCC, Rankine)**
  - Therefore, when comparing cycle variations within these three individual groups, the HPU size is not directly considered
- **For the optimum cycle within each family, the influence of HPU size is subsequently evaluated**

Cycle Analysis

- **Input variables together with basic thermodynamic relations, are used to calculate the temperatures and pressures at each component's inlet and outlet**
- **Brayton cycle**
  - Fixed heat exchanger efficiencies
  - Fixed pressure drop percentages for piping and heat exchangers
  - Fixed reactor design
  - Fixed compressor and turbine efficiencies
- **Rankine cycle**
  - Maximum steam pressure is fixed
  - Upper limit is set for maximum steam temperature
  - Turbine and pump efficiencies are fixed
  - Fixed pressure drop percentages through SG and re-heater
  - Optimize RIT for maximum GTCC efficiency
  - Limit low pressure turbine outlet quality to more than 88%

Cycle Optimization

- **Gas Turbo Units**
  - Combination of speed, blade safety factor, etc. was optimized to ensure the minimum capital cost (smallest machine) at every operating point
- **GTCC**
  - Rankine Cycle was custom-designed to exactly fit the Brayton cycle at every considered operating point
  - Brayton cycle and Rankine cycle were optimized to ensure the maximum combined efficiency at every operating point

Input Parameters

- Generic inputs
  - PBR power = 500 MW_{th}
  - DPP Reactor design
  - Primary and secondary fluid = Helium
- Brayton Cycle inputs
  - Turbine inlet temperature = 900°C (assumed for 20.4)
  - Min helium coolant temp = 22.5°C (assumed for 20.4)
  - $\eta_{compressor}$ = 89%; $\eta_{turbine}$ = 91%; η_{blower} = 80%
  - Compressor outlet axial velocity = 135 m/s
  - $\eta_{recuperator}$ = 97%
  - IHX pressure drop = 0.5% of inlet pressure
  - Piping pressure drop = 0.2% of inlet pressure
  - Brayton house load (HL) = 6.5 MW_e
  - Primary circuit maximum pressure = 9 MPa
  - IHX approach temperature = 50°C (indirect cycles)
  - Secondary circuit pressure = 8.8 MPa
- Reactor and Brayton Cycle constraints
  - Maximum RIT = 500°C (Core Barrel < 427°C)
  - Maximum mass flow = 200 kg/s (V < 100m/s)
  - Maximum Turbo Unit pressure ratio = 3.5
- Rankine Cycle inputs
  - Maximum steam pressure = 180 bar
  - Condenser temperature = 35°C
  - Turbine exhaust quality = ~0.88
  - $\eta_{turbine}$ = 89%; η_{pumps} = 72%
  - SG and re-heater pressure drop = 3% of inlet pressure
  - Piping pressure drop ignored
  - $HL_{Rankine} = 0.9915*Power_{Rankine}$
  - Pinch Temperature = 30°C
- Rankine Cycle constraints
  - Max steam temperature $\leq$ 540°C
- GTCC inputs
  - (G)(J) $HL_{CC} = 0.8*HL_{Brayton} + 0.9915*Power_{Rankine}$
  - (H)(I) $HL_{CC} = 0.6*HL_{Brayton} + 0.9915*Power_{Rankine}$

Part 2 Outline

- **Introduction**
- **Analysis Methodology**
- **Evaluation**
  - Brayton Cycles
  - GTCC
  - Rankine Cycles
- **Cycle Trade-offs**
- **Summary**

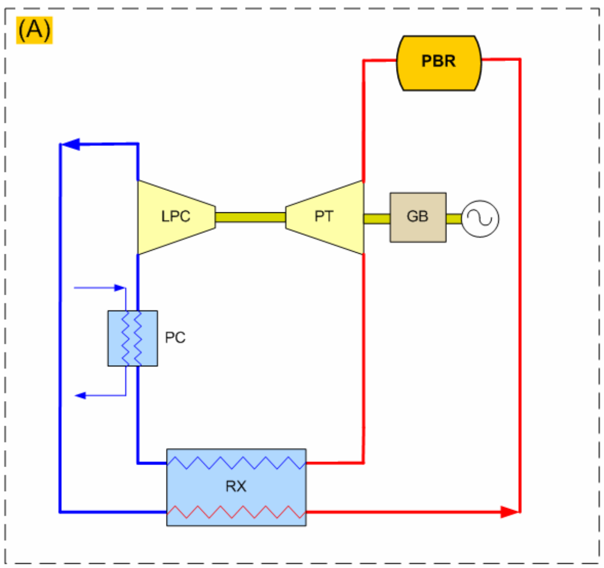
Brayton Cycle Configurations

- (A) Single-shaft
- (B) Single-shaft with inter-cooling
- (C) Two-shaft with inter-cooling
- (D) Three-shaft with inter-cooling
- (E)* Three-shaft with two-step inter-cooling

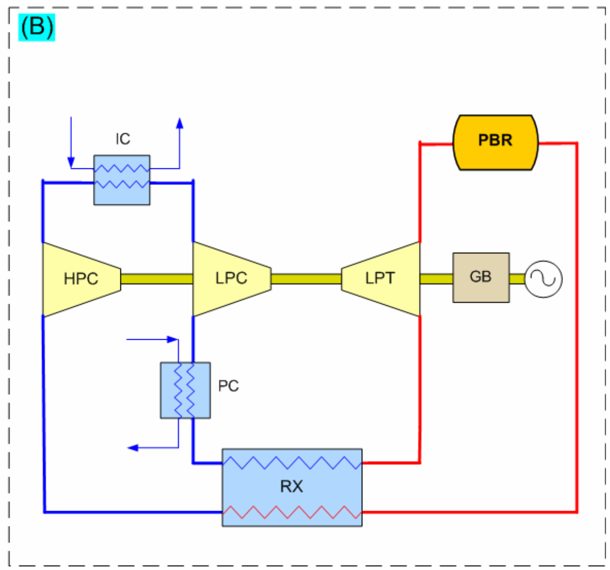
*Indirect Cycle F to follow later

Brayton Cycle Options
A, B, C

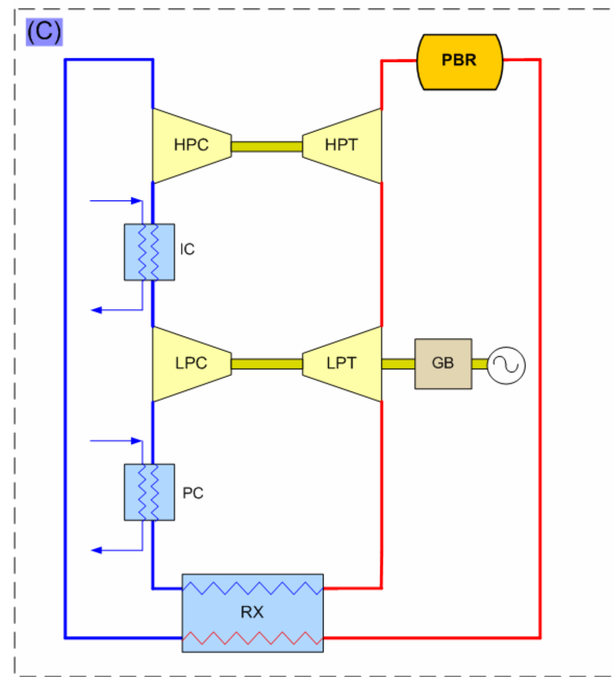
(A) Single-shaft



(B) Single-shaft with inter-cooling



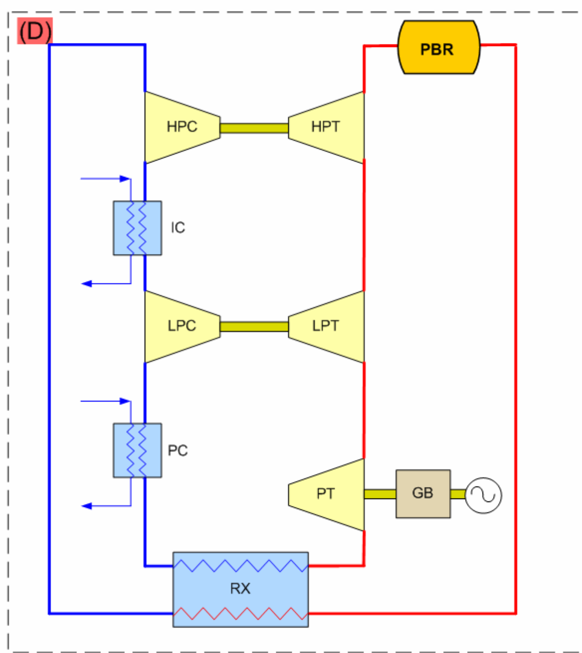
(C) Two-shaft with inter-cooling



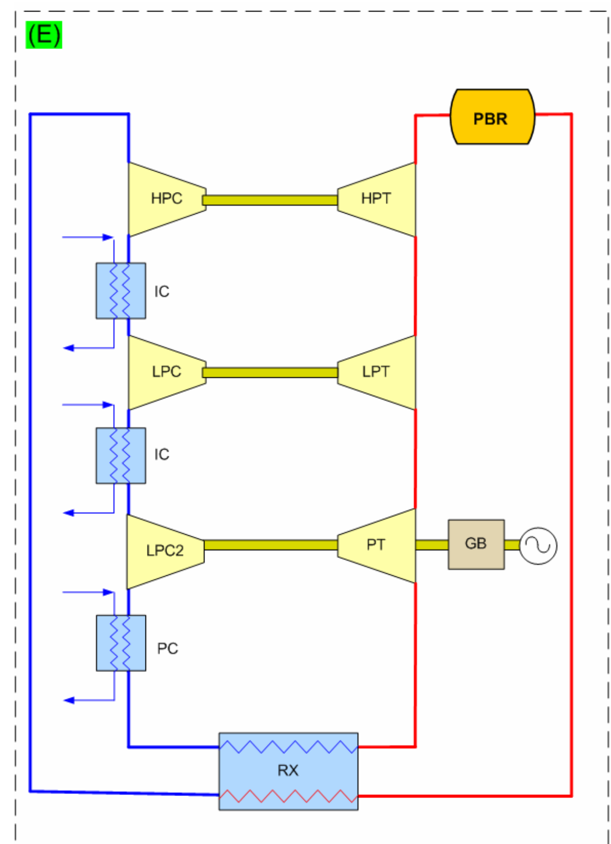
Brayton Cycle Options

D, E

(D) Three-shaft with inter-cooling

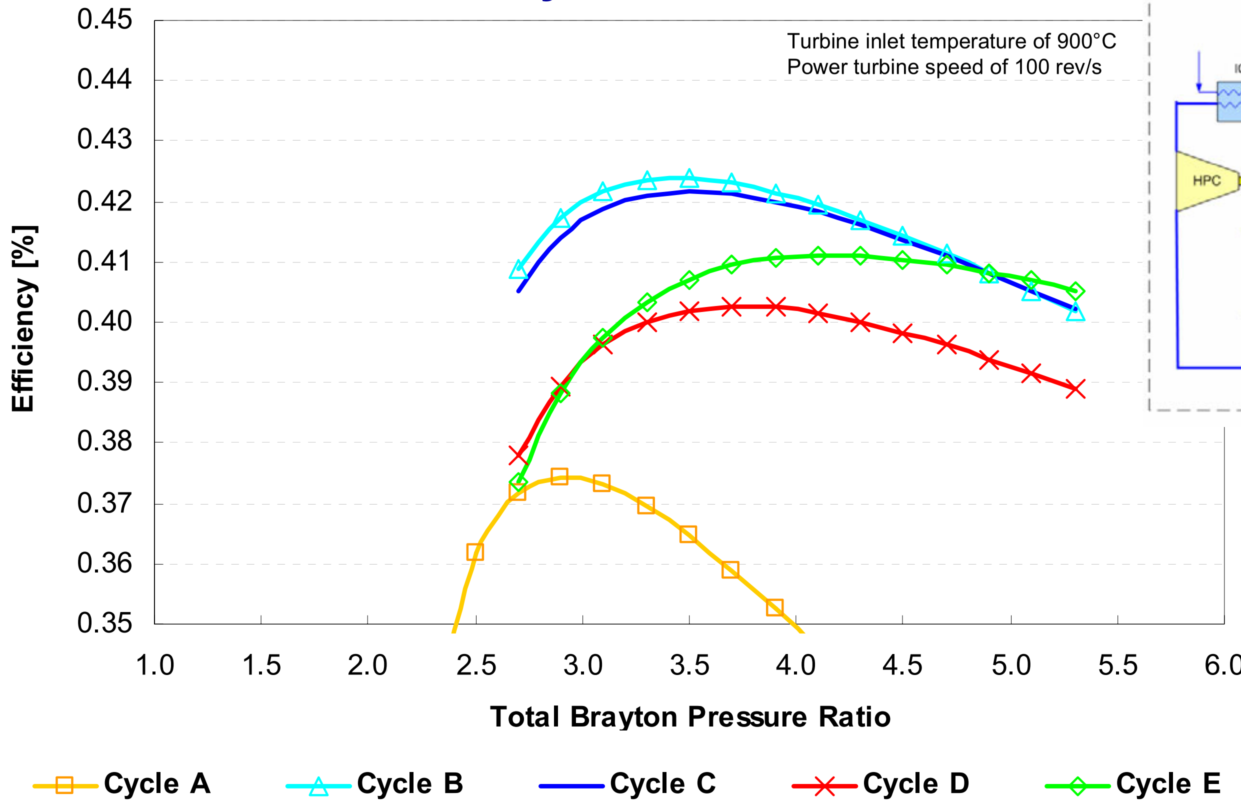


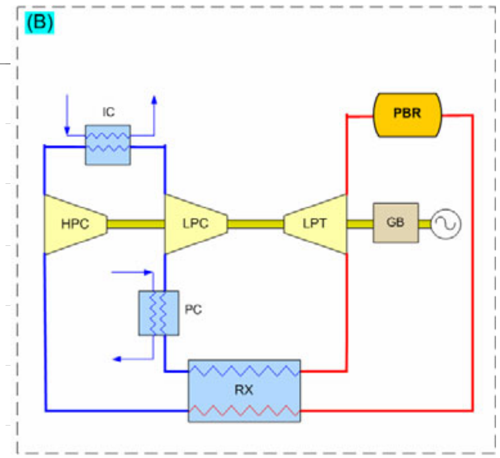
(E) Three-shaft with two-step inter-cooling



Brayton Cycles
Net Cycle Efficiency

Net efficiency vs. Pressure ratio



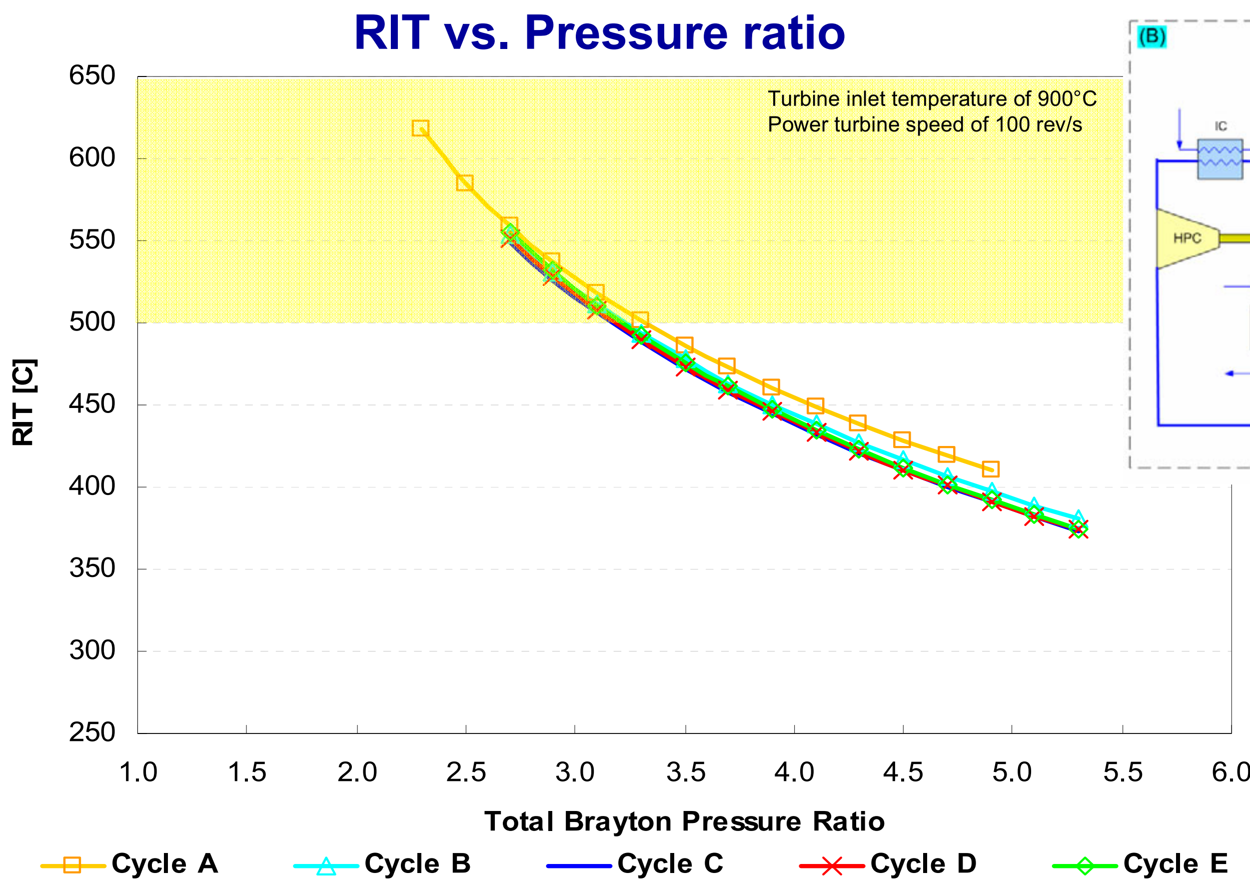


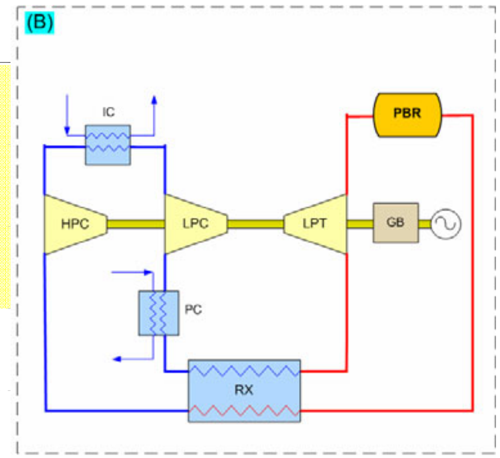
(A) 1-Shaft
(B) 1-Shaft IC
(C) 2-Shaft IC
(D) 3-Shaft IC
(E) 3-Shaft ICx2

- **Best efficiency – Cycle B: Single shaft Brayton cycle with intercooler**

Brayton Cycles

RIT

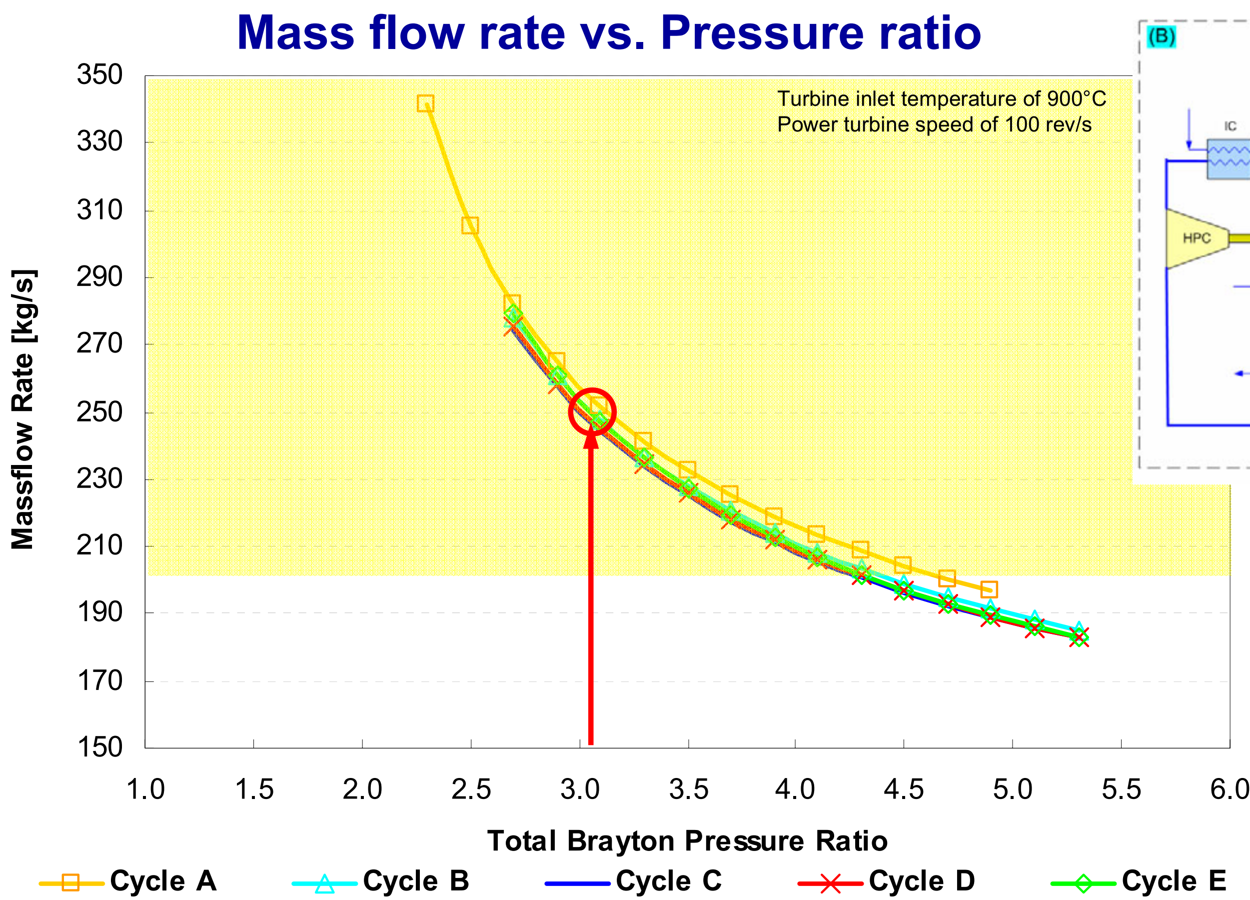


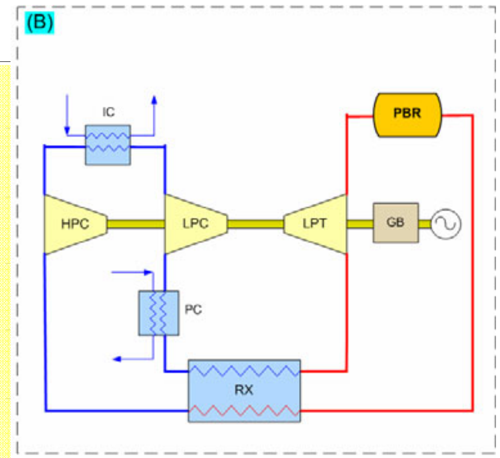


(A) 1-Shaft
(B) 1-Shaft IC
(C) 2-Shaft IC
(D) 3-Shaft IC
(E) 3-Shaft ICx2

- **Maximum RIT of 500°C; to enable Core Barrel to operate below 427°C**
  - All cycles to operate above 3.1 pressure ratio to enable RIT < 500°C

Brayton Cycles
Mass Flow Rate



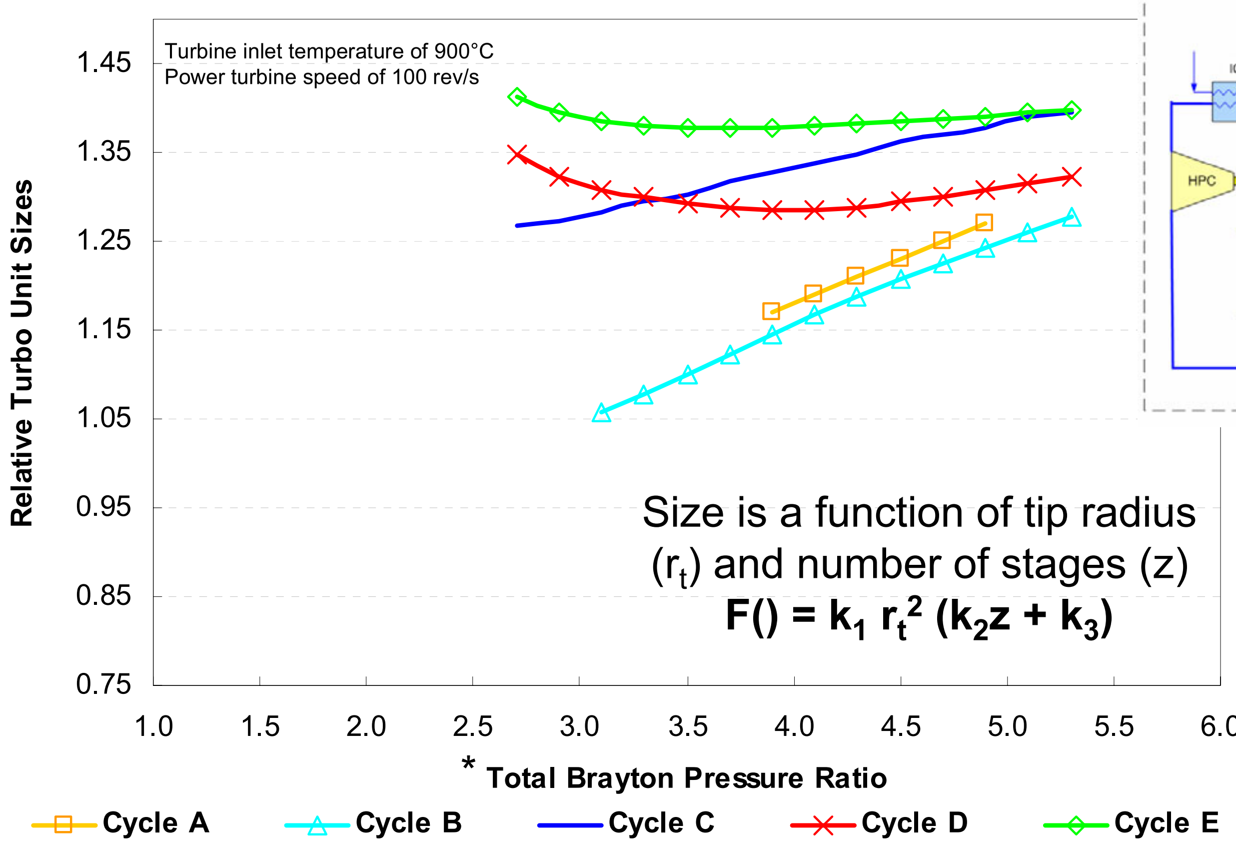


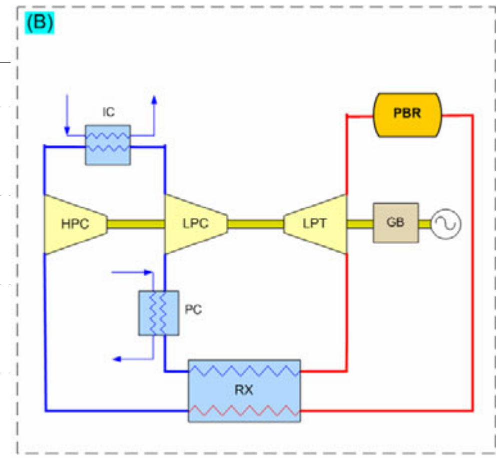
(A) 1-Shaft
(B) 1-Shaft IC
(C) 2-Shaft IC
(D) 3-Shaft IC
(E) 3-Shaft ICx2

- **Maximum mass flow of ~200 kg/s; to limit reactor core velocity**
  - Brayton cycles unable to operate at their maximum cycle efficiency within reactor design envelope at 500 MW

Brayton Cycles
Relative Turbo Unit Size

Relative turbo unit size vs. Pressure ratio





Size is a function of tip radius (r_t) and number of stages (z)

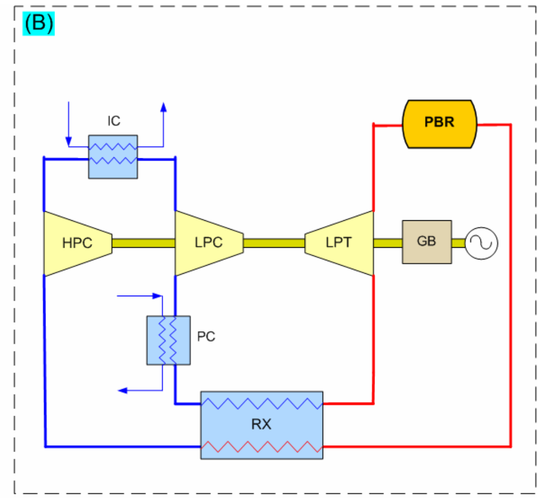
$$F() = k_1 \, r_t^2 \, (k_2 z + k_3)$$

(A) 1-Shaft
(B) 1-Shaft IC
(C) 2-Shaft IC
(D) 3-Shaft IC
(E) 3-Shaft ICx2

- Single-shaft designs have highest gradients (fixed rotational speed)
- Three-shaft designs have lowest gradient (only third shaft has a fixed rotational speed) – free shafts rotational speed optimized

(*See appendix for effect of rotational speed and ROT)

Choice of Brayton Cycle



- **Criteria**
  - ➢ Performance (MEDIUM)
    - – *Efficiency* — *Cycle B highest*
  - ➢ Component Size (LOW)
    - – *Turbo Units* — *Cycle B lowest*
  - ➢ Design Envelope (HIGH)
    - – *mass flow rate< 200 kg/s; 280<RIT<500; pressure ratio<3.5*
    - – *All Brayton cycles exceed the mass flow rate limitation at 500 MWt*
- **Conclusion**
  - ➢ Cycle B preferred Brayton Cycle
  - ➢ However, Cycle B exceeds the mass flow rate limitation (at 500MW)

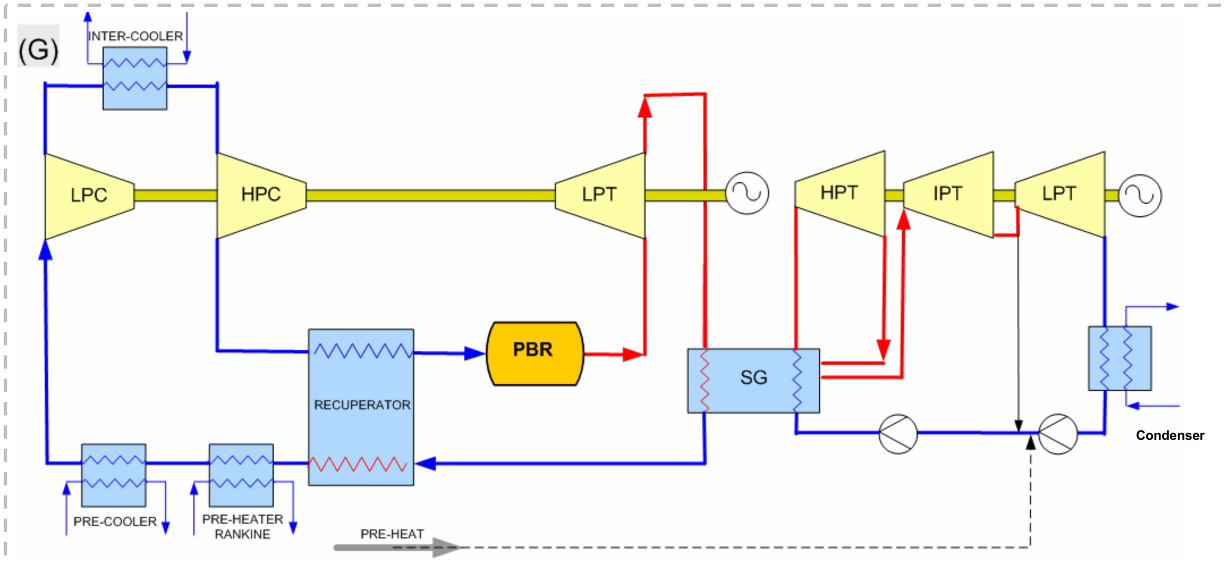
GTCC Configurations

- **(G) Single-shaft recuperative Brayton with inter-cooling**
- **(H)* Single-shaft Brayton without inter-cooling**
- **(J) Single-shaft recuperative Brayton without inter-cooling**

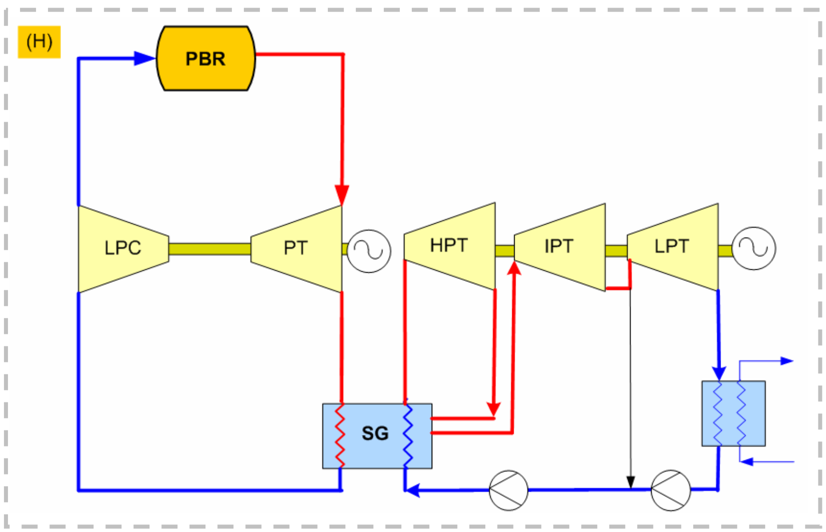
***Indirect Cycle I to follow later**

GTCC Configurations

G, H



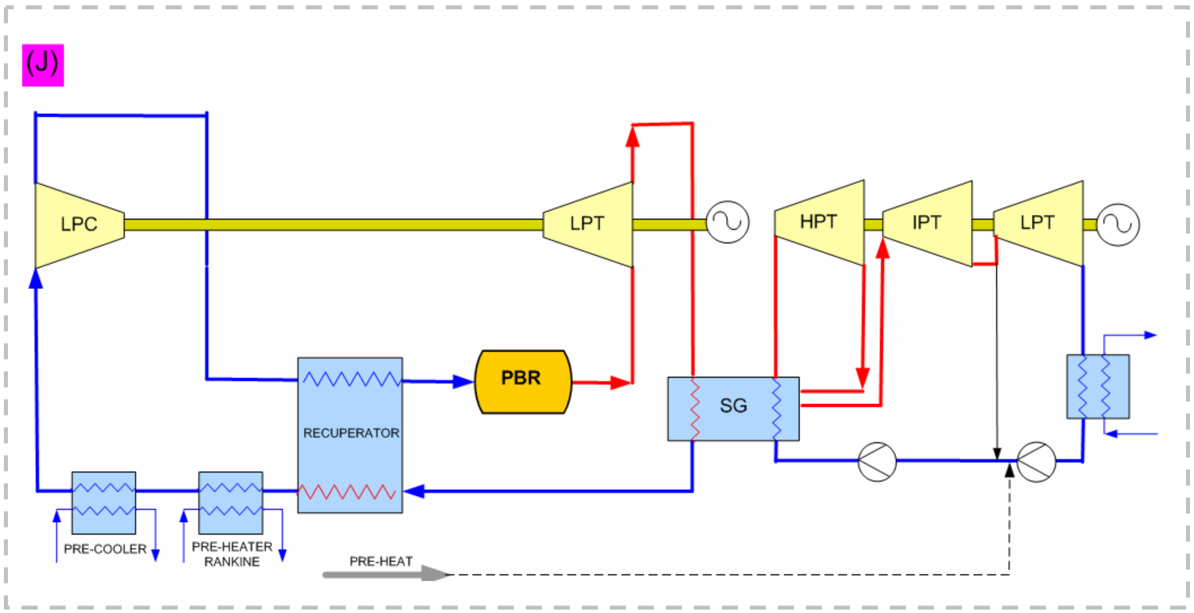
G: Single-shaft recuperative Brayton with inter-cooling



H: Single-shaft Brayton without inter-cooling

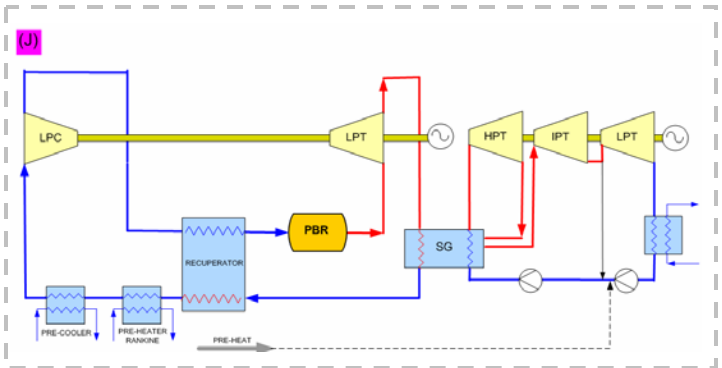
GTCC Configurations

J

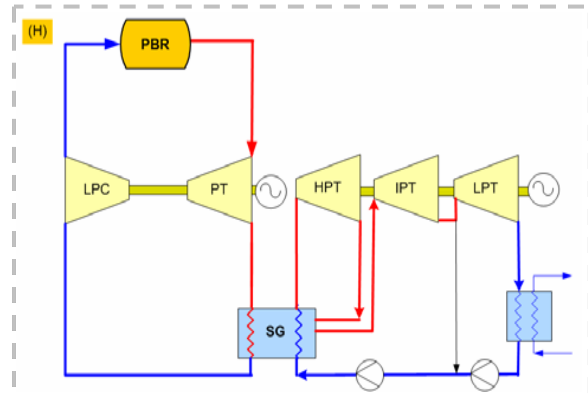


J: Single-shaft recuperative Brayton without inter-cooling

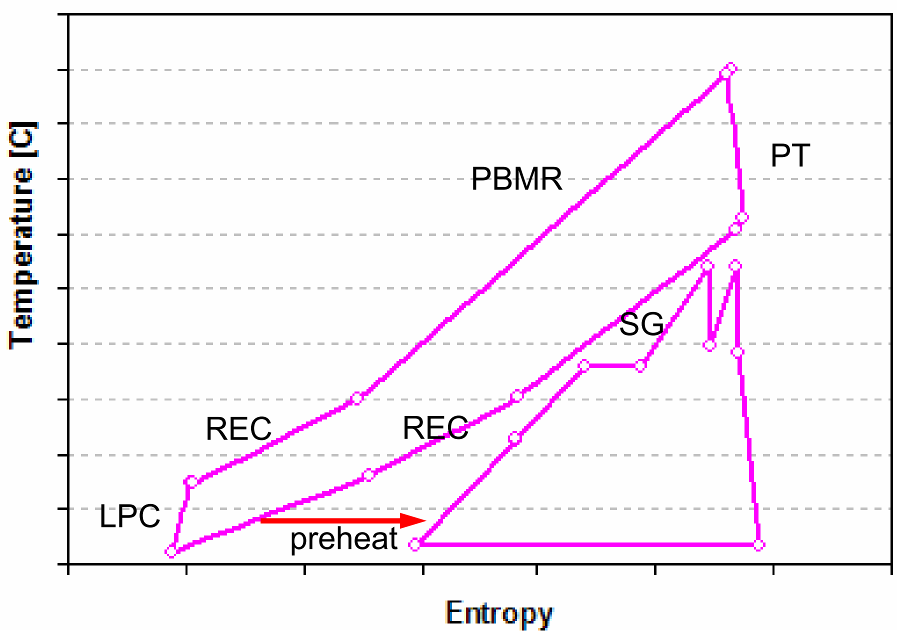
Brayton/Rankine Cycle Power Tradeoff

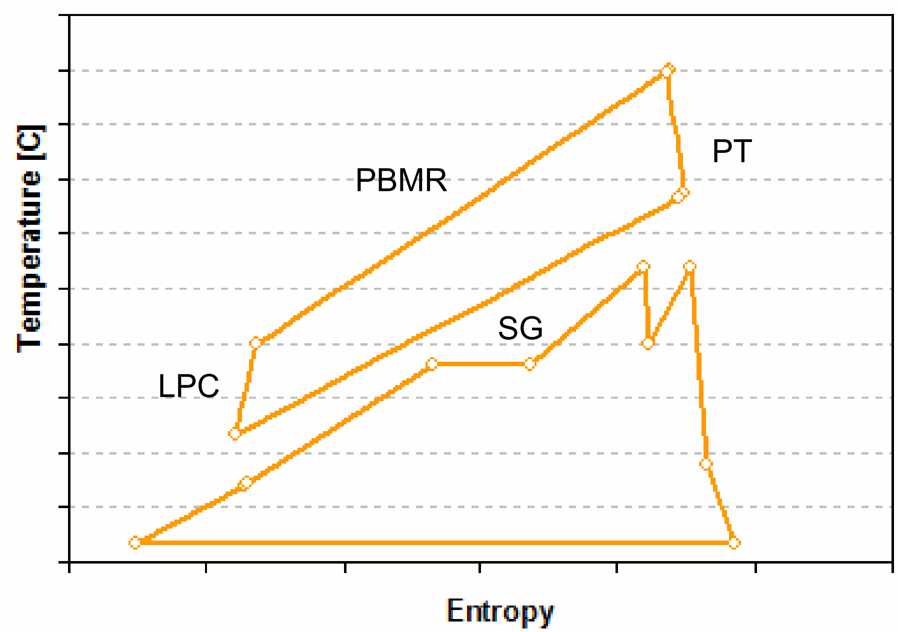


Cycle (J)



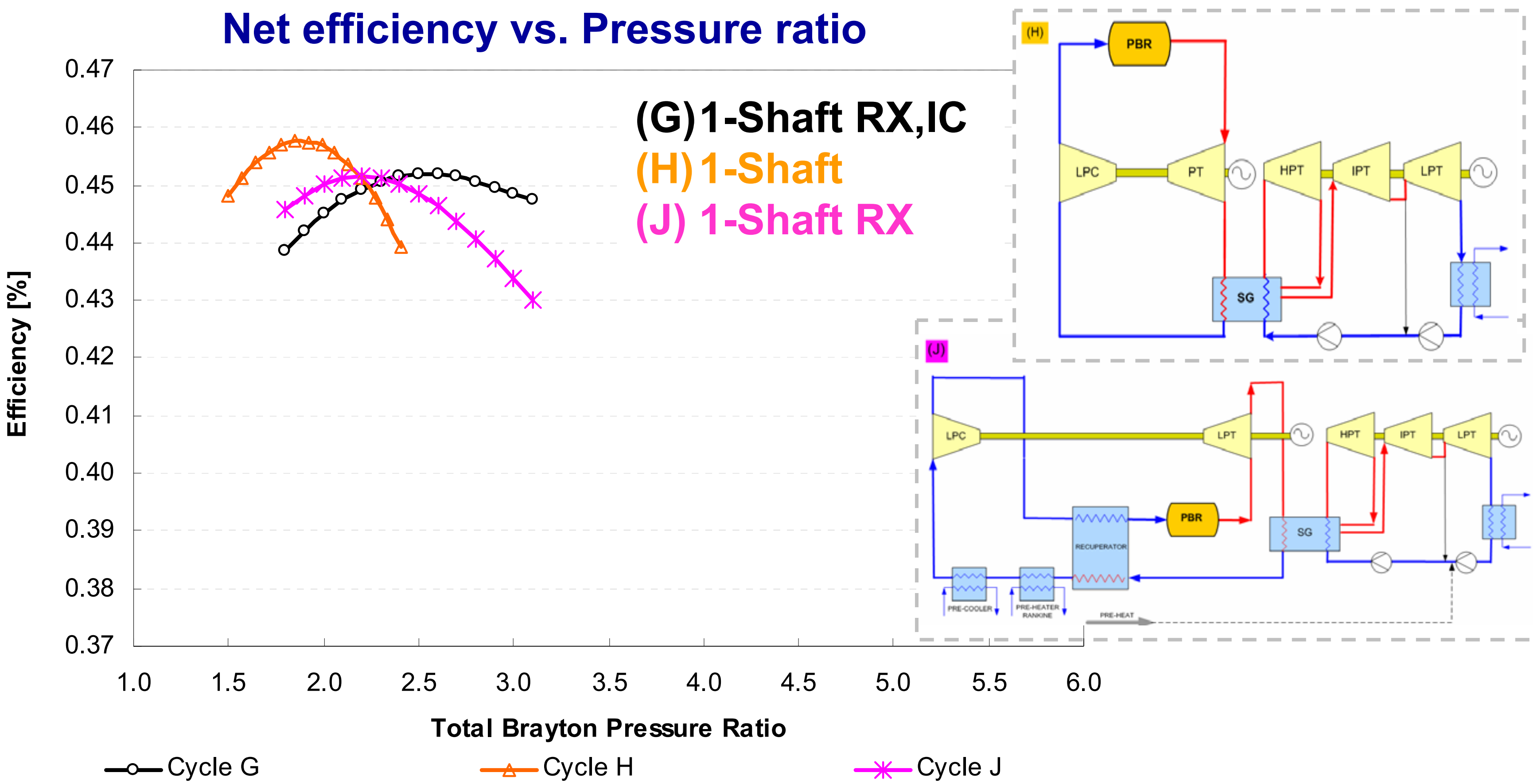
Cycle (H)





GTCC

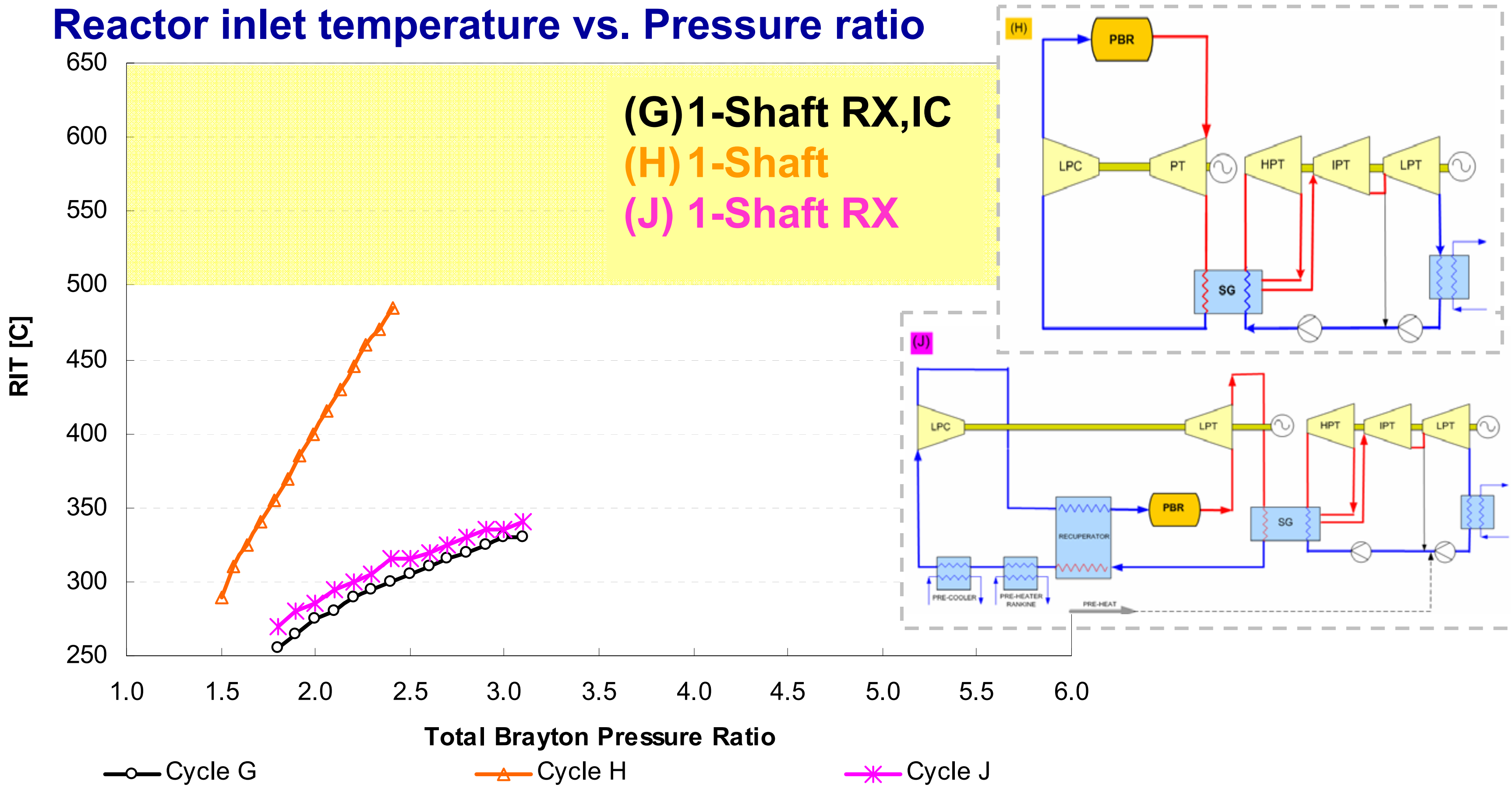
Net Cycle Efficiency



- **Cycle H has highest net cycle efficiency, however only a small difference exists between GTCC efficiencies**
  - Resulting from optimization and preheat at (G) and (J)

GTCC
RIT

Reactor inlet temperature vs. Pressure ratio

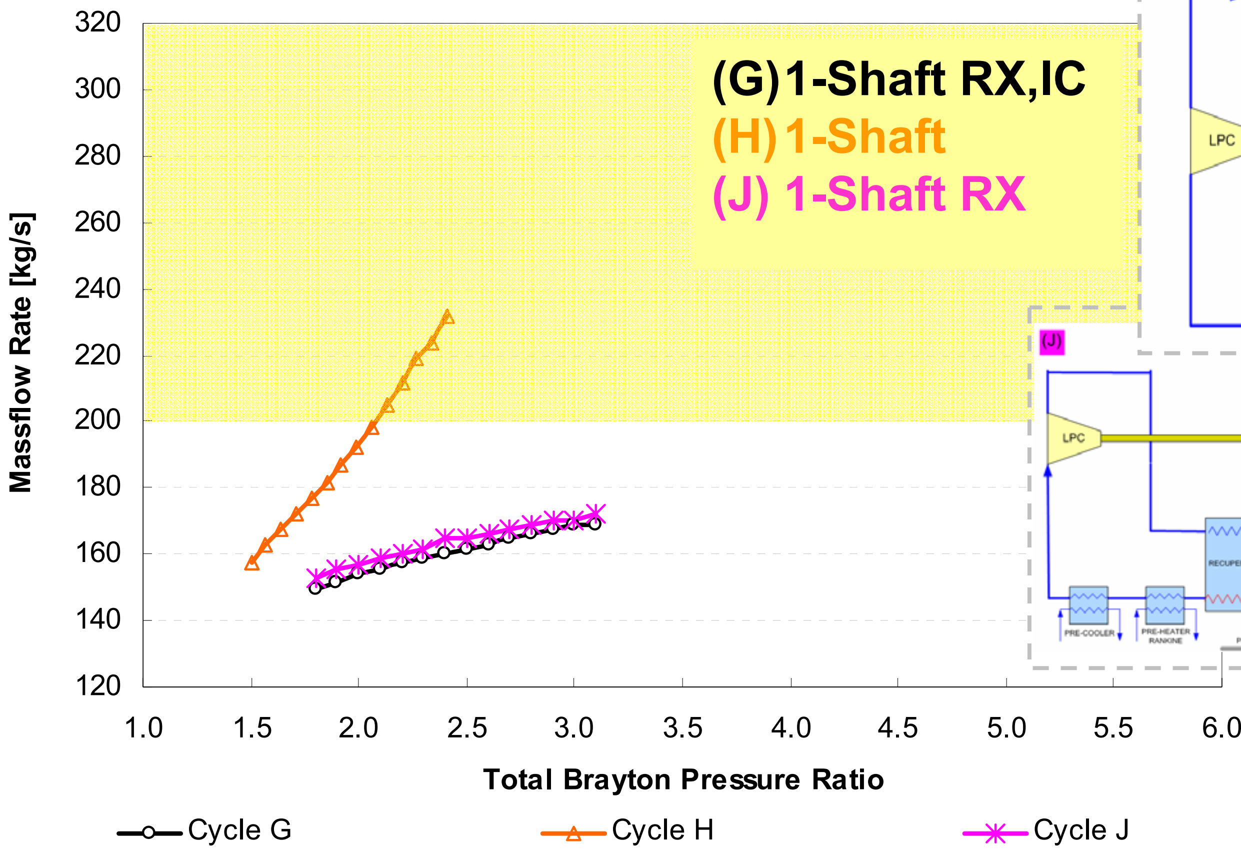


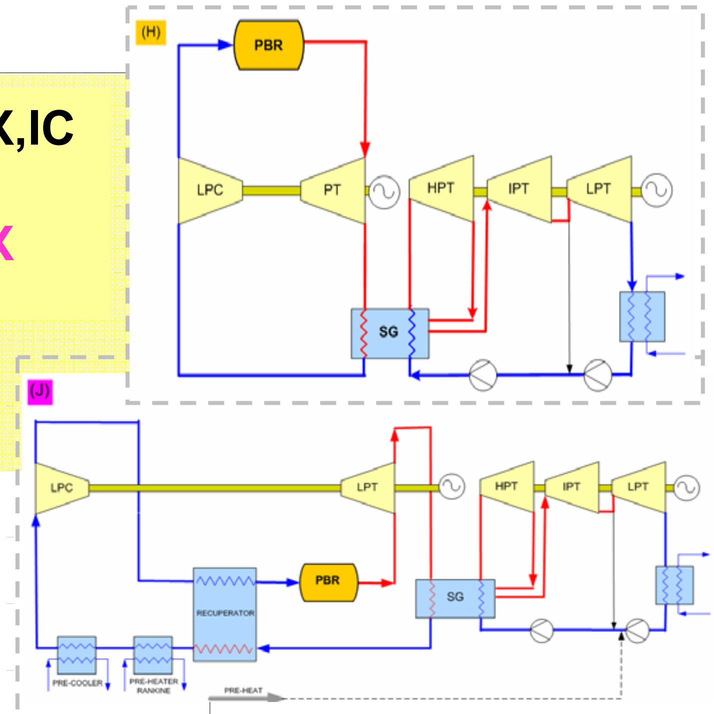
- **Maximum RIT of 500°C; to enable Core Barrel to operate below 427°C**
  - ➢ All GTCCs are able to operate at its maximum efficiencies within the envelope

GTCC

Mass Flow Rate

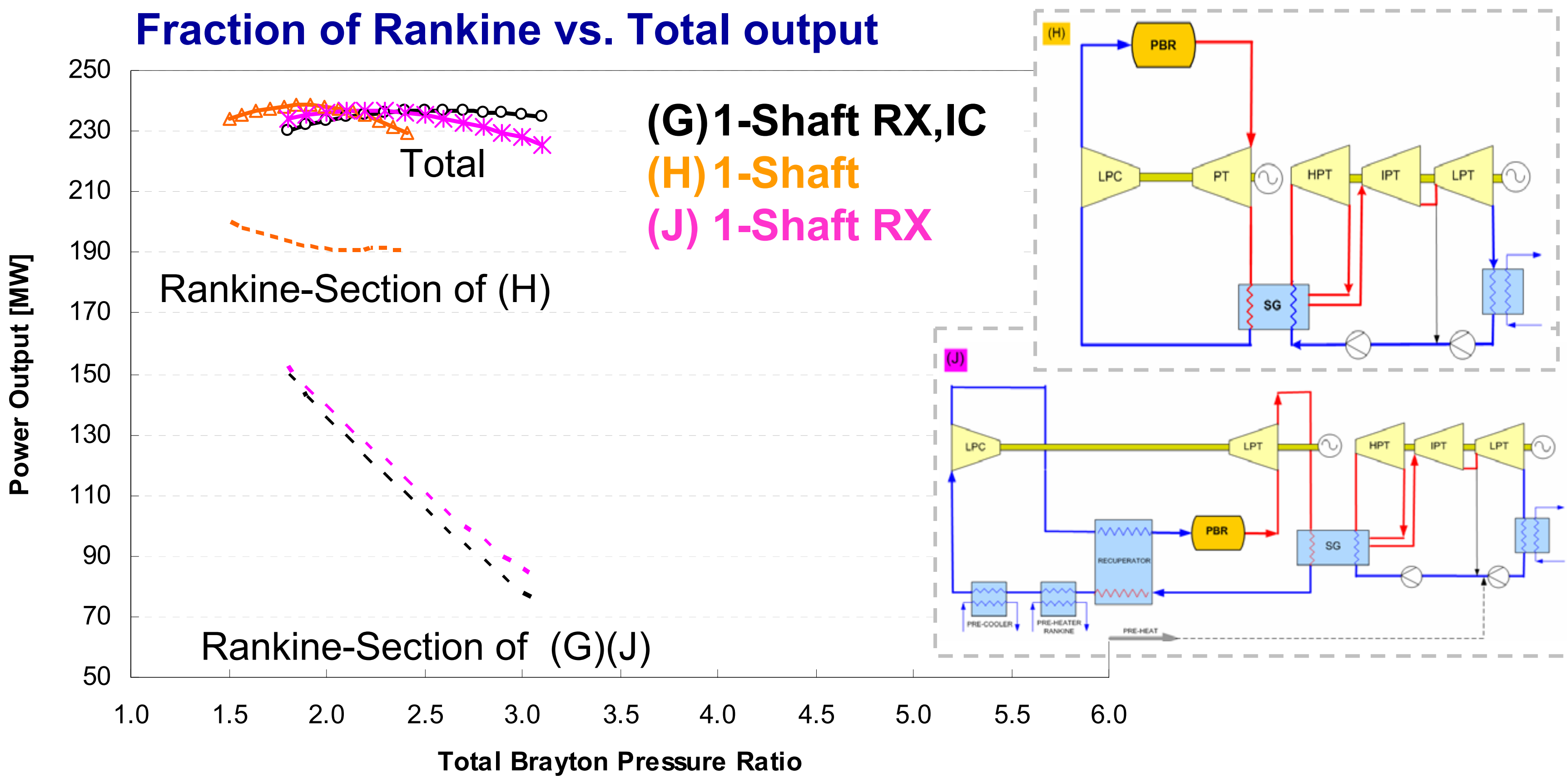
Mass flow rate vs. Pressure ratio





- **Maximum mass flow of ~200 kg/s; to limit reactor core velocity**
  - All the GTCCs are able to operate at its maximum efficiencies within the envelope

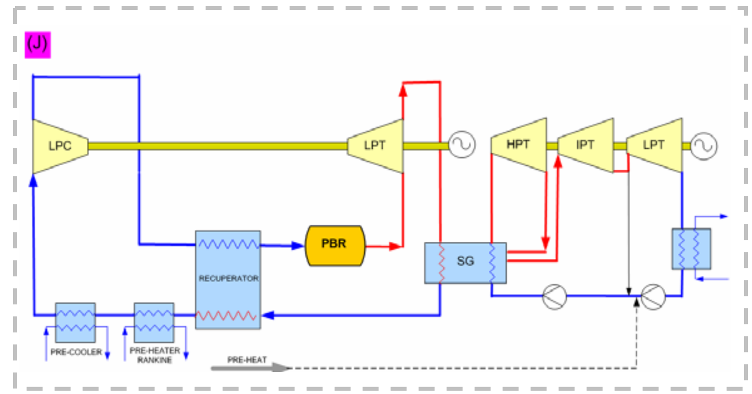
GTCC
Work Split



- **Cycle H: ~80% Rankine and 20% Brayton (large Rankine)**
- **Cycle J: ~50% Rankine and 50% Brayton (equal split)**

Choice of GTCC

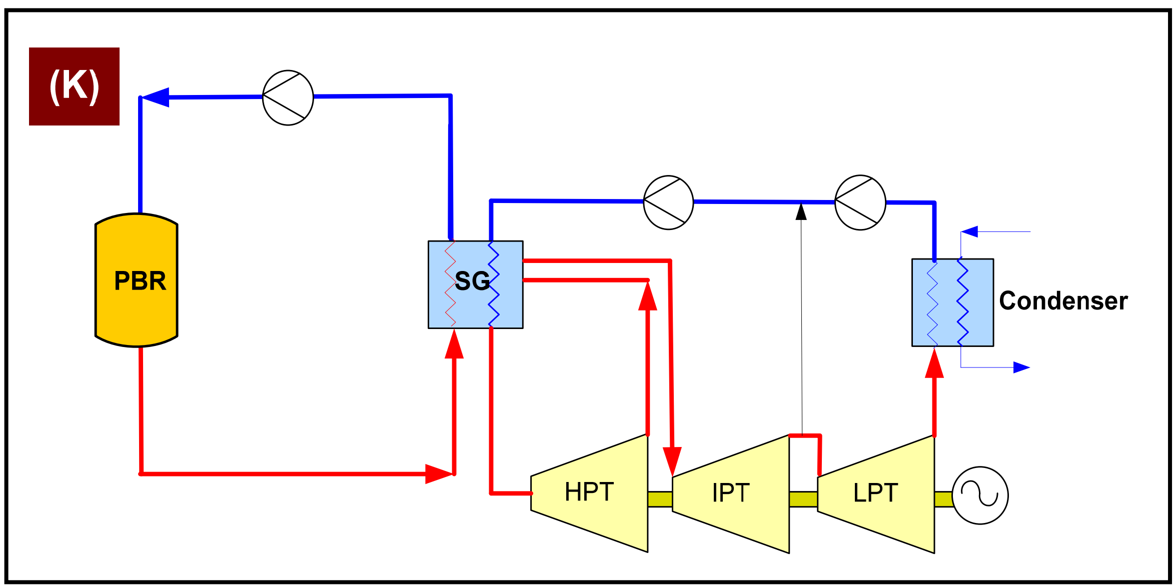
- **Criteria**
  - ➢ Performance (MEDIUM)
    - – *Net Cycle Efficiency –*
      - Cycle H – 45.8%,
      - Cycle J – 45.1%
  - ➢ Design Envelope (HIGH)
    - – *All GTCCs within envelope*
  - ➢ Readiness (HIGH)
    - – *Cycle H -*
      - Compressor inlet temperature ~200˚C – new turbo machine design (PBMR DPP 23˚C)
      - Cooling flow required
    - – *Cycle J:*
      - Builds on current PBMR DPP Brayton design (layout)
      - Utilizes PBMR DPP helium turbo machinery (operating conditions similar to DPP)



- **Conclusion**
  - ➢ Cycle J and H both good choices, however, Cycle J is perceived as lowest risk due to known Brayton turbo machinery
  - ➢ Cycle J selected as reference GTCC

Choice of Rankine

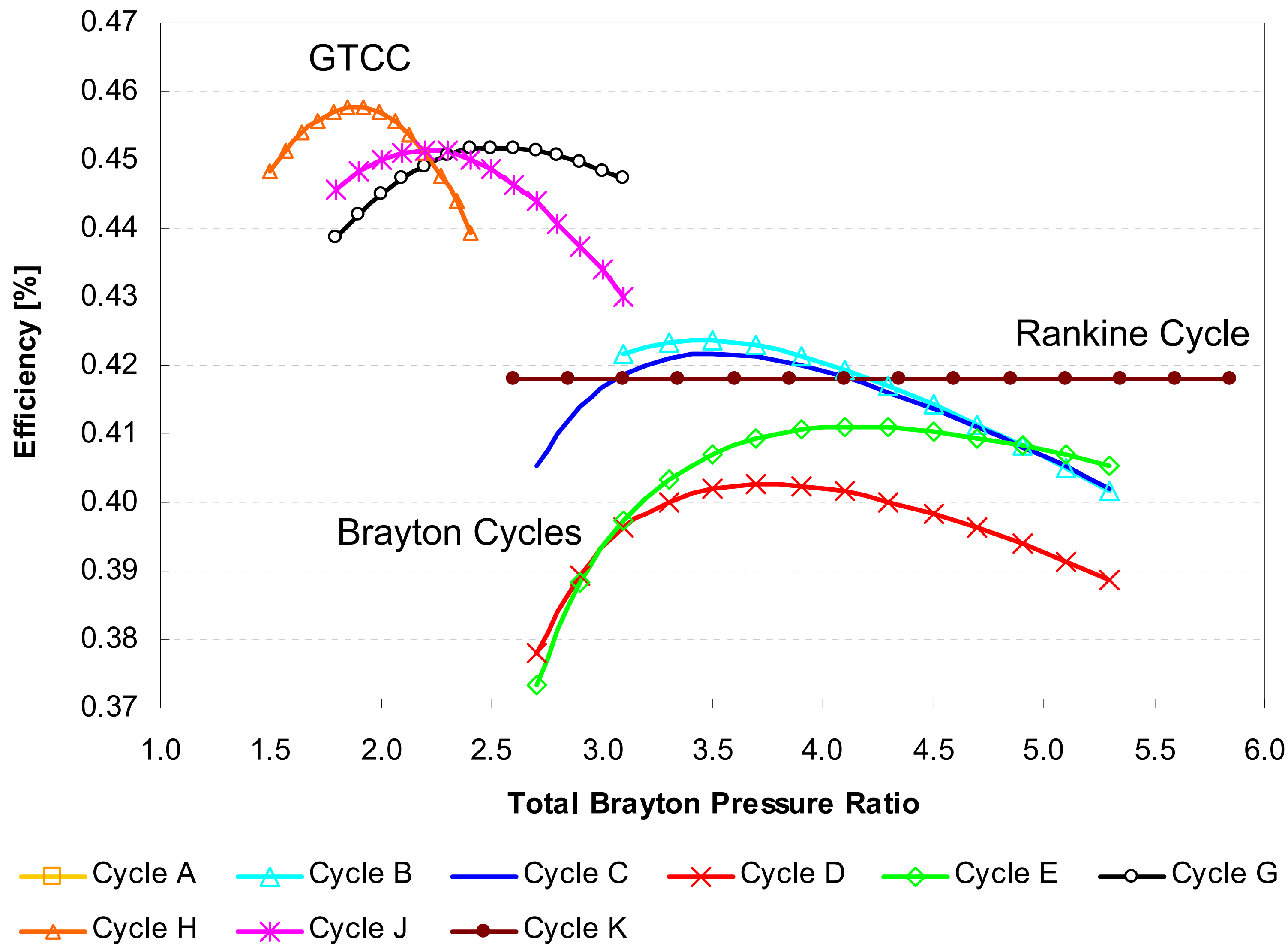
- **Evaluated a single "representative" Rankine cycle and hence Cycle K chosen by default**
  - Efficiency = 42%
  - Primary side mass flow = 160 kg/s (within reactor design envelope)
  - RIT = 300˚C (within reactor design envelope)



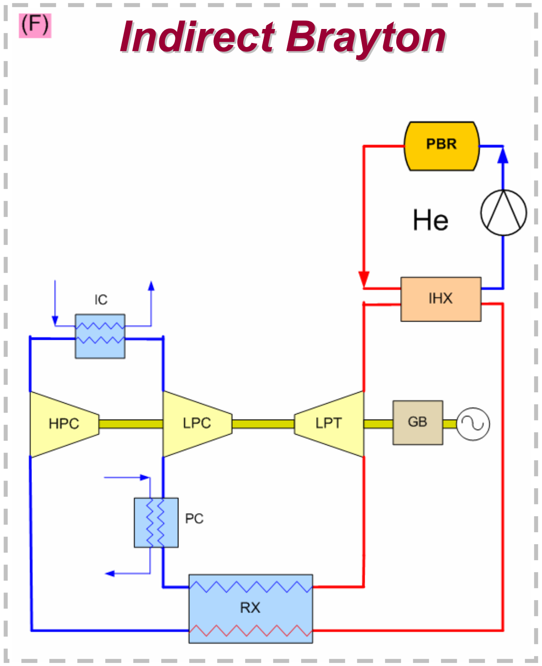
Part 2 Outline

- **Introduction**
- **Analysis Methodology**
- **Evaluation**
  - Brayton Cycles
  - GTCC
  - Rankine Cycles
- **Cycle Trade-offs**
- **Summary**

Net Cycle Efficiencies
Direct Cycles A, B, C, D, E, G, H, J, K



Direct- vs. Indirect Cycles

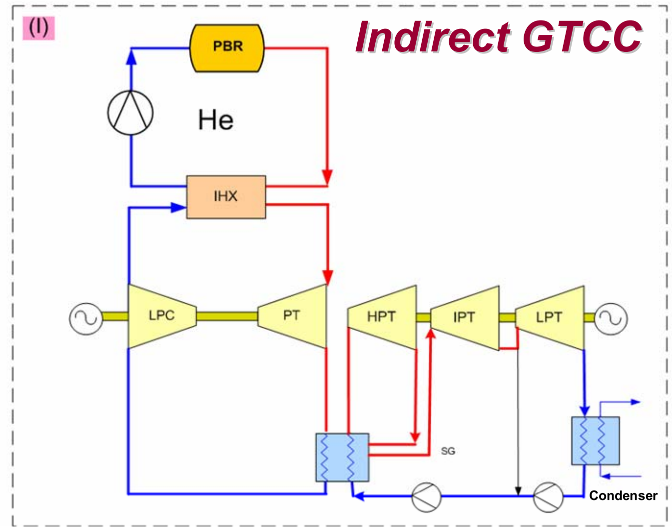


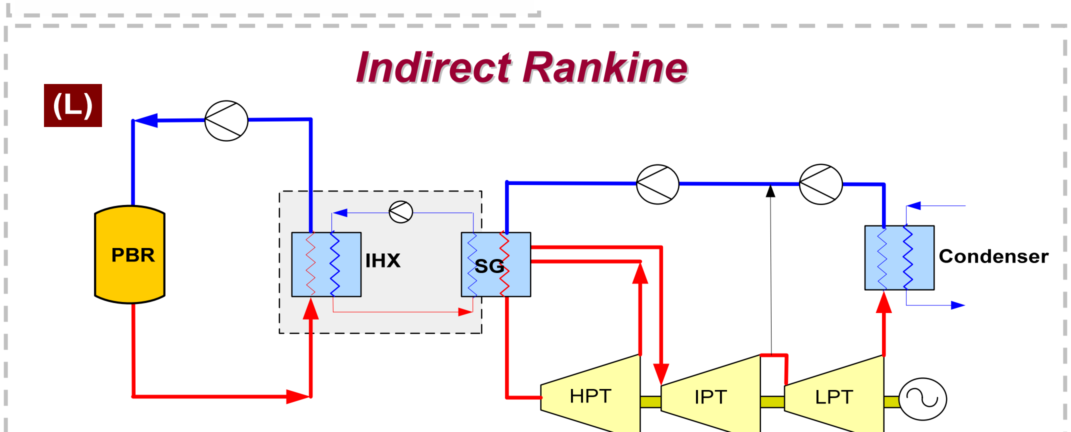
(F) Indirect single-shaft with inter-cooling

(Indirect version of Cycle B)

(I) Indirect single-shaft Brayton

(Indirect version of Cycle H)

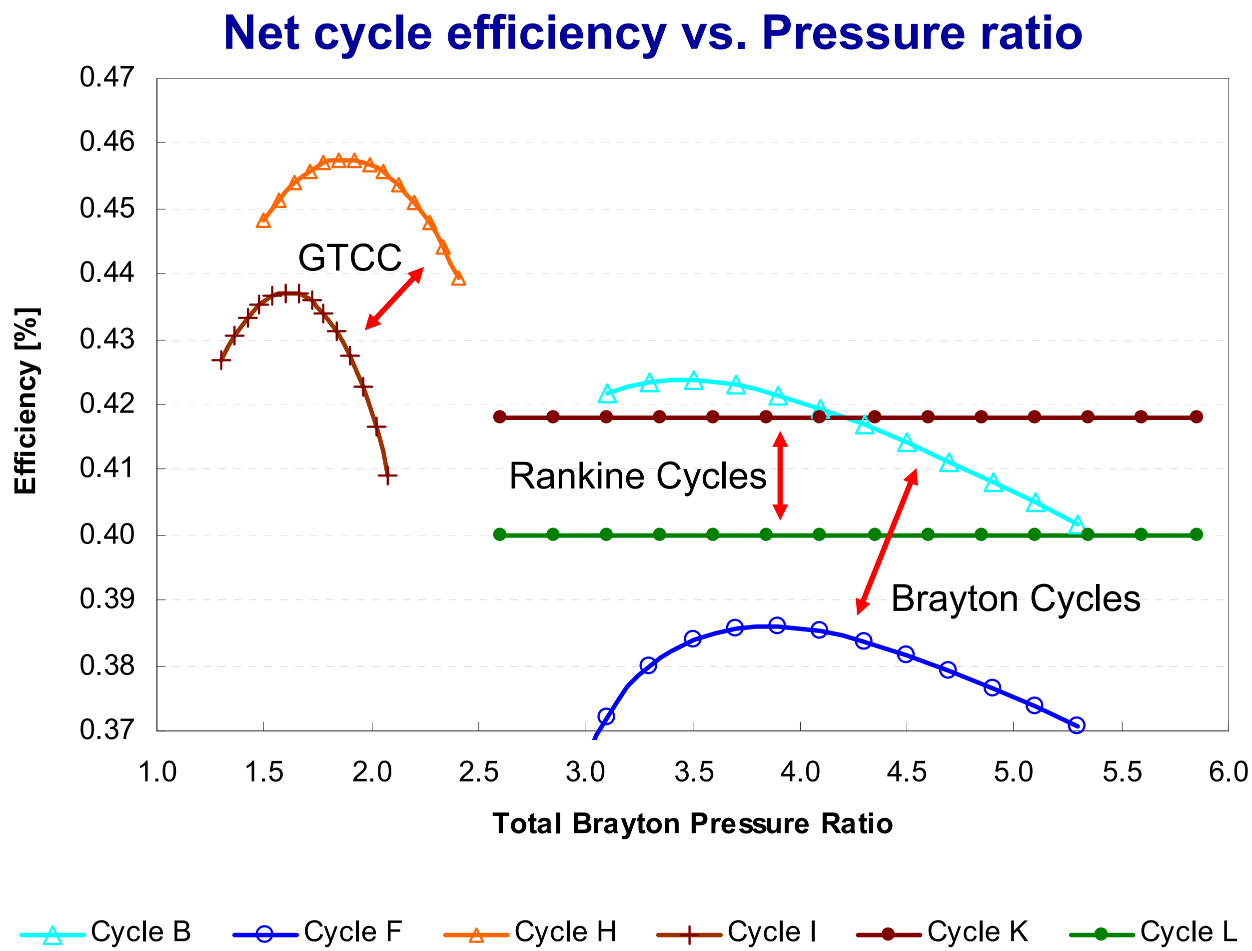




(L) Indirect secondary steam cycle

(Indirect version of Cycle K)

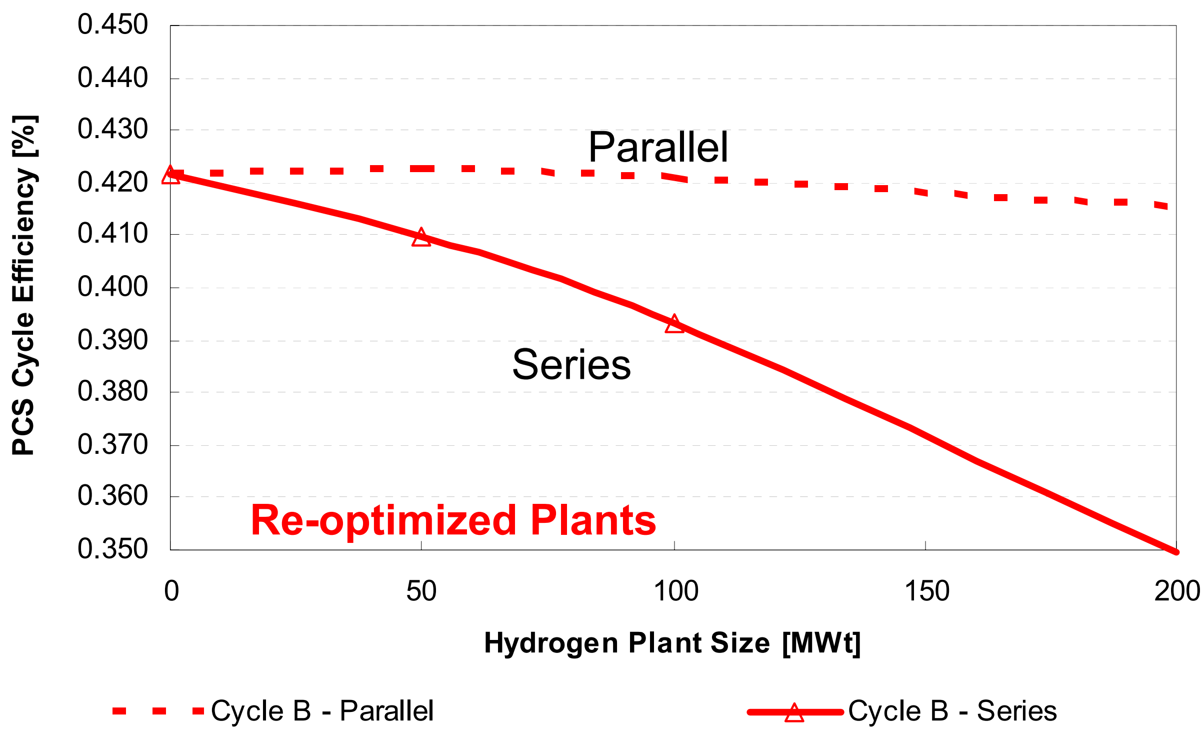
Indirect Cycles
Net Cycle Efficiency

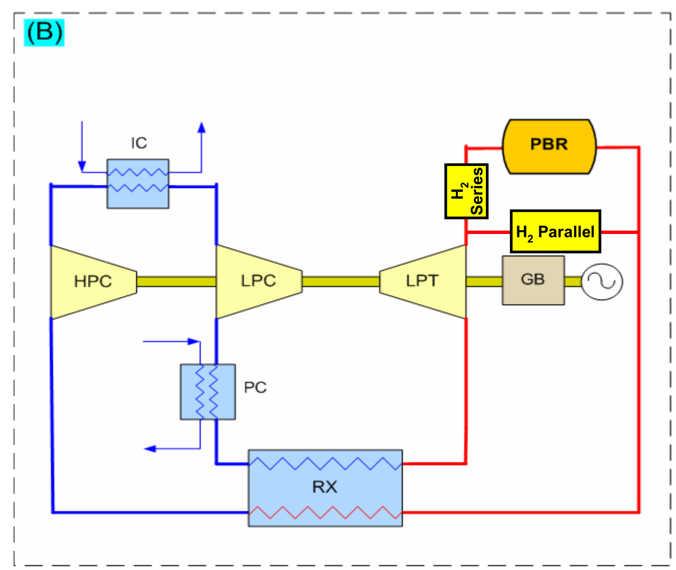


- **Indirect Cycles reduces the net cycle efficiency by:**
  - Brayton Cycle ~4%, GTCC ~2%, Rankine Cycle ~2%

Configuration Trade-offs
Brayton Series vs. Parallel

- **Effect of H_2 plant size and configuration on Direct Brayton Cycle (B) thermal efficiency**
  - Please note: parallel blower house load not included; parallel mixing not included

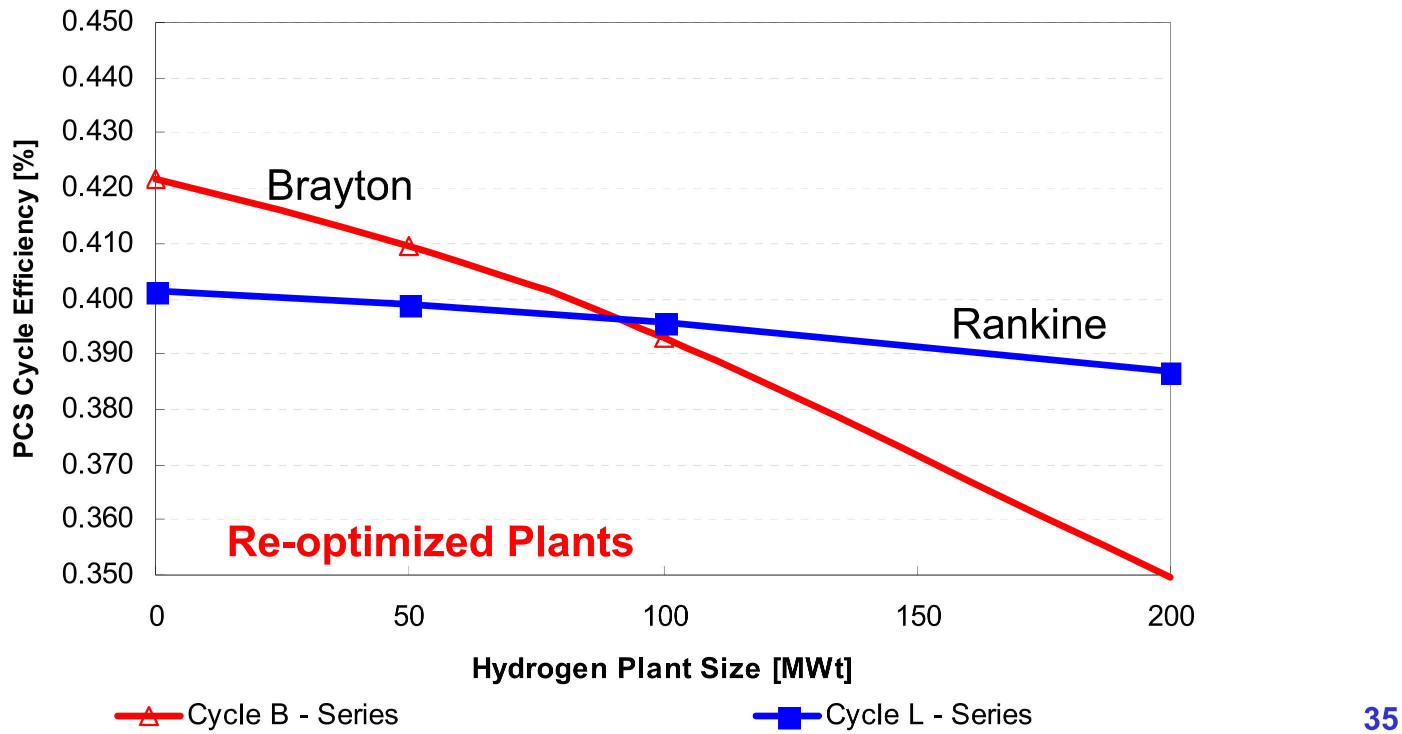




Configuration Trade-offs

Influence of Hydrogen plant size

- **Effect of H_2 plant size coupled in series on the thermal efficiency of a Direct Brayton Cycle (B) vs. Rankine Cycle (L)**
  - Rankine cycle efficiency > Brayton cycle efficiency above 100 MW hydrogen plant



Part 2 Outline

- **Introduction**
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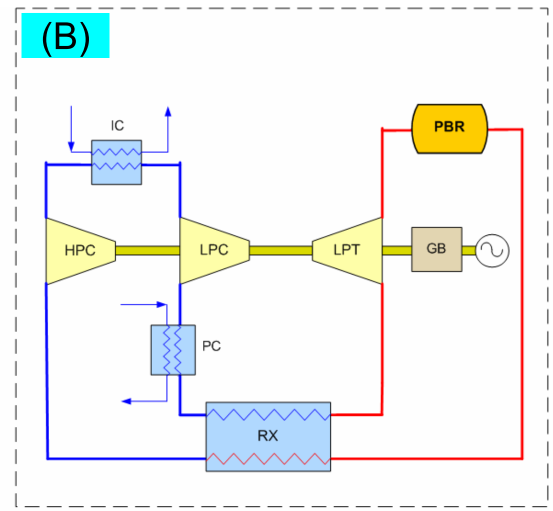
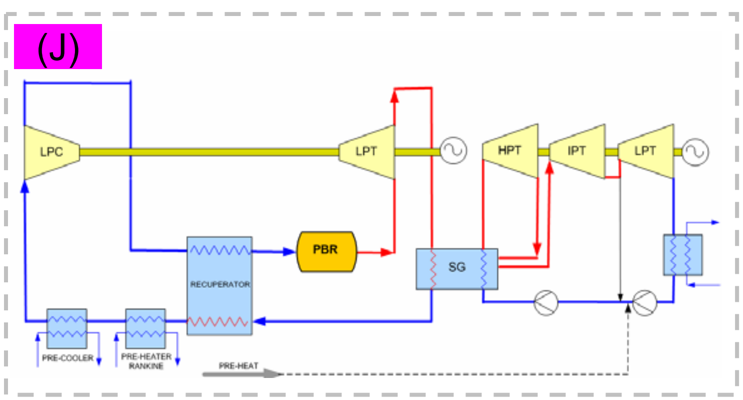
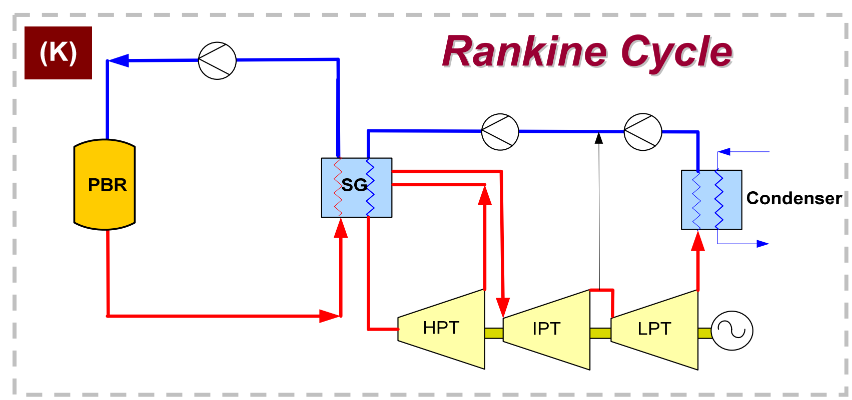
- **Evaluation**
  - Brayton Cycles
  - GTCC
  - Rankine Cycles
- **Cycle Trade-offs**
- **Summary**

Summary

- **Cycle B chosen as reference Brayton Cycle PCS**
  - Best efficiency
  - Turbo machine growth path
- **Cycle J chosen as reference GTCC PCS**
  - Builds on current PBMR DPP Brayton desigı
- **Conventional Rankine Cycle chosen for reference Rankine Cycle PCS**







APPENDIX 20.3.1: SPECIAL STUDY 20.3.1 SLIDES

PART 3 – HPU, IHX/MATERIALS, SHTS WORKING FLUID

SPECIAL STUDIES:
20.3 - HEAT TRANSPORT SYSTEM
20.4 - POWER CONVERSION SYSTEM

Part 3 – HPU, IHX/Materials, SHTS Working Fluid

December 6, 2006

Outline

- **Objective and Scope**
- **Study Inputs**
  - Commercial applications and performance requirements
  - Key NGNP HTS demonstration objectives
  - Key HTS functional requirements
- **Screening Criteria**
- **Power Conversion System Options (20.4)**
- **H_2 Production Unit Size (20.7)**
- **IHX/High-Temperature Materials**
- **Secondary Working Fluid**
- **HTS Configuration Options**
- **Recommended HTS Configuration**

H_2 Production Unit (HPU) Size: Input from Special Study 20.7

- **Minimum size that would allow scale-up of most critical component to commercial size**
  - ~5MWt
- **Scale of single train of commercial HPU**
  - ~50MWt

Outline

- **Objective and Scope**
- **Study Inputs**
  - Commercial applications and performance requirements
  - Key NGNP HTS demonstration objectives
  - Key HTS functional requirements
- **Screening Criteria**
- **Power Conversion System Options (20.4)**
- **H_2 Production Unit Size (20.7)**
- ➡ **IHX/High-Temperature Materials**
- **Secondary Working Fluid**
- **HTS Configuration Options**
- **Recommended HTS Configuration**

Introduction

- The IHX represents one of the most significant development challenges associated with the NGNP and related commercial process heat plants
- As earlier noted, the IHX is a key demonstration objective of the NGNP

Outline
IHX/High-Temperature Materials

- Introduction
- ➡ IHX Functions and Requirements
- IHX Design Options
- Readiness of Candidate Materials
- Codes and Standards Readiness
- Conclusions and Recommendations for NGNP

IHX Functions

- **Transfer thermal energy produced in the reactor from the helium primary coolant to the secondary heat transport system (SHTS) fluid**
  - During normal operational modes in which the thermal energy is utilized in the process
  - For designated events within the duty cycle, wherein reactor heat (reduced power or decay heat) is to be transported to an alternate heat sink, either in the SHTS or the process
- **Contain the helium primary coolant and the SHTS working fluid**

Key PBMR NGNP IHX Requirements

Configuration	HPU and PGS+	HPU Only
SHTS Working Fluid	Helium*	Helium*
Thermal Rating, MWt	510	5 – 50 From Special Study 20.7
PHTS Pressure, MPa	9.0	9.0
SHTS Pressure, MPa	9.0	9.0
Primary Outlet Temp, ºC	950	950
Primary Inlet Temp, ºC	340	Based on thermal rating [938 - 710]
Secondary Outlet Temp, ºC	900-925	900-925
Secondary Inlet Temp, ºC	290	Application Specific

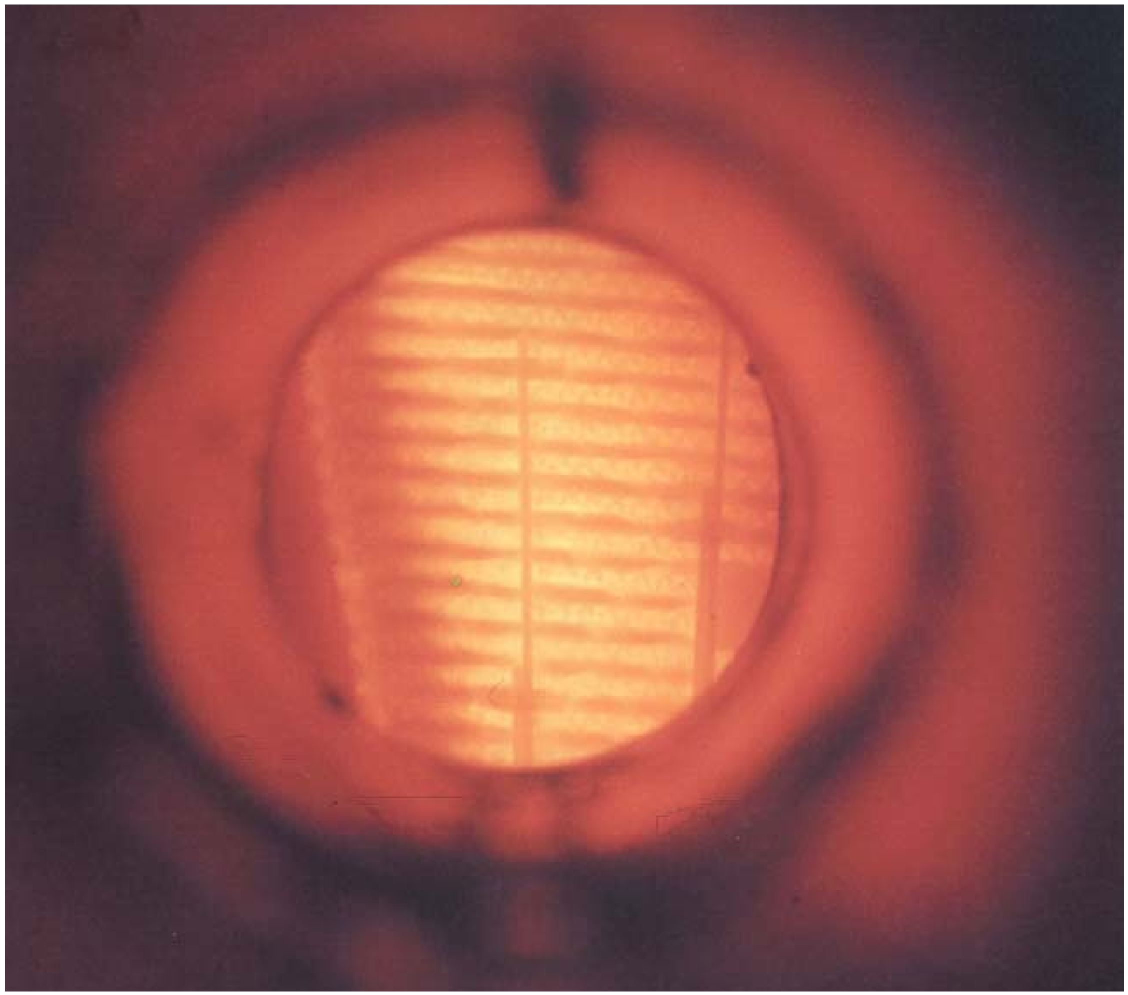
Additional Requirements for Commercial Plants (Preliminary):[Ref. 4]

Design Life (Minimum): 20yrs
Forced Outage Allocation: ~<1%

+ Essentially equivalent to commercial plant IHX

* Preliminary selection, based on prior work - to be confirmed

Test Plate-Fin HX at 1000C



(Courtesy C.F. McDonald)

Outline
IHX/High-Temperature Materials

- Introduction
- IHX Functions and Requirements
- ➡ IHX Design Options
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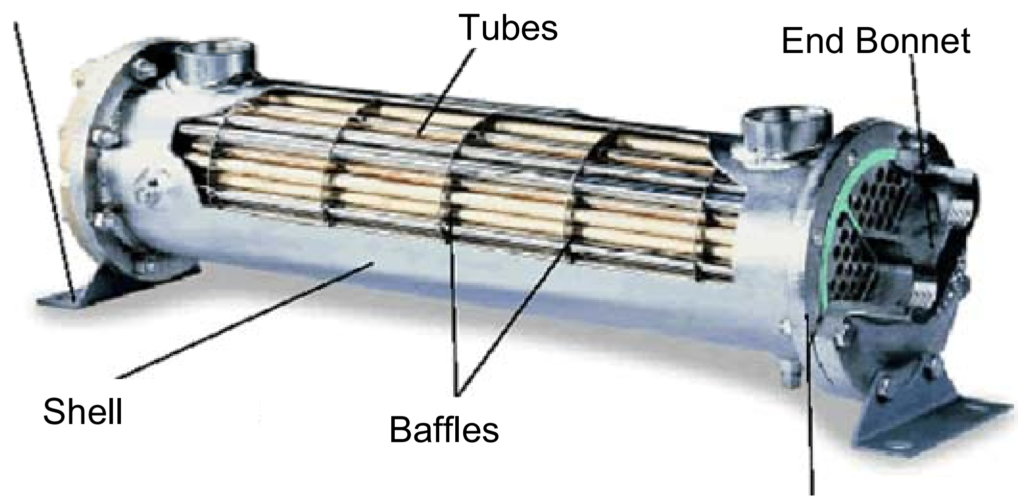
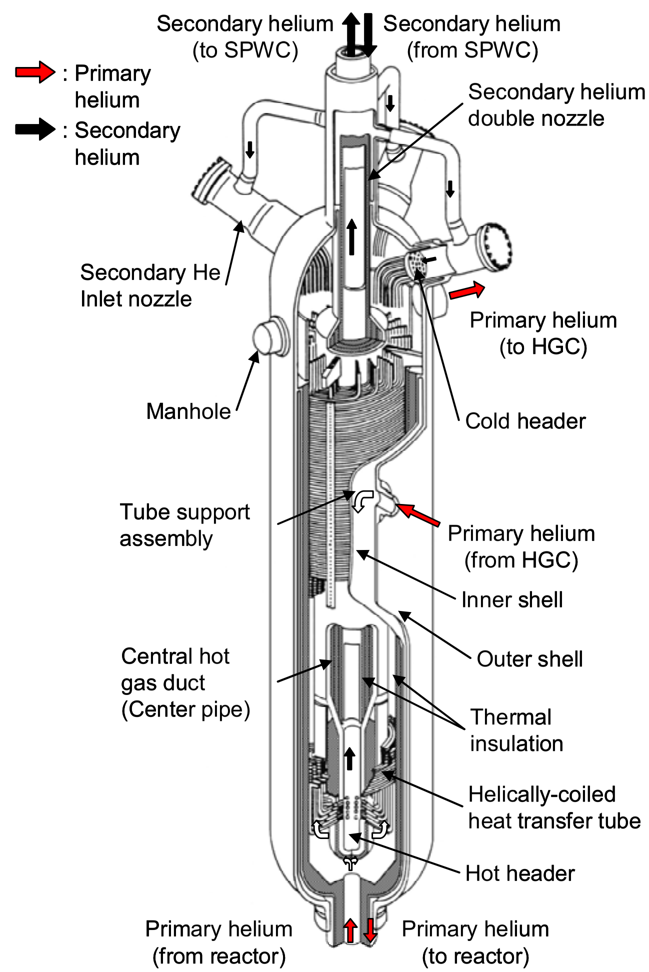
Tube and Shell HXs



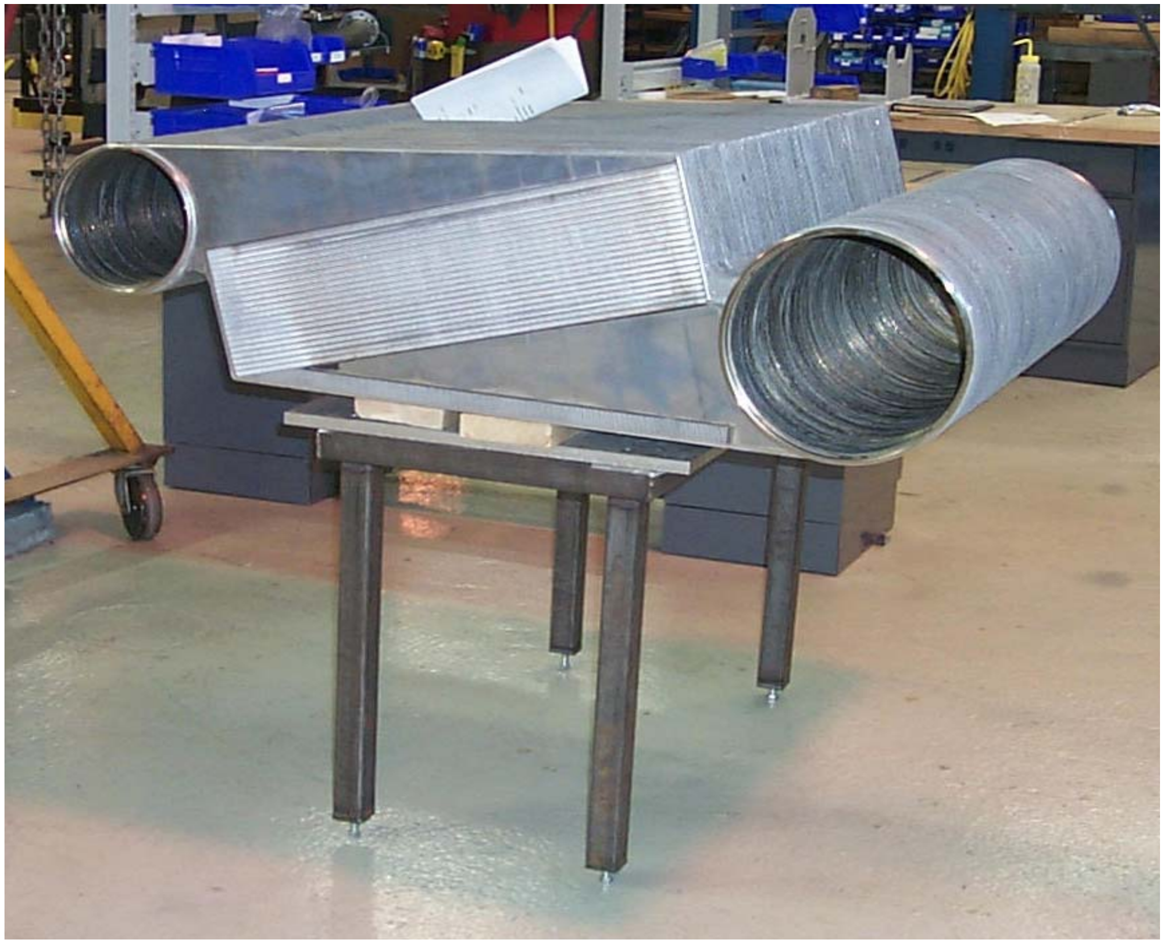
Straight-Tube HX

(Photo From API Heat Transfer)



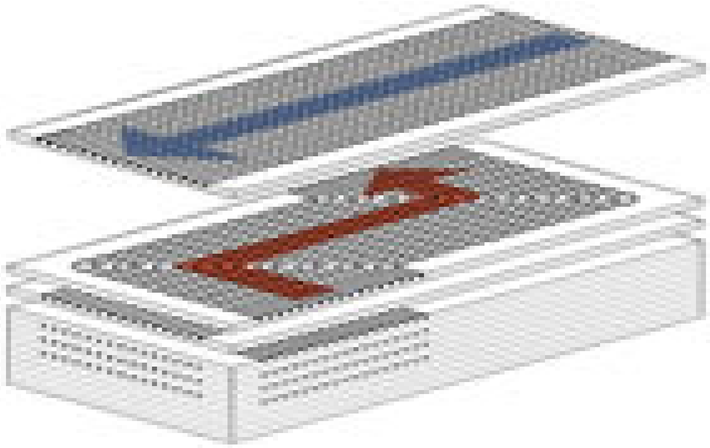
HTTR Helical Coil IHX

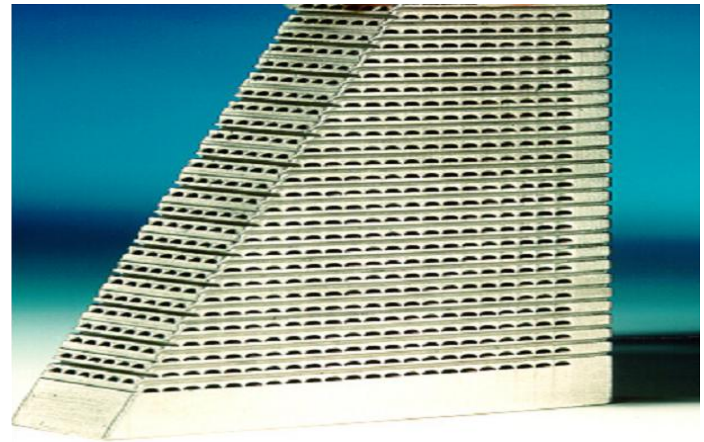
Plate-Fin HX



(Ingersoll Rand Energy Systems)

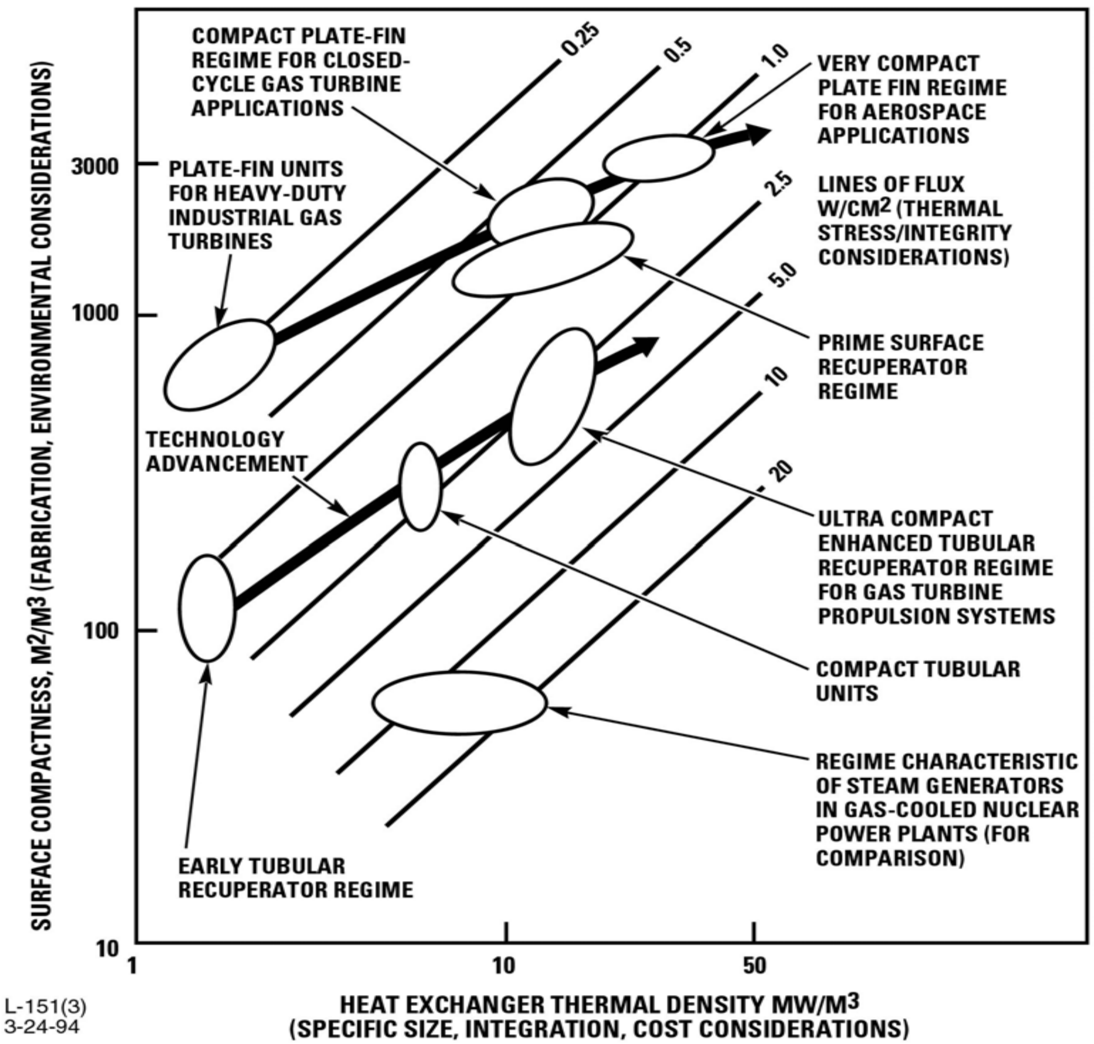
Printed Circuit Heat Exchanger (PCHE)





(Heatric)

Heat Exchanger Metrics



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3-24-94

Design Tradeoffs

Metric	Shell & Tube	Plate-Fin & Prime Surface	PCHE
Compactness (m^2/m^3 & MW/m^3)	Poor	Best	Good
Cost (t/MWt)	Poor: (13.5 tons/MWt)* Unlikely to be commercially viable	Best: Most compact, least materials	Good: (0.2 tons/MWt)* Estimated to be ~1/68 that of S&T
Experience Base	HTTR, German PNP Development	Conventional GT recuperators	PBMR DPP Recuperator, other commercial products
Robustness	Best: Simple cylindrical geometry, stress minimized in HT area	Worst: Thin foils; stressed welds in pressure boundary; stress risers in pressure boundary welds; Small material and weld defects more significant	Good: Thicker plates; local debonding does not immediately affect pressure boundary; potential for higher transient thermal stresses vs. P-F
Inspection and Maintenance	Design facilitates inspection and plugging of individual tubes	Inspection and maintenance difficult or impractical below module level	Inspection and maintenance difficult or impractical below module level
HX Integration	Headers and HX-vessel integration demonstrated	More difficult HX integration with multiple series/parallel modules	More difficult HX integration with multiple series/parallel modules
Code Basis for Design	Existing Sect VIII Code basis for tubular geometries	No existing Code basis	No existing Code basis
* Reference 5			

Preliminary Design Selection

PCHE selected as preliminary basis for NGNP IHX:

- **Shell & tube (S&T) eliminated as not commercially viable for large IHX**
- **PCHE judged to be more robust than other compact designs**
  - Solid basis of commercial experience, albeit at lower temperatures
- **Tradeoffs vs. S&T include:**
  - More difficult inspection and maintenance
  - Need to establish design basis for Code acceptance (additional discussion follows)

Outline
IHX/High-Temperature Materials

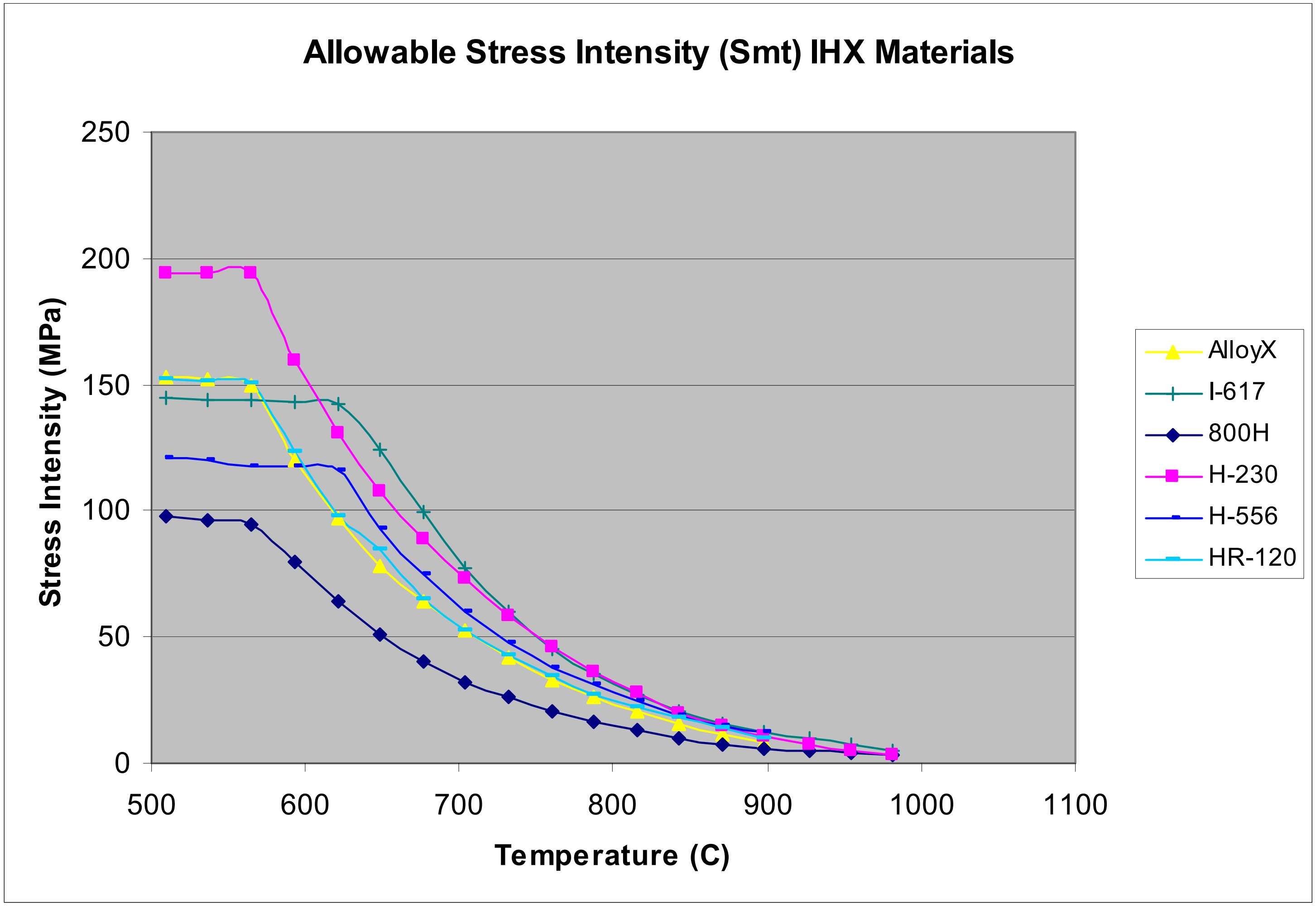
- **Introduction**
- **IHX Functions and Requirements**
- **IHX Design Options**
- **Readiness of Candidate Materials**
- **Codes and Standards Readiness**
- **Conclusions and Recommendations for NGNP**

Leading Candidate Metallic Materials for IHX

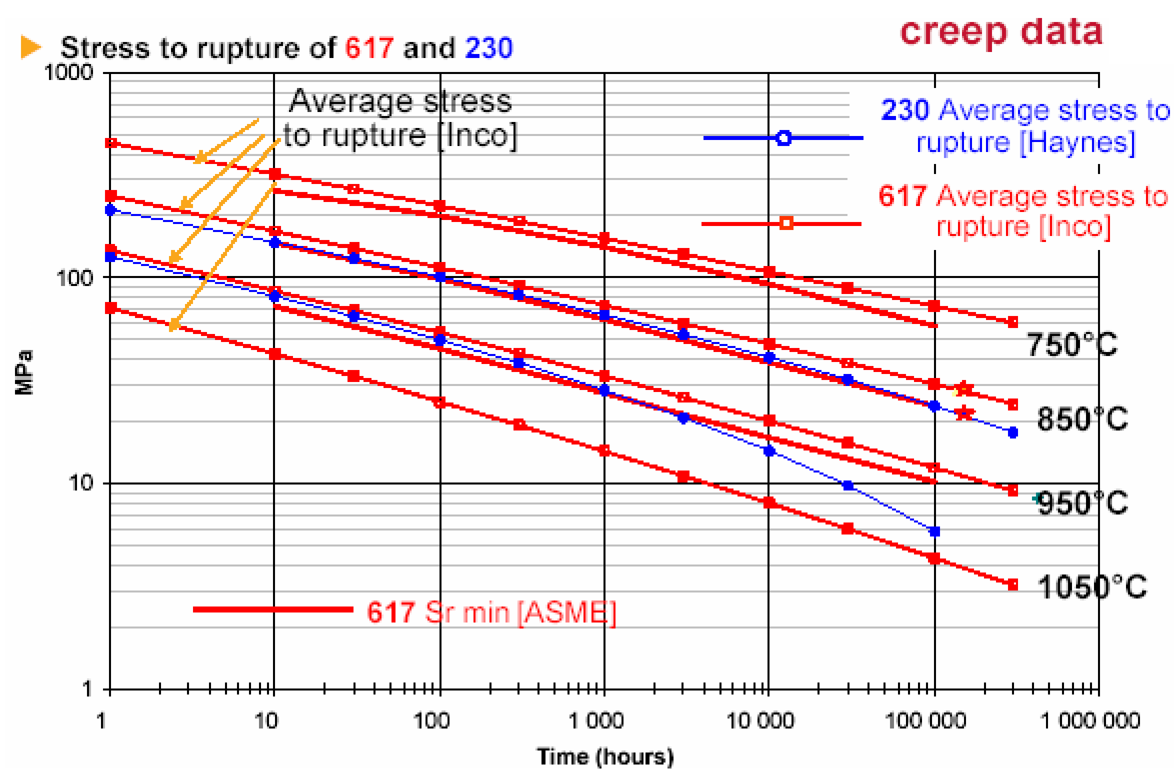
- **Candidate metallic materials (~30) identified in NGNP Materials R&D Program Plan [Ref. 6]**
- **Further evaluation has identified four leading candidates that should be given further consideration:**
  - Inconel 617CCA*
  - Haynes 230 (a main focus of EU HTGR materials development)
  - Haynes 556
  - HR-120
- **Other advanced metallic materials (e.g., Oxide Dispersion Strengthened [ODS]) potentially have higher temperature capability, but are not practical alternatives in timeframe of NGNP**
  - For ODS, no practical manufacturing technologies exist that do not degrade material properties

* **More tightly controlled I-617 specification developed within the Ultrasupercritical Fossil Program**

Metallic Materials Overview



Creep data for I-617 & H-230
(Data from INCO & Haynes)



Marginal design properties at highest temperatures of interest. Note fall-off of Haynes 230 at highest temperatures

Pros and Cons of Metallic Materials Candidates

- **Inconel 617**

  Pros: Best HT mechanical properties; significant helium database in Germany (but access to German data uncertain)

  Cons: High Co; greater susceptibility to internal oxidation; wide specification range leads to inconsistent properties

- **Haynes 230**

  Pros: Low Co; more corrosion resistant than I-617; focus of EU development

  Cons: High W, mechanical properties fall off in highest temperature regions

- **Haynes 556**

  Pros: Second best HT mechanical properties; highest carburization resistance

  Cons: High Co; no experience in helium, implies increased R&D needs

- **HR-120**

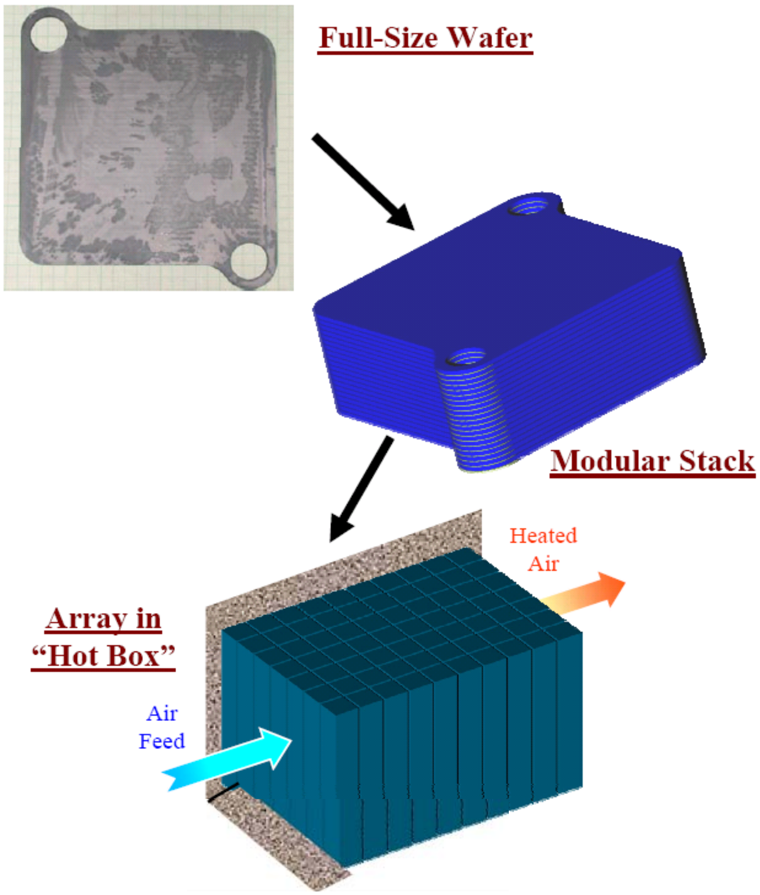
  Pros: Low Co

  Cons: Less stability at high temperature; no experience in helium, implies increased R&D needs

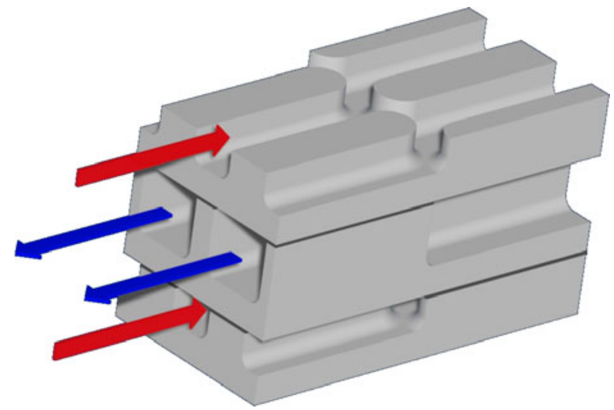
Metallic Materials Summary

- **Existing metallic materials can be applied in temperature regime of NGNP IHX, albeit with significant limitations:**
  - Will require designs based on very low stresses during normal long-term operation
  - Transient-related stresses will be more significant in compact IHXs (needs further evaluation)
  - Likely need to replace IHX core multiple times over 60-year design life of plant
- **Present metallic materials are likely not the optimum long-term solution for commercial process heat plants operating in the NGNP temperature range**

Ceramic HX Concepts



SiC HX Concept
(Ceramatec)



Unit cell of offset-fin Liquid Si Injected composite plate HX
(UC Berkley)

Ceramic Materials Summary

- **Ceramic materials presently being evaluated are:**
  - Monolithic SiC
  - Composites, such as carbon fiber reinforced composites with liquid Si injection
- **Challenging development issues**
  - Development of reliable, cost effective HX design and associated fabrication technologies
  - Ceramic-metallic interfaces must also be addressed
  - No Code basis exists for the use of ceramic materials in pressure boundary applications
- **Ceramic IHXs are unlikely to be available in a timeframe that would support initial NGNP deployment**
  - But, high incentives for ultimate demonstration of a IHX based on ceramics (or other advanced material)
  - Given their importance, ceramic HX development deserves accelerated effort in parallel with metallic options

Outline
IHX/High-Temperature Materials

- Introduction
- IHX Functions and Requirements
- IHX Design Options
- Readiness of Candidate Materials
- ⇨ **Codes and Standards Readiness**
- Conclusions and Recommendations for NGNP

Codes and Standards Readiness

- **Metal alloys that could potentially be used to construct the IHX are not currently a part of the ASME Nuclear Code, Section III**
  - A significant effort will be required to resolve this issue because a reliable database potentially useful for a code case based on three well-documented heats of material is not available
- **There is no existing ASME Code basis (Section III or other) for the application of ceramics in pressure boundary applications**
- **There is no existing ASME Section III design basis for either a conventional tube and shell IHX or less conventional plate-type IHX**
- **The most expedient approach for the NGNP IHX appears to be development of an application-specific design basis and submittal of a Section III code case associated with Subsection NH**
  - A significant effort will also be required to resolve this issue because an openly available design basis is not available in a format suitable for a code case
- **If a plate-type IHX is selected, testing of prototype IHX units would be needed to support the code case design basis for the specific IHX design selected**

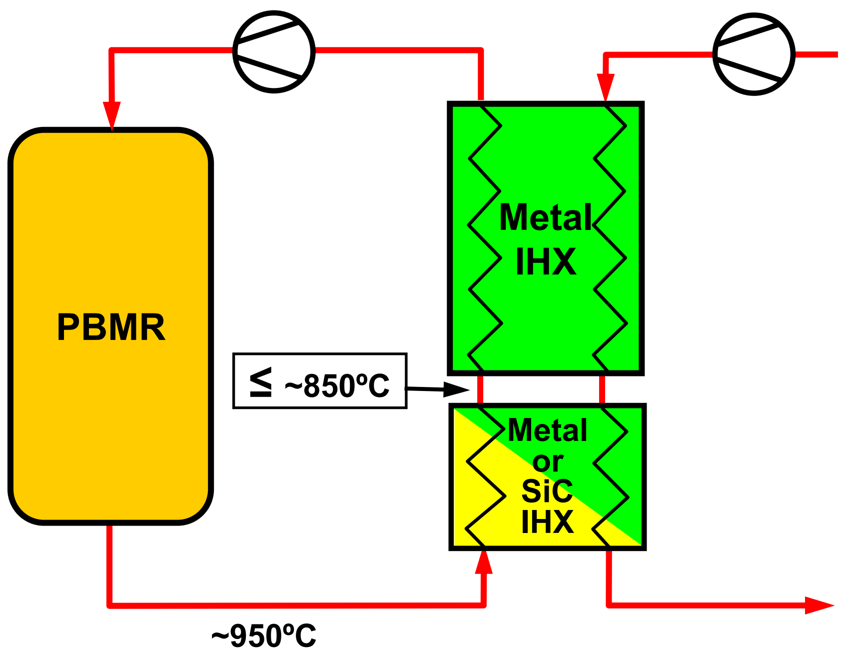
Outline
IHX/High-Temperature Materials

- Introduction
- IHX Functions and Requirements
- IHX Design Options
- Readiness of Candidate Materials
- Codes and Standards Readiness
- ⇨ Conclusions and Recommendations for NGNP

Recommendations for NGNP IHX Design

- **The reference IHX for NGNP preconceptual design should be a PCHE utilizing one of the four earlier identified metallic alloys**
  - I-617 and Haynes 230 are leading candidates, based on reduced R&D needs
- **If a large IHX is applied, it the HX should be designed to allow replacement of the highest temperature section, independent of the remainder of the IHX (see following figure)**
- **The IHX core should be contained within a pressure vessel(s) that is designed to ASME Section III, Subsection NB (no creep) and should be insulated and cooled as required**
- **The functions and requirements of the IHX heat transfer surface with respect to control of radionuclide release should be further evaluated**

Large, 2-Section IHX



A two-section IHX, which applies different materials in each section may provide an acceptable solution

- 2-Section IHX applies ceramic or composite materials in high-temperature section, metal in lower temperature areas
- Potential to start with metal in high-temperature section (short lifetime) and then replace with ceramic/composite when ready
- Potential to operate at ≤ ~850ºC without high temperature section and then add later
- Impacts of transient events need to be assessed

Recommendations for NGNP Development

- **An appropriate design and materials development program should be pursued for the IHX**
  - The development program should include fabrication and testing of representative IHX modules in a heat transfer test facility (modified PBMR Helium Test Facility potential option)
- **Based on the above, a shorter term target should be development of one or more code cases that provide an ASME basis for the materials, design and fabrication of the NGNP IHX**
- **A longer term target should be revision of Subsection NH**

IHX/Materials References

1. Lahoda, E.J., et.al., "Estimated Costs for the Improved HyS Flowsheet", HTR2006, October 2006.
2. H2-MHR Conceptual Design Report: SI-Based Plant (GA-A25401), General Atomics, April 2006.
3. H2-MHR Conceptual Design Report: HTE-Based Plant (GA-A25402), General Atomics, April 2006.
4. IHX Information Needs, PBMR, December 2005.
5. Dewson, 2003, (The Development of High Efficiency Heat Exchangers for Helium Gas Cooled Reactors), Paper 3213, ICAPP.
6. Hayner et al, 2006 (NGNP Materials R&D Program Plan), INL/EXT-06-11701, August 2006.
7. K. Natesan, A. Moisseytsev, S. Majumdar and P. S. Shankar, "Preliminary Issues Associated with the NGNP IHX Design", ANL/EXT-06-46, September 2006.

Outline

- **Objective and Scope**
- **Study Inputs**
  - Commercial applications and performance requirements
  - Key NGNP HTS demonstration objectives
  - Key HTS functional requirements
- **Screening Criteria**
- **Power Conversion System Options (20.4)**
- **H_2 Production Unit Size (20.7)**
- **IHX/High-Temperature Materials**
- ⇨ **Secondary Working Fluid**
- **HTS Configuration Options**
- **Recommended HTS Configuration**

Outline
Secondary Working Fluid

- ⇒ Introduction
- Key Functions & Requirements
- Overview of Coolant Properties
- Comparison of Options
- Summary & Recommendations

Introduction

- **Commercial PHP applications and the NGNP require transport of high temperature thermal energy from the nuclear heat source to the point of use**
  - Presently 100m for HyS for nominal reference [Ref.1]
- **Prior SHTS working fluid evaluation resulted in selection of helium for PBMR PHP**
- **For the NGNP, the secondary heat transport system (SHTS) working fluid selection will influence both the configuration and Hydrogen Production Unit (HPU) designs**
  - Key components: IHX, Process Coupling Heat Exchanger (PCHX)
  - Candidate fluids include helium, CO_2, liquid salts and liquid metals

Ref.1: Smith, C., S. Beck, and B. Galyean, 2005, "An Engineering Analysis for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor", INL/EXT-05-00137 Rev 0, March 2005.

Secondary Coolant Options

- **Helium**
  - Experience base with HTGRs
  - Chemically inert
  - Highest conductivity of candidate gases → smaller heat exchangers
- **CO2**
  - Experience base with Magnox/AGRs
  - Potentially reduces pumping power requirements, cost relative to helium
- **Liquid Salt (LS)**
  - Prior nuclear experience at high temperatures (MSRE, ATR)
    - *Molten Salt Reactor Experiment/Molten Salt Breeder Reactor (MSRE/MSBR)*
    - *Aircraft Reactor Experiment/Aircraft Reactor Test (ARE/ART)*
  - Industrial experience, but with different compounds in baths vs. loops
  - Feasibility established
  - Temperature range of applicability bounded by melting/boiling points
- **Liquid Metal**
  - No experience in temperature range of interest
  - Materials compatibility at high temperatures problematical per ORNL
  - Temperature range of applicability bounded by melting/boiling point
- **This NGNP evaluation focused on helium, CO_2 and LS**

Overview of Tradeoffs

- **Performance**
  - Volumetric heat capacity (ρC_p) and viscosity (η) influence pumping power
  - Thermal conductivity (k) influences heat exchanger size
- **Components**
  - Design considerations
  - Materials adequacy and compatibility
- **Operational**
  - Implications for duty cycle
- **Availability, Reliability & Investment Protection**
  - Probability of failures
  - Failure modes and effects
- **R&D Requirements**
- **Economics**
  - Size and cost
  - Pumping power

Outline
Secondary Working Fluid

- Introduction
- ➡ **Key Functions & Requirements**
- Overview of Coolant Properties
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SHTS Functions

- **Principal Functions**
  - During operational modes in which the thermal energy produced in the nuclear reactor is utilized in the process, transport thermal energy produced in the reactor from the IHX to the process coupling heat exchanger (PCHX)
  - Contain the secondary fluid during all operational modes
- **Potential Function**
  - For designated events within the duty cycle, transport reactor heat (reduced power or decay heat) to an alternate heat sink, either in the SHTS or the process. [Note: The scope of this function is TBD.]
- **Ancillary Functions**
  - Minimize energy losses (regenerative and to the environment)
  - Support personnel and investment protection goals
  - Support reliability and economic goals

Outline
Secondary Working Fluid

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Properties of Candidate SHTS Fluids

Property	Helium	CO_2	$(LiF)_2 \cdot BeF_2$ (FLiBe)	NaF-KF-LiF (11.5-42-46.5) (FLiNaK)	$NaF \cdot BeF_2$ (57 – 43)	$KF\text{-}ZrF_4$ & $RbF\text{-}ZrF_4$	Alkali Fluroborates (Mix Req'd)
T_{melt}, C	NA	NA	459	455	340	380 - 410	TBD
T_{boil}, C	NA	NA	1430			ZrF_4 family recommended for consideration by ORNL.	
ρ, kg/m^3 (7MPa/9MPa)	4.3/5.5 (@500C) 2.6/3.4 (@1000C)	47.6/61.1 (@500C) 34.0/43.5 (@800C)	2036 (@500C) 1792 (@1000C)	2078 (@500C) 1785 (@1000C)	2010 (@700C)		Fluroborates recommended for consideration by ORNL.
C_p, J/(kg·K)	5200	1190 (@500C) 1270 (@800C)	2380	1889	2230		
ρC_p, kJ/(m^3·K) (avg. 500-1000C)	17.9 @7MPa 23.1 @9MPa	40.8 @7MPa 52.3 @9MPa (avg. 500-800C)	4555	3649	4270	Individual salts investigated by ONRL. Mixtures not well characterized.	$NaF\text{-}NaBF_4$ was reference secondary coolant for MSBR (700C), but V.P too high > 700C.
k, W/(m·K)	0.368 (avg. 500-1000C)	0.066 (avg. 500-800C)	1	4.5	0.87		
η, (Pa·s) x 10^3	0.039 (@500C) 0.055 (@1000C)	0.035 (@500C) 0.044 (@800C)	23 (@500C) 2.2 (@1000C)	13 (@500C) 1.7 (@1000C)			
Comments		NIST data not provided above 800C	Well characterized; Used in MSRE; Expensive, Toxic	Well characterized; Reference for MSBR secondary; Inexpensive	Well characterized; Expensive; Toxic	Melt range is estimate for various mixtures.	Mixtures may be suitable.

Implications of Differences in Thermophysical Properties

- **CO_2 has higher volumetric thermal capacity (ρCp) than helium**
  - Reduced pumping power
- **Helium has higher thermal conductivity (k) than CO_2**
  - Smaller heat exchangers (IHX and PCHX)
- **Liquid salt has a much higher volumetric thermal capacity (ρCp) than helium**
  - Piping diameter 1/5th
  - Pumping power 1/20th or lower
- **Liquid salt has much higher heat transfer coefficients**
  - Reduced LMTD requirements → lower reactor outlet temperature for given process temperature or higher process temps for increased efficiency
  - Smaller HXs

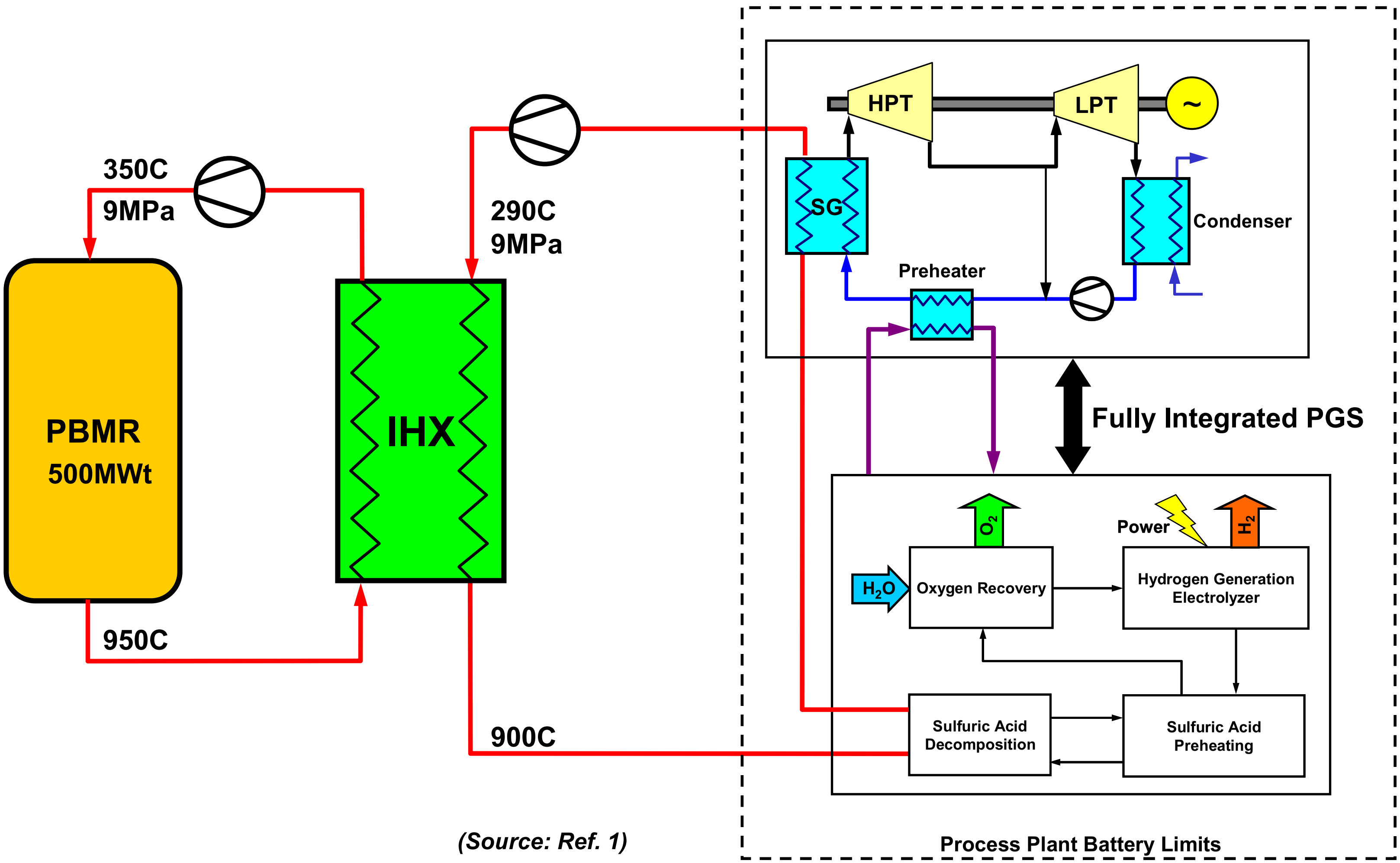
Outline
Secondary Working Fluid

- Introduction
- Key Functions & Requirements
- Overview of Coolant Properties
- ➡ Comparison of Options
- Summary & Recommendations

Comparison of Options

Item	Helium	CO_2	LS
• Design Compatibility	+	-	- -
• Influence on Major Components			
➢ Heat Exchangers	+	-	+/-
➢ Circulators/Pumps	-	+	++
➢ Piping and Insulation	++	+	- -
➢ Valves and Seals	- -	-	+
• System Integration	+	-	- -
• System Operation	+	-	- -
• Availability and Reliability	+	-	- -
• Safety & Licensing	+/-	-	+/-
• Economic Considerations	+/-	+/-	+
• R&D	+	-	- -

H_2 via Hybrid Sulfur (HyS) Cycle
Reference Commercial Plant Configuration

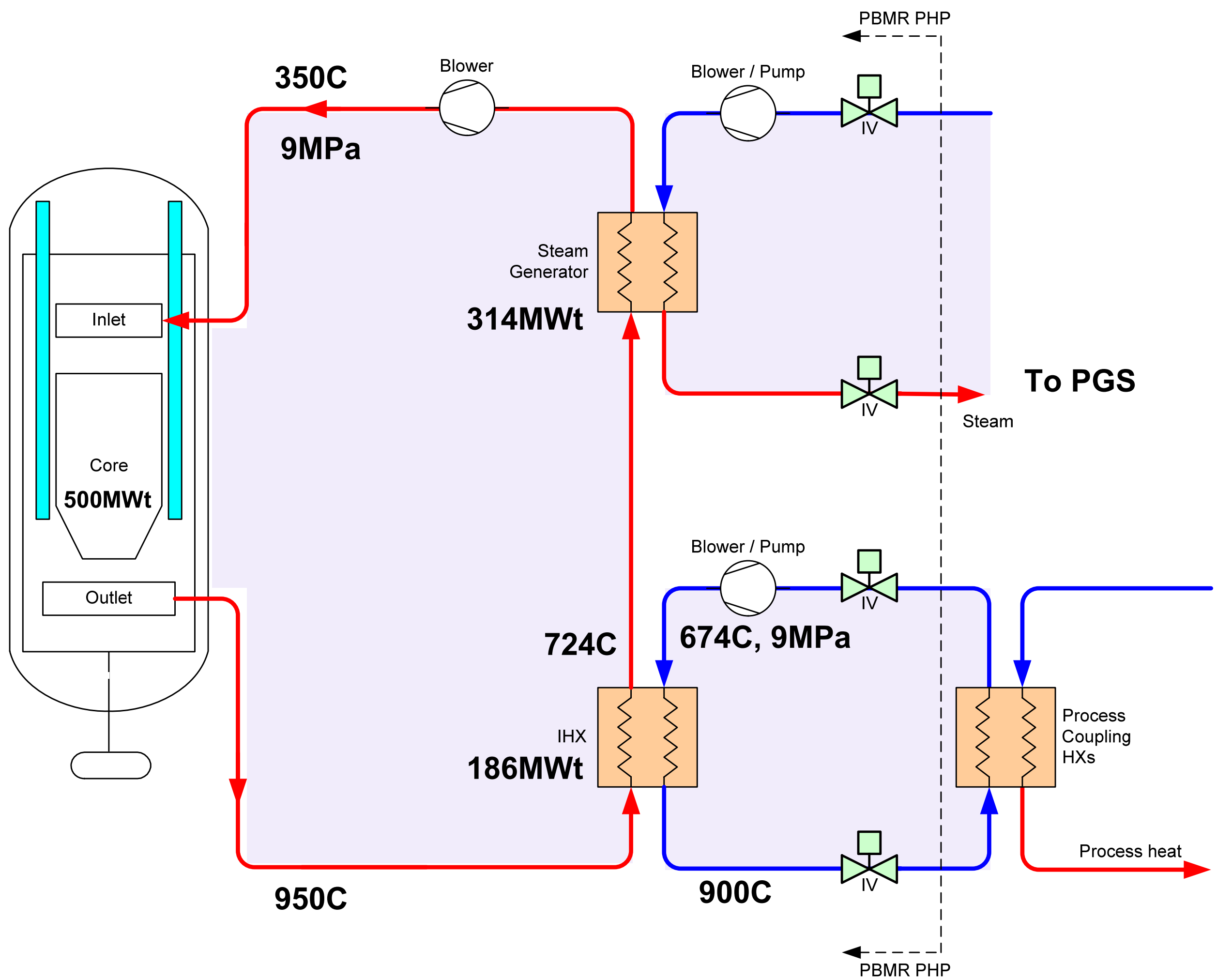


(Source: Ref. 1)

Design Compatibility

- **Reference PBMR PHP configuration for HyS is compatible with helium, CO_2 as SHTS fluid**
  - Compatibility of CO_2 at high temperatures an issue
- **Temperatures in SG, return piping to IHX are incompatible with LS working fluid due to freezing point of candidate salts**

Alternate NHS Coupling for LS SHTS



Design Compatibility

- **Separation of process heat, SG coupling results in increased secondary loop return temperature to IHX**
  - Compatible with LS freezing point
- **For SHTS with gas working fluid:**
  - Increased return temperatures poses feasibility issues for gas circulator
  - Increased SHTS return temperature implies increased pumping power, but offset by decreased volumetric flow rate
- **HPU/PCS integration more difficult with separation of process heat/SG coupling**

Heat Exchangers

<u>Helium SHTS</u>

- **High SHTS pressure required for efficient heat transport**
  - Consistent with IHX pressure balancing
  - Implies high dP across PCHX
- **Comparable heat transport characteristics on both sides of IHX**
- **Metallic HXs feasible, albeit marginal**

<u>CO_2 SHTS</u>

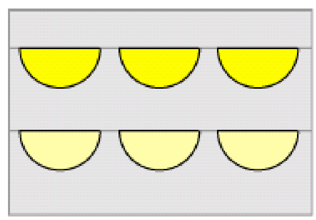
- **High SHTS pressure required for efficient heat transport**
  - Consistent with IHX pressure balancing
  - Implies high dP across PCHX
- **Secondary heat transfer coefficient will govern HX sizing**
  - For given duty, HX will be larger, more expensive
- **Metallic HX feasibility questionable**

<u>LS SHTS</u>

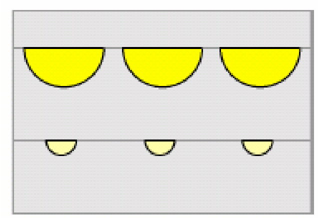
- **Flexible operating pressure, established by cover gas**
  - Can stage pressure differences between primary loop and process
- **Potential to operate with lower LMTD**
  - Reduce ROT for given process temperature, or
  - Allow increased process temperature for given ROT
- **Mismatch in heat transport characteristics**
  - HT coefficient, volumetric heat capacity much higher on LS side
  - Primary heat transfer coefficient will govern HX sizing
  - Simplifies manifolding in compact HXs (see next slide)
  - Flow area needs to be much smaller on LS side
    - *Fewer, smaller channels*
    - *Concern with plugging of small channels in compact HX designs*
- **Likely to require ceramic/CFRC HXs**
  - Metal to ceramic/CFRC interfaces an issue

Inlet/Outlet Manifolds in He-He vs. He-LS HXs

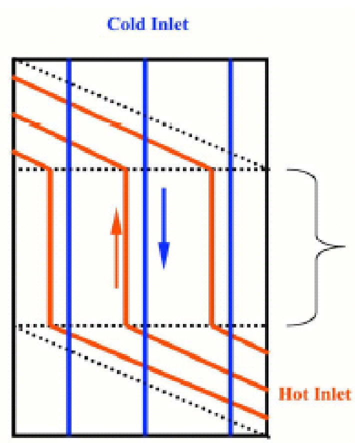
- **Advantages in design of inlet/outlet manifolds with LS HXs**
  - Greater volumetric heat capacity results in designs with smaller passages, low pressure losses on LS side
  - Allows smaller HXs and/or reduced pressure losses



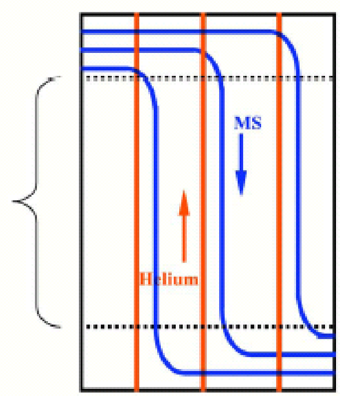
He-to-He



He-to-LS



Helium-to-Helium IHX



Helium-to-LS IHX

Heat Exchangers (Cont'd)

Helium SHTS

- **Compatible with present tube & shell convective reformer designs**

CO_2 SHTS

- **Compatible with present tube & shell convective reformer designs**
- **For given duty, HX will be larger, more expensive**

LS SHTS

- **Not compatible with tube & shell PCHX designs**
  - Flow area outside of tubes is too large for LS
  - Would need new PCHX design
- **For given duty, HX will be smaller, much less expensive**

Advantage for helium/disadvantage for CO_2/LS with available technology. Future advantage for LS with compact ceramic/CRFC HXs

Circulators/Pumps

Helium SHTS

- **Highest pumping power**
- **R&D issues with temperatures above ~350C**

CO_2 SHTS

- **Pumping power lower than helium, but >> than LS**
- **R&D issues with temperatures above ~350C**

LS SHTS

- **Pumping power << than for gases**
- **Pumps demonstrated in earlier LS applications**

Advantage for CO_2 vs. helium.
Large advantage for LS

Piping and Insulation

Helium SHTS

- **Internal insulation typically used to reduce pressure boundary temperature, reduce energy losses**
- **Potential to use coaxial ducts for hot/cold legs**
- **Piping systems demonstrated, including in nuclear applications**
- **Similar systems used in PBMR DPP**
  - However, internal cooling applied in DPP would be more difficult in PHP and involve increased energy losses

CO_2 SHTS

- **As with helium except that piping and valves may be somewhat smaller**

LS SHTS

- **Pipe size ~ 1/5 that of He pipe**
- **No known practical LS wetted insulation system**
  - Implies pressure boundary must operate at or near LS temperature
  - Eliminates or makes more difficult potential for coaxial heat transport
- **Suggests CFRC pressure boundary**
  - Metallic materials may not be adequate at 900ºC
- **External insulation will be required to reduce energy losses**

Established technology a major advantage for helium, reduced pipe size a modest advantage for CO_2. Lack of internal insulation system a feasibility issue for LS.

Valves & Seals

Helium SHTS

- **Very large valves required**
  - Size and potential for leakage problematical for SHTS isolation valves, if required
- **Leak-tight seals difficult**
  - Welded seals typical for pressure boundary
  - Non-welded seals have been demonstrated for internal components

CO_2 SHTS

- **Large valves required**
  - Size and potential for leakage problematical for SHTS isolation valves, if required
  - Pipe diameters may be reduced relative to helium
- **Leak-tight seals less difficult than with helium**

LS SHTS

- **Small valves required**
- **Mechanical closure valves have not yet been developed**
  - In early applications, LS tended to clean surface to condition that promoted self-welding
  - Freeze valves were used in some early applications; effective, but slow
  - Newer material alternatives make feasibility likely
- **No mechanical seals used in prior designs**
  - Newer material alternatives make feasibility likely

Significant R&D issue for helium/CO_2 If SHTS isolation valves required. LS would require much smaller valves/seals.

System Integration

Helium SHTS

- **Pressure differential from primary to process must largely be taken across PCHX**
- **Leakage biases:**
  - More flexible for IHX
  - PCHX biased toward process

CO_2 SHTS

- **Pressure differential from primary to process must largely be taken across PCHX**
- **Leakage biases:**
  - IHX must be biased toward SHTS
  - PCHX biased toward process

LS SHTS

- **Flexibility to stage primary to process pressure differential**
- **Leakage biases:**
  - IHX leakage must be biased toward LS side of IHX
  - PCHX leakage bias:
    - *If toward LS side, need to evaluate consequences of process gas ingress*
    - *If toward LS side, implies high dP across IHX*
    - *If toward process side, must assess consequences of salt contamination*

Leakage bias and consequences a disadvantage for CO_2; feasibility issue for LS.

System Operation

Helium SHTS

- **Significant operational experience with helium heat transport; no major issues**

CO_2 SHTS

- **Significant operational experience with CO_2 heat transport at lower temperatures; no major issues**

LS SHTS

- **Startup/Shutdown**
  - Salt must be heated to liquid state and introduced to SHTS as part of startup
  - LS must be drained for cold shutdown
  - Temperature must be maintained above minimum level for hot standby
  - Alternate heat source required for above
- **Steady State/Transients**
  - No unusual issues anticipated with steady state operation
  - Transients resulting in shutdown addressed above

Freezing of LS implies significant operational issues with startup, shutdown and response to certain transients. Operational experience with helium at high temperatures an advantage.

Availability/Reliability

Helium SHTS

- **Continued operation with small HX leaks may be possible**
- **Difficulty in locating/repairing leaks a problem with compact HXs**

CO_2 SHTS

- **Must be shut down when any leak is detected**
- **Difficulty in locating/repairing leaks a problem with compact HXs**

LS SHTS

- **Must be shut down when any leak is detected**
- **Difficulty in locating/repairing leaks a problem with compact HXs**

Consequences of leaks a disadvantage of CO_2, major disadvantage of LS.

Safety/Licensing

Helium SHTS

- **Requires process to be close to reactor**

CO_2 SHTS

- **Requires process to be close to reactor**
- **Consequences of CO_2 ingress into primary loop may have to be addressed**

LS SHTS

- **Flexibility for moving process farther from reactor**
- **Consequences of salt ingress into primary loop may have to be addressed**

Potential for SHTS leaks into primary system a disadvantage for CO_2, potentially a major issue for LS. LS would allow greater distance between reactor and process.

Economics

Helium SHTS

- **Base for comparison**

CO_2 SHTS

- **Tradeoff of larger heat exchangers (IHX, PCHX) vs. reduced pumping costs**
  - Further evaluation required to determine net impact

LS SHTS

- **Capital cost likely to be lower**
  - IHX, PHCE, main SHTS components will be smaller, less expensive
  - However, an offset will be additional auxiliary systems required for melting, LS temperature control
  - Capital cost advantage will increase with distance between IHX an PCHX
- **Operating costs may be higher or lower**
  - Lower pumping costs (distance a key parameter)
  - Higher maintenance costs

Potentially significant capital cost advantage for LS, but operating cost tradeoffs uncertain.

R&D Requirements

Helium SHTS

- **IHX**
- **IHX core to metal transitions**
  - Applies to ceramic/CFRC IHX
- **Isolation valves**
- **PCHX**

CO_2 SHTS

- **IHX**
  - **Material compatibility at issue for metallic HXs**
- **IHX core to metal transitions**
  - Applies to ceramic/CFRC IHX
- **Isolation valves**
- **PCHX**

LS SHTS

- **IHX**
  - **Will almost certainly require ceramic/CFRC IHX**
- **IHX core to metal transitions**
  - Applies to ceramic/CFRC IHX
- **Isolation valves**
- **SHTS piping and insulation**
- **PCHX**
- **Pump and seals**

R&D somewhat greater for CO_2 if metallic HXs are feasible. LS requires major R&D initiative.

Outline
Secondary Working Fluid

- **Introduction**
- **Key Functions & Requirements**
- **Overview of Coolant Properties**
- **Comparison of Options**
  - Influence on Major Components
  - System Integration and Operation
  - Availability and Reliability
  - Safety & Licensing
  - Economic Considerations
  - R&D
- **Summary & Recommendations**

Conclusions and Recommendations

- **With relatively low return temperature of commercial PBMR PHP for HyS, incentives for CO_2 vs. helium are likely to be modest, if at all**
  - Materials compatibility issues may be significant
- **Design and operational issues make LS problematical at current stage of development**
  - Incentives are increased with greater distance between heat source and process plant
- **NGNP preconceptual design should be based on helium SHTS with PCHX located at a relatively short distance (e.g., 100m) from the reactor that is representative of commercial applications**
- **Continue development of LS HTS – longer term enhancing technology**
  - Tertiary loop on NGNP could be potential basis for future demonstration

APPENDIX 20.3.1: SPECIAL STUDY 20.3.1 SLIDES

PART 4 – HEAT TRANSPORT SYSTEM OPTIONS

SPECIAL STUDIES:
20.3 - HEAT TRANSPORT SYSTEM
20.4 - POWER CONVERSION SYSTEM

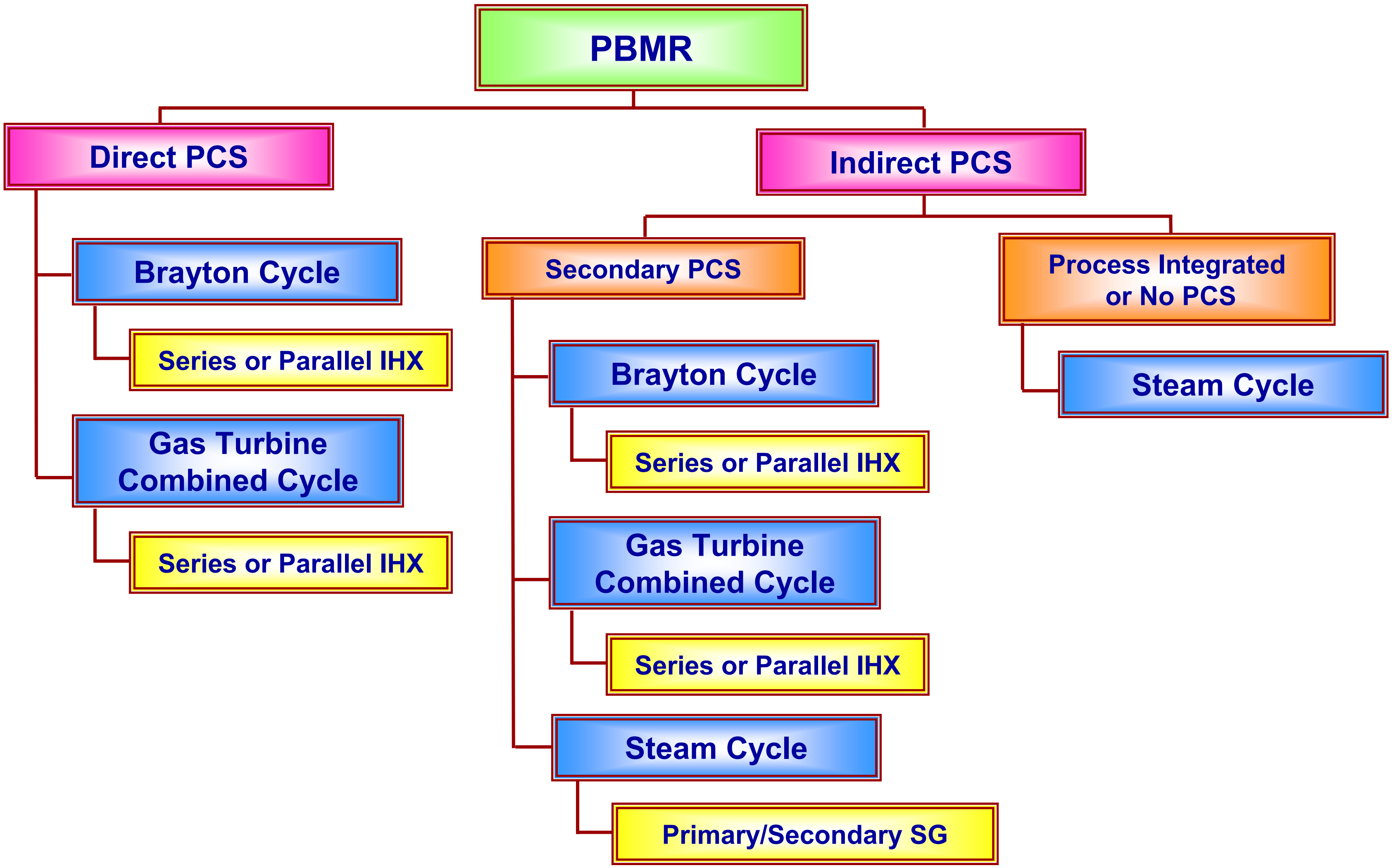
Part 4 – Heat Transport System Options

December 6, 2006

Outline

- **Objective and Scope**
- **Study Inputs**
  - Commercial applications and performance requirements
  - Key NGNP HTS demonstration objectives
  - Key HTS functional requirements
  - Other input requirements and data
- **Screening Criteria**
- **Power Conversion System Options (20.4)**
- **H_2 Production Unit Size (20.7)**
- **IHX/High-Temperature Materials**
- **Secondary Working Fluid**
- **HTS Configuration Options**
- **Recommended HTS Configuration**

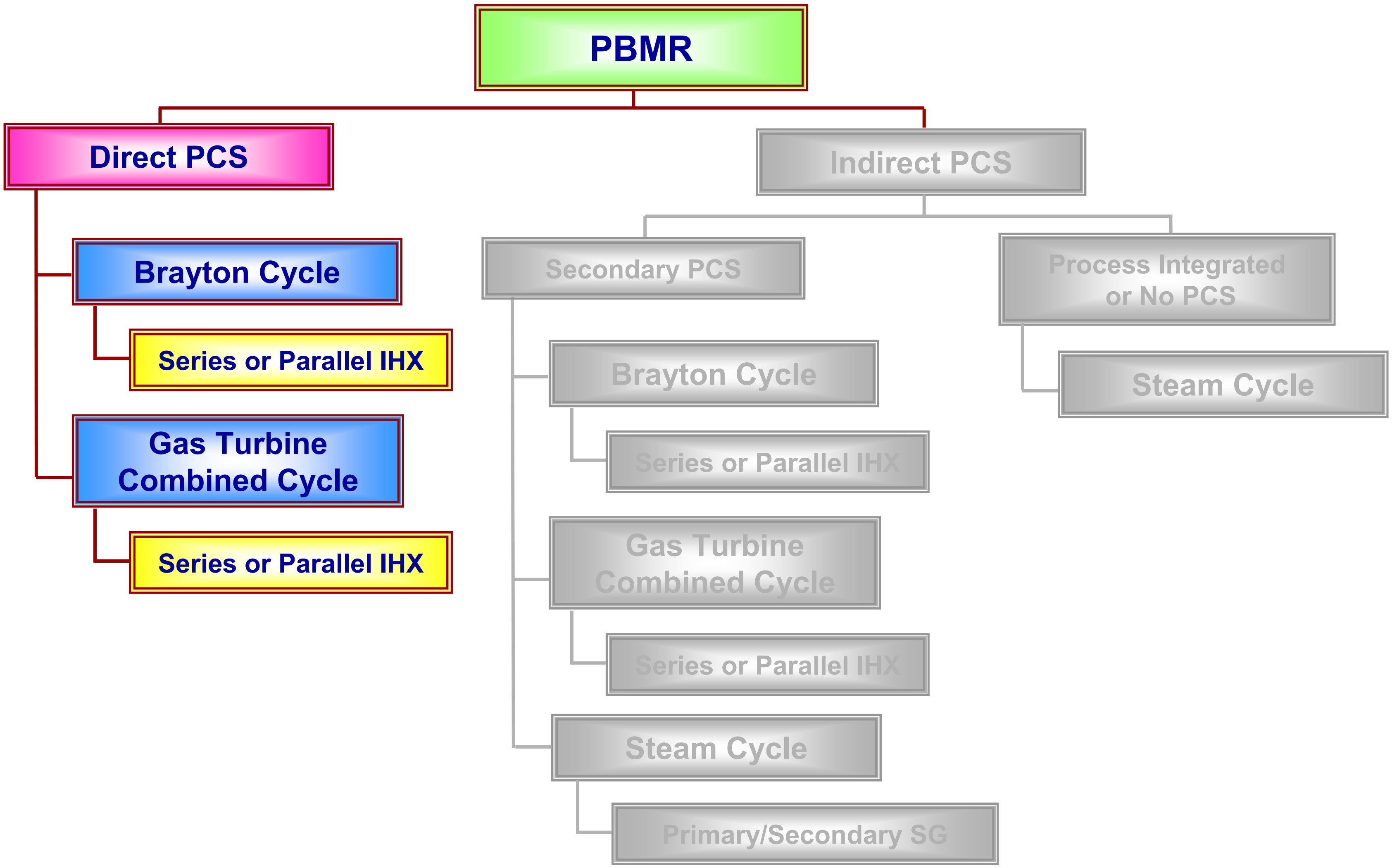
Process Heat/PCS Configuration Hierarchy



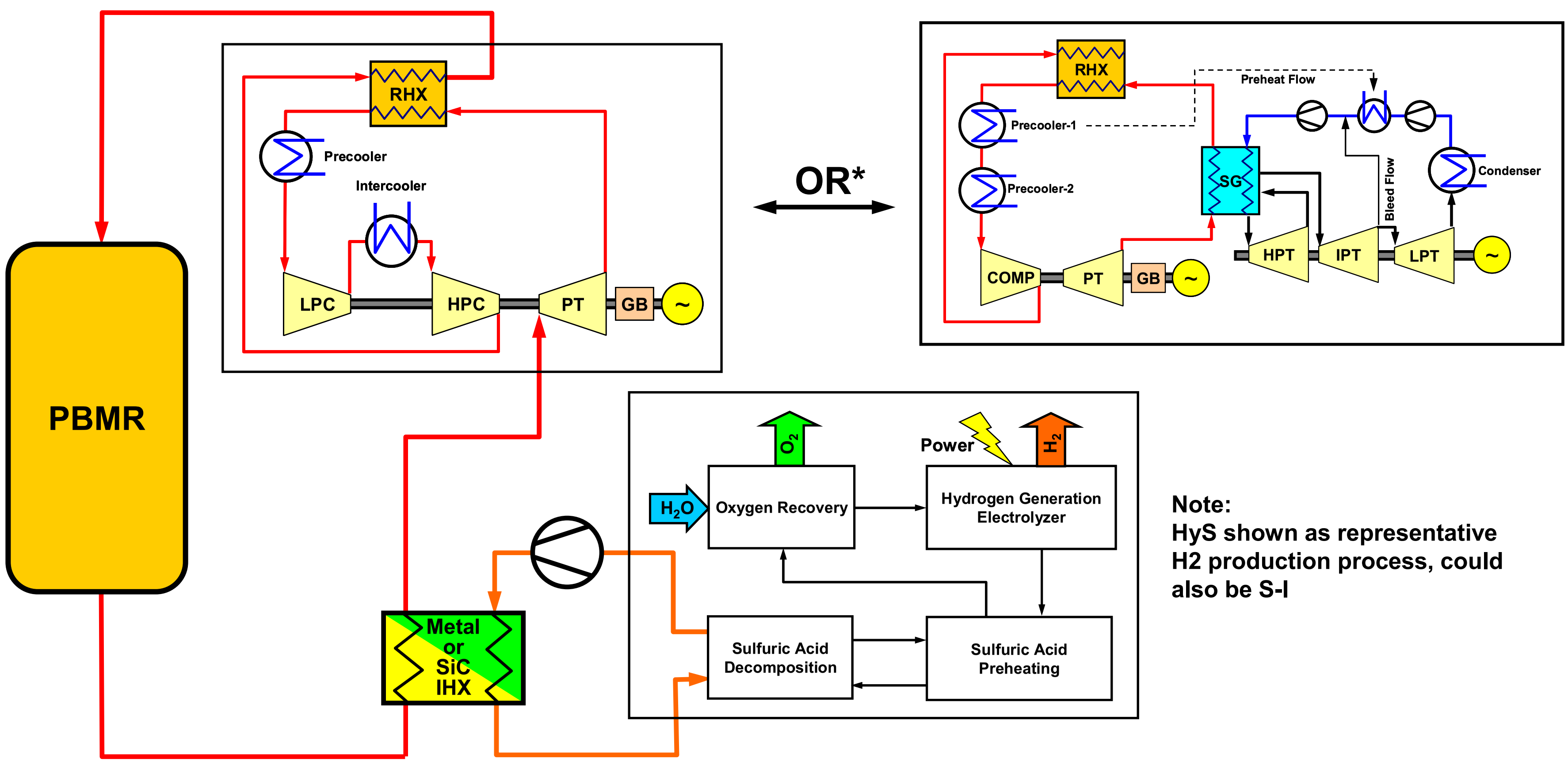
Screening Criteria

Attribute	Importance
• Readiness	
➢ Ability to meet NGNP timeline (startup: 2016-2018)	**High**
➢ NGNP R&D Requirements/Cost/Risk	Med
➢ Vendor/Supplier/Regulatory Infrastructure Development	Med
• Support of Commercial Applications	
➢ Adequately demonstrates commercial process heat applications	**High**
➢ NHS commonality with commercial products	**High**
➢ Can serve as process heat prototype for design certification	**High**
➢ Flexibility for demonstrating advanced applications	Med
➢ Flexibility for ultimate NGNP conversion to full-scale H2 production	Med
• Performance	
➢ Ability to meet operational performance goals	**High**
➢ Overall Plant Efficiency	Low
➢ Operability	Med
➢ Availability	Low
• Cost	
➢ NGNP Capital Cost	**High**
➢ NGNP Operating Cost	Low

Process Heat/PCS Configuration Hierarchy



Option 1:
Primary Brayton Cycle/GTCC, Series IHX



Note:
HyS shown as representative H2 production process, could also be S-I

* To be selected in PCS Special Study 20.4, if required

Option 1:
Primary Brayton Cycle/GTCC, Series IHX

Key Features

- **Small (≤ ~50MWt) topping IHX**
  - Designed for easy replacement, but more difficult than parallel (Option 2)
  - Option to use liquid salt SHTS working fluid
  - Option to operate without IHX
- **Direct Brayton or GTCC bottoming cycle**
  - Option to use 900ºC DPP PCS

Readiness

- **Brayton cycle/GTCC based on DPP**
  - No R&D at 900ºC or modest R&D to 950ºC
- **Option to operate PCS without IHX installed**
- **Significant primary/ secondary flow mismatch**
  - Primary side of IHX must be designed for full flow (potential issues with bypass/hot streaks)
  - SHTS circulator temperature an issue

Support of Commercial Applications

- **Low NHS commonality with commercial PHP**
  - May be inadequate as prototype for design certification of PHP commercial plants
- **GTCC variant supports deployment of AEP**

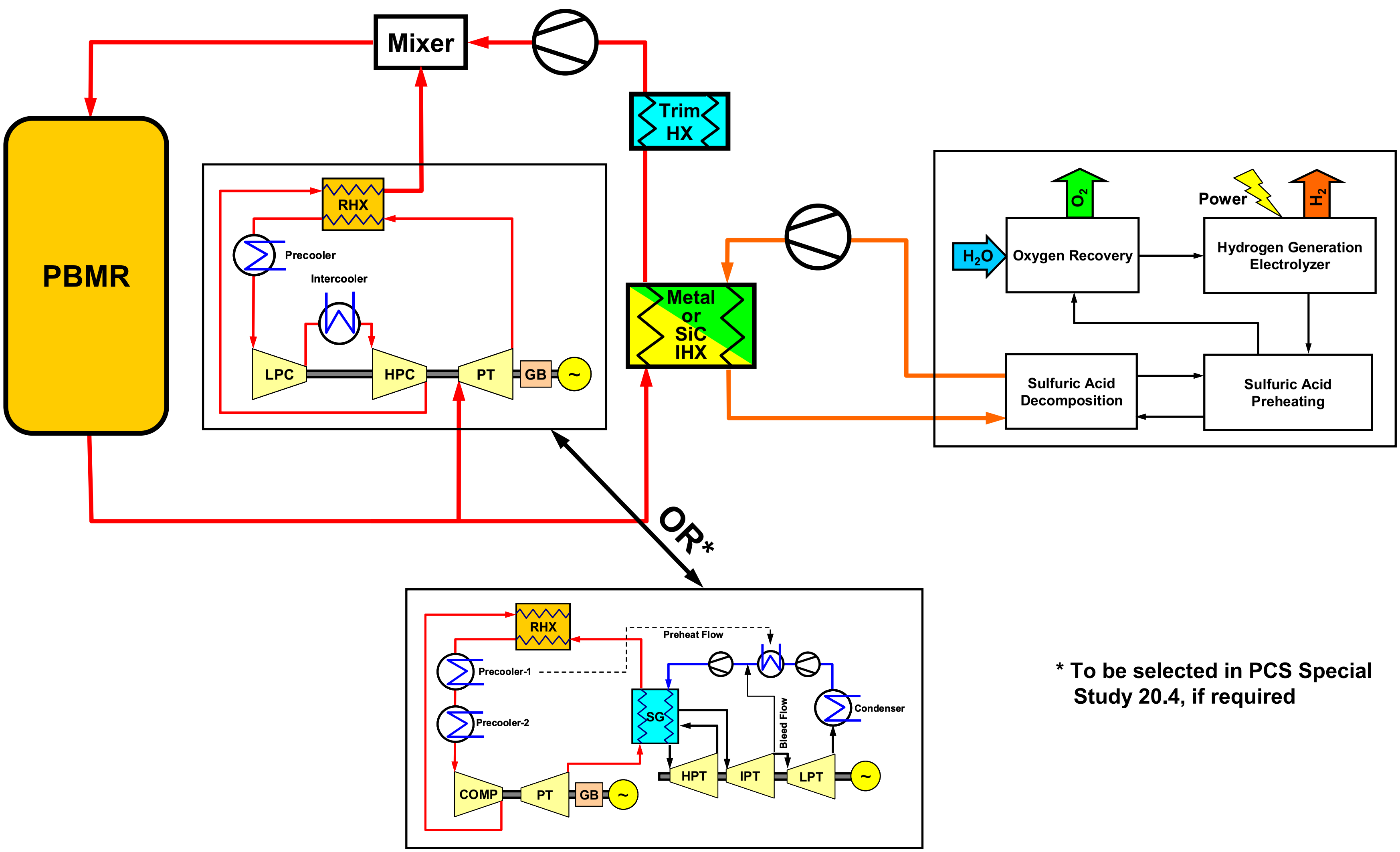
Performance

- **Single PHTS flow path avoids operational issues with remixing of separate flows (Option 2)**
- **PCS provide alternate heat sink (coolers) for off-normal events**
- **Pressure transients associated with Brayton cycle transients must be considered**

Cost

- **Capital**
  - Along with Options 2 and 5, among lowest capital cost options
  - Small IHX implies modest replacement capital cost
- **Operating**
  - Potential for good efficiency, high availability to maximize cost offsets via electric sales
  - PCS maintenance higher with direct cycle

Option 2:
Primary Brayton Cycle/GTCC, Parallel IHX



* To be selected in PCS Special Study 20.4, if required

Option 2: Primary Brayton Cycle/GTCC, Parallel IHX

Key Features

- **Small (≤ ~50MWt) parallel IHX**
  - Designed for easy replacement (easiest)
  - Option to operate without IHX
- **Direct Brayton cycle or GTCC**
  - Requires 950ºC design basis

Readiness

- **Brayton cycle/GTCC extrapolated from DPP**
  - Modest R&D at 950ºC
- **Option to operate PCS without IHX installed**
  - Facilitated by smaller, parallel PHTS piping
- **Requires provisions to control parallel flows, remix parallel streams that are potentially at different temperatures**

Support of Commercial Applications

- **Low NHS commonality with commercial PHP**
  - May be inadequate as prototype for design certification of PHP commercial plants
- **GTCC variant supports deployment of AEP**

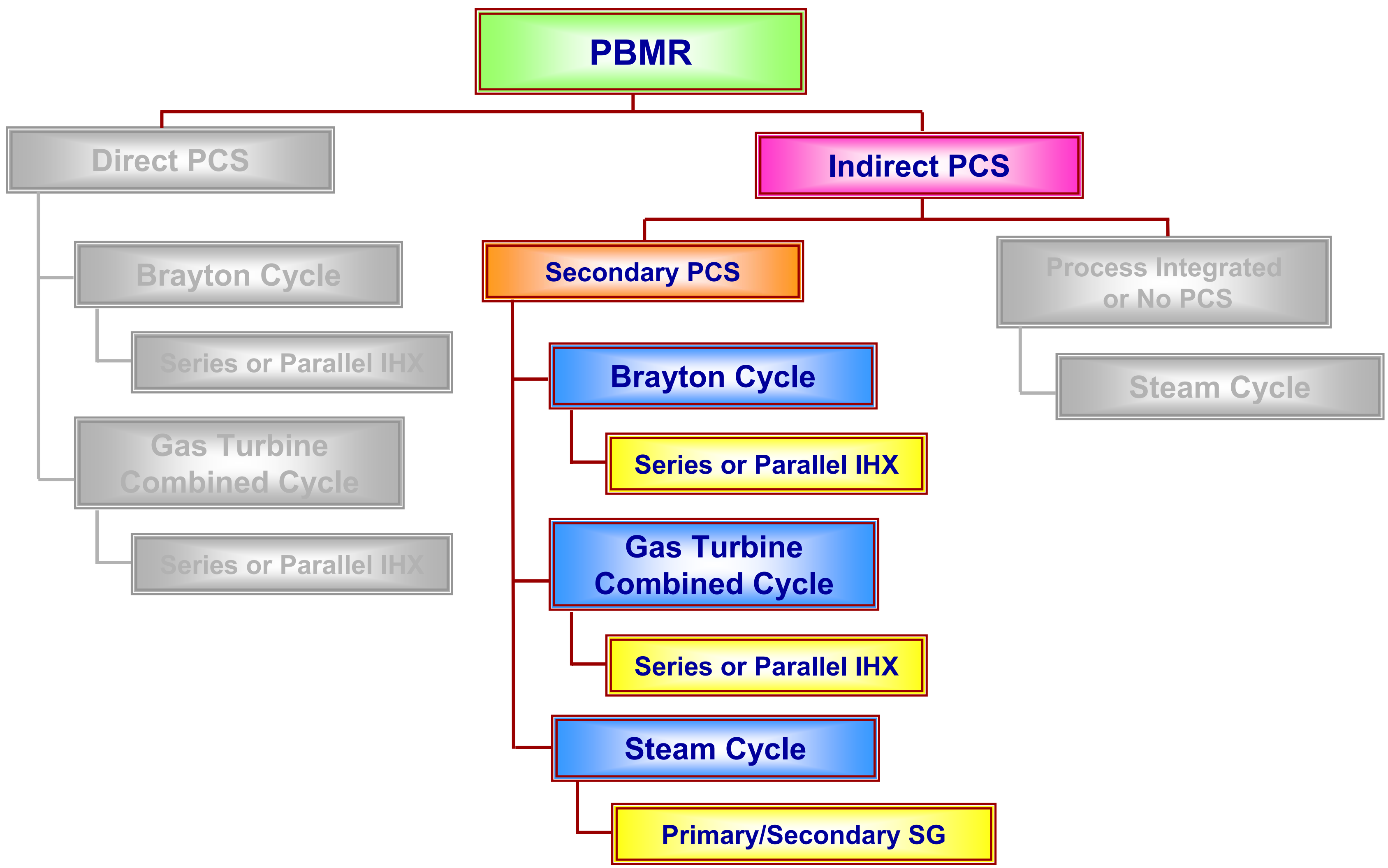
Performance

- **Parallel PHTS flow paths imply operational issues with remixing**
- **PCS provides alternate heat sink (coolers) for off-normal events**
- **Pressure transients associated with Brayton cycle transients must be considered**

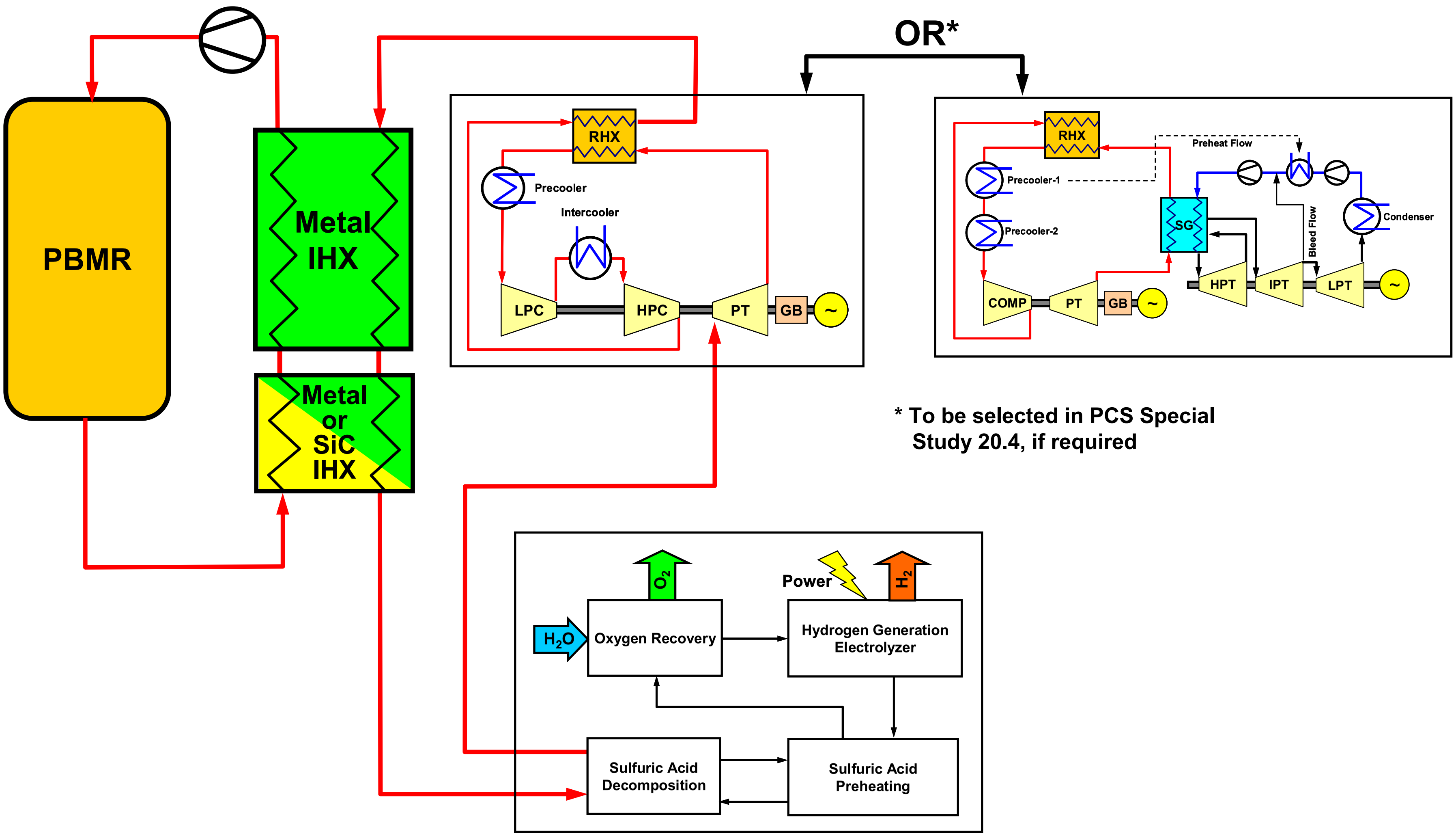
Cost

- **Capital**
  - Along with Options 1 and 5, among lowest capital cost options
  - Small IHX implies modest replacement capital cost
- **Operating**
  - Potential for good efficiency, good availability to maximize cost offsets via electric sales
  - PCS maintenance higher with direct cycle

Process Heat/PCS Configuration Hierarchy



Option 3:
Secondary Brayton Cycle/GTCC, Series PCHX



* To be selected in PCS Special Study 20.4, if required

Option 3:
Secondary Brayton Cycle/GTCC, Series PCHX

Key Features
- **Full-size IHX transfers all reactor heat to SHTS**
- **Small (≤ ~50MWt) PCHX as topping cycle**
- **Brayton cycle or GTCC bottoming cycle**
  - 850ºC PCS design basis
- **PCHX/PCS likely need to be co-located**

Readiness
- **Brayton cycle/GTCC extrapolated from DPP**
  - No R&D to 900ºC
- **Option to operate PCS without PCHX installed**
- **Large IHX poses greatest challenge to readiness**

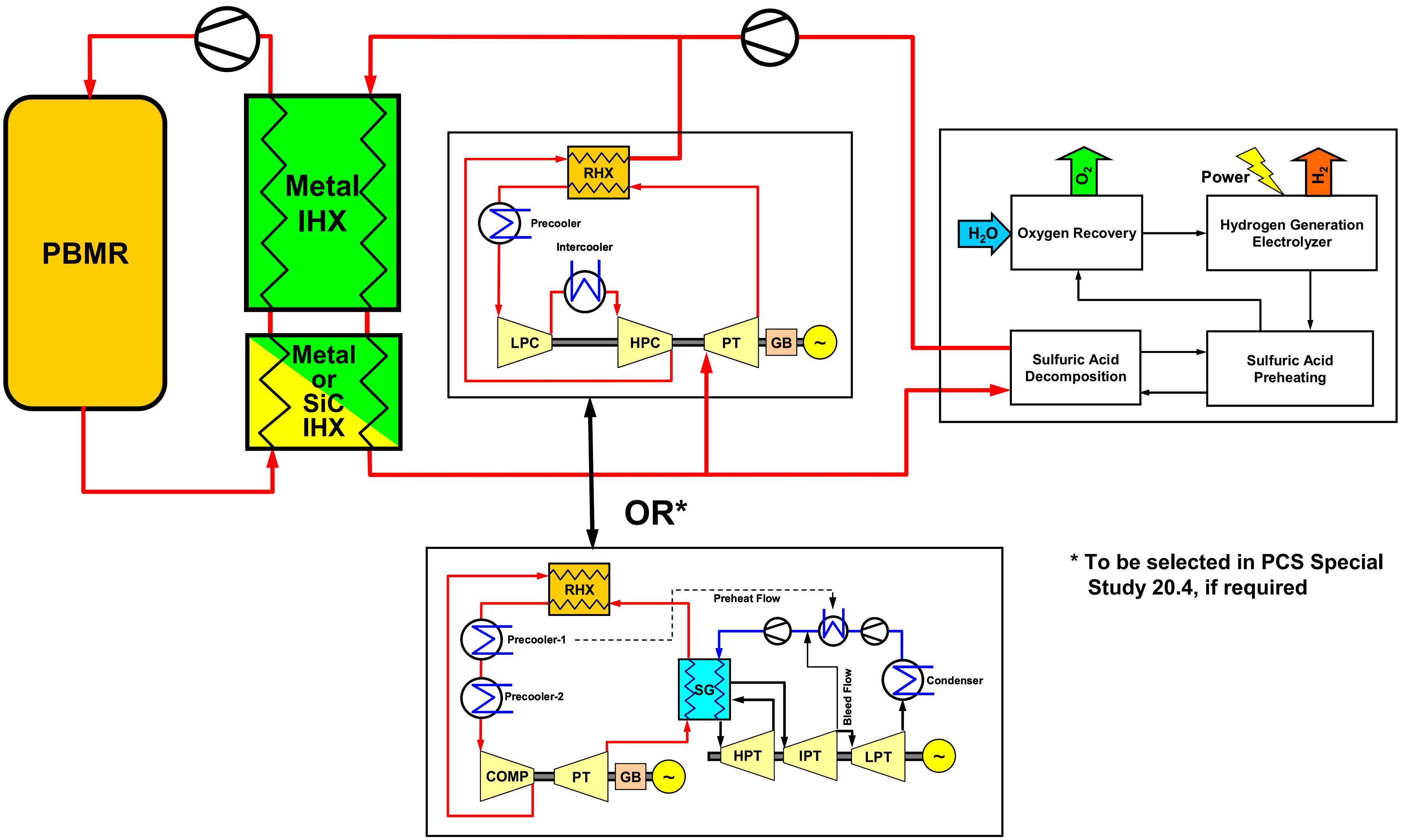
Support of Commercial Applications
- **High NHS commonality with commercial PHP**
  - If successful, resolves IHX issue for commercial plants
  - Adequate prototype for design certification of PHP commercial plants
- **GTCC variant supports deployment of AEP**

Performance
- **PCS provides alternate heat sink (coolers) for off-normal events**
  - Requires operational PHTS
- **Pressure transients associated with Brayton cycle transients must be considered**
- **Significant availability risk associated with potential for IHX leaks**

Cost
- **Capital**
  - High capital cost relative to direct PCS options
  - Large IHX implies potential for high replacement capital costs
    - *May be mitigated by selection of ceramic material and/or split section design*
- **Operating**
  - Lower efficiency, availability risk may reduce cost offsets via electric sales
  - Maintenance costs involve tradeoff of IHX/circulator vs. PCS

Option 4:

Secondary Brayton Cycle/GTCC, Parallel PCHX



* To be selected in PCS Special Study 20.4, if required

Option 4:
Secondary Brayton Cycle/GTCC, Parallel PCHX

Key Features
- **Full-size IHX transfers all reactor heat to SHTS**
- **Small (≤ ~50MWt) parallel PCHX**
- **Brayton or GTCC cycle**
  - ➢ Requires 900ºC design basis
- **PCHX/PCS likely to be co-located**

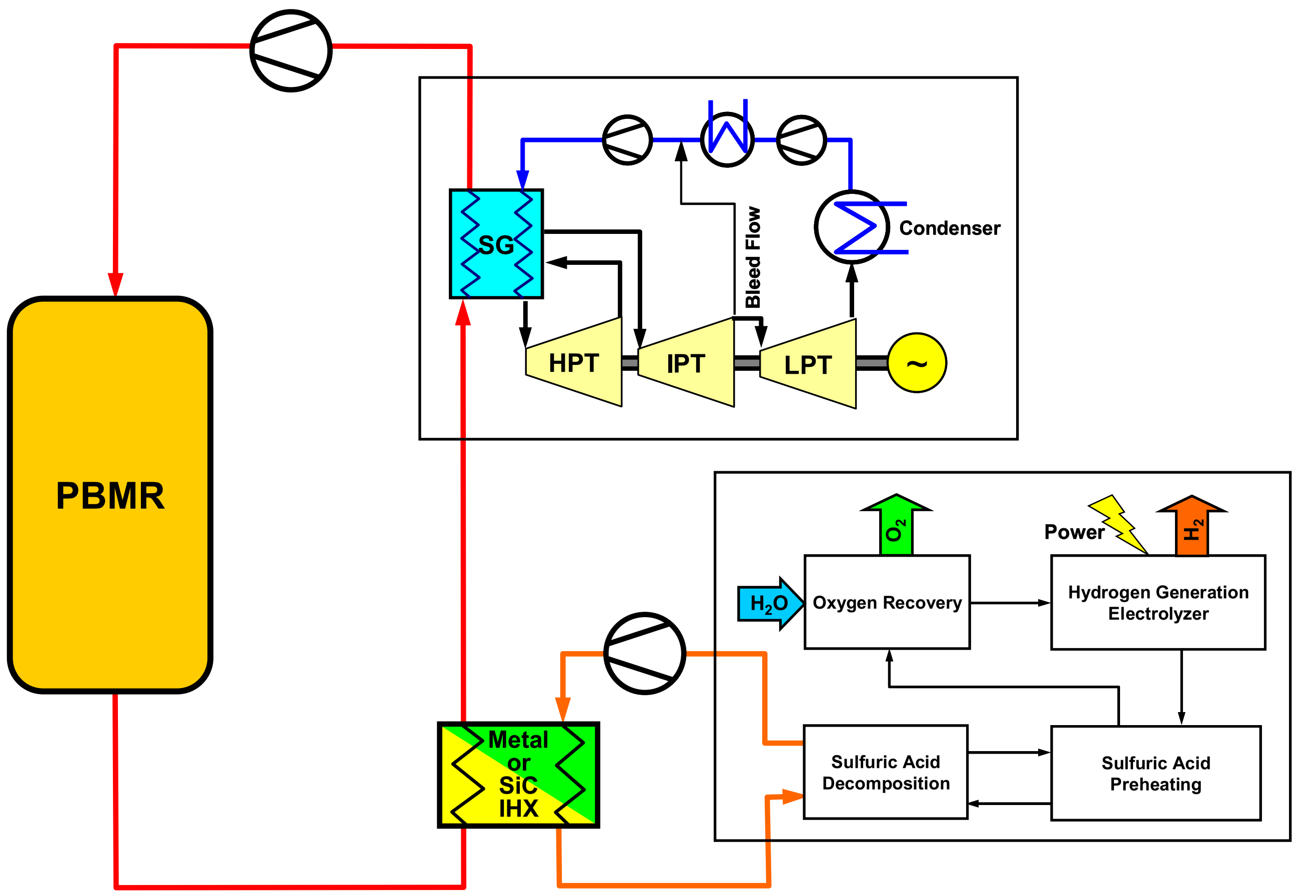
Readiness
- **Brayton cycle/GTCC extrapolated from DPP**
  - ➢ No R&D at 900ºC
- **Option to operate PCS without PCHX installed**
- **Large IHX poses greatest challenge to readiness**
- **Requires provisions to control parallel flows, remix parallel streams that are potentially at different temperatures**

Support of Commercial Applications
- **High NHS commonality with commercial PHP**
  - ➢ If successful, resolves IHX issue for commercial plants
  - ➢ Adequate prototype for design certification of PHP commercial plants
- **GTCC variant supports deployment of AEP**

Performance
- **PCS provides alternate heat sink (coolers) for off-normal events**
  - ➢ Requires operational PHTS
- **Parallel PHTS flow paths imply operational issues with remixing**
- **Significant availability risk associated with potential for IHX leaks**
- **Pressure transients associated with Brayton cycle transients must be considered**

Cost
- **Capital**
  - ➢ Higher capital cost relative to direct PCS options
  - ➢ Large IHX implies potential for high replacement capital costs
    - – *May be mitigated by selection of ceramic material and/or split section design*
- **Operating**
  - ➢ Lower efficiency, availability risk may reduce cost offsets via electric sales
  - ➢ Maintenance costs involve tradeoff of IHX/circulator vs. PCS

Option 5:
Bottoming Steam Cycle, Series IHX



Option 5:
Bottoming Steam Cycle, Series IHX

Key Features

- **Small to medium (Up to ~200MWt) topping IHX**
  - Option to use liquid salt SHTS working fluid
  - Option to operate without IHX
- **Bottoming steam generator**
  - 700ºC-950ºC design basis, nominal depends on IHX rating

Readiness

- **Conventional steam cycle, with steam generator based on earlier HTGRs → no R&D**
- **Option to operate steam cycle without IHX installed**
- **Significant mismatch between primary/ secondary flows**
  - Primary side of IHX must be designed for full flow (potential issues with bypass/hot streaks)
  - Mismatch decreases as IHX power increases
  - SHTS circulator temperature an issue

Support of Commercial Applications

- **Larger engineering scale demonstrations of HyS/S-I feasible (up to ~100+ MWt)**
  - Possibly even larger with reductions of SC efficiency
- **Low NHS commonality with commercial PHP**
  - May be inadequate as prototype for design certification of PHP commercial plants

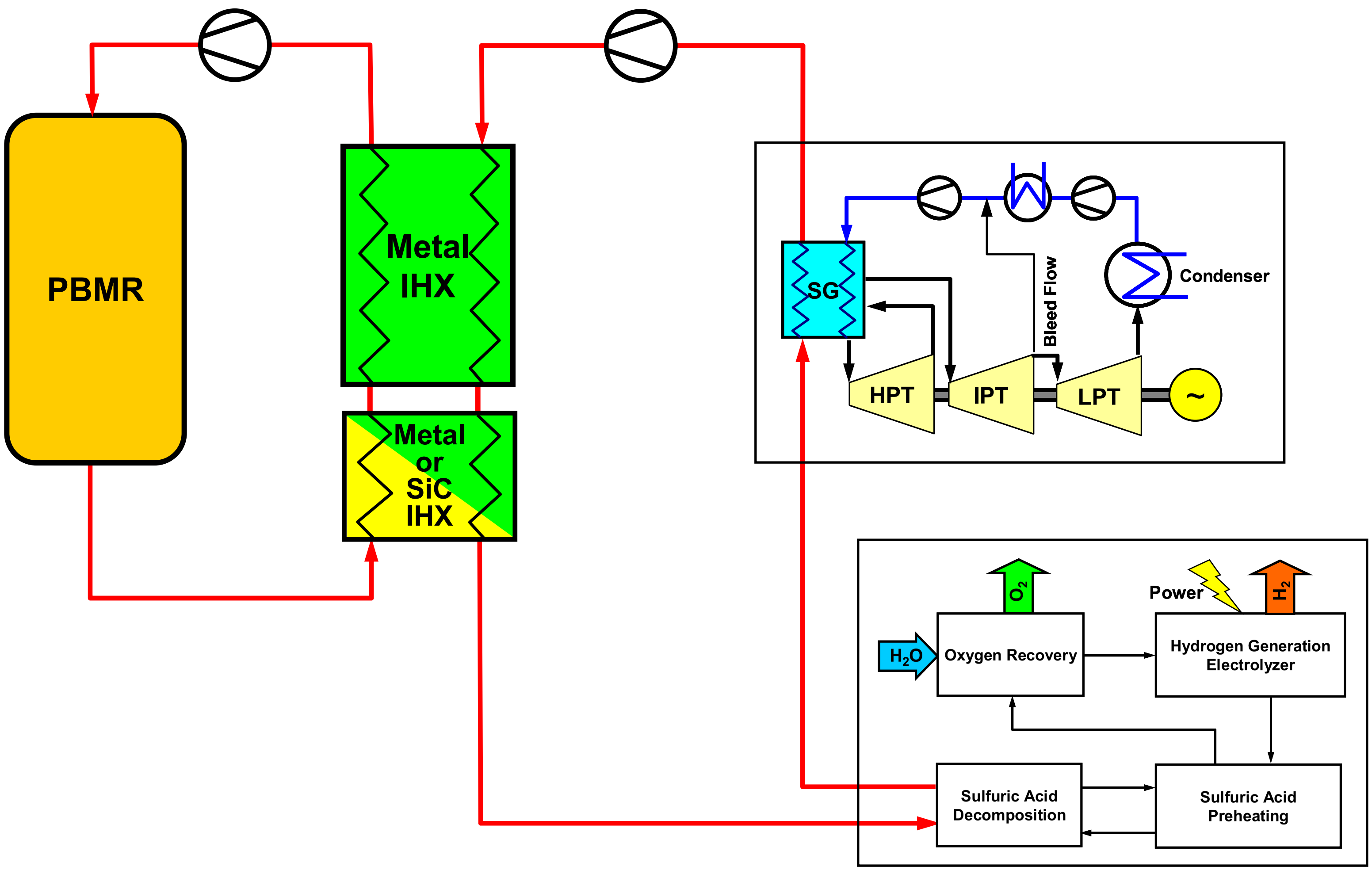
Performance

- **PCS temperatures consistent with modern steam conditions**
  - Steam cycle not as sensitive to thermal rating as GT cycles
- **Steam cycle provides alternate heat sink (coolers) for off-normal events**
  - Requires operational PHTS
- **Potential for water ingress must be considered**

Cost

- **Capital**
  - Along with Options 1 and 2, among the lowest capital cost options
  - Small IHX implies modest replacement capital cost
- **Operating**
  - Potential for reasonable efficiency, high availability to maximize cost offsets via electric sales
  - PCS maintenance conventional

Option 6:
Secondary Steam Cycle, Series PCHX



Option 6: Secondary Steam Generator, Series PCHX

Key Features

- **Full-size IHX transfers all reactor heat to SHTS**
- **Small to Medium PCHX as topping cycle**
  - Up to ~200MWt
- **Steam generator as bottoming cycle**
  - 700ºC-900ºC design basis, nominal depends on PCHX rating
- **PCHX/PCS likely to be co-located**

Readiness

- **Conventional steam cycle, with steam generator based on earlier HTGRs → no R&D**
- **Option to operate PCS without PCHX installed**
- **Large IHX poses greatest challenge to readiness**

Support of Commercial Applications

- **Larger engineering scale demonstrations of HyS/S-I feasible (up to ~100MWt)**
  - Possibly even larger with reductions of SC efficiency
- **High NHS commonality with commercial PHP**
  - If successful, resolves IHX issue for commercial plants
  - Adequate prototype for design certification of PHP commercial plants

Performance

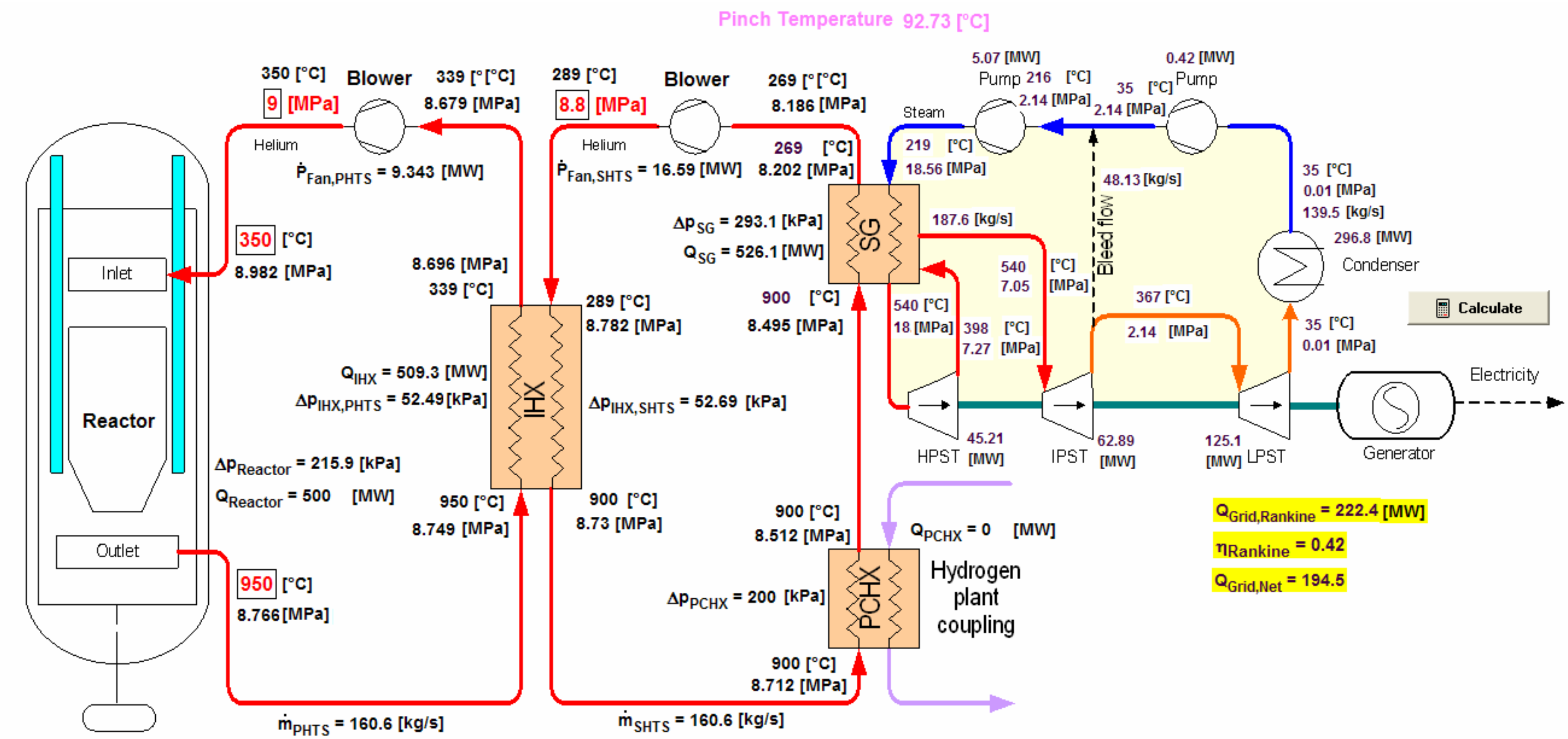
- **PCS temperatures consistent with modern steam conditions**
  - Steam cycle not as sensitive to thermal rating as GT cycles
- **Steam cycle provides alternate heat sink for off-normal events**
  - Requires operational PHTS and SHTS
- **Significant availability risk associated with potential for IHX leaks**

Cost

- **Capital**
  - Large IHX implies potential for high replacement capital costs
    - *May be mitigated by selection of ceramic material and/or split section design*
- **Operating**
  - Lower efficiency, availability risk may reduce cost offsets via electric sales
  - Tradeoff of IHX/circulator vs. PCS maintenance costs

Cycle L – Rankine Cycle Parameters

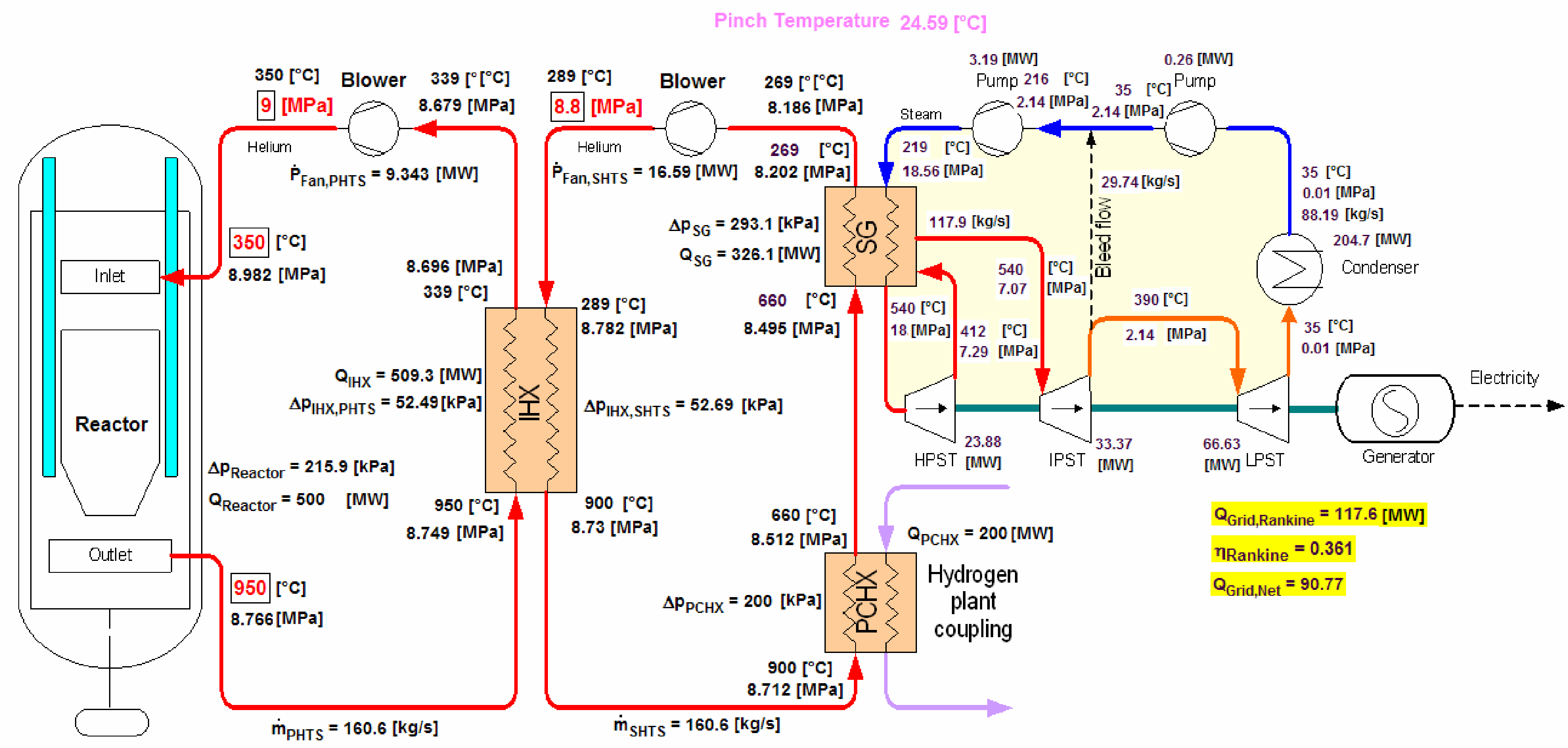
0-10 MW H_2 Plant Size



- Rankine plant sized for 526 MW (Rankine Cycle Design point)
- Steam Turbine efficiencies - 89%
- Rankine cycle efficiency - 43%

Cycle L – Rankine Cycle Parameters

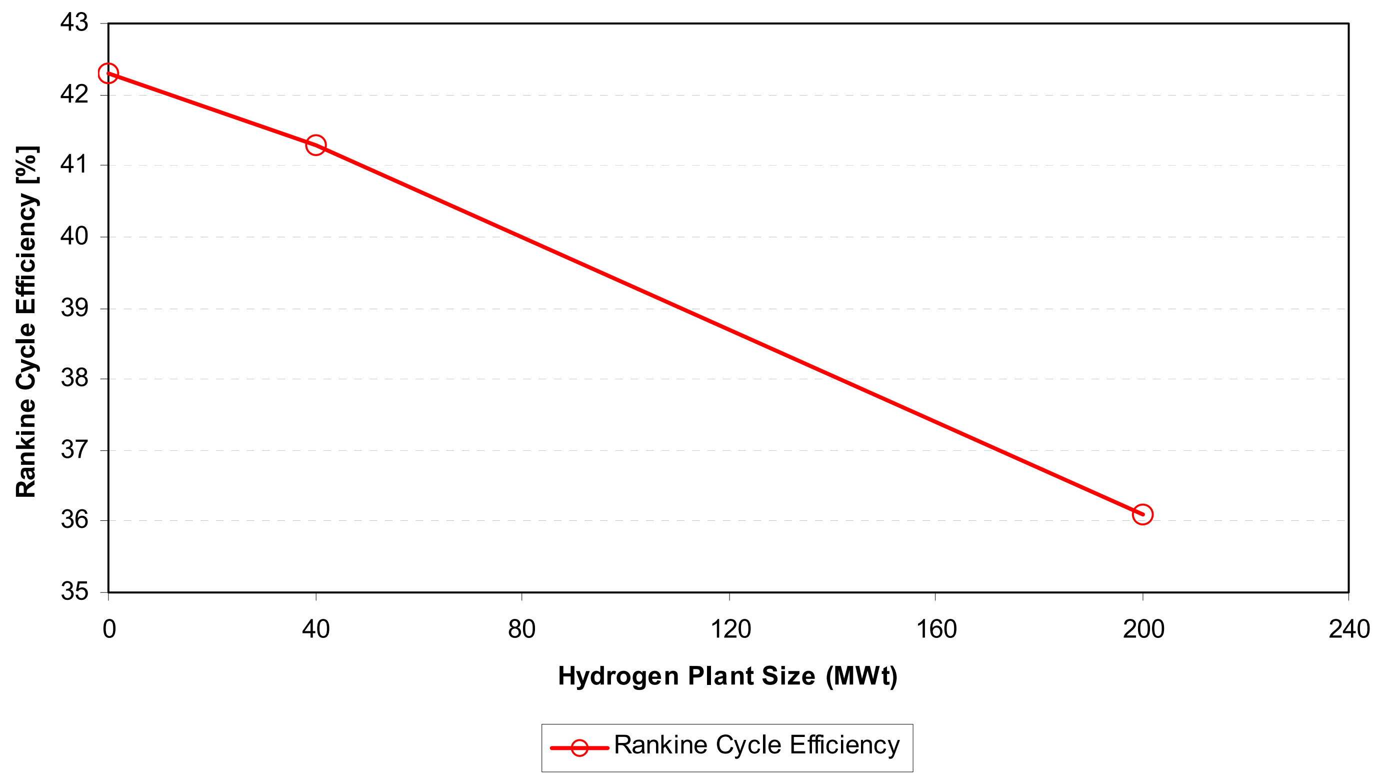
200 MW H_2 Plant Size



- **Rankine power level - 326 MW (Rankine Cycle Off-design point)**
- **Steam Turbine efficiencies - 75% (Off-design)**
- **Rankine cycle efficiency 37% (Assume a 6% Rankine Cycle efficiency decrease at 326 MW)**

Cycle L

Influence of Hydrogen Plant Size



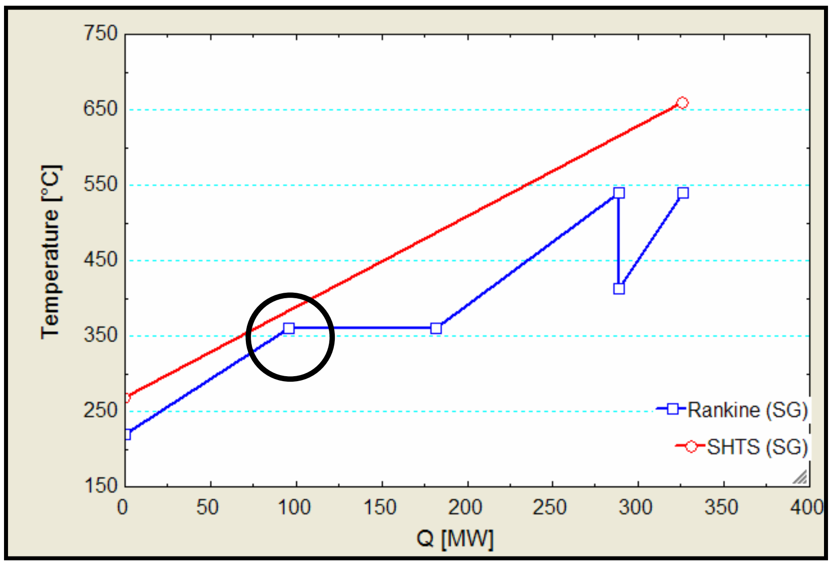
- **Sensitivity of Rankine Cycle efficiency to a change in the Hydrogen plant size (Rankine cycle design point = 0 MWt H_2)**

Cycle K – Rankine Cycle

SG Pinch Temperature (20.3)

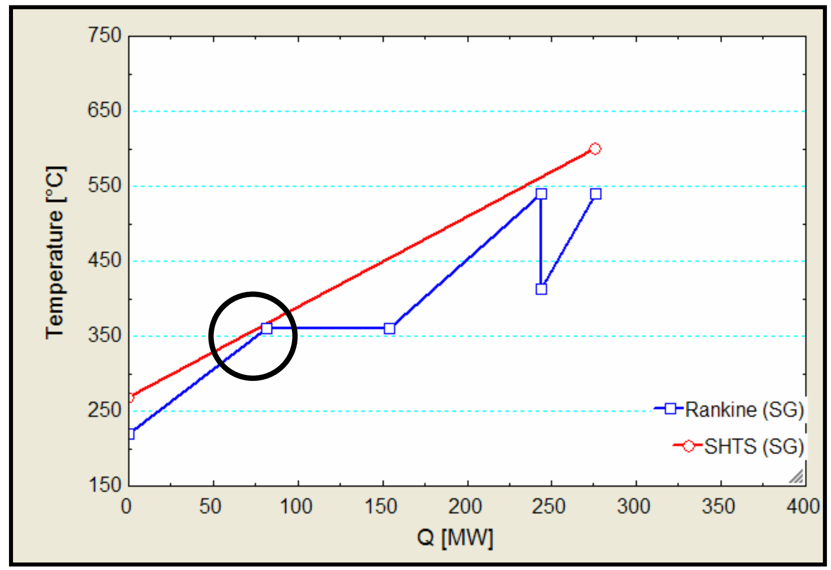
H_2 - 200 MW (Rankine 325 MW)

SG Pinch Temp of 25°C



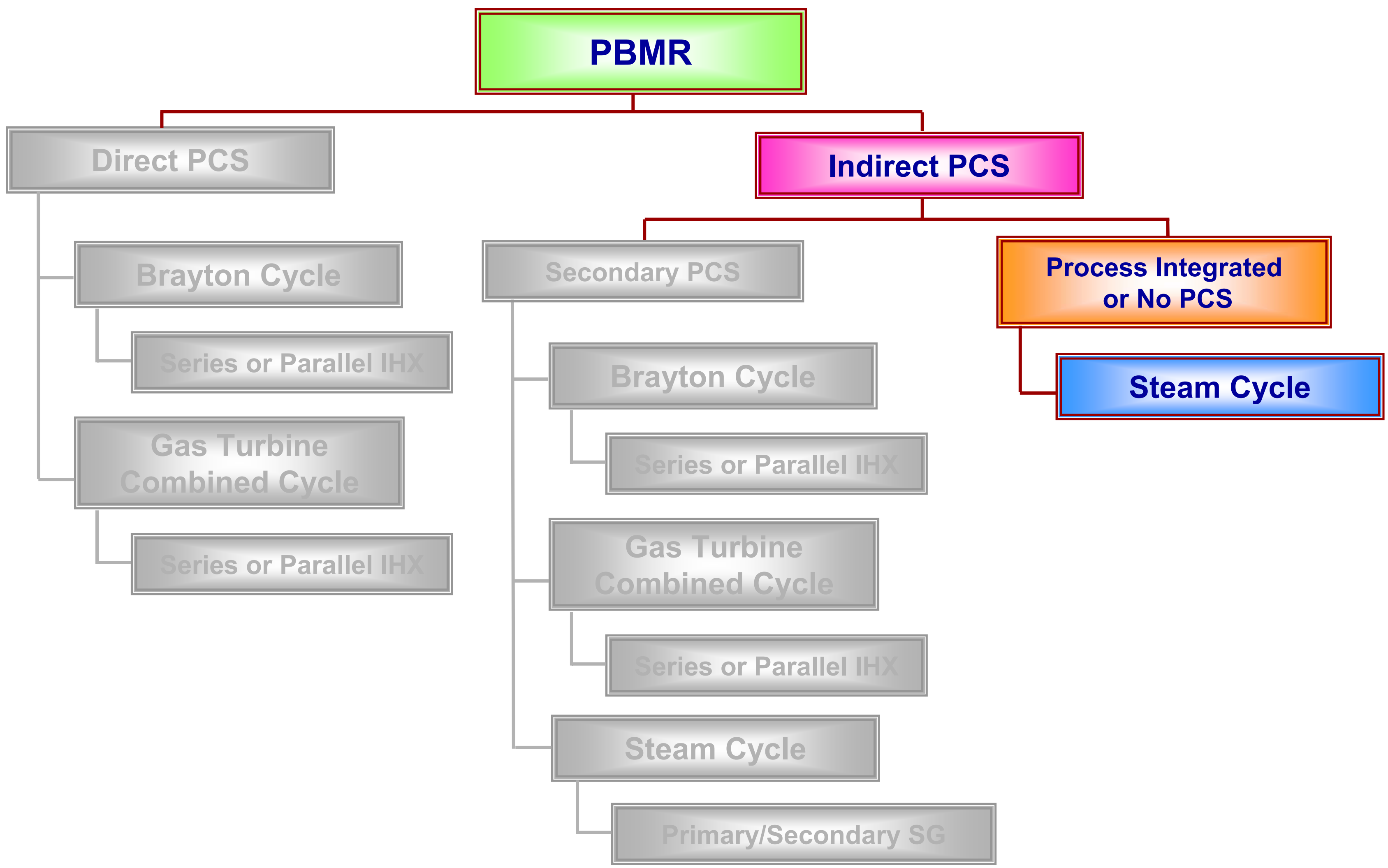
H_2 - 250 MW (Rankine 275 MW)

SG Pinch Temp of 7°C

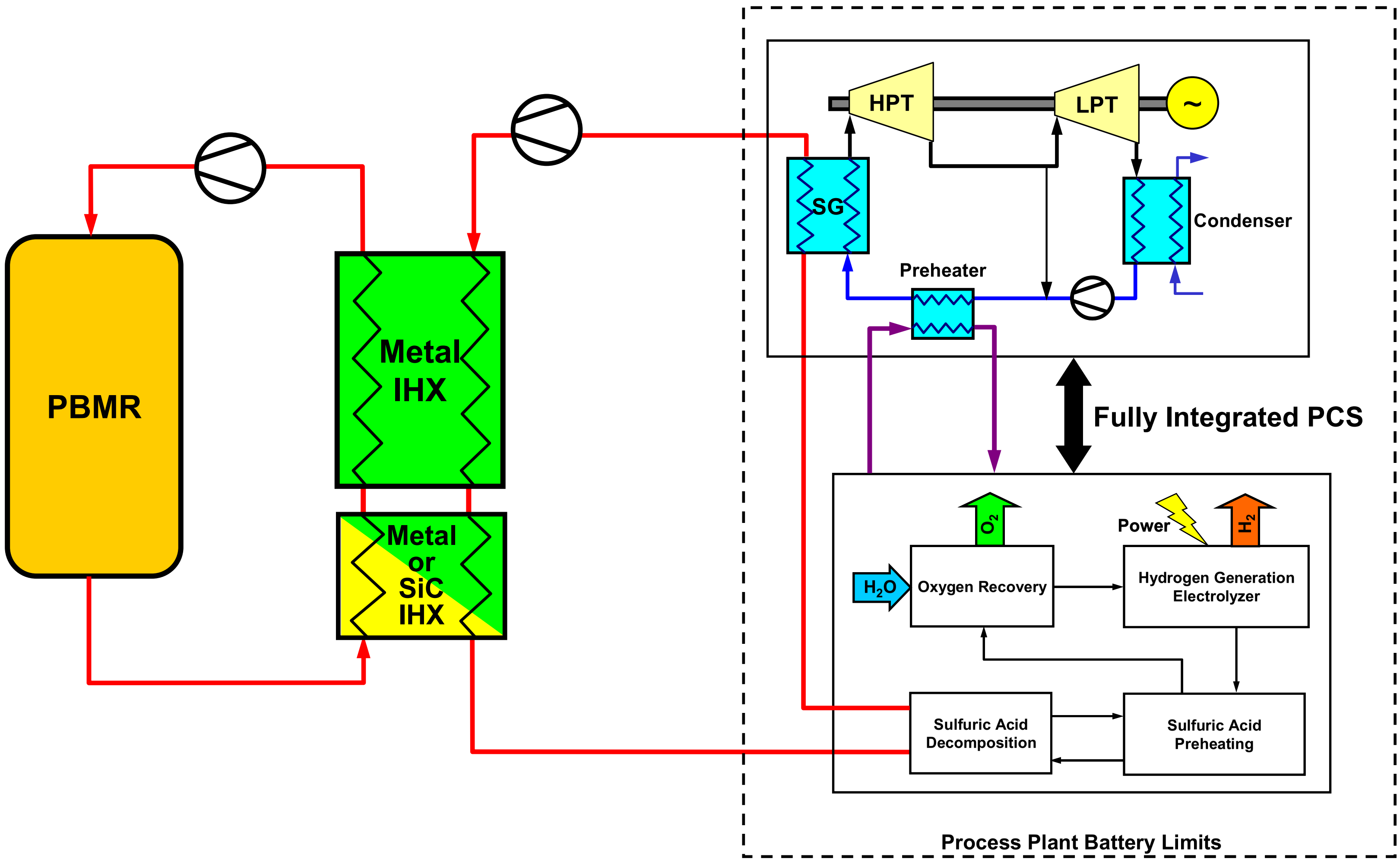


- **SG Pinch Temperature: 93°C (0 MW), 25°C (200 MW), 7°C (250 MW)**
- **Rankine plant sized for 526 MW (0-10 MW H_2 plant)**
- **Maximum H_2 plant power level ~200 MW**

Process Heat/PCS Configuration Hierarchy



Option 7:
PCS Integrated with Process



Option 7: PCS Integrated with Process

Key Features
- **Full-size IHX transfers all reactor heat to SHTS**
- **Full-size PCHX transfers all thermal energy to process**
- **Steam cycle-based PCS integrated with process**
  - Size/configuration is process dependent

Readiness
- **Large IHX poses greatest challenge to readiness**
- **Requires process availability for operation**
- **Minimum flexibility for demonstration of multiple applications**
  - Requires reconfiguration of both process and PCS for individual applications

Support of Commercial Applications
- **Not consistent with HTE architecture**
- **Up to full-scale demonstrations of PHP**
- **High NHS commonality with commercial PHP**
  - If successful, resolves IHX issue for commercial plants
  - Best prototype for design certification of PHP commercial plants

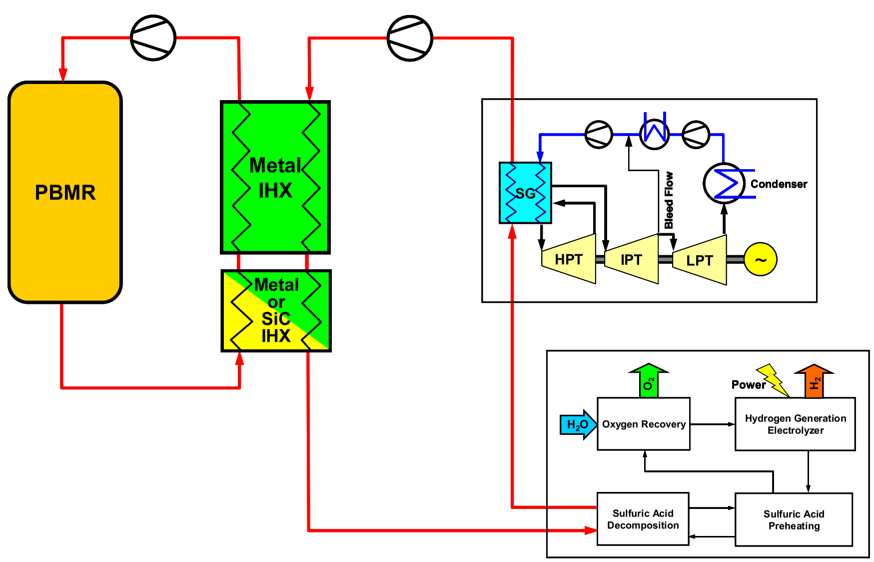
Performance
- **Prototypical of commercial applications**
- **Provisions for alternate heat sink in SHTS or process are process dependent**
  - Requires operational PHTS
- **Significant availability risk associated with potential for IHX leaks, process-related outages**

Cost
- **Capital**
  - Added cost for multiple demonstrations
  - Large IHX implies potential for high replacement capital costs
    - *May be mitigated by selection of ceramic material and/or split section design*
- **Operating**
  - Low efficiency, availability likely to minimize cost offsets via electric sales
  - PCS maintenance costs moved to process

Outline

- **Objective and Scope**
- **Study Inputs**
  - Commercial applications and performance requirements
  - Key NGNP HTS demonstration objectives
  - Key HTS functional requirements
  - Other input requirements and data
- **Screening Criteria**
- **Power Conversion System Options (20.4)**
- **H_2 Production Unit Size (20.7)**
- **IHX/High-Temperature Materials**
- **Secondary Working Fluid**
- **HTS Configuration Options**
- ⇨ **Recommended HTS Configuration**

Recommendation



Option 6: Secondary Steam Cycle, Series PCHX

The recommended HTS is <u>Option 6</u>:

- **Full-size IHX best represents commercial applications and provides optimum basis for design certification of process heat applications**
- **GT/GTCC commercial applications adequately supported by DPP in South Africa**
- **Steam cycle provides greater flexibility for balancing needs of demonstration loop and PCS**
  - Wide range of energy allocation to PCHX vs. PCS (0 – 200MWt)
  - Best protects IHX against transient events (temperature, pressure)
- **Minimizes R&D and risk not directly associated with process heat objectives**

Option 6 Evaluation

Attribute	Importance	Assessment
• **Readiness**		
➢ **Ability to meet NGNP timeline (startup: 2016-2018)**	**High**	**7-8**
➢ NGNP R&D Requirements/Cost/Risk	Med	5
➢ Supplier Infrastructure Development	Low	10
• **Support of Commercial Applications**		
➢ **Adequately demonstrates commercial process heat applications**	**High**	**10**
➢ **NHS commonality with commercial products**	**High**	**8**
➢ **Can serve as process heat prototype for design certification**	**High**	**10**
➢ Flexibility for demonstrating multiple applications	Med	
➢ Flexibility for ultimate conversion to full-scale H2 production	Med	10
• **Performance**		
➢ **Ability to meet operational performance goals**	**High**	**8-9**
➢ Efficiency	Low	7
➢ Operability	Med	9-10
➢ Availability	Low	6
• **Cost**		
➢ **NGNP Capital Cost**	**High**	**7**
➢ NGNP Operating Cost	Low	8