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Next Generation Nuclear Plant: Intermediate Heat Exchanger Development and Trade Studies

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ACRONYMS

Acronym	Definition
ASME	American Society of Mechanical Engineers
BEA	Battelle Energy Alliance
BMW	Bi-metallic Weld
CCS	Core Conditioning System
COP	Core Outlet Pipe
CIP	Core Inlet Pipe
CUD	Core Unloading Device
DBA	Design Basis Accident
DDN	Design Data Needs
DPP	Demonstration Power Plant
FEA	Finite Element Analysis
FHSS	Fuel Handling and Storage System
FOAKE	First-of-a-Kind Engineering
GS	Grain Size
HPB	Helium Pressure Boundary
HPS	Hydrogen Production System
HRB	Hochtemperatur Reaktorbau (High Temperature Reactor Builders)
HSS	Helium Services System
HTGR	High Temperature Gas-Cooled Reactor
HTIV	High Temperature Isolation Valve
HTR	High Temperature Reactor (Germany)
HTR-10	10MWt High Temperature Test Reactor (Chinese)
HTS	Heat Transport System
HTTR	30MWt High Temperature Test Reactor (Japanese)
HX	Heat Exchanger
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency
KVK	Komponentenversuchskreislauf (Component Test Facility)
KWU	Kraftwerk Union (incorporated into AREVA)
LCF	Low Cycle Fatigue

Acronym	Definition
LWR	Light Water (Nuclear) Reactor
MHTGR-SC	Steam Cycle Modular HTGR
MIT	Massachusetts Institute of Technology
NGNP	Next Generation Nuclear Plant
NHSB	Nuclear Heat Supply Building
NHSS	Nuclear Heat Supply System
ORNL	Oak Ridge National Laboratory
PBMR	Pebble Bed Modular Reactor
PCDR	Preconceptual Design Report
PCHE	Printed Circuit Heat Exchanger
PCHX	Process Coupling Heat Exchanger
PCS	Power Conversion System
PFHE	Plate-Fin Heat Exchanger
PHTS	Primary Heat Transport System
PNP	German HTR development program for coal conversion applications
R&D	Research and Development
RIT	Reactor Inlet Temperature
ROT	Reactor Outlet Temperature
RPV	Reactor Pressure Vessel
SG	Steam Generator
SHTS	Secondary Heat Transport System
SSCs	Systems, Structures, Components
TMF	Thermal-Mechanical Fatigue
VHTR	Very High Temperature Gas-Cooled Reactor

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SUMMARY AND CONCLUSIONS

The Intermediate Heat Exchanger (IHX) Development and Trade Studies Priority Task has achieved its objectives and has contributed substantially to the resolution of critical path issues associated with the PBMR NGNP IHX and Heat Transport System (HTS). Significant achievements include the development of an IHX concept for intermediate temperature (750-800°C) applications, identification of a reference heat transfer surface material for those intermediate temperatures and selection of a reference basis for coupling the IHX to the PHTS. A cursory evaluation of a helical-coil shell-and-tube heat exchanger design was also completed.

The overall results of the IHX Development and Trade Studies Priority Task are summarized in the following sections that parallel the sections of the main report. Conclusions deriving from these results are given at the end of this summary, along with recommendations for further work.

IHX Functions and Requirements

The functions and requirements initially developed in conjunction with the PBMR NGNP Preconceptual Design (Ref. 1) and the 2008 IHX and HTS Conceptual Design Study (Ref. 2) were updated in this report for an assumed intermediate temperature application that produces high-quality steam as its principal product. The basis for the present study was an indirect-cycle configuration (Figure 1) that maintains maximum commonality with the high-temperature preconceptual design for hydrogen production. In addition to the 750°C reactor outlet temperature (ROT) appropriate for steam production, a temperature of 800°C was also specified in the context of intermediate temperature direct heat applications, such as ammonia production and ethylene cracking. Other changes to functions and requirements were based upon insights obtained from the 2008 study and related tasks.

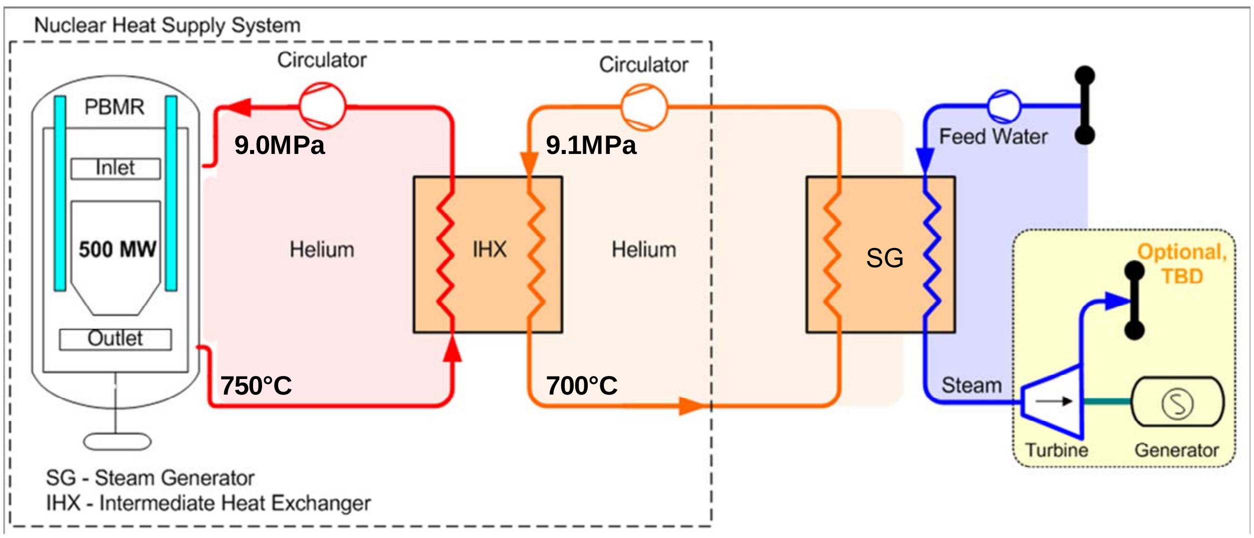

Figure 1 Intermediate Temperature Application for Steam Production

Unit Cell IHX

The reference basis for the PBMR NGNP IHX design is a compact heat exchanger, nominally of the plate-fin or plate-type. For continuity with the 2008 IHX and HTS Conceptual Design Study, and to minimize resources required for the present task, the Unit Cell IHX was used as the basis for the present evaluation. The general features of the IHX at the unit cell and module levels are unchanged from the 2008 study, with the differences being found in the sizing of the components and the materials that are employed.

A key result of the 2008 study was the revelation that corrosion associated with exposure to the Primary Heat Transport System (PHTS) helium environment would likely be the limiting factor in the lifetime of compact heat exchangers operating at high temperatures and employing very thin material cross-sections. On this basis, a review of candidate materials potentially suitable for intermediate temperature applications was conducted. It was concluded that, for the intermediate temperature range corresponding to the present evaluation, Hastelloy X offers the greater potential for achieving acceptable lifetimes in materials having thin cross-sections. In particular, available data suggest that Hastelloy X is at least three times more resistant to corrosion in the HTGR PHTS environment than Alloy 800H, which was earlier recommended for temperatures up to 760°C. Alloy 800H remains a principal candidate for these high-temperature components and, particularly, for those having thicker cross-sections. It is urgently recommended that thin-section corrosion data be obtained for both materials on a priority basis.

The thermal-hydraulic design of the IHX was developed in a two-stage process that was iterative with the steady state and transient analyses that are summarized later. Designs for both 750°C and 800°C ROT were developed. It was confirmed as a result of this process that the IHX could be configured within a single pressure vessel. This results in a very compact design, with the overall vessel dimensions being only 3.5 m diameter by 7.8 m high. As with the two-stage IHX developed in the course of the 2008 study, the present design offers the potential for detecting, locating and isolating PHTS to SHTS leaks at the module level.

Scoping thermal and structural assessments were undertaken at the unit cell and heat transfer module levels to obtain an initial indication of IHX structural adequacy for steady-state operation and representative transients. The assessed transients included startup, shutdown, loss of secondary pressure and loss of secondary cooling with failure to trip the primary circulator. These transients were arbitrarily selected as being likely to challenge the structural integrity of the IHX. The results of the scoping assessments were encouraging in that there were large margins to failure for the events that were analyzed. However, at the current stage of design, it was not possible to evaluate the interactions of the heat transfer modules with the internal piping and supports and much additional analysis is required to ultimately validate the structural adequacy of the IHX.

Shell-and-Tube IHX

The present task included a further evaluation of a helical-coil shell-and-tube heat exchanger to evaluate its prospects as a backup for the reference compact IHX design. From the results of the evaluation, it is clear that shell-and-tube heat exchangers, particularly at the intermediate temperatures evaluated in the present task, represent a practical and robust technical solution. However, in addition to much larger heat exchangers, a shell-and-tube IHX-based plant design would require a multi-loop architecture (3 loops vs. 1 loop in the case of the reference PBMR NGNP) that would significantly impact the scope and cost of the Nuclear Heat Supply System (NHSS) and the enclosing buildings and structures. Based on the results of this task and other referenced studies, it is our judgment that the incremental capital and operating costs, plus the transport issues associated with the use of conventional shell-and-tube heat exchangers, are a deterrent to their use in relatively small nuclear applications, such as the PBMR NGNP, where economics rely upon efficiency, simplicity and volume manufacturing.

It is, therefore, recommended that compact heat exchangers be retained as the reference basis for the PBMR NGNP IHX and that high priority be given to the design trade studies and associated R&D activities required to select a specific concept (e.g., plate-fin, plate-type) and to confirm its acceptability in terms of defined functions and requirements.

IHX-HTS Integration

Integration of the IHX with the remainder of the HTS and with the enclosing buildings and structures was a central focus of the IHX Development and Trade Studies Priority Task. Significant progress was made in addressing the issues identified in the 2008 IHX and HTS Conceptual Design Study.

A priority issue remaining from the 2008 study was determining whether the core-side or shell-side of the IHX should be coupled to the PHTS. It was recognized at the conclusion of that earlier study that resolution of the IHX coupling issue should be pursued with highest priority. This is because it fundamentally impacts the architecture of the NHSS, particularly in terms of piping layout and the integration of the HTS components within the NHSS buildings and structures. In reevaluating the coupling issue as part of the present task, it became evident that the reduced temperatures and simplified HTS architecture associated with a single-vessel IHX clarified some of the issues with respect to IHX coupling. Additional insights were obtained regarding the reduced potential for neutron activation of heat transfer surfaces, factors related to circulating dust and cooling of the high-temperature sections of the PHTS piping. With these insights, the Kepner-Tregoe method was used as a framework for reevaluating core- versus shell-side coupling to the PHTS.

It was concluded that shell-side coupling to the PHTS should be selected as the reference basis for conceptual design. Key factors influencing this decision were:

- Reduced complexity of PHTS piping and supports
- Uncontaminated access to the core (SHTS) side of the IHX for inspection and maintenance
- Easier control of SHTS coolant chemistry on the structurally significant core side of the IHX unit cells (note that this is not a differentiating factor for plate-type heat exchangers)
- Potential for reducing the effects of circulating dust

Based on the selection of shell side coupling to the PHTS, concepts were developed for integration of the IHX with the HTS piping and integration of the HTS components as a whole with the enclosing buildings and structures. It must be emphasized, however, that the insulation and cooling provisions related to the PHTS and SHTS piping remain open issues to be addressed in future trade studies. For purposes of the present task, it was assumed that the PHTS Reactor Outlet Pipe would be actively cooled and would parallel the design of the PBMR Demonstration Power Plant. Passive insulation was assumed for the SHTS piping. Results of the transient assessments, summarized below, underscore the need for trade studies addressing insulation and cooling issues.

IHX and HTS Analyses

The thermal-hydraulic code Flownex was used to develop a detailed model of the IHX. The resulting IHX model was then integrated into an overall model of the Nuclear Heat Supply System (NHSS) that was developed as part of a companion priority task addressing plant level analysis and fission product transport (Ref. 3). The integrated model was used to develop steady-state conditions and to perform transient analyses of two low-probability plant events that would potentially challenge the IHX design. The results of the steady-state and transient analyses were used as input to the assessments of IHX structural integrity.

Steady-state analyses were developed for both 750°C and 800°C. These were used to update the initial sizing assumptions for the IHX, as earlier described above. Start-up and shut-down transients were then assessed. Based on the relatively long timeframes involved, the IHX sees these transients as quasi-steady-state events. The important consideration for the IHX is the periods during which pressure differentials are significant at elevated temperatures. Based on preliminary structural assessments of the unit cell IHX, these conditions are not seen as limiting and there are options in terms of plant operation for their further moderation.

The Loss of Secondary Pressure (LOSP) transient is also seen by the IHX as a quasi steady-state event. Again, the principal influence on the IHX is high differential pressures during a limited period at high temperatures. Preliminary assessments of the unit cell IHX indicate that there is significant margin in the IHX design for withstanding the effects of this rare event.

The Loss of Secondary Cooling (LOSC) with Failure to Trip the Primary Circulator event is the most severe of the assessed transients in terms of thermal effects on the IHX structure. This is associated with a rapid rise in the PHTS temperature at the IHX outlet. Maximum temperatures and pressure differentials within the IHX, however, do not substantially exceed those associated with normal operation. While severe, this rare event, likely beyond the design basis, would not be expected to result in IHX internal pressure boundary failure.

As already noted, the steady-state and transient analyses summarized here, in conjunction with the IHX thermal-structural assessments summarized above, suggest large margins for the IHX features that were analyzed. However, rigorous definition and analysis of transients influencing the IHX design will be required to fully validate IHX structural integrity.

Further, the results of the LOSC event suggest that the PHTS piping, including the outer pressure boundary, may be exposed to high temperatures as a result of transients. This further confirms the need for analyses and trade studies addressing the insulation and cooling features of the HTS piping.

IHX Technology Development

Design Data Needs (DDNs) supporting the design and development of the IHX for intermediate temperature applications were assessed and updated as part of the present task. Key differences relate to the selection of Hastelloy X as the material for the IHX heat transfer surface. Alloy 800H is retained as a primary candidate material for thicker cross-section components of the IHX.

Conclusions

The principal conclusions of the IHX Development and Trade Studies Priority Task are summarized as follows:

1. At the intermediate temperatures assessed herein, the helical-coil shell-and-tube heat exchanger represents a robust and established technical option. However, the size of the individual heat exchangers and the requirement for multiple HTS loops imply significant economic penalties relative to the compact heat exchanger options (estimated by PBMR to be a factor of 10 for the heat exchangers alone). The incremental costs (including influences on the overall design of the NHSS), plus transport issues, are judged to be a deterrent to their use in small nuclear applications, such as the NGNP, where economics rely upon efficiency, simplicity and volume manufacturing.
2. Based on the use of compact heat exchangers, such as the plate-fin heat exchanger (PFHE) technology evaluated herein, the PBMR NGNP IHX, with a nominal capacity of 512MWt, can be configured within a single vessel.
3. Comparisons of the single-stage IHX design developed herein with the corresponding design of the two-stage IHX previously developed for the higher temperature (950°C) hydrogen production application, suggest that the incentives for the two-stage design may be less than previously thought, especially when considering the added complexity and technical challenges introduced by the connecting piping.
4. Hastelloy X should be included as a primary candidate material for the IHX heat transfer surface in the intermediate temperature range. The basis for this recommendation is the expectation of superior corrosion resistance. Note, however, that the corrosion resistance

of Hastelloy X has not yet been fully characterized for thin sections in the HTGR PHTS environment.

5. Based upon the steady-state and transient operating conditions assessed in this report, no thermal or structural limitations have been identified for the IHX; however, additional thermal and structural assessments are required to fully validate structural adequacy.
6. The shell-side of the IHX should be coupled to the PHTS and the core-side to the SHTS.
7. At the intermediate temperatures evaluated herein, the IHX can withstand the loss-of-secondary-pressure event with significant margin.
8. The IHX can withstand the loss-of-secondary-cooling event, with failure to trip the primary circulator, with significant margin. However, unless mitigating steps are taken, other portions of the PHTS circuit, especially the PHTS circulator and pressure boundary piping, will be exposed to conditions that exceed their design envelopes.

Recommendations

The key recommendations that evolve from the IHX Development and Trade Studies Priority Task are summarized as follows:

1. Compact IHX designs should remain the reference basis for the PBMR NGNP IHX.
2. R&D characterizing the corrosion resistance of Hastelloy X, Alloy 800H and other candidate heat transfer surface materials (e.g., Alloy 617 at higher temperatures) in thin sections in the HTGR PHTS and SHTS environments should be undertaken with highest priority. This is the single go/no-go feasibility issue thus far identified with the compact IHX designs.
3. The preconceptual design of an IHX applying plate-type technology, such as the Heatric Printed Circuit Heat Exchanger (PCHE), should be developed and assessed in a trade study along with the PFHE design evaluated herein. The objective would be to provide a basis for selecting one of these concepts as the basis for the IHX.
4. High priority should be given to undertaking the insulation and cooling trade study for the PHTS and SHTS piping that was recommended in the 2008 IHX and HTS Conceptual Design Study. The objective would be to confirm the feasibility of passive insulation for the SHTS piping and to evaluate the relative trade-offs associated with passive insulation versus active cooling for the PHTS piping.
5. Additional transient studies, in conjunction with thermal and structural assessments should be utilized to more fully validate the structural adequacy of the IHX.

References

1. *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.
2. *NGNP Conceptual Design Study: IHX and Heat Transport System,* NGNP-HTS-RPT-TI001, Revision 0, Westinghouse Electric Company LLC, April 1, 2008.

3. *NGNP Initial Conceptual Plant Level Assessments Leading to Fission Product Retention Allocations*, NGNP-PLD-GEN-RPT-N-00007, 2009.

INTRODUCTION

This report documents the results of the Intermediate Heat Exchanger (IHX) Development and Trade Studies Priority Task. The objectives of the task and the organization of this report are summarized below.

Objectives and Scope

The IHX Development and Trade Studies Priority Task initiates work on certain critical path issues that were identified in the PBMR Pre-conceptual Design Report (PCDR) and/or the 2008 IHX and Heat Transport System (HTS) Conceptual Design Study. Specifically, trade studies were recommended to define the architecture for coupling of the IHX to the HTS and to establish the insulation and cooling features of the Primary Heat Transport System (PHTS) vessels and piping. The preferred architecture for coupling the IHX to the HTS has been addressed in this task. Trade studies to resolve the insulation and cooling features of the PHTS vessels and piping will be undertaken in the course of future efforts.

In addition, the transition to lower reactor outlet temperatures implies the need to evaluate a single-vessel compact IHX arrangement that would potentially result in reduced complexity and cost. That has also been completed as part of the effort reported herein. Finally, the prospects for a helical-coil shell-and-tube heat exchanger have been further evaluated as a prospective backup for the PBMR NGNP IHX preconceptual design.

In support of this task, a simplified add-on transient analytical module has been developed to characterize the IHX and interfacing PHTS/SHTS piping, including insulation and cooling features. The module is an extension of and has been integrated with the overall NHSS analytical model developed in conjunction with Task 2.32. NHS.FAC.01: Plant Level Assessments in Support of Fission Product Retention Allocations. The IHX module was developed in sufficient detail to support the analyses and trade studies reported herein.

Organization of the Report

The IHX Development and Trade Studies Priority Task Report is organized within seven sections that follow this introduction. Section 1 provides an update of IHX functions and requirements to provide a basis for design of the IHX for intermediate temperature (750-800°C) applications.

Section 2 develops the design of a representative compact IHX design, the plate-fin heat exchanger (PFHE), in response to the intermediate temperature requirements of Section 1. In addition to basic design and sizing, Section 2 includes an assessment of materials for the IHX at intermediate temperatures. The resulting layout provided in Section 2.4 further incorporates the results of Section 4.1, which summarizes the re-evaluation of IHX coupling options. Section 2 concludes with scoping thermal and structural assessments of the IHX that take input from the transient analyses of Section 5.

Section 3 provides a semi-quantitative assessment of shell-and-tube heat exchangers as a prospective backup for the compact heat exchanger designs that are the main focus of this report.

Section 4 addresses IHX-HTS integration. The section begins with a reevaluation of IHX coupling options and the selection of a preferred IHX to HTS coupling architecture. IHX-piping and HTS-building integration are also addressed in Section 4.

Section 5 documents the results of steady-state and transient assessments in support of both IHX design and integration.

Section 6 summarizes the implications for IHX technology development, including Technology Readiness Levels (TRLs) and Technology Development Road Maps (TDRMs). Updated Design Data Needs (DDNs) are also provided as appendix.

The report concludes with Section 7, which provides the conclusions of the report and recommendations for further work.

1 IHX FUNCTIONS AND REQUIREMENTS

This section summarizes the functions and requirements that are the basis for the present Intermediate Heat Exchanger (IHX) Development and Trade Studies Task. In establishing these functions and requirements, the starting point was the reference PBMR NGNP Preconceptual Design, as described in the PBMR NGNP Preconceptual Design Report (PCDR) (Ref. 1-1) and as further developed in the 2008 IHX/HTS Conceptual Design Study (Ref. 1-2).

The reference Preconceptual Design and the IHX designs evaluated in the 2008 Conceptual Design Study were based upon a hydrogen production application employing thermochemical water splitting. The nominal operating parameters for this application are shown in Figure 1-1. As can be seen from the figure, the reactor outlet temperature (ROT) for the H_2 application was 950°C. Under normal operating conditions, the full thermal output of the reactor was transported via the primary helium working fluid to the IHX, where it was transferred to the helium of the secondary heat transport system (SHTS). In the SHTS, the secondary helium was split into two streams, with the smaller portion being routed to a Process Coupling Heat Exchanger (PCHX) and, thence, to a Mixer, before being rejoined to the main stream from the IHX (note that in the commercial version of the PBMR NGNP, the entirety of the secondary helium stream would be routed to the PCHX and the Mixer would not be required). From there it was sent to the Steam Generator, which served as a bottoming cycle, before being returned to the IHX via the SHTS Circulator.

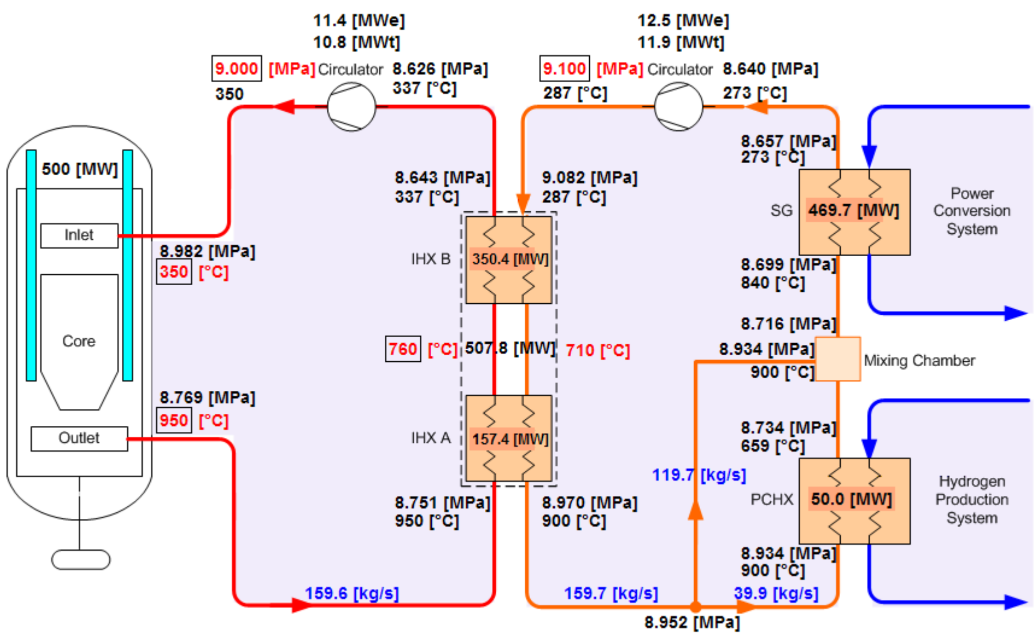

Figure 1-1 Nominal Operating Parameters for 950°C NGNP Demo Plant

The PBMR NGNP configuration documented in the PCDR was selected on the basis of the following key considerations:

- Optimum utilization of high temperature thermal energy
- Flexibility for operation in a steam-only mode using up to the full output of the reactor
- Pressure-balanced operation between the PHTS and SHTS across the high temperature IHX pressure boundary
- Commonality with the PBMR NGNP Commercial Plant, an important consideration for licensing/design certification

For the purposes of the present IHX Task, a representative intermediate temperature application has been selected in which the reactor outlet temperature is reduced to 750°C and the thermal output of the reactor is used to produce steam. The overall configuration of the intermediate temperature application (Figure 1-2) maximizes commonality with the higher temperature PBMR NGNP Demonstration Plant, described above. While the depicted architecture is for steam only, the potential exists to insert a topping process coupling heat exchanger in the SHTS (similar to the configuration of Figure 1-1) as a means of providing direct heat at intermediate temperatures. The resulting configuration would be appropriate for intermediate temperature direct heat applications, such as reforming associated with an ammonia production process or ethylene cracking.

Other key parameters maintain similarity to the PCDR design. The nominal pressure is 9MPa at the PHTS circulator outlet. Consistent with the performance assessments of Reference 1-2, a 50°C temperature drop across the IHX has been specified, and the corresponding SHTS temperature at the IHX outlet is 700°C, a temperature typical of prior HTGR steam applications. The SHTS pressure, 9.1MPa at the SHTS circulator outlet, has been selected to provide a slight secondary-to-primary pressure bias. Although primary-to-secondary bias would allow rapid detection of small primary-to-secondary leaks via radionuclide monitoring, the secondary-to-primary bias ensures that IHX leaks will not lead to contamination of the SHTS and possibly, the process loop. Note that the plate-fin heat exchanger design is potentially sensitive to the direction of pressure differential, and this is a factor in the evaluation of coupling options that follows later in this report (see Section 4.1).

It should be noted that the Nuclear Heat Supply System (NHSS) architecture and the associated operating parameters shown in Figure 1-2 are the same as those being used for the companion priority task addressing plant level analysis and fission product transport (Ref. 1-3). This is an important consideration for reducing the overall cost of the priority task effort associated with design and analysis.

As initially recommended in the PCDR, and confirmed through the 2008 IHX/HTS Conceptual Design Study, the IHX is assumed to be a compact heat exchanger. Leading candidates are the plate-fin heat exchanger (PFHE) (e.g., Brayton Energy Unit Cell) and plate-type (e.g., Heatric Printed Circuit Heat Exchanger (PCHE)). For continuity with the 2008 IHX/HTS Conceptual Design Study, the PFHE has again been selected as the principal focus of

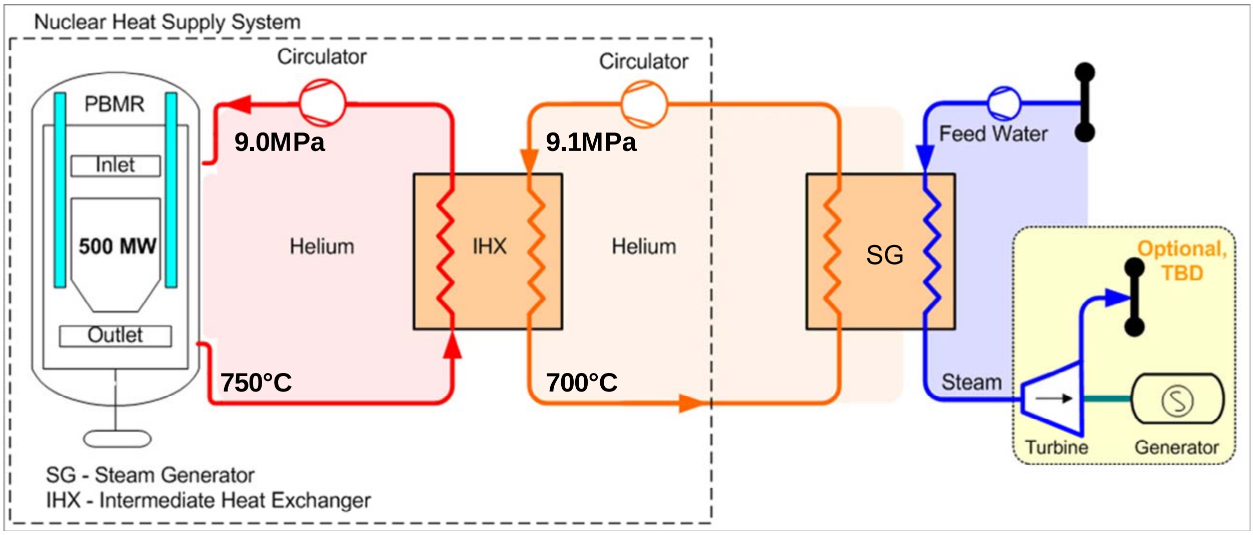

Figure 1-2 Intermediate Temperature Application for Steam Production

the present HTS evaluation. However, the PCHE is viewed as an equally promising IHX candidate and the selection of a specific compact IHX technology will take place in the course of Conceptual Design.

The sections that follow identify the principal functions of the IHX, describe the boundaries and interfaces associated with the IHX and HTS and summarize the key IHX requirements that were used as the basis for this task.

1.1 IHX Functions

The functions of the IHX are to:

- Transfer thermal energy between the PHTS and SHTS

  This function is applicable to normal operation modes and states when thermal energy is being utilized to produce steam and/or direct heat. It is also applicable to certain modes and states and to some licensing basis events in which the normal heat transport path is utilized to remove decay heat.

- Provide separation between the PHTS and SHTS helium working fluids
  This function relates to the higher level functions to retain helium within the primary pressure boundary and to control radionuclide release. In this case, control of radionuclide release means to prevent contamination of the SHTS and, possibly, the process loop.

1.2 IHX Boundaries and Interfaces

The Primary Heat Transport System (PHTS) comprises the primary piping, primary circulator and primary helium working fluid. Its main function is to transport thermal energy from the reactor to the SHTS via the IHX. The IHX, which transfers thermal energy between the PHTS and the Secondary Heat Transport System (SHTS), is by definition also considered part of the PHTS. The SHTS comprises the secondary piping, secondary circulator and secondary helium working fluid. Its main function is to transport thermal energy from the IHX to the Process Coupling Heat Exchanger and/or Steam Generator.

Consistent with the allocation in the recent Technology Readiness Level (TRL)/Technology Development Road Map (TDRM) Report (Ref. 1-4), the Intermediate Heat Exchanger (IHX) consists of the:

- Heat Transfer Surface
- IHX Internals
- IHX Vessel

The Heat Transfer Surface comprises the tubes in tubular heat exchangers or the core modules containing the heat transfer surface in the case of compact heat exchangers.

The IHX Internals include the headers and/or piping that provide a transition between the heat transfer surface and/or heat transfer core modules and the PHTS/SHTS piping, the internal structures that provide for support (steady state, transients and seismic loading) of the IHX and related internal components within the IHX vessel and the thermal baffles and/or insulation that is attached to the above IHX components.

The IHX Vessel comprises that part of the helium pressure boundary that encloses the above-described components of the IHX. The IHX vessel includes internal support features, incorporated within the vessel structure, that interface with the IHX internal supports. It also includes thermal baffles and/or insulation that are directly attached to the vessel itself.

1.3 IHX Requirements

The requirements provided in Table 1-1 have been specifically developed for the purposes of this IHX and HTS Priority Task. They will be further reviewed and updated, as appropriate, as a basis for conceptual design. The requirements identified as "Fixed" are assumed as the basis for this priority task. Requirements identified as "Subject to Review" (STR) are tentative selections from the Preconceptual Design and/or the 2008 IHX and HTS Conceptual Design Study that are to be further explored as part of this priority task and in future studies. Items identified as “Preference” are not fixed requirements, but simply indicate a preference from the NHSS viewpoint.

Table 1-1 IHX Requirements

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
1. Interface Requirements				
a) The IHX headers and piping shall be designed to interface with the PHTS and SHTS piping and the associated internal piping components, where applicable.	X			Internal piping components include internal insulation and flow paths for cooling flows. See Figure 1-3 together with Figure 1-4 to Figure 1-7 for the piping interface dimensions.
b) Pipe 1 (see Figure 1-3) shall be a coaxial pipe with active cooling.	X			Coaxial piping is employed to enable the pressure boundary to be cooled with cooling flow from the circulator outlet. This configuration is consistent with the design of the DPP. A trade study to evaluate passive insulation has been recommended as part of conceptual design.
c) The PHTS IHX outlet piping should be at the top (or close to top) of vessel.		X		The PBMR inlet is at the top of the RPV, thus, the simplest return piping is facilitated by an IHX outlet at the top.
d) The PHTS IHX inlet piping should be located towards the bottom of IHX.		X		Piping at bottom of PHTS IHX inlet will simplify the piping layout from reactor. Note that this is a relatively complex coaxial pipe.
e) The IHX internal structures and fluid flow shall ensure that the IHX vessel temperature is limited to 371°C (with appropriate margin) during normal operation.	X			The IHX vessel material shall be SA-508/ SA-533 low-alloy steel (which is limited to <371°C during normal operation). For this reason, it is preferred that the coolest gas in the shell-side of the IHX is closest to the vessel and the hot gas is the furthest away.

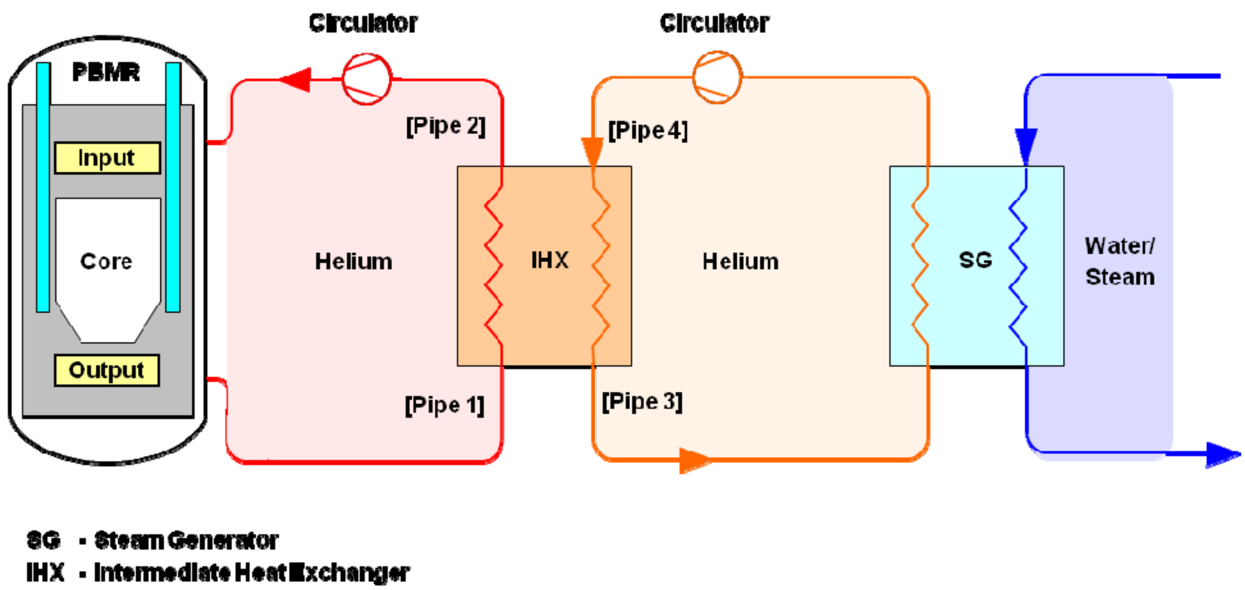

Figure 1-3 IHX/Piping Interface Drawing Pipe Definitions

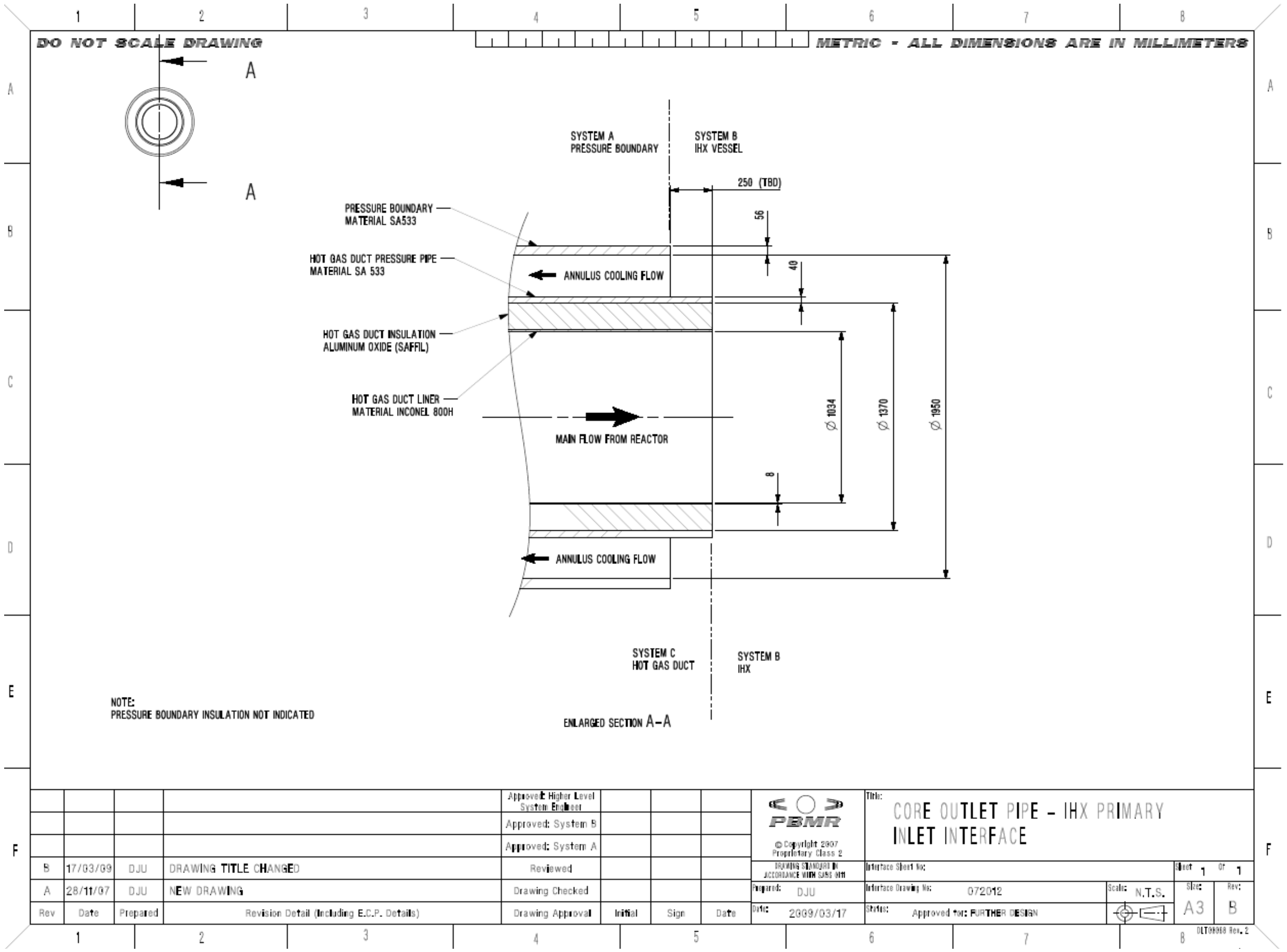

Figure 1-4 IHX-Reactor Outlet Pipe Interface Drawing (Pipe 1)

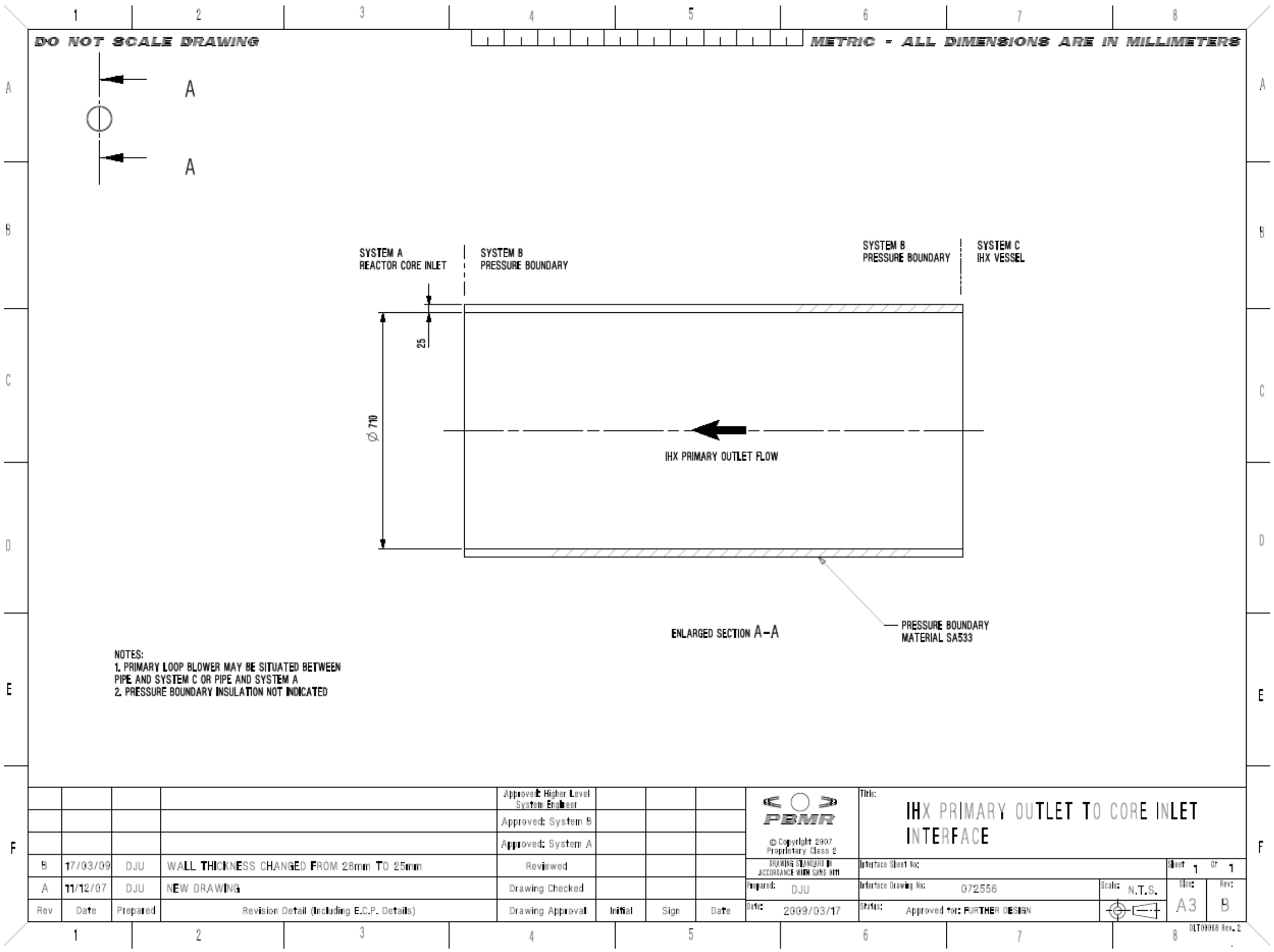

Figure 1-5 IHX-Reactor Inlet Pipe Interface Drawing (Pipe 2)

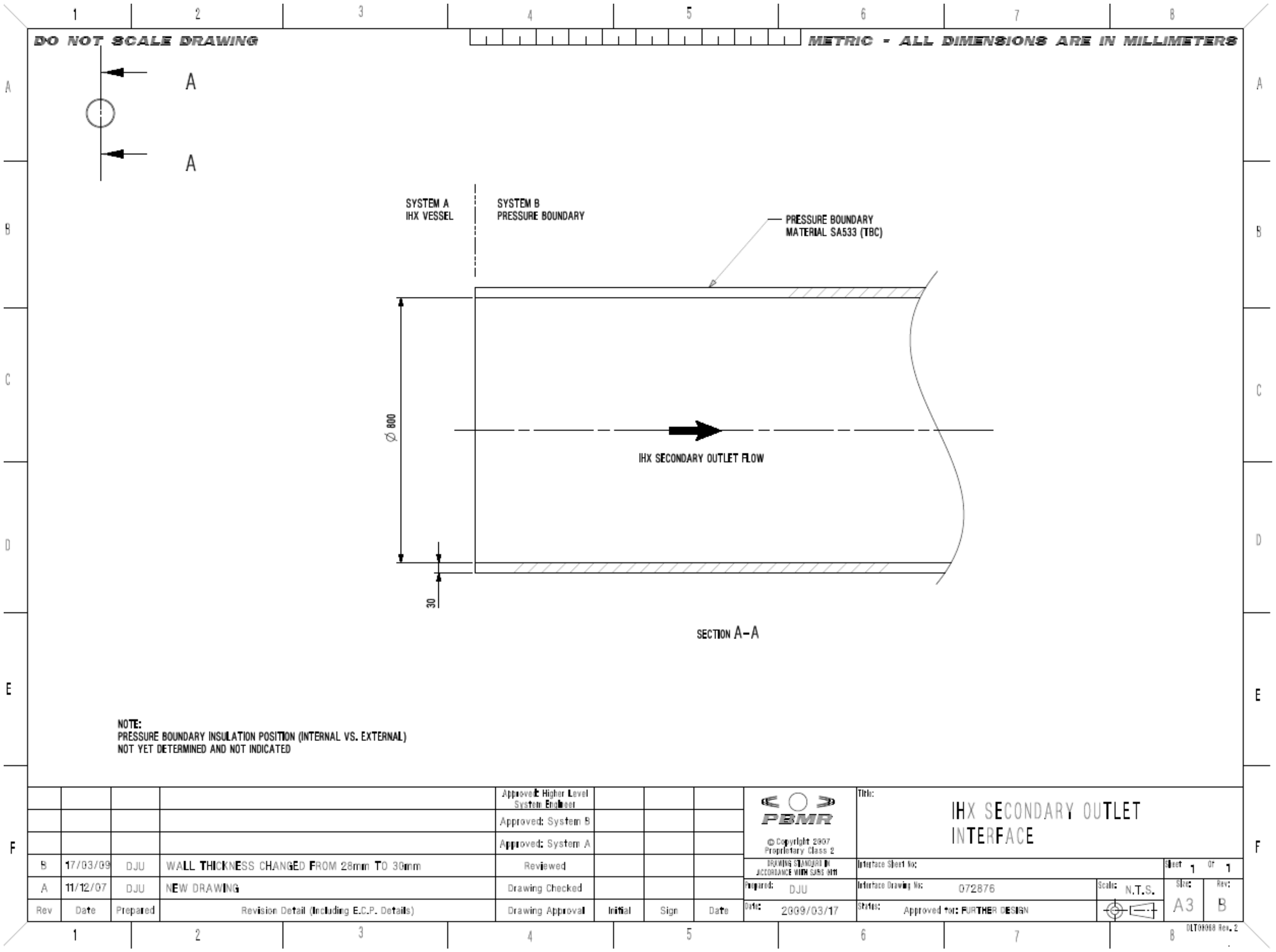

Figure 1-6 IHX-Secondary Outlet Pipe Interface Drawing (Pipe 3)

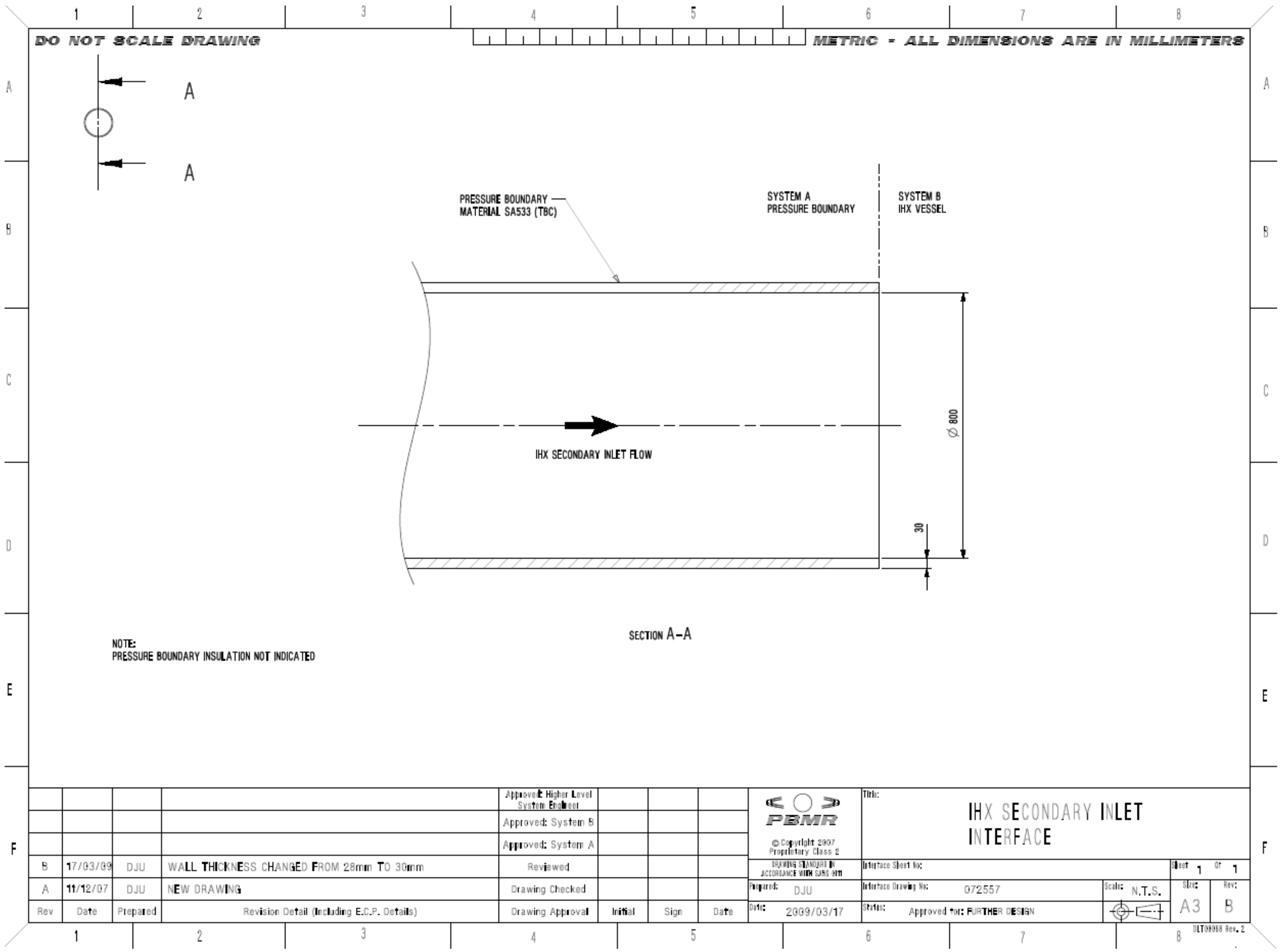

Figure 1-7 IHX-Secondary Inlet Pipe Interface Drawing (Pipe 4)

Table 1-1 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
2. System Configuration and Essential Features				
a) The IHX design shall have a single hot inlet pipe from the Reactor (PHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
b) The IHX design shall have a single hot outlet pipe to the Steam Generator (SG) or Process Coupling Heat Exchanger (SHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
c) The IHX design shall have a single cold outlet pipe to the Reactor (PHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
d) The IHX design shall have a single cold inlet pipe from the Steam Generator (SG) or Process Coupling Heat Exchanger (SHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
e) The working fluids in both the PHTS and SHTS shall be helium.	X			
3. Operational Requirements				
a) The IHX shall be designed for an operating life of 60 years.			X	Conditional requirement to be confirmed through the technology program. Potential limitation is corrosion of thin-section materials.
b) The IHX shall be designed to transfer nominally 512 MW (including primary circulator power) from the PHTS to the SHTS at the design conditions listed below.			X	Nominal value to be adjusted as part of steady state analysis.

Table 1-1 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
c) The pressure loss across primary side and also across secondary side of IHX shall be smaller than 1.23 % of its respective inlet pressures.		X		$\left(\frac{\text{IHX }A_{inlet} - \text{IHX }B_{outlet}}{\text{IHX }A_{inlet}}\right)_{Primary} < 1.23\%$ $\left(\frac{\text{IHX }B_{inlet} - \text{IHX }A_{outlet}}{\text{IHX }B_{inlet}}\right)_{Secondary} < 1.23\%$ The 1.23% value was derived from analogous pressure loss estimates from DPP.
d) IHX PHTS inlet pressure shall nominally be 8675 kPa.			X	Initial estimate, based on circulator outlet pressure of 9000 kPa and reactor pressure drop of 300 kPa.
e) The PHTS/SHTS shall be essentially pressure-balanced during normal steady-state operations.	X			
f) IHX SHTS inlet pressure shall nominally be 9082 kPa.			X	Initial estimate, based on circulator outlet pressure of 9200 kPa.
g) The PHTS/SHTS pressure drop rate shall be such that the SHTS pressure is always higher that the PHTS pressure during normal steady-state operations.	X			Pressure bias direction selected to avoid SHTS contamination in the event of IHX leaks.
h) Primary-side IHX inlet/outlet shall be 750°C/266°C.			X	To be re-evaluated as part of design.
i) Primary-side and Secondary-side IHX mass flow rate shall nominally be 204 kg/s.			X	To be re-evaluated as part of conceptual design.
j) The steady state secondary side IHX outlet temperature shall not be lower than 700°C.			X	To be re-evaluated as part of conceptual design.
k) The IHX shall be able to accommodate 600 start-up/shut-down cycles.	X			
l) The IHX shall withstand a 9 MPa nominal pressure differential resulting from loss of SHTS pressure from full power operating conditions for at least one event without consequent failure of the PHTS/SHTS pressure boundary.	X			See Section 5.3.2 for definition of the loss-of-secondary-pressure transient.

Table 1-1 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
4. Structural Requirements				
a) The IHX vessel outer diameter shall not exceed 6 m; hence, IHX internals shall be designed to fit within a 6 m vessel.		X		Construction and/or transport constraint.
5. Environmental Requirements				
a) Those portions of the IHX exposed to PHTS coolant helium shall be designed to resist chemical impurities within the limits (Table 1-2) specified for the primary coolant.			X	PHTS chemistry is principally driven by the requirements of the graphite Core Structures Ceramics components.
b) Those portions of the IHX exposed to SHTS coolant helium shall be designed to resist chemical impurities within the limits [TBD] specified for the secondary coolant.			X	There is a possibility to optimize the SHTS coolant chemistry to enhance the lifetime of the IHX.
c) Requirements related to Tritium transport are TBD			X	Consideration of Tritium transport is beyond the scope of the present study.
d) The IHX shall be designed for the Operating Basis Earthquake [TBD g] and for the Safe Shutdown Earthquake (SSE) [TBD g].			X	The IHX must remain functional following an OBE. Requirements related to the SSE, particularly with respect to the integrity of the PHTS/SHTS interface, require further assessment. The actual OBE and SSE impacts on the IHX will be site and design (building and supports) specific.
6. Instrumentation and Control Requirements				
				None at this stage.
7. Availability and Reliability				
a) The inherent availability (safe life design) of the IHX shall be ≥ 99.98%			X	Consistent with the reliability expected for steam generators in water reactors.
8. Maintenance Requirements				
• The IHX shall not require preventative maintenance.	X			

Table 1-1 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
8. Maintenance Requirements (cont'd)				
• The IHX shall include provisions for detecting and locating leaks and for repairing, isolating and/or replacing failed components		X		The leak detection capability may be implemented elsewhere in the HTS, however locating and repairing or isolating leaks remains an IHX requirement. This requirement is subject to the future development of an overall HTS maintenance philosophy that includes consideration of the tradeoffs between maintainability and availability.
• The PHTS side of the IHX shall be designed to operate for its full design life in the presence of circulating dust.	X			Dust profile to be separately evaluated.
9. Transport Requirements				
a) Design features shall be included to allow for transportation of sub-assemblies with final assembly on site.			X	The current transport constraint for the INL site is 3.5 m by 24 m. Since the RPV will be fabricated/welded on site, the equipment will be on site to assemble the IHX - hence current assumption is that it is not required to impose specific transportability requirements on the IHX. It is noted that transportability constraints are site specific.
10. Testing, Qualification, Commissioning (TQC)				
a) Provisions shall be made for pressure testing of the PHTS in accordance with ASME pressure vessel requirements with the SHTS at ambient pressure.	X			The entire PHTS must be pressure tested on site after assembly in the field. The IHX internals would be in place at this time.

Table 1-2 Nominal PHTS Coolant Chemistry

Gaseous Impurity	Steady-State Approach Value (ppmv)
N_2 (no Low Temperature Absorber (LTA))	126
N_2 (with LTA)	0.45
CO	3.9
H_2	3.9
CH_4	< 0.1
O_2	< 0.1

1.4 References

1-1 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.

1-2 *NGNP Conceptual Design Study: IHX and Heat Transport System*, NGNP-HTS-RPT-TI001, Revision 0, Westinghouse Electric Company LLC, April 1, 2008.

1-3 *NGNP Initial Conceptual Plant Level Assessments Leading to Fission Product Retention Allocations*, NGNP-PLD-GEN-RPT-N-00007, 2009.

1-4 *NGNP and Hydrogen Production Conceptual Design Study: NGNP Technology Development Road Mapping*, NGNP-CTF MTECH-TDRM, Revision 0, November 2008.

2 UNIT CELL IHX

A compact-surface plate-fin heat exchanger concept has been conceived by Brayton Energy LLC in response to the requirements of Section 1.3. This heat exchanger technology and several integration schemes are discussed in the following paragraphs.

2.1 Core Concept

2.1.1 Construction

The unit-cell heat exchanger presented here falls into the broad category of "counterflow-plate-fin heat exchangers with crossflow headers". It differs from the typical construction in that the brazed unit is the minimum repeatable pressure-bounding fraction of the heat exchanger core, whereas an entire core is brazed with most plate-fin heat exchangers. Units are welded manifold-to-manifold to create cores, a construction economically produced by applying automated assembly methods. Also, thermal-mechanical stress in the cell and core is minimized by the narrow aspect ratio of the cores. The proposed geometry better manages thermal strains while avoiding the fluid's pressure-loss in the short, two-sided, crossflow headers.

A unit-cell is composed of two parting sheets and three layers of extended heat-transfer surface, which are assumed to be of the folded-wavy fin type for this application. Figure 2-1 illustrates these components and the manifold rings, incorporated as joining features and to resist hydraulic loads.

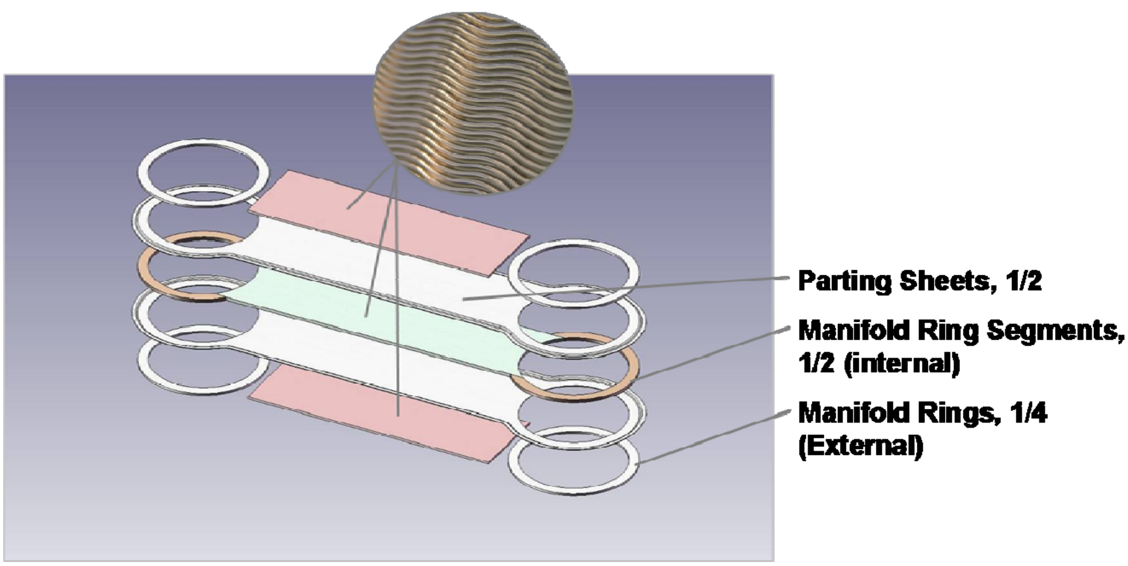

Figure 2-1 Exploded View of Unit-Cell Details

Parting sheets create the pressure boundary at the perimeter of the cell. One of two parting sheets used per unit-cell brazement is shown in Figure 2-2. As seen in Figure 2-2, the formed edge is pressed into the sheets and is precisely dimensioned to one-half the internal fin-height. This ensures intimate contact between the sheets, fin, and periphery in each cell assembly.

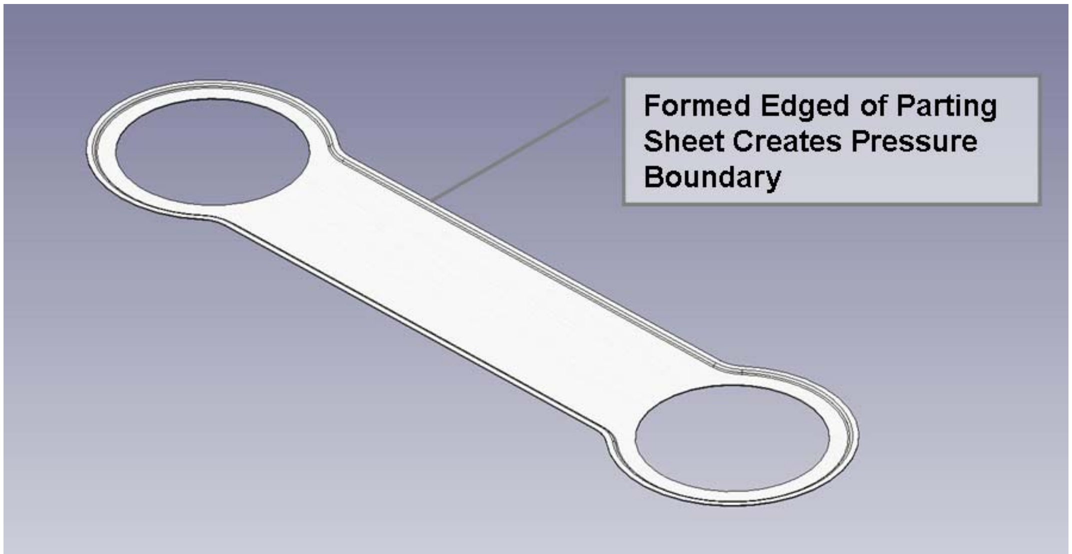

Figure 2-2 Parting Sheet Detail

The cell elements are assembled and furnace-brazed to complete a unit-cell as seen in Figure 2-3. Note that the manifold rings provide features for cell-to-cell welding. The heat exchange matrix comprises three layers of extended surface. This is a factory inspectable assembly that can be leak-tested and subjected to a high internal pressure to verify its integrity prior to assembly within the IHX module. Statistical sampling of cells for destructive testing is incorporated into the manufacturing process to economically obtain process-control data.

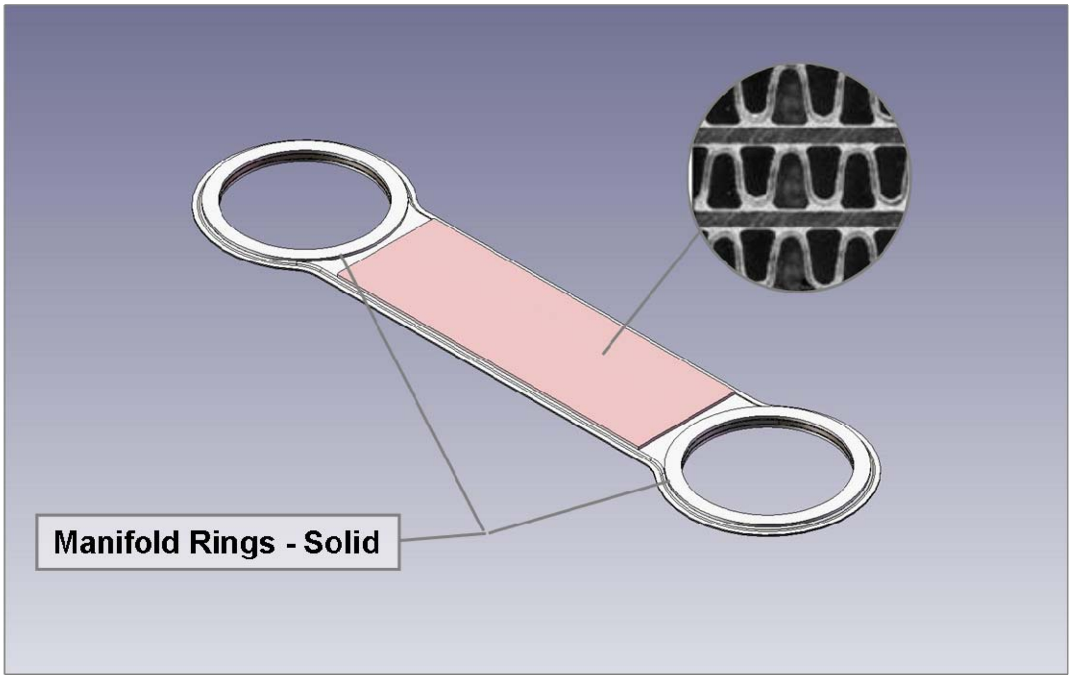

Figure 2-3 Unit Cell Brazement

As seen in Figure 2-4, cells are joined only at the manifolds by an orbital welding process, leaving the crowns of fins in the fin-fin plane between cells free to slip as required in response to thermal deflections of cores with changes in operating state. Sample locations of welds are shown in Figure 2-4.

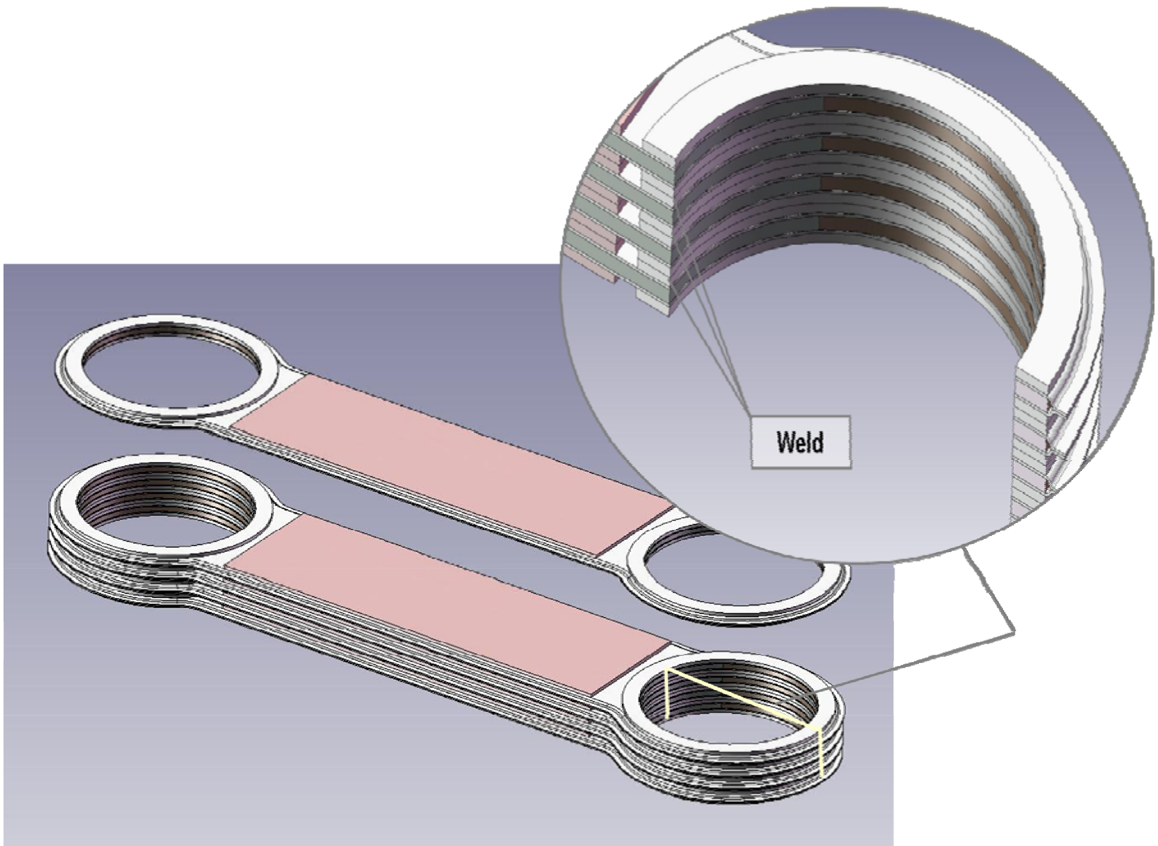

Figure 2-4 Core Under Construction

The core is leak-tested periodically during construction to assure hermeticity. Final leak and pressure tests are conducted on the complete assembly, with terminal flanges welded in place. There is little risk of failure at this point given the repeated intermediate checks during fabrication.

2.1.2 Function

Assignments of gas flows within the cell are made with these considerations:

- Stress state during normal operation
- Stress state in a loss-of-secondary-pressure event
- Maintainability considering radionuclide contamination of the primary side

The heat exchanger can function adequately with either the primary or secondary circuit coupled to the internal side of the cores. A comprehensive review, reported in Section 4.1, concluded that coupling the PHTS with the shell side (external) pass is most technically favorable. The differential pressure is 240 kPa at the hotter end of the heat exchanger, with the higher SHTS pressure producing a modest tensile load on the internal fins. While this load tends to open the cell, its magnitude is small relative to the creep resistance of the candidate materials, Incoloy 800H and Hastelloy X. With this configuration, the direction of pressure would be reversed in a loss-of-secondary-pressure event and the stress would indeed be in a direction tending to collapse the cell pressure boundary. With an internal cell spacing of less than a millimeter, even the unlikely collapse of internal fins is likely a benign consequence. A risk to be mitigated analytically is the possibility of compressive buckling of the 50 mm manifolds in a creep mode during a rapid decompression of the SHTS. With an initial hoop load less than 80MPa and reactor-outlet temperature and pressure falling rapidly after one hour, this risk appears modest.

Flow through an IHX unit cell is depicted in Figure 2-5. Primary gas flows between manifolds through the internal heat exchange passages. Secondary flow enters from both sides of the manifold at one end and flows counter to the primary through the outer, external passages of the cell and exits around both sides of the primary inlet manifold.

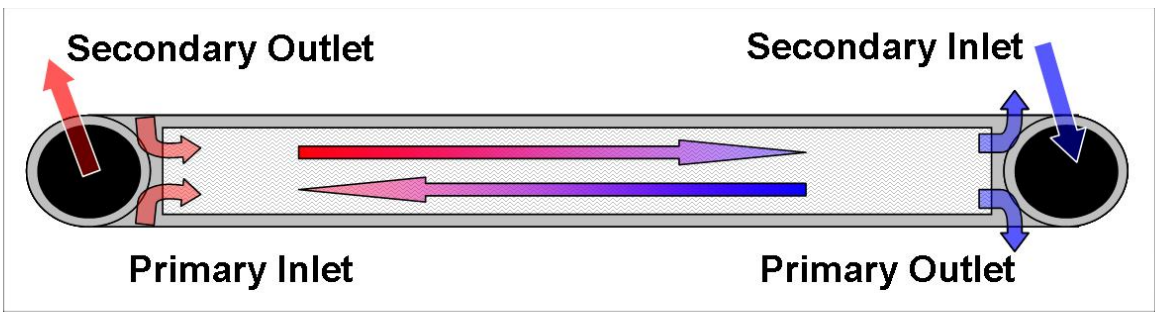

Figure 2-5 Flow Pattern through a Unit-Cell

Figure 2-6 shows a sample of a unit-cell in cross section. Secondary flow is between parting sheets while primary flow is above and below in the external fin passages.

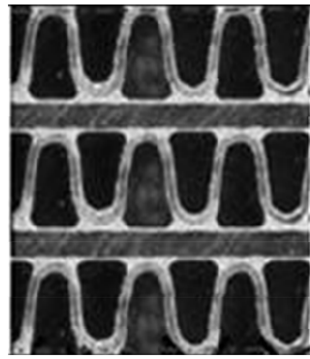

Figure 2-6 Sample Cross Section from a Unit-Cell

2.2 Materials Assessment for 750°C to 800°C

Assessments are ongoing relative to several critical path issues that were identified for the NGNP PBMR compact IHX designs in the PCDR (Ref. 2-2) and/or the IHX/HTS Conceptual Design Study (Ref. 2-1). In particular, attention is being given to a 500 MWt IHX with an inlet PHTS temperature of 750-800°C. The heat exchange sections would be contained in a single IHX vessel and would be designed for full reactor lifetime.

The two metallic alloys being given most serious consideration for construction of the IHX modules are Alloy 800H and Hastelloy X. The remainder of this section provides a detailed comparison of these two materials relative to a number of factors including ASME Code status, mechanical and thermal/physical properties, and manufacturing and joining.

2.2.1 Characteristics and Uses of the Two Candidate Alloys (Ref. 2-3)

Alloy 800H is a nickel-iron-chromium austenitic alloy with good strength and relatively good resistance to oxidation and carburization in high-temperature exposures. The nickel content of the alloy makes it resistant to both chloride stress-corrosion cracking and to embrittlement from precipitation of sigma phase. General corrosion resistance is very good and it has superior creep and stress rupture properties.

Alloy 800H is generally used in high temperature (>600°C) applications requiring good resistance to creep and creep-rupture. It is not embrittled even after long periods of use at temperatures in the range 650-875°C. The alloy exhibits excellent cold forming characteristics and can be welded by common techniques used for stainless steels.

Alloy 800H is used in a variety of applications involving exposure to corrosive environments and high temperatures such as in heat treating equipment, chemical and petrochemical processing, nuclear power plants (e.g., steam generator tubes in GCRs and LWRs), and the paper pulp industry. Service experience with Alloy 800H is long, extensive, and very successful.

Hastelloy X is a nickel-chromium-iron-molybdenum alloy with outstanding high temperature strength, oxidation resistance, and fabricability. (Other common designations for the alloy are Alloy X and Inconel HX.) It is exceptionally resistant to stress-corrosion cracking in petrochemical applications. Matrix stiffening provided by the molybdenum content results in a high-strength solid-solution strengthened alloy having good fabrication characteristics even by cold forming. It can be welded by both manual and automatic methods including shielded metal arc, gas tungsten arc, and gas metal arc, submerged arc, and resistance welding processes.

Hastelloy X is one of the most widely used nickel base superalloys for gas turbine combustion zone components such as transition ducts, combustor cans, and flame holders as well as in afterburners and tailpipes. It is recommended for use in industrial furnace applications because of its resistance to oxidizing, reducing, and neutral atmospheres. Applications in the chemical processing industry include retorts, muffles, catalyst support grid baffles, tubing for pyrolysis operations, and flash drier components. A sister alloy, Hastelloy XR, has been used successfully in the IHX of the High-Temperature Test Reactor (HTTR) in Japan. As with the Alloy 800H discussed earlier, service experience with Hastelloy X is extensive and successful.

2.2.2 Alloy Chemistry and Specifications (Ref. 2-3)

All standard mill forms including rod, bar, plate, sheet, strip, shapes, and tubular products are available for Alloy 800H. Specific appropriate ASME specifications are SB-409 for plate and sheet and SB-407 for seamless pipes and tubes. Its UNS Number is N08810. An ASTM Grain Size of 5 or coarser is specified for most Alloy 800H products; however, grain size is typically in the range of 2-5 for sheet.

The nominal chemistry of Alloy 800H is given in Table 2-1. Note that a ‘sister’ alloy, Alloy 800HT, has identical chemistry except that the minimum C content is 0.06% rather than 0.05% and that minimum Al + Ti is 0.85% rather than 0.30%. The higher minimum C and Ti + Al contents are intended to maximize high temperature strength. However, as was shown by analyses in Reference 2-1, the strength of Alloy 800H is more than sufficient for an IHX operating at 760°C. Further, as was also discussed in Reference 2-1, minimizing Al and Ti is very beneficial to the brazing process for manufacture of IHX plate-fin heat transport modules. On this basis, Alloy 800H would be preferred to Alloy 800HT for the NGNP PBMR IHX.

Hastelloy X (UNS Number N06002) is available as plate, sheet, strip, bar, tubing and pipe under ASME specifications SB-435, SB-572, SB-619, SB-622 and SB-626. Grain size for high temperature applications will normally be in the ASTM Grain Size range 5-6.

Table 2-1 Typical Chemical Composition Ranges for Alloy 800H

Element	%
Nickel	30.0 – 35.0
Chromium	19.0 – 23.0
Iron	39.5 minimum
Carbon	0.05 – 0.10
Aluminum	0.15 – 0.60
Titanium	0.15 – 0.60
Aluminum + Titanium	0.30 – 1.20

The nominal chemistry specified for Hastelloy X is shown in Table 2-2. As with the Alloy 800H/800HT variants discussed above, there is a closely-related variant of Hastelloy X designated as Hastelloy XR. This latter alloy was developed in Japan for their HTGR program and has been used as IHX tubing in their HTTR. A major chemical difference between Hastelloy X and Hastelloy XR appears to be the imposition of a limit on Ti + Al for the latter (0.08% maximum). However, there are no intentional additions of Ti or Al for Hastelloy X. Also, Hastelloy XR has specified minimums for Mn and Si of 0.75% and 0.25, respectively, while the specification for Hastelloy X calls only for 1% maximum of each. The only other obvious difference in chemical composition is for Co (0.5-2.5% for Hastelloy X and 0.0-2.5% for Hastelloy XR). The Japanese advertise their version as having improved properties but their database is not currently available in the US. Therefore, Hastelloy X would be preferred to Hastelloy XR for the NGNP PBMR IHX.

2.2.3 Status of ASME Code Qualification for Nuclear Service

Alloy 800H is incorporated into a number of ASME Code standards. The ASME Code applicable to the nuclear application of the alloy is Section III, Subsection NH and permits the use of Alloy 800H at temperatures to 760°C as a pressure boundary material. ASME Section III, Code Case N-201 (applicable to core support applications) also includes Alloy 800H to 760°C. Further, data currently available to support the necessary increase in maximum temperature in both Subsection NH and Code Case N-201 are sufficient or nearly so. An extension of ASME Section III, Subsection NH allowable stresses for Alloy 800H to 900°C is presently being pursued as one task in a cooperative agreement between DOE and ASME (Ref. 2-4). Additional data required will be identified in this activity.

Hastelloy X is not included for nuclear applications in any ASME code case or standard. However, it is currently being considered for addition to ASME Code Case N-201 under Task 4 of the DOE/ASME cooperative agreement initiated in 2006 (Ref. 2-4). No efforts are currently in progress to incorporate Hastelloy X into ASME Section III, Subsection NH. There is little doubt, however, that there exists data sufficient for this purpose.

Table 2-2 Typical Chemical Composition Ranges for Hastelloy X

Element	%
Nickel	Balance (Nominal Range ~46-60)
Chromium	20.5 – 23.0
Iron	17.0 – 22.0
Molybdenum	8.0 – 10.0
Cobalt	0.5 – 2.5
Tungsten	0.2 – 1.0
C	0.10
Manganese	1.0 maximum
Silicon	1.0 maximum
Boron	0.01 maximum

2.2.4 Mechanical Property Comparisons (Refs. 2-3, 2-5)

This section provides a one-to-one comparison of the mechanical properties of Alloy 800H and Hastelloy X. The properties presented are generally for plate and sheet product forms and are derived primarily from multiple supplier sources (Ref. 2-4) and other literature (Ref. 2-5). Table 2-3 shows typical values of ultimate tensile strength (UTS), yield strength (YS), and elongation for the two alloys and Table 2-4 gives the dynamic tensile modulus of elasticity. Note that the UTS and YS for Hastelloy X are greater than those for Alloy 800H at all temperatures through 871°C. At 760°C the strength values for Hastelloy X are twice those for Alloy 800H. However, the lower strength of Alloy 800H would not preclude its use in the IHX application at 760°C. Tensile modulus values for the two alloys are comparable.

Table 2-3 Typical Tensile Properties of Alloy 800H and Hastelloy X

Temperature °C	Ultimate Tensile Strength - MPa		Yield Strength MPa		Elongation in 2-in. %	
	800H	Hast X	800H	Hast X	800H	Hast X
20	560	767	225	379	52	44
538	473	614	146	245	51	49
649	394	581	139	244	50	54
760	230	463	124	237	78	53
871	130	310	90	194	120	59

Table 2-4 Dynamic Tensile Modulus of Elasticity For Alloy 800H and Hastelloy X

Temperature - °C	Tensile Modulus - GPa	
	Alloy 800H	Hastelloy X
20	196	205
538	162	178
649	154	170
760	145	161
871	-	153

Typical 10,000 hr creep-rupture strengths for both Alloy 800H and Hastelloy X are shown in Figure 2-7 and in Table 2-5; stresses to produce minimum creep rates from 0.0001 %/hr to 0.1 %/hr are given in Table 2-6. At 760°C, the 10,000 hr creep-rupture strength of Alloy 800H is ~67% of that for Hastelloy X. However, the stress analyses performed in Reference 2-1 for the Alloy 800H IHX at 760°C demonstrated that Alloy 800H creep properties are sufficient for full lifetime. Life predictions for Alloy 800H based on minimum creep rates confirmed the lifetime predictions at 760°C. Minimum creep-rate values for the two alloys are quite comparable with perhaps a slight edge to Hastelloy X. Comparison of the Table 2-5 and Table 2-6 values for Hastelloy X with those for Alloy 800H indicate that a full IHX lifetime with Hastelloy X is also without question.

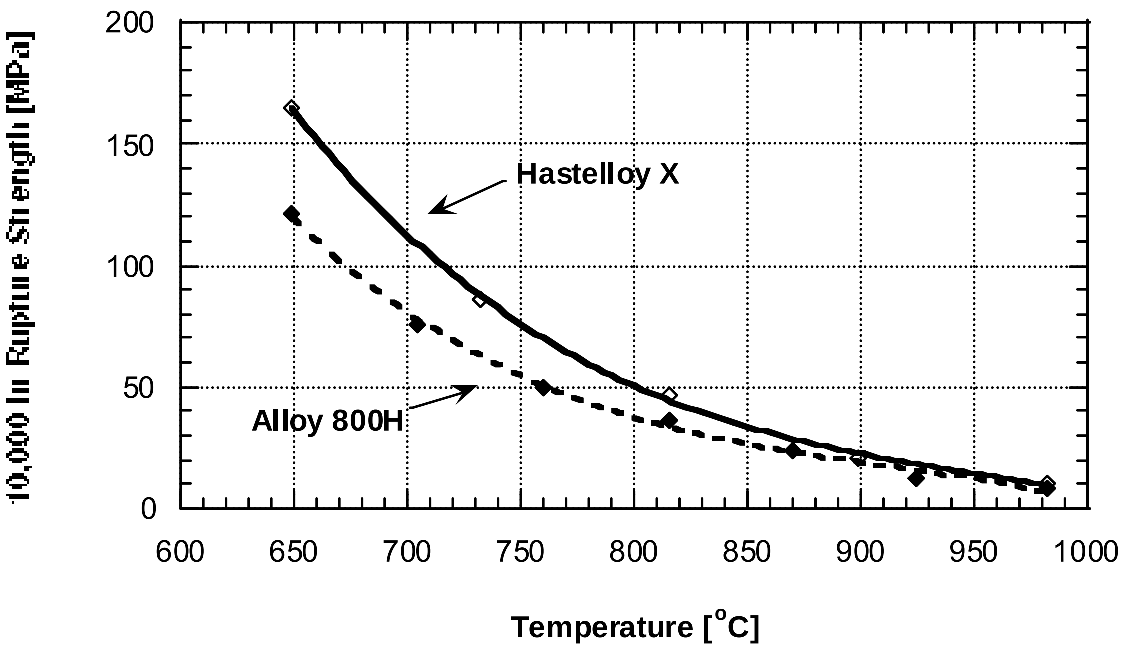

Figure 2-7 10,000 hr Creep-Rupture Strength for Alloy 800H and Hastelloy X

Table 2-5 Typical Creep-Rupture Data for Alloy 800H and Hastelloy X

Temperature - °C	10,000 hr Rupture Strength - MPa	
	Alloy 800H	Hastelloy X
649	121	170
760	51	77
871	24	30

Table 2-6 Typical Minimum Creep Rates for Alloy 800H and Hastelloy X

Temp. °C	Stress to Produce Given Minimum Creep Rates - MPa							
	0.0001 %/hr		0.001 %/hr		0.01 %/hr		0.1 %/hr	
	800H	Hast X	800H	Hast X	800H	Hast X	800H	Hast X
649	124	101	152	145	193	214	248	303
760	43	50	56	69	76	97	90	134
871	26	19	34	28	45	43	59	63

Nominal values for low-cycle fatigue cycles to failure as a function of total axial strain range are shown in Table 2-7 for both Alloy 800H and Hastelloy X at temperatures from 538° to 871°C. For 1000 and more cycles, Hastelloy X appears slightly more fatigue resistant in terms of strain range than is Alloy 800H. Further, higher stresses are required in Hastelloy X than in Alloy 800H to reach identical strain ranges. However, again as per analyses performed in Reference 2-1, Alloy 800H meets fatigue resistance requirements for the IHX plate-fin modules at 760°C.

Table 2-7 Nominal Values for Low-Cycle Fatigue Cycles to Failure For Alloy 800H and Hastelloy X

Temp. °C	Total Axial Strain Range (%) for the Cycles to Failure Shown Below							
	100 cycles		1000 cycles		10000 cycles		100000 cycles	
	800H	Hast X	800H	Hast X	800H	Hast X	800H	Hast X
538	4.3	4.0	1.6	1.8	0.6	0.8	0.4	0.6
649	5.2	-	1.5	-	0.5	-	-	-
760	5.0	4.0	1.2	1.1	0.4	0.6	-	0.4
871	-	4.0	-	1.0	-	0.4	-	-

2.2.5 Thermal/Physical Property Comparisons (Ref. 2-3)

Several typical thermal and physical properties for Alloy 800H and Hastelloy X obtained from Reference 2-3 are shown in Table 2-8 through Table 2-11. With respect to the values of density and melting range shown in Table 2-8, Alloy 800H may have a slight, but probably not significant, advantage over Hastelloy X. There is essentially no difference between the thermal conductivities (see Table 2-9) of the two alloys or of their specific heats (Table 2-11). As shown in Table 2-10, the mean coefficient of thermal expansion is about 10% lower for Hastelloy X than for Alloy 800H. Whether or not this is significant is up to the designer to decide.

Table 2-8 Density and Melting Range for Alloy 800H and Hastelloy X

Density – g/cm^3		Melting Range - °C	
Alloy 800H	Hastelloy X	Alloy 800H	Hastelloy X
7.94	8.22	1357-1385	1260-1355

Table 2-9 Thermal Conductivity of Alloy 800H and Hastelloy X

Temperature - °C	Thermal Conductivity – W/m°C	
	Alloy 800H	Hastelloy X
20	11.5	9.7
500	19.5	-
600	21.1	20.6
700	22.8	22.8
800	24.7	25.0
900	27.1	27.4

Table 2-10 Mean Coefficient of Thermal Expansion for Alloy 800H and Hastelloy X

Temperature - °C	Mean Coefficient of Thermal Expansion – μm/m/°C	
	Alloy 800H	Hastelloy X
20-500	16.8	14.9
20-600	17.1	15.3
20-700	17.5	15.7
20-800	18.0	16.0
20-900	-	16.3

Table 2-11 Specific Heat Values for Alloy 800H and Hastelloy X

Temperature - °C	Specific Heat – J/kg°C	
	Alloy 800H	Hastelloy X
20	The Specific Heat value for 0-100°C is given as 500 J/kg°C and likely mimics the increase with temperature as for Hastelloy X	486
538		544
649		582
760		632
871		699

2.2.6 Effects of Thermal Exposure on Properties (Refs. 2-3, 2-5)

Table 2-12 shows Charpy V-notch impact strengths and tensile properties of Alloy 800H measured at room temperature after aging for up to 12,000 hr at 538°C and 649°C. The starting material was 20% cold worked and this will tend to somewhat mask the hardening that results from the aging process. For example, room temperature elongation for solution-treated Alloy 800H would be ~50% as opposed to the 15.5% shown below for the cold worked alloy. Room temperature values of UTS and YS for annealed Alloy 800H are 560MPa and 225 MPa, respectively. It is obvious, then, that thermal aging at 538°C and 649°C is causing an increase in tensile strengths and a reduction in ductility and impact strength. However, in no case does thermal aging appear to have a serious deleterious effect on the properties shown in Table 2-12 and using Alloy 800H under these conditions should not be of concern. Notice also that the extent of property change appears to stabilize early in the aging process.

A direct comparison of the influence of thermal aging on the ductility (i.e., tensile elongation) of Alloy 800H and Hastelloy X is presented in Table 2-13. All aging treatments were for 8000 hr. The elongation of the Alloy 800H falls from a pre-aged value of 47% to values of 37%, 42%, and 40% after aging at 649°C, 760°C, and 871°C, respectively. The agreement of the 37% value with 25.5% value shown in Table 2-12 for the same aging conditions is not poor considering that the data are from different heats of material with different starting conditions (i.e., solution treated versus 20% cold worked).

Identical aging conditions for Hastelloy X produced a larger decrease in ductility than for Alloy 800H. Elongation fell from a pre-aged value of 57% to 19%, 19%, and 30% after aging at 649°C, 760°C, and 871°C, respectively. However, even the lowest of these values should not be a matter of concern.

Table 2-12 Room Temperature Properties of 20% Cold-Worked Alloy 800H After Aging at 538°C and 649°C

Aging Temperature °C	Aging Time hr	Charpy V-Notch Impact Strength - J	UTS MPa	YS MPa	Elongation %	Reduction in Area %
Not aged	None	152	786	779	15.5	58.0
538	1000	85	879	789	18.5	50.5
	4000	106	865	776	20.0	52.5
	8000	83	886	783	20.0	47.0
	12000	83	886	783	20.0	52.0
649	1000	118	752	624	23.0	46.5
	4000	88	738	547	21.5	43.0
	8000	84	734	561	25.5	52.5
	12000	85	724	544	24.0	50.0

Table 2-13 Room Temperature Tensile Elongation of Alloy 800H and Hastelloy X Sheet Materials after Aging for 8000 hr at 649°C, 760°C, and 871°C

Material	Aging Temperature - °C			
	Not aged	649	760	871
Alloy 800H	47	37	42	40
Hastelloy X	57	19	19	30

The effects of thermal aging at 649°C, 760°C, and 871°C for up to 10000 hr on the tensile properties of Hastelloy X are shown in Table 2-14. (The Hastelloy X data shown above in Table 2-13 is a subset of the Table 2-14 data.) The UTS and YS show moderate increases on aging at 649°C and 760°C but much less change after exposures at 871°C. Although elongation is reduced substantially by the thermal aging exposures, values remain at levels that do not give rise to substantial concern for its application under these temperature conditions.

Similarly, Table 2-15 gives values of room temperature Charpy V-notch impact strength and Rockwell A hardness for Hastelloy X after aging at 649°C, 760°C, and 871°C. The changes in hardness are not inconsistent with those for UTS and YS in Table 2-14. Impact strength appears to be affected to a greater extent than is that for Alloy 800H (Table 2-14).

Table 2-14 Effects of Thermal Aging on Room Temperature Tensile Data for Hastelloy X

Aging Temperature °C	Aging Time hr	UTS MPa	YS MPa	Elongation %
Not aged	None	788	381	57
649	1000	862	421	35
	4000	991	525	19
	8000	1020	542	19
	10000	1020	538	15
760	1000	945	450	23
	4000	928	443	18
	8000	903	423	19
	10000	869	409	17
871	1000	848	369	26
	4000	813	340	29
	8000	793	332	30
	10000	766	318	29

Table 2-15 Effects of Thermal Aging on Room Temperature Charpy V-Notch Impact Strength and Hardness of Hastelloy X

Aging Temperature °C	Aging Time hr	Charpy V-Notch Impact Strength J	Rockwell A Hardness
Not aged	None	129	54
649	1000	33	56
	4000	16	62
	8000	20	63
760	1000	14	62
	4000	14	61
	8000	11	60
871	1000	20	61
	4000	16	58
	8000	20	55
	16000	16	-

In summary, thermal aging phenomena in Hastelloy X have a larger negative influence on ductility and impact resistance than in Alloy 800H. This difference is recognized generally in the materials industry. Although Alloy 800H is better than Hastelloy X in terms of thermal aging effects, this does not preclude a successful outcome with IHX heat transfer modules made from Hastelloy X, as opposed to Alloy 800H.

2.2.7 Manufacturing and Joining Considerations

Up until this point, consideration of the two material candidates (Alloy 800H and Hastelloy X) for manufacture of heat exchanger cores of an IHX has been independent of the choice of design, whether tube-and-shell, Printed Circuit Heat Exchanger (PCHE), or Plate-Fin Heat Exchanger (PFHE). All of these designs require that the material used be readily and easily formable and joinable. In every case it will be necessary to form, usually by cold working, the tubes, plates, etc. necessary for heat exchanger core fabrication. Although these pieces differ according to the design under consideration, there are no questions as to whether or not they can be mechanically fabricated using either Alloy 800H and Hastelloy X. Further, there are well-established techniques and standards, applicable to all designs, for successfully joining these pieces by welding. However, there are some different considerations, primarily associated with joining, for the PCHE and PFHE.

In the PFHE, plates that are seal welded at the edges separate the primary and secondary fluids. Thin corrugated sections comprising fins (102 μm thick) are typically incorporated between the plates (380 μm thick) and brazed to the plates on one or both sides (Ref. 2-1). The plate-fin assemblies are stacked to form the complete heat exchanger. Overall, PFHE cell manufacture involves die forming, blanking, fin folding, resistance welding, brazing, and welding. As a first step in creating the necessary unit cells, the parting sheets and fins will be formed by mechanical working. The fins are tightly folded and formed in waves while the sheets are stamped so as to form an elevated land at the periphery to accommodate the braze joint. Although the forming capability of Alloy 800H is slightly better than that of Hastelloy X, both possess the necessary fabricability to permit these operations.

Parting sheets, fins, and rings are brazed to form the unit cell of the PFHE. In general, brazing is the joining of two base metals (either similar or dissimilar but similar in the case here) with a braze alloy that has a melting point lower than those of the base metals. In the case of either the Alloy 800H of Hastelloy X, the braze alloy will likely be Ni-base with Cr added in the range 7-22%. Additionally, elements such as Si and P will be added to lower the melting point of the braze alloy. Use of the correct braze alloy and process parameters (cleanliness, fixturing for the brazing operation, and atmosphere) can produce braze joints with strengths and properties approaching or identical to those of the base metals (Ref. 2-1). However, the strength of the resulting composite brazed plate-fin structure can be affected by the composition of the base alloy. For example, oxides of elements such as Ti and Al can inhibit wetting of the molten braze metal and wetting is required to form strong fillets. Alloy 800H contains intentional additions of Al and Ti (up to 1.2% total) and this could present a challenge to proper wetting. If this is found to be a problem, a nickel coating can be applied to the base metals prior to brazing to provide an oxide-free surface more amenable to wetting. Al, Ti and similar elements are intentionally excluded from the chemistry specification of Hastelloy X. Therefore, brazing should present even less of a challenge for Hastelloy X than for Alloy 800H.

The PCHE (Ref. 2-1) consists of metal plates (>500 μm thick) on the surface of which semicircular channels (typically one-half or more of the plate thickness) are chemically etched. The plates are subsequently diffusion bonded together to form a heat exchanger core. Formability questions or concerns are non-existent so that Alloy 800H and Hastelloy X need not be compared in this regard for the PCHE. The two new areas that arise for consideration for the PCHE are diffusion bonding and the etching of the plates.

Diffusion bonding is the joining method that would be used for assembly of the PCHE IHX cores. It is a process by which two flat and clean interfaces can be joined at elevated temperature (usually 50-80% of the melting point of the parent metals). The bonding is normally performed in an inert atmosphere or vacuum using an applied pressure. The loading pressure is usually less than that which would cause macro deformation of the metals being joined. Holding times under pressure can range from a few minutes to a few hours. Diffusion bonding has the capability of producing high quality joints with neither metallurgical discontinuities nor porosity. With proper care and control of the process, the diffusion-bonded joint should have strength and ductility equivalent to those of the base metals. Without a more extensive study, it is not now possible to project whether Alloy 800H or Hastelloy X has the better diffusion bonding characteristics. However, diffusion bonds have been successfully used in the manufacture of structures of both alloys and for the joining of both alloys to dissimilar metals and to ceramics.

The details of the processes by which the channels on the surfaces of the PCHE plates are chemically formed are proprietary to the manufacturer. However, the chemical etching likely involves masking and an acid treatment. No further description of the process is possible here and that makes difficult any assessment of the relative ease of the chemical etching process for Alloy 800H as compared with Hastelloy X. One would assume, based on engineering judgment and some knowledge of their relative resistance to corrosion, that the process might be slightly more difficult for Hastelloy X. It is essentially certain that the process is doable with both alloys.

Manufacture of the IHX will involve joining of the heat exchange modules to various pipes and ducts necessary for direction of the primary and secondary flows. Even if the heat exchange modules are manufactured of Hastelloy X, it may still be desirable because of cost to use Alloy 800H for all or most of the piping and ducting. Since these items will have wall thicknesses considerable greater than those of the plates and fins in the compact heat exchange modules, any concerns relative to their possible failure by corrosion will be minimized.

A decision to construct the IHX in such a fashion (i.e., Hastelloy X heat exchange modules and Alloy 800H pipes and ducting) would give rise to questions relative to the welding of Hastelloy X to Alloy 800H and the resultant properties of such weldments. A study conducted some years ago at the Oak Ridge National Laboratory addresses both of these questions (Ref. 2-6). Weldments joining Hastelloy X to Alloy 800H were made by use of two welding processes, gas tungsten arc welding (GTAW) using ERNiCr-3 filler and shielded metal arc welding

(SMAW) using Inco Weld A filler. Both of these filler metals are high in Ni (nominally 72% and 69%, respectively) relative to the alloys being joined and have Cr at comparable levels. Most of the weldments samples were aged for up to 10,000 hr at 482°C, 593°C, or 649°C before undergoing tensile and creep tests.

Tensile tests of the two weldment types yielded comparable results, not unexpected since all failures occurred in the Alloy 800H base metal. Similarly, the creep behavior of the two weldments was essentially identical with highest creep rates and ruptures occurring in the Alloy 800H. In general, aging caused only small changes in tensile and creep properties. The study concluded that both Inco Weld A and ERNiCr-3 are suitable filler metals for joining Hastelloy X to Alloy 800H and that the weldments retain good properties after long exposure times.

2.2.8 Relative Material Cost for Alloy 800H and Hastelloy X

The most significant factor in the relative costs of austenitic steels, Fe/Ni-base, and Ni-base alloys is the nickel content of the alloys. This is demonstrated by data taken from Reference 2-7 for 304SS, Alloy 800H, and Hastelloy X. Here, 304SS was assigned a cost basis of 1.0. Using this approach, Alloy 800H would have a cost of 2.8 and Hastelloy X a cost of 5.2. The ratio of cost of Hastelloy X to Alloy 800H is then ~1.8. Not surprisingly, the ratio of nickel contents for the two alloys is ~1.6. Although the cost of the Hastelloy X material is substantially higher than that of Alloy 800H, the difference in cost will be small in terms of the IHX heat transport modules and inconsequential in terms of the overall HTS cost.

2.2.9 Corrosion Performance Assessment

There is little if any doubt that heat transfer modules for the IHX can be designed, fabricated, and operated efficiently using either Alloy 800H or Hastelloy X. The biggest challenge to the IHX is the corrosion of the very thin sections required in both the PCHE and the PFHE and the effect of this corrosion on module lifetime. This was documented extensively in Reference 2-1. The highest temperatures now under consideration (750-800°C) are much lower than the 950°C maximum considered earlier and, based on data shown in Reference 2-1, the resultant corrosion depth should be up to a factor of 4 less. Even so, the rates of corrosion (best defined by the rates of internal oxidation and depletion of chromium) are significant and likely life limiting for the IHX. For example, studies on Alloy 800H at 675°C and 800°C (Ref. 2-8) resulted in predicted corrosion allowances for 36 years (extrapolated from ~1 yr [9000 hr] on a $t^{1/2}$ basis) of 60 μm and 280 μm, respectively. If these results (based on depletion of chromium) are representative of the material and the chemistry of the He to be applied in the IHX, one would conclude that the lifetime at 800°C would be very considerably less than 36 yr.

Other studies reported in Reference 2-9 provided comparisons of the corrosion of Alloy 800H and Hastelloy X at 750°C and 850°C for exposures in a similar but different He chemistry to 10,000 hr. The results in terms of rates of internal oxidation and chromium depletion are summarized in Table 2-16. These data would need to be extrapolated from 10,000 hr on a $t^{1/2}$ basis to predict corrosion depths (allowances) at longer times. For example, depths after 100,000 hr would be expected to be no greater than the square root of 10 times those at 10,000 hr.

Table 2-16 Depths of Internal Oxidation and Chromium Depletion Based on 10,000 hr Exposure

Temperature °C	Corrosion Rates (μm/yr) Based on 10,000 hr Exposure			
	Alloy 800H		Hastelloy X	
	Internal Oxidation	Chromium Depletion	Internal Oxidation	Chromium Depletion
750	8	35	7	8
850	16	24	11	14

Neither carburization nor decarburization was observed in the corrosion studies referenced above. However, carburization and decarburization have frequently been observed in VHTR environmental studies, especially at higher temperatures. As long as the environment-alloy combination is capable of forming and maintaining a protective oxide film, the likelihood of carburization or decarburization will be reduced. Considerable effort has been expended in the past to quantify the combined effects of oxidation and carburization potentials and temperature on the presence or absence of protective films. However, there remains uncertainty as to what the exact environment will be in an operating HTR and the possibility that it might be carburizing, with possibly deleterious effects on ductility, must not be ignored.

Observations on the data presented in Table 2-16 include:

- Internal oxidation in Alloy 800H and Hastelloy X are equivalent at 750°C.
- Chromium depletion at 750°C in Hastelloy X is only ¼ of that in Alloy 800H.
- Internal oxidation at 850°C is greater for Alloy 800H than Hastelloy X.
- Chromium depletion at 850°C in Hastelloy X is about ½ that in Alloy 800H. Other data show a factor of about 1/3 even at temperatures as high as 950°C.
- There is a discrepancy in the chromium depletion depths for Alloy 800H. The rate is greater at 750°C than at 850°C, whereas the opposite would be expected. However, such variability in corrosion data from impure He is not unusual.

The fact that chromium depletion in Hastelloy X is less than that in Alloy 800H is not unexpected based on general corrosion experience with the alloys. Hastelloy X is generally considered to be about a factor of 3 better at these high temperatures.

The potential effects of both internal oxidation and chromium depletion remain rather cloudy. The extent of internal oxidation has usually been determined rather qualitatively by metallographic examinations without characterization as to amount. Therefore, property changes related both to the depth of internal oxidation and to the extent of internal oxidation need to be determined and evaluated. As an even more critical item, chromium depletion needs to be characterized quantitatively in terms of percentage chromium available as a function distance below the metal surface. Reduction in chromium level will result in property changes and, most importantly, at some stage there will not be enough chromium reaching the corrosion interface to support the formation of a protective oxide film. At this point, breakaway corrosion would begin and result in rapid breakthrough of the IHX plates (PCHE and PFHE) and fins (PFHE).

2.2.10 Summary and Conclusions

Observations and conclusions from our comparison of Alloy 800H and Hastelloy X for application in IHX heat exchange modules at 750-800°C are presented below in bullet form, first for Alloy 800H and then for Hastelloy X.

- Alloy 800H is the only ASME Section III, Subsection NH approved high temperature alloy reasonably applicable to the IHX. It can be used today at temperatures as high as 760°C and, therefore, would suit the 750°C application. However, there is currently no Section III design code for compact heat exchangers and only a tubular heat exchanger could be designed and Code-approved with Alloy 800H at 750°C.
- Alloy 800H is suitable for the IHX application in terms of availability, fabricability, joining, mechanical properties, thermal/physical properties, and thermal stability. Service experience in conventional applications is excellent. The major downside for Alloy 800H is the question of corrosion of the very thin sections of material used in the manufacture of compact IHX cores. The uncertainty in corrosion implications on lifetime will, of course, be even greater at 800°C than at 750°C.
- An extension of the temperature limits for Alloy 800H in Subsection NH would be required to permit its use at 800°C. Review of existing data for Alloy 800H as part of a joint ASME/USDOE agreement has resulted in the conclusion that it is feasible to extend the qualification of Alloy 800H in Subsection NH to 900°C. Directed and dedicated efforts to this end should be able to achieve qualification in a 2 to 3 year period; however, this timeframe could be influenced if requests for additional data arise during the course of the Code application.
- Additionally, use of Alloy 800H at either 750°C or 800°C will require all of the efforts identified in the TDRM process (Ref. 2-10).
- Hastelloy X, relative to Alloy 800H, has equivalent availability and service experience, moderately better mechanical and thermal/physical properties, and comparable fabrication and joining capabilities. In terms of joining by brazing, it may be superior to Alloy 800H. The only areas in which Alloy 800H has a slight edge are cost and thermal stability. The price of Hastelloy X may be as much as 75% higher than that for Alloy 800H. However, this is likely insignificant in terms of the overall initial plant cost. Although the thermal stability of Hastelloy X is not as great as that for Alloy 800H, it should be more than sufficient for the IHX application.
- The major advantage of Hastelloy X over Alloy 800H is the fact that its corrosion resistance appears to be 3 times better. It should be expected, then, that this could translate to a 3x extension of useable life. However, quantification of the corrosion kinetics in expected environments and effects of corrosion phenomena is critical for both alloys.
- Hastelloy X is not currently qualified for high temperature nuclear service under the ASME Code. However, study under the joint ASME/USDOE agreement has stated that Hastelloy X is a candidate for inclusion in ASME Section III Code Case N-201 (core

support applications). It is feasible as well to, in parallel, incorporate Hastelloy X into ASME Section III, Subsection NH. This would require 3 to 5 years of dedicated effort.
- Other efforts required for use of Hastelloy X in the IHX application mirror those outlined in the TDRM process for Alloy 800H.

The results of this comparison of Hastelloy X and Alloy 800H for use in a compact IHX at 750-800°C suggest that Hastelloy X may well be the preferred material for the heat transport modules. However, it is preferable in the near term to consider both of these alloys as candidates for the thin sections of the IHX and other HTS components. Alloy 800H may still be preferred for components in the IHX with thick sections (e.g., internal piping and ducts) and for the PHTS and SHTS piping liners.

Use of either material at either temperature will require the development of an ASME design code or an alternative design basis for compact heat exchangers that is acceptable to the NRC. Activities needed to achieve this goal have been identified and described in the TDRM process.

2.3 Thermal-Hydraulic Design

The IHX design for 750-800˚C begins with the following assumptions:

- Architectural similarity to Concept-C, which was recommended in Reference 2-1
- Hastelloy X construction of the heat transfer modules (see Section 2.2)
- Heat transfer modules arranged in a single pressure vessel.
- Shell-side coupling to the PHTS, as concluded in the evaluation of Section 4.1

Two thermodynamic statepoints are provided in Section 5.2 and evaluated herein. The first statepoint corresponds to the steam production application introduced in Section 1, with a nominal ROT of 750˚C. The second statepoint extends the ROT to 800˚C, a temperature that would be representative of certain intermediate temperature direct heat applications. These statepoints can be seen in Figure 5-2 and Figure 5-3 and the corresponding inputs to the IHX design are summarized in Table 2-17.

Table 2-17 Thermodynamic Statepoints for 750˚ and 800˚C Reactor Outlet Temperatures

		750˚ ROT		800˚ ROT	
Parameter	**Units**	**Secondary**	**Primary**	**Secondary**	**Primary**
Mass Flow	kg/s	203.8	203.8	184.2	184.2
Inlet Temperature	C	216	750	217	800
Discharge Temperature	C	700	266	750	267
Inlet Pressure	kPa	9082	8675	9082	8718
Discharge Pressure	kPa	8970	8568	8970	8611

A spreadsheet-based program using the ε-N_{TU} method was used to predict performance for the designs described below. Heat transfer (*St*-$Pr^{2/3}$ vs. *Re*) and friction (Fanning-*f* vs. *Re*) data for wavy-fin configuration 11.44-3/8W employed in the design model are published in Reference 2-11.

2.3.1 750°C-ROT IHX

Thermal-hydraulic design data are presented in Table 2-18 for configurations meeting the following performance parameters inferred from the 750°C statepoint:

- Thermal Effectiveness: 0.906
- Secondary Total-Pressure Loss: 1.23% (See Table 1-1 for definition)
- Primary Total-Pressure Loss: 1.23% (See Table 1-1 for definition)

In addition to the heat exchanger core design, loss allowances are made and reported for piping and header pressure losses to reflect flange-to-flange performance. No heat loss or bypass-leakage is assumed. These losses will be accounted for once design details for baffling, insulation and supports are defined.

In summary, the required performance for the 750˚C-ROT IHX can be achieved with 180 heat transfer modules, each 1-meter tall, and with counterflow heat exchange matrices measuring 50-mm across and 554-mm in flow-length.

2.3.2 800˚C-ROT IHX

Pressure loss requirements for the 800˚C-ROT IHX are identical to the 750˚C case, but a higher thermal effectiveness of 0.914 is specified. Thermal-hydraulic design data for an IHX meeting these requirements, again with no bypass leakage or heat loss assumed, is presented in Table 2-19. As with the 750˚C-ROT case, allowances are made and reported for piping and ducting pressure losses to reflect flange-to-flange performance.

This design is rendered into a mechanical layout described in the following Subsection 2.4. It achieves the required performance with 160 modules, each 1-meter tall, and with counterflow heat exchange matrices measuring 50-mm across and 556-mm in flow-length.

2.4 IHX Layout and Mechanical Design

The design described herein is based on the Concept-C layout recommended in Reference 2-1, but with these exceptions:

- The entire IHX is housed in a single pressure vessel
- Heat transfer modules are constructed from Hastelloy X
- The balance of the internal assembly is constructed from Alloy 800H

The assembly in its pre-conceptual design state answers requirements for thermodynamic performance in a compact arrangement within a pressure vessel with flange locations consistent with integration requirements. To further the design, details remain to be developed for

Table 2-18 Thermal-Hydraulic Design Data for 750°C-ROT IHX

		Internal Pass (SHTS)	External Pass (PHTS)
Re		1566	1337
$StPr^{2/3}$		0.0128	0.0135
f, fanning		0.0678	0.0722
Fin pitch	mm	0.5907	0.5907
Fin density	fin/m	1693	1693
Height between separation plates	mm	2.54	2.6416
Plate width (across flow direction)	mm	50	50
Plate length (in flow direction)	mm	553.7	553.7
Plate thickness	mm	0.381	
Number of unit cells per module		163	
Core length (along the flow)	mm	553.7	553.7
Core width (across flow)	mm	50	50
Core height	mm	1000	
Number of modules		180	
Fin thickness	mm	0.102	0.102
Surface heat transfer area per unit cell	m^2	0.2725	0.3039
Surface efficiency, η_o		41.9%	36.8%
Total heat transfer area per unit cell	m^2	0.5764	
Total *effective* heat transfer area per unit cell	m^2	0.22597227	
Heat transfer area / volume between plates	m^2/m^3	3875	4155
*Effective h*eat transfer area / volume between plates		1625	1527
Total IHX heat transfer area	m^2	16879	
Total *effective* IHX heat transfer area	m^2	6617	
Heat Exchange Rate	MW	511	
Total Heat Exchange Volume	m^3	4.983	
Hydraulic diameter	mm	0.827	0.755
Free-flow cross-sectional area)	m^2	2.793	3.048
Thermal density	MW/m^3	103	
Heat transfer coefficient (h)	$w/(m^2K)$	6118	6324
Ntu		9.74	
Effectiveness		90.69%	
DP/P - HX Cores		0.85%	1.13%
DP/P Piping and Headers		0.36%	0.09%
DP/P Flange-Flange		1.22%	1.22%

Table 2-19 Thermal-Hydraulic Design Data for 800˚C-ROT IHX

		Internal Pass (SHTS)	**External Pass (PHTS)**
Re		1463	1254
$StPr^{2/3}$		0.0131	0.0138
f, fanning		0.0697	0.0740
Fin pitch	mm	0.5907	0.5907
Fin density	fin/m	1693	1693
Height between separation plates	mm	2.413	2.4892
Plate width (across flow direction)	mm	50	50
Plate length (in flow direction)	mm	556.3	556.3
Plate thickness	mm	0.381	
Number of unit cells per module		170	
Core length (along the flow)	mm	556.3	556.3
Core width (across flow)	mm	50	50
Core height	mm	1000	
Number of modules		160	
Fin thickness	mm	0.102	0.102
Surface heat transfer area per unit cell	m^2	0.2615	0.2905
Surface efficiency, η_o		44.3%	38.8%
Total heat transfer area per unit cell	m^2	0.5519	
Total *effective* heat transfer area per unit cell	m^2	0.228472694	
Heat transfer area / volume between plates	m^2/m^3	3896	4196
*Effective h*eat transfer area / volume between plates		1724	1629
Total IHX heat transfer area	m^2	15991	
Total *effective* IHX heat transfer area	m^2	6620	
Heat Exchange Rate	MW	509	
Total Heat Exchange Volume	m^3	4.728	
Hydraulic diameter	mm	0.820	0.744
Free-flow cross-sectional area)	m^2	2.609	2.834
Thermal density	MW/m^3	108	
Heat transfer coefficient (h)	$w/(m^2K)$	6044	6299
Ntu		10.70	
Effectiveness		91.45%	
DP/P - HX Cores		0.85%	1.15%
DP/P Piping and Headers		0.35%	0.07%
DP/P Flange-Flange		1.20%	1.22%

controlling thermal strains in flexible piping, supporting and sealing modules against primary-side bypass leakage and for assuring the integrity of the pressure boundary between primary and secondary for the design-basis event involving rapid depressurization of the secondary side (Section 5.3.2). Thermal insulation requirements for the vessel and primary outlet must also be addressed in the context of a loss-of-secondary-cooling event (Section 5.3.3). While the IHX design, at present, does not specifically include these features, it anticipates their inclusion as the configuration develops.

2.4.1 Arrangement

Heat transfer modules are arranged in two circumferential rows about central secondary-side distribution headers located on the axis of the vessel, as shown in Figure 2-8 and Figure 2-9. The secondary discharge header mounts to the lower head of the vessel and serves as the foundation for the assembly. The secondary inlet header is joined to the upper head of the vessel. Modules are suspended[1] by pipes between these two headers, one inlet and two discharge pipes per module. These pipes are intended to provide strain relief by deflecting under the differential expansion of connected structural components. Not shown in these figures are features for channeling primary flow through the heat exchange matrices, minimizing bypass leakage from inside to outside. These features may serve to attach modules directly to the secondary discharge header, to provide buckling protection or other functions that require attachment to the modules. Thermal insulation has yet to be specified for the vessel, as well. While the flow arrangement provides for cooler gas temperatures on pressure-bounding structures, certain events, such as the loss-of-secondary-cooling event may produce gas temperatures exceeding ASME materials temperature limits at these surfaces, implying the need for thermal insulation as a remedy.

2.4.2 Gas Flow Paths

PHTS gas is assigned to the shell-side of the IHX, as illustrated in Figure 2-10. Entering through the side of the vessel in the internally-insulated and cooled pipe described in Section 4.2.1, reactor-discharge gas is directed via an insulated duct to a plenum below the heat exchanger modules. Gas flows upward from the plenum in the annular space between the heat exchanger modules and the outer diameter of the secondary discharge header, distributing gas to the shell-sides of the modules (exterior sides of unit cells). Exiting the modules, the cooled gas flows in a least-resistance pattern in the space between the modules and the inner wall of the vessel, and into the outlet pipe on its way to the PHTS circulator.

On the internal pass, SHTS gas enters on the centerline at the top of the vessel and flows directly into the secondary inlet header where it is distributed into secondary inlet pipes, one for each module. Gas enters each module at the upper-most plane of the outboard manifold and distributes flow to the inside of each heat exchanger unit cell. Flow exiting the heat exchange matrices divides into two streams and exits the inboard manifold through pipes at the top and bottom, each directing half the module flow to a central discharge header. That header channels

[1] In the preconceptual design described herein, there are no secondary structures constraining the position or orientation of heat exchanger cores. These will be added as suggested by further analysis.

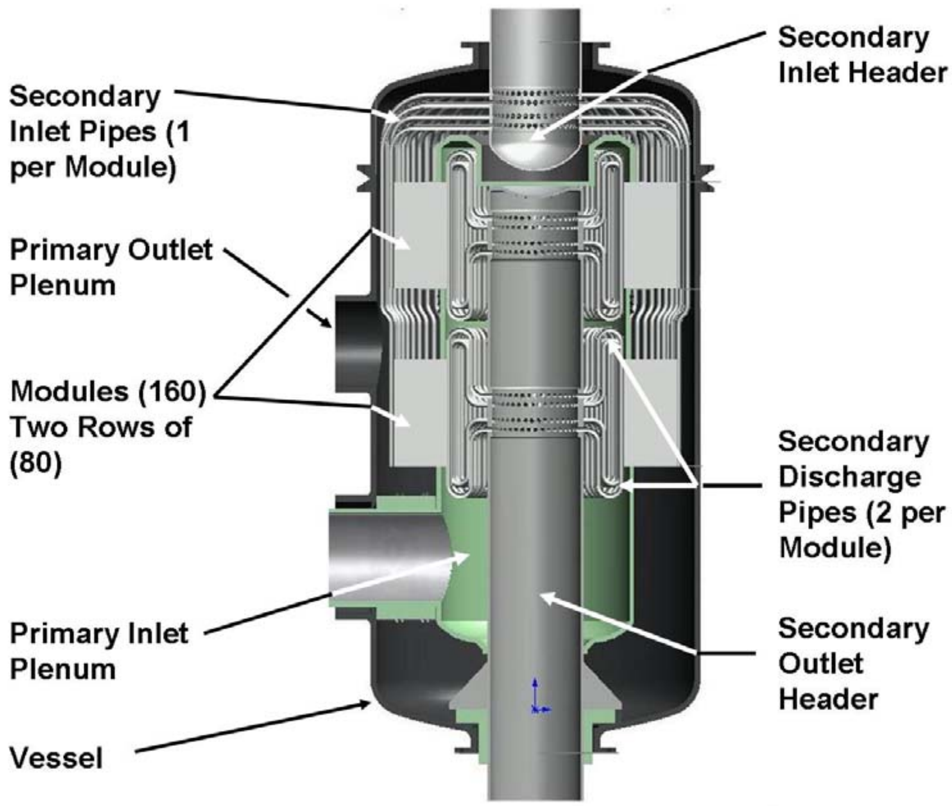

Figure 2-8 IHX Assembly Annotated Vertical-Section View

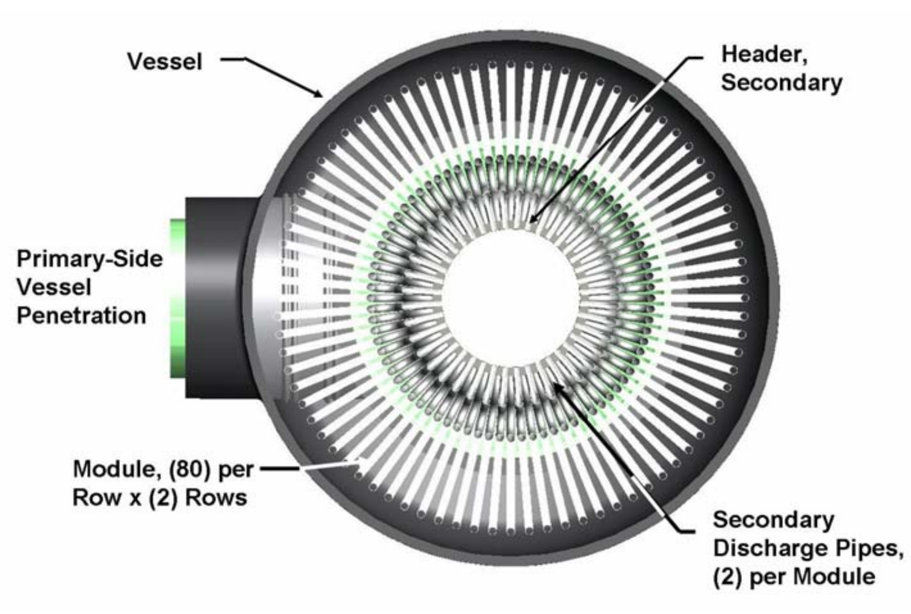

Figure 2-9 IHX Assembly Annotated Plan-Section View

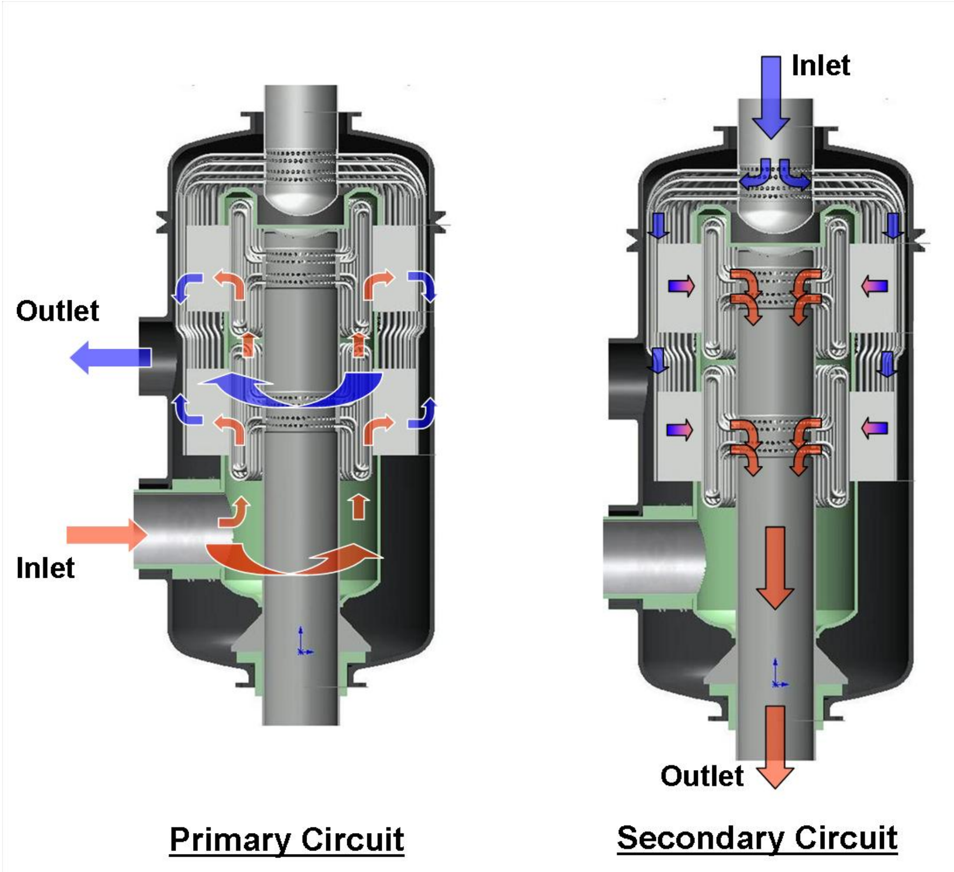

Figure 2-10 IHX Assembly Flow Circuits

flow to the secondary discharge pipe and to the object process. This flow circuit is also illustrated in Figure 2-10.

2.4.3 Basic IHX Dimensions

As seen in Figure 2-11, the IHX is very compact for its ~512 MWt rating. The heat exchanger modules and associated plumbing fit within a 3.5 m diameter vessel 7.8 m in length with elliptical heads. Note that these dimensions do not include space for internal insulation and will increase slightly if internal insulation is required to avoid excessive vessel temperatures during transients, such as the loss-of-secondary-cooling event, described in Section 5.3.3.

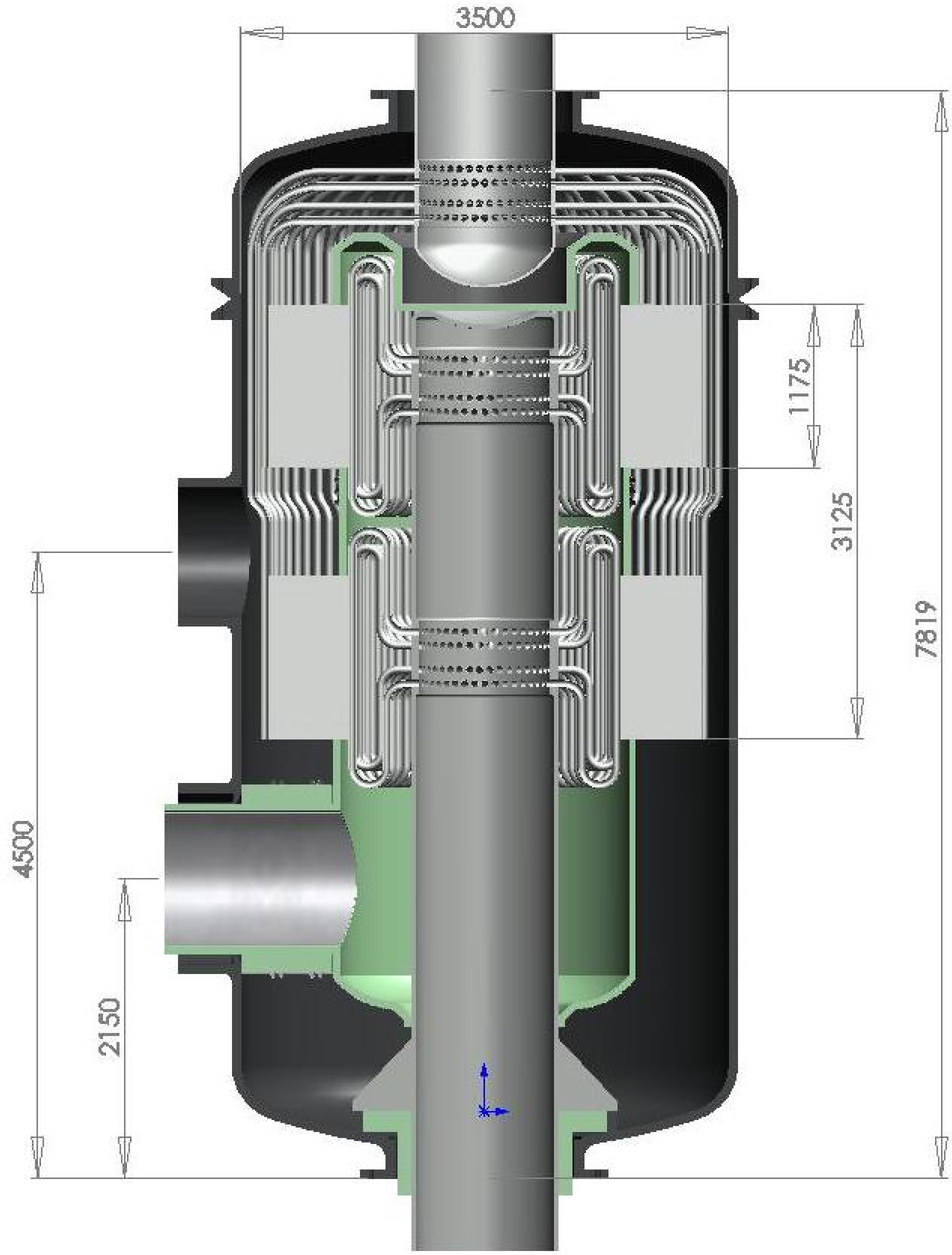

Figure 2-11 Dimensioned Vertical Cross-Section View of the IHX

2.5 Scoping Thermal/ Structural Assessments

In the IHX and HTS Conceptual Design Study (Ref. 2-1), scoping analyses focused on the unit-cell heat exchangers (IHX A and IHX B) for the 950°C H_2 production application in normal operation and for a loss-of-secondary-pressure event. Those analyses included:

- Internal Fin-Creep Life, IHX A, Normal Operation
- Internal Fin-Creep Life, IHX B, Normal Operation
- Unit-Cell Thermal-mechanical Fatigue, IHX A
- Unit-Cell Under Loss-of-Secondary-Pressure Loading

Objectives for the present scoping analyses include updates to creep and fatigue life estimates for the single-vessel layout with new fluid-circuit assignments (PHTS – Shell-Side, see Section 4.1), new thermodynamic statepoints (Section 5.2) and a new material selection (Section 2.2). The updated creep and fatigue life assessments are provided in Section 2.5.1.

With the SHTS assigned to the internal side of the heat exchanger cores, buckling of fins and manifolds is of interest for the loss-of-secondary-pressure event that is analyzed in Section 5.3.2. The thermal/structural implications of this transient for the IHX are assessed in Section 2.5.3.

Loss-of-secondary-cooling has been analyzed for the first time in this present study in Section 5.3.3. The thermal/structural implications for the IHX are evaluated in Section 2.5.4

Additional assessments were seen as valuable in the near term, but have been deferred to meet programmatic constraints. These include:

- Analyses of heat exchanger core stability along the axes of manifolds and compression of the heat-exchange matrix region between manifolds during a loss-of-secondary-pressure event. These are of keen interest, but can only be quantified once support structures suggested by the displacement analysis can be modeled.
- Thermo-structural stress analyses for the IHX assembly as a whole are needed to determine the durability of the heat exchanger. These analyses are seen as part of an iterative design-analysis effort to refine the configuration until adequate life margins are attained.

2.5.1 Steady-State Creep Life

For steady-state normal operation in accordance with the parameters of Section 5.2, two locations are identified as having the highest potential for metal creep within the IHX heat exchanger cell. These are the internal fins near the secondary-side exit and the adjacent discharge manifold. These structures are at the highest temperature on the secondary side; the side structurally reacting to the differential pressure between the primary and secondary streams. Creep calculations for these locations have been conducted for the 800˚C case, assuming the metal to be at the arithmetic mean of the secondary gas exit temperature of 750˚C and the primary inlet temperature of 800˚C (775˚C) as shown in Figure 5-5, and supporting a differential pressure of 201.1kPa. Typical creep-rupture data for Hastelloy X sheet are taken from Haynes International's Brochure, excerpted and shown in Table 2-20, and used to create the Larson-Miller-Parameter (LMP) plot in Figure 2-12 for interpolating those data. A log-function equation fitting the LMP versus stress data is also provided in that figure.

From the thermal-hydraulic design described in Section 2.3, 1693 0.102mm fins-per-meter support the local 200.1kPa differential pressure. This implies a tensile membrane stress of 0.94MPa in each fin at the most creep sensitive location. For a conservative time to creep rupture of (10^6 hours), a stress of up to 26.9 MPa could be supported at 775˚C. This provides a stress margin to rupture of 28-times.

The secondary discharge manifold is loaded by the same pressure differential and at the same temperature, but in the hoop direction. Pure hoop-stress in the 23.1 mm^2 cross-section of the manifold amounts to 1.3 MPa. A stress-to-rupture assessment, similar to that used above for the fins, yields a margin-to-rupture of 19-times for 10^6 hours at 782˚C.

Table 2-20 Haynes International - Creep-Rupture Life of Hastelloy X

Average Rupture Data, Sheet*

Test Temperature °F	°C	Approximate Rupture Life Strength for Time Indicated, Ksi (MPa) 10 Hours		100 Hours		1,000 Hours		10,000 Hours	
1200	649	67.0	(462)	48.0	(331)	34.0	(170)	24.9	(170)
1400	760	32.0	(221)	22.5	(155)	15.8	(77)	11.1	(77)
1600	871	17.0	(117)	10.6	(73)	6.5	(28)	4.0	(28)
1800	982	6.5	(45)	3.7	(26)	2.1	(8)	1.2	(8)
2000	1093	2.4	(17)	1.2	(8)	0.6	(4)	-	

* Solution heat-treated. Based on over 100 tests.

2.5.2 Fatigue Life during Startup and Shutdown

The potential for fatigue damage in normal operation is assessed with respect to changes in differential pressure and temperature in the IHX as reported in Section 5.3.1.

2.5.2.1 Pressure-Induced Fatigue Assessment

The largest differential pressure in the course of normal operation occurs during a cold start. As shown in Figure 5-8, a 2400 kPa compression of the IHX modules occurs 15 hours into a start-up transient. Elevated stresses occur in internal fins nearest the edge of the core and at the intersections with manifolds. Of these, 33.5 MPa at the secondary outlet manifold, shown in Figure 2-13, is of the greater magnitude. Coincident with the peak pressure differential, the temperature in both the secondary outlet and primary inlet is at 600˚C. A conservative interpolation of 0.2% yield strength data published by Haynes International Corporation for Hastelloy X indicates a 0.2%-offset-yield-strength of 244 MPa at 600°C, a value well above the

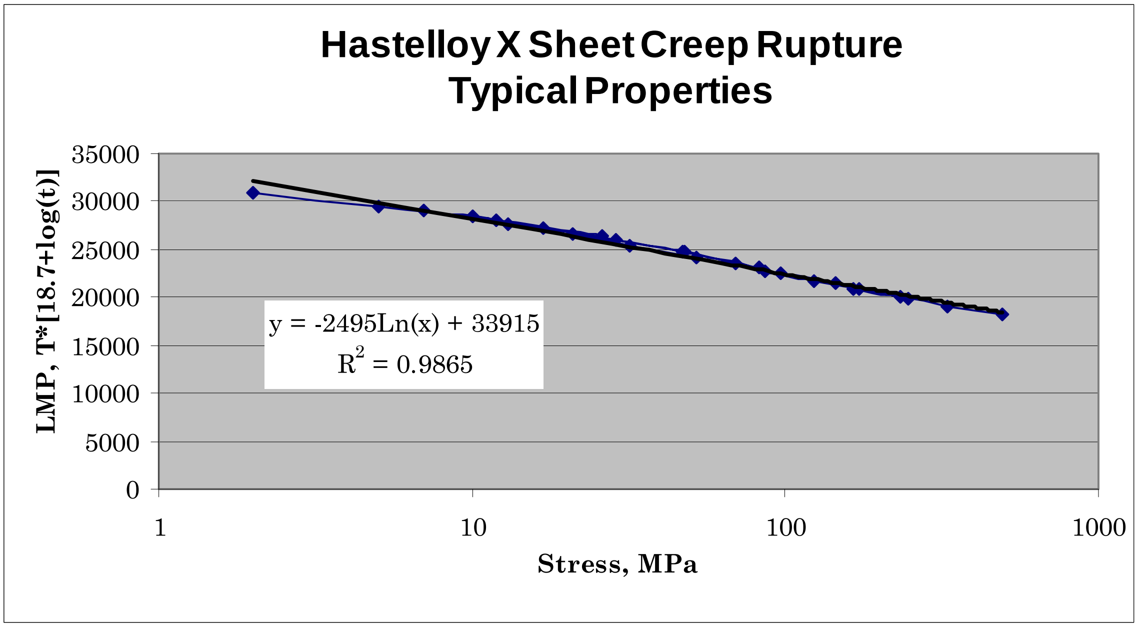

Figure 2-12 LMP Plot of Creep-Rupture Data for Hastelloy X Sheet

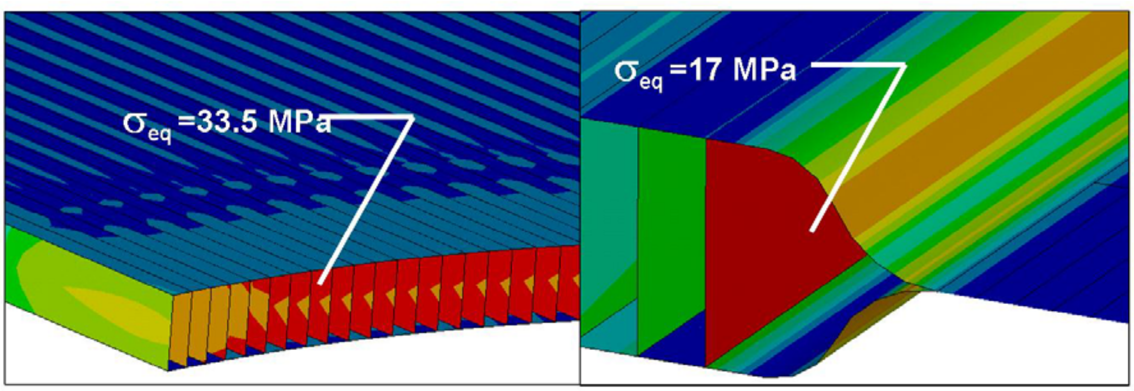

Figure 2-13 Peak Stress Intensities in the IHX Module During Normal Start-Up

applied stress during a start-up transient. At the locations within the unit-cells judged to be most challenging, fatigue damage to IHX modules due to normal operating pressure excursions is improbable.

2.5.2.2 Thermo-mechanical Fatigue (TMF) Assessment

Thermal transients in normal start-ups and shutdowns described in Section 5.3.1 are, at elevated temperatures, slow (on a scale of hours) relative to experience with similar heat exchanger designs in applications with time constants on the order of tens-of-minutes. With this observation, it is judged that peak temperature gradients occur at the steady operating condition.

Cycling between an isothermal room-temperature state and the maximum steady operating state encompasses the maximum stress and strain ranges for assessment of TMF.

The potential for TMF is diminished in the present design relative to the IHX A design reported in Reference 2-1 due to a greater flow length-to-width ratio. The steady thermal strain in a heat exchanger cell results from mechanical reconciliation of the natural bowing of the rectangular core in response to an imposed linear thermal gradient and the isothermal (and therefore geometrically similar) header shapes. A convenient metric of this effect is angulation of the core-sides parallel to the nominal direction of flow as shown in Figure 2-14. The greater the angulation, the greater the thermal strain induced to produce thermal-mechanical fatigue. Table 2-21 provides a comparison of the 2008 IHX-A design in steady operation versus the present design in the bounding conditions of the 800˚C ROT case. In so far as the present design results in less angulation, strain is reduced. Steady[2] thermal-mechanical stress scaled from the 2008 IHX A analysis is 27 MPa, a value well below 235 MPa, the 0.2%-offset yield strength for annealed[3] Hastelloy X at 782˚C. This simple analysis implies that thermal-mechanical fatigue will not be limiting to a unit cell for normal start-ups and shutdowns. Future analysis will be required to assess TMF at the module level.

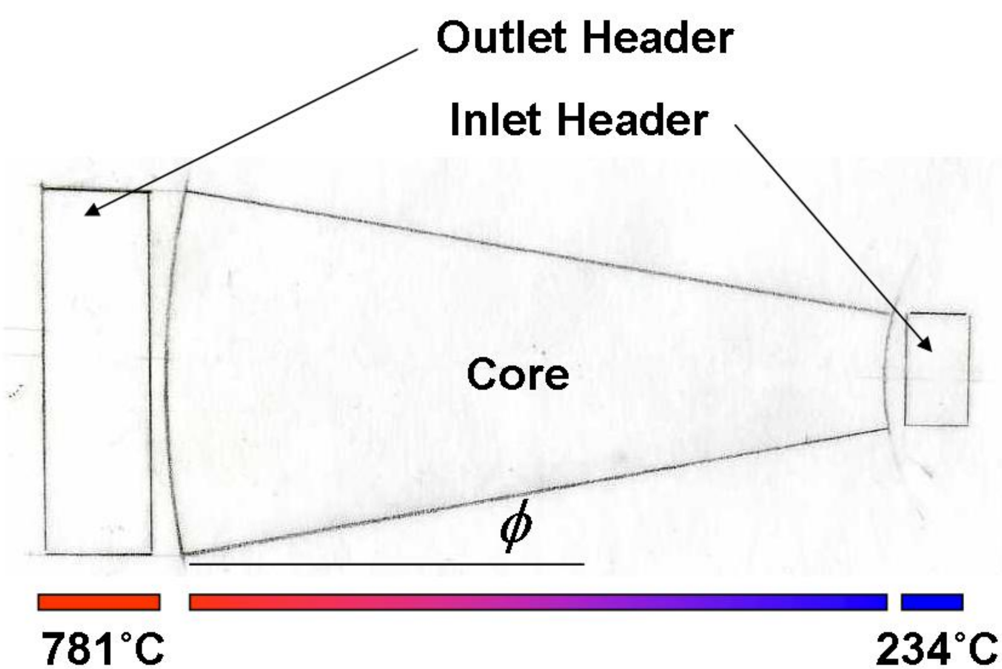

Figure 2-14 Exaggerated Unconstrained Thermal Displacement of Core and Headers

[2] Since the start-up transient for the plant is on the order of hours, and the time constants for heat exchangers of this construction are on the order of tens-of-minutes, the transient behavior is expected and assumed to be quasi-steady-state.
[3] Bright annealed at 1177˚C, hydrogen cooled.

Table 2-21 Comparison of Parameters Relating to Thermal Strain

Parameter	Units	2008 IHX-A	2009 IHX
Flow Length	mm	150	553
Flow Width	mm	50	50
CTE	$^{\circ}C^{-1}$	1.58E-05	1.39E-05
Internal Min Temp	˚C	772	200.3
Internal Hot Temp	˚C	950	763.4
Angulation of Sides	rad	4.69E-04	3.54E-04
	deg	0.027	0.020
Elastic Modulus	GPa	149	165
Stress	MPa	38.6[4]	32.3[5]

2.5.3 Loss-of-Secondary-Pressure Scoping Analyses

Section 5.3.2 describes the transient system response to a notional double-guillotine break of the SHTS hot pipe causing a rapid depressurization of the secondary loop.

This Loss-of-Secondary-Pressure (LOSP) event puts the core into a compressive state until remedial action is taken to lower the pressure in the PHTS, restoring balanced pressure loading. As the remaining fluid boundary between the radionuclide-containing PHTS and the environment in this scenario, integrity of the internal IHX PHTS to SHTS pressure boundary is essential throughout the duration of the transient.

The other consequence is a rapid decrease in the secondary–side gas inlet temperature. Over a span of twenty seconds, the temperature drops 350˚C. This is considerably faster than the time constant of the IHX modules, but similar to typical thermal transients in gas turbine applications where similar heat exchanger designs survive thousands of cycles.

The four basic analyses needed to assess survival of the IHX modules during the LOSP event are:

a) Fin buckling analysis
b) Secondary-discharge manifold hoop buckling analysis
c) Core buckling analysis
d) Manifold bucking under axial compression

[4] FEA thermal-mechanical analysis
[5] Scaled from analysis using “Angulation of Sides” and Elastic Moduli

e) Thermo-mechanical fatigue of the module due to the rapid temperature decline at the secondary inlet

Analyses ‘c’ and ‘d’ are strongly dependent upon stabilizing mounting and sealing features not yet included in the IHX system design configuration. Analysis ‘e’ is also needed, but must be deferred to a conceptual design stage due to programmatic constraints. Focus in this assessment is placed on analyses ‘a’ and ‘b’, where design features are adequately defined.

2.5.3.1 Fin Buckling Analysis

Wavy heat-transfer fins are specified in the thermal-hydraulic design of the IHX and reported in Section 2.3. During normal operation, the fins operate in a modest tensile field. During a LOSP transient, however, the direction of applied pressure reverses and is quickly elevated to a differential pressure that may be seen in a comparison of Figure 5-14 and Figure 5-19. The limiting case is the primary pressure ~9MPa, which was used for this assessment. With fin thicknesses of 0.102 mm and a height of 2.54 mm, buckling was seen as a possible consequence of these transient conditions. To assess this possibility, a finite-element analysis was conducted on a representative sample of the basic plate-fin structure. The finite-element model, shown in Figure 2-15, includes wavy fins; braze fillets and parting sheets representative of the nominal design.

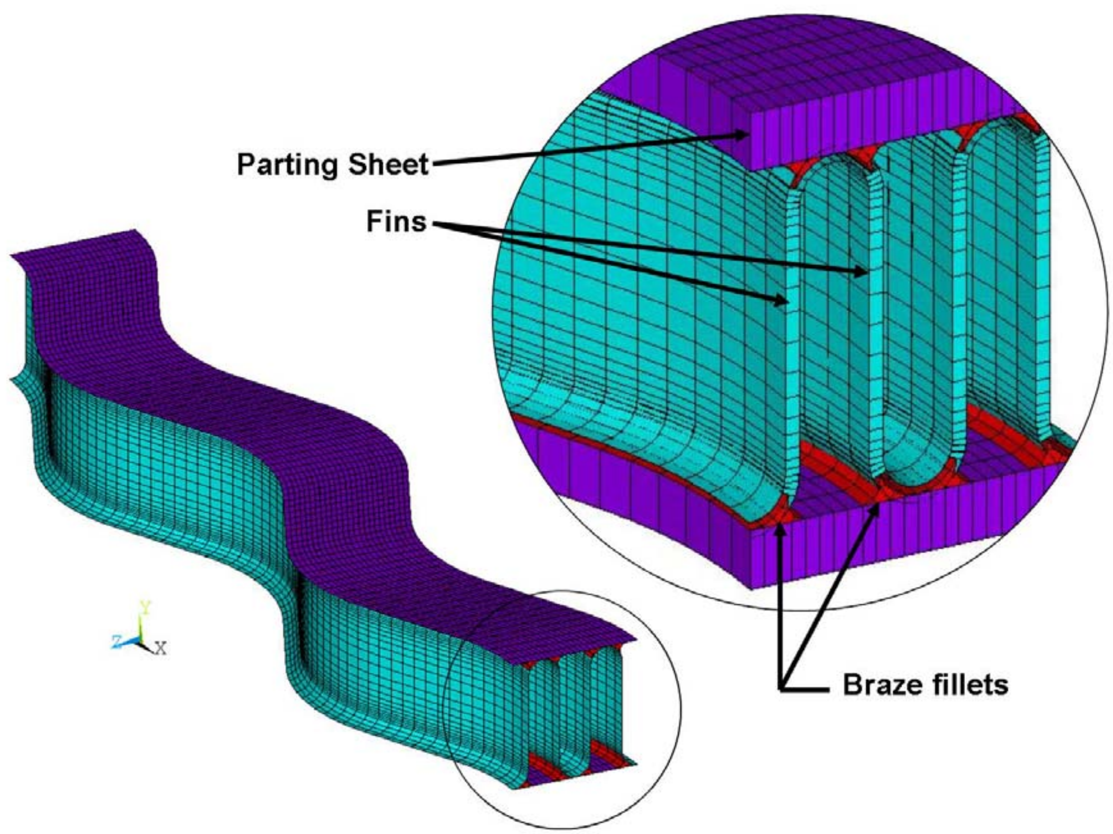

Figure 2-15 Finite-element Model of Representative Plate-Fin Construction

The model was exercised in a non-linear analysis, and the elastic buckling pressure was determined to be 570MPa (Figure 2-16). This provides an instantaneous margin of 41.2 times the limiting pressure of 9MPa. Though this analysis does not include creep, a further destabilizing phenomenon, the temperature falls to less than 500˚C within 90 minutes per the analysis reported in Section 5.3.2. This is a relatively short period of time in a temperature range where creep would be an active phenomenon. The sizable buckling margin and short event duration indicate that collapse of fins during a loss-of-secondary-pressure event is improbable.

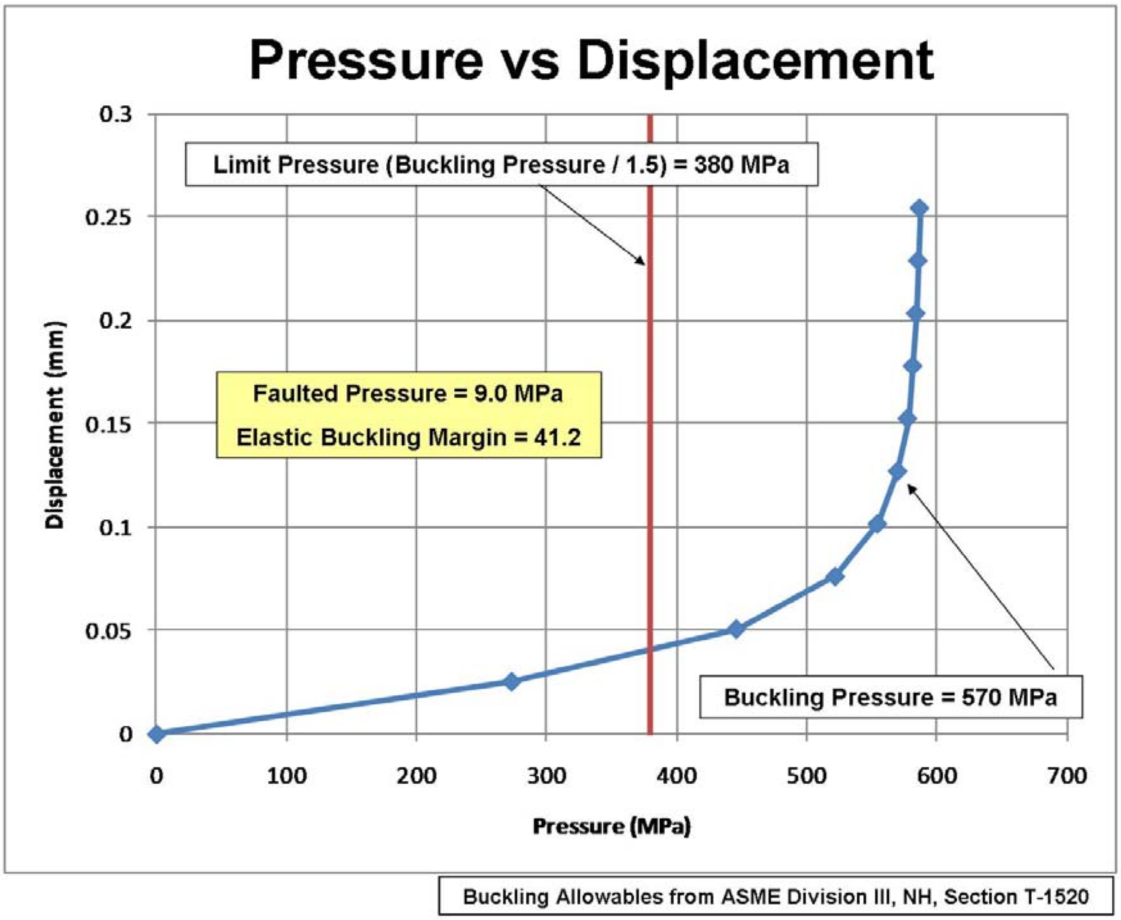

Figure 2-16 Fin Buckling Plot – Displacement vs. Pressure

2.5.3.2 Manifold Hoop Buckling Analysis

Loss of secondary pressure also produces elevated compression around the 50 mm-diameter distribution manifolds in the unit-cells. The discharge manifold, which collects the heated gas, would be the limiting side, due to depression of the material's elastic modulus. Included in the model shown in Figure 2-17 are half the manifold and a portion of the internal core. Since external fins offer only modest support or stability in the hoop direction, they are omitted from the model. While referred to as a hoop, the manifold cross-section is not uniform. Flow area is required for gas to flow from the core into the manifold, therefore, thin-walled heat-transfer fins occupy the space between parting sheets where the manifold intersects the core (Figure 2-18).

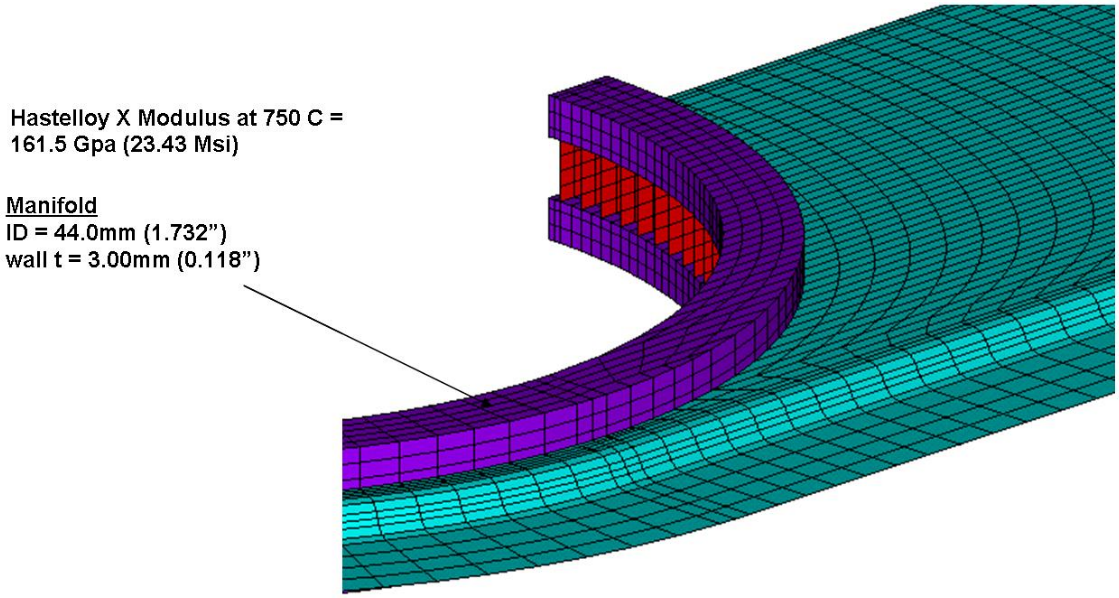

Figure 2-17 Unit Cell Manifold Finite-Element Model

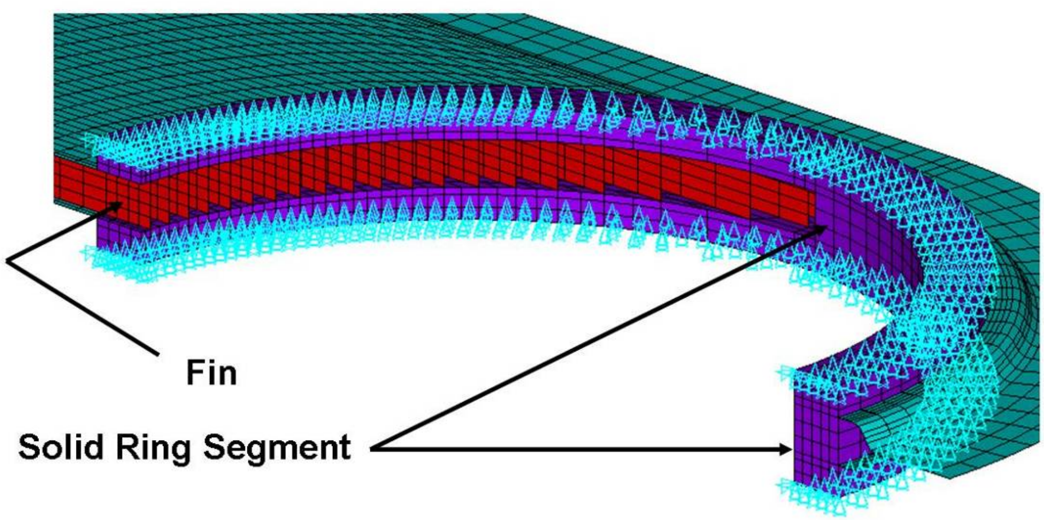

Figure 2-18 View of Unit-Cell Manifold Showing Fins and Solid Ring Segment

The manifold ring is otherwise solid. In the non-linear buckling analysis conducted using this model, 9 MPa is applied to all external surfaces. The analysis produced an unexpected result.

Rather than buckling in the hoop, as expected, buckling occurs in the core region due to pressure applied to the 2.5 mm tall sides of the unit-cell. This mode is depicted in Figure 2-19 as a second-bending shape. The calculated *critical buckling pressure*, seen in Figure 2-20, is 83 MPa, implying a *limit pressure* of 55.3 MPa, when a safety factor of 1.5 is taken into account. This is a factor of 6.1 above the 9 MPa maximum compression load that bounds a loss-of-secondary-pressure event.

Though the calculated buckling margin can be expected to decline with more conservative assumptions of core-length modeled, refining the model to include the more stable wavy fins specified in the design (straight fins modeled for simplicity), and including the stabilizing housing and seal structures to be added, are expected to restore and perhaps add margin to the design for this loading event.

2.5.4 Loss-of-Secondary-Cooling Scoping Assessment

The Loss-of-Secondary-Cooling (LOSC) with Failure to Trip the PHTS Circulator event described in Section 5.3.3 leads to a rapid rise in the IHX primary outlet temperature, as shown in Figure 5-23. This, in turn, results in a corresponding rise in metal temperatures that is shown in Figure 5-27. The rise of ~500˚C in 1-minute is likely to produce large, one-time, thermal gradients near the outlets of IHX modules, with commensurate thermal-mechanical strains. Though these strains may yield the material, rupture due to a single cycle is an unlikely consequence. The extreme and unusual magnitude of the event, however, justifies a detailed thermal-mechanical finite-element transient analysis to confirm survival of the IHX.

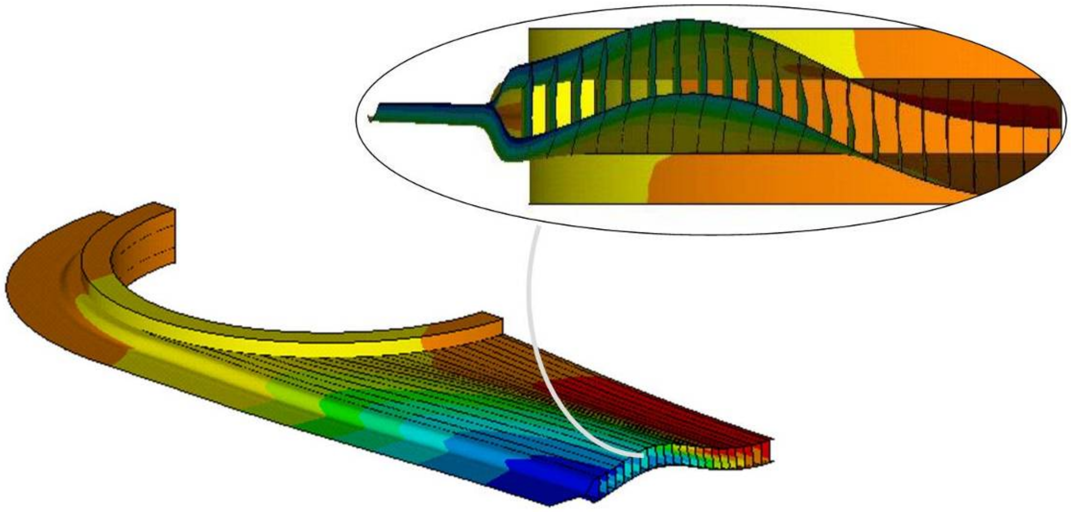

Figure 2-19 Buckling Near Manifold of Unit Cell

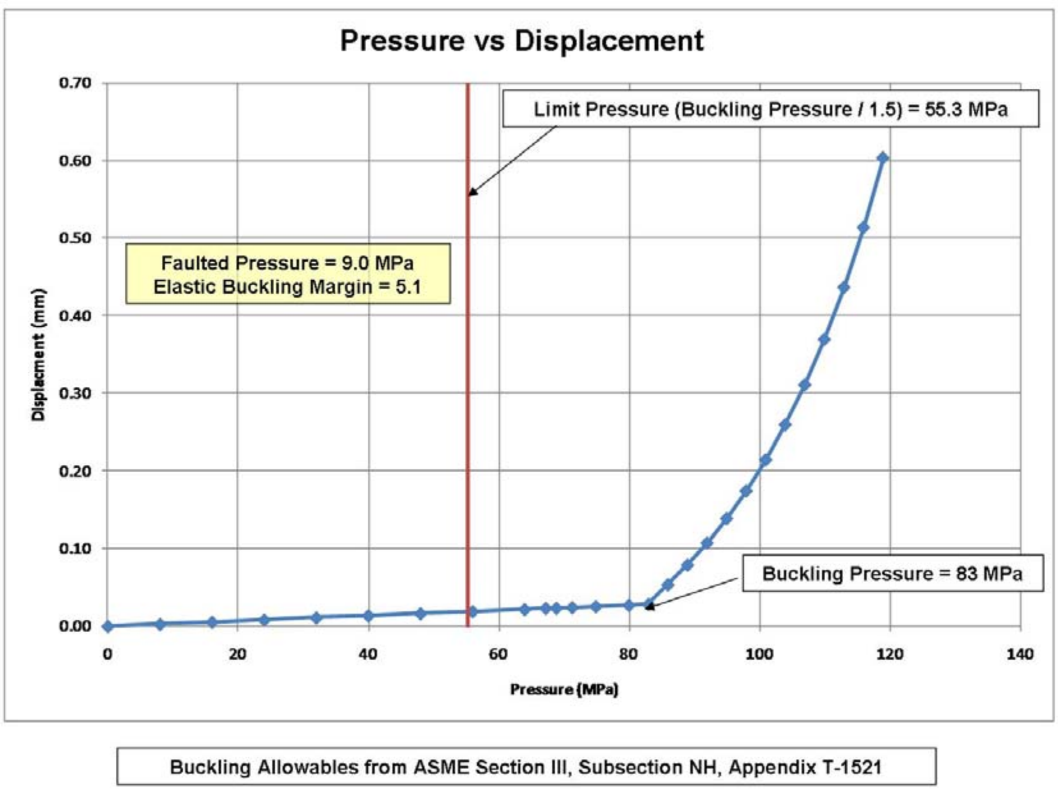

Figure 2-20 Manifold Region Buckling Plot – Displacement vs. Pressure

2.6 References

2-1 *NGNP Conceptual Design Study: IHX and Heat Transport System*, NGNP-HTS-RPT-TI001, Westinghouse Electric Company LLC, April 1, 2008.

2-2 *NGNP and Hydrogen Production Preconceptual Design Report, Section 6: Heat Transport System*, NGNP-06-RPT-001, Rev. 0, Westinghouse Electric Company LLC, May 2007.

2-3 Manufacturers Literature from the Internet including <www.specialmetals.com> , <www.sandmeyersteel.com>, <www.steelforge.com>, <www.megamex.com>, <www.haynesintl.com>, and www.hightempmetals.com.

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2-10 *NGNP and Hydrogen Production Conceptual Design Study, NGNP Technology Development Road Mapping Report, Section 5: Intermediate Heat Exchanger*, NGNP-CTF-MTech-TDRM-005, Rev. 1, November 2008.

2-11 Kayes, W.M. and London, A.L., *Compact Heat Exchangers (Third Edition)*, Krieger Publishing Company, 1984, (See Figure 10-73).

3 SHELL-AND-TUBE IHX

A preliminary qualitative evaluation of IHX technology options was undertaken as part of the initial PBMR NGNP Preconceptual Design (Refs. 3-1, 3-2). The scope of this initial evaluation included both conventional shell-and-tube heat exchangers and compact heat exchangers. A more extensive qualitative evaluation was undertaken as part of the 2008 IHX and HTS Conceptual Design Study (Ref. 3-3). The latter study extended the evaluation to include small-tube or "capillary" heat exchangers. In both cases, it was concluded that compact heat exchangers represented the best overall selection for the PBMR NGNP IHX and are likely required to meet economic objectives. It was recognized, however, that compact heat exchangers pose significant design, development and licensing challenges for the NGNP, especially at the higher temperatures required for hydrogen production. On this basis, a further semi-quantitative evaluation of the shell-and-tube IHX option has been undertaken as part of this present study.

3.1 Background

Shell-and-tube heat exchangers are common in conventional industrial plants and are well known in the nuclear industry. Typical shell-and-tube heat exchanger layouts are shown in Reference 3-4 and include straight tube, U-tube, bayonet-tube, serpentine and helical-coil variants.

Steam generators used in pressurized light water reactors are typically U-tube or straight-tube heat exchangers, with the primary fluid on the tube side and the secondary in the shell. The tubes of these steam generators have no heat transfer enhancement such as internal or external fins. The bare tube is a boundary between the primary and secondary fluids that is simple to analyze and inspect.

Serpentine or helical-coil steam generators have historically been used in gas-cooled reactor applications. Typically, the primary coolant gas is on the shell side and water/steam on the tube side. The advantage of these configurations is that they allow the shell-side (gas-side) to operate in a cross-flow mode, which enhances the overall heat transfer coefficient. Typically, the serpentine configuration is used when the heat exchanger is located in an annular space, such as in some British AGR's, whereas the helical-coil design is used when the heat exchanger is located in a circular enclosure, such as in Fort St. Vrain and THTR.

When considering conventional size tubes (as opposed to the capillary tube heat exchanger concept described in Ref. 3-3), a bare-tube, shell-and-tube type heat exchanger of the helical-coil type is appealing for use as an IHX, because of its similarity to previously successful HTGR steam generators. A recent study by INL tends to confirm the conclusion that the most suitable shell-and-tube option for HTGRs is the helical-coil design (Ref. 3-5). This is the approach taken for the Japanese HTTR, which to date has had favorable operating experience with its 10MWt IHX at temperatures up to 950°C (however, most operating time has been at temperatures at or below 850°C).

For equivalent reactor outlet temperatures, the average metal temperatures in the tubes of a gas-cooled reactor IHX would be significantly higher than the temperatures seen by the tubes in a comparable stream generator. This is because the tube-side heat transfer coefficient is much lower and the peak secondary-side gas temperature is typically higher in an IHX. On this basis, the AVR steam generator operated for extended periods of time at 950°C reactor outlet temperature and with a high pressure differential between the water/steam and helium sides. Comparable reactor outlet temperatures and pressure differentials would be problematic for an IHX. At the intermediate temperatures considered in this study (750-800°C) a successful IHX design is certainly supported by the HTTR experience. Note also that, for a material like Alloy 800H, the ASME Boiler & Pressure Vessel Code, Section III, Rules for Construction of Nuclear Facility Components, Division 1, Subsection NH, currently offers the possibility of a 760°C design temperature.

In the 2008 IHX and HTS Conceptual Design Study (Ref. 3-3), various types of heat exchangers were qualitatively evaluated and the following positive observations were made with regards to the shell-and-tube heat exchanger option:

- An established manufacturing and operating base exists
- It is a very robust design under normal operating conditions
- The shell-and-tube design provides the maximum resistance to corrosion and erosion effects and tritium transport because of its heavier section thicknesses.
- Inspection for leaks would be simpler than for any other type of heat exchanger
- There is an existing ASME Code basis for the design of shell-and-tube heat exchangers.

However, the shell-and-tube heat exchanger's utilization of materials is poor due to the size required, which results in a poor performance in terms of cost. This high overall cost tends to offset the other advantages named above.

3.2 Evaluation

The incremental costs associated with shell-and-tube versus compact heat exchangers are the result of two components. The first is the cost of the heat exchangers themselves. The second is the necessity to incorporate multiple loops, due to limitations in manufacturing and/or transportation. It is beyond the scope of this present study to provide cost estimates for the heat exchangers and their corresponding heat transport system variants; however, some indications of relative cost can be obtained by looking at the heat exchangers themselves.

3.2.1 Heat Exchanger Differences

Table 3-1 compares heat exchanger design and performance data from References 3-5, 3-6 and 3-7. While insufficient information was provided to calculate the weights of the respective heat exchangers (which could provide a direct indication of relative materials costs), the differences in volumetric efficiency can be clearly seen. A comparison of the compact heat exchanger designs in the second and last columns with the helical-coil designs in the remaining

Table 3-1 Comparison of Heat Exchangers

Source	Ref. 3-5	Ref. 3-5	Ref. 3-6	Ref. 3-6	Ref. 3-6	Ref. 3-7	Ref. 3-7	Ref. 3-7	This Report
Section/Page	NA/5	NA/5	3.3.1.1.1/21	3.3.1.2/31	5.4.2/192	4.3.1.1/45	4.3.1.2/51	4.3.1.2/51	2.4/55
Source	INL	INL	Sulzer/KVK	JAERI/HTTR	AREVA	GA/Toshiba	GA/Toshiba	GA/Toshiba	PBMR
Total Duty, MWt	612	612	10	10	580	534	216	384	510
Number of IHXs	1	1	1	1	2	3	3	3	1
Duty, MWt	612	612	10	10	290	178	72	128	510
HX Type	Helical Coil	PCHE	Helical Coil	Helical Coil	Helical Coil	Helical Coil	Helical Coil	Helical Coil	PFHE
Primary Side									
Tin, °C	900	900	950	950	900	900	900	750	800
Tout, °C	594.5	594.5	293	390	490	480	750	481	268
Nominal Pressure, MPa	7	7	4		5	7	7	7	8.7
Flow Rate, kg/s	385	385	2.95	12	136	81.8	91.96	91.96	185
Secondary Side									
Tin, °C	492.5	492.5	220	300	415	308	673	312	218
Tout, °C	884.8	884.8	900	860	825	700	875	673	750
Nominal Pressure, MPa	7.6	7.6	4		5.5	7	7	7	8.9
Flow Rate, kg/s	300	300	2.85	12	136	87.64	68.44	68.44	185
LMTD, °C	46	46	61	90	75	186	46	117	50
Tubes									
Number	5025		117	96	2966	550	1025	914	
OD, mm	20		22	31.8	21	45	31.8	31.8	
Thickness, mm	1		2	3.5	2.2	5	3.5	3.5	
Length, m	42.9		43		18.3	22.05	21.39	17.62	
Inner Coil Diameter, mm	490				1500	1870	1600	1600	
Outer Coil Diameter, mm	4600				3490	4080	3950	3762	
Coil Height, m	9.86				7.8	4.58	4.45	3.66	
Coil Layers						18	26	24	
Modules									
Number		34							180
Length, mm		430							553.7
Width, mm		600							50
Height, mm		600							1000
HT Core Volume, m^3	162.0	5.29			60.8	47.3	45.6	33.3	4.98
Total HT Area, m^2	13540	5805	348		3581	1714	2190	1609	16879
U, $W/m^2\cdot°K$	1189	2313	473		1080	559	711	680	604
Vessel									
ID, mm [1]			2400	2000	6380	5000	5000	4750	3500
Height, mm			24980	11000		18350	18500	17500	7819
Approx. Volume, m^3 [2]	163.8		177	61		275	278	246	70
Surface Efficiency, kW/m^2 [3]			29		81	104	33	80	30
Core Compactness, MW/m^3	3.8	116			5	4	2	4	102
HX Compactness, MW/m^3	3.74		0.06	0.16		0.65	0.26	0.52	7.29

Notes:
[1] AREVA IHX diameter From Fig. 5-5, Ref. 3-6; believed to be flange OD
[2] Assumes spherical heads
[3] Heat Transfer Active Area Only

columns shows that the compactness of the heat transfer cores ranges from 20 to 50 times greater in the compact designs than in the helical-coil designs. When the complete heat exchanger is taken into account, the compactness advantage is reduced, however, remains very significant. A comparison of the data from Reference 3-7 with the data pertaining to the plate-fin heat exchanger (PFHE) developed in the present report indicates a heat exchanger compactness advantage of greater than a factor 10 for the PFHE. This is consistent with the earlier qualitative evaluations of References 3-1 through 3-3. Given the efficiency of materials use and modular construction in compact heat exchangers versus the shell-and-tube designs, a comparable or greater advantage in cost is likely, but remains to be verified.

3.2.2 Heat Exchanger Influence on the Number of HTS Loops

Perhaps more significant than the heat exchangers themselves, is the influence of the heat exchanger design selection on the required number of HTS loops. It is clear from the results of this report, that the 750-800°C PFHE IHX can be configured within one relatively small pressure vessel in a single-loop architecture. It is equally clear, based upon inputs from all three design teams, that multiple-loop architectures will be required for shell-and-tube heat exchangers of comparable duty. In addition to requiring multiple heat exchangers, a modification will be required to the reactor to accommodate multiple inlets and outlets and other components of the Primary and Secondary Heat Transport Systems will have to be duplicated, notably including circulators and complex high-temperature piping. Further the Nuclear Heat Supply System building will have to be expanded to accommodate the additional HTS components, along with their supports and auxiliaries.

3.2.2.1 AREVA Assessment

As part of the *IHX and Secondary Heat Transport Loop Alternatives Study*, documented in Reference 3-6, AREVA evaluated the number of HTS loops to be included in their 600MWt NGNP Demonstration Plant design. The results are summarized in Section 5.4.2 of that study as follows:

> "The IHX design that supports two loop operations contains approximately 3000 tubes and is based largely on a tubular IHX built and tested at 950°C for the Prototype Nuklear Process Heat (PNP), a past process heat HTR development program in Germany. Increasing the size of this IHX design to accommodate the needed flow and heat transfer area for single loop operation is considered to be unfeasible, particularly in light of the tight schedule for NGNP development."

The two-loop design, recommended in the above report, replaced the 3-loop HTS architecture that was the prior reference for the AREVA NGNP Demonstration Plant.

3.2.2.2 General Atomics Assessment

In their own *NGNP IHX and Secondary Heat Transport Loop Alternatives Study*, Reference 3-7, General Atomics also assessed the number of HTS loops required to accommodate helical shell-and-tube exchangers. The results are summarized by the following, which was taken from the Executive Summary:

> "With respect to helical-coil heat exchangers for the parallel primary loop configuration, one "small IHX" would be needed for the hydrogen loop and a minimum of three "PCS-side IHXs" would be needed for the PCS loop, again due to manufacturing limitations. If a compact heat exchanger is used, a small 65-MWt IHX would be needed for the hydrogen loop and a single 535-MWt PCS-side IHX would suffice for the PCS loop."

3.2.2.3 PBMR Assessment

To estimate the size of the shell-and-tube IHX that would be required for the current NGNP layout, PBMR utilized the results of a separate internal study based on a simple sizing model which considered a helically wound, tubular IHX. Consistent with the above, a helical configuration was selected for the evaluation because, for a bare-tube heat exchanger, the helical configuration is the most compact shell-and-tube design, because the resulting configuration supports shell-side cross flow and because longer tubes can be accommodated than with a U-tube. The PBMR model was used to evaluate a particular case which, though not entirely aligned to the conditions in Sections 1.3 and 5.2, is indicative of the size of the heat exchanger required. The most significant inputs that were used are summarized in Table 3-2.

The inputs summarized in Table 3-2, in conjunction with the rules and manufacturing constraints inherent to the PBMR model, yielded the following results:

- Three separate IHXs would be required, each approximately 137 MWt
- The total mass of each of these heat exchangers is 450 ton (158 ton for the tubes)
- The vessel diameter is 4.5 m
- The vessel height is 16.4 m

The above is not an optimized design; however, it does provide a further indication of the significant differences in size between compact and tubular IHX's. Note that the higher capacity (approximately 510 MWt) reference compact design described in Section 2.4 fits in a single vessel 3.5 m diameter, 7.9 m high. The heat transfer section of the compact IHX has a mass of about 12 ton.

As part of their internal study, PBMR estimated the as-manufactured cost of the shell-and-tube IHXs to be on the order of 10 times the cost of an equivalent single compact IHX. In addition to the IHX(s) themselves, the impact of the respective IHX designs on the overall cost of the Nuclear Heat Supply System must be considered. This includes modifications to the reactor and all of the incremental HTS components that would be associated with a 3-loop configuration. Major impacts on the layouts and associated costs of the NHS buildings and structures would also have to be taken into account. In addition to cost, transport limitations may become a factor for some sites, due both to the size and mass of the shell-and-tube heat exchangers.

It is also noted that the PBMR results, summarized above, for the helical-coil design are generally consistent with those obtained by other investigators (Refs. 3-5, 3-6 and 3-7). In each case, application of the helical-coil IHX technology resulted in a requirement for multiple (two to four) heat transport loops and very large heat exchangers, with dimensions, in some cases, exceeding the size of the reactor itself.

Table 3-2 Representative Helical Coil IHX Sizing Parameters

Reactor Thermal Power	450 MW
Reactor Outlet Temperature	750°C
Reactor Inlet Temperature	280°C
PHTS Mass Flow	163.1 kg/s
PHTS Nominal Pressure	7 MPa
IHX Primary Outlet Temperature	265°C
IHX Approach Temperature	50°C
SHTS Mass Flow	163.1 kg/s
SHTS Nominal Pressure	7 MPa
IHX Secondary Outlet Temperature	700°C
IHX Secondary Inlet Temperature	215°C
IHX Tube Material	Alloy 800H
IHX Tube Side Pressure Drop	100 kPa

3.3 Conclusions

The compact IHX is a much more efficient user of both space and the high temperature heat transfer material that is incorporated within. This affects not only number and size of components, but also the size and configuration of the buildings and structures enclosing the PHTS, plus supporting auxiliary systems. At 750°C, the capital cost penalty paid by the tubular IHX in terms of size and number of components can already be intuitively appreciated; however, the capital cost penalty would become an even larger factor when the temperatures are higher and the alloys are more expensive.

In summary, this semi-quantitative evaluation does not change the conclusions of prior qualitative assessments. It is clear that shell-and-tube heat exchangers, particularly at the intermediate temperatures evaluated in the present study, represent a practical and robust technical solution. However, it is our judgment, based on this and other referenced studies, that the incremental capital and operating costs associated with the use of conventional shell-and-tube heat exchangers (including influences on the overall design of the NHSS) are a significant deterrent to their use in relatively small nuclear applications, such as the NGNP, where economics rely upon efficiency, simplicity and volume manufacturing. On this basis, it is recommended that compact heat exchangers be retained as the reference basis for the PBMR NGNP IHX and that high priority be given to the design trade studies and associated R&D activities required to select a specific concept (e.g., plate-fin, plate-type) and to confirm its acceptability in terms of defined functions and requirements.

3.4 References

3-1 *NGNP and Hydrogen Production Preconceptual Design Report: Special Study 20.3: High Temperature Process Heat Transfer and Transport*, NGNP-20-RPT-003, Westinghouse Electric Company LLC, January 2007.

3-2 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.

3-3 *NGNP Conceptual Design Study: IHX and Heat Transport System*, NGNP-HTS-RPT-TI001, Westinghouse Electric Company LLC, April 1, 2008.

3-4 *Standards of the Tubular Exchanger Manufacturers Association*, 8th edition, TEMA, 1999.

3-5 Oh, C.H. and Kim, E.S., "Design Option of Heat Exchanger for the Next Generation Nuclear Plant" HTR2008-58175, *Proceedings of HTR2008*, Washington, DC, September 28-October 1, 2008.

3-6 *NGNP IHX and Secondary Heat Transport Loop Alternatives Study*, 911119 Revision 0, General Atomics, April 23, 2008.

3-7 *NGNP with Hydrogen Production IHX and Secondary Heat Transport Loop Alternatives*, Document No. 12-9076325-001, AREVA, April 2008.

4 IHX-HTS INTEGRATION

This section addresses the integration of the IHX with the remainder of the Heat Transport System (HTS) and the overall integration of the HTS with the enclosing Nuclear Heat Supply System (NHSS) buildings and structures. The section begins with a reevaluation of the core-side and shell-side options for coupling of the IHX to the Primary Heat Transport System (PHTS) and Secondary Heat Transport System (SHTS). Given the results of that reevaluation, the integration of the IHX with the PHTS and SHTS piping is described in further detail. Finally, the overall integration of the HTS components within the NHSS buildings and structures is developed and presented.

It is worth noting that, in addition to supporting the needs of the IHX and HTS priority task, the results of this IHX/HTS integration effort serve as input to the companion priority task addressing plant level analysis and fission product transport (Ref. 4-1).

4.1 Reevaluation of IHX Coupling Options

The 2008 IHX and HTS Conceptual Design Study (Ref. 4-1) included an assessment of whether the core-side or shell-side of the IHX should be coupled to the PHTS. Two candidate configurations were identified, designated P1 (core-side coupling) and S3 (shell-side coupling), as shown in Figure 4-1. The conclusion at that time was that a decision could not be supported, given available information and the scope of that prior study. It was noted that the consideration of core-versus shell-side coupling to the PHTS involves a number of trade-offs, notably:

- HTS layout and building integration
- Pressure bias during normal operation and during loss of secondary pressure (expected to be a design basis event (DBE))
- Insulation and cooling of vessels and piping
- Access for inspection and maintenance

It was recognized at the conclusion of the 2008 study that resolution of the IHX coupling issue should be pursued with highest priority because it fundamentally impacts the architecture of the NHSS, particularly in terms of piping layout and the integration of the HTS components within the NHSS buildings and structures. From the evaluation perspective, the architecture of the HTS influences initial plant cost, operation and maintenance considerations and their associated costs and safety and investment protection. The latter relates to the response of HTS systems and components to various duty cycle and licensing basis events. As already noted, resolution of this issue was a highly desirable input to the companion priority task addressing plant level analysis and fission product transport. For all of these reasons, resolution of the IHX coupling issue was taken as a principal objective of the present IHX and HTS priority task.

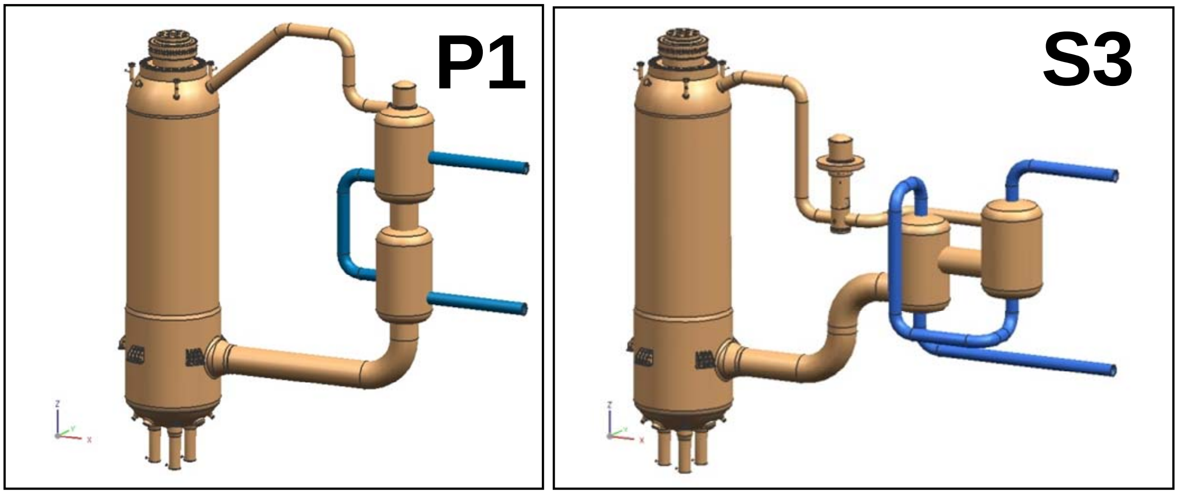


Figure 4-1 IHX Coupling Options for 950°C Architecture

In structuring the IHX and HTS priority task to resolve the IHX coupling issue, it was initially believed that parallel designs would have to be developed, one based on core-side coupling to the PHTS and a second based on shell-side coupling. The parallel designs would potentially include piping layouts and building integration concepts. If necessary, computer models would be developed and representative transients assessed to reveal differences in the response of the respective systems to LBEs.

In the course of initial work, it became evident that a great deal of additional information had been developed since the 2008 IHX and HTS Conceptual Design Study. This suggested that the selection of core-side or shell-side coupling might be possible without detailed development and assessment of two configurations. This, in fact, was found to be true and a qualitative evaluation was undertaken that was successful in identifying the preferred coupling option.

The evaluation, as summarized herein, begins with a description of the core-side and shell-side coupling options, based on the single-vessel configuration described in Section 2. The significance of changes relative to the 2008 conceptual design study and the additional information that has become available since that time are then discussed. This is followed by a review of the methodology for the evaluation and the corresponding update of the evaluation criteria that were used as a basis for comparisons. The assessment of the coupling options is then summarized, followed by conclusions and recommendations

4.1.1 Description of PHTS/IHX Coupling Options

As already noted, two options have been evaluated for coupling the IHX to the remainder of the HTS. In the first option, the core side of the IHX is coupled to the PHTS, as shown in Figure 4-2. In that configuration, the double-walled, actively-cooled pipe carrying the helium from the reactor outlet to the IHX is connected to the bottom of the IHX vessel. A ninety-degree bend is required to turn the reactor outlet pipe from its horizontal run to a vertical connection. Once inside the IHX vessel, the primary helium is fed into a central duct and, from there, through parallel pipes that connect the central duct to the inlet manifolds of the individual IHX modules. From there, the helium passes through the core side of the IHX unit cells (see Figure 4-3) and is then collected into the outlet manifolds of the IHX modules. Individual pipes connect the outlet manifolds to the central outlet duct at the top of the IHX vessel. The central outlet duct is connected to the PHTS cold leg piping, which routes the helium, via the circulator, back to the Reactor.

The secondary (SHTS) helium flow enters the IHX through the side of the pressure vessel, cooling the vessel inner walls as it is distributed to the IHX modules. The helium flows on the outside (shell side) of the unit cells (Figure 4-3) and is collected into an insulated internal plenum from where it leaves the vessel and is connected to the hot leg of the SHTS loop.

Notice that, as shown in Figure 4-2, the PHTS circulator is now mounted in a pressure vessel connected to the return pipe from the IHX to the RPV. This is a variation from the design presented in Reference 4-2 and results from further consideration of both circulator size and maintainability. Additional detail is provided in Section 4.1.2.3. Notice also the presence of a small pipe connecting the circulator outlet to the reactor outlet pipe near its connection with the IHX vessel. This pipe carries the helium flow required to cool the outer wall of the reactor outlet pipe.

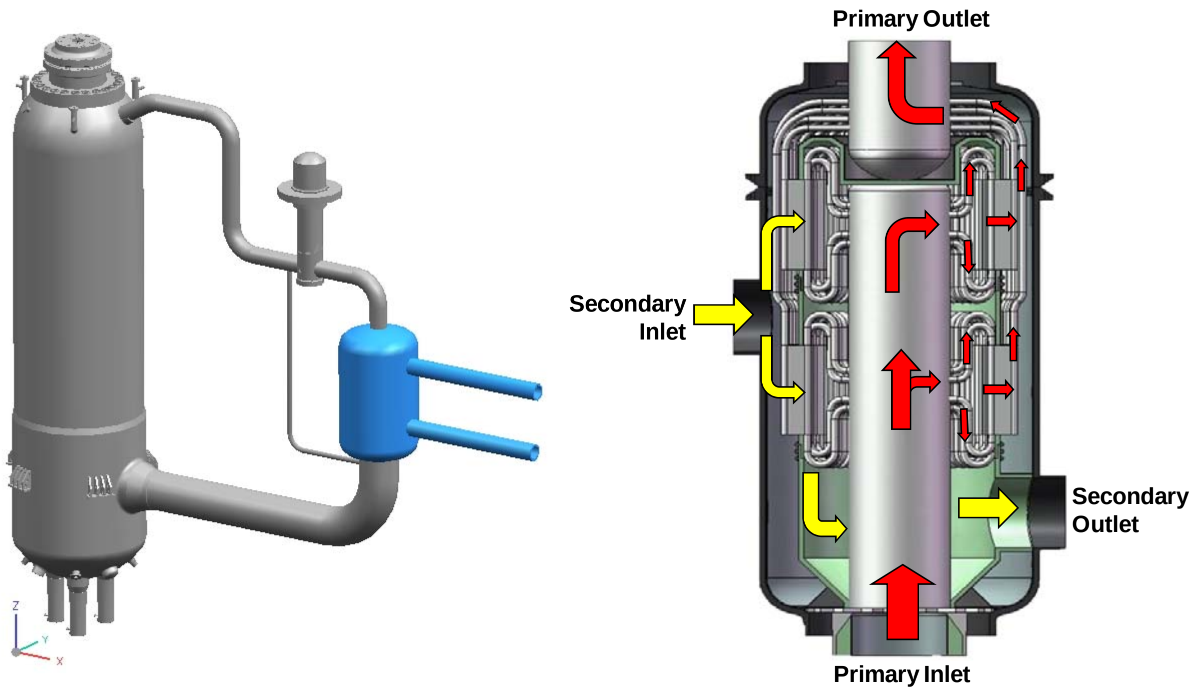


Figure 4-2 Coupling of the IHX Core Side to the PHTS

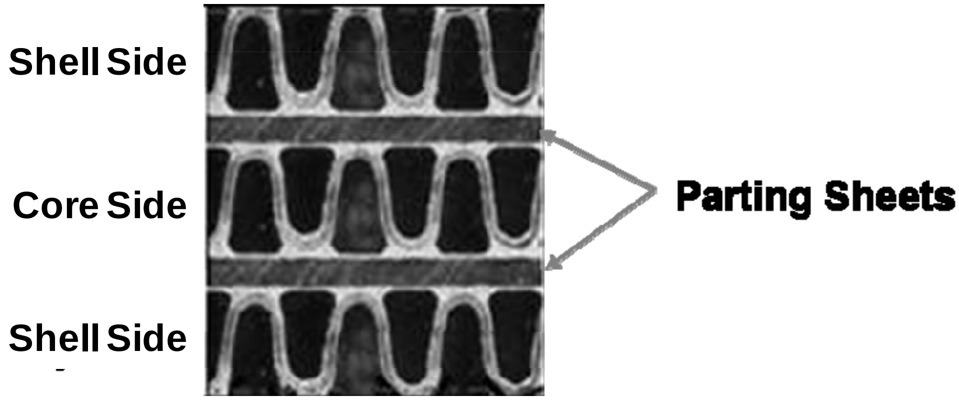


Figure 4-3 Cross Section of the IHX Unit-Cell

The second option, in which the shell side of the IHX is coupled to the PHTS,is shown in Figure 4-4. In this configuration, the double-walled, actively cooled pipe carrying the helium from the reactor outlet enters the IHX through the side of the pressure vessel near the bottom. A straight pipe connection is possible for this configuration. Once inside the IHX vessel, the primary helium is fed into a central insulated plenum. From there it flows on the shell side (outside) of the unit cells that make up the IHX modules (see Figure 4-3), giving up heat to the secondary helium. The PHTS helium leaves the IHX vessel though a pipe connected at the side, cooling the vessel as it passes along the inner wall.

The SHTS helium flow enters the IHX pressure vessel through a centrally located duct at the top of the vessel and is fed via individual pipes into the manifolds of the respective IHX modules. From there, the SHTS helium enters into the core sides of the IHX unit cells (see Figure 4-3) where it receives heat from the PHTS side. The heated helium is then collected into the outlet plenums of the IHX modules and channeled via their individual pipes to a central duct at the bottom of the IHX pressure vessel and back into the SHTS loop.

Notice that also for this second option (see Figure 4-4) the PHTS circulator is mounted in a pressure vessel connected to the return pipe from the IHX to the RPV. In this configuration there is also a small pipe connecting the circulator outlet to the hot duct near its coupling with the IHX vessel.

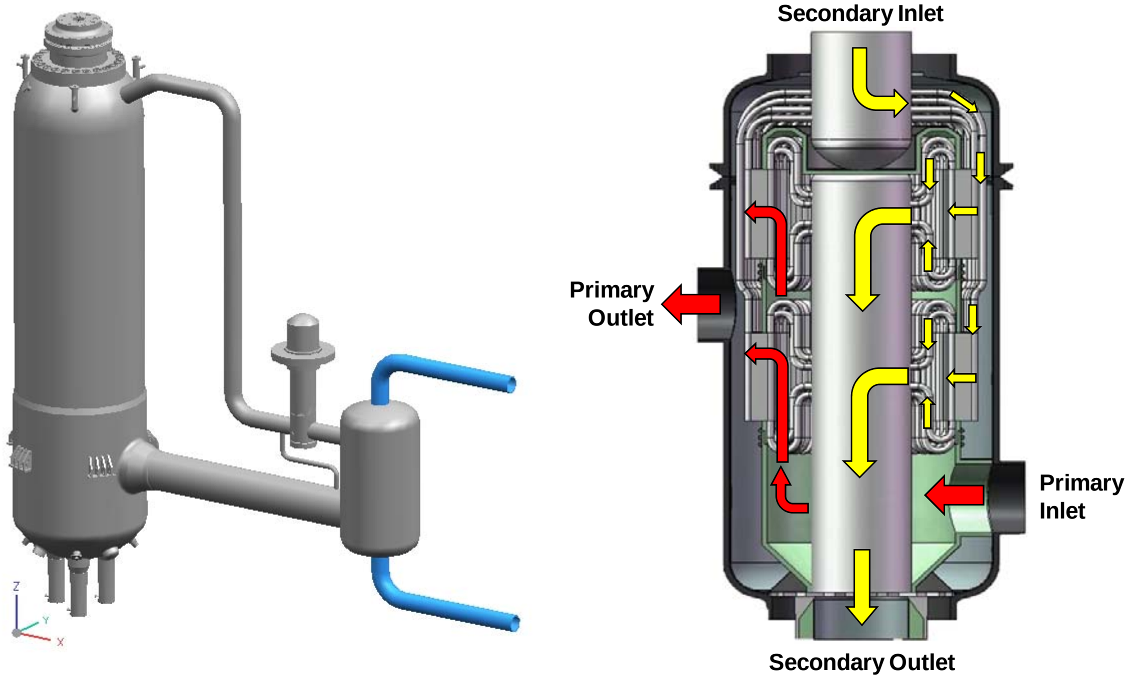


Figure 4-4 Coupling of the IHX Shell Side to the PHTS

4.1.2 Differences Relative to 2008 IHX/HTS Evaluation

A number of differences have evolved since the completion of the IHX and HTS Conceptual Design Study in 2008. The most significant change is the reduction in reactor outlet temperature (ROT) from 950°C to 750-800°C as a basis for the present task. Other changes and additional information have evolved from the ongoing DPP design effort. Key differences relative to the 2008 Conceptual Design Study and their influences on the core-versus shell-side coupling issue are described in the following sections.

4.1.2.1 Reduction in Temperature

As already noted, the most significant change relative to the 2008 IHX and HTS Conceptual Design Study is the reduction in ROT from 950°C to 750-800°C. At 950°C, the availability of a metallic material for the heat transfer surface that would last the full lifetime of the plant (60 years) was found to be seriously in question. The strategy that was adopted in the course of the preconceptual design was to structure the IHX into two sections, IHX A and IHX B. The heat exchanger core components of IHX A, the higher temperature section, would initially be made of a metallic material. At some point during plant life, nominally identified as 10 years, IHX A would be replaced by a heat exchanger that incorporates an advanced ceramic material in the core modules. IHX B, the lower temperature section of the IHX, would be designed for the full lifetime of the plant. Based on the tentative selection of Alloy 800H for the heat transfer surface of IHX B, the temperature breakpoint between the two IHX sections was nominally identified as 760°C (the present upper limit of coverage in ASME Section III, Subsection NH for that material). Note, however, that the results of the materials assessment in Section 2.2 would now suggest the selection of Hastelloy X for IHX B.

Given the reduction in ROT to 750-800°C, there is a significantly increased likelihood that the IHX heat transfer surface will last for the full life of the plant, or a significant fraction thereof. On this basis, there is no longer an incentive for a two-section IHX (Figure 4-5).

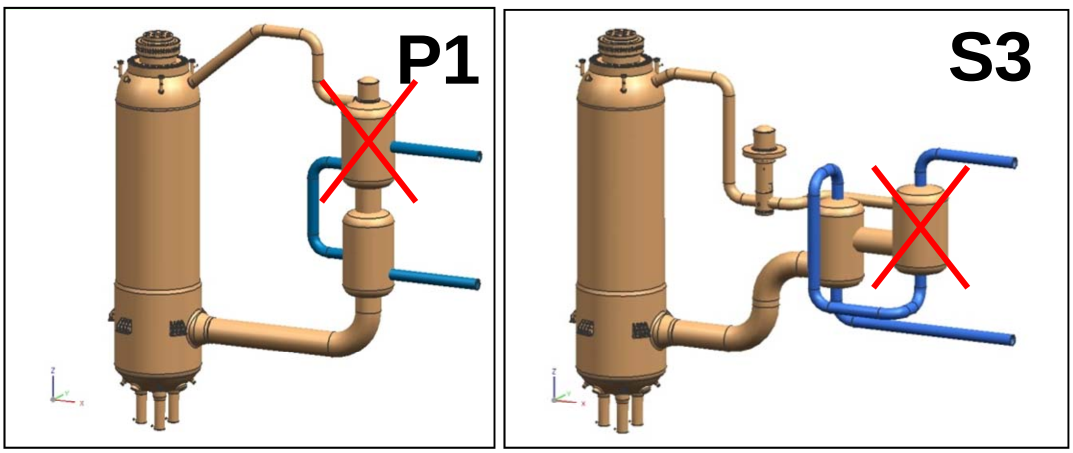
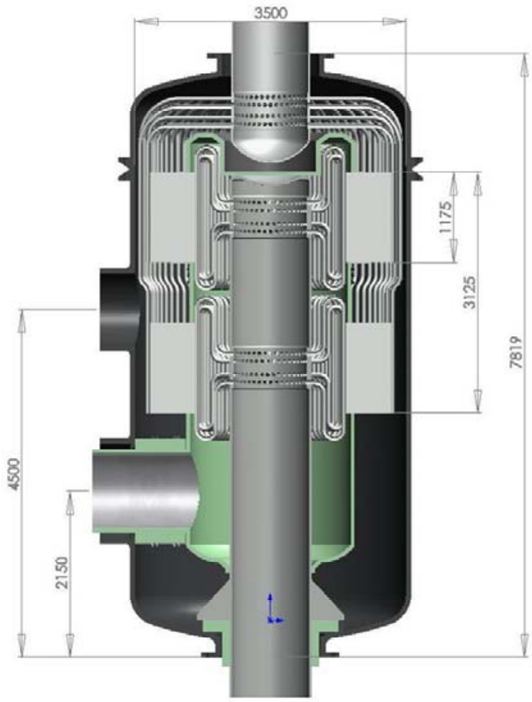


Figure 4-5 Single-Section IHX at 750-800°C

In the course of sizing a single-section IHX for the 750-800°C application, a further observation was made. Referring to Figure 4-6, it is evident that the overall size of the single-section IHX at 512 MWt is not substantially larger than IHX A (157 MWt) or IHX B (350 MWt) individually. In further evaluating this result, it was observed that the overall size and weight of the PFHE compact heat exchanger is largely driven by the internal structures that couple the large PHTS and SHTS inlet and outlet pipes to the individual core modules and the inlet and outlet plenums of the core modules themselves. None of these structures make a significant contribution to heat transfer. In going from the lower energy throughputs of IHX A and IHX B to the higher thermal energy throughput of the 750-800°C IHX design, the principal difference influencing the physical size and weight of the IHX is the heat transfer length of the individual core modules. The implication is that the additional complexity and cost of a two-section IHX is probably not justified, even at 950°C. A possible exception may be the NGNP demonstration plant, in which the principal objective is to validate technology options, such as ceramic heat exchangers.



Feature	950°C H_2		750-800°C
	IHX A	IHX B	
Power, MWt	157	350	512
Number of Cores	138	170	160
Core Material	I-617	800H	Hastelloy X
Vessel OD, m	3.0	3.3	3.5 (ID)
Vessel Height, m	6.6	6.8	7.8
Total Weight, t	125		TBD

Figure 4-6 Comparative Sizing of IHXs

4.1.2.2 Neutron Streaming

The high-temperature piping that connects the reactor outlet to the IHX primary-side inlet is a relatively complex structure that comprises an internally-insulated pressure boundary containing a hot gas duct (HGD), located within and concentric with the outer helium pressure boundary (Figure 4-7 - see Section 4.2.1 for additional detail).

At the time of the 2008 IHX and HTS Conceptual Design Study, there was concern that neutron streaming from the reactor outlet plenum to the IHX might result in significant activation of the IHX internals, which for the 950°C application were based on Alloy 617. This alloy contains nominally 12 wt.% cobalt and is easily activated. On that basis, the shell-side coupling option (S3) incorporated two 90° bends between the reactor and the IHX vessel (Figure 4-8). This significantly increased the complexity of the shell-side coupling option relative to Option S2, a straight-pipe coupling option, which was eliminated on that basis.

Since the time of the 2008 Conceptual Design Study, more detailed assessments of the DPP design have led to the conclusion that there is no significant neutron streaming from the reactor outlet plenum, which is located well below the core level. Further, for the reduced temperature range of 750-800°C, the candidate materials do not contain significant amounts of cobalt. The overall conclusion is that bends to prevent neutron streaming will not be required in the high-temperature pipe between the reactor and the IHX, possibly even for a 950°C application.

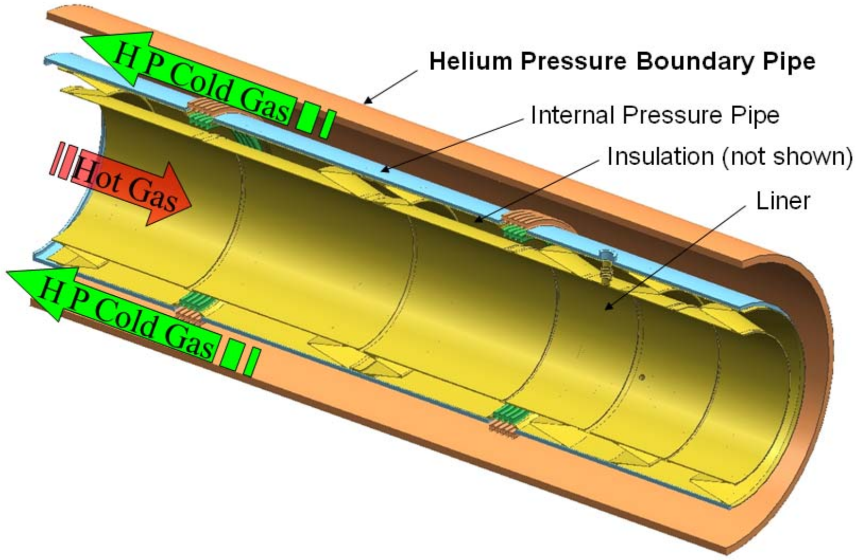


Figure 4-7 PHTS Hot Gas Pipe

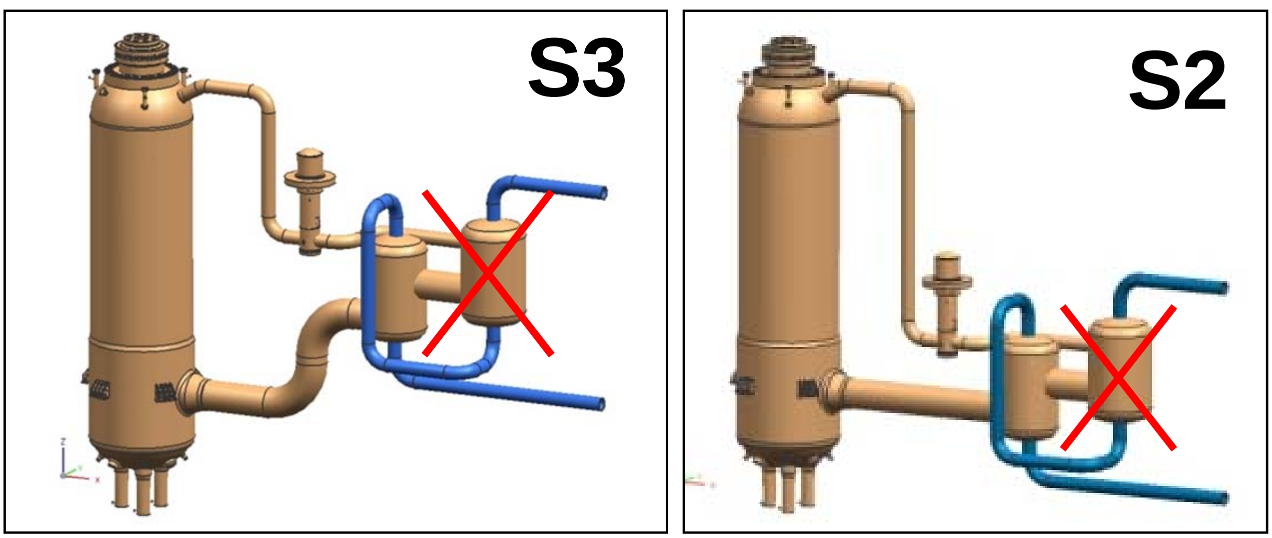


Figure 4-8 Pipe Bend in S3 to Prevent Neutron Streaming

4.1.2.3 Initial Vessel/Piping Layouts for 750-800°C

In the course of developing the initial vessel and piping layouts for the 750-800°C case, two factors emerged that have some influence on the core-versus shell-coupling decision. The first is that the sizes of both the PHTS and SHTS circulators (estimated to be on the order of 15 MW and 8 MW, respectively) are too large to consider integrating with the relatively small IHX vessel and would, therefore, be located in-line with the PHTS and SHTS piping. Effectively, this means that the location of the circulator has no bearing on the coupling decision.

It is also now clear that the cooling flow for the high-temperature pipe between the reactor outlet and the IHX inlet must be obtained from the PHTS circulator outlet, which is the highest pressure point in the system. The red arrows in Figure 4-9 show the source and direction of the cooling flow (approximately 10% of the total), which is taken from the PHTS cold leg piping in the vicinity of the PHTS circulator outlet and directed through a small pipe to the annulus between the inner and outer pressure boundaries of the reactor outlet pipe (Figure 4-7). The cooling flow is injected into the annulus at a point close to the IHX vessel. It rejoins the remainder of the reactor inlet stream at a point within the reactor vessel. The basis for these selections is to ensure that any leakage between the cooling path for the high-temperature piping and the remainder of the PHTS volume is always from a lower-temperature to a higher-temperature region.

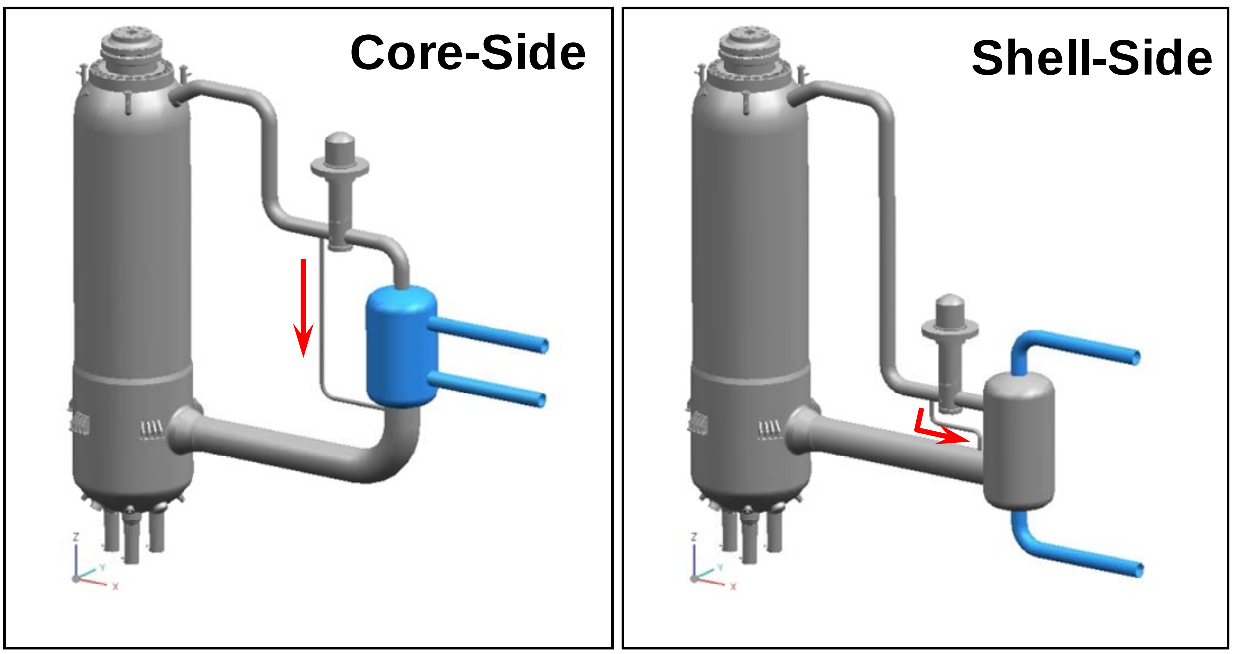


Figure 4-9 Cooling Source for High-Temperature Reactor Outlet Pipe

4.1.2.4 Circulating Dust within the PHTS

The presence of graphite structures and fuel elements within the reactor implies the need to consider the implications of graphite dust circulating within the PHTS. For the PBMR, this consideration is heightened by the continuous movement of pebble fuel elements through the reactor during operation. From the perspective of the IHX, the implications of graphite dust circulating within the PHTS include the following considerations:

- Blockage of micro-channels within the IHX core modules
- Erosion, particularly of the thin structures within the IHX core modules
- Transport and deposition of radionuclide contamination within the IHX, potentially impacting inspection and maintenance activities

With core-side coupling to the PHTS, primary helium containing circulating dust enters the IHX via the central duct at the bottom of the vessel (Figure 4-10) and is channeled through pairs of connecting pipes to the core side (inside) of the individual IHX heat transfer modules. The fins located within the core side of the IHX modules serve a structural function, thus, the potential for erosion is of greater concern. Note that the helium entering the IHX is at the highest temperature within the PHTS circuit, which tends to correspond with high velocity.

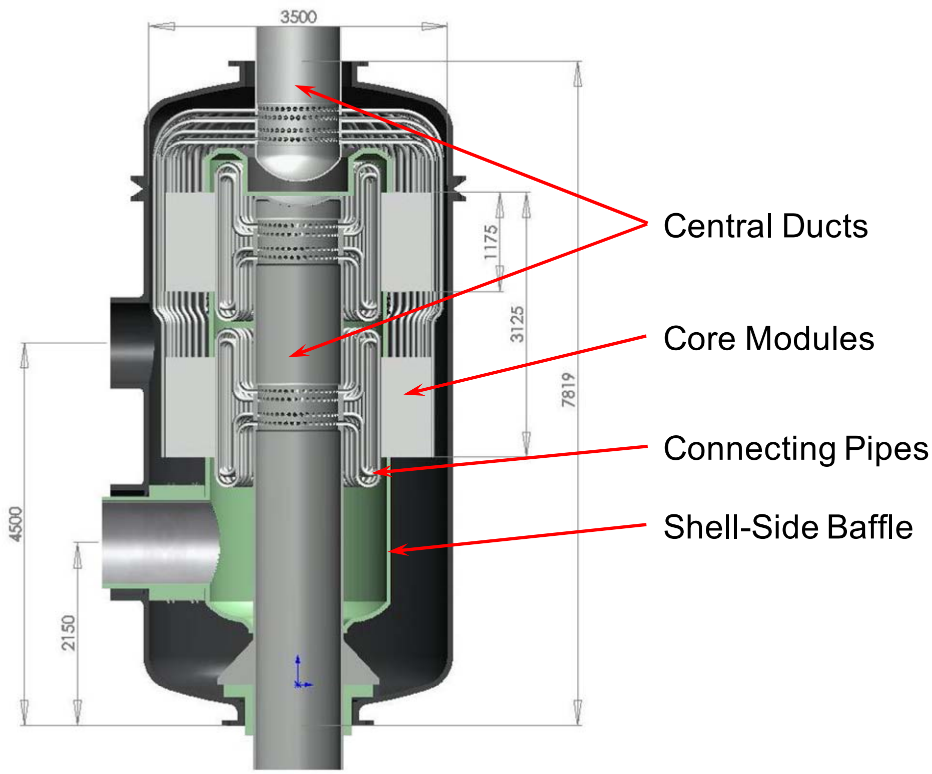


Figure 4-10 IHX

With shell-side coupling to the PHTS, primary helium containing circulating dust enters the IHX via the shell-side baffle and is distributed vertically to the shell-side (outside) of the core modules. Note that the fins located on the external side of the core modules do not serve a major structural function, so the principal concern with the possibility of erosion is loss of heat transfer effectiveness.

Without further analysis, and perhaps testing, it is difficult to say whether core-side or shell-side coupling would more likely lead to blockage of the microchannel gas flow paths within the unit cells (core-side coupling) or between the unit cells (shell-side coupling). However if dust accumulation and consequent channel blockage is found to be a problem, there is a potential to configure the entry region of the shell side baffle to act as a dust-separation device. This possibility should be further explored during conceptual design.

4.1.3 Assessment of Coupling Options

The PHTS/IHX coupling options described in Section 4.1.1 were evaluated in two steps. The first step was a qualitative evaluation in which the advantages and disadvantages of each option were assessed. This step started with a grouping of potentially differentiating characteristics into categories and subcategories. For each of the identified characteristics, advantages and disadvantages were developed using engineering judgment and consultation among experts. This process created a certain amount of confidence that all the elements affecting the comparison were covered.

The second step was a semi-quantitative assessment of the identified advantages and disadvantages. The Kepner-Tregoe approach was used in this process. Normalized numerical weights were first assigned to each of the selected categories and subcategories. Then each advantage and disadvantage was given a numerical score, again based on engineering judgment and consultation among experts. Each score was then multiplied by the weight of its category and/or subcategory and the results were summed for each of the two options. The option with the higher score is the recommended option.

4.1.3.1 Assessment of Advantages and Disadvantages

The assessment of advantages and disadvantages was conducted within the framework of five categories that describe different aspects of the IHX layout and design:

- Design/Technology Development
- Manufacturing and Transportability
- Operation and Maintenance
- Safety and Investment Protection
- Lifecycle Cost

Each of these five categories was further divided into sub-categories to evaluate different aspects of the design.

The results of the assessment of the advantages and disadvantages of each option are detailed in Table 4-1 and summarized in Table 4-2. A color code has been used to highlight the relative advantages **(green)** and relative disadvantages **(red)**. When a design feature was evaluated to be neutral or there was no relative advantage or disadvantage for either option, black type was used.

Several assumptions had to be made in order to create a level playing field for a fair comparison. These are identified at the top of Table 4-1.

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options

Objectives:

1. **Provide a qualitative comparison of alternatives for coupling the IHX to the PHTS and SHTS**
2. **Include consideration of pressure biasing with higher pressure in the PHTS vs. SHTS**
3. **Include consideration of heat exchanger type (PFHE vs. PCHE)**

Assumptions

1. PHTS and SHTS are pressurized helium closed loops.
2. Consideration shall be given to a NHSS with ROT of both 750°C and 800°C.
3. The IHX core is located in a single vessel and it may be of the PFHE Unit Cell (plate-fin) or PCHE (microchannel plate) type. Differences will be noted, where relevant.
4. The PHTS and SHTS are nominally pressure balanced except during "Loss of Secondary Pressure" (LOSP) which is assumed to be a Design Basis Event (DBE).
5. SHTS piping is designed with passive insulation (instead of active cooling).
6. Tubes connecting individual IHX modules to top/bottom central ducts can be plugged.
7. Activation of the IHX structure due to neutron streaming from the core is not significant, due to the location of the outlet plenum/hot gas duct well below the core and the selected IHX materials.
8. For the option in which the PHTS is coupled to the core side of the IHX modules, the arrangement is assumed to be as shown in Figure 1. For the option in which the PHTS is coupled to the shell side of the IHX modules, the arrangement is assumed to be as shown in Figure 2.

Figure 1 - PHTS Core Side

Figure 2 - PHTS Shell Side

Color Key: Green = Relative Advantage, Red = Relative Disadvantage, Black = Neutral/No Difference

Note: As used in this Table, the color coding is intended to highlight relative differences among options, not to indicate whether a particular option or feature is acceptable or unacceptable.

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options (cont'd)

Consideration	PHTS Core-Side Coupling	PHTS Shell-Side Coupling
Design & Technology Development		
Vessel Supports	RPV position fixed, IHX Vessel fixed laterally, but allowed to grow vertically and rotate on trunnion; flexibility built into Reactor Outlet and Inlet Pipes.	**RPV fixed, IHX Vessel allowed to move on sliding supports along axis of reactor outlet pipe; constrained vertically and laterally perpendicular to pipe axis. Flexible piping to and from Circulator. Concept similar to LWR supports.**
Location of PHTS and SHTS Circulators	No significant differences. With separate PHTS reactor outlet pipe and cold-leg return pipes circulators to be located in cold-leg piping on both sides to facilitate access/maintenance.	
Reactor Outlet Pipe		
- Cooling	No significant differences. Source of reactor outlet pipe outer annulus cooling gas must be from circulator outlet, requiring small separate pipe to provide gas to annulus in vicinity of IHX vessel.	
- Pipe Lengths	**Longer pipe required for bend, flexibility**	**Shortest lengths**
- Pipe Complexity	**Bend in RPV to IHX pipe**	**Straight pipe only**
- Shell-Side Internal Interfaces	No significant differences. Internal features of nozzle/internal manifold interface are essentially the same for both coupling options.	
Cold-Leg Piping		
- Pipe Lengths	No significant differences	
- Pipe Complexity	No significant differences	
IHX		
- Cores	No significant differences	
- Manifolds/Internal Piping	**Normal operating temperature ~ 750°C - 800°C**	**Normal operating temperature ~ 700°C - 750°C**
- Shell-Side Internal Ducts, Baffling	**Normal operating temperature ~ 700°C - 750°C; shell-side flow from outside to center.**	**Normal operating temperature ~ 750°C - 800°C; shell-side flow from center to outside.**

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options (cont'd)

Consideration	PHTS Core-Side Coupling	PHTS Shell-Side Coupling
- Pressure Biasing: Plate-Fin		
SHTS > PHTS	Normal operation: 100kPa external pressure (loading from the shell side) **LOSP: 9MPa internal pressure (loading from the core side)** (LOSP = Loss of Secondary Pressure)	Normal operation: 100kPa internal pressure (loading from the core side) **LOSP: 9MPa external pressure (loading from the shell side)**
PHTS > SHTS	Normal operation: 100kPa internal pressure (loading from the core side) **LOSP: 9MPa internal pressure (loading from the core side)**	Normal operation: 100kPa external pressure (loading from the shell side) **LOSP: 9MPa external pressure (loading from the shell side)**
- Pressure Biasing: PCHE	No significant differences	
IHX Vessel		
- Insulation/Cooling	SHTS cooling gas available at ~216°C	PHTS cooling gas available at ~266°C
Manufacturing and Transportability		
IHXs, Vessels and Piping	No significant differences	
Operation and Maintenance (O&M)		
Performance	No significant differences	
Reliability and Integrity Management (RIM)		
- Leak Detection - Plant in Operation		
· SHTS Pressure > PHTS	**Small leaks would likely not be detected. Indications of larger leaks would be inability to maintain bias dP and/or excessive injection of makeup helium into SHTS and withdrawal from PHTS. Since no contamination, larger leaks may be allowed.**	
· PHTS Pressure > SHTS	**Small leaks would be detected by presence of small amounts of radionuclides in SHTS.**	

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options (cont'd)

Consideration	PHTS Core-Side Coupling	PHTS Shell-Side Coupling
- In-Service Inspection		
· Central Ducts and Manifolds	**Access for NDE (non-destructive examination) conceptually available from contaminated PHTS side. Would require isolation of reactor (e.g., maintenance disks as envisioned for DPP) and opening of PHTS pressure boundary (PB). Access to top and bottom of IHX would involve removal of PHTS pipe sections above and below the IHX vessel. Note that the pipe from the RPV to the IHX vessel is actively cooled and double-walled.**	**Access for NDE is available from uncontaminated SHTS side. Requires removal of single wall pipe sections from above and below the IHX vessel. No requirement to open PHTS PB**
· IHX Cores	NDE methods, such as UT, MT, RT do not appear to be practical. One option is to pressure test individual modules. Access via manifolds is as described above.	NDE methods, such as UT, MT, RT do not appear to be practical. One option is to pressure test individual modules. Access via manifolds is as described above.
- Leak Location and Isolation	Individual modules may be tested for leakage and isolated by plugging via access to IHX central duct. This access is obtained as described above.	
- IHX Replacement	No significant differences	
- Circulator Maintenance	No significant differences	
Investment Risk		
- Chemistry/Corrosion		
· Plate-fin	**Internal core must be compatible with PHTS chemistry (more difficult to control). Fins loaded in tension during LOSP.**	**Internal core must be compatible with SHTS chemistry (less difficult to control). Fins loaded in compression during LOSP**
· PCHE	No significant differences	

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options (cont'd)

Consideration	PHTS Core-Side Coupling	PHTS Shell-Side Coupling
- Dust (blockage, erosion)	**Dust more likely to enter IHX core passages. Likely deposition points in core module inlet/outlet manifolds.**	**Dust more likely to drop out before reaching core modules, less likely to result in blockage. May be possible to design internal manifold at PHTS inlet to preferentially separate dust from helium stream.**
Safety & Licensing		
ALARA		
- Neutron Activation	No significant differences	
- Direction of Pressure Bias		
· SHTS Pressure > PHTS	**IHX internal pressure boundary leaks during normal operation do not contaminate the SHTS**	
· PHTS Pressure > SHTS	**IHX internal pressure boundary leaks during normal operation imply contamination of the SHTS (levels, implications TBD)**	
Loss of Primary Pressure	**Smaller (~5-10% less) PHTS helium inventory.**	**Larger (~5-10% more) PHTS helium inventory. May provide marginally greater ability to lift off and transport fission products during primary pipe break Design Basis Accident.**
Loss of Secondary Pressure		
- Plate-fin	**Internal pressurization of cores makes consequent failure of heat transfer pressure boundary between PHTS/SHTS more likely. Likelihood may be further increased by corrosion effects leading to internal fin degradation. Internal pressurization of manifolds, ducts reduces likelihood of buckling.**	**External pressurization of cores, and likelihood of less corrosion due to the improved ability to control SHTS chemistry makes consequent failure of heat transfer pressure boundary between PHTS/SHTS less likely. Manifolds and ducts must be designed for external loads during LOSP.**
- PCHE	**Internal pressurization of manifolds and ducts reduces likelihood of buckling.**	**Manifolds and ducts must be designed for external loads during LOSP.**

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options (cont'd)

Consideration	PHTS Core-Side Coupling	PHTS Shell-Side Coupling
Lifecycle Cost		
Design & Development Costs	**Maintenance design and qualification more challenging**	**Maintenance design and qualification less challenging**
Capital Costs	No significant differences	
Project Schedule	No significant differences	
Operating Costs	**Maintenance costs would be higher for equivalent functions**	**Maintenance costs would be lower for equivalent functions**
Risk	**Consequences of leaks, dust/erosion, LOSP would be more significant**	**Consequences of leaks, dust/erosion, LOSP would be less significant**

Table 4-2 Summary of the Qualitative Comparison of PHTS/IHX Coupling Options

Rating: Good OK Challenge Not acceptable	**PHTS Core Side** 	**PHTS Shell Side** 
Design & Technology Development		
Vessel Supports	OK	Good
PHTS Circulator	OK	OK
Cooled Hot gas Ducts/Pipes		
- Hot Duct Cooling	OK	OK
- Pipe Lengths	OK	Good
- Pipe Complexity	OK	Good
- Shell-Side Internal Interfaces	OK	OK
Cold-Leg Piping		
- Pipe Lengths	OK	OK
- Pipe Complexity	OK	OK
IHX		
- Cores	OK	OK
- Manifolds/Internal Piping	Challenge	Good
- Shell-Side Internal Ducts, Baffling	Good	Challenge
- Pressure Biasing: Plate-Fin		
SHTS > PHTS	Challenge	OK
PHTS > SHTS	Challenge	Good
- Pressure Biasing: PCHE	OK	OK
IHX Vessel		
- Insulation/Cooling	OK	OK
Manufacturing and Transportability		
IHXs, Vessels and Piping	OK	OK
Operation and Maintenance (O&M)		
Performance	OK	OK

Table 4-1 Detailed Comparison of the PHTS/IHX Coupling Options (cont'd)

Rating: **Good** **OK** **Challenge** **Not acceptable**	**PHTS Core Side** 	**PHTS Shell Side** 
Reliability & Integrity Management (RIM)		
- Leak Detection - Plant in Operation		
SHTS Pressure > PHTS	**Challenge/ Good**	**Challenge/ Good**
PHTS Pressure > SHTS	**Good /Challenge**	**Good /Challenge**
- In-Service Inspection		
Central Ducts and Manifolds	**Challenge**	**Good**
IHX Cores	**Challenge**	**Good**
- Leak Location and Isolation	**OK**	**OK**
- IHX Replacement	**OK**	**OK**
- Circulator Maintenance	**OK**	**OK**
Investment Risk		
- Chemistry/Corrosion		
Plate-fin	**Challenge**	**Good**
PCHE	**OK**	**OK**
- Dust (blockage, erosion)	**Challenge**	**Good**
Safety & Licensing		
ALARA		
- Neutron Activation	**OK**	**OK**
- Direction of Pressure Bias		
SHTS Pressure > PHTS	**Good**	**Good**
PHTS Pressure > SHTS	**Challenge**	**Challenge**
Loss of Secondary Pressure		
- Plate-fin	**Challenge**	**Good**
- PCHE	**OK**	**OK**
Lifecycle Cost		
Design & Development Costs	**OK**	**Good**
Capital Costs	**OK**	**OK**
Project Schedule	**OK**	**OK**
Operating Costs	**Challenge**	**Good**
Risk	**Challenge**	**Good**

4.1.3.2 Kepner-Tregoe Evaluation

A Kepner-Tregoe analysis was employed as the second step in the evaluation of alternate plant configurations with the PHTS coupled to the core- versus the shell-side of the IHX. As input to the Kepner-Tregoe analysis, criteria were identified in the same five main categories used in the assessment of advantages and disadvantages: Design/Technology Development, Manufacturing and Transportability, Operation and Maintenance, Safety and Licensing and Lifecycle Cost. As shown in Table 4-3, each category is weighted proportionally to its perceived importance, with the total being normalized to 100. Within each category, the assigned weight is allocated among sub-criteria, based on the perceived importance of each criterion to the overall category.

The weights of the five major categories were selected as follows:

- **Design/Technology development** has a weight of **15 (15%).** This relatively low weight was selected based on the fact that design and technology development are one-time costs. Further, the risks associated with design and technology development are expected to be reduced for IHX inlet temperatures in the range of 750 and 800°C as opposed to the 950°C considered earlier.

- **Manufacturing and transportation** has a weight of **20 (20%).** The value of this weight was determined based on the potential fabrication challenges of the IHX cores and their supports and baffles. Transportation of these components to the plant site should not be a problem.

- **Operation and Maintenance** has a weight of **30 (30%).** This relatively high weight value was given in consideration of the fact that plant reliability is essential for meeting economic objectives. Detection of a helium leak from the PHTS to the SHTS (or vice versa), ISI of the IHX and the plugging of leaking cores are operations necessary to avoid major sources of outages. These operations will require the development of special ad hoc tools and procedures.

- **Safety and Investment Protection** has a weight of **20 (20%).** The relatively low value of this weight is based on the fact that a failure of one of the components under consideration (IHX, circulator, vessels and piping) will affect primarily the plant investment. Moreover, a leak in one of the IHX cores, if small enough, should not prevent continued operation of the plant and a larger leak could be dealt with shutting down the plant, finding and plugging the leaking core, and resuming plant operation. Only very large or multiple leaks would require replacing the IHX with a serious implication on the plant investment.

- **Lifecycle Cost** has a weight of **15 (15%).** This low value of the weight is due to the fact that the design, capital and operating costs for the components under consideration are small compared to the total cost of the plant and the impact of their development and fabrication on the plant schedule should be relatively small.

Each of the five main categories discussed above was subdivided into lower-level criteria that were normalized to 1 for each category (see Table 4-3). The weights of each of these criteria were selected as follows:

- **Design/Technology development** has three criteria:
  - Vessel support, piping and circulator with a weight of **0.2 (20%).**
  - IHX and IHX vessel with a weight of **0.6 (60%).**
  - Risk- Design/Technology with a weight of **0.2 (20%).**

  The selection of the weights for these three criteria was based on the fact that the design and development of helium-to-helium IHX with high inlet temperatures is the most demanding task. The design and development of the other components (circulator, vessels and piping) should be less demanding. Moreover, the risk of failing to design and develop these components got a low weight because of the extensive experience available in several specialized industries.

- **Manufacturing and Transportability** has three criteria:
  - Manufacturability and Constructability with a weight of **0.5 (50%).**
  - Transportability with a weight of **0.1 (10%).**
  - RISK - Manufacturing and Construction with a weight of **0.4 (40%).**

  The transportability criteria got a very low weight because the size and weight of the components under consideration are within the capabilities of present transportation means. On the other hand, the construction of the IHX cores and their supports could require some development and a very careful quality control. Furthermore, there is some risk that the IHX as a finished product will not meet the design specifications because of tight tolerances and welding required along the core primary boundaries.

- **Operation and Maintenance** has three criteria:
  - Leak Detection, ISI and IHX Replacement with a weight of **0.4 (40%).**
  - Performance and Operational with a weight of **0.2 (20%).**
  - RISK - Operation and Maintenance with a weight of **0.4 (40%).**

  Performance and operation criteria got a low weight because the IHX is expected to achieve its design performance and to operate within acceptable margins due to previous industrial experience in the fields of plate/fin and printed circuit heat exchangers. The same applied to the other components under consideration. On the other hand, leak detection and ISI of a contaminated IHX in a nuclear environment are difficult tasks that require specialized tools and they involve a certain amount of risk of failure.

- **Safety and Investment Protection** has three criteria:
  - Loop Chemistry, Corrosion and Dust with a weight of **0.4 (40%).**
  - IHX Transient Loads with a weight of **0.2 (20%)**
  - Loop Contamination with a weight of **0.2 (20%).**
  - RISK - Safety and Investment Protection with a weight of **0.2 (20%).**

  Loop chemistry, corrosion prevention and dust control are very important factors in keeping the required IHX performance during its operating life and preventing damage to the primary boundary surfaces for a plate/fin IHX design. For these reasons, this criterion got the highest weight factor. Lower weights were given to the remaining criteria because the IHX will be designed to withstand the expected structural loads, the above rating for ISI under O&M will take in consideration potential contamination, and IHX internal failures do not have safety implications. A serious loss of investment will occur only in a case of a very large IHX leak. Moreover, chronic failures of the IHX internal heat transfer surface could be very costly in terms of downtime, which is very expensive.

- **Lifecycle Cost** has five criteria:
  - Design Development Cost (Non-recurring) with a weight of **0.1 (10%).**
  - Capital Cost (Recurring) with a weight of **0.25 (25%).**
  - Project Schedule with a weight of **0.15 (15%).**
  - Operating Cost with a weight of **0.3 (30%).**
  - RISK - Lifecycle Cost with a weight of **0.2 (20%).**

  Larger weights were given to the capital and operating costs because the construction of the IHX will require specialized companies and the use of expensive materials and only a small number of these components will be built at the beginning. Operation will also be expensive because maintenance could require additional plant downtime and specialized tools. The cost for developing the design of these components has a lower weight because of the available industrial experience in this area and because it is a one-time expense.

In the summary of the evaluation shown in Table 4-3, each criterion is rated for each of the two cases based on the relative success with which the case met the criterion. The case meeting a given criterion most successfully was awarded a rating of 10 with a proportionately lower rating awarded to the other case based on its relative success in meeting that criterion. A score for each case in each criterion was calculated by multiplying the weight times the weight allocation times the rating. These scores were added for each case to give a resultant case score.

Table 4-4 summarizes the scores for each criterion in the five categories described above, and includes a brief description in support of the selection for each score.

Table 4-3 Summary of Kepner-Tregoe Evaluation Scores

Criteria	Weight	Weight Allocation	PHTS Connected to the IHX Core Side		PHTS Connected to the IHX Shell Side	
			Rating	Score	Rating	Score
1.0 Design/ Technology Development	**15**					
1.1 Vessel Support, Piping and Circulator		0.2	9	27	10	30
1.2 IHX and IHX Vessel		0.6	10	90	10	90
1.3 RISK - Design/ Technology Development		0.2	9	27	10	30
Subtotal		**1**		**144**		**150**
2.0 Manufacturing and Transportability	**20**					
2.1 Manufacturability and Constructability		0.5	10	100	10	100
2.2 Transportability		0.1	10	20	10	20
2.3 RISK - Manufacturing and Construction		0.4	10	80	10	80
Subtotal		**1**		**200**		**200**
3.0 Operation and Maintenance	**30**					
3.1 Leak Detection, ISI IHX Replacement (RAM)		0.4	6	72	10	120
3.2 Performance and Operational		0.2	10	60	10	60
3.3 RISK - Operation and Maintenance		0.4	8	96	10	120
Subtotal		**1**		**228**		**300**
4.0 Safety and Investment Protection	**20**					
4.1 Loop Chemistry, Corrosion and Dust		0.4	6[8]	48[64]	10	80
4.2 IHX Transient Loads		0.2	9[10]	36[40]	10[9]	40[36]
4.3 Loop Contamination		0.2	10	40	10	40
4.4 RISK - Safety and Investment Protection		0.2	10	40	10	40
Subtotal		**1**		**164[184]**		**200[196]**
5.0 Lifecycle Cost	**15**					
5.1 Design Development Cost (Non-recurring)		0.1	10	15	10	15
5.2 Capital Cost (Recurring)		0.25	10	38	10	38
5.3 Project Schedule		0.15	10	23	10	23
5.4 Operating Cost		0.3	8	36	10	45
5.5 RISK - Lifecycle Cost		0.2	9	27	10	30
Subtotal		**1**		**138**		**150**
Total	**100**			**874[894]**		**1000[996]**

Note: Numbers in [ ] are for an IHX utilizing PCHE core modules.

Table 4-4 Discussion of Kepner-Tregoe Evaluation Scores

Criteria	PHTS Coupling at the IHX Core Side	PHTS Coupling at the IHX Shell Side	Core vs. Shell side PHTS Coupling Discussion
Column Number	**[1]**	**[2]**	**[1] vs. [2]**
1.0 Design/ Technology Development		**Better**	
1.1 Vessel Support, Piping and Circulator	**9**	**10**	Both options for supporting the RPV and the IHX vessel are acceptable. Option 2 gets a higher score because is simpler and is based on LWR experience. The piping for Option 1 is a little more complicated and longer because of the 90 degree bend in the double wall pipe between the RPV and the IHX vessel. Seismic design will be somewhat easier for Option 2. There are no significant differences regarding the mounting and location of the PHTS circulator.
1.2 IHX and IHX Vessel	**10**	**10**	Option 1 has the advantage that the IHX shell-side internal ducts and baffling operate at slight lower temperature, but the IHX core has to be designed for tension loading during a LOSP. On the other hand, Option 2 operates at a slightly higher temperature at the IHX shell-side internal ducts and baffling, but the IHX core will be designed for compression loading during LOSP. All in all, there are no significant differences for the design and development point of view.
1.3 RISK - Design/ Technology Development	**9**	**10**	There is a slightly lower risk for Option 2 in the design and development of the vessel supports and the connecting pipes because of a simpler arrangement and design.
2.0 Manufacturing and Transportability			
2.1 Manufacturability and Constructability	**10**	**10**	Due to the similarity of the design and the availability of specialized industries to manufacture the components under consideration, there are no significant differences between Option 1 and 2 for this criterion.
2.2 Transportability	**10**	**10**	There are no significant differences between Option 1 and 2 for this criterion because of the similarity of the designs and the relatively small size and weight of the components under consideration.
2.3 RISK - Manufacturing and Construction	**10**	**10**	There is an equal amount of risk for the two options of encountering serious problems during fabrication because of the similarity of the designs.
3.0 Operation and Maintenance		**Better**	
3.1 Leak Detection, ISI and IHX Replacement (RIM)	**6**	**10**	The ease of detecting leakage across the IHX boundary between the PHTS and the SHTS is more related to the pressure bias between these two loops than the PHTS coupling with the IHX. There are some advantages and disadvantages for each pressure bias, but these do not effect the selection between Options 1 and 2.

Criteria	PHTS Coupling at the IHX Core Side	PHTS Coupling at the IHX Shell Side	Core vs. Shell side PHTS Coupling Discussion
Column Number	**[1]**	**[2]**	**[1] vs. [2]**
			With Option 2, access for NDE and the detection and isolation of leaks is available from the uncontaminated SHTS side. With Option 1, access is conceptually available from contaminated PHTS side; however, this would require isolation of the reactor (e.g., maintenance disks as envisioned for DPP) and opening of PHTS pressure boundary (PB). Access to top and bottom of IHX would involve removal of PHTS pipe sections above and below the IHX vessel. Note that the pipe from the RPV to the IHX vessel is actively cooled and double-walled. The replacement of the entire IHX vessel is equally challenging for the two Options.
3.2 Performance and Operational	**10**	**10**	There are no significant differences between Option 1 and 2 for this criterion because of the similarity of the designs. .
3.3 RISK - Operation and Maintenance	**8**	10	There is an equal amount of risk for the two Options of not meeting operating requirements, but clearly there are some maintenance advantages for Option 2 because of better accessibility. For Option 1, access for maintenance requires opening of the central ducts at the top and bottom. With core-side coupling, the bottom pipe is the multi-layer pipe from the reactor to the IHX. This will make opening this interface more complicated, especially with contamination taken into account.
4.0 Safety and Investment Protection		**Better**	
4.1 Loop Chemistry, Corrosion and Dust	**6 [8]**	**10**	Corrosion of the internal fins is a major concern for a plate/fin design, as the internal fins serve a structural function. In this regard, there is a clear advantage for Option 2 because the chemistry of the SHTS flowing through the core side is less difficult to control, and is potentially less corrosive. This difference is not found with the PCHE, so the greater PHTS corrosion potential would not be a differentiating factor. Dust circulating in the PHTS is more likely to drop out before reaching the IHX core modules in the case of Option 2 and there is a potential to configure the shell-side baffle to separate dust before it reaches the core modules.
4.2 IHX Transient Loads	**9 [10]**	**10 [9]**	The distinguishing transient load is LOSP. The internal fins are a primary structural element of the PFHE cores. These are loaded in tension with Option 1 and in compression with Option 2. Failure of the PHTS to SHTS pressure boundary within the cores is evaluated to be more likely with tension loading for this transient. In the case of the PCHE, there is no difference. With Option 1, ducts and manifolds are also loaded in tension and with Option 2 in compression. For these components, compression loading is less desirable, but can be accounted for in the component design.

Criteria	PHTS Coupling at the IHX Core Side	PHTS Coupling at the IHX Shell Side	Core vs. Shell side PHTS Coupling Discussion
Column Number	**[1]**	**[2]**	**[1] vs. [2]**
4.3 Loop Contamination	**10**	**10**	Equal score has been assigned to this criterion to avoid double counting. Loop contamination has been addressed in 3.1.
4.4 RISK - Safety and Investment Protection	**10**	**10**	Option 2 has an advantage from the investment protection point of view because the fins in the IHX core operate in compression during LOSP and therefore, they are less likely to fail. In the case of the PCHE, there is no difference in this characteristic. There is an equal amount of risk for the two Options from the safety point of view, with a slight bias toward Option 1. Larger (~5-10% more) PHTS helium inventory with Option 2 may provide marginally greater ability to lift off and transport fission products during primary pipe break Design Basis Accident.
		Better	
5.0 Lifecycle Cost			
5.1 Design Development Cost (Non-recurring)	**10**	**10**	There are no significant differences between Option 1 and 2 for this criterion because of the similarity of the design.
5.2 Capital Cost (Recurring)	**10**	**10**	There are no significant differences between Option 1 and 2 for this criterion because of the similarity of the design.
5.3 Project Schedule	**10**	**10**	There are no significant differences between Option 1 and 2 for this criterion because of the similarity of the design.
5.4 Operating Cost	**8**	**10**	There is a bias toward Option 2 for this criterion because ISI and, possibly, module isolation are highly likely maintenance operations and avoiding opening the PHTS is a major advantage from the cost point of view.
5.5 RISK - Lifecycle Cost	**9**	**10**	There is a slightly less risk on the plant lifecycle cost for Option 2 because a simpler IHX maintenance presents a lower risk of unscheduled plant downtime.

The final Kepner-Tregoe score, 1000 to 874, is in favor of coupling the PHTS to the shell-side of the IHX. If the PCHE were to be used for the IHX core modules instead of the PFHE, the result is the same; however, the evaluated difference is reduced, 996 to 894.

In summary, the key features that played a role in deciding the preferred option in this comparison were:

For Option 1 (coupling of the PHTS to the core side of the IHX)

On the positive side

- The IHX shell-side internal ducts and baffling operate at slightly lower temperatures.
- Smaller (~5-10% less) total PHTS helium inventory could reduce predicted radionuclide releases from liftoff for very low frequency design basis accidents (large PHTS pipe break).

On the negative side

- Longer and more complex hot gas duct required from the RPV to the IHX to account for a bend and flexibility.
- Manifolds and internal piping on the IHX core side operate at a slightly higher temperature.
- During a LOSP the IHX core side is loaded (~ 9 MPa) in tension.
- Access for NDE would require isolation of reactor (e.g., maintenance disks as envisioned for DPP) and opening of PHTS pressure boundary (PB). Access to top and bottom of IHX sections would involve removal of PHTS pipe sections above and below the IHX vessel. PHTS contamination is a potentially significant factor.
- Internal core must be compatible with the PHTS chemistry (more difficult to control) and likely more corrosive.
- Dust more likely to enter IHX core passages. Likely deposition points in core module inlet/outlet manifolds.
- Maintenance design and qualification potentially more challenging and costly for equivalent functions.

For Option 2 (coupling of the PHTS to the shell side of the IHX)

On the positive side

- The arrangement of the RPV and IHX vessels supports is simpler and is based on LWR experience.
- The hot gas duct from the RPV to the IHX vessel is straight and shorter.
- Manifolds and internal piping on the IHX core side operate at a slightly lower temperature.
- During a LOSP the IHX core side is loaded (~ 9 MPa) in compression.

- Access for NDE is available from uncontaminated SHTS side. Requires removal of single wall pipe sections from above and below the IHX vessel. No requirement to open PHTS PB. PHTS contamination not a significant factor.
- Internal IHX core must be compatible with SHTS chemistry that is less difficult to control and less corrosive.
- Dust more likely to drop out before reaching core modules, less likely to result in blockages.
- Maintenance design and qualification potentially less challenging and costly for equivalent functions.

On the negative side

- The IHX shell-side internal ducts and baffling operate at slightly higher temperatures.
- Larger (~5-10% more) PHTS helium inventory may provide marginally greater ability to lift off and transport fission products during primary pipe break Design Basis Accident.

4.1.4 Conclusions and Recommendations

Due to simpler arrangement of the vessels and supports, operation with a better helium control chemistry and dust abatement on the core side, improved access for NDE and maintenance, safer operation during design basis accidents (core in compression) and slightly less costly capital and operating costs, it is recommended that shell-side coupling of the PHTS to the IHX be selected.

4.2 IHX-Piping Integration

This section describes the physical connections of the PHTS and SHTS to the IHX. As part of this task, concepts were developed for both core-side and shell-side coupling of the PHTS to the IHX. Having an actively cooled core outlet pipe (COP) on the PHTS side and passively insulated IHX outlet pipe on the SHTS side implies that there are some differences in the interfaces, depending on the coupling choice; however, both are technically feasible. Bearing in mind the choice of shell-side coupling for the PHTS, as described above in Section 4.1, the interfaces and piping layout associated with the shell-side option are illustrated below in Figure 4-11 and Figure 4-12.

The general flow path is depicted diagrammatically in Section 1, Figure 1-2. The hot primary gas flows within the actively-cooled reactor outlet pipe to the IHX. The cooled primary helium flows from the IHX to the circulator inlet which returns most of the gas to the top of the Reactor Pressure Vessel (RPV). A fraction (~10%) of the circulator outlet flow is supplied to the cooling annulus of the reactor outlet pipe. This flow is counter to the hot internal flow. The annulus cooling rejoins the main reactor inlet flow within the RPV in region of the core connection, after the main flow has washed over the length of the vessel. The cold secondary inlet flow is supplied to the top of the IHX vessel from the SHTS circulator outlet. The high temperature secondary helium exits the bottom of the IHX and is conveyed via a passively insulated pipe to the steam generator.

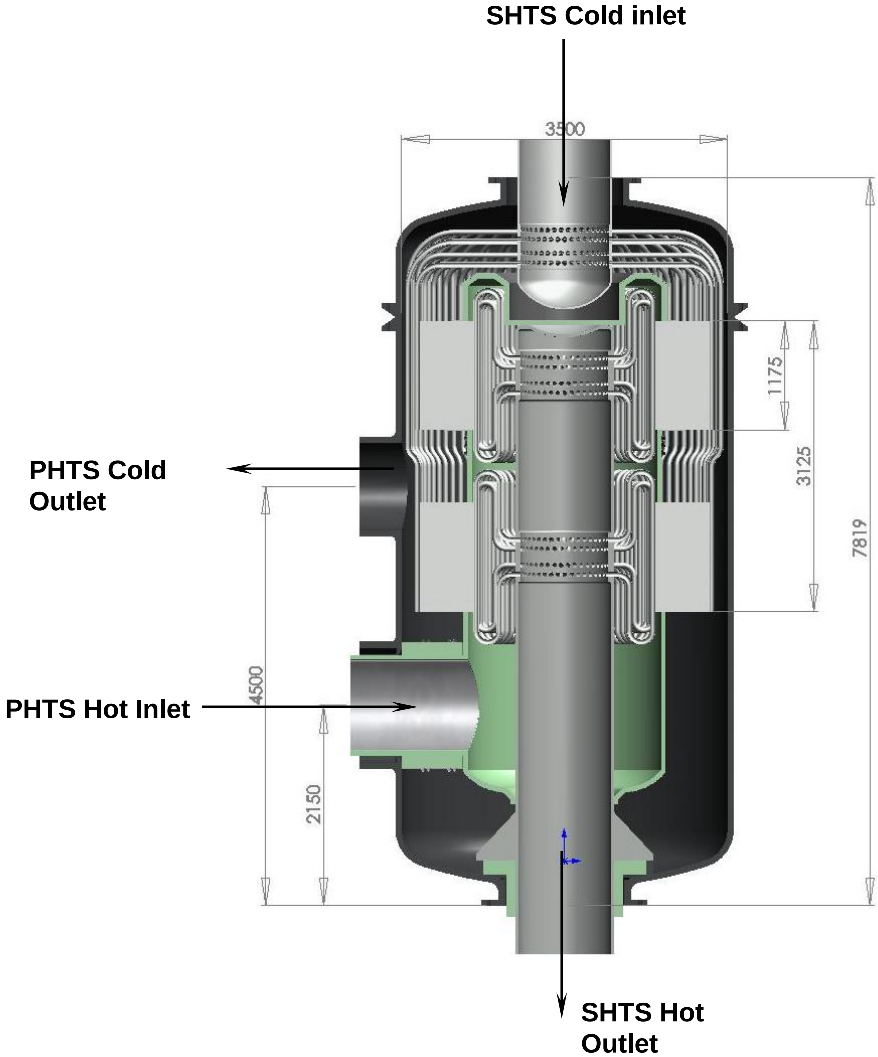


Figure 4-11 IHX Conceptual Layout, Shell-Side Coupling

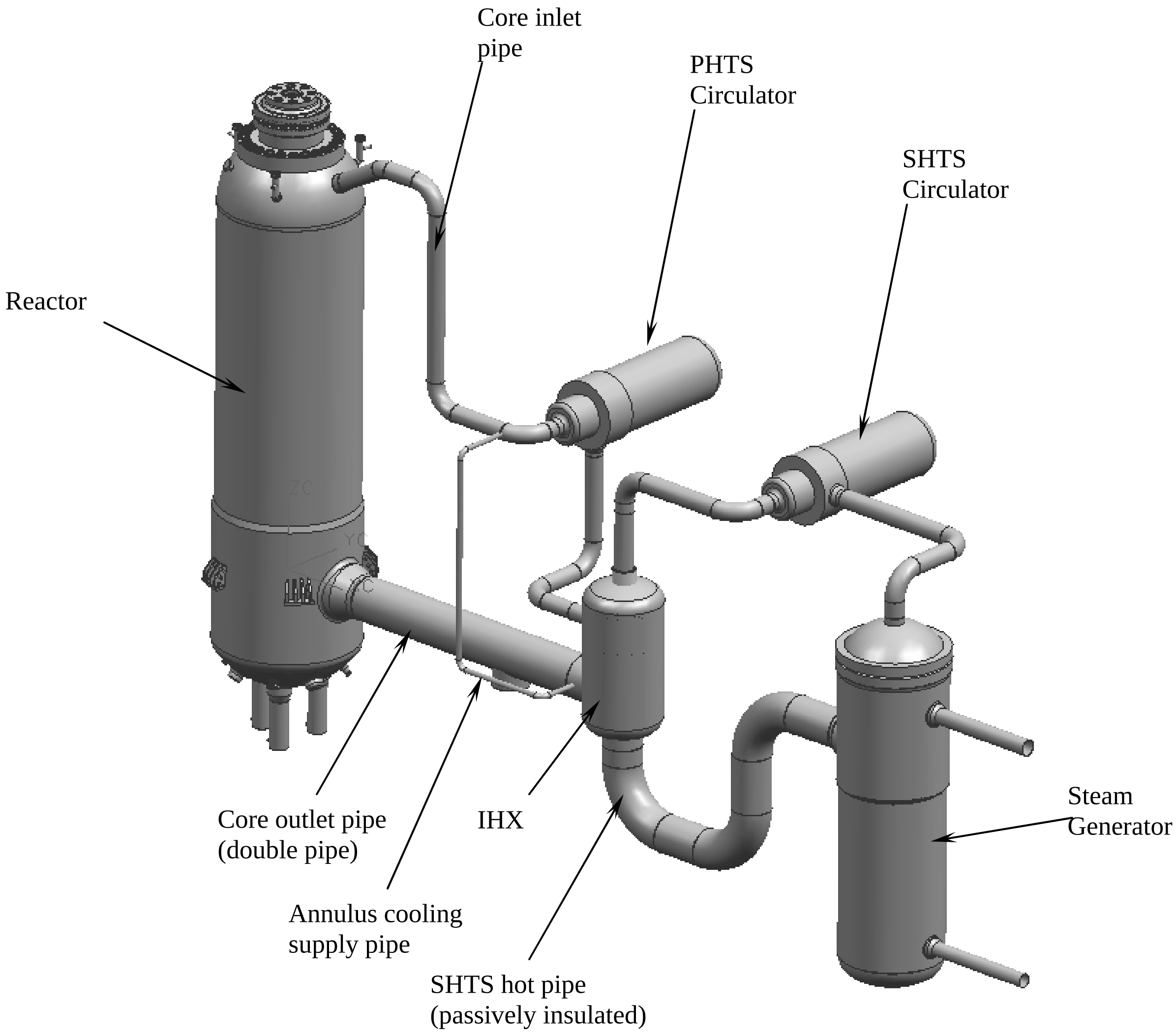


Figure 4-12 IHX Conceptual Layout in Relation to PHTS and SHTS

4.2.1 PHTS Piping

The core outlet pipe (COP) of the PHTS is assumed to be a double pipe as depicted in Figure 4-13. Refer to References 4-2 and 4-3 for a more detailed description. This is consistent with other gas cooled reactor designs (e.g., German HTR program). The inner pressure pipe is low-alloy steel (SA-508/533). It is kept at a low operating temperature (<371°C) by a layer of Al_2O_3 (Saffil™) insulation. The insulation is protected by a (non pressure bearing) inner liner made of a high-temperature compatible metal, such as Alloy 800H. The temperature of the inner pressure pipe is also kept low by the cooling gas passed in counter flow over its exterior surface in the annular space between the inner pressure pipe and the helium pressure boundary. As noted earlier, the cooling gas is sourced from the outlet of the primary circulator. This is nominally the highest pressure gas in the primary circuit; hence, any leakage is from the cooler gas in the annulus towards the hotter gas in the duct, i.e., small cracks in the inner pipe would not result in hot gas impinging upon the helium pressure boundary (which is also typically SA-508/533). The temperature of the cooling gas is nominally 280°C and the flow rate is sufficiently high that the normal operating upper limit of the pressure boundary material (371°C) is not exceeded during normal operation. Note, however, that transient conditions remain to be assessed and have the potential to exceed this upper limit. Provisions to mitigate the effects of such transients in the piping are beyond the scope of the present study and will be addressed within a follow-on study or as part of conceptual design.

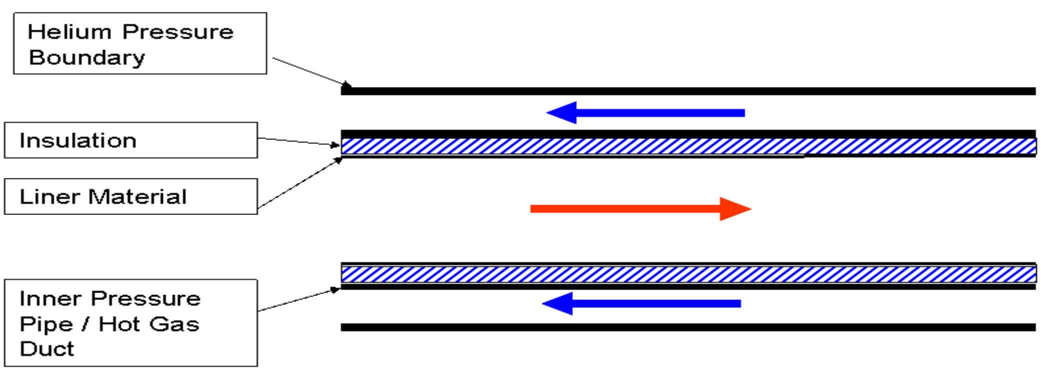


Figure 4-13 Schematic of Actively Cooled Pipe

The basic sizing criterion with respect to the liner is a gas velocity of 60 m/s at normal operation. A 200 kg/s mass flow rate at 750°C-800°C, 9 MPa, gives a diameter of about 1 m. The diameter of the pressure boundary pipe is about 2 m in this case. The size is determined from performance and constructability considerations.

The interface of the COP to the IHX is conceptually depicted in Figure 4-14. There is similarity to the core outlet connection. The hot gas must be delivered to the insulated plenum within the IHX vessel, while not heating up the helium pressure boundary. The connection must take up thermal deflection along the COP axis and the IHX vessel axis. No calculations have been performed to ensure the adequacy of the double bellows arrangement or to confirm that the dimensions are sufficient to ensure that the pressure boundary is within its normal operation upper temperature limit. These assessments are beyond the scope of the present study and will be undertaken within a follow-on study or as part of conceptual design.

The cold piping and cold interface are superficially simple (refer to Figure 4-15). The pipe is of a single-walled low-alloy steel construction, again presently assumed to be SA-508/533. The primary being on the shell-side, implies a relatively simple interface, with the pipe being connected to the vessel nozzle. The difficulty on the cold side of the IHX stems from the consideration of a loss of secondary cooling scenario in conjunction with a failure of the PHTS circulator to trip (see Section 5.3.3). This leads to the potential for high temperature gas contacting the pressure boundary material in both the cold and hot legs (the latter via the cooling bypass line). Temperatures as high as 538°C are allowed for the pressure boundary material for limited periods; however, depending on the duration of the transient, this temperature limit might be exceeded.

A possible solution to this is internal passive insulation. One such option, proposed in Reference 4-4, is high efficiency Aerogel™ insulation. There are issues to consider for the use of passive internal insulation:

- Insulation material properties in a high temperature impure helium environment
- Influence of insulation on in-service-inspection of the pressure boundary
- Reliability and inspection requirements related to the insulation itself (the double pipe hot gas duct insulation is not currently inspectable)

There is a size penalty incurred when using internal insulation due to the larger pressure boundary diameters required. The wall thickness of pressure bearing components is proportional to diameter in ASME basic sizing calculations. At first glance this does not appear prohibitive for the IHX vessel or the PHTS cold piping.

Note that external insulation is shown on the primary outlet nozzle as an interim reference until the issue is resolved.

4.2.2 SHTS Piping

The SHTS hot pipe is assumed to be a passively insulated pipe, as depicted above, using high-efficiency Aerogel™ insulation. The issues with respect to this choice are listed above. Using the 0.45 m thickness recommended in Reference 4-4, the SHTS hot pipe is similar in outer diameter to the COP. The passively insulated pipe appears to have simplicity and cost benefits.

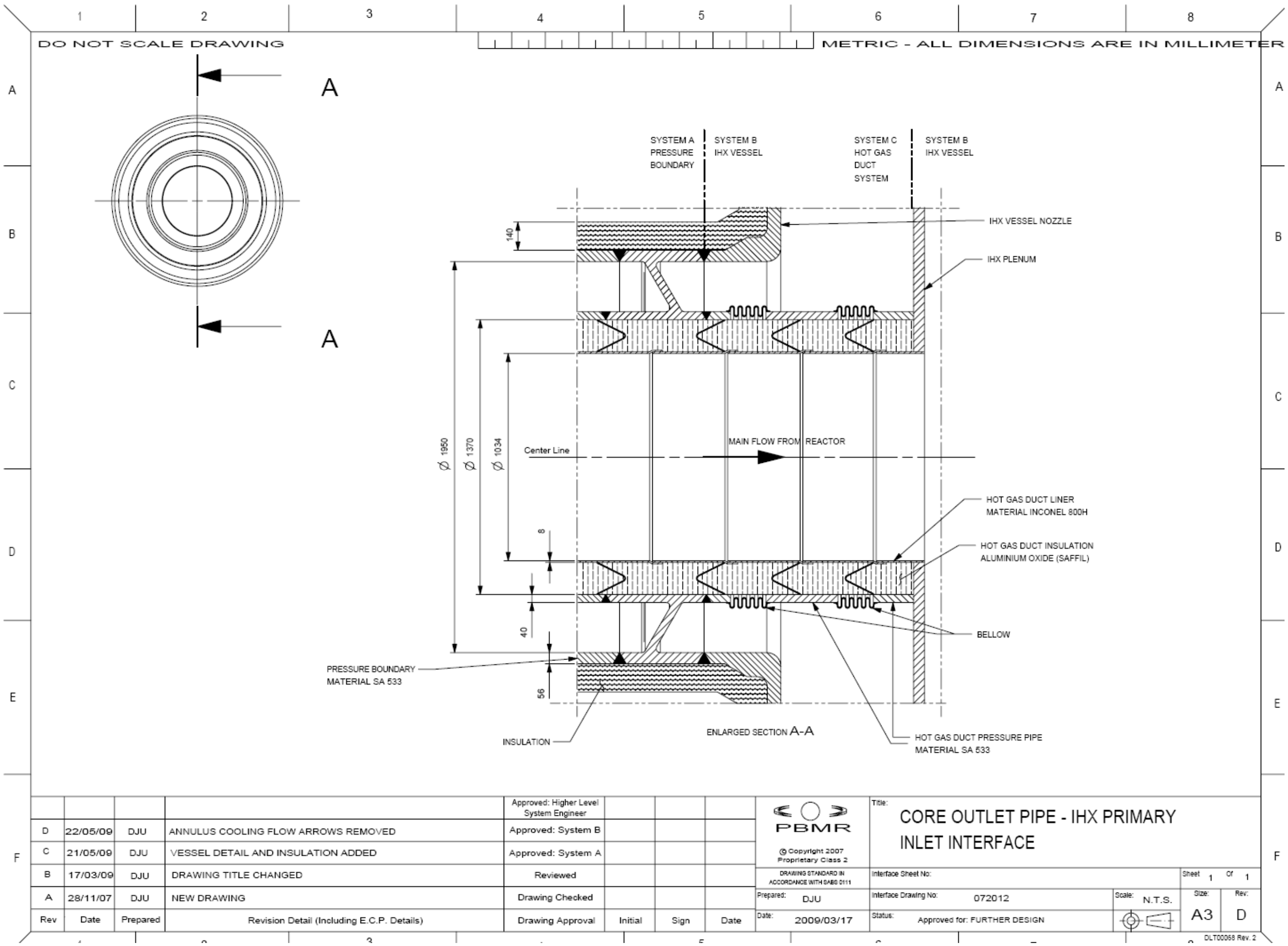


Figure 4-14 IHX PHTS Hot Inlet

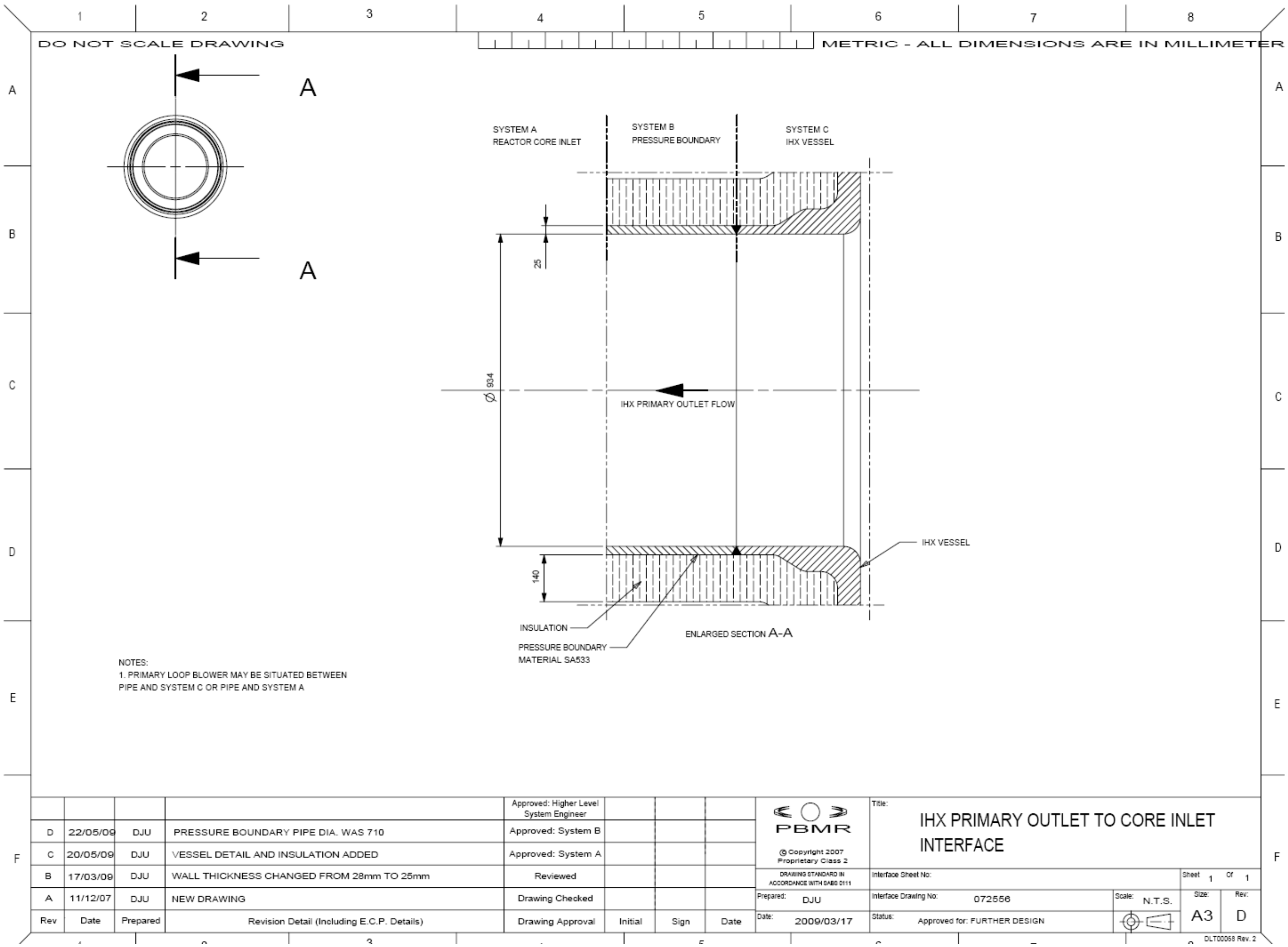


Figure 4-15 IHX PHTS Cold Outlet

Conceptually, the passively insulated pipe (Figure 4-16) is similar in configuration to the inner pressure pipe of the PHTS COP, differing in the type and thickness of the insulation. There is a non pressure retaining liner, insulation and pressure bearing pipe.

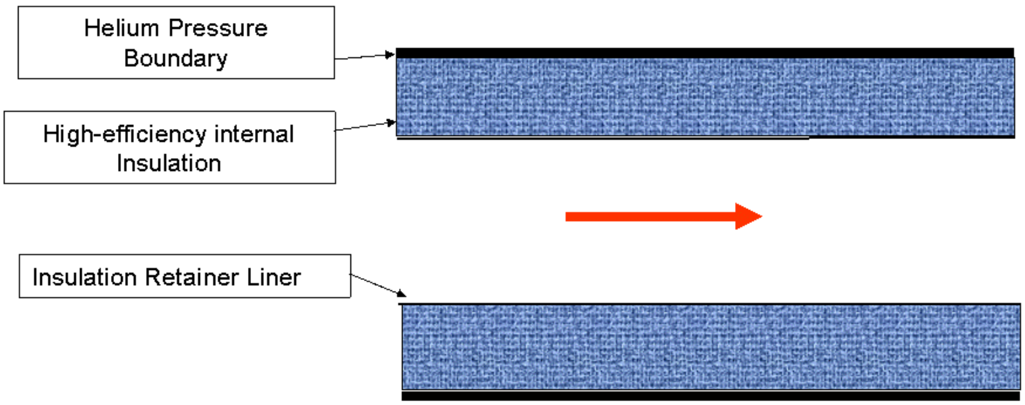


Figure 4-16 Schematic of Passively Insulated Pipe

A likely further issue on the secondary circuit is the possibility of water ingress into the circuit (possible with the high pressure power generation Rankine cycle) and its effect on the insulation.

The multiple bends in the SHTS hot pipe shown in Figure 4-12 are a result of the steam generator layout. The steam generator concept is similar to that of other gas cooled reactors (MHTGR-SC, HTR Modul) with the hot gas entering on the upper third of the vessel. Without the bends, the steam generator would reach a low elevation and could negatively influence building design.

The SHTS cold and hot leg interfaces with the IHX vessel are depicted in Figure 4-17 and Figure 4-18, respectively. The passively insulated single walled pipe is beneficial with respect to the simplicity of the interface. A caveat is that vessel/internals integration and vessel/internals thermal displacement differentials have not been considered for their influence on the design. These features are beyond the scope of the present study.

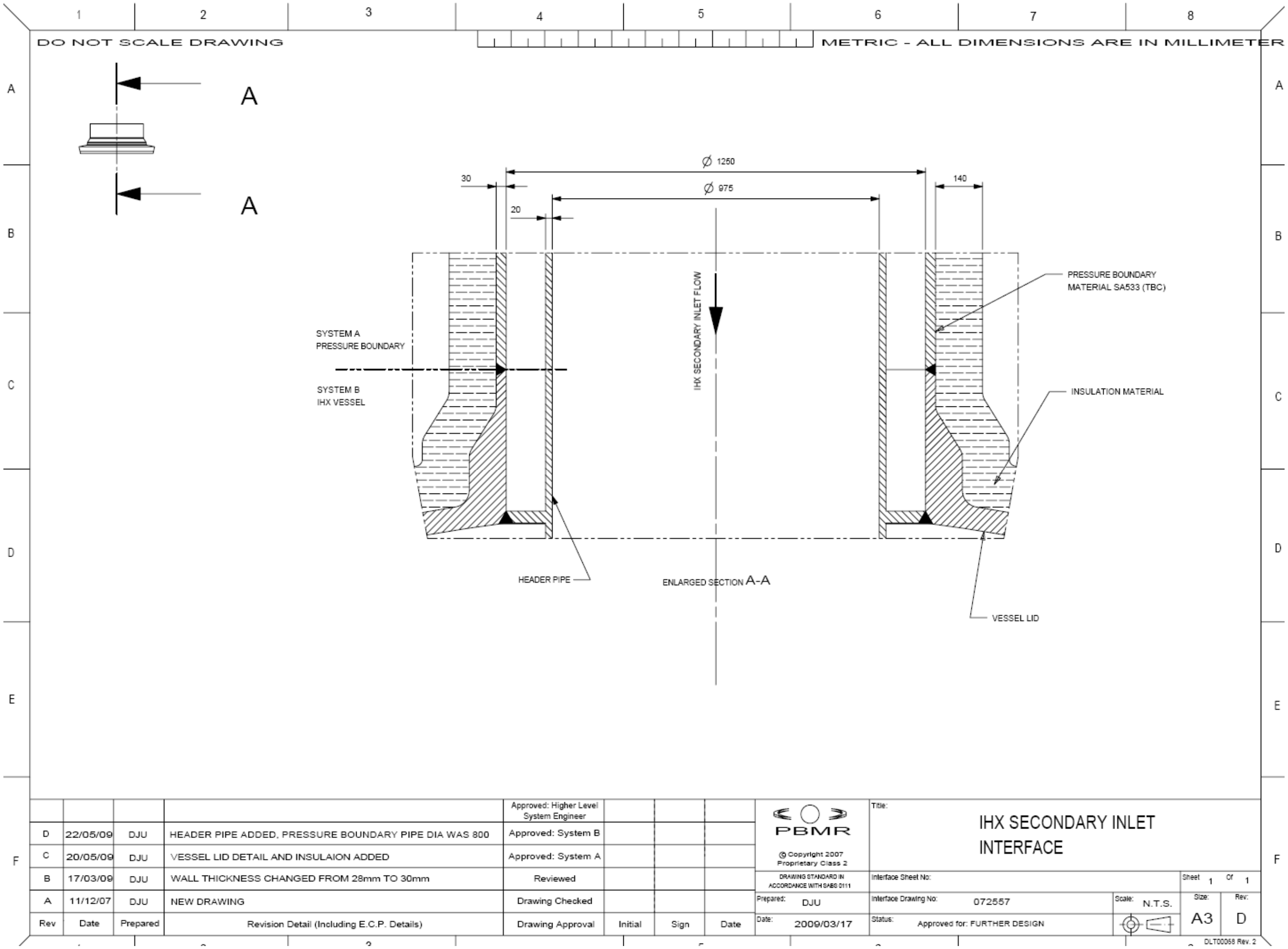


Figure 4-17 IHX SHTS Cold Inlet

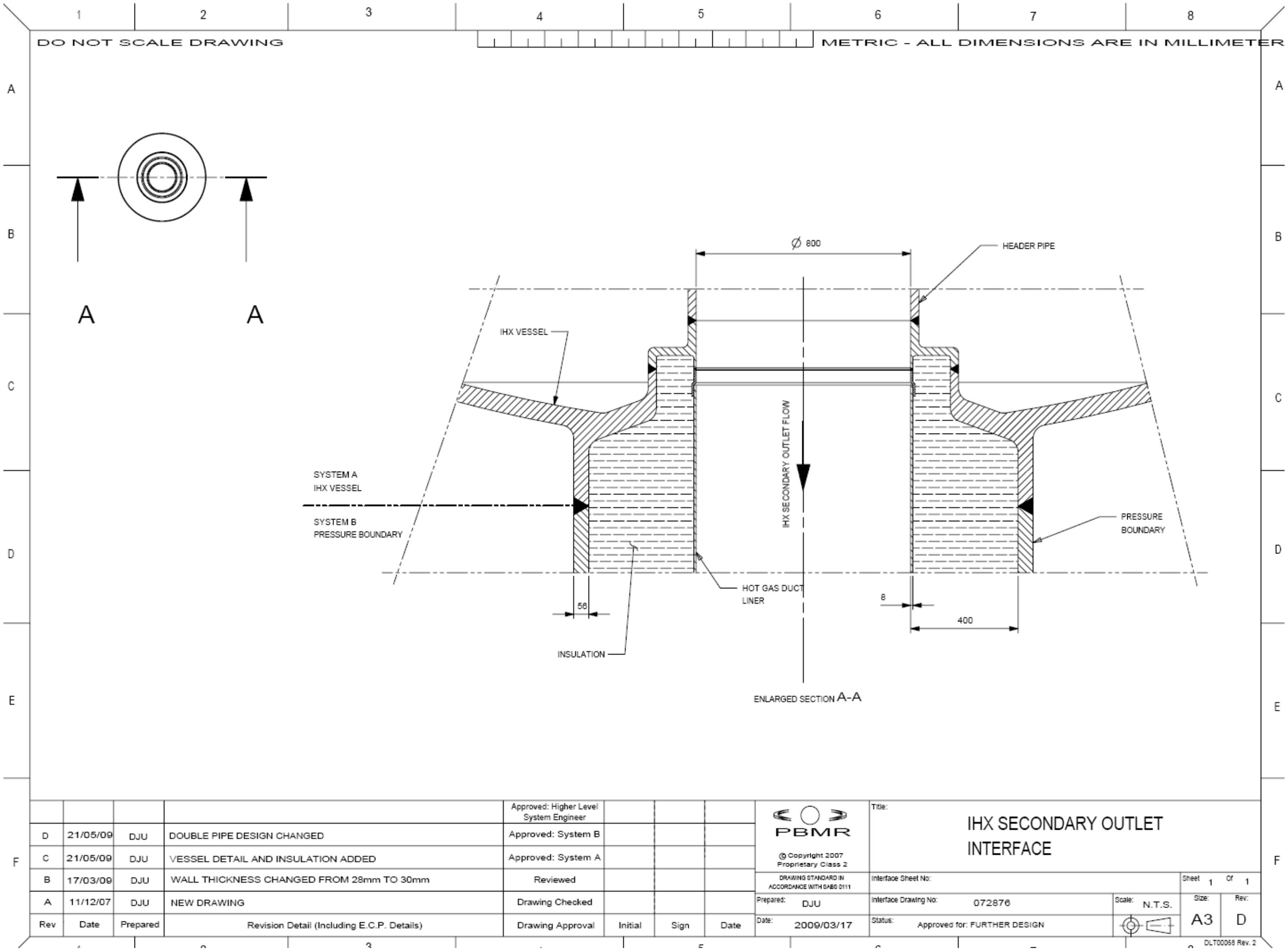


Figure 4-18 IHX SHTS Hot Outlet

4.3 HTS-Building Integration

The conceptual building layout is shown in Figure 4-19. The preliminary support concept is similar to that of a light water reactor. The reactor is fixed, while the IHX is allowed to move on sliding supports along the axis of the COP. Depending upon further design of the piping from the IHX to the SG, the SG may be fixed or may also be mounted on sliding supports that allow for thermal expansion. For the latter case, snubbers will likely be necessary for the steam generator.

As described above, the steam generator layout and the desire for a smaller building, drives the SHTS hot pipe layout. A short building, with heavy components situated lower, is favorable for seismic design. With that in mind, the circulators could be positioned lower; however, there are penalties to consider. The additional pipe length required may be a negligible one, but there would likely be an increase in building footprint.

The decay heat removal system also influences the layout. The reference design includes a CCS. This is connected to the COP, influencing its length and taking up the area immediately below it.

4.4 References

4-1 *NGNP Initial Conceptual Plant Level Assessments Leading to Fission Product Retention Allocations*, NGNP-PLD-GEN-RPT-N-00007, 2009.

4-2 *NGNP Conceptual Design Study: IHX and Heat Transport System*, NGNP-HTS-RPT-TI001, Revision 0, Westinghouse Electric Company LLC, April 1, 2008.

4-3 *NGNP, Report on Update of Technology Development Roadmaps for NGNP Steam Production at 750°C-800°C*, NGNP-TDI-TDR-RPT-G- 00003, Revision 1, Westinghouse *Electric Company LLC, May 2009.*

4-4 *NGNP Conceptual Design Study: Composites R&D Technical Issues*, NGNP-NHS-RPT-TI002, Westinghouse Electric Company LLC, October 2008.

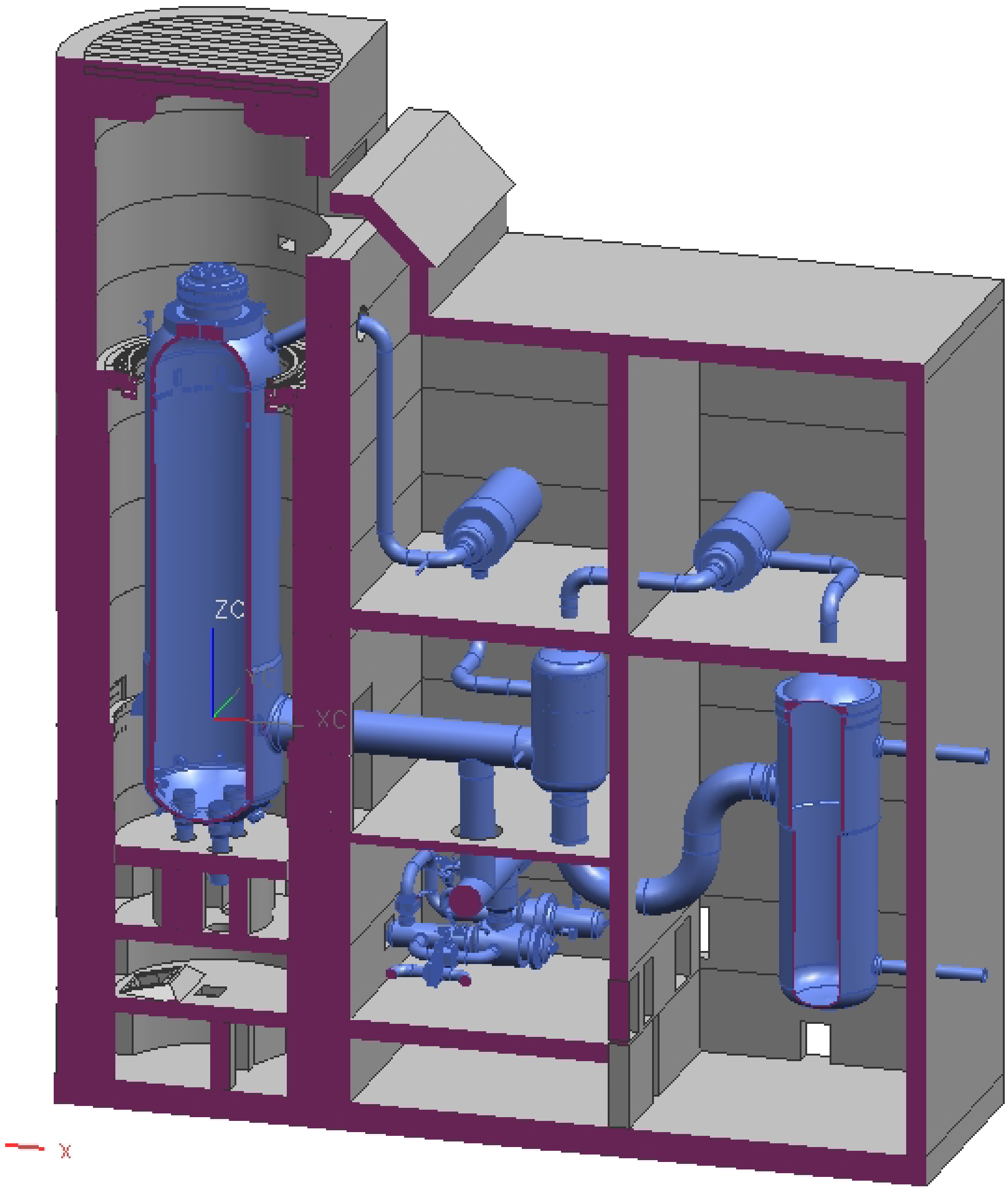


Figure 4-19 Section through Conceptual Building Layout

5 IHX AND HTS ANALYSES

This section describes the development of an analytical model for the IHX and its integration into an overall model of the Nuclear Heat Supply System (NHSS). The overall NHSS model is an adaptation of the PBMR DPP model as developed for the companion priority task addressing plant level analysis and fission product transport (Ref. 5-1). The integrated model was used to develop steady state conditions and to perform transient analyses of two low-probability plant events that would potentially challenge the IHX design. The temperature, pressure and flow rates experienced during these transients are used in Section 2.5 as input for structural assessment and material lifetime calculations.

In the sections that follow, the thermal hydraulic analysis code used for the assessments is first described, followed by the model development and integration. Steady state operation is then summarized. This is followed by definitions of the assessed transient and the results of the transient assessments.

5.1 Description of IHX Analytical Model

The thermal hydraulic code Flownex was used to develop a detailed model of the IHX, as well as an overall model of the NHSS. Flownex is a thermal fluid network analysis code that uses the basic principles of mass, momentum and energy conservation to numerically solve a network of interconnected elements. The code can solve steady state equilibrium, as well as transient conditions. The Flownex code was also used to model the PBMR Demonstration Power Plant (DPP) Main Power System.

The overall model of the NHSS was developed as part of the accompanying plant level assessment and fission product allocation task (Ref. 5-1). In addition to the IHX, this model includes the reactor, circulators, check valve, piping, steam generator, core conditioning system and all interconnecting pipes[6]. All components were modeled with performance characteristics that allow for off-design conditions, realistic thermal capacitances, heat losses and gas inventories.

A representation of the IHX and NHSS model, as it is displayed on the Flownex Graphical User Interface, is shown in Figure 5-1. An advantage of incorporating the IHX model within the overall NHSS model is that the integrated system response based on plant control and component interaction can be captured. This gives much better estimates of the transient conditions experienced by the IHX than the severe boundary conditions assumed for the 2008 NGNP IHX study.

The IHX model developed for this task[7] and described in this section (Ref. 5-2) is based on the PHTS/Shell-side coupling design, as described in Sections 2.3 and 4.1. The IHX is modeled as a

[6] A majority of these component models was originally developed for the PBMR DPP and have been adapted for the NGNP specific design and operating conditions.
[7] Even though the IHX model was developed for this task, it still uses the DPP Recuperator Element within the code.

true counter-flow heat exchanger with uniform flow distribution. The model uses as input the heat transfer area, the flow area, flow path length, hydraulic diameter, friction factor and Colburn j-factor ($StPr^{2/3}$) characteristics, the thermal capacitance and conduction thickness of the heat transfer surface. The helium volume and pressure drop between the vessel and heat transfer module entrances and exits are also taken into account. Furthermore, metal and helium physical property relationships as a function of temperature and/or pressure are applied.

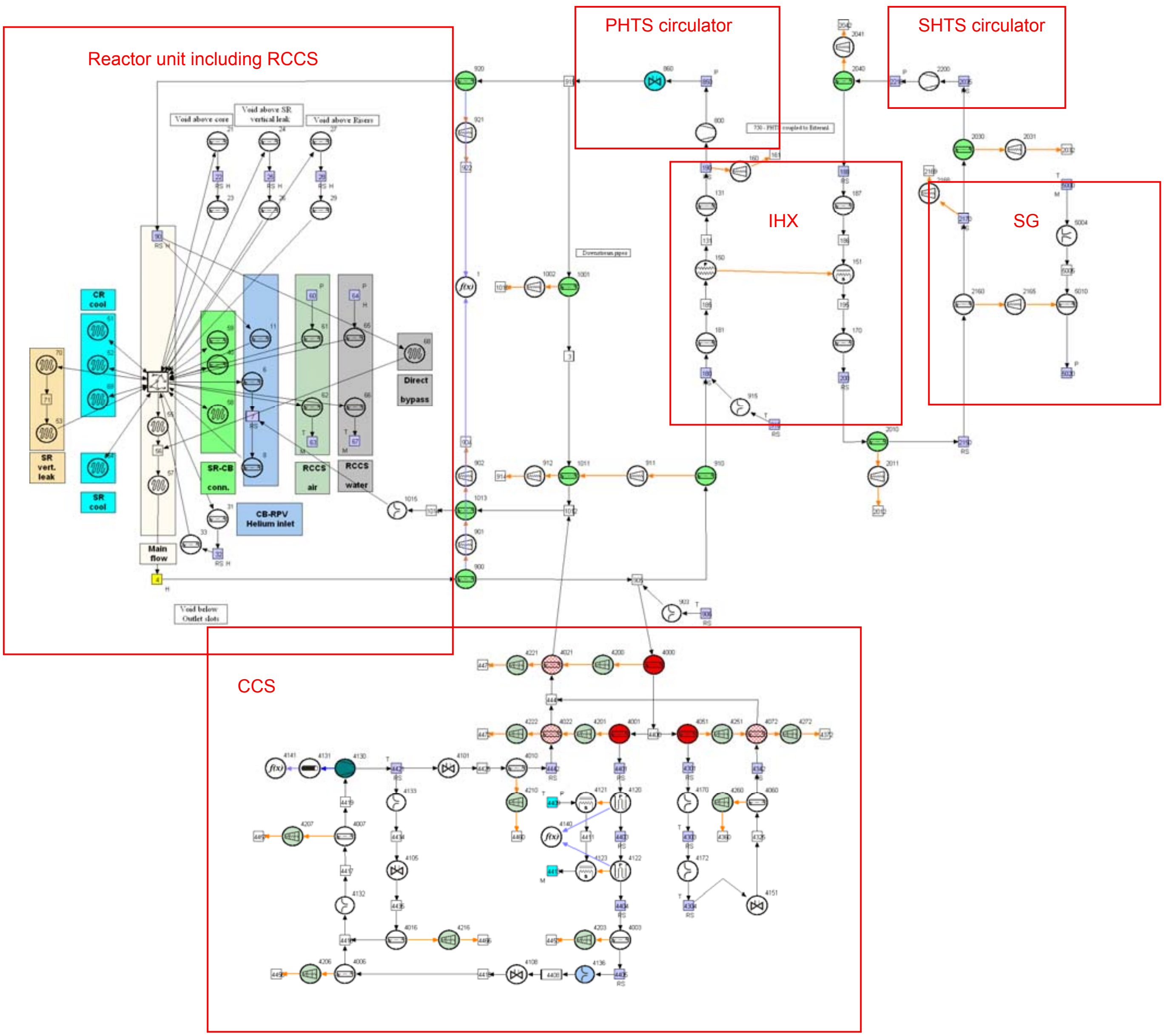


Figure 5-1 Flownex Model of the NHSS

It is important to note that the model has some limitations. No heat losses between the hot and cold gas inside vessel were modeled (i.e. no heat transfer outside the heat transfer modules). The thermal capacitance of the vessel internals is also not included. This will, in reality, slow down the very fast temperature response of the gas inside the vessel. Not taking these factors into account results in the prediction of higher temperature spikes and increased gradients, which is conservative for most cases.

Furthermore, the current model does not take into account axial conduction along the length of the heat transfer modules. With large flow rates, convection is the dominant phenomena and conduction is negligible. However in cases where the forced convection has stopped, conduction along the length of the modules should aid in equalizing the metal temperature. By not modeling this conduction, the skew temperature profile along the core length is exaggerated and, therefore, should also be conservative.

The validity of the friction factor and $StPr^{2/3}$ performance characteristics at very low Reynolds numbers is also questionable. At Reynolds numbers associated with very low natural convection, these equations might predict heat transfer coefficients lower than that caused by natural convection.

5.2 NHSS Steady State Operating Conditions

The design and performance of the IHX and the NHSS are mutually interdependent. For that reason, the IHX design and modeling and the NHSS design and modeling were accomplished on an iterative basis.

In order to establish a starting point for the IHX design, a high level thermal-hydraulic model was developed and used to establish the operating parameters shown in Figure 5-2 and Figure 5-3. The steady state operating conditions shown in Figure 5-2 are based on the assumptions that there is a
3 MWt heat loss from the reactor to the RCCS, that the helium blowers will be designed to perform at 80% isentropic efficiency (with 5% electric to thermal loss), that the piping will be sized to ensure less than 0.2% pressure loss in each pipe, that the IHX design ensures less than 1.23% pressure loss per side for the overall IHX, and that the PCHX and SG are designed to ensure less than 200 kPa and 42 kPa pressure loss, respectively.

The operating conditions shown in Figure 5-2 and Figure 5-3 were used to develop the initial sizing of the IHX and to support the assessment of IHX coupling options, as earlier described in Section 4.1. In parallel with the IHX coupling assessment, a detailed model of the integrated NHSS was being developed as part of the accompanying plant level assessments and fission product allocation task. Upon completion of the coupling assessment, the resulting IHX analytical model was incorporated into the overall NHSS model.

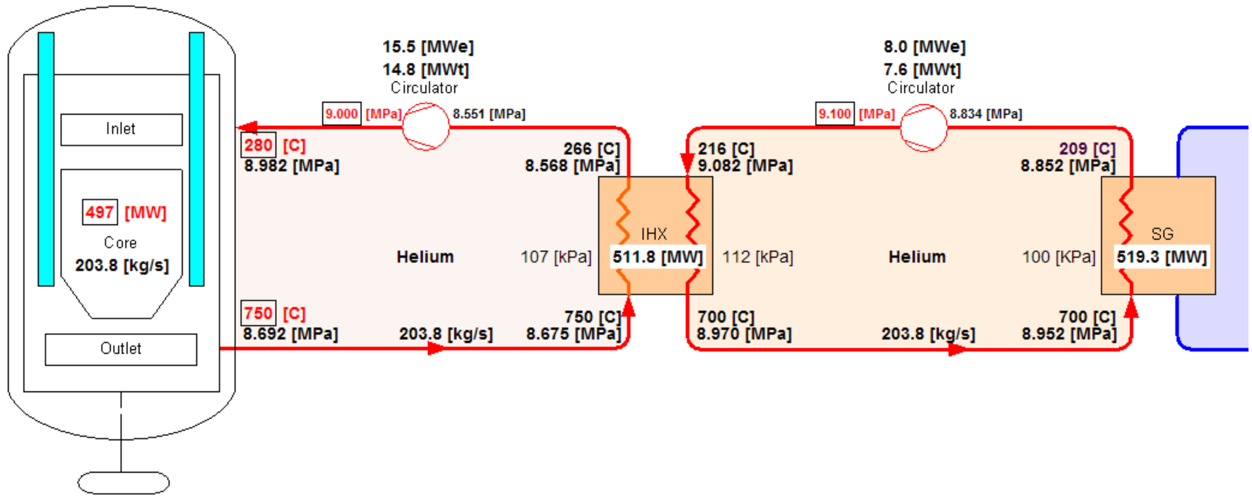


Figure 5-2 Parameters Used for IHX Design (750°C ROT)

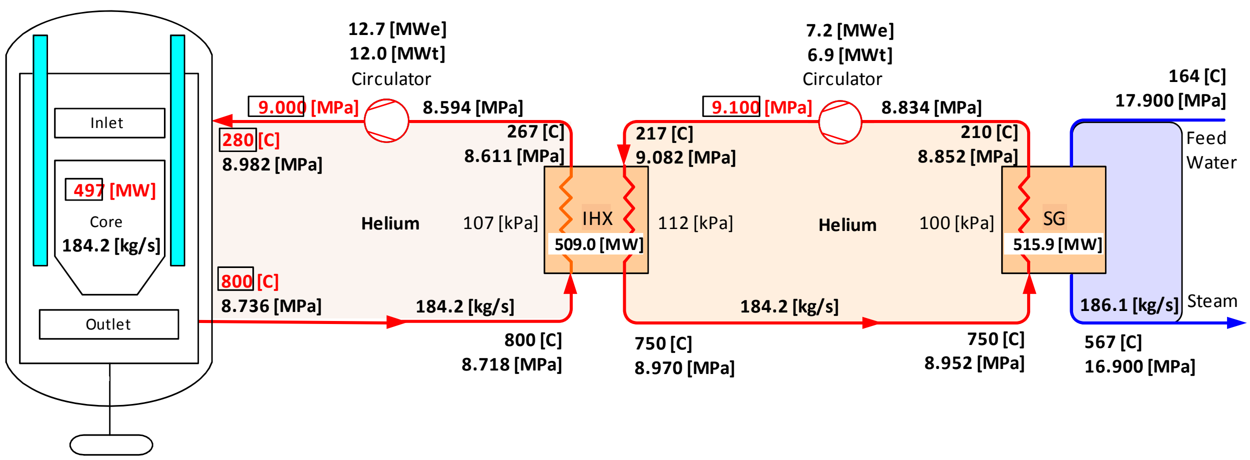


Figure 5-3 Parameters Used for IHX Design (800°C ROT)

The resulting integrated model was, therefore, based on realistic design input, not only for the IHX but also the other major components. Furthermore, the modeling methodology used was much more refined. This resulted in better estimates for pressure drop, heat losses and flow rates expected in the system. The integrated IHX/NHSS model was used to analyze the steady state operating conditions for both the 750°C and the 800°C design points (Ref. 5-3). The results are shown in Figure 5-4 and Figure 5-5.

Note that in the initial design points shown in Figure 5-2 and Figure 5-3, high level assumptions were made with regards to the pressure drop in the various components. The more accurate modeling of components resulted in a different pressure ratio being required from the

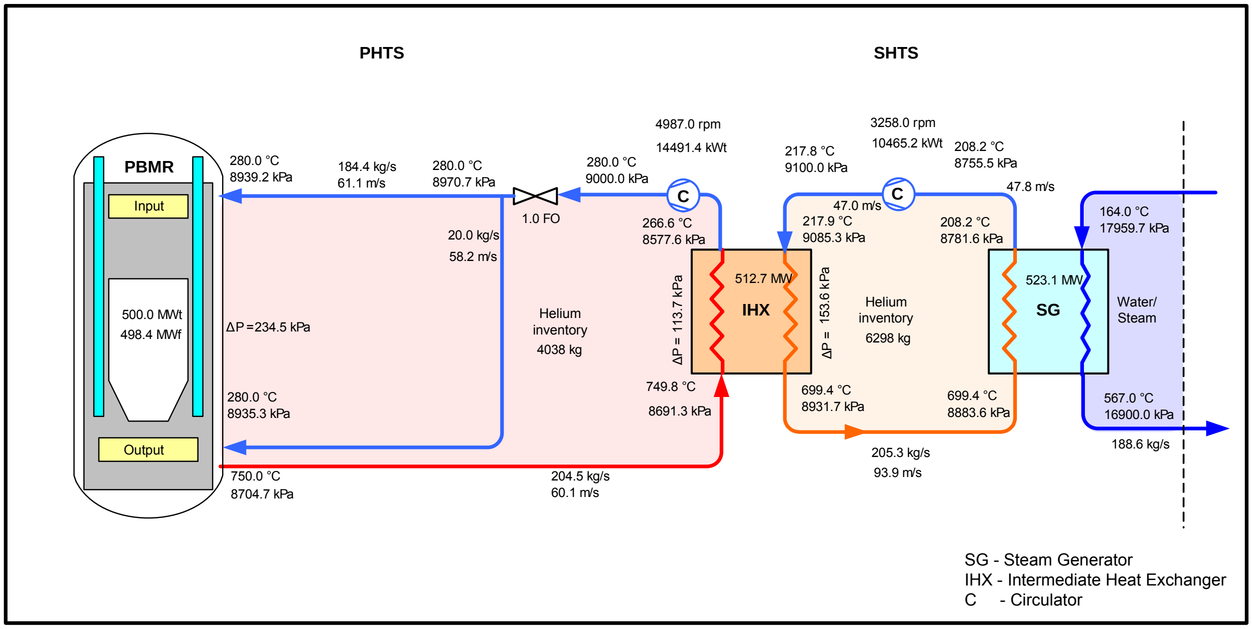


Figure 5-4 Steady State Operating Conditions for 750°C ROT

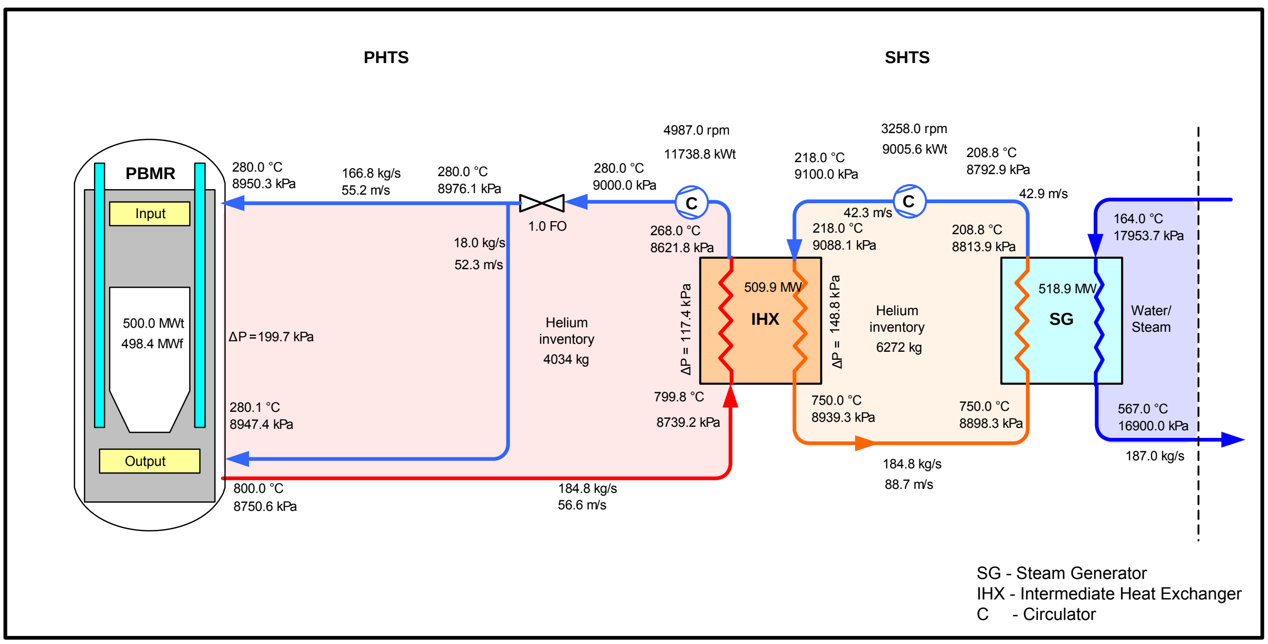


Figure 5-5 Steady State Operating Conditions for 800°C ROT

circulators. The circulator pressure ratio determines the heat input into the system and hence the temperatures. Therefore, the boundary conditions that serve as input for the IHX design also changed slightly.

Also, the IHX SHTS pressure drop is slightly larger than the specified 1.23%. This number was a preliminary estimate and will mainly influence the circulator size. The current SHTS circulator size is still acceptable, as it is smaller than the PHTS circulator. Any technology development for the circulator will be based on the larger of the two.

While the principal focus of this task is the 750°C design point that is common to the plant level analysis and fission product allocation task, an extrapolation to 800°C is included to identify any significant impact on the IHX design and/or materials. The operating conditions utilized for this extrapolation are shown in Figure 5-5. The same assumptions were used as those for the 750°C ROT case. The RIT and power level are kept at 280°C and 500 MWt, respectively. This allows the maximum process heat output, while the circulator size and reactor temperature difference is still within the acceptable range.

5.3 Scoping Transient Assessments

Four events have been identified as the basis for evaluating transient effects on the IHX. These are normal operation (startup and shutdown), loss of secondary pressure (LOSP), which is a Design Basis Event (DBE), and Loss of Secondary Cooling (LOSC) with Failure to Trip the PHTS Circulator, which is expected to be within the licensing basis, most likely as a BDBE. The 750°C operating parameters are used as the initial conditions in all of the transient assessments..

5.3.1 Startup and Shutdown

5.3.1.1 Startup

The startup procedure was developed and described in detail in the accompanying plant level assessments task (Ref. 5-1). A summary of the procedure is given below:

- Start from the depressurized maintenance condition (CCS in operation) – this is similar to a hot restart.
- Pressurize the system
- Switch from CCS operation to operation of the main circulators and steam generator
- Increase the reactor power and outlet temperature by controlled extraction of the control rods.
- The system reaches 100% power 24 hours after the onset of startup.

Temperature, pressure, and mass flow results during startup are shown in Figure 5-6 through Figure 5-9.

Note that significant pressure differentials occur across the IHX during startup. This occurs at fairly high temperatures and mass flow rates. This differential is caused by the

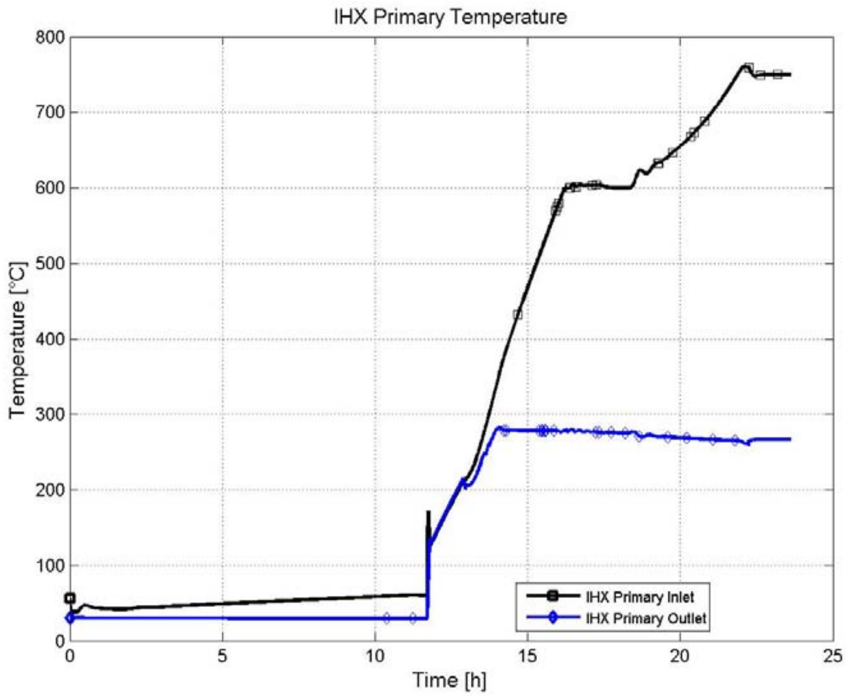


Figure 5-6 IHX PHTS Temperatures during Startup

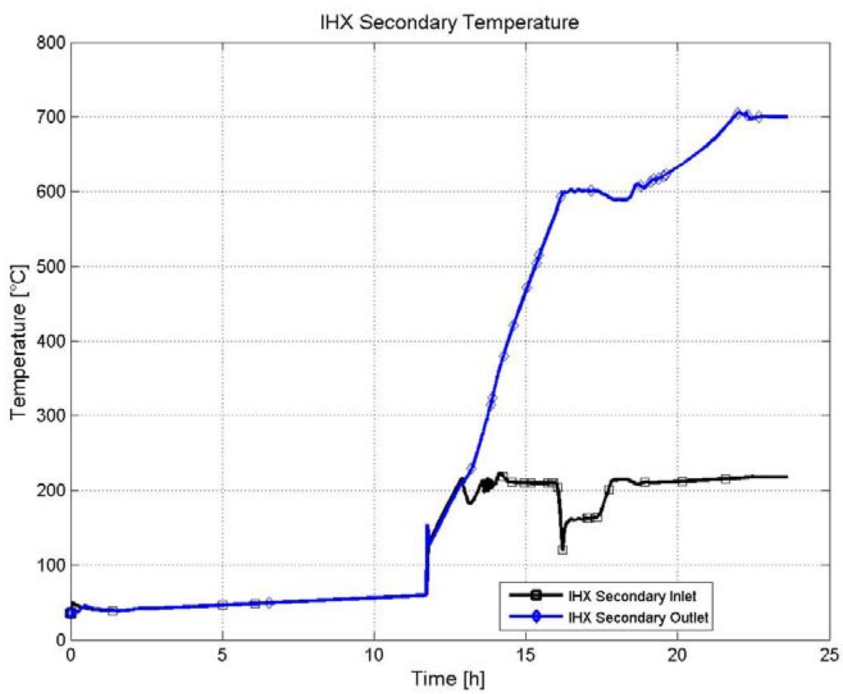


Figure 5-7 IHX SHTS Temperatures during Startup

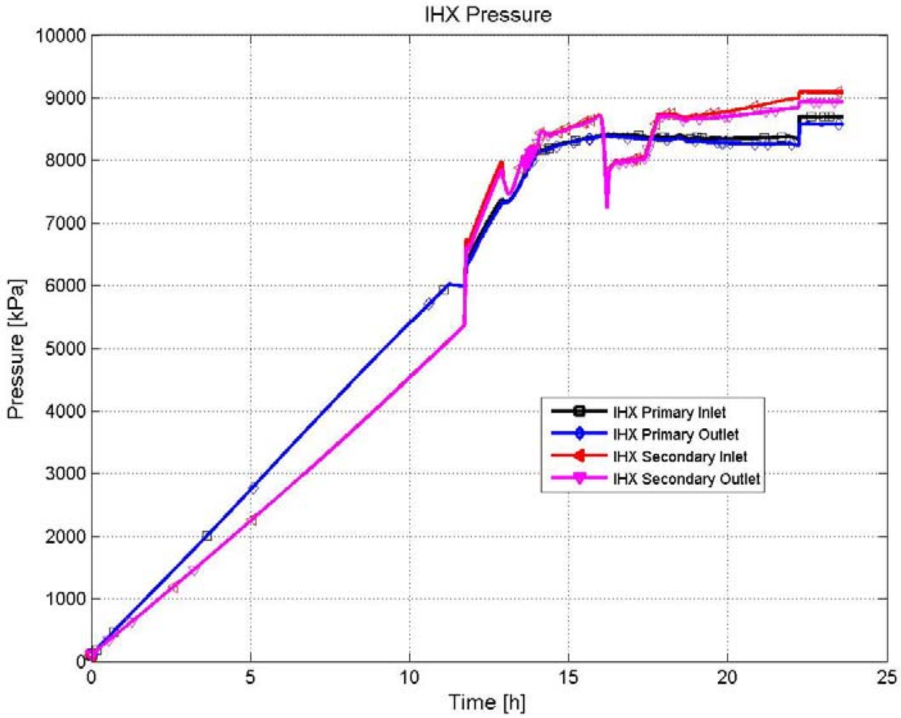


Figure 5-8 IHX Pressures during Startup

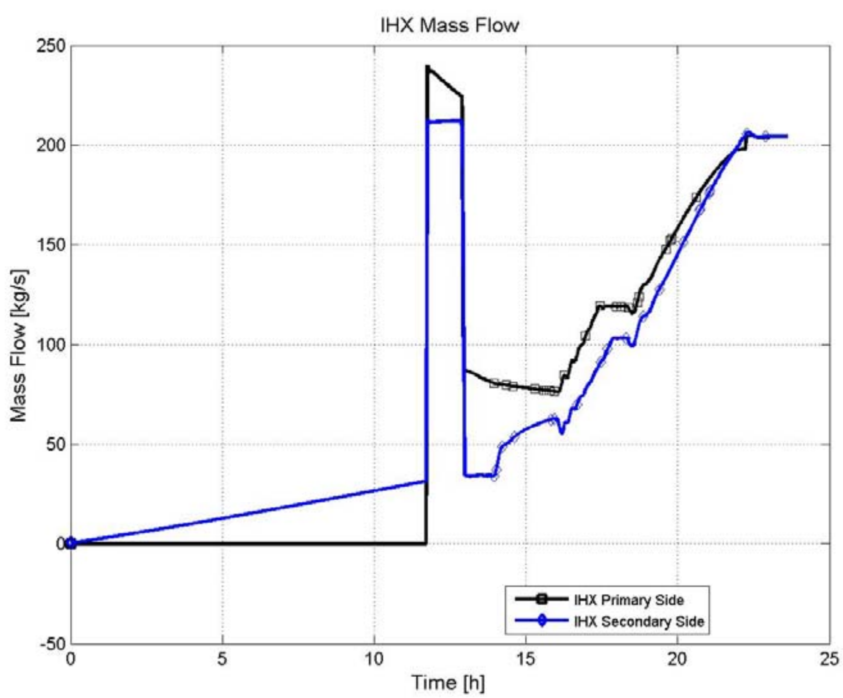


Figure 5-9 IHX Mass Flow Rates during Startup

introduction of cold feed water when the reactor goes critical, to prevent the reactor inlet temperature from going above its nominal value. It causes a drop in the SHTS cold temperature, which decreases the pressure significantly.

It must be assessed whether this will be a problem for the heat exchange modules, as well as the internals and vessel components such as bellows. The plant will not operate for prolonged periods of time in this condition, but will go through many startup cycles in the plant lifetime.

There are ways to prevent the drop in SHTS pressure, either by preheating the feed water, or introducing a smaller mass flow rate into the SG during startup. However, to prevent boiling of the water at low mass flow rate (which is undesirable due to two-phase instabilities), the water would need to be pressurized from the start.

5.3.1.2 Shutdown

The shutdown procedure was developed and described in detail in the accompanying plant level assessments task (Ref. 5-1). A summary of the procedure is given below:

- Decrease the reactor power and outlet temperature by controlled insertion of the control rods.
- Decrease the speed of the main circulators and the feed water pump.
- When the reactor outlet temperature reaches approximately 300°C, switch to CCS operation.
- When the reactor outlet temperature has decreased to 200°C, depressurize to atmospheric pressure.
- The system is fully depressurized 24 hours after shutdown is initiated.

The results are shown in Figure 5-10 through Figure 5-13.

A high pressure differential across the IHX occurs after about 5 hours, when the reactor is shutdown completely and the circulators stopped. This occurs at practically zero mass flow rates on both sides of the IHX and at low temperatures. The impact of this needs to be assessed, but it would be less severe than that of the pressure differential during startup.

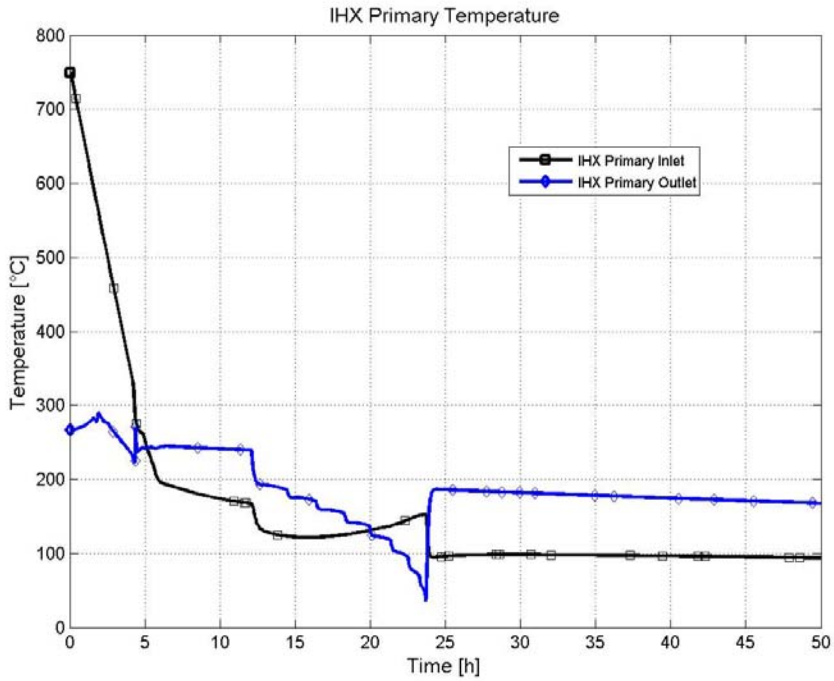


Figure 5-10 IHX PHTS Temperatures during Planned Shutdown

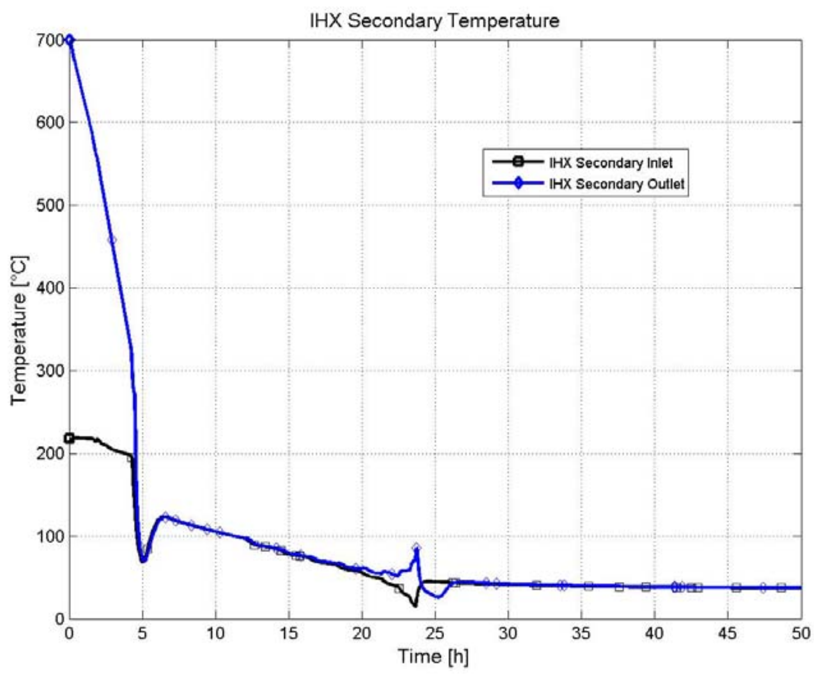


Figure 5-11 IHX SHTS Temperatures during Planned Shutdown

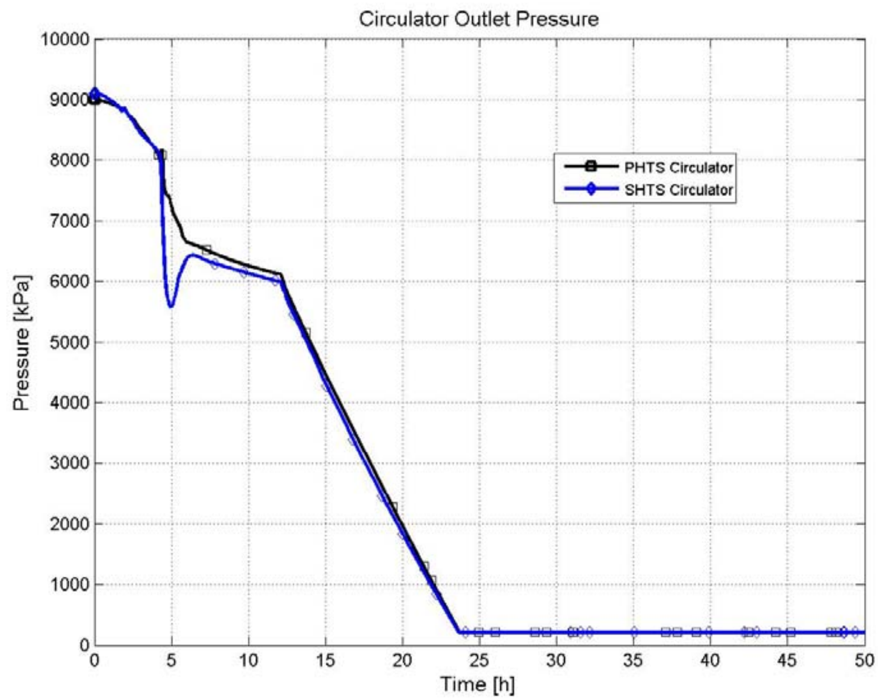


Figure 5-12 IHX Pressures during Planned Shutdown

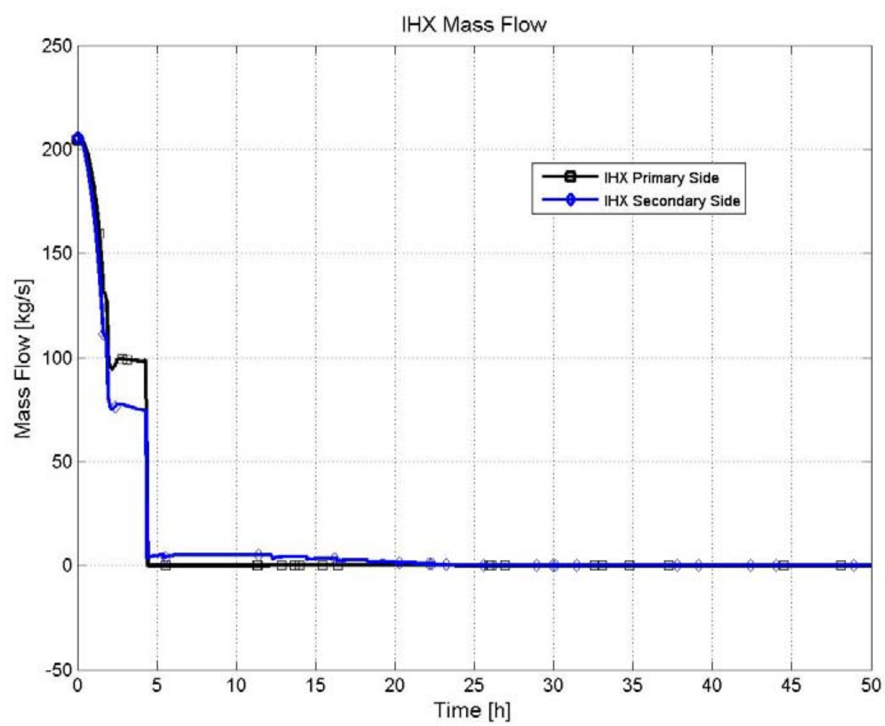


Figure 5-13 IHX Mass Flow Rates during Planned Shutdown

5.3.2 Loss of Secondary Pressure (LOSP)

The loss of secondary pressure event is defined as a double ended guillotine break of the largest pipe in the SHTS. Since all the pipes in the SHTS have similar diameters, the break was assumed to occur in the IHX secondary outlet pipe, which has an internal diameter of 800 mm (refer to Figure 1-6). Unless otherwise noted, it is assumed that all other Systems Structures and Components (SSCs), including control and protection systems, are intact and functional.

Note that the location of the break has a significant impact on results. If the break is upstream of the secondary inlet, flow reversal will occur and this has different implications for the gas temperature and heat transfer.

The transient is initiated by assuming the break occurs instantaneously. At the same time, both circulators receive a trip signal, which quickly reduces the mass flow rate to zero on both sides of the IHX. The SHTS depressurizes fully in a matter of 20 seconds (0.4 minutes), as can be seen in Figure 5-14.

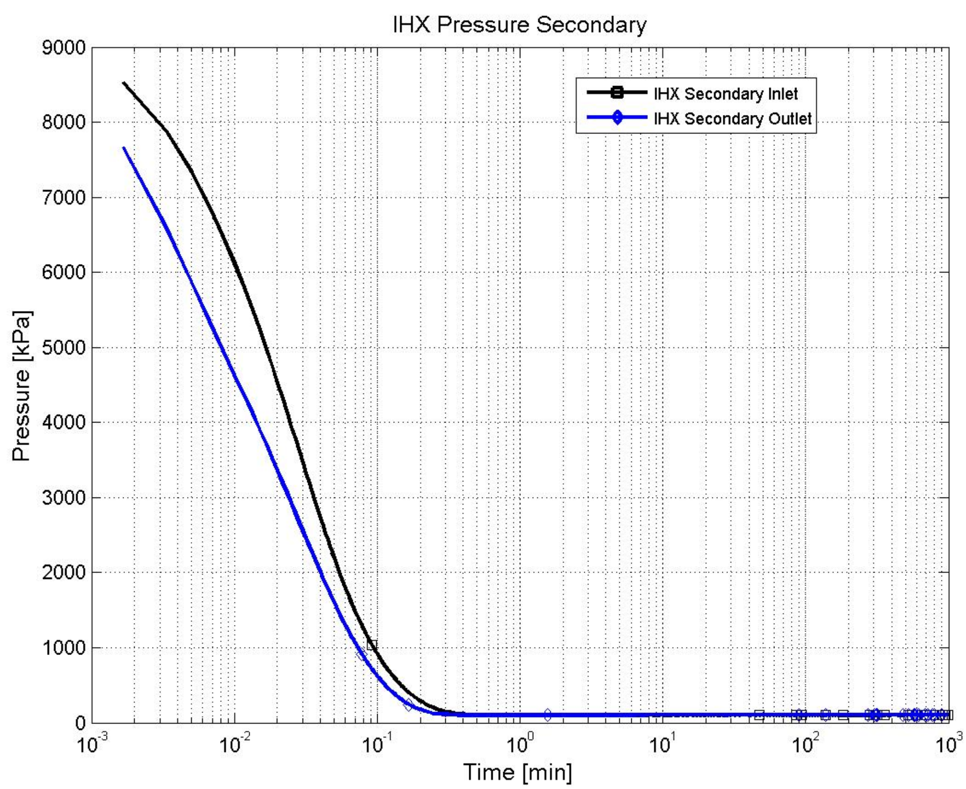


Figure 5-14 SHTS Pressure during LOSP Event

The reactor control rods are inserted at their maximum insertion rate, and the Core Conditioning System (CCS) comes online to remove residual and decay heat from the core. The PHTS circulator check valve closes as soon as the backpressure resulting from operation of the CCS circulator causes a negative pressure differential across the valve.

Due to the very sudden expansion of the SHTS gas, the temperature of the gas on the secondary side of the IHX drops significantly before receiving heat from the primary side to counteract this effect. This causes the IHX core metal temperatures to drop rapidly as well (the thin cores have low thermal capacitance). The gas on the primary side, although not expanding, experiences a similar drop in temperature due to the heat being extracted through the metal. This is displayed in Figure 5-15, Figure 5-16 and Figure 5-17. Note that these graphs are presented on a semi-log scale to enable display of the fast behavior early in the transient.

Hot gas is drawn into the IHX before the mass flow in the primary side of the IHX comes to a complete standstill. As the secondary cooling is lost, the hot gas moves through the IHX and causes the metal temperature to rise again. The mass flow (Figure 5-18) is almost zero by this time, so the effect of this hot gas on the cold leg piping is insignificant.

Extraction of the helium inventory to the Helium Services System (HSS) is initiated after 1 minute. The depressurization takes almost 12 hours to complete as shown in Figure 5-19. This implies that the IHX experiences a high pressure differential for this time. However, after approximately 8 hours, the core metal temperatures have dropped to less than 200°C, according to Figure 5-17, which means that a high pressure differential is experienced at high temperature only for part of the time.

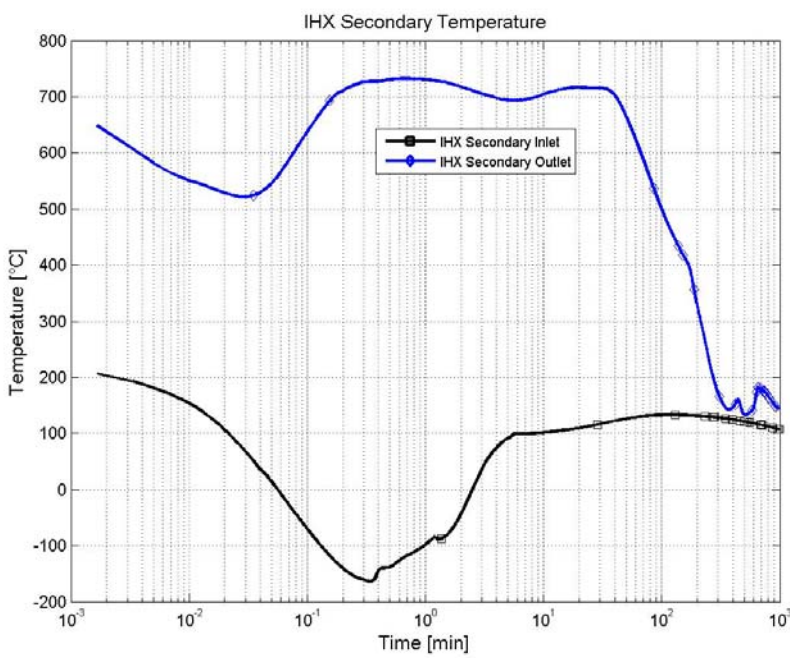


Figure 5-15 IHX Secondary Gas Temperature during LOSP Event

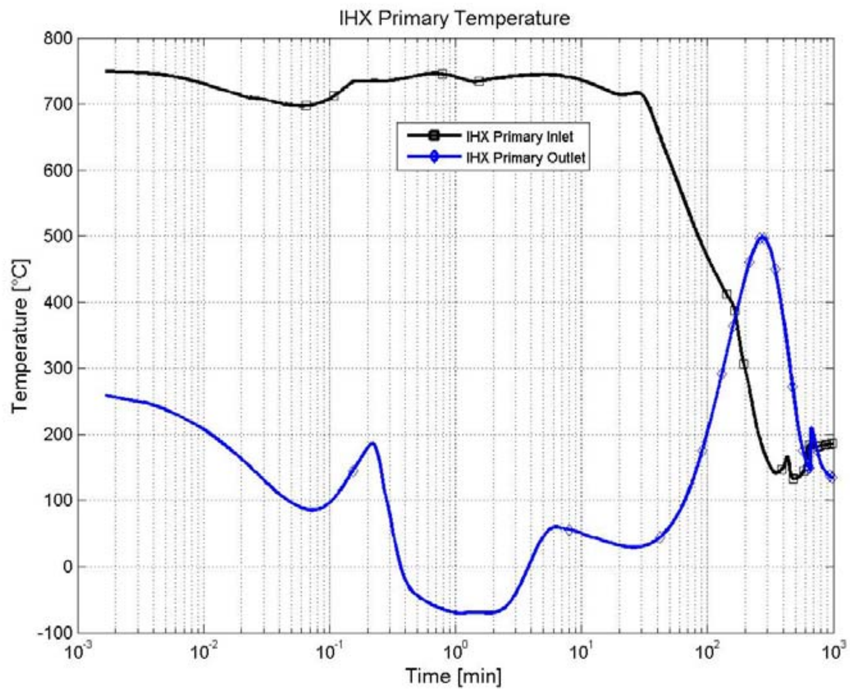


Figure 5-16 IHX Primary Gas Temperature during LOSP Event

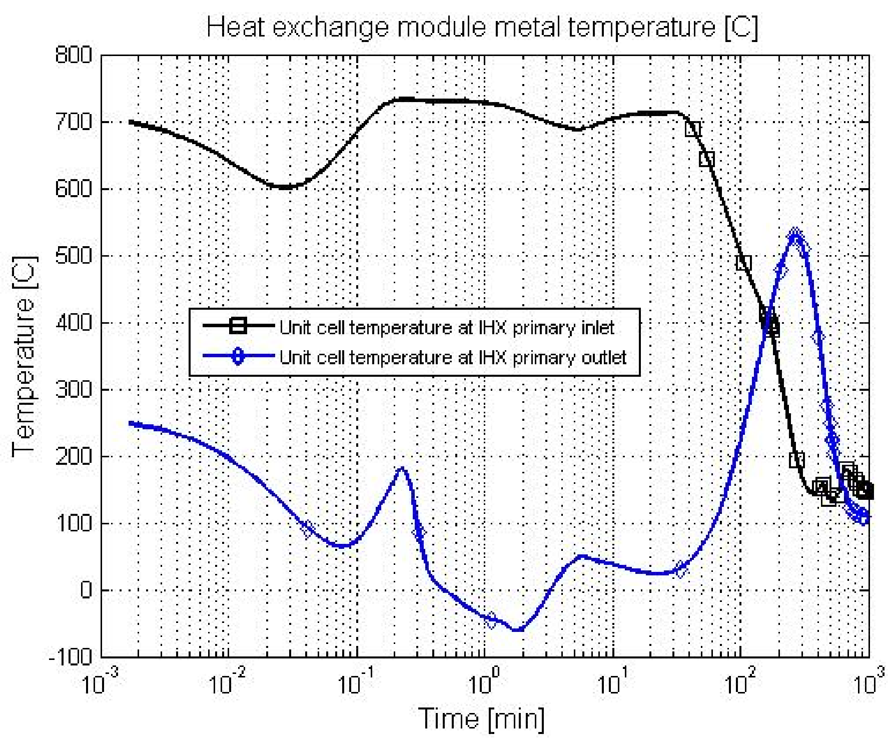


Figure 5-17 IHX Core Average Metal Temperatures during LOSP Event

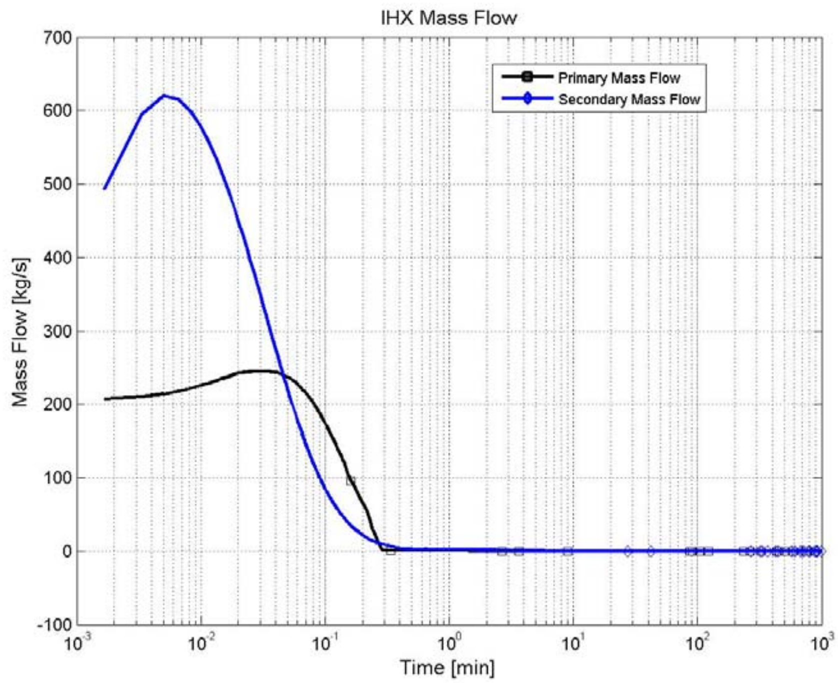


Figure 5-18 IHX Mass Flow Rates during LOSP Event

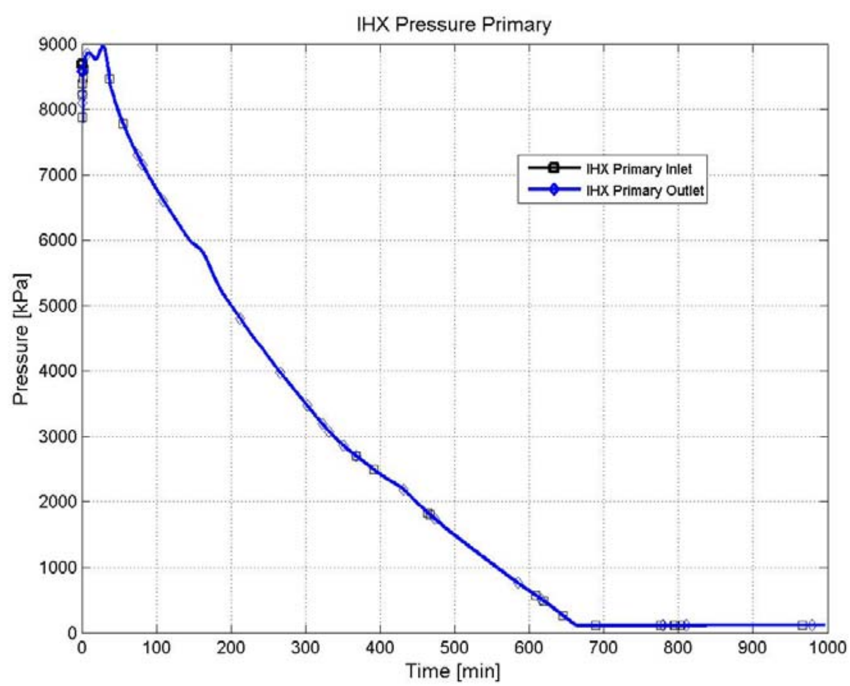


Figure 5-19 IHX Primary Pressure during LOSP Event

5.3.3 Loss of Secondary Cooling (LOSC) with Failure to Trip the PHTS Circulator

The loss of secondary cooling transient is initiated by a trip of the SHTS circulator. The planned response to this event would be to trip the PHTS circulator. In order to judge the ultimate structural capability of the IHX, this transient assumes that this does not occur so as to subject the IHX to high reactor outlet temperatures. Pressurization is initially maintained on both sides of the IHX. All other SSCs, including control and protection systems are assumed to be intact and functional, unless otherwise noted.

The transient is initiated by a trip of the SHTS circulator and it is assumed that the PHTS does not trip. So as not to further compound failures until systematic risk analyses are available to identify both the events to be designed for (DBEs) and the events for which the IHX has capability (BDBEs), this analysis assumes that the CCS circulator simultaneously starts. However, the pressure delivered by the CCS circulator is not high enough to override the PHTS circulator and a mixture of cold gas from the CCS and hot gas from the IHX enters the reactor. The CCS circulator non-return valve opens after about 30 seconds, once the CCS circulator delivers a high enough pressure to push the valve open (against the back pressure caused by the PHTS circulator). While the valve is still closed, hot gas is continuously circulated by the PHTS circulator (Figure 5-20) and, therefore, the RIT increases (Figure 5-21). The reactor core inlet temperature rises to almost 500°C and remains above 320°C for almost an hour. Furthermore, the cold leg piping experiences even higher temperatures, as high as 700°C for a brief time period and significantly higher than the design temperature for over an hour. This could pose a design challenge for the piping and the reactor core barrel design. The capability of the PHTS circulator to withstand these temperatures also needs to be examined.

Assuming that the PHTS circulator continues to operate, the temperature of the whole of the PTHS also increases substantially, which causes a rise in system pressure. The Vessel Overpressure Protection System relief valve opens to prevent the pressure exceeding an assumed setpoint of 9.7 MPa. The valve closes once the pressure has reduced to lower than ~8.7 MPa. This happens repeatedly until the system temperature and pressure start to decrease due to the CCS heat removal. Note that a significant amount of inventory is lost as a result. This is shown in Figure 5-22. The spikes in temperature and pressure observed on the graphs are a result of the relief valves opening and closing.

The temperatures entering the IHX (ROT) and leaving (RIT) the IHX are shown in Figure 5-21. Note that the combined RIT in the figure is at the location where the flow from the IHX to the reactor (RIT) mixes with the CCS flow before it enters the reactor core. Once the CCS check valve opens, cool gas from the CCS mixes with the hot gas coming from the IHX. This results in a decrease in the reactor core inlet temperature.

The temperatures in the IHX on the primary and secondary sides, respectively, are shown in Figure 5-23 and Figure 5-24. The PHTS and SHTS pressure are shown in Figure 5-25 and Figure 5-26. Note that these graphs are presented on a semi-log scale to enable display of the fast behavior early in the transient.

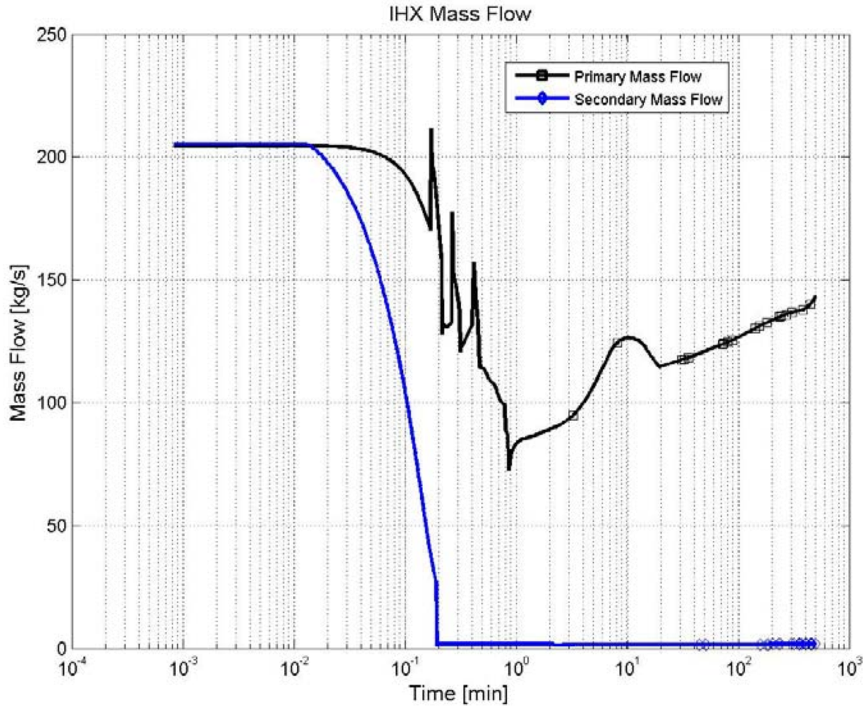


Figure 5-20 IHX Mass Flow Rates during LOSC Event

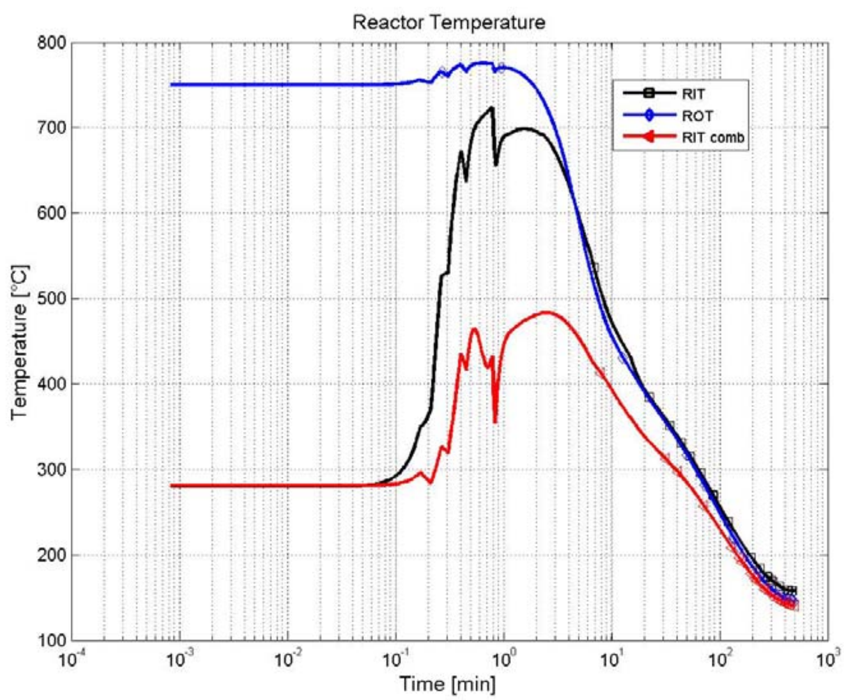


Figure 5-21 IHX Temperatures during LOSC Event

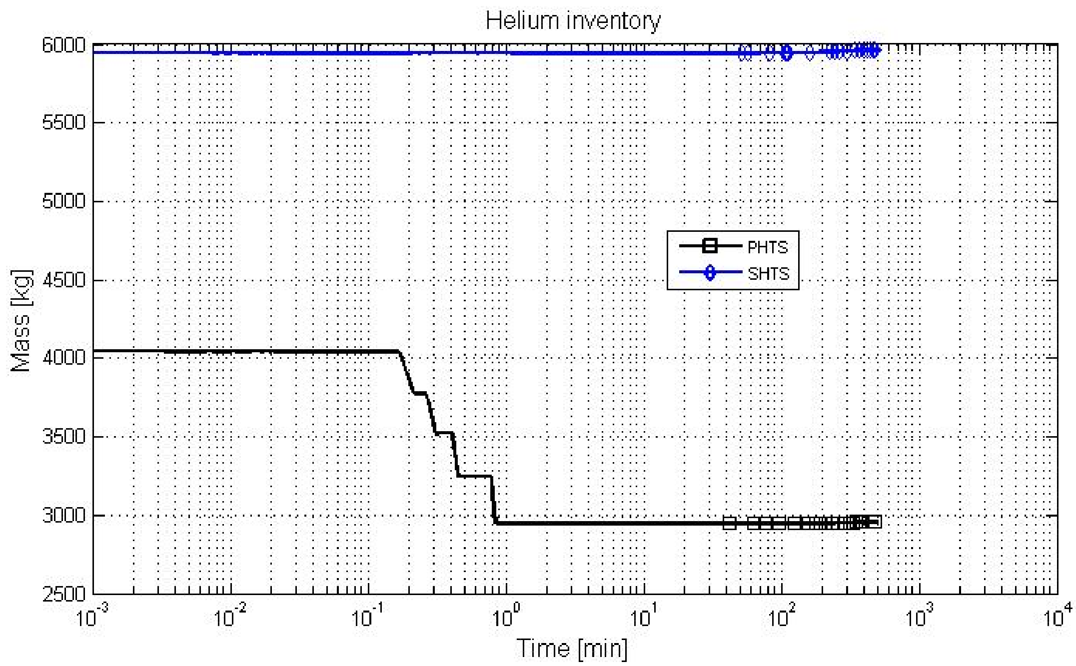


Figure 5-22 System Inventory during LOSC Event

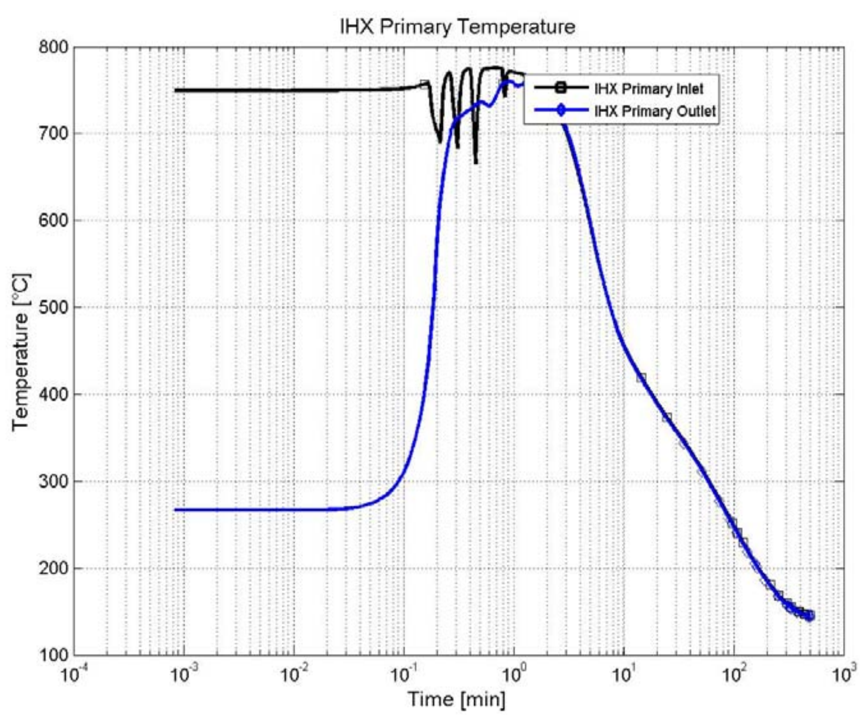


Figure 5-23 IHX Primary Temperatures during LOSC Event

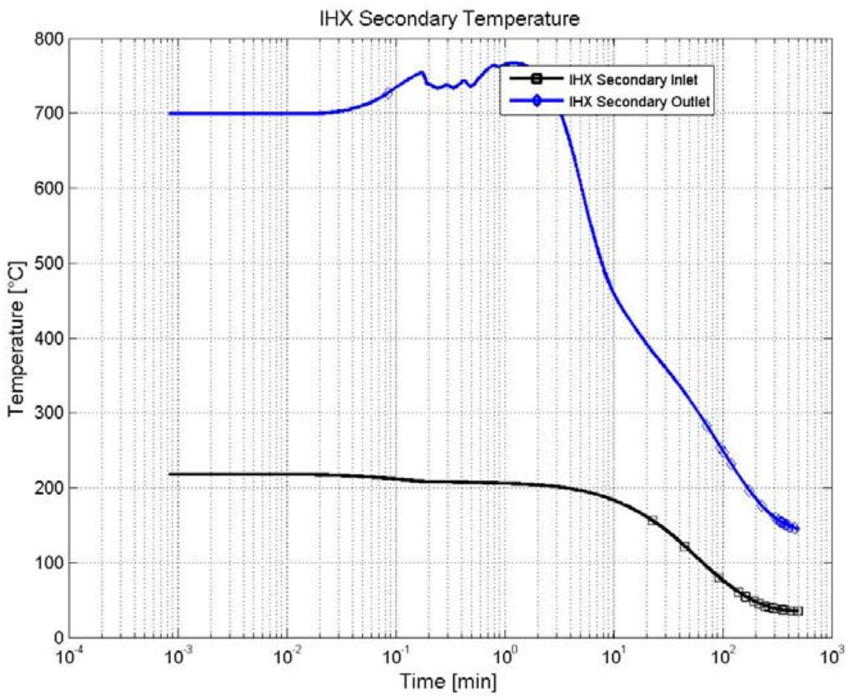


Figure 5-24 IHX Secondary Temperatures during LOSC Event

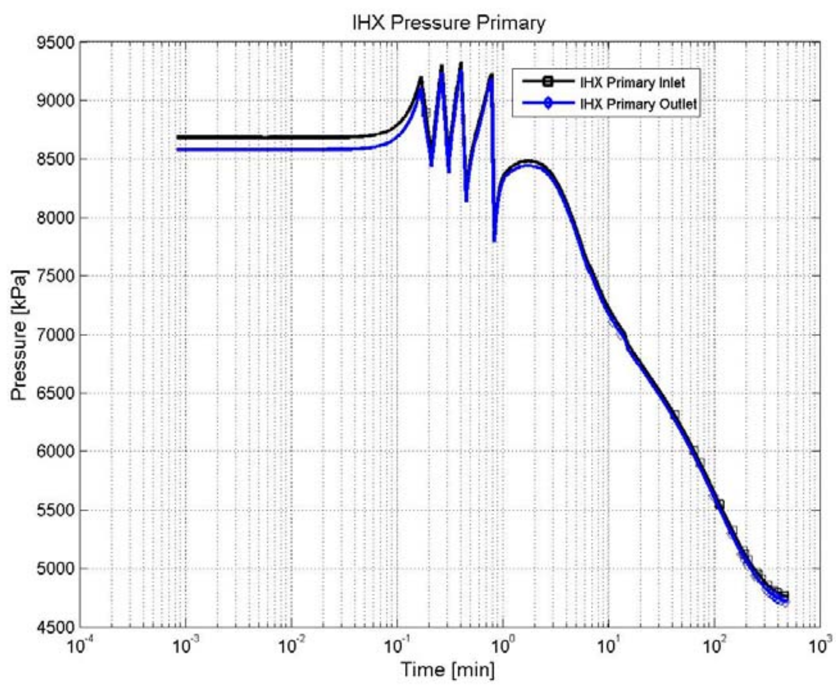


Figure 5-25 PHTS Pressure during LOSC Event

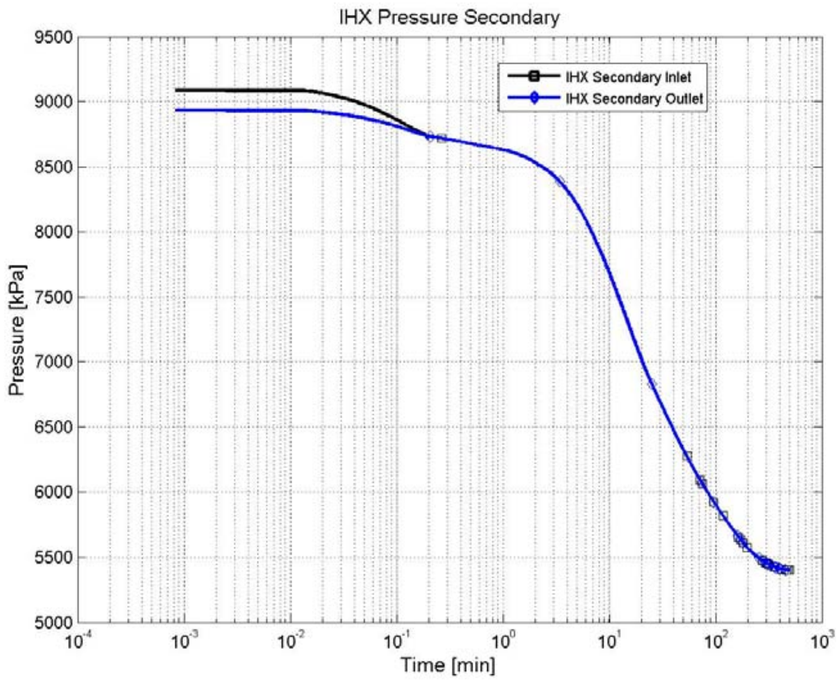


Figure 5-26 IHX Secondary Pressure during LOSC Event

In the meantime, the reactor power has dropped substantially because of the temperature rise in the reactor (the negative temperature coefficient effectively stops the neutronic reaction) and the insertion of the control rods. The heat added to the gas, therefore, decreases. The mass flow rate through the reactor is still very large due to the combined flow from the CCS and PHTS circulators. The temperature difference across the reactor, therefore, starts to decrease, which causes the temperature as well as the pressure in the PTHS to reduce as well. Eventually, after approximately 3.5 hours, the gas as well as core metal temperatures in the IHX (Figure 5-27) drops below 200°C.

As summarized earlier in Section 2.5.4, the principal consequence to the IHX as a result of the LOSC event is the rapid rise in temperature at the normally cooler end (PHTS outlet/SHTS inlet). However, the maximum temperatures seen by the IHX during the transient are not substantially greater than those seen during normal operation. By contrast, these very preliminary analyses indicate that other components within the PHTS are likely to be more limiting. In particular, the influence of design selections (e.g., active cooling vs. insulation) and transients on the primary system piping need to be determined. This confirms the need for the trade studies recommended in the prior IHX and HTS Conceptual Design Study (Ref. 5-4).

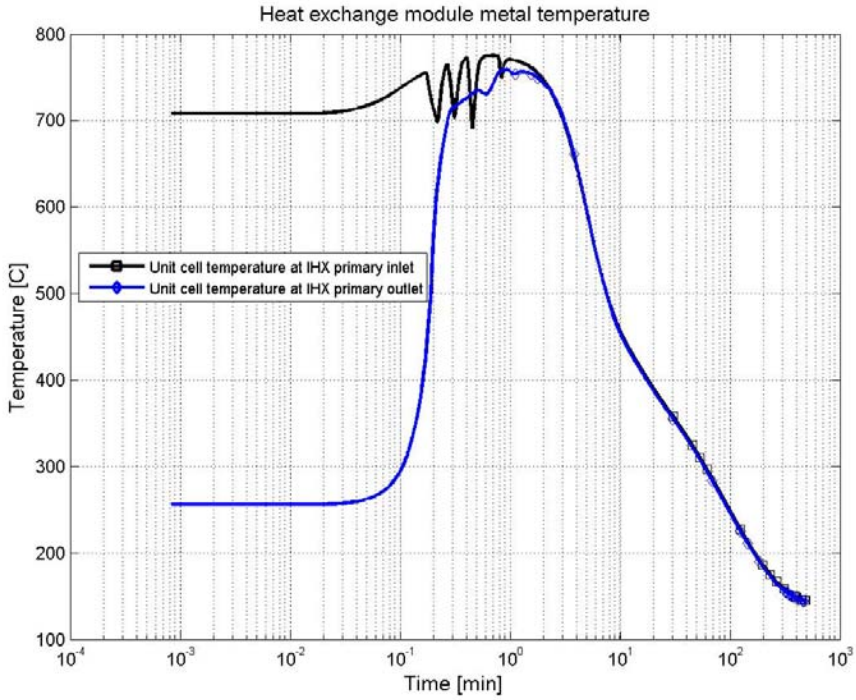


Figure 5-27 IHX Core Average Metal Temperatures during LOSC Event

5.4 References

5-1 *NGNP Initial Conceptual Plant Level Assessments Leading to Fission Product Retention Allocations*, NGNP-PLD-GEN-RPT-N-00007, 2009.

5-2 *NGNP IHX Flownex Report*, T001726, Revision 1, PBMR (PTY) Ltd., June 2009.

5-3 *NGNP NHSS Operating Parameters - 750°C & 800°C ROT,* PHP-NHSS-PBMR-001, Revision 1, PBMR (Pty) Ltd., June 2009.

5-4 *NGNP Conceptual Design Study: IHX and Heat Transport System*, NGNP-HTS-RPT-TI001, Revision 0, Westinghouse Electric Company LLC, April 1, 2008.

6 IHX TECHNOLOGY DEVELOPMENT

Technology development requirements for the IHX in the form of Design Data Needs (DDNs) and a scoping technology development plan were initially defined in Reference 6-1. The DDNs were subsequently updated for the 950°C hydrogen production application in Reference 6-2. Since that time, IHX development requirements were further refined in the form of Technology Readiness Levels (TRLs) and Technology Development Road Maps (TDRMs) and subsequently updated for the 750-800°C application. These evolutions are summarized in the following subsections.

6.1 TRLs and TDRMs

Initial refinements of the technology and technology development requirements for a high-temperature (950°C) IHX A and a lower temperature (760°C) IHX B were described in the *NGNP Technology Development Road Mapping Report* in Section 4 (Ref. 6-1) and Section 5 (Ref. 6-4), respectively. With the change in emphasis to an IHX operating at 750°C to 800°C, the Technology Development Road Map (TDRM) section for the IHX was updated in Reference 6-5. In the latter, the TDRM relating to IHX A is no longer applicable and has been deleted. Similarly, the Design Data Needs (DDNs) related solely to Alloy 617 for IHX A were also deleted.

What was designated as IHX B in Reference 6-4 is now labeled simply as the IHX in Reference 6-5. A major change in Reference 6-5 for the 750°C-800°C IHX is that Hastelloy X was identified, in addition to Alloy 800H, as a prime candidate material. Note that Hastelloy X, because of its superior corrosion resistance, is shown in the current report as the preferred material for the thin cross sections in the core region of the compact heat exchanger. However, Alloy 800H is retained as a primary candidate for use in thicker section components of the IHX.

Reference 6-5 also included modifications of the temperatures in the PHTS and SHTS piping downstream of the IHX. Finally, additions and changes were made to the sections on Decision Discriminators, primarily because considerable information provided relative to IHX A in Reference 6-1 was only referenced and not repeated in Reference 6-4 for the 750°C IHX.

The TRL level of 3 for IHX B was retained for the 750°C-800°C IHX, due to uncertainties related to the corrosion of thin section materials in the IHX core. On that basis, the Road Map for the 750°C-800°C IHX remained essentially as that for IHX B, except for the addition of Hastelloy X. The IHX B Technology Maturation Plan was examined and it was concluded that no major changes would be required to adopt it for the 750°C-800°C IHX. However, some modifications will be needed to reflect items such as the addition of Hastelloy X and the new temperatures associated with the PHTS and SHTS.

6.2 Design Data Needs

As noted above, revisions to the Design Data Needs (DDNs) that guide technology developments for a two-part compact IHX operating at up to 950°C were presented and discussed in Reference 6-2. Since that time emphasis has changed to systems with maximum operating temperatures of 750°C to 800°C and this requires additional changes to the DDNs. This was recognized and noted in Reference 6-5; however, the details of the changes to the DDNs were not developed and presented at that time. A summary of the changes to the DDNs is given below in Table 6-1. Full texts of the DDNs relating to a compact IHX operating at 750°C to 800°C are provided in Appendix 1.

6.1 References

6-1 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.

6-2 *NGNP Conceptual Design Study: IHX and Heat Transport System*, NGNP-HTS-RPT-TI001, Revision 0, Westinghouse Electric Company LLC, April 1, 2008.

6-3 *NGNP and Hydrogen Production Conceptual Design Study*, *NGNP Technology Development Road Mapping Report*, Section 4: Intermediate Heat Exchanger A, NGNP-CTF-MTECH-TDRM-004, Revision 1, Westinghouse Electric Company LLC, November 2008.

6-4 *NGNP and Hydrogen Production Conceptual Design Study*, *NGNP Technology Development Road Mapping Report*, Section 5: Intermediate Heat Exchanger B, NGNP-CTF-MTECH-TDRM-005, Revision 1, Westinghouse Electric Company LLC, November 2008.

6-5 *NGNP: Report on Update of Technology Development Roadmaps for NGNP Steam Production at 750°C-800°C*, NGNP-TDI-TDR-RPT-G-00003, Revision 1, Westinghouse Electric Company LLC, May 2009.

Table 6-1 List of DDN Revisions for the 750°C-800°C IHX

DDN Number	DDN Title	Status and Reason for Revision
HTS-01-01	Establish reference specifications and procurement for Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-02	Thermal/physical and mechanical properties of Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-03	Welding and as welded properties of materials of Alloy 617 for compact heat exchangers	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-04	Aging Effects of Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-05	Environmental effects of impure He on Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-06	Grain size assessment of Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-13	Methods for thermal/fluid modeling of compact heat exchangers	Modified to delete Alloy 617 and add Hastelloy X
HTS-01-14	Methods for stress-strain modeling of compact heat exchangers	Modified to delete Alloy 617 and add Hastelloy X
HTS-01-15	Criteria for structural adequacy of compact heat exchangers	Unchanged
HTS-01-16	Methods for performance modeling of compact heat exchangers	Unchanged
HTS-01-17	IHX performance verification	Unchanged
HTS-01-18	Data supporting materials code case	Modified to delete Alloy 617 and add Hastelloy X
HTS-01-19	Data supporting design code case	Unchanged
HTS-01-20	Influence of Section Thickness on Materials Properties of Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-21	Corrosion Allowances for Alloy 617	Deleted, Alloy 617 not needed for 750°C-800°C
HTS-01-22	Establish reference specifications for Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-23	Supplemental high temperature mechanical properties of Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-24	Effects of joining techniques on the properties of Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-25	Effects of aging on the properties of Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-26	Effects of exposure in impure He on Alloy 800H and Hastelloy X properties	Hastelloy X added
HTS-01-27	Influence of grain size on material properties of Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-28	Influence of section thickness on material properties of Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-29	Corrosion allowances for Alloy 800H and Hastelloy X	Hastelloy X added
HTS-01-30	Brazing and diffusion bonding processes for Alloy 800H and Hastelloy X	Modified to delete Alloy 617 and add Hastelloy X

7 CONCLUSIONS AND RECOMMENDATIONS

The objectives of the IHX Development and Trade Studies Priority Task have been attained and the results are documented in this report. These objectives included advancing the designs of the PBMR NGNP IHX and HTS, resolving the issues associated with the preferred IHX to HTS coupling architecture and assessing the implications of intermediate temperatures (750°C-800°C) for the IHX design. A semi-quantitative assessment of a shell-and-tube heat exchanger was also completed. The principal conclusions of the IHX Development and Trade Studies task are summarized in Section 7.1. Recommendations for further advancement of the IHX and HTS designs are provided in Section 7.2.

7.1 Conclusions

The principal conclusions of the IHX Development and Trade Studies Priority Task are summarized as follows:

1. At the intermediate temperatures assessed herein, the helical-coil shell-and-tube heat exchanger represents a robust and established technical option. However, the size of the individual heat exchangers and the requirement for multiple HTS loops imply significant economic penalties relative to the compact heat exchanger options (estimated by PBMR to be a factor of 10 for the heat exchangers alone). The incremental costs (including influences on the overall design of the NHSS), plus transport issues, are judged to be a deterrent to their use in small nuclear applications, such as the NGNP, where economics rely upon efficiency, simplicity and volume manufacturing.
2. Based on the use of compact heat exchangers, such as the plate-fin heat exchanger (PFHE) technology evaluated herein, the PBMR NGNP IHX, with a nominal capacity of 512MWt, can be configured within a single vessel.
3. Comparisons of the single-stage IHX design developed herein with the corresponding design of the two-stage IHX previously developed for the higher temperature (950°C) hydrogen production application, suggest that the incentives for the two-stage design may be less than previously thought, especially when considering the added complexity and technical challenges introduced by the connecting piping.
4. Hastelloy X should be included as a priority candidate material for the IHX heat transfer surface in the intermediate temperature range. The basis for this recommendation is the expectation of superior corrosion resistance. Note, however, that the corrosion resistance of Hastelloy X has not yet been fully characterized for thin sections in the HTGR PHTS environment.
5. Based upon the steady-state and transient operating conditions assessed in this report, no thermal or structural limitations have been identified for the IHX; however, additional thermal and structural assessments are required to fully validate structural adequacy.
6. The shell-side of the IHX should be coupled to the PHTS and the core-side to the SHTS.
7. At the intermediate temperatures evaluated herein, the IHX can withstand the loss-of-secondary-pressure event with significant margin.

8. The IHX can withstand the loss-of-secondary-cooling event, with failure to trip the primary circulator, with significant margin. However, unless mitigating steps are taken, other portions of the PHTS circuit, especially the PHTS circulator and pressure boundary piping, will be exposed to conditions that exceed their design envelopes.

7.2 Recommendations

The key recommendations that evolve from the IHX Development and Trade Studies Priority Task are summarized as follows:

1. Compact IHX designs should remain the reference basis for the PBMR NGNP IHX.
2. R&D characterizing the corrosion resistance of Hastelloy X, Alloy 800H and other candidate heat transfer surface materials (e.g., Alloy 617 at higher temperatures) in thin sections in the HTGR PHTS and SHTS environments should be undertaken with highest priority. This is the single go/no-go feasibility issue thus far identified with the compact IHX designs.
3. The preconceptual design of an IHX applying plate-type technology, such as the Heatric Printed Circuit Heat Exchanger (PCHE) should be developed and assessed in a trade study along with the PFHE design evaluated herein. The objective would be to provide a basis for selecting one of these concepts as the basis for the IHX.
4. High priority should be given to undertaking the insulation and cooling trade study for the PHTS and SHTS piping that was recommended in the 2008 IHX and HTS Conceptual Design Study. The objective would be to confirm the feasibility of passive insulation for the SHTS piping and to evaluate the relative trade-offs associated with passive insulation versus active cooling for the PHTS piping.
5. Additional transient studies, in conjunction with thermal and structural assessments should be utilized to more fully validate the structural adequacy of the IHX.

BIBLIOGRAPHY

None. References are provided in individual sections.

DEFINITIONS

None

REQUIREMENTS

Requirements are provided in Section 1.2.

LIST OF ASSUMPTIONS

The following assumptions served as a basis for this report:

1. Active cooling of the Primary Heat Transport System (PHTS) helium pressure boundary and passive insulation of the Secondary Heat Transport System (SHTS) pressure boundary were assumed. A trade study to evaluate these features has been recommended.

2. The assessment was limited to metallic heat exchangers.

TECHNOLOGY DEVELOPMENT

Technology Development is addressed in Section 6.

APPENDIX 1: DESIGN DATA NEEDS

DDN HTS-01-13 METHODS FOR THERMAL/FLUID MODELING OF COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Thermal structural modeling, for quasi-steady state and transient analyses, is required to provide a predictive basis for operation and performance characteristics of a compact IHX. A suitable model will need to be developed for this task. The data obtained during the execution of DDNs for Hastelloy X and Alloy 800H will need to be input into the model to provide a physical and mechanical design basis for the IHX alloy selected. The predictive output from the model will be compared and modified as appropriate, based on the results of prototype IHX testing and other verification and validation activities. These results will form the basis for development of the ASME Code Case for design. Some type of simplified modeling techniques or the development of specific modeling test specimens may be required due to the complexity of the model required.

2. Current Database Summary

The physical and mechanical properties database for the potential IHX structural alloys will be developed during the execution of DDNs for Hastelloy X and Alloy 800H. Other aspects of model development will be based on known finite element analysis (FEA) modeling techniques and known mathematical relationships of the selected IHX structure as a function of gas temperature, fluid flow, interface conditions, structural stresses and other factors. An actual design database required for ASME fabrication of a compact heat exchanger is not available and will be developed in DDNs HTS-01-13 through HTS-01-16 and become a part of the ASME Code (DDNs HTS-01-18 and HTS-01-19).

3. Summary of Data Needed

Data needed include all information required to validate the operational and design basis of the compact heat exchanger design selected, all information required to develop a theoretical design basis for comparison with empirical data resulting from the prototype IHX testing performed in response to DDN HTS-01-17 and all information required to perform verification and validation of the analytical model developed.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloys and to support the development of ASME Section III Code Cases for the alloys and the design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of prototype IHX modules prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-14 METHODS FOR STRESS-STRAIN MODELING OF COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Stress-strain structural modeling is required to provide a predictive basis for operation and performance characteristics of a compact IHX. A suitable model will need to be developed and data obtained during the execution of DDNs for Hastelloy X and Alloy 800H will need to be input to provide a physical and mechanical design basis for the IHX alloy selected. The predictive output from the model will be compared and modified, as appropriate, based on the results of prototype IHX testing and verification and validation activities. These results will form the basis for development of the ASME Code Cases for the alloys and IHX design selected. Some type of simplified modeling techniques or the development of specific modeling test specimens may be required due to the complexity of the model required.

2. Current Database Summary

The physical and mechanical properties database for IHX structural alloys will be developed during the execution of DDNs for Hastelloy X and Alloy 800H. Other aspects of model development will be based on known finite element analysis (FEA) modeling techniques and known mathematical relationships of the selected IHX structure as a function of gas temperature, fluid flow, interface conditions, structural details and other factors, assuming that a heat exchanger design not currently covered in ASME Section III or Section VIII is used. An actual design database required for ASME fabrication of a compact heat exchanger is not available and will be developed in response to DDNs HTS-01-13 through HTS-01-16 and will become a part of the ASME Code Cases (DDNs HTS-01-18 and HTS-01-19) for materials and design.

3. Summary of Data Needed

Data needed include all information required to validate the operational and design basis of the compact heat exchanger design selected, all information required to develop a theoretical design basis for comparison with empirical data resulting from the prototype IHX testing performed in response to DDN HTS-01-17 and all information required to perform a verification and validation of the analytical model developed.

4. Designer’s Alternatives

The designer’s alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloys and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of a prototype IHX modules prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-15 CRITERIA FOR STRUCTURAL ADEQUACY OF COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

The criteria for acceptable stresses and strains and the development of acceptable safety factors are required for ASME Code Case development and to establish the operational boundaries of the IHX prototype testing activities. These criteria will be developed from a review of appropriate ASME Code documentation, discussion with appropriate ASME Code committee personnel and interaction during the development of the stress-strain model (DDN HTS-01-14).

2. Current Database Summary

The current ASME design database for shell and tube heat exchangers provides general guidance for development of appropriate stress/strain criteria for the design of plate type heat exchanger systems.

3. Summary of Data Needed

Data needed include the results from DDNs HTS-01-14 and HTS-01-17, review of prior appropriate ASME documentation, and discussions with appropriate ASME committee personnel.

4. Designer’s Alternatives

The designer’s alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of a prototype IHX module prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an existing ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-16 METHODS FOR PERFORMANCE MODELING OF COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Performance modeling methods are required to adequately evaluate the results of DDNs HTS-01-13 and HTS-01-14, provide guidance to testing performed in DDN HTS-01-17 and provide the basis for the discussion of modeling performed during the development of the design code case (DDN HTS-01-19).

2. Current Database Summary

The current ASME design database for shell and tube heat exchangers provides general guidance for development of appropriate performance modeling methods for the design of plate type heat exchanger systems.

3. Summary of Data Needed

Data needed include all information required to establish appropriate performance modeling methods.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloys and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of a prototype IHX module prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-17 IHX PERFORMANCE VERIFICATION

1. Assumptions (to be confirmed by the related R&D program)

IHX performance verification is required to empirically validate the IHX design, to resolve issues noted regarding the design and to serve as a primary input to the validation and verification process of the modeling performed. IHX performance verification includes test facility development, prototype IHX test module fabrication, IHX life prediction, IHX durability testing, IHX performance testing, IHX materials testing and interfaces with the models developed.

2. Current Database Summary

There is essentially no available database to support this DDN.

3. Summary of Data Needed

Data needed include all information required to establish the empirical basis for IHX performance, life prediction, durability and acceptability of fabricated materials in support of the required ASME Code Cases (DDNs HTS-01-18 and HTS-01-19) and all information needed to provide an empirical basis for model validation.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloys and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required in the second half of FY2011 to support design, procurement of long-lead NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-18 DATA SUPPORTING MATERIALS CODE CASE

1. Assumptions (to be confirmed by the related R&D program)

The IHX high-temperature primary to secondary system interface will be designed as an ASME Section III component and the alloys selected for this interface (Hastelloy X and Alloy 800H)) must be qualified under ASME Section III service. Alloy 800H can be used for a 750°C ROT because it is qualified under ASME Section III, Subsection NH to 760°C. Its use at 800°C will require extension of its qualification to at least 850°C. Use of Hastelloy X at either 750°C or 800°C will require its incorporation into ASME Section III, Subsection NH.

2. Current Database Summary

Alloy 800H is a well-characterized material with a long history of successful service experience in applications including gas-cooled reactors. A substantial database exists for Alloy 800H for temperatures to 1000°C. ASME Section III, Subsection NH permits its use to 760°C; applying the material for an 800°C ROT would require a temperature extension within Subsection NH. A joint ASME/DOE study has indicated that increasing the temperature to 900°C in Subsection NH can be supported technically.

Hastelloy X is also a material with a long history of excellent service in many oxidizing and corrosive environments. Although Hastelloy X is not currently included in Section III, Subsection NH, existing data are sufficient for this task. Also, a study under a joint ASME/DOE agreement has concluded that Hastelloy X is a candidate for inclusion in ASME Section III Code Case N-201-5.

3. Summary of Data Needed

Data needed includes all information required to prepare the desired materials code cases for Alloy 800H and Hastelloy X and to resolve issues that may occur during further discussions with the ASME during the code case approval process and during subsequent discussions with the NRC during NGNP licensing.

4. Designer's Alternatives

The designer's alternative is to select an alloy listed in ASME Section II for application in ASME Section III or to use Alloy 800H at no greater than 760°C.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 800H and Hastelloy X and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required during the first half of FY2012 to support NRC licensing discussions associated with the NGNP. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.
2. USDOE/ASME Standards Technology, LLC Cooperative Agreement to Expand Appropriate Materials, Construction, and Design Codes for Application in Future Gen IV Nuclear Reactor Systems, June 17, 2006, files.asme.org/STLLC/9274.

DDN HTS-01-19 DATA SUPPORTING DESIGN CODE CASE

1. Assumptions (to be confirmed by the related R&D program)

The IHX primary to secondary system interface will be designed as an ASME Section III component and the selected IHX compact heat exchanger design will not be included in ASME Section III in the required timeframe.

2. Current Database Summary

The current ASME design database for shell and tube heat exchangers provides general guidance for the development of a design code case for the design of plate type heat exchanger systems.

3. Summary of Data Needed

Data needed includes all information required to draft a design code case for the IHX design selected, resolve issues that may occur during further discussions with the ASME during the code case approval process and during subsequent discussions with the NRC during NGNP licensing.

4. Designer's Alternatives

The designer's alternatives are to select an IHX design listed in ASME Section VIII and use the design as the basis for a new ASME Section III Code Case or to assume that the IHX primary to secondary interface will not be designed as an ASME Section III class component.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloys and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required during the first half of FY2012 to support NRC licensing discussions associated with the NGNP. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database, to use an ASME Code approved heat exchanger design and to use material for the IHX application or to proceed assuming that a Section III design is not required.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-22 ESTABLISH REFERENCE SPECIFICATIONS FOR ALLOY 800H AND HASTELLOY X

1. Assumptions

The standard ASTM specifications for Alloy 800H and Hastelloy X will provide materials suitable for use in the compact IHX.

2. Current Database Summary

Alloy 800H is a well-characterized material with a long history of successful service experience in applications including gas-cooled reactors. A substantial database exists for Alloy 800H for temperatures to 1000°C. It is ASME qualified under Section VIII for use to 816°C and under certain circumstances to 982°C. Section III, NH permits its use to 760°C and a joint ASME/DOE study has indicated that raising this temperature to 900°C is not unwarranted. ASTM specifications relative to its use are well established and generally accepted.

Hastelloy X is also a material with a long history of excellent service in many oxidizing and corrosive environments. Although Hastelloy X is not currently included in Section III, Subsection NH, existing data are sufficient for this task. Also, a study under a joint ASME/DOE agreement has concluded that Hastelloy X is a candidate for inclusion in ASME Section III Code Case N-201-5. ASTM specifications relative to its use are well established and generally accepted.

3. Summary of Data Needed

None.

4. Designer's Alternatives

Not applicable

5. Selected Design Approach and Explanation

The proposed approach is to accept the standard ASTM specifications for Alloy 800H and Hastelloy X.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Revise ASTM specification for Alloy 800H and Hastelloy X.

9. References

1. Swindeman, R. W., et.al., *A Report on the Review of Databases, Data Analysis Procedures, and Verification of Minimum Yield and Ultimate Strengths for Alloy 800H in ASME Section III, Subsection NH*, March 2007.
2. Swindeman, R. W., et.al., *Creep-Rupture Data Sources, Data Analysis Procedures, and the Estimation of Strength for Alloy 800H at 750^{o}C and Above*, March 2007.

DDN HTS-01-23 SUPPLEMENTAL HIGH TEMPERATURE MECHANICAL PROPERTIES OF ALLOY 800H and Hastelloy X

1. Assumptions

The existing high temperature mechanical properties of Alloy 800H are sufficient to provide for a design of an IHX operating at 750°C and extension of the temperature limits in ASME Section III, Subsection NH would permit its use at 800°C. Although Hastelloy X is not currently included in Subsection NH, extensive data exist to temperatures >800°C. Exceptions to the above are addressed in DDNs HTS-01-24 through HTS-01-29.

2. Current Database Summary

See References and ASME Section III, Subsection NH for Alloy 800H; see References for Hastelloy X.

3. Summary of Data Needed

No basic properties required.

4. Designer's Alternatives

Develop new database.

5. Selected Design Approach and Explanation

The proposed approach is to accept the current databases for Alloy 800H and Hastelloy X.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

None.

9. References

1. Swindeman, R. W., et.al., *A Report on the Review of Databases, Data Analysis Procedures, and Verification of Minimum Yield and Ultimate Strengths for Alloy 800H in ASME Section III, Subsection NH*, March 2007.
2. Swindeman, R. W., et.al., *Creep-Rupture Data Sources, Data Analysis Procedures, and the Estimation of Strength for Alloy 800H at 750^{o}C and Above*, March 2007.
3. Manufacturers Literature on Hastelloy X from Internet including <www.specialmetals.com>, <www.sandmeyersteel.com>, <www.steelforge.com>, <www.megamex.com>, <www.haynesintl.com>, and www.hightempmetals.com.

DDN HTS-01--24 EFFECTS OF JOINING TECHNIQUES ON THE PROPERTIES OF ALLOY 800H AND HASTELLOY X

1. Assumptions

Alloy 800H joined by conventional welding processes, by diffusion bonding, and by brazing will have properties suitable to permit safe and successful operation of an IHX of compact design. The same assumption is true for Hastelloy X.

2. Current Database Summary

The current databases for Alloy 800H and Hastelloy X include extensive information on conventional welding processes. However, the existing databases contains very little information on diffusion bonding or brazing of thin sheet materials, both of which are needed for the fabrication of compact heat exchangers.

3. Summary of Data Needed

Data are needed on the effects of brazing and diffusion bonding of thin sheet Alloy 800H and Hastelloy X materials on all standard mechanical properties (tensile, creep, fatigue, and fracture toughness) at temperatures up to 850°C.

4. Designer's Alternatives

Assume the risk of not confirming the DDN Assumption.

5. Selected Design Approach and Explanation

Obtain the data needed described above.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Accept the existing state of knowledge relative to joining effects and design for a shell-and-tube IHX.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN-HTS-01-25 EFFECTS OF AGING ON THE PROPERTIES OF ALLOY 800H AND HASTELLOY X

1. Assumptions

Thermal aging will not significantly degrade the properties of Alloy 800H or Hastelloy X in IHX service exposures at 750 to 800°C for full reactor lifetime.

2. Current Database Summary

The stability of properties of Alloy 800H during long-term service in industrial processes and in gas-cooled reactors has been demonstrated by experience and testing. Although the thermal stability of Hastelloy X is slightly less than that of Alloy 800H, it is more than sufficient for the IHX application. Additionally, the effects of aging and exposures to gas-cooled reactor environments have been studied for both alloys .

3. Summary of Data Needed

New data are not likely to be needed but this should be confirmed by documentation of existing service experience and R&D results.

4. Designer's Alternatives

Conduct new studies on aging effects.

5. Selected Design Approach and Explanation

Accept the existing database.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Not applicable.

9. References

1. Swindeman, R. W., et.al., *A Report on the Review of Databases, Data Analysis Procedures, and Verification of Minimum Yield and Ultimate Strengths for Alloy 800H in ASME Section III, Subsection NH*, March 2007.
2. Swindeman, R. W., et.al., *Creep-Rupture Data Sources, Data Analysis Procedures, and the Estimation of Strength for Alloy 800H at 750^{o}C and Above*, March 2007.
3. Manufacturers Literature for Hastelloy X from Internet including <www.specialmetals.com>, <www.sandmeyersteel.com>, <www.steelforge.com>, <www.megamex.com>, <www.haynesintl.com>, and www.hightempmetals.com.
4. USDOE/ASME Standards Technology, LLC Cooperative Agreement to Expand Appropriate Materials, Construction, and Design Codes for Application in Future Gen IV Nuclear Reactor Systems, June 17, 2006, files.asme.org/STLLC/9274.
5. Alloy 800, Proceedings of Petten International Conference, March 14-16, 1978, North Holland Publishing Company.

DDN HTS-01-26 EFFECTS OF EXPOSURE IN IMPURE HELIUM ON ALLOY 800H AND HASTELLOY X PROPERTIES

1. Assumptions

Alloy 800H and Hastelloy X can be used at very high temperatures in impure primary and secondary helium environments containing CO, CO_2, H_2, H_2O and O_2at up to 800ºC for full reactor lifetime without unacceptable degradation of mechanical properties or microstructure.

2. Current Database Summary

The current databases for Alloy 800H and Hastelloy X contain considerable information on the corrosion, microstructural stability, and consequent mechanical property changes as a function of time, temperature and environmental conditions. The databases contain little or no information on the effects of long-term environmental exposure on welded, brazed, or diffusion bonded specimens.

3. Summary of Data Needed

Data needed include selected mechanical properties (yield, tensile strength and elongation; fatigue and creep strength; fracture toughness, etc.) following environmental exposure at temperatures up to 850ºC on welded, brazed, and diffusion bonded test specimens of Alloy 800H and Hastelloy X.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption.

5. Selected Design Approach and Explanation

Obtain environmental effects data on welded, brazed, and diffusion bonded Alloy 800H and Hastelloy X.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This must be done prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of conventional welding processes. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-27 INFLUENCE OF GRAIN SIZE ON MATERIAL PROPERTIES OF ALLOY 800H AND HASTELLOY X

1. Assumptions

Alloy 800H and Hastelloy X materials with fine grain size will have acceptable mechanical properties at temperatures to 800^{o}C for long periods of time. Further, a reasonably fine grain size can be maintained following joining and high temperature long-term exposure.

2. Current Database Summary

There is little if any information available on the properties of Alloy 800H with grain size smaller than that given by ASTM 5 ; Hastelloy X is normally used with grain size in the range of ASTM 5 to 7.

3. Summary of Data Needed

Obtain property information on Alloy 800H in the grain size range ASTM 5 to 8. This could be done on one or more heats of Alloy 800H acquired specifically for NGNP or on existing large-grained materials processed to achieve a smaller grain size. Although the grain size for Hastelloy X is closer to that desired, additional data are still desirable.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption and design with standard Alloy 800H and Hastelloy X properties.

5. Selected Design Approach and Explanation

Obtain creep and fatigue property data for fine-grained Alloy 800H and Hastelloy X.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This must be done prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of large grained material. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-28 INFLUENCE OF SECTION THICKNESS ON MATERIAL PROPERTIES OF ALLOY 800H AND HASTELLOY X

1. Assumptions

Very thin material sections of Alloy 800H and Hastelloy X are required for the cores of compact type IHXs. It is assumed that materials of these section thicknesses will have mechanical properties equivalent to or only slightly degraded relative to those of plate materials with more typical thicknesses.

2. Current Database Summary

There are no data available on the properties of thin sheet Alloy 800H and Hastelloy X and no correlations of properties versus thickness.

3. Summary of Data Needed

Data are needed to establish the any variation of the properties of Alloy 800H and Hastelloy X as a function of material thickness over the range 100 to 500 μm.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption and design with standard Alloy 800H and Hastelloy X properties.

5. Selected Design Approach and Explanation

Obtain creep and fatigue property data for thin sheet Alloy 800H and Hastelloy X.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This must be done prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of heavy section materials. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-29 CORROSION ALLOWANCES FOR ALLOY 800H AND HASTELLOY X

1. Assumptions

The exposure of Alloy 800H and Hastelloy X to impure helium at high temperatures for full reactor lifetime does not compromise the structure and integrity of the material cross-section by oxide scale formation, internal oxidation, or other phenomena.

2. Current Database Summary

A significant amount of information is available relative to corrosion mechanisms for Alloy 800H and Hastelloy X in simulated gas-cooled reactor helium as a function of temperature and coolant chemistry. However, the amount of quantitative information available for the prediction of corrosion allowances is quite limited and often contradictory.

3. Summary of Data Needed

Data are needed to characterize the oxide scale thickness, depth of internal oxidation, and degree and depth of Cr depletion at 700°C through 850°C on exposure of Alloy 800H and Hastelloy X to environments characteristic of both primary and secondary side He. Exposure times should range from 100 h to at least 10,000 h. These data are needed to determine “corrosion allowances” and effects of corrosion phenomena on structural integrity.

4. Designer’s Alternatives

Accept the risk of not confirming the DDN Assumption and design without corrosion allowances.

5. Selected Design Approach and Explanation

Determine corrosion allowances for Alloy 800H and Hastelloy X.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of heavy section materials without significant concern about corrosion. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

2. PBMR: Oxidation and Carburization of Steels and Nickel-based Alloys, Westinghouse Reaktor GmbH, GBRA 063689, March 2003.

3. Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program Quarterly Progress Reports, July 1, 1980 through September 30, 1983, DOE-ET-3402 –51, -54, -57, -64, -67, -71, -73, -83, -85, -87, and –90.

DDN HTS-01-30 BRAZING AND DIFFUSION BONDING PROCESSES FOR HASTELLOY X AND ALLOY 800H

1. Assumptions

Thin sections of Hastelloy X and Alloy 800H can be brazed and/or diffusion bonded to produce structurally sound joints in compact heat exchangers.

2. Current Database Summary

There is very little information or data on materials and techniques for brazing and diffusion bonding thin sections of Hastelloy X and Alloy 800H and most of this is likely company proprietary. Also, information on the strength and structural integrity of such joints is lacking.

3. Summary of Data Needed

Data and information needed include determination and documentation of suitable braze materials and conditions and diffusion bonding techniques for joining of thin sections of Hastelloy X and Alloy 800H. Assessment of the structural integrity of these joints by microscopic examination and mechanical testing is also needed.

4. Designer's Alternatives

Use properties of base material and accept the risk of not confirming the Assumption.

5. Selected Design Approach and Explanation

Demonstrate joining by brazing and diffusion bonding and confirm the structural integrity of the joints.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of standard welding practice. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.
2. *IHX and HTS Conceptual Design Study*, April 2008, Appendix 1.

APPENDIX 2: 50% REVIEW VIEWGRAPHS

INTRODUCTION

Scott Penfield

IHX/HTS Priority Task
50% Design Review

May 8, 2009

Agenda Overview

Introduction
- Background
- Objectives and Approach

Subtask 1: Requirements and Interfaces
- IHX Functions
- Key Requirements and Bases

Subtask 2: IHX Design
- Review of IHX Unit Cell Design
- IHX Layout for 750-800°C ROT
- Materials Evaluation for 750-800°C ROT

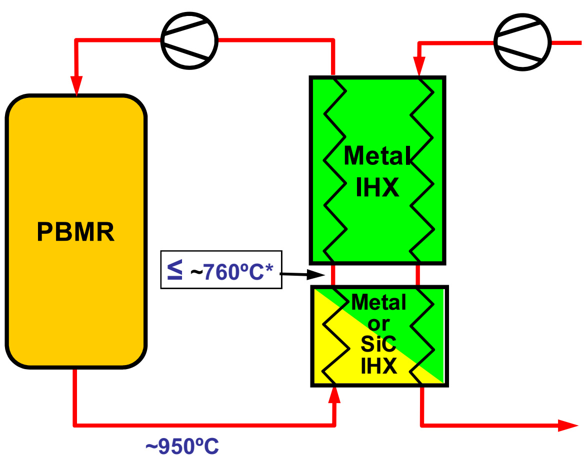
Subtask 3: IHX-HTS Integration
- Reevaluation of Coupling Options
- IHX-Piping Integration
- IHX-NHSS Building Integration

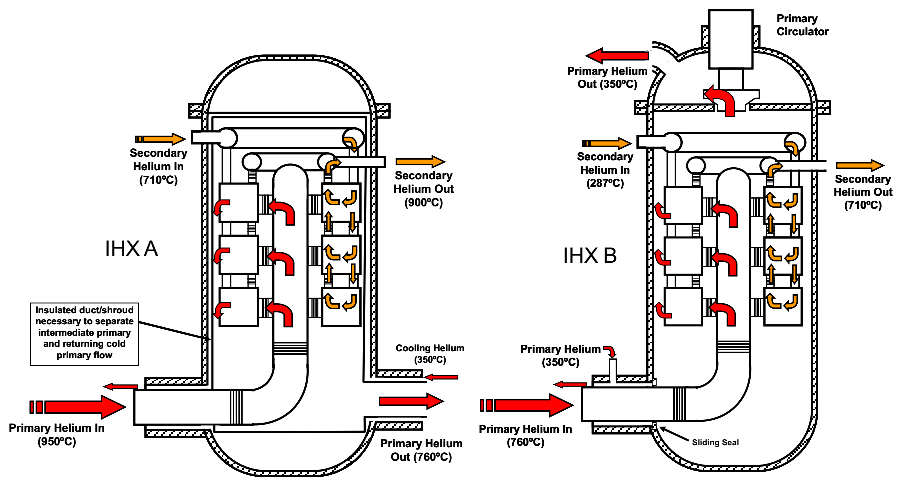
Subtask 4: Preliminary Assessment of IHX Transients
- Development of IHX Transient Model and Integration with FPT Model
- Assessment of Limiting Transients

Status of IHX/HTS Priority Task
- Summary of Work Remaining
- Issues and Projected Solutions
- Cost & Schedule Performance

Background: PCDR Design

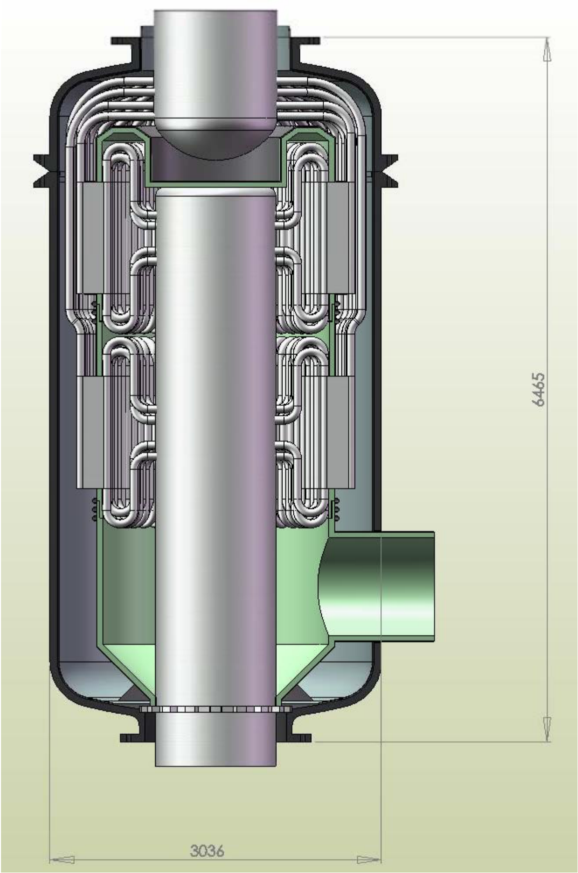
- PBMR PCDR NGNP design was based on 950°C for H_2 production
- Full thermal output of reactor transported via IHX and SHTS to topping Process Coupling HX and bottoming SG
  - Maximum commonality with commercial NGNP
  - Flexibility for steam-only operation
- 2-Section pressure-balanced compact IHX proposed to address limitations of metallic materials, facilitate transition to ceramic HXs





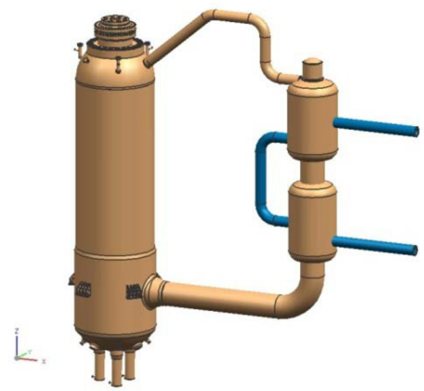
Background:
2008 IHX/HTS Conceptual Design Study

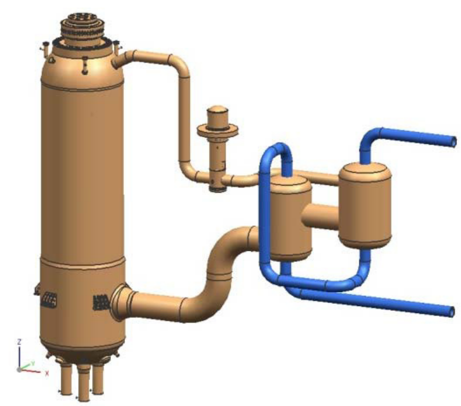
- Survey/qualitative evaluation of candidate compact and tubular IHX designs
  - Confirmed incentives for compact IHX
- Developed compact IHX based on Brayton Energy Unit Cell (Plate-Fin HX)
  - Developed compact IHX with potential for leak detection and isolation at module level
  - Selected I-617/800H as reference materials
  - Assessed structural feasibility of pressure-balanced IHX at 950°C (creep/fatigue not limiting <u>for steady state</u>)
  - Identified corrosion of thin sections (especially on PHTS side) as most significant technical issue for all compact HXs
  - Assessed IHX layout and system integration options
- Assessed options for other HTS components (circulator, isolation valves, SG)
- Updated HTS Design Data Needs (DDNs)
  - Input to TRL/TDRM effort



Background:
2008 IHX/HTS CDS Open Issues

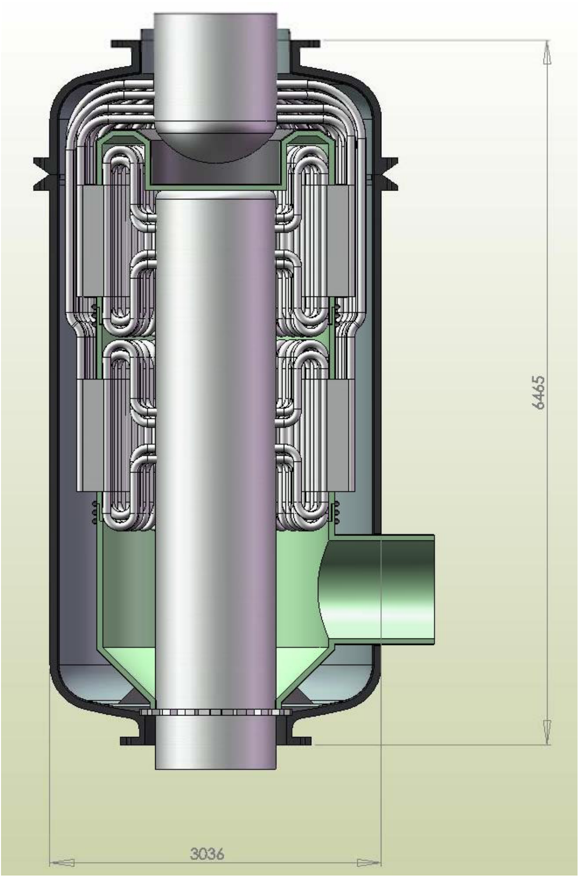
- Need to confirm feasibility of compact metallic IHX at 950°C
  - Present materials database for thin sections is inadequate to support a definitive assessment
  - Additional analysis to confirm response to LBEs
- Resolution of core-side vs. shell-side coupling of IHX to PHTS, taking into account:
  - Layout and support of RPV, two IHX vessels, plus PHTS circulator
  - Integration with PHTS piping, including provisions for active cooling of piping and, potentially, vessels
  - Preferred pressure bias direction (steady state, LBEs)
  - Access for inspection and/or maintenance
  - Concern with potential for activation of Co in I-617
- Trade study to evaluate passive insulation vs. active cooling of PHTS
  - Transients involving loss of heat removal via SHTS a potential concern with process heat configurations





Background:
Basis for Present Study

- Reduction in Reactor Outlet Temperature (ROT) to range of 750-800°C
  - Steam/cogeneration
  - Intermediate temperature process heat
- Prospects for single vessel IHX
- Need to resolve open issues from 2008 Study; especially PHTS coupling
- Required inputs for:
  - Fission Product Transport Task
  - Update of TRLs/TDRMs for 750-800°C applications



Objectives

- Develop single-vessel compact IHX design for 750-800°C
  - Update input functions and requirements
  - Evaluate material options for reduced temperature
- Resolve core-side vs. shell-side coupling issue, taking into account:
  - Piping interface and cooling
  - Interfaces with NHSS building and supports
  - Transient response
  - Access for inspection and maintenance
- Assess IHX thermal and structural adequacy
- ~~Develop and~~ evaluate backup shell & tube IHX design
- Update DDNs as input to TRL/TDRM update

Approach

1. Update input functions and requirements
   - Use PCDR configuration at 750°C ROT (option of 800°C for process heat)
   - SG only (optional of PCHX + SG)
   - PHTS piping actively cooled
2. Develop single-vessel compact IHX layout
   - Assess materials for 750-800°C
3. IHX-HTS Integration
   - Initial screening evaluation of core-side vs. shell-side coupling to PHTS
   - IHX-piping integration layout~~s~~
   - IHX-NHSS building integration layout~~s~~
   - ~~Conduct detailed analyses, if required to support selection~~
4. Develop IHX analytical model as input to FPT Task transient analysis
   - Assess IHX limiting transients
   - ~~Analyze core-side and shell-side coupling options, if required to support selection~~
5. Update DDNs and identify TRL/TDRM impacts
6. Support Reviews and Final Report

REQUIREMENTS AND INTERFACES

Scott Penfield

IHX/HTS Priority Task
50% Design Review

May 8, 2009

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Status of IHX/HTS Priority Task
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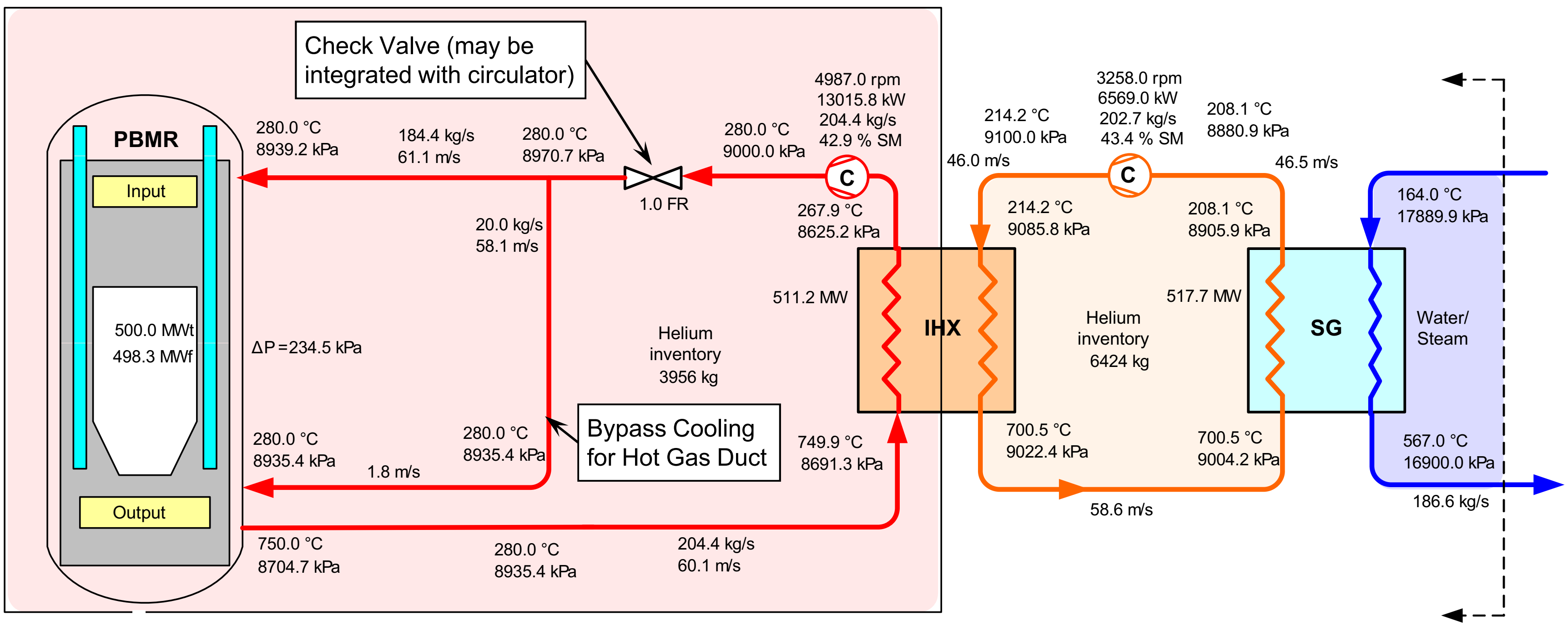
IHX Functions

- Transfer thermal energy from the PHTS to the SHTS
  - ➢ To support production of steam, direct heat and/or power during normal operation
  - ➢ To remove decay heat during certain modes and states and for certain transient events
- Provide separation between the PHTS and SHTS helium working fluids

Reference Parameters Basis for Selection

- Reference parameters taken from Fission Product Transport (FPT) Priority Task
  - Based on steam/cogeneration application at 750°C ROT
  - Use of common parameters allows IHX/HTS Task to “piggyback” on FPT Task
  - IHX design provides input to FPT task
- IHX thermal/structural integrity at 800°C to also be evaluated by extrapolation (adjust materials properties)
  - Potential support for intermediate direct heat applications (ammonia production, ethylene cracking)

Reference Parameters
Nominal Steady State

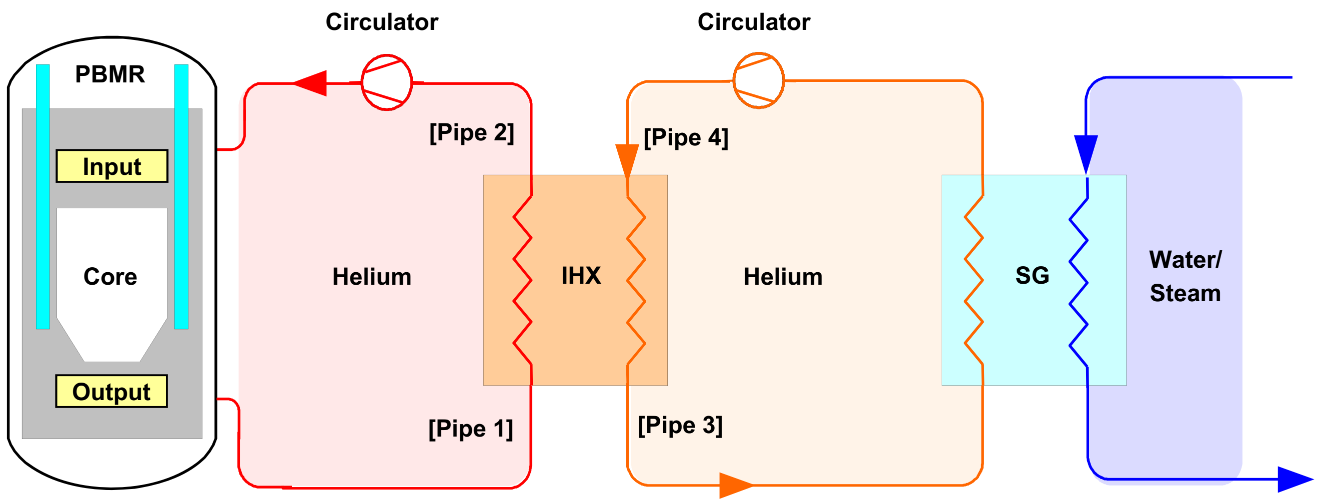


SG - Steam Generator
IHX - Intermediate Heat Exchanger
C - Circulator

Piping Interface Definitions Bases for Selection

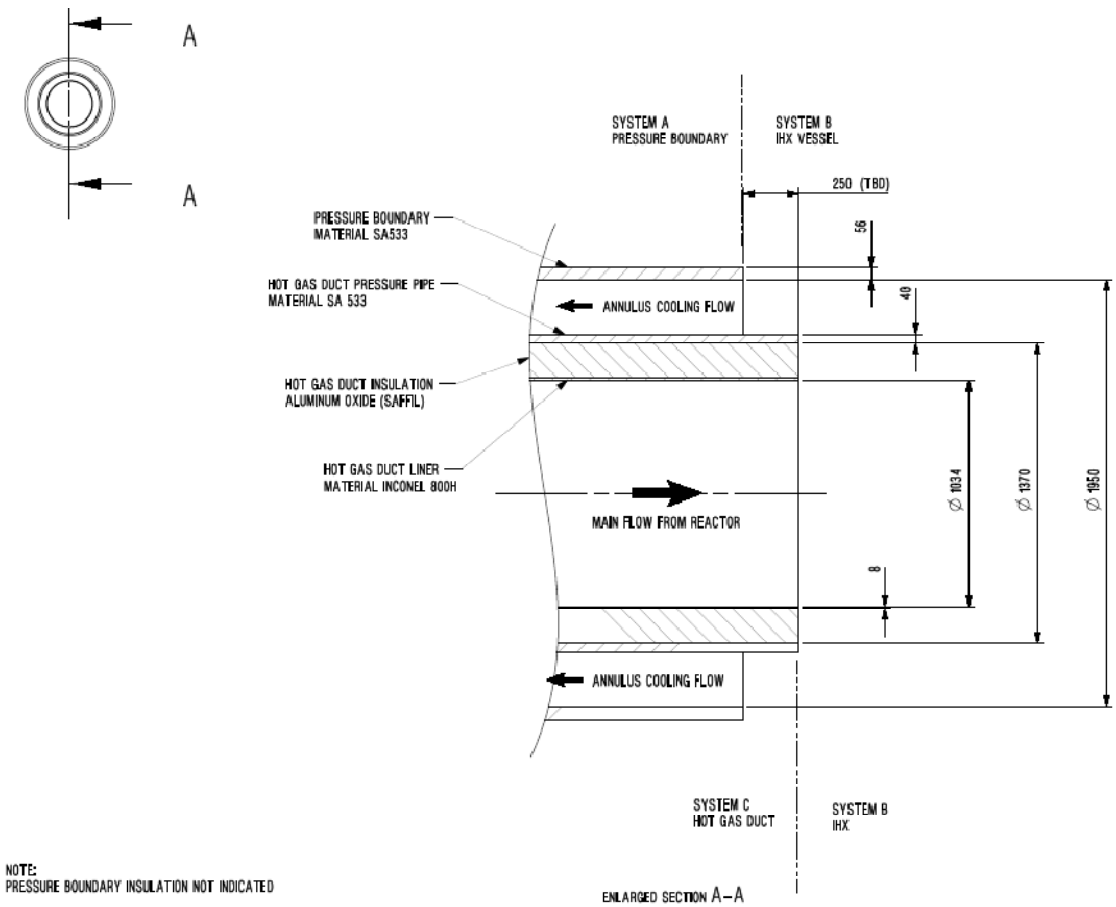
- Helium pressure boundary material is SA508/SA533
  - Temperature limited to 371°C for normal operation; to 540°C for DBEs
- Hot Gas Duct (HGD - Reactor to IHX) assumed to be actively cooled
- IHX SHTS outlet pipe (to SG) assumed to be internally insulated
  - Micropore insulation (e.g., Microtherm) with internal liner
  - Evaluated in Composites Conceptual Design Study
- Cold-leg pipes (PHTS and SHTS) assumed to be externally insulated
- Insulation/Cooling Trade recommended for Conceptual Design
  - Passive insulation of HGD would simplify design, reduce cost and avoid implications of potential transient (loss heat removal via SHTS with failure of PHTS circulator to trip)
  - Internal passive insulation increases challenges for validating integrity of PHTS helium pressure boundary using present PRA database

Piping Interface Definitions

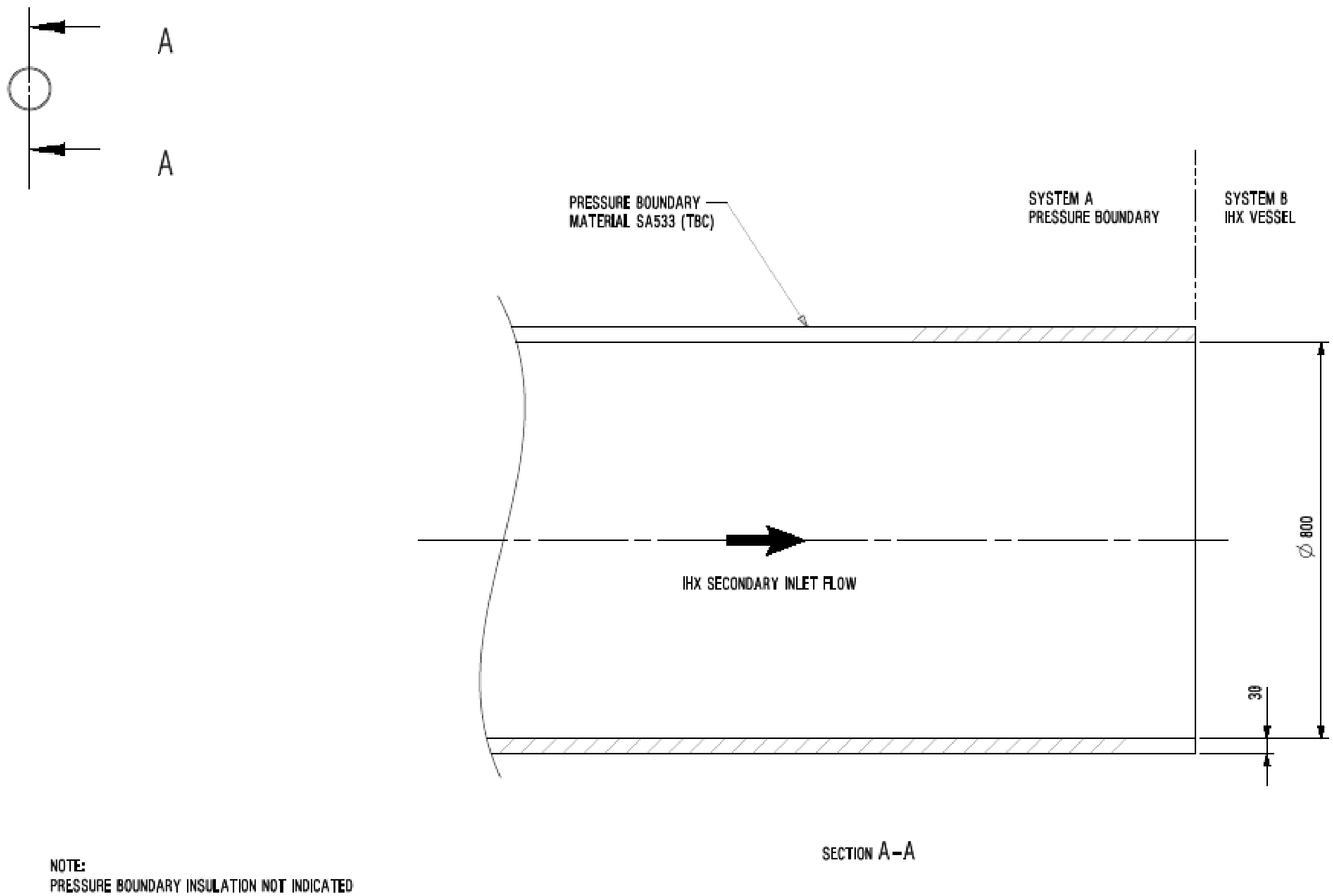


SG - Steam Generator
IHX - Intermediate Heat Exchanger

Reactor to IHX (Pipe 1) Actively Cooled, Coaxial Duct



Other Pipes
External and/or Internal Passive Insulation



Other Key Input Requirements

- IHX to be designed for full plant life (60 years)
  - Thermal/structural analyses in this study to provide scoping assessment; not expected to be limiting
  - Corrosion of thin sections a potential limitation that must be assessed via technology program (recommended as high priority)
- IHX to be pressure balanced during normal operation, with slight bias from secondary to primary
  - Objectives are to minimize normal loads on IHX internal pressure boundary and avoid contamination of SHTS circuit
- IHX to be designed for loss of secondary pressure from full power
- The IHX shall include provisions for detecting and locating leaks and for repairing, isolating and/or replacing failed components
  - Feasibility indicated via earlier IHX/HTS study

IHX Design

Jim Nash, Brayton Energy
Scott Penfield
Phil Rittenhouse

IHX/HTS Priority Task
50% Design Review

May 8, 2009

P B M R

Shaw®

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Status of IHX/HTS Priority Task
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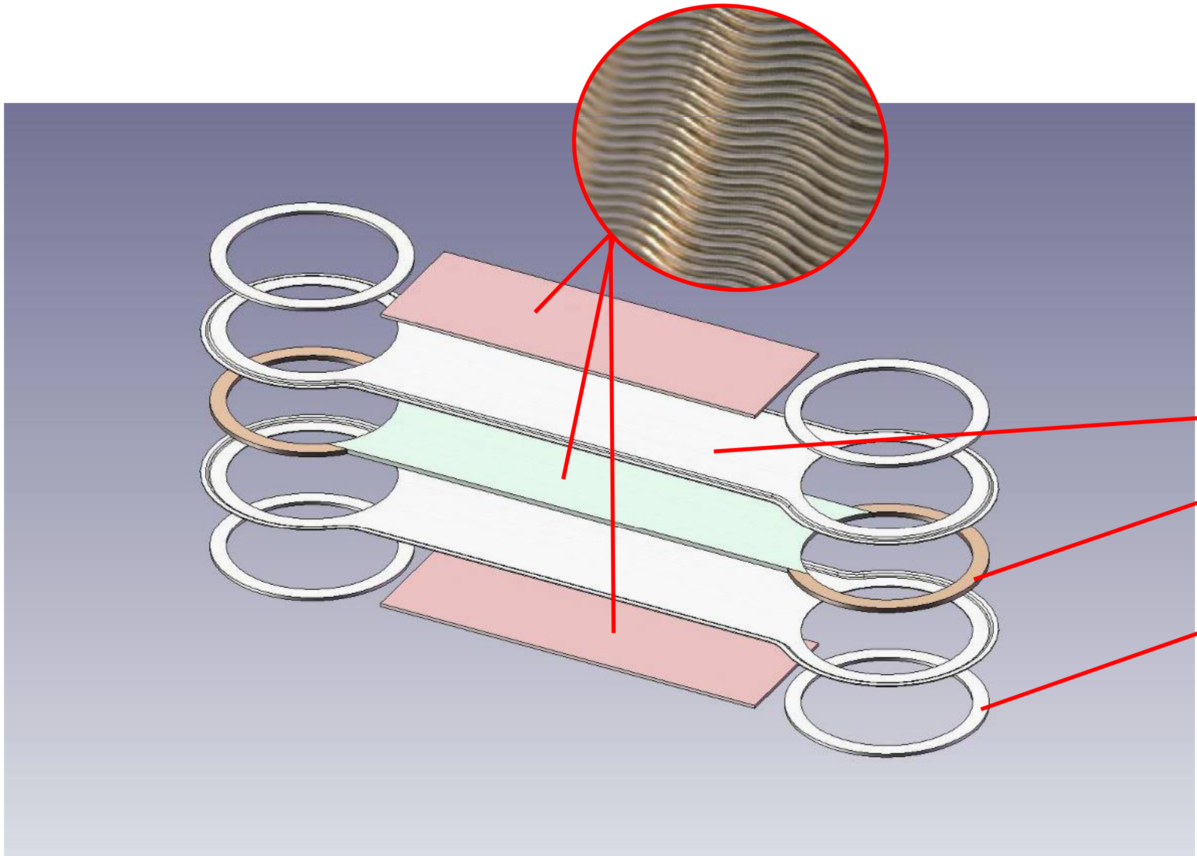
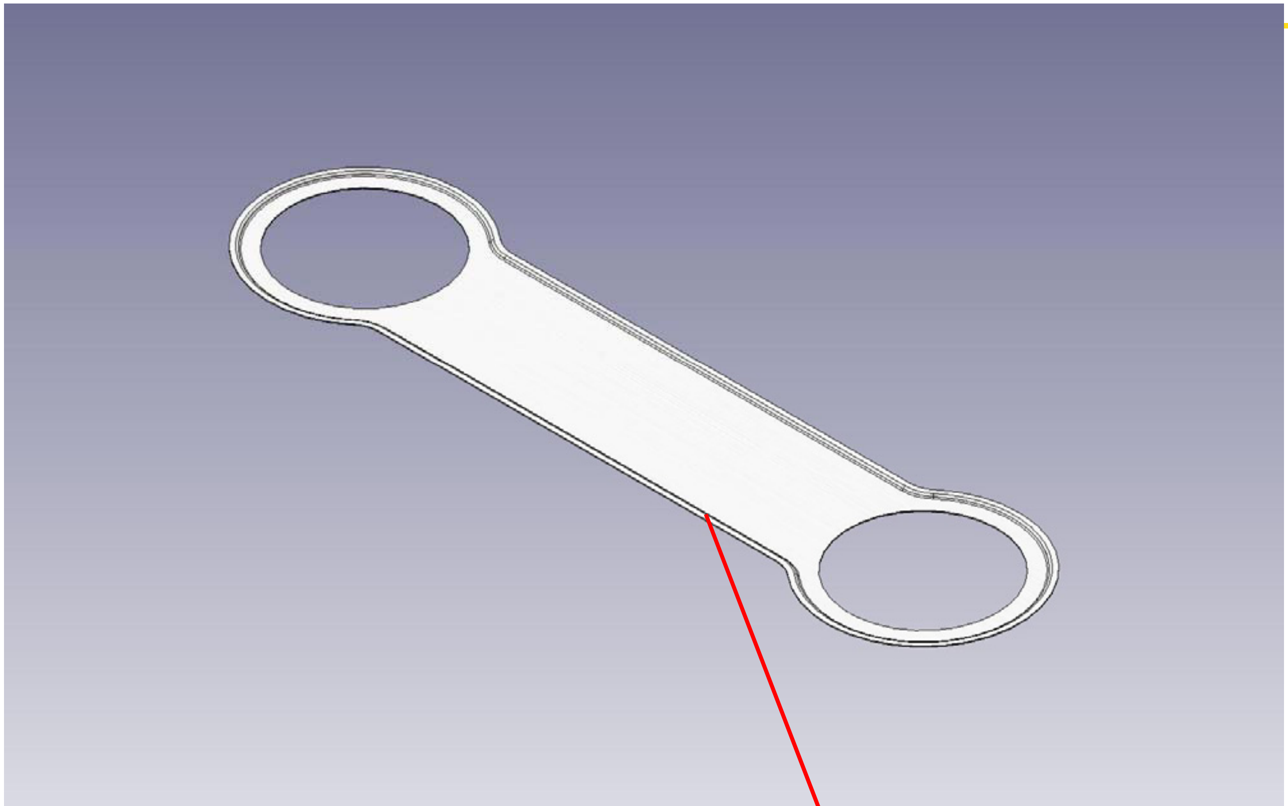
Unit-Cell Construction
Exploded View

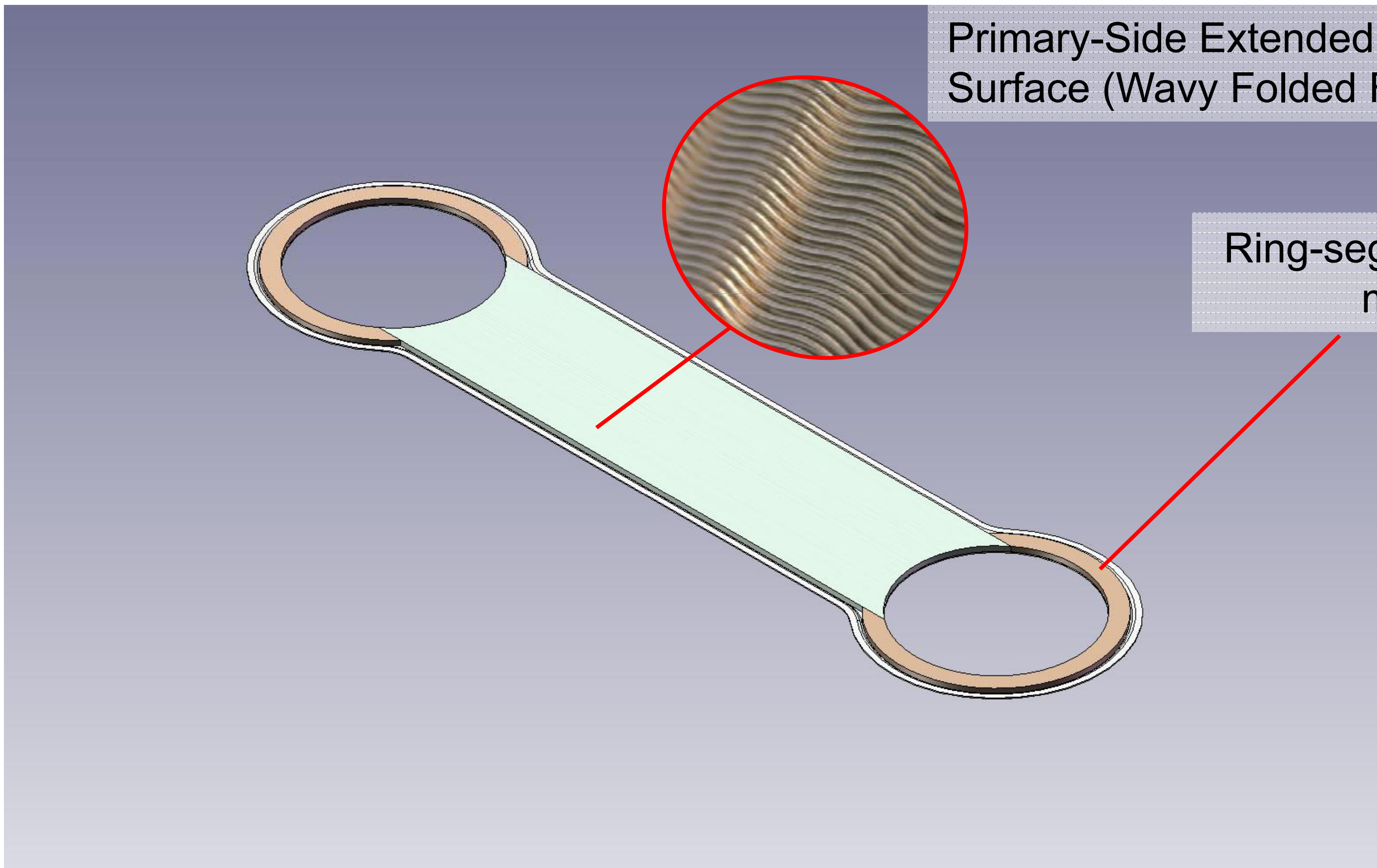


Parting Sheet

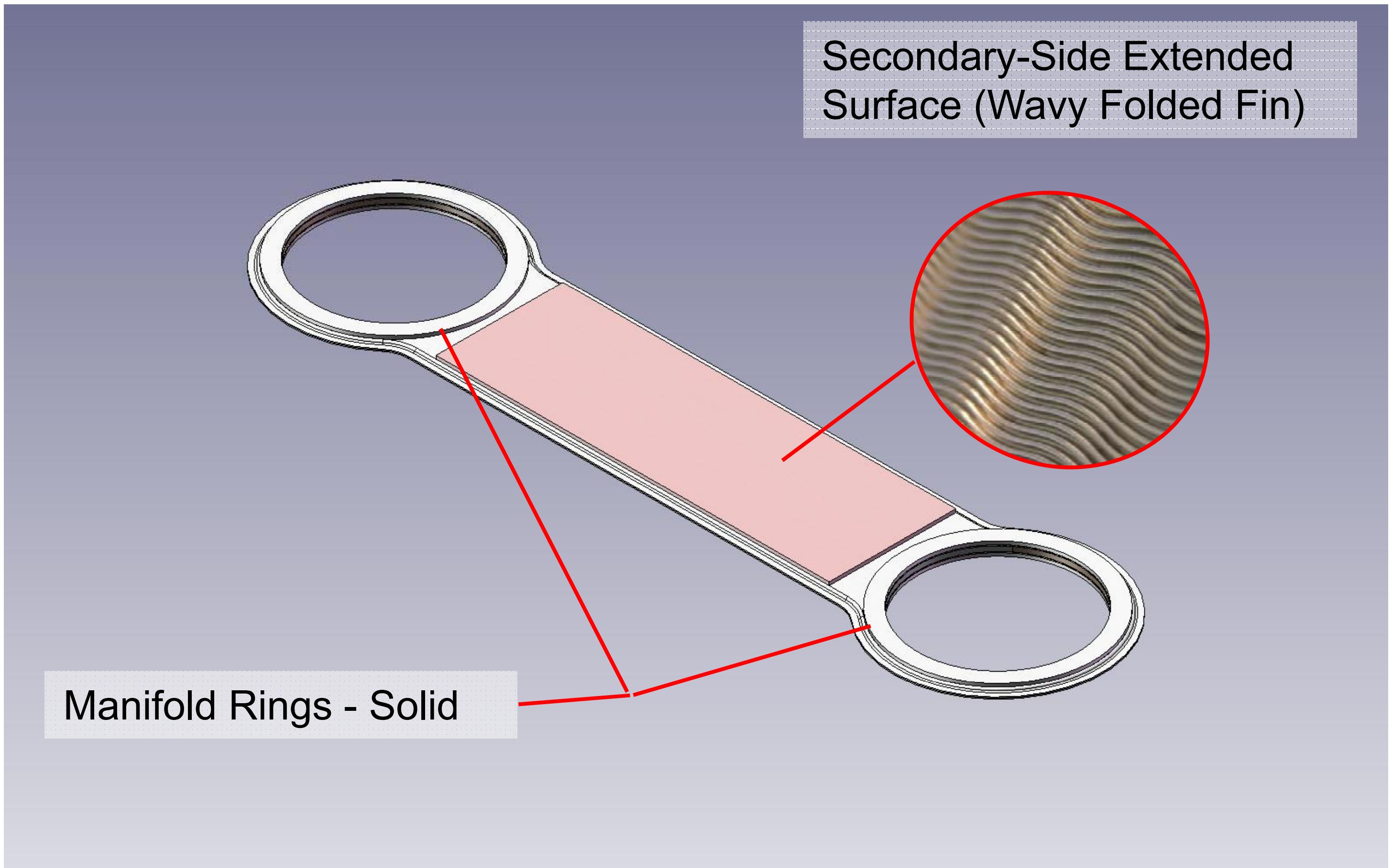


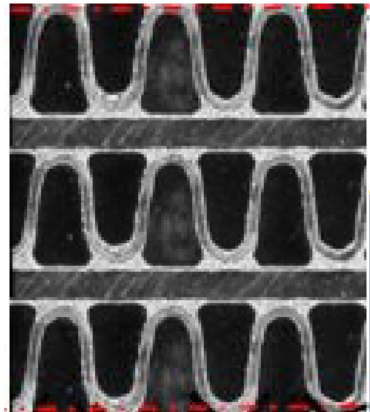
Formed Edged of Parting Sheet
Creates Pressure Boundary

Unit-Cell Internal Detail

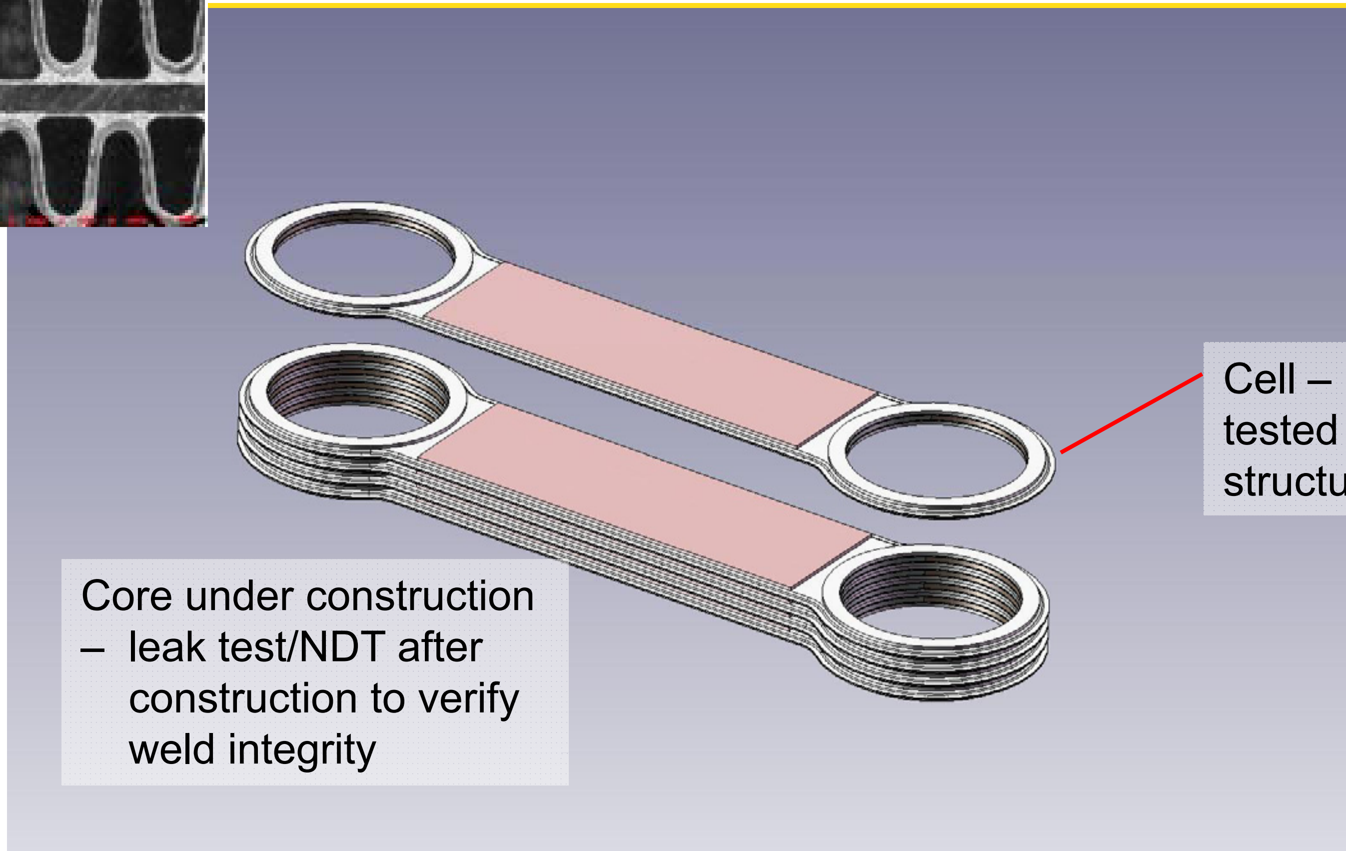


Complete Unit-Cell (Brazed Assembly)



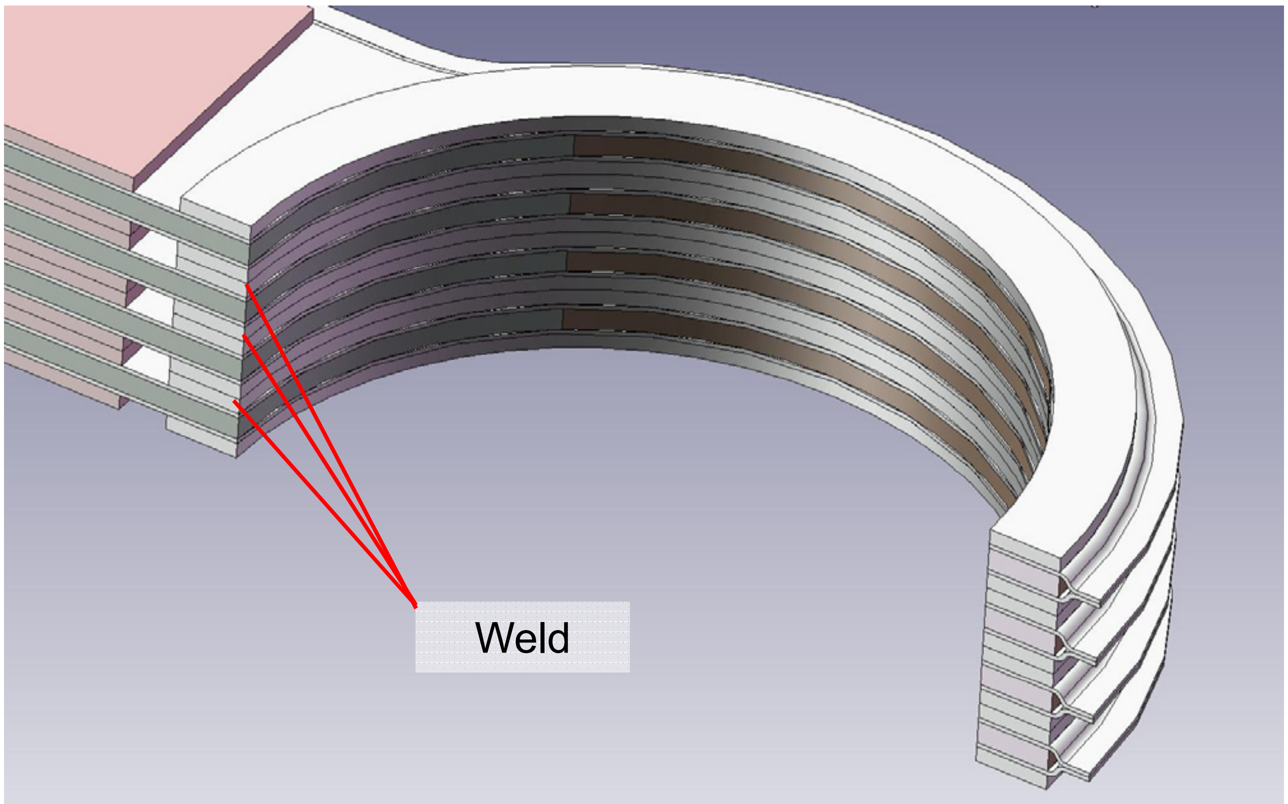


Core Construction
Join at Manifolds

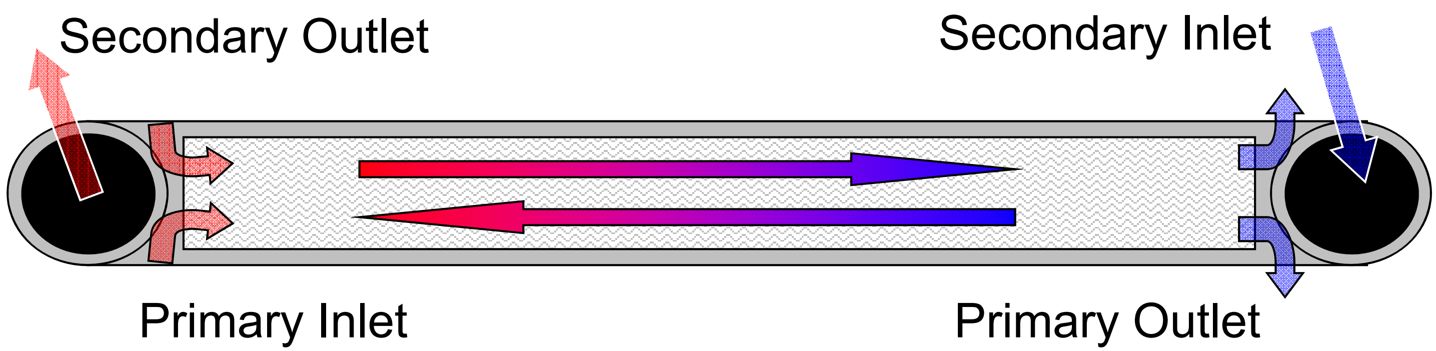


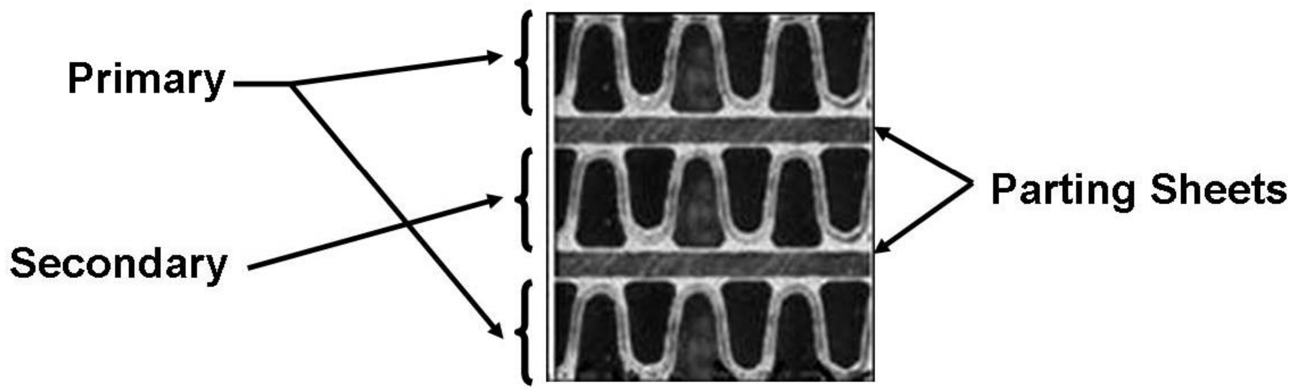
Cells welded at manifolds <u>only</u> to create core. Construction allows slip between cells for low stress

Cell-Cell Weld Location

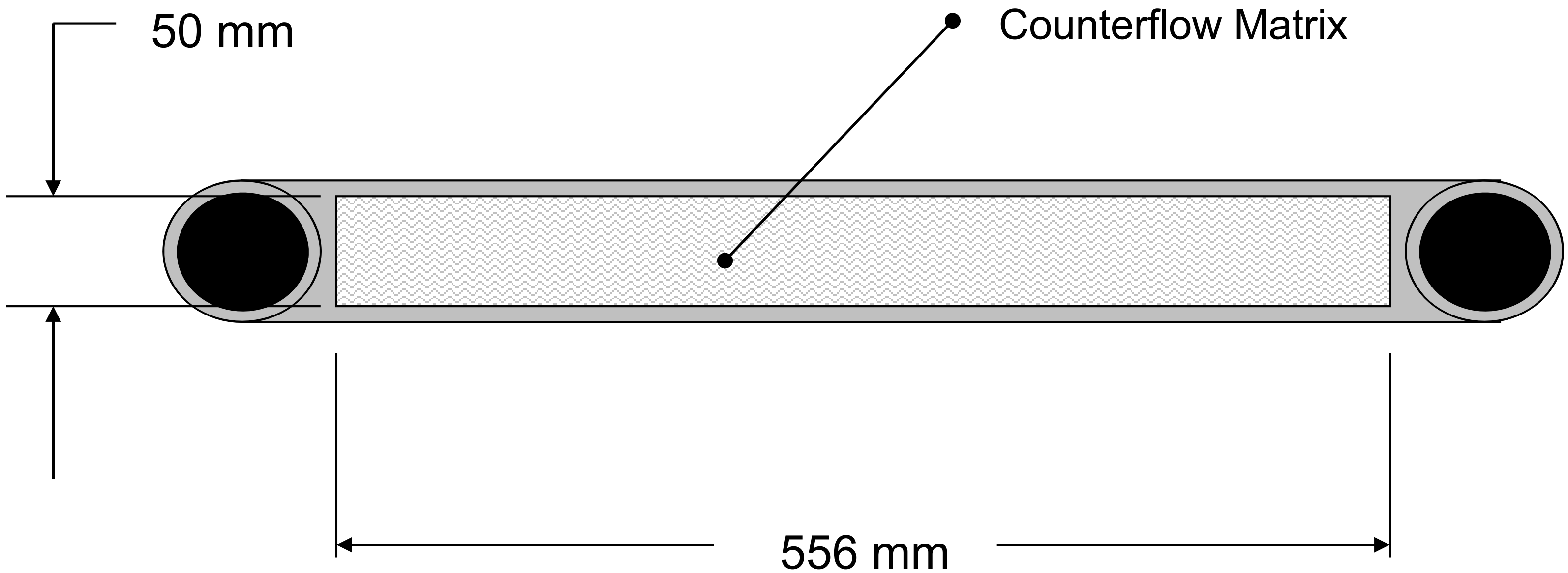


Unit Cell Flow

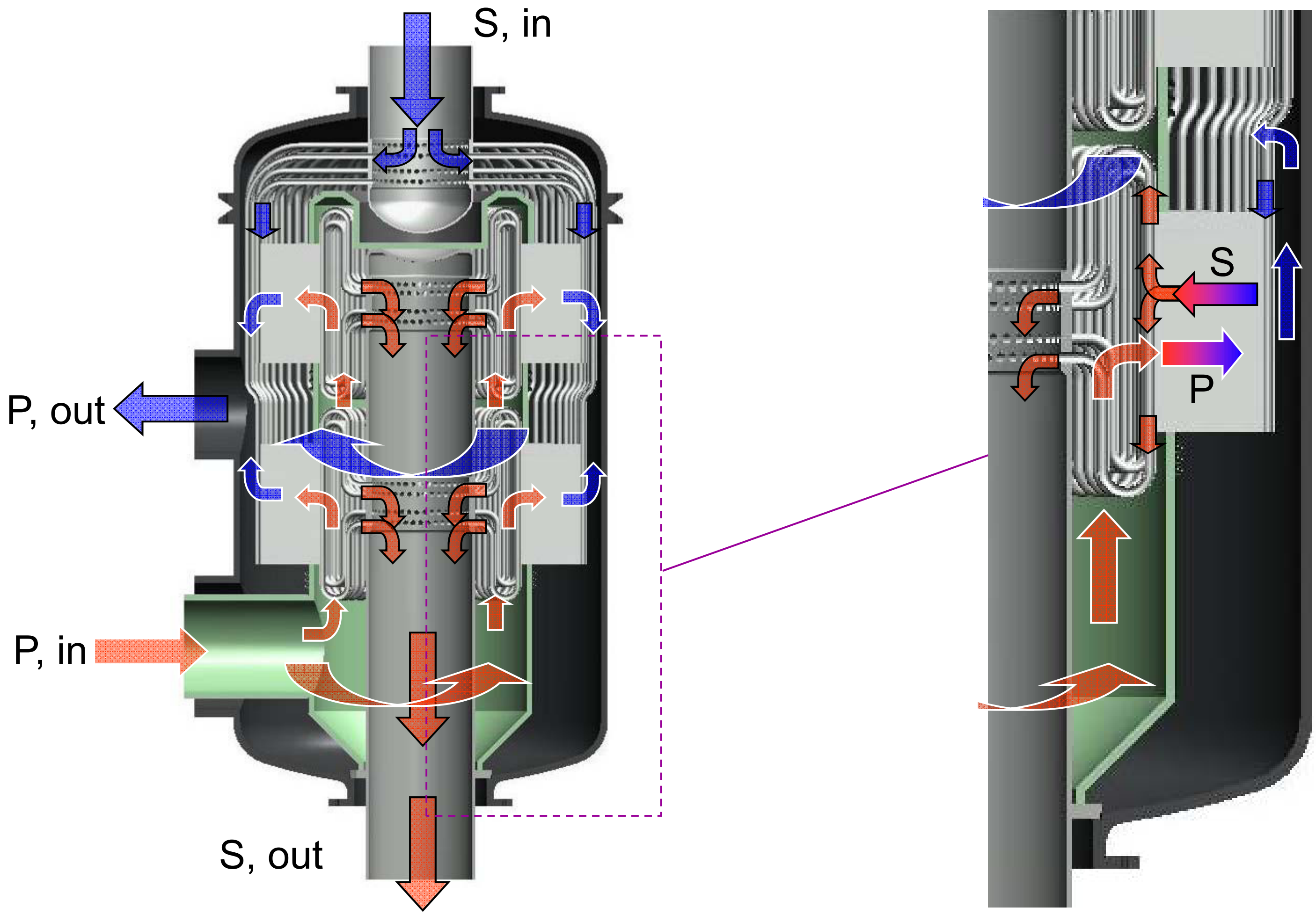




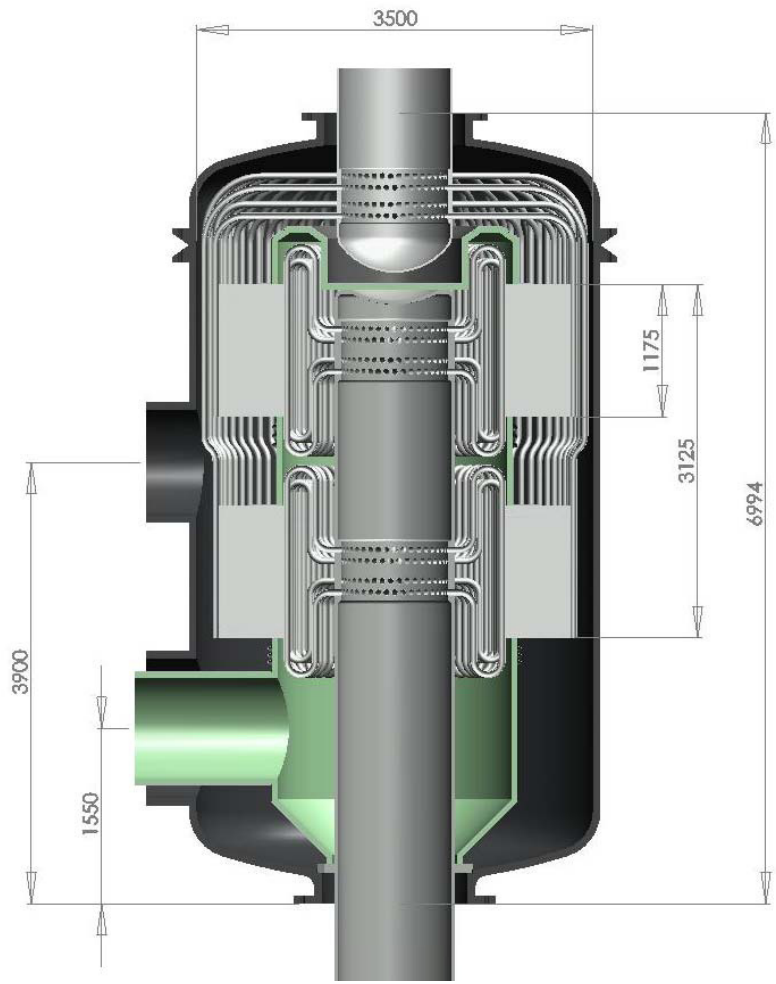
Basic Cell Dimensions for 800C ROT Design



IHX Layout for 750-800˚C ROT – Flow Circuits



IHX Design for 750-800˚C ROT



Internals:

- Alloy X Construction
- 160 Cores, each 1175 mm tall
- Two radial arrays
- PHTS coupled to shell-side

Vessel:

- 3500 mm inner diameter
- 5000 mm cylinder
- 6994 mm overall length

Work Remaining in IHX Design

- Refine layout for selected coupling option
- Preliminary thermal/structural assessment of IHX at 750-800°C using results of transient analysis work (to be discussed later in this review)

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Evaluation of Materials for 750°C to 800°C Application

- Comparison of Alloy 800H and Hastelloy X for single vessel IHX operating at an ROT of 750°C or 800°C
- Factors included in the comparison were:
  - Characteristics and uses
  - Alloy chemistry and specifications
  - Status of ASME Code qualification
  - Mechanical Properties
  - Thermal/physical properties
  - Effects of thermal exposure on properties
  - Manufacturing and joining
  - Material cost
  - Corrosion performance

Observations on Properties, Availability, Use and Cost

- Mechanical and thermal/physical properties and thermal stability of Alloy 800H are suitable for the IHX application at both 750°C and 800°C
- Mechanical and thermal/physical properties of Hastelloy X are moderately better than those of Alloy 800H at both temperatures
  - Thermal stability is slightly less than that of Alloy 800H, but more than adequate for the application.
- All product forms required for the manufacture of the IHX are readily available for both Alloy 800H and Hastelloy X from a number of suppliers
- High-temperature service experience with both alloys is extensive and excellent
- Cost of Hastelloy X may be as much as 75% greater than Alloy 800H
  - Likely insignificant in terms of the overall initial plant cost

Observations on Manufacturability

- Formability
  - The materials used for plates, fins, manifolds, pipes, ducts, etc. needed in the construction of the PCHE and PFHE designs need to be readily formable
  - Both Alloy 800H and Hastelloy X meet this requirement
- Weldability
  - Well established techniques and standards exist for the successful welding of Alloy 800H and Hastelloy X, both to themselves and, where necessary, as bimetallic joints
- Diffusion Bonding and Brazing
  - The diffusion bonds and braze joints required for the PCHE and PFHE, respectively, are feasible but require additional technology development for confirmation
- Hastelloy X is superior to Alloy 800H in terms of brazing

Observations on Corrosion

- Corrosion of thin sections of the IHX core is likely the limiting factor in achievable lifetime, both for Alloy 800H and Hastelloy X
  - Rates of corrosion in both primary and secondary circuit He are best defined by depths of internal oxidation and depletion of Cr
  - Corrosion in secondary circuit He should be less than that in primary circuit He because control of impurity levels will be easier
- The depth of Cr depletion for Hastelloy X exposed to simulated PHTS He at 750°C is only about 25% that of Alloy 800H
  - It is generally observed that the corrosion rates for Hastelloy X in oxidizing and corrosive environments are no greater than 30% of those for Alloy 800H
- Depths of internal oxidation and Cr depletion in primary and secondary circuit He and the effects of these on properties need to confirmed through technology development

Status of ASME Codes

- Alloy 800H is the only material applicable to the IHX that is currently qualified for nuclear service (ASME Section III, Subsection NH).
  - Qualified in Subsection NH to 760°C
  - Application at 800°C would require extension of Code temperature limits.
  - Per ASME/DOE agreement, sufficient data are available to permit this extension for Alloy 800H. Qualification over a 2 to 3 year period is feasible.
- Hastelloy X is not currently qualified under ASME Section III, Subsection NH but is a candidate for inclusion in ASME Section III Code Case N-201 for core support applications
  - Sufficient data are available to qualify Hastelloy X under Section III for IHX service. This could be accomplished in a 3 to 5 year period.
- Use of either material at any temperature will require the development of an ASME-approved design code applicable to compact heat exchangers, or an acceptable alternative

Important Technology Development Needs

- Determine corrosion rates in terms of depths of internal oxidation and Cr depletion for Alloy 800H and Hastelloy X in both primary and secondary circuit He
- Determine the effects of these corrosion parameters on properties and thin section integrity
- Establish parameters and standards for the diffusion bonding and brazing of Alloy 800H and Hastelloy X
- Characterize the properties and behavior of the diffusion bonds and braze joints
- Extend ASME Section III, Subsection NH qualification of Alloy 800H to at least 850°C
- Establish ASME Section III, Subsection NH qualification for Hastelloy X to at least 850°C
- Develop ASME Section III design code for compact heat exchangers, or acceptable alternative

Major Conclusions

- Hastelloy X is the preferred material for thin section components in the IHX cores
  - Primarily because its corrosion resistance is far superior to that of Alloy 800H
- However, Alloy 800H is a prime candidate for thick section components (manifolds, ducts, etc.) in the IHX
  - It has the advantage of lower cost and ASME Section III qualification up to 760°C
- Use of Alloy 800H at 800°C and Hastelloy X at either 750°C or 800°C will require qualification within Section III of the ASME Code
- ASME design codes for compact heat exchangers, or an acceptable alternative, must also be developed
- There are Technology Development needs in areas related to joining, corrosion, and ASME Code qualification
  - These have been detailed in the recent TDRM exercise.

IHX-HTS INTEGRATION

Scott Penfield

IHX/HTS Priority Task
50% Design Review

May 8, 2009

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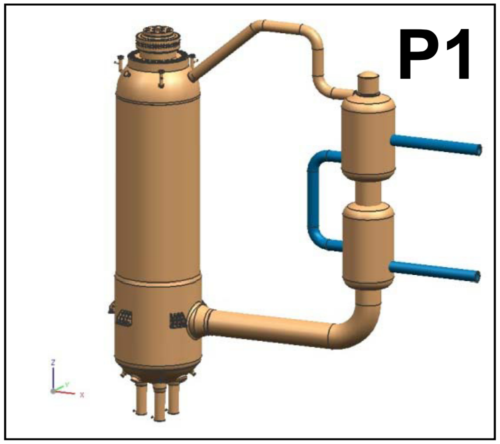
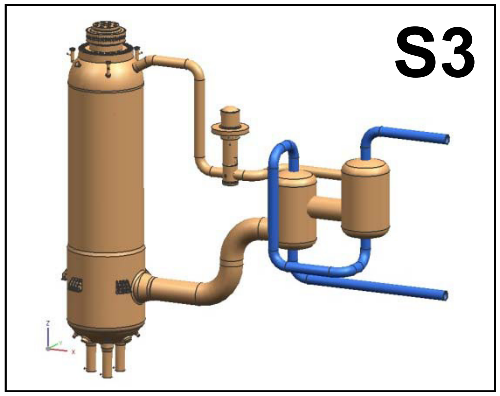
Reevaluation of Coupling Options

Results of 2008 IHX/HTS Conceptual Design Study

- Both Options P1 (core-side) and S3 (shell-side) coupling to PHTS viewed as potentially being able to meet requirements
- Consideration of core- vs. shell-side coupling to the PHTS involves a number of tradeoffs, notably:
  - HTS layout and building integration
  - Pressure bias during normal operation and during loss of secondary pressure (Licensing Basis Event)
  - Insulation and cooling of vessels and piping
  - Access for inspection and maintenance

Developing the information to resolve the core-side vs. shell-side coupling issue was beyond the scope of the original study





Reevaluation of Coupling Options

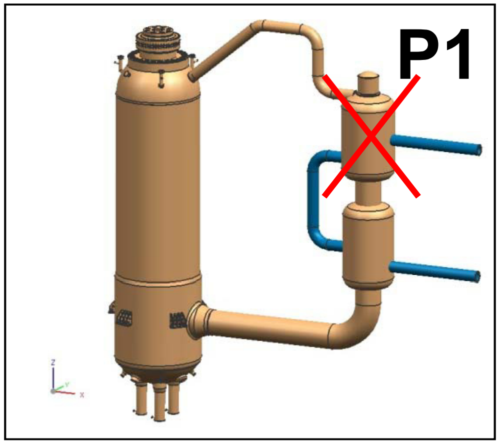
Original Plan for this Priority Task

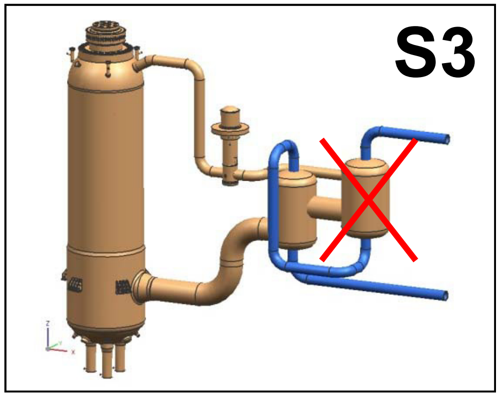
- IHX Design
  - Develop layouts for both coupling options
- Piping and Building Integration
  - Develop piping and building layouts for both coupling options
  - Assess differences in layout efficiency and supports (vessels and piping)
- Transient Assessment
  - Develop transient models for both layouts and assess differences in response to limiting LBEs
- Using the above inputs, reevaluate coupling options and select preferred architecture

In the course of initial work, it became evident that a selection might be possible without detailed development and assessment of two configurations

Reevaluation of Coupling Options
What Has Changed: Reduction in Temperature

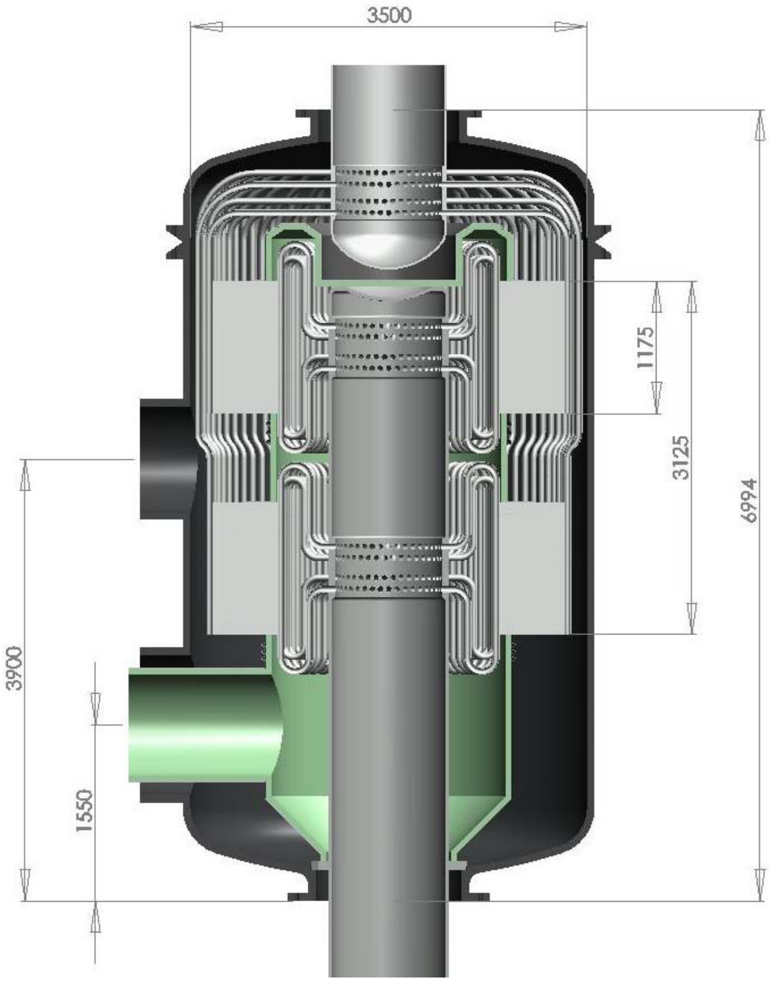
- Reactor core outlet temperature has been reduced from 950°C to 750-800°C
  - ➢ At these temperatures, it is possible that the IHX core can be designed to operate for the entire life of the plant
- Conclusion: Use single-vessel IHX





Reevaluation of Coupling Options

What Has Changed: 2-Vessel vs. 1-Vessel Comparison



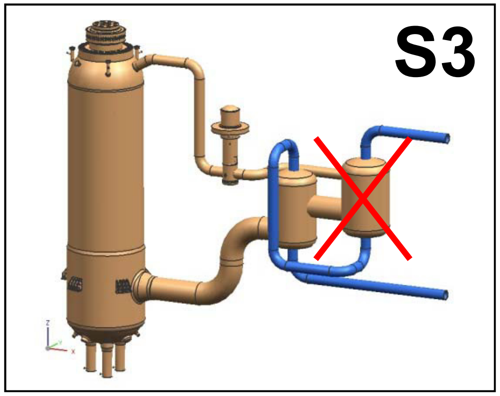
Feature	950°C H_2		750-800°C
	IHX A	IHX B	
Power, MWt	157	350	511
Number of Cores	138	170	160
Core Material	I-617	800H	Hastelloy X
Vessel OD, m	3.0	3.3	3.5 (ID)
Vessel Height, m	6.6	6.8	7.0
Total Weight, t	125		TBD

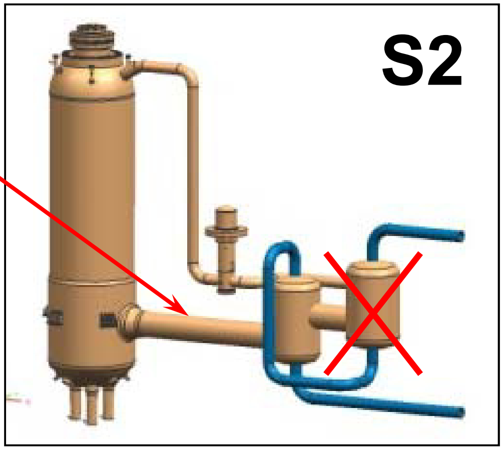
Comparison suggests that 2-vessel IHX may not be best solution, even for H_2 at 950°C

Reevaluation of Coupling Options

What Has Changed: Neutron Streaming

- Significance of neutron streaming reevaluated
  - More recent DPP assessments indicate that neutron streaming will be low from reactor outlet plenum
  - Materials recommended for IHX at 750-800°C less prone to activation
- Conclusion: Straight HGD an option for shell-side coupling

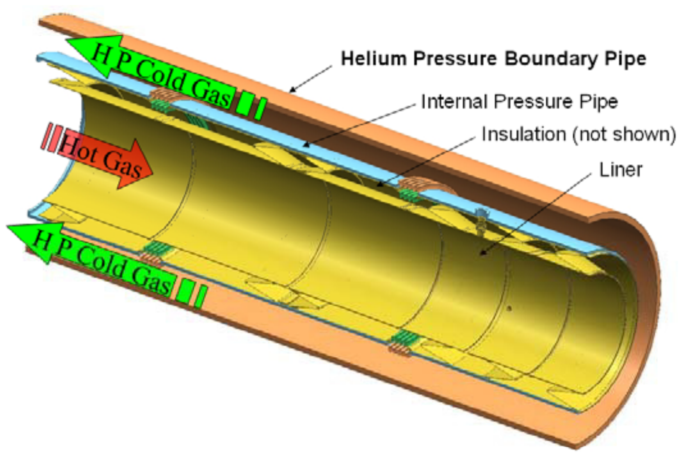


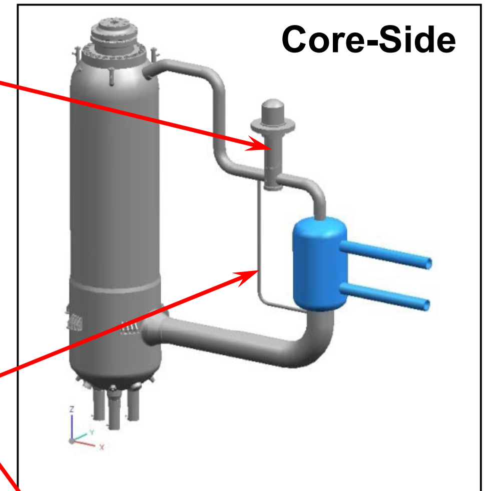


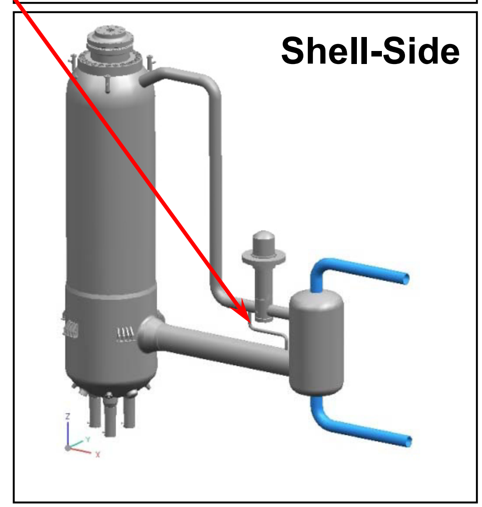
Reevaluation of Coupling Options

What Has Changed: Initial Vessel/Piping Layouts for 750-800°C

- Size of PHTS circulator will not allow integration with IHX vessel for core-side coupling option
- HGD annulus cooling gas must be diverted from circulator outlet for both options

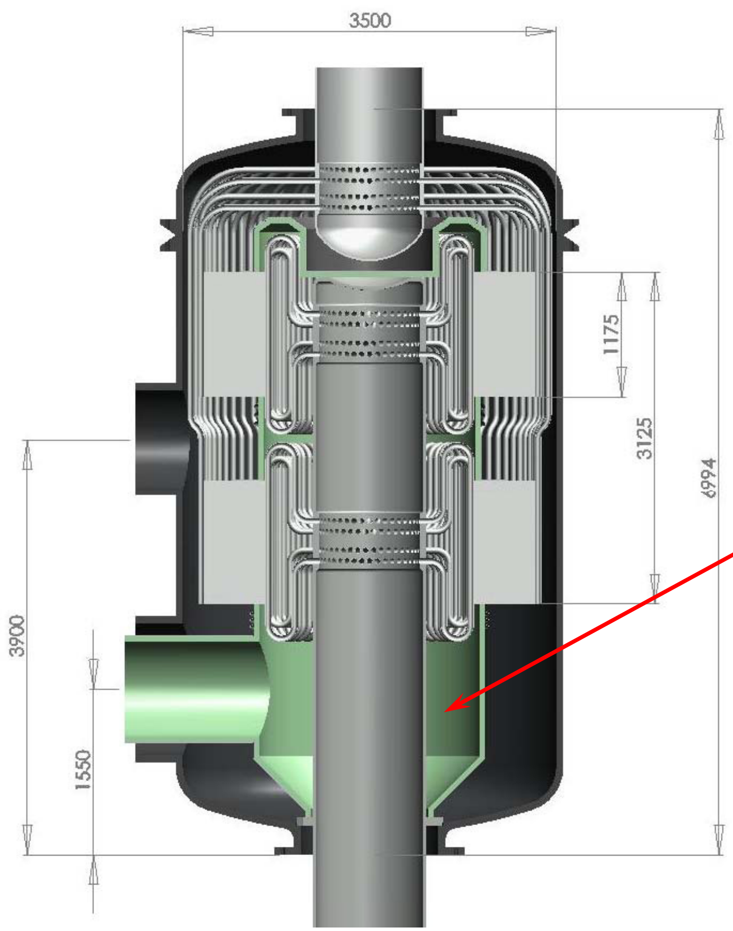






Reevaluation of Coupling Options

What Has Changed: Increased Concern with Dust

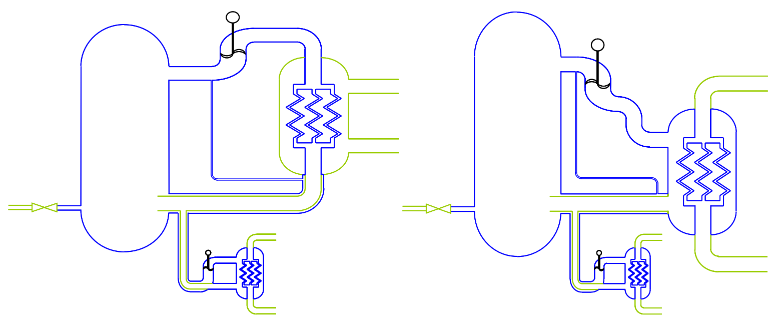


- Shell-side coupling offers additional options for mitigation of dust effects
  - ➢ Less direct path to heat transfer modules
  - ➢ Potential to use shell-side baffle as dust separation device

Reevaluation of Coupling Options

Evaluation Approach

- As in the 2008 IHX/HTS Conceptual Design Study, the evaluation of the PHTS/IHX coupling options was done in three steps:
  - Listing design, development, fabrication, operation and cost characteristics for each option and identifying advantages and disadvantages
  - Review and update of evaluation criteria
  - Quantification of the stated advantages and disadvantages using the Kepner-Tregoe methodology



Core-Side Coupling **Shell-Side Coupling**

Reevaluation of Coupling Options

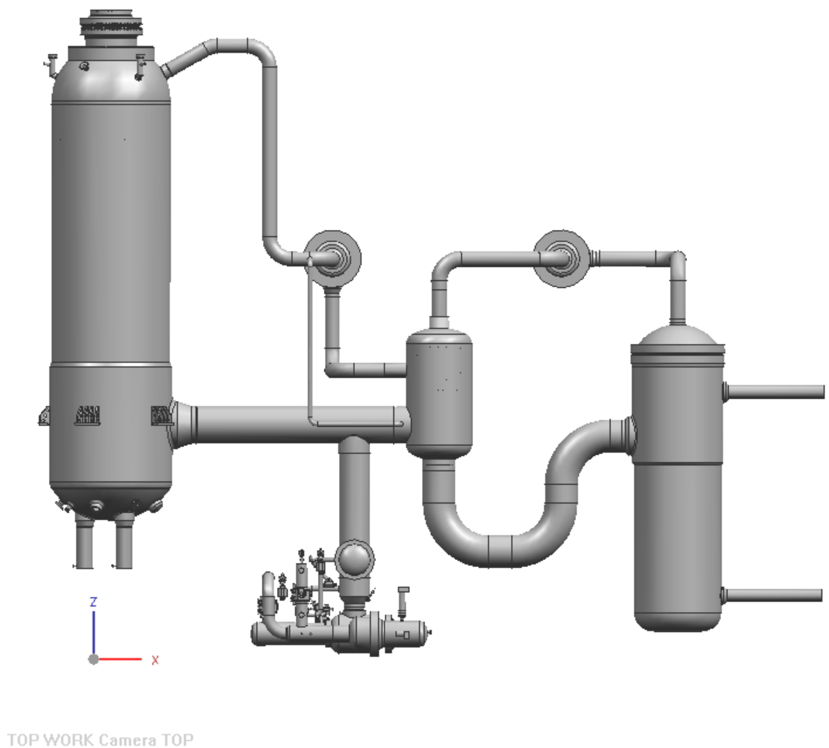
Summary of Key Decision Factors

Core Side Coupling	Shell Side Coupling
• The IHX shell-side internal ducts and baffling operate at **slightly lower temperatures** • Smaller (~5-10% less) total PHTS helium inventory **could reduce** predicted **radionuclide releases** resulting from PHTS pipe break LBE	• The RPV and IHX vessel **supports are simpler** • The **hot gas duct** is **straight and shorter** • For a LOSP, the IHX core side is loaded (~ 9 MPa) in **compression** • Maintenance/ISI access is available from **uncontaminated** SHTS side • Potential for **dust mitigation** measures
• **Longer and more complex** hot gas duct • For a LOSP, the IHX core side is loaded (~ 9 MPa) in **tension** • Maintenance/ISI access requires reactor **isolation** and **opening** of PHTS pressure boundary	• The IHX shell-side internal ducts and baffling operate at **slightly higher temperatures** • Larger (~5-10% more) total PHTS helium inventory **could increase** predicted **radionuclide releases** resulting from PHTS pipe break LBE

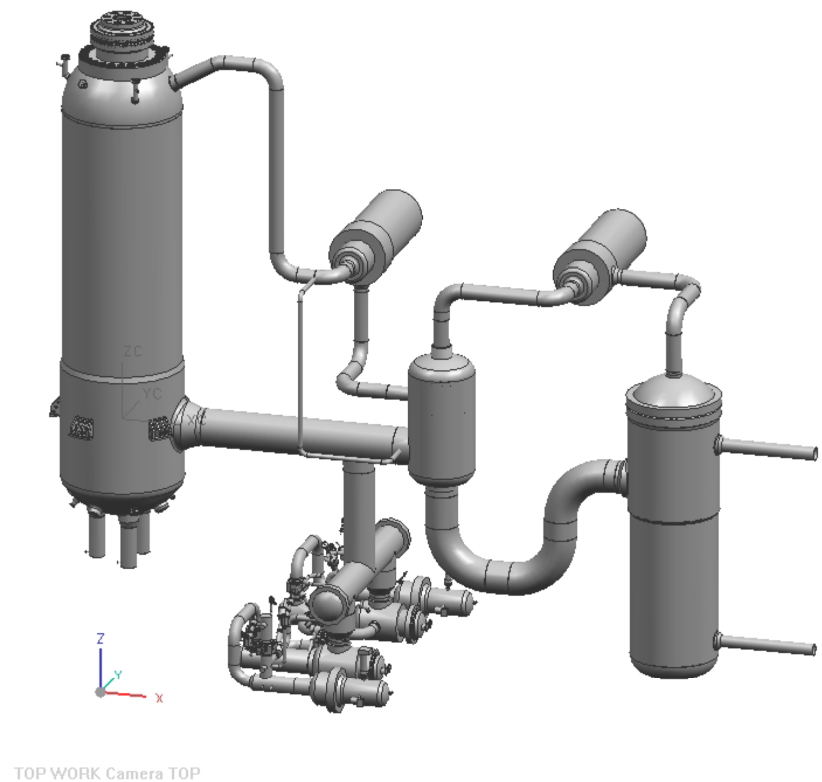
Reevaluation of Coupling Options
Results and Recommendations

- It is recommended that the shell-side of the IHX be coupled to the PHTS because:
  - ➢ Simpler arrangement of the vessels and their supports; particularly the Hot Gas Duct
  - ➢ Reduced likelihood of IHX internal pressure boundary failure during the loss-of-secondary-pressure licensing basis event
    - HX module cores in compression
  - ➢ Improved access for maintenance and ISI
    - Access is from the uncontaminated SHTS side
  - ➢ Operation with a better helium chemistry control and absence of dust on the core side of the heat exchanger modules
    - Internal fins are structural components; external fins are not
  - ➢ Slightly lower capital and operating costs

Piping Integration
Overview

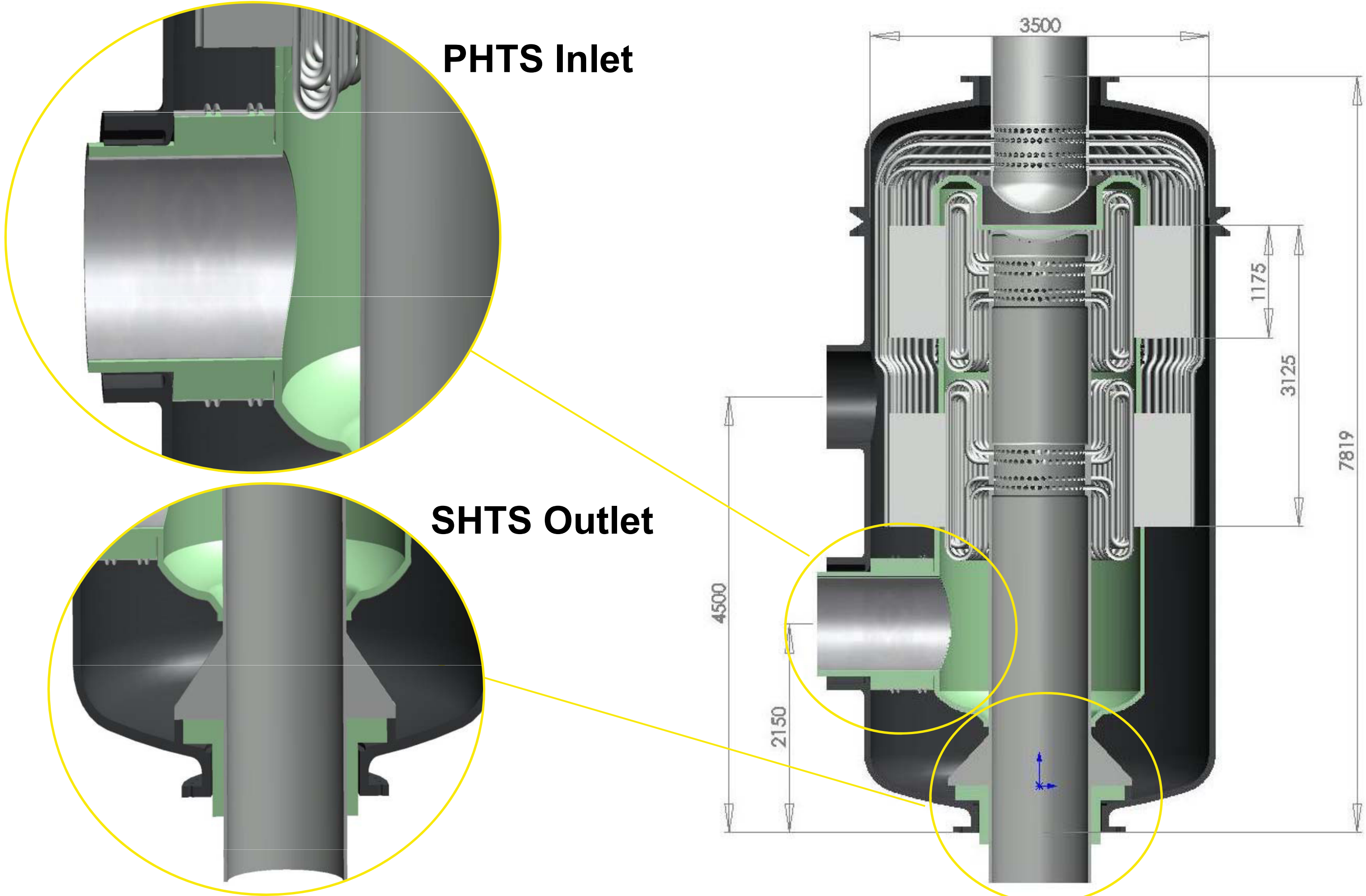


Elevation View

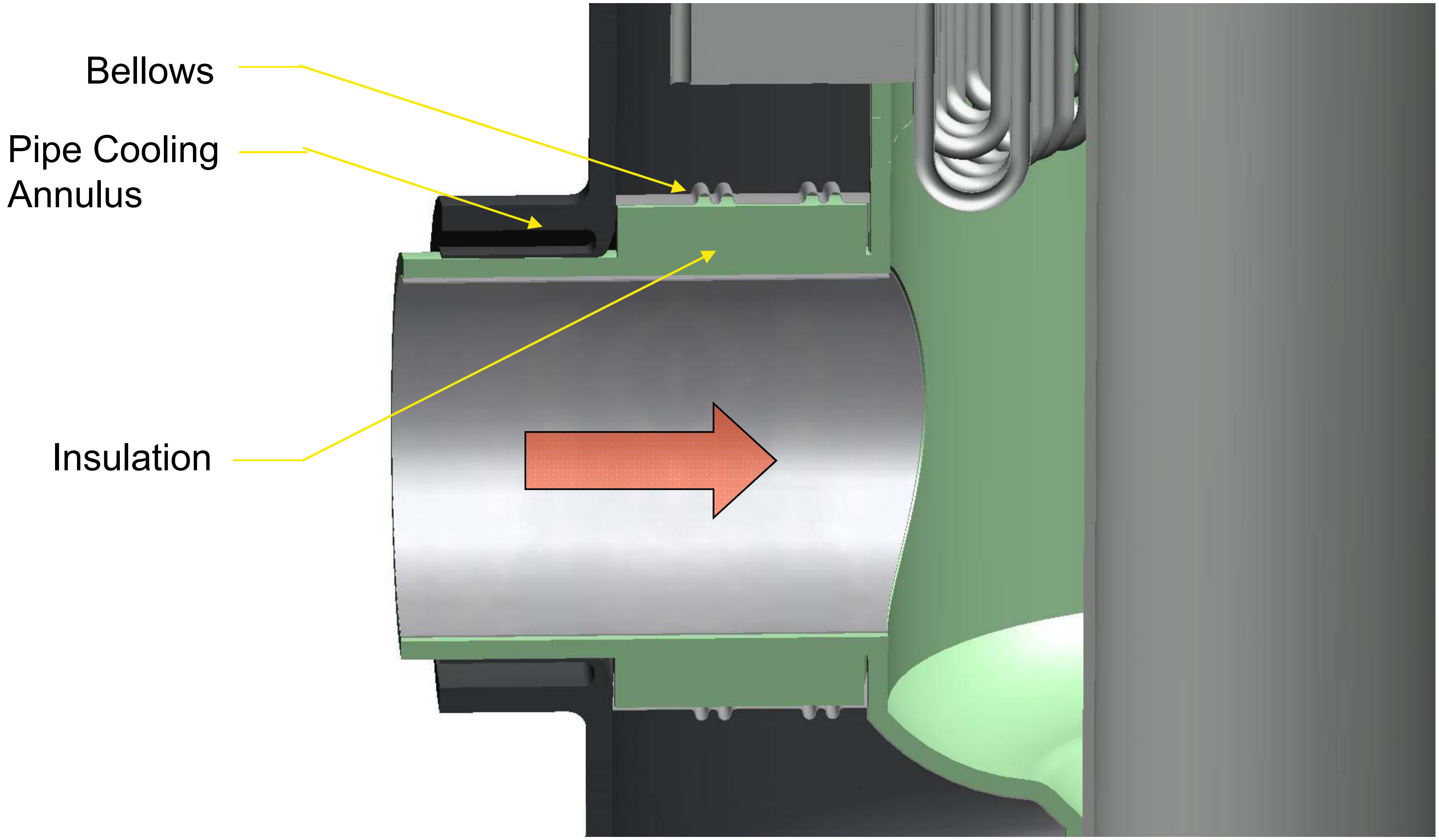


Isometric View

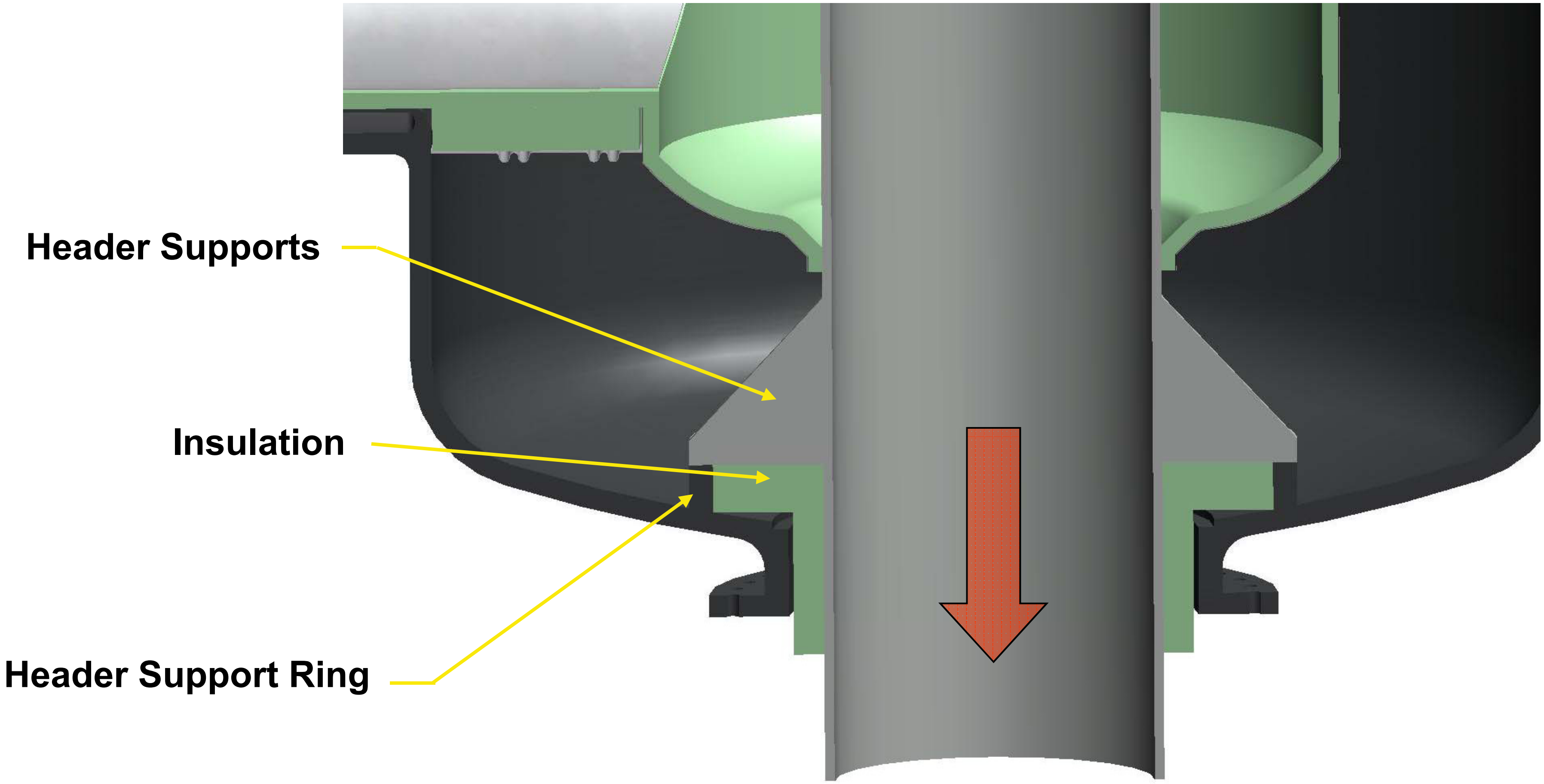
IHX Hot Interface Concept Details



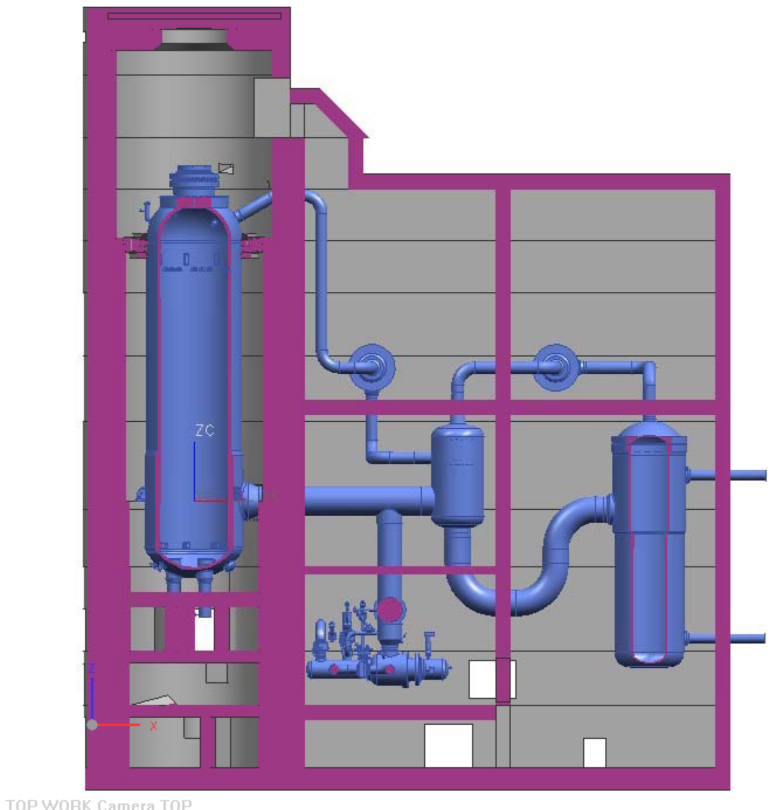
PHTS inlet Concept Detail



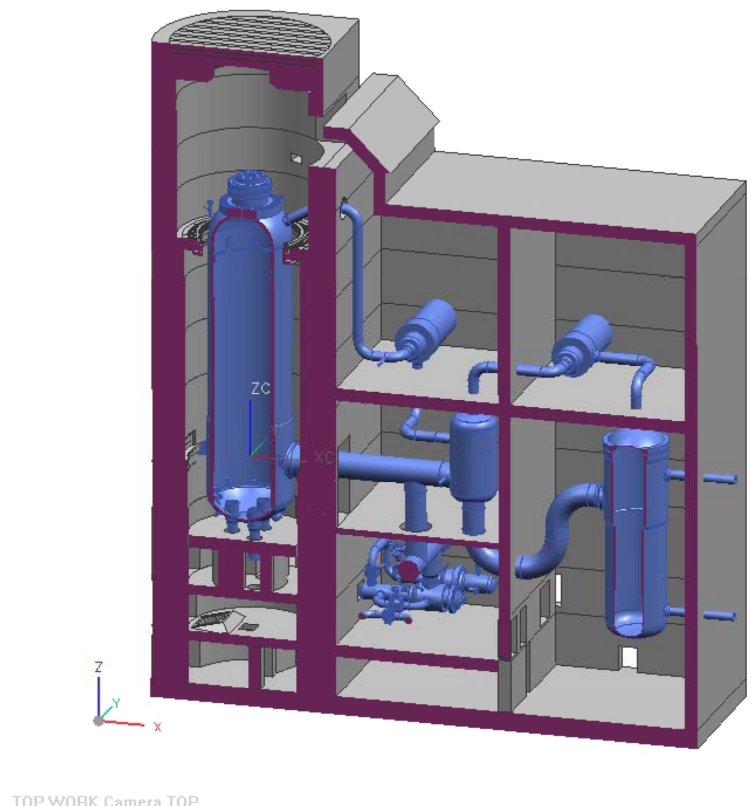
SHTS Outlet Concept Detail



Building Integration



Elevation View



Isometric View

Summary of Remaining Integration Work

- Refine IHX/piping internal interfaces
- Identify reference IHX vessel insulation approach
- Refine building integration layout to include conceptual support concept

PRELIMINARY ASSESSMENT OF IHX TRANSIENTS

Wilma van Eck
Desna Pretorius
Bernard Muller

IHX/HTS Priority Task
50% Design Review

May 8, 2009

PBMR TEAM

P B M R

Shaw®

Agenda Overview

Introduction
- Background
- Objectives and Approach

Subtask 1: Requirements and Interfaces
- IHX Functions
- Key Requirements and Bases

Subtask 2: IHX Design
- Review of IHX Unit Cell Design
- IHX Layout for 750-800°C ROT
- Materials Evaluation for 750-800°C ROT

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- Reevaluation of Coupling Options
- IHX-Piping Integration
- IHX-NHSS Building Integration

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- Development of IHX Transient Model and Integration with FPT Model
- Assessment of Limiting Transients

Status of IHX/HTS Priority Task
- Summary of Work Remaining
- Issues and Projected Solutions
- Cost & Schedule Performance

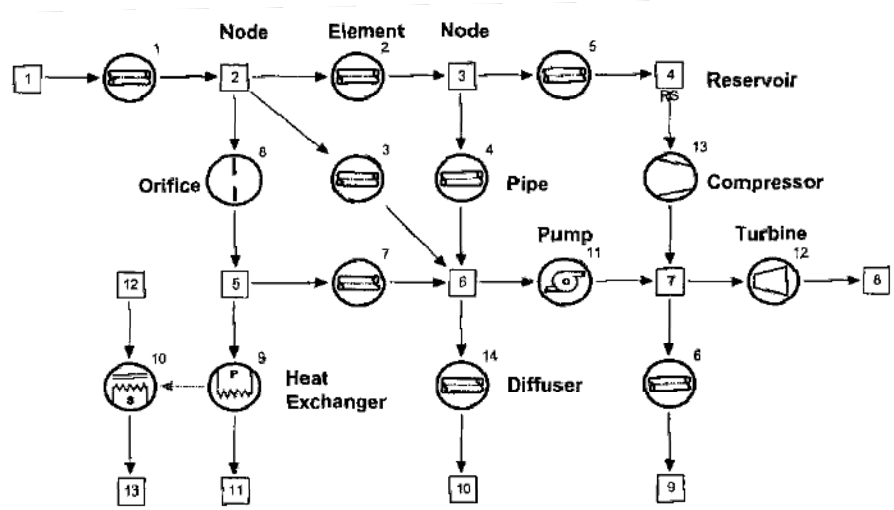
Contents

- FLOWNEX background
- Model description
- Transient definitions
- Results
- Conclusion and outstanding issues

FLOWNEX Code Overview

FLOWNEX is a thermal-fluid network analysis code. It is based on the numerical solution of flow, pressure and temperature distribution in any unstructured collection of one-dimensional elements with connecting nodes by implementing the conservation laws of mass, momentum and energy. It is an integrated systems-CFD code used for the design, simulation and optimization of thermal-fluid systems such as:

- Gas, steam or combined cycle power plants
- High temperature gas-cooled nuclear power plants
- Gas turbine combustion chambers
- Aircraft air conditioning systems
- Oil and gas distribution networks
- Heat exchanger networks
- Ventilation systems



FLOWNEX Background

- FLOWNEX is widely used in industry.
- At PBMR, FLOWNEX has been used to model the:
  - Pressure relief system (PRS)
  - Core barrel conditioning system (CBCS)
  - Core conditioning system (CCS)
  - Fuel handling and storage system (FHSS)
  - Main power system integration (MPS)
  - Turbo generator system (TGS)
  - Primary loop initial cleanup system (PLICS)
  - Helium test facility support (HTF)
  - Core connection test facility (CCTF)
  - Reactor unit - advanced model and flow model
  - NGNP

- Rolls Royce (UK)
- Qinetiq (UK)
- Mitsubishi Heavy Industries
- Massachusetts Institute of Technology (USA)
- Cranfield University (UK)
- ConceptsNREC (USA)
- PCA Engineers (UK)
- QfinSoft (Canada)
- Institut für Kernenergetik und Energiesysteme (Germany)
- Netherlands Reactor Group
- (Netherlands)
- PBMR (Pty.) Ltd. (RSA)
- ESKOM (RSA)
- TWP Consulting Engineers (RSA)
- Kobe Steel (Japan)
- Samsung Thales (Korea)
- SASOL (RSA)
- IST / Westinghouse (RSA)
- Defencetech (RSA)
- Denel Aviation (RSA)
- Steinmuller (RSA)
- Resonant Solutions (RSA)
- Aerosud (RSA)
- Anglo Operations Ltd. (RSA)
- HMS Sultan (UK)
- Beijing Institute of Petrochemical Technology (China)
- Mittal Steel (RSA)
- Hyosung Corporation
- Korea Aerospace University (South Korea)
- Samyang (South Korea)
- Royal Navy (UK)
- Babcock Engineering (RSA)

Contents

- FLOWNEX Background
- ➡ Model Description
- Transient Definitions
- Results
- Conclusion and Outstanding Issues

Model Description

- IHX Model Inputs
  - ➢ The geometry is calculated from first principles based on core layout
  - ➢ Heat exchanger performance independently calculated from:
    - Basic geometry of unit cell
    - Number of unit cells
    - Empirical correlations for friction factor and $StPr^{2/3}$ supplied by Brayton Energy
  - ➢ Calculation performed with effectiveness NTU method
  - ➢ Steady state results reflect good correspondence with Brayton Energy data
- Assumptions
  - ➢ Uniform flow distribution across cores
  - ➢ Plugging allowance not accounted for in the thermo-hydraulic model
  - ➢ Model does not presently include heat transfer outside cores
  - ➢ Thermal capacitance of internal structures is not yet modeled

Model Description

- IHX model integrated into NHSS model
  - Developed in Fission Product & Plant Level Assessment Task
- Value of detailed model:
  - Provides design data for the IHX based on its integrated behavior with the NHSS and control system
  - Ability to determine dynamic response due to material mass and gas volumes (improvement from pre-conceptual design phase)
  - Can supply input for structural analyses

Contents

- FLOWNEX Background
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Preliminary IHX Transients - Description

- Case 1: Double Ended Guillotine Break of the largest pipe in the SHTS (preliminary)
  - Circulators trip
  - Check valves close
  - Reactor shuts down
  - Decay heat removal system starts up
  - PHTS starts depressurizing.
- Case 2: SHTS Circulator failure (to be done)
  - PHTS Circulator fails to trip
  - Reactor shuts down
  - Decay heat removal system starts up
  - PHTS and SHTS starts depressurizing

Control Strategy

- Preliminary control strategy developed in pre-conceptual phase
- Adjusted as part of Plant Level Assessment Task
- To be refined in conceptual design phase

Preliminary IHX Transients - Description

Case 1: Double Ended Guillotine Break of the largest pipe in the SHTS

t=0s:

- Double ended guillotine break in the SHTS (cold leg pipe)
- PHTS and SHTS circulators trip
- CCS circulator starts up
- PHTS check valve closes on negative pressure
- Core Conditioning System (CCS) check valve opens on positive pressure
- Control rods are inserted at a rate of 1cm/s
- PHTS depressurizes to the Helium Services System at a rate of 2.5kg/s

t=120s:

- PHTS depressurization rate is decreased to 0.1kg/s

Contents

- FLOWNEX Background
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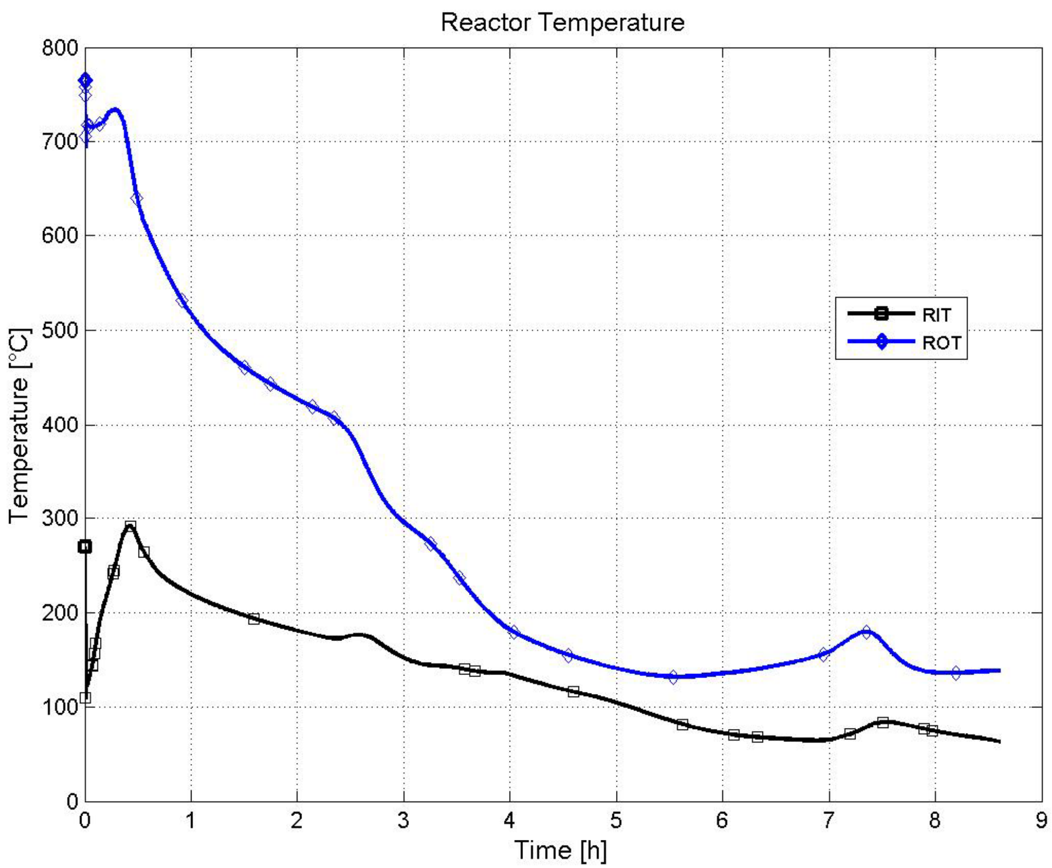
- Transient Definitions
- ⇨ Results
- Conclusion and Outstanding Issues

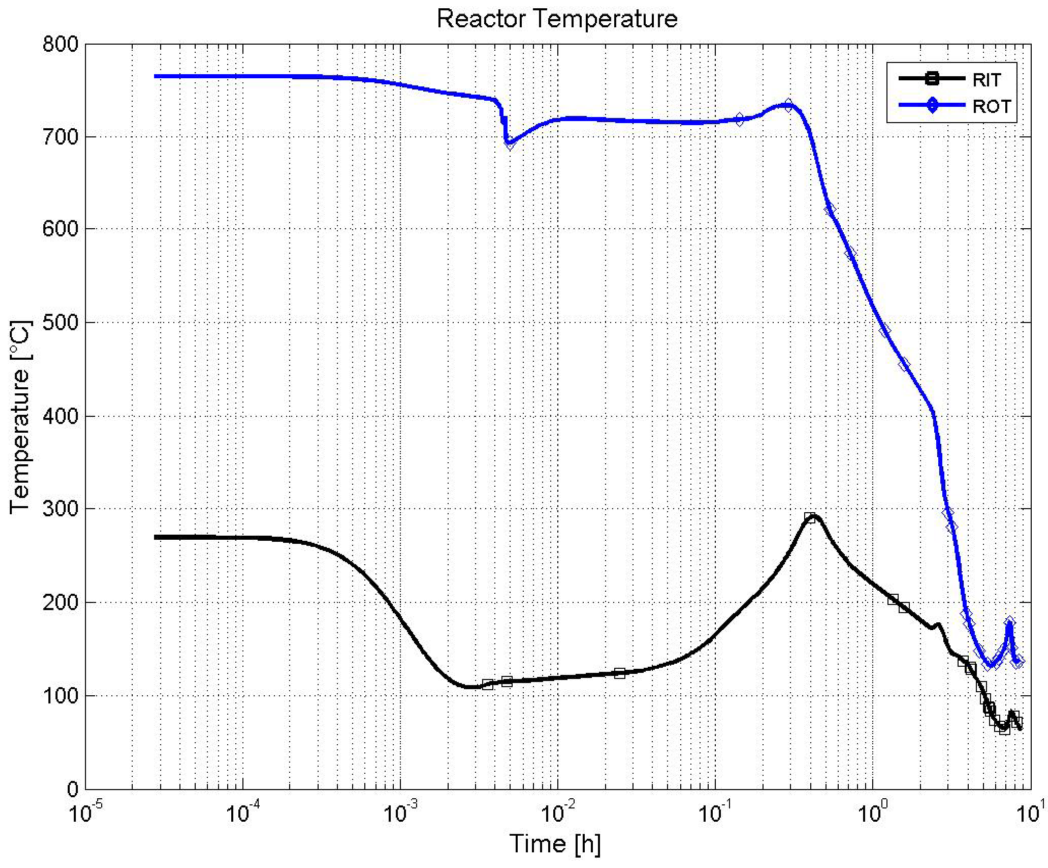
Preliminary IHX Transients - Case 1

- ROT & RIT Temperature (ROT cooldown at 100°C/h)



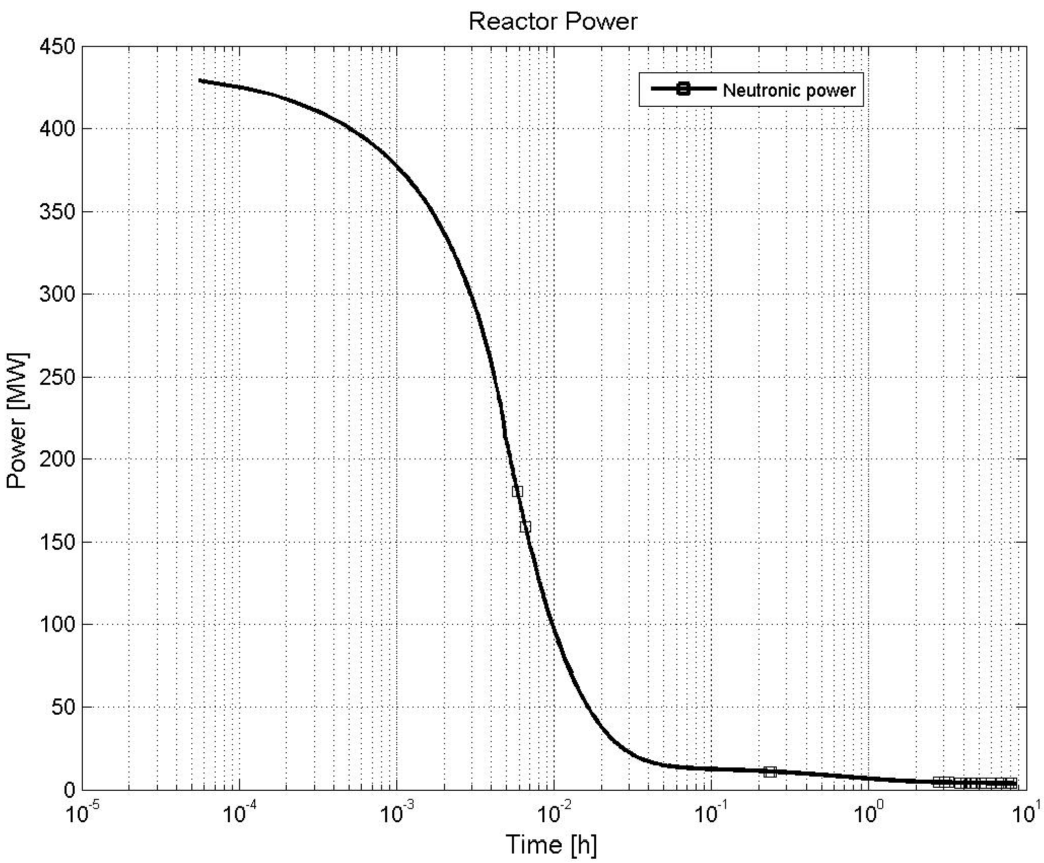
Preliminary IHX Transients - Case 1

- ROT & RIT Temperature – Logarithmic Time Scale



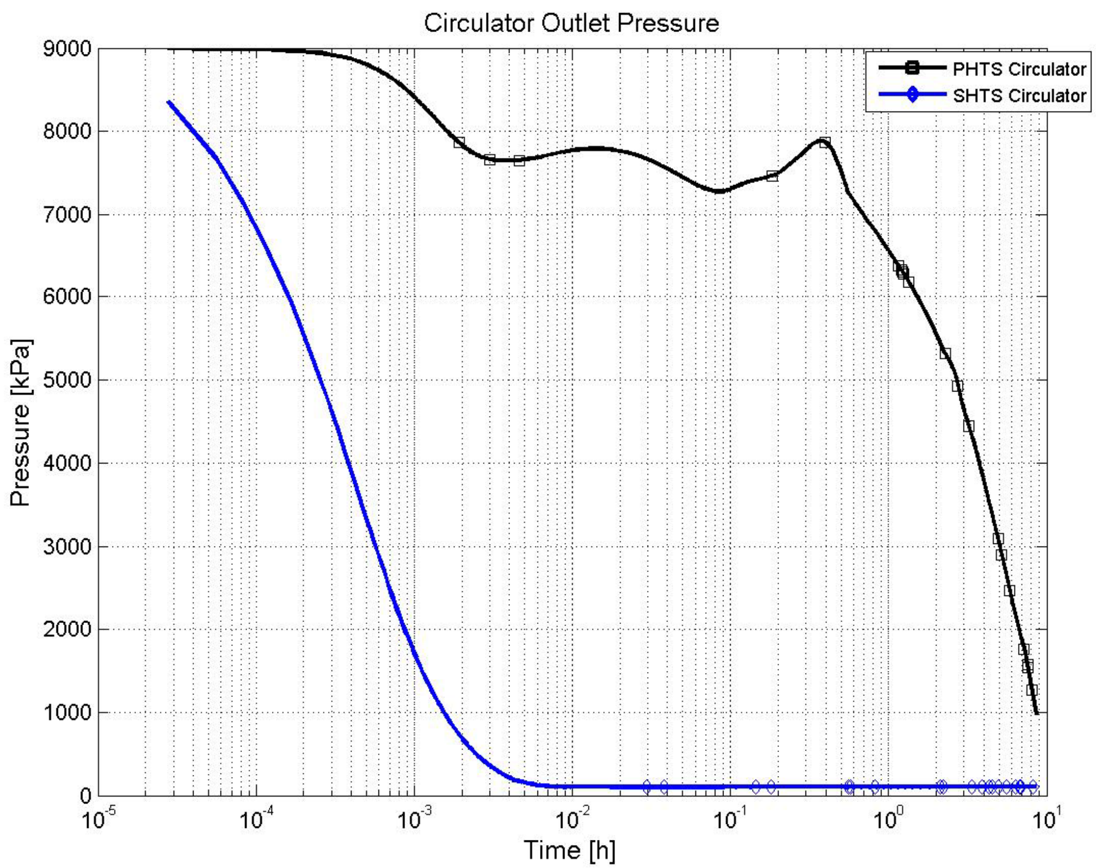
Preliminary IHX Transients - Case 1

- Reactor Power



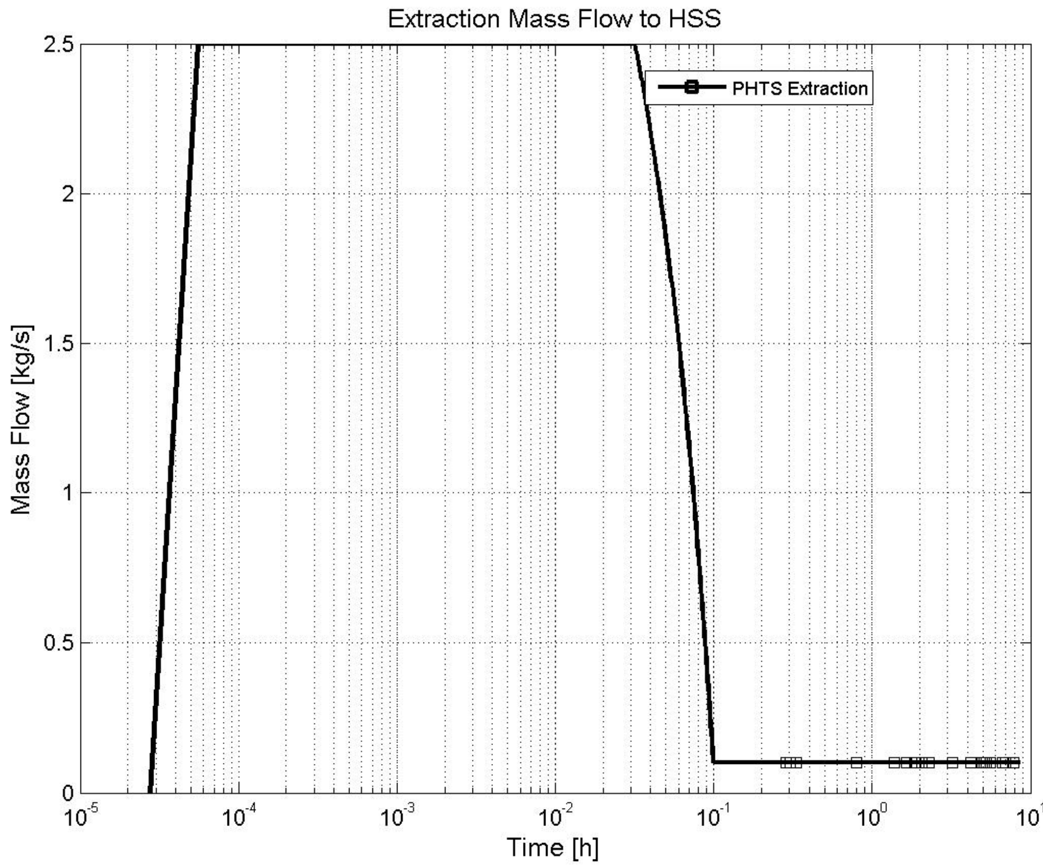
Preliminary IHX Transients - Case 1

- PHTS & SHTS Circulator Outlet Pressure



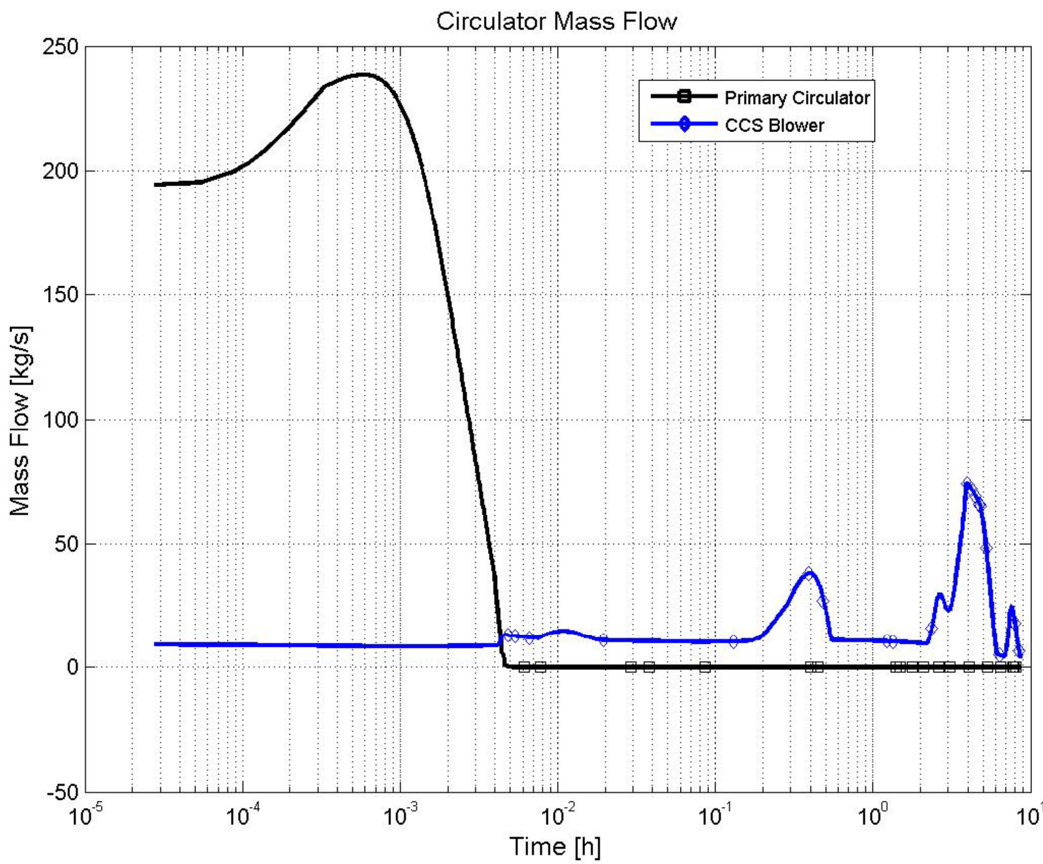
Preliminary IHX transients case 1

- Mass Flow to HSS (helium extraction from primary side)



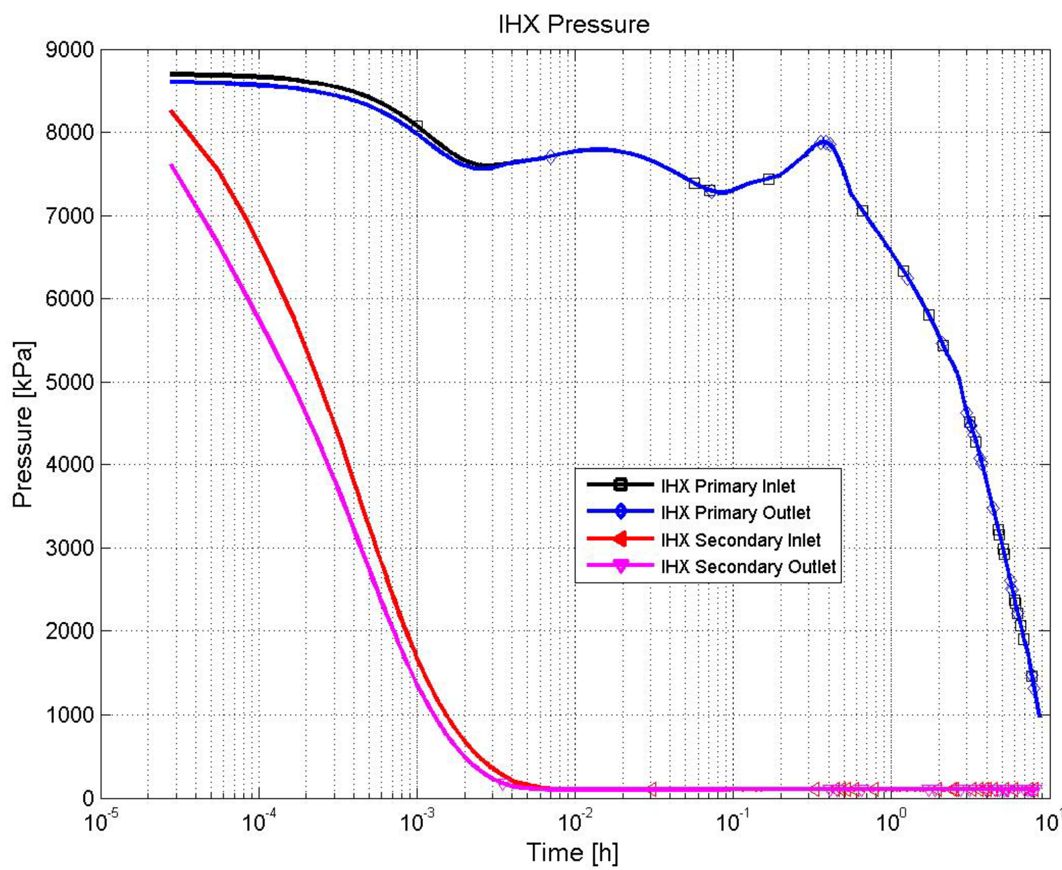
Preliminary IHX Transients - Case 1

- Mass Flow through CCS Circulator and PHTS Circulator



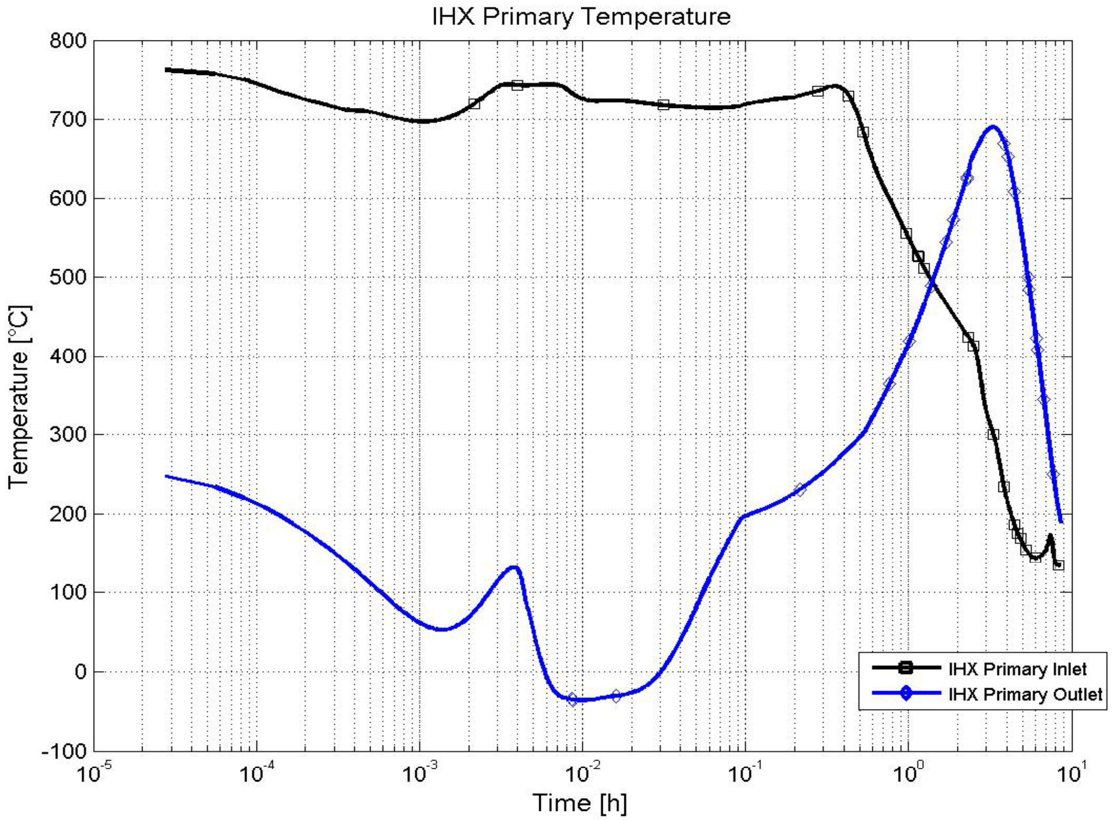
Preliminary IHX Transients - Case 1

- IHX Pressure



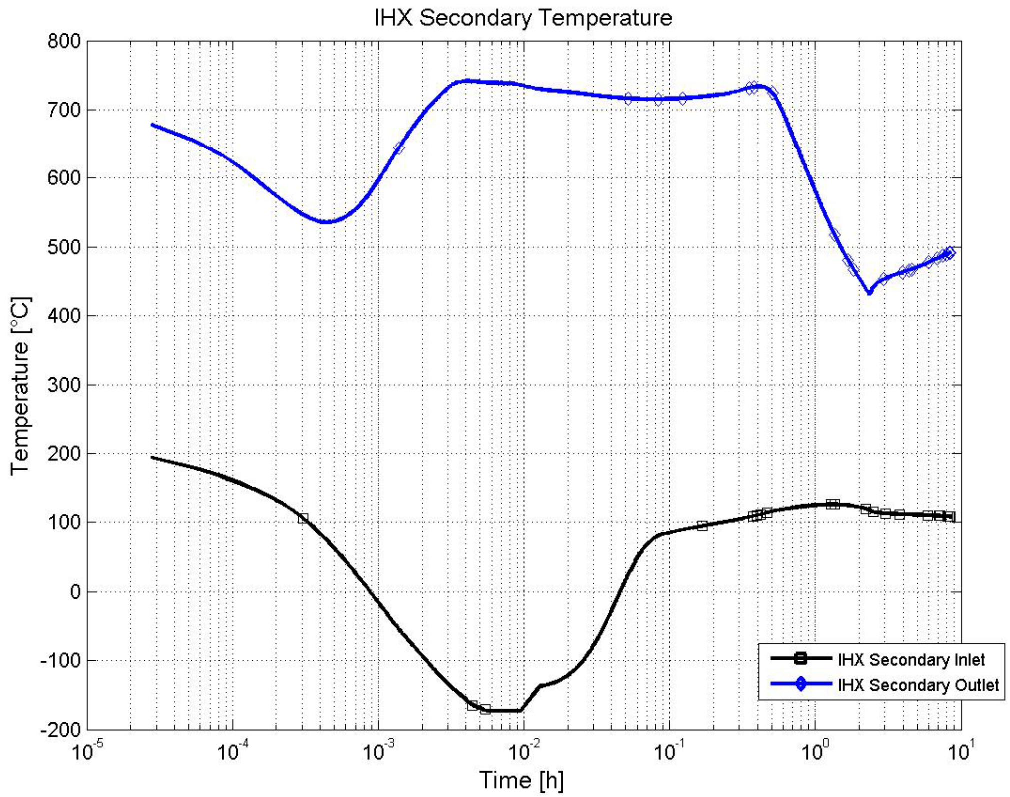
Preliminary IHX Transients - Case 1

- IHX Primary Temperature (temperature crossover due to heat transfer from metal)



Preliminary IHX Transients - Case 1

- IHX Secondary Temperature (initial temperature reduction due to fast depressurization)



Contents

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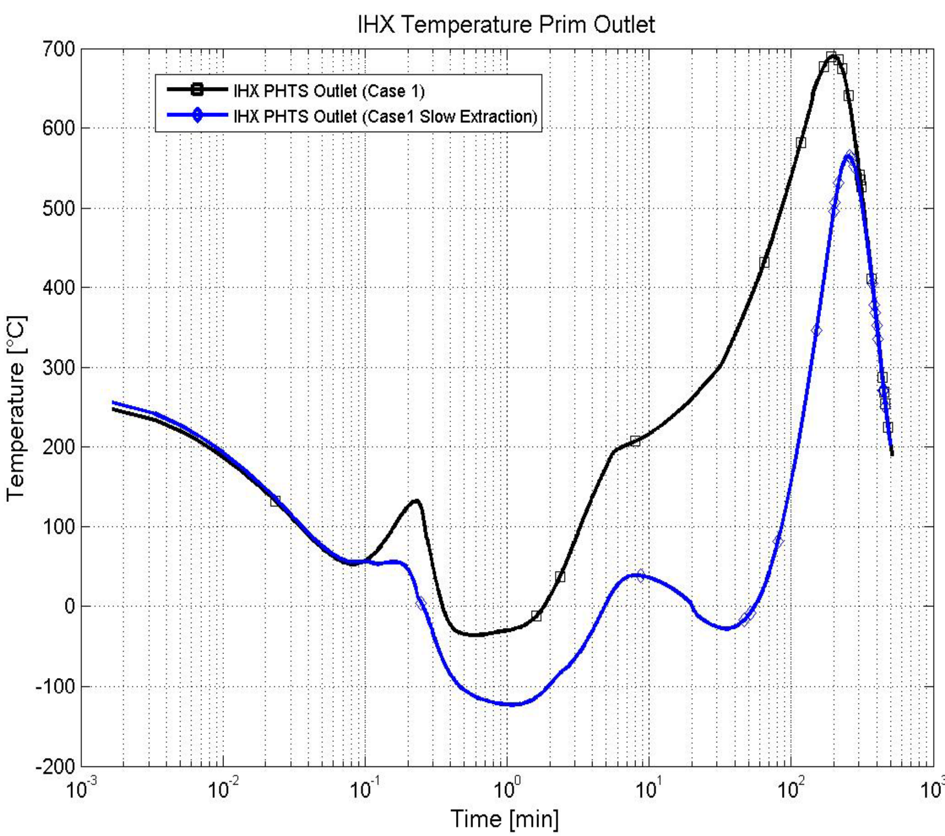
Conclusions and Lessons Learned (1)

- Analytical model compares well with supplier input
- During a loss of secondary pressure event:
  - The IHX experiences a large pressure differential at high temperature for about 10 hours
  - After 10 hours the pressure has equalized but the temperature is still high

Conclusions and Lessons Learned (2)

- Using a low (0.5kg/s) PHTS gas extraction rate during a SHTS pipe break, the IHX outlet gas temperature drops to extremely low values (below -100°C)
  - ➢ This drop can be reduced by increasing the gas extraction rate to the Helium Services System
  - ➢ At 2.5kg/s extraction rate, IHX gas outlet temperature drops to about -30°C
- **Note:** Helium must be extracted between the IHX and the circulator



Outstanding Issues and Remaining Work

- Remaining work in this task:
  - Additional transient case will be done (loss of SHTS circulator with failure of PHTS circulator to trip)
- Outside the scope of this task:
  - Benchmark/verification of transient results
  - Development of control strategy
- From FP task:
  - The amount of fission product release is sensitive to the helium inventory, therefore accurate gas volumes are required in the IHX model

STATUS OF IHX/HTS PRIORITY TASK

Scott Penfield

IHX/HTS Priority Task
50% Design Review

May 8, 2009

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Status of IHX/HTS Priority Task
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Key Results to Date

- Majority of task objectives already achieved:
  - Development of single-vessel compact IHX concept for 750-800°C applications
  - Assessment of high-temperature materials at 750-800°C
  - Selection of shell-side coupling to PHTS as basis for Conceptual Design
  - IHX DDNs updated as input to update of IHX TRLs/TDRMs

Work Remaining

- Refine design integration
  - IHX/piping interfaces
  - Vessel insulation
  - Vessel supports within NHSS Building
- Complete transient analyses
  - Input to thermal/structural assessments, below
- Thermal/structural assessments of IHX for limiting transients
  - Loss-of-Secondary Pressure
  - Loss of heat removal via SHTS with failure to trip PHTS circulator
  - Extrapolation to 800°C
- Complete inputs to Final Report

Schedule and Budget Status

Schedule Status

Start Date	
- Per Task Plan	Jan 15
- Actual	Feb 16
50% Review	
- Date	May 8
- % Complete	~70%
Completion Date	
- Per Task Plan	June 30
- Expected	June 30*
90% Review	
- Planned Date	June 22*
- Planned Method	Telecom

*Need to discuss

Budget Status

Initial budget	$200k
Expended through 50% Review	$157k
Expected at Task completion	$200k**

** Based on Issues and Projected Solutions (next)

Issues and Projected Solutions

Issue:

- Inadequate resources for engineering labor to complete proposed scope at negotiated cost

Proposed Solution:

- Qualitative evaluation used successfully to resolve PHTS coupling
- Toshiba subcontract to evaluate tubular IHX not placed
  - Information from multiple sources suggests that tubular IHX is not economically practical
- Defer lower priority design activities, as necessary
  - Details related to internal insulation of IHX vessel and PHTS/SHTS piping
  - Details related to IHX-NHSS building integration

Issues and Projected Solutions

Issue:

- 90% Review and Report Completion Dates

Scott's Schedule
June - July 2009

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18

Vacation
ANS Course
Boy Scout Camp

Issues and Projected Solutions

Issue:

- 90% Review and Report Completion Dates

Proposed Solution:

- Do not have 90% Review
  - Need believed marginal based on progress underlying this “ 50%” review
  - Both time and travel cost are factors
- Draft report to be submitted by June 26
- Final report submitted by July 10 or 1 week after comments are received from INL