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NGNP with Hydrogen Production

Primary and Secondary Cycle Concept Study

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Record of Revisions

Revision	Date	Pages/Sections Changed	Brief Description
000	3/14/2007	All	Initial Issue
001	4/18/2007	3.4.3, 3.4.4, 5.0	Add Figure 3-16 to provide schematic of four loop configuration. Add discussion of Option B and add to discussion of Option C in Section 3.4.4. Updated citations for References 1 and 4.

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1.0 INTRODUCTION

The Primary and Secondary Cycle Concept Study is one of four Next Generation Nuclear Plant (NGNP) preconceptual design special studies performed by the AREVA NGNP team:

- Reactor Type Comparison Study
- Prototype Power Level Study
- Power Conversion System Study
- Primary and Secondary Cycle Concept Study

1.1 Background

The NGNP project is intended to demonstrate the applicability of the high temperature reactor (HTR) to high efficiency electricity production and to nuclear hydrogen production. The Idaho National Laboratory (INL) is facilitating the NGNP project for the U.S. Department of Energy (DOE). A goal of the project is to perform the concept development, technology development, and prototype demonstration in cooperation with industry to lead to the future commercialization of this technology.

The NGNP project is currently in the Preconceptual Design phase. INL and laboratory operator Battelle Energy Alliance (BEA) contracted with the AREVA NGNP team and other design teams to perform preconceptual design engineering studies. The resulting studies and design recommendations will be used to determine and refine the NGNP technical and functional requirements that will form the basis for future Conceptual Design phase work and they will be used to focus and prioritize NGNP R&D activities.

The AREVA NGNP team agreed scope of work includes four special studies, as noted above, and development of an NGNP preconceptual design concept adapted from AREVA's ANTARES commercial HTR concept.

Each of the studies being performed will provide information to INL to be used in the selection of one or more design concepts to be further evaluated and developed during the Conceptual Design phase.

1.2 Primary and Secondary Cycle Concept Study Objectives

The main objective of the Primary and Secondary Cycle Concept Study is to establish the basic NGNP operating parameters. The Prototype Power Level Study will establish the design reactor power level for the NGNP and the power that must delivered to the Hydrogen production process. The primary and secondary study determines the remaining key parameters. Specifically, the parameters to be established are the primary and secondary temperatures and the system pressure.

In addition, the basic configuration of the NGNP nuclear heat supply system (NHS) will be established. Two distinct aspects of the system configuration are of interest. The first deals with whether the heat loads from the hydrogen production plant and the electricity generating system are placed in series with one another or in parallel. The second deals with the number of primary loops to be used to support these heat loads.

In establishing these parameters, the study will confirm or modify key parameters in the NGNP Preconceptual Design Baseline document [1], and it will enhance the basis for the Design Baseline.

A secondary purpose of all the special studies is to provide a basis for the selection of the NGNP concept to be developed during the Conceptual Design phase.

1.3 Scope and Assumptions

The purpose of this study is to recommend operating parameters for the NGNP NHS and associated systems. The detailed design of those systems and the implementation of the selected parameters is not part of the study scope. These parameters will be used in separate design activities where plant systems and components will be developed as defined in AREVA's NGNP Preconceptual Design Work Plan [2] as approved by INL.

In addition, while this study provides an enhanced basis for the NGNP Design Baseline [1], it supports only a limited number of design baseline parameters. Only the primary and secondary hot and cold leg temperatures and the system pressures are developed within the study. As part of the Preconceptual Design Study phase, other lower level parameters will be established based on direct design adaptation from the ANTARES reference HTR concept. Other lower level parameters will be the subject of more detailed evaluation during the Conceptual Design phase.

Several assumptions govern this study and the application of its results.

Implicit in this study is the fact that the AREVA NGNP team's design activity is limited to an adaptation of the ANTARES which is AREVA's commercial HTR design concept. Therefore, for the Primary and Secondary Cycle Concept Study, it is predetermined that the NGNP concept is based on an indirect cycle prismatic block design coupled to a combined cycle gas turbine (CCGT) generating system. Heat from the HTR is supplied to the Power Conversion System (PCS) through an intermediate heat exchanger (IHX) for electricity production. The heat supplied to the PCS first drives a Brayton topping cycle and then a Rankine bottoming cycle. Similar to ANTARES, the NGNP Brayton topping cycle is assumed to use a nitrogen-based fluid to allow the use of air-breathing gas turbine technology. Thus, when the characteristics of the PCS must be considered in evaluating the issues addressed by this study, those of the ANTARES concept are assumed.

Since the design of the Hydrogen Production Process Plant and the High Temperature Heat Transport Loop which carries heat between the NHS and the hydrogen plant are outside of the AREVA NGNP team's assigned scope, assumptions must be made about these systems for this study.

The Hydrogen Production Process Plant is assumed to demonstrate two high temperature hydrogen production processes consistent with the goals of the NGNP program high level technical requirements [3] and the AREVA NGNP Preconceptual Design System Requirements Manual [4]. Based on these, the NGNP is required to demonstrate the direct Sulfur-Iodine thermochemical process and the high temperature electrolysis (HTE) process. These processes are assumed in the determination of the required NHS operating parameters and configuration.

The High Temperature Heat Transport Loop is assumed to be a closed helium system. A single intermediate heat transport loop between nuclear heat source and hydrogen process is assumed. This implies two intermediate heat exchangers. One is the IHX between the primary and heat transport loop. This IHX is taken as part of the NHS. The second intermediate heat exchanger is the process heat exchanger between the heat transport loop and the chemical process reactants. Thus, if the reactor outlet temperature is "r", the NHS IHX approach temperature is "d1", and the process heat exchanger approach temperature is "d2", the temperature in the process itself would be $p = r - d1 - d2$.

The evaluations and results obtained within this study are obviously tentative in nature. As preconceptual design studies, they are limited due to the incomplete and speculative nature of all the information on which they are based. Therefore, all of the results will have to be reconfirmed during the Conceptual Design phase. This includes any detailed analyses or evaluations performed as a part of this study. None of these calculations represent formal design calculations.

1.4 Document Structure

Following this introduction, the main body of this report is divided into three main sections.

Section 2.0 identifies each of the questions to be answered. The current baseline is recalled, and the potential alternatives are identified for each decision. The decision process to be used to answer all of the identified questions is outlined.

Section 3.0 provides the evaluation of each question including the tradeoffs between the key considerations affecting each of the questions. Each question is addressed in a specific subsection:

Section 3.1 Reactor Outlet Temperature

Section 3.2 Reactor Inlet Temperature

Section 3.3 Configuration – Parallel or Series

Section 3.4 Configuration – Number of Loops

Section 3.5 Secondary Temperatures

Section 3.6 System Pressures

Section 3.7 provides a brief review of the decision results to make sure that they are compatible.

Section 4.0 summarizes the overall conclusions and results.

References are listed in Section 5.0.

Appendix A discusses high temperature heat transport options. This was not part of the study scope, but it is relevant to many of the issues discussed.

2.0 PRIMARY AND SECONDARY CYCLE CONCEPT STUDY DEFINITION

The problem statement to be addressed by the study is defined in the following subsections. This consists of the questions that must be answered, the considerations and criteria that must be satisfied in selecting the best solution, and the approach to the study that is to be employed. The range of alternatives is also discussed.

2.1 Questions Addressed by Primary and Secondary Concept Special Study

The questions that must be resolved within this study are divided into five main issues:

Issue 1 - What is the recommended reactor Tout?

Issue 2 - What is the recommended reactor Tin?

Issue 3 - What should the system configuration be?

Issue 3.1 - Should heat supply to the hydrogen process be parallel or in series with power generating system?

Issue 3.2 - How many loops should the system have?

Issue 4 - What is the secondary side T_{hot} and T_{cold}?

Issue 5 - What are the primary and secondary system pressures?

Considering that there are two distinct aspects of the system configuration issue, this results in six main questions that must be addressed. Each of these questions is evaluated individually in Section 3.0.

2.2 Overall Considerations

Having established the questions to be evaluated, the next step is to define the criteria used to evaluate questions. There are three main requirements which drive this special study:

- Demonstrate scalability to commercial electricity and hydrogen production
- Demonstrate advanced hydrogen production processes
  - Sulfur-Iodine
  - High Temperature Electrolysis
- Initial NGNP operation by 2018

When selecting the NGNP operating parameters and system configuration, it is important to consider whether the resulting NGNP concept will satisfy these requirements, since the selected parameters will implicitly define the NGNP concept characteristics.

The first driving requirement is intended to ensure that the NGNP will provide a near term step to commercial electricity and hydrogen production using an HTR. The NGNP must demonstrate technologies and approaches applicable to a commercial plant, and the demonstration must be such that the NGNP concepts can be scaled directly to a commercial plant. The second driving requirement is intended to ensure that the NGNP will demonstrate advanced hydrogen production processes in order to maximize the performance of the resulting commercial system. The Sulfur-Iodine (SI) and High Temperature Electrolysis (HTE) processes are widely considered to be the most likely candidate processes. The third main driving requirement is intended to ensure that the NGNP demonstration will provide the required technology for commercial deployment on a timescale compatible with end user considerations and the need for alternate energy sources.

Together these driving requirements dictate the performance requirements that will be imposed on the NGNP and the level of feasibility and technical maturity required of potential NGNP systems.

Table 2-1 provides a more complete list of all the considerations that affect the selection of the NGNP system parameters and configuration. They are divided into the areas of Feasibility and Risk, Safety, Performance, Flexibility, Cost, and Schedule. All of these considerations are important in the design of the NGNP and in addressing the full set of NGNP design requirements, but not all are distinguishing factors in determining the NGNP parameters.

The feasibility and technical risk considerations are very important in the evaluations performed in this study, particularly in light of the planned 2018 NGNP startup. The study examines the feasibility of the NHS and to a lesser extent the PCS and hydrogen process plant, since the selected operating parameters have a strong impact on these feasibilities.

Safety is undoubtedly an important parameter in the development of the NGNP concept. However, it is assumed that the plant will be designed to the same safety guidelines regardless of the system operating parameters selected. Therefore, it is not a direct discriminator in selecting the operating parameters and heat delivery system configuration. Safety considerations are reflected indirectly in the decisions to the extent that other parameters are constrained in order to maintain consistent safety margins. For example, if a design option requires the power level to be reduced in order to maintain consistent safety margin, then that is reflected as a tradeoff against plant performance (i.e., power level), since that is what is impacted. The safety margin is kept constant.

Several aspects of the NGNP plant performance are important. Foremost in selecting the operating parameters is the plant efficiency, since both the electricity generating efficiency and the hydrogen production efficiency are expected to be affected by temperature. In addition, the power level that the plant can achieve will be affected by the operating parameters. The operating parameters and system configuration also influence the other performance characteristics including maneuverability, maintainability, etc.

Three distinct aspects of NGNP flexibility are important. The first is basic operational flexibility which deals with the plants ability to operate in an all electric mode, an all hydrogen production mode, a cogeneration mode, and the ability to switch back and forth between these modes. The second deals with the adaptability of the plant to demonstrate other technologies including alternate hydrogen production processes and alternate power conversion system concepts. This flexibility is supported both by a system configuration that is adaptable to alternate equipment and a plant that can accommodate a range of operating parameters. The third aspect of flexibility deals with market flexibility. This consideration values NGNP concepts which have the flexibility to economically support a greater number of applications in the marketplace.

Cost is an important factor in determining the commercial applicability of an NGNP concept, including the development cost, the plant capital cost, and the operating and maintenance costs.

Schedule considerations have direct bearing on the ability to meet the requirement for NGNP startup by 2018. This includes the design schedule, the fabrication and construction of the plant, and the time required for technology development. The design selections made within the special study may impact each of these schedules depending on the resulting design complexity, the need for long-lead component procurement, and the time required to develop supporting technologies.

Given this broad set of general considerations, many of the decisions in the Primary and Secondary Cycle Concept Study come down to the competition between two main factors: hydrogen process requirements on one hand, and NHS design impact on the other. A major factor for the hydrogen process is the range over which heat must be supplied (both the peak temperature and the energy use temperature spectrum). For the NHS, the main factor is the decreasing feasibility that comes at higher heat delivery temperatures and the resulting increase in design difficulty.

The specific considerations that are dominant for each issue to be evaluated are emphasized at the beginning of each evaluation in Section 3.0.

Table 2-1: Overall Considerations for Primary and Secondary Cycle Concept Study

- **Feasibility and risk**
  - **NHS feasibility**
  - **PCS feasibility**
  - **Hydrogen process impact**
- **Safety**
  - **Accident scenarios**
  - **Accident frequency**
  - **Accident severity**
  - **Safety margins**
  - **Inherent safety**
- **Performance**
  - **Plant efficiency**
  - **Power level**
  - **Maneuverability**
  - **Availability**
  - **Maintainability**
- **Flexibility**
  - **Operational flexibility**
  - **Demonstration flexibility (alternate hydrogen, electricity, or other)**
  - **Market flexibility of commercial concept**
- **Cost**
  - **Development**
  - **Capital**
  - **O&M**
- **Schedule**
  - **Design**
  - **Procurement**
  - **R&D**

2.3 Decision Process

As indicated in Section 2.1, there are six major decisions to be made within the Primary and Secondary Cycle Concept Study. These decisions are not independent, since each decision is influenced by the results of one or more of the other decisions. Table 2-2 shows the general interdependency of each of the decisions. The decision process used to evaluate each of the six questions must take this interdependence into account. The basic approach is to answer the questions in sequence. The intent is to first answer the study questions most narrowly constrained by the study considerations and least influenced by the other study questions. Then the questions most strongly dependent on the preceding questions will be evaluated.

Table 2-2: Multiple decisions and interdependencies

	Other Questions						Main Driver		
For each question below, table indicates major dependency on other questions shown at right	Reactor Tout	Reactor Tin	Parallel or Series	No. Loops	Secondary Temps	Pressure	NHS Feasibility	Performance	Cost
Reactor Tout?					x		X	X	
Reactor Tin?	X						X		
Parallel or Series?	X	X					X	X	
No. Loops?	X	X	X			x	X		X
Secondary Temps?	X						X	X	X
System Pressure?		X		X			X		X

The reactor outlet temperature is perhaps the most independent of the questions. It is driven by the NHS feasibility and the hydrogen process performance characteristics. It has a strong impact on the remaining decisions.

The reactor inlet temperature has a significant impact on the NHS feasibility. A key consideration is that it can be used to compensate for the effects of higher reactor outlet temperature, if that has been selected. As will be discussed later, selecting a higher core inlet temperature can reduce peak operating fuel temperatures, although other NHS factors are also affected.

Whether the NHS configuration should supply heat to the hydrogen process and the PCS in series or in parallel is driven by the hydrogen process energy use spectrum. If the energy is needed only over a small fraction of the range from reactor outlet temperature down to reactor inlet temperature, then a series option may be preferred. On the other hand, if the energy is needed over the full core temperature range, then a parallel configuration may be best.

The decision regarding how many loops the plant should have is driven by the feasibility of the NHS components at the selected temperatures. It is also obviously affected by the decision whether the system should be in series or parallel, since the parallel configuration is inherently more adaptable to multi-loop arrangements.

The secondary side hot and cold leg temperatures are driven by NHS feasibility and hydrogen process performance. The decision is also influenced by plant cost. In essence, the question is how high of an effectiveness should be specified for the IHX. The reactor outlet temperature decision is somewhat dependent on this decision, since a lower effectiveness IHX can be compensated for by a higher reactor outlet temperature. However, the reactor outlet temperature decision is given higher priority, since it is more severely constrained by the NHS feasibility.

The primary and secondary system pressures are driven by NHS component feasibility and cost. The main tradeoff is between circulator pumping power requirements and vessel system cost. The decision is strongly impacted by the number of loops, since multiple loops significantly reduce the performance requirements for individual circulators.

The decisions to be made within the Primary and Secondary Cycle Concept Study are also closely connected with the decisions in other special studies. For example, the system operating temperatures directly affect allowable power level that can be achieved while maintaining passive cooling capability. The power level affects system design constraints, including operating fuel temperature, component sizing and feasibility, and component service conditions and material requirements, all of which influence the selection of the operating parameters.

There is a similar connection with the PCS Study. The PCS design and performance depends on the system temperature. And for indirect cycle systems the IHX design must accommodate the reactor outlet temperature. (Of course, the turbine must accommodate this temperature for direct Brayton cycles.)

Finally, the design adaptation of the Nuclear Island and the PCS are certainly impacted by the system parameters.

Considering all these factors the decision sequence is as follows:

1. Establish reactor outlet temperature

   This is primarily a tradeoff between hydrogen process performance and nuclear heat source (and hydrogen plant) feasibility.

2. Establish reactor inlet temperature

   Given the tentative reactor outlet temperature, the reactor inlet temperature decision is then a tradeoff between core design, vessel and internals materials considerations.

3. Establish plant schematic

   The optimum plant schematic (series or parallel heat loads) is determined by the hydrogen plant energy requirement spectrum and operational flexibility issues. The key question is whether the hydrogen plant needs all of its energy input at the reactor outlet temperature or over a broad range more consistent with the reactor temperature range.

4. Establish secondary temperatures

   The decision of how close the secondary coolant temperatures should be to the primary coolant temperatures is determined by economics. It is a tradeoff between system performance and component (primarily IHX) cost.

5. Establish system pressure

   This is a tradeoff between vessel cost and pumping power.

Once all the decisions have been evaluated, the initial decisions are revisited in light of the subsequent decisions. This is done to ensure that the initial decisions (e.g., reactor outlet temperature) did not unintentionally constrain one of the later decisions to an unanticipated and undesirable outcome.

2.4 Alternatives Considered

The key parameters in the initial AREVA NGNP Preconceptual Design Baseline are summarized in Table 2-3. These parameters provide the starting point for the current study. The study results either confirm or replace these values.

The range of alternatives considered within the study to replace these initial values is noted in Table 2-4. It is noted that the question of how many loops is somewhat more complicated than simply saying one loop or three loops, etc., since the number of circulators and heat exchangers can be different. This will be addressed more specifically in the detailed evaluation.

Table 2-3: Original NGNP Preconceptual Design Baseline

Initial NGNP Design Baseline (Selected parameters) Starting point for Primary and Secondary Cycle Concept Study	
Reactor outlet temperature	900°C
Reactor inlet temperature	500°C
System configuration	H2 and PCS in parallel
Number of loops	4 loops
	3 tubular IHX for PCS
	1 compact IHX for hydrogen plant
Secondary temperatures	450-850°C for PCS (50°C approach)
	475-875°C for hydrogen plant (25°C approach)
System pressure	5.0 MPa

Table 2-4: Range of Options Considered in Study

Reactor outlet temperature	Overall range 850-950°C Emphasis on 875°C, 900°C, and 925°C
Reactor outlet temperature	Overall range 400-600°C Emphasis on 500°C, 525°C, and 550°C
System arrangement	Parallel H2 IHX and PCS Series (H2 IHX ahead of PCS) Single loop vs. multiple loop (X PCS + 1 H2)
Secondary temperatures	IHX approach temperature between 25°C – 50°C
System pressure	Overall range 4.0-8.0 MPa Emphasis on 5.0 MPa, 5.5 MPa, 6.0 MPa, and 6.5 MPa

3.0 DECISION EVALUATION

3.1 Issue 1 – Evaluation of Reactor Outlet Temperature

The first decision to be addressed is the reactor outlet temperature. A summary of the issue is reviewed in the following subsection. The next subsection provides the evaluation of the discriminating considerations. Then the conclusion for this decision is summarized in the final subsection on this decision.

3.1.1 Summary of Reactor Outlet Temperature Issue

Key question:

"What is the recommended reactor T_{out}?"

Range of options:

Overall range 850-950°C with emphasis on 875°C, 900°C, and 925°C

Major considerations:

Hydrogen plant performance

Nuclear heat source feasibility

Other discriminators:

PCS performance

R&D Schedule

NHS and PCS cost

3.1.2 Assessment of Reactor Outlet Temperature Considerations

3.1.2.1 Hydrogen Plant Performance Considerations for Reactor T_{out}

An important NGNP mission is to demonstrate nuclear hydrogen production, and the temperature at which heat is supplied to the hydrogen process is a key factor in determining the success of the process demonstration. The NGNP is expected to demonstrate both the sulfur-iodine (S-I) thermochemical process and the high temperature electrolysis (HTE) process. It is likely that other processes will also eventually be demonstrated in the NGNP facility, but the S-I and HTE processes provide reasonably bounding surrogates for many other processes in terms of the required thermal and electrical loads which might be placed on a commercial nuclear hydrogen facility.

The S-I process puts a greater burden on the high temperature process heat delivery capability of the NGNP, so it will be the main process considered in evaluating the required heat delivery temperature and indirectly the required reactor outlet temperature. The S-I process temperature governs both the process efficiency and the process equipment sizing for the thermochemical hydrogen production process. The process efficiency is essentially the thermodynamic efficiency of the process. It provides a measure of the net energy content of the hydrogen produced for a given thermal energy input to the process. The temperature also affects the reaction yields within the process. While this does not directly affect the process efficiency, it has a significant impact on the size of the piping, pumps, heat exchangers and other equipment used in the process plant. Therefore, this also affects the plant economics.

HTE requires a relatively small amount of thermal energy and a large amount of electrical energy. Therefore, the plant's electricity generating efficiency is very important for HTE. The HTE process does require process temperatures in the neighborhood of approximately 800°C. However, the process performance does not vary strongly above this temperature. So there is little incentive to apply significantly higher temperatures for HTE. This implies a minimum NGNP outlet temperature of 850°C.

As suggested in the previous paragraph, the temperature drop between the reactor and the hydrogen process must be considered in assessing the impact of the hydrogen process on the required reactor outlet temperature. This temperature drop must take into account all temperature drops between the NHS core outlet and the hydrogen process peak chemical reactor temperature. A single intermediate heat transport loop is assumed. Therefore, the resulting temperature drop must include the main IHX between the NHS primary circuit and the intermediate heat transport loop and the process heat exchanger (chemical reactor) which separates the intermediate heat transport loop fluid and the chemical reactants.

In addition, any temperature drop along the intermediate heat transport loop will also have to be accounted for. For a well designed commercial scale intermediate heat transport loop, this temperature drop is expected to be minimal. The actual drop for the NGNP will have to be evaluated considering the smaller heat transport lines and the actual distance to the hydrogen production plant. This evaluation is beyond the scope of this study, but it is reasonable to assume that this temperature drop will be small compared to the heat exchanger temperature drops for a well designed NGNP system.

For this study, an NGNP hydrogen production process temperature 50°C below the reactor outlet temperature is assumed. This is based on a 25°C approach temperature in the IHX and a 25°C approach temperature in the process heat exchanger. This represents reasonable performance based on the anticipated heat exchanger technology. This assumption will be revisited in Section 3.5.

As indicated above, the first temperature consideration for the S-I process is the effect of temperature on the theoretical hydrogen process efficiency and the resulting energy requirement. Application of Knoche and Funk's analysis [5] shows that the ideal efficiency limit for a coupled water-splitting process will be only a mild function of the reactor coolant outlet temperature for operations above 800°C. The return temperature of the coolant, however, has a significant effect on the ideal efficiency limit. This is illustrated in Figure 3-1 below. Knoche and Funk's analysis shows that the relative increase in net thermal efficiency achieved by increasing the reactor outlet temperature from 850°C to 950°C is only about 2%, and decreases as the return temperature is increased.

Efficiencies of real water-splitting processes can be expected to behave in proportion to ideal efficiencies. Evaluations of different detailed hydrogen processes coupled to high temperature reactor heat source have been performed by various investigators. The relative efficiency and temperature regime are shown for some of these in Figure 3-2. The 2002 S-I flowsheet had a suboptimal S-I Section 2 (H_2SO_4 decomposition), an infeasible S-I Section 3 (HI decomposition), and achieved 42% net thermal efficiency (Higher Heating Value (HHV) basis) at an 827°C peak process temperature (875°C reactor temperature). The 2005 S-I flowsheet had an optimized Section 2, a redesigned Section 3 (reactive distillation), and achieved 46% net thermal efficiency (HHV) at a 900°C peak process temperature (950°C reactor temperature). The 2004, 2005, and 2006 Hybrid-Sulfur flowsheets achieved successively higher net thermal efficiencies (46, 48.5, and 52%, HHV basis) at peak process temperatures between 850°C and 900°C due primarily to improved energy recovery. As can be seen in Figure 3-2, increasing the peak process temperature does not have a significant effect on net thermal efficiency. The blue line extrapolates the 2002 S-I flowsheet performance at different temperatures in proportion to its ideal efficiency limit, while the orange line describes 70% of ideal efficiency. Real process efficiencies can be expected to vary with reactor temperature in similar fashion.

The magenta-shaded region between 850°C and 950°C, and between 50 and 60% net thermal efficiency (HHV) represents a reasonable performance target for sulfur-based thermochemical cycles.

The conclusion that can be drawn from this analysis is that as long as the reactor outlet temperature is above 800°C, the effect of higher temperatures on net thermal efficiency will not be very significant.

With regard to capital cost, temperature does affect conversion in the sulfuric acid decomposition reactor. As is typical of endothermic reactions, higher temperatures favor increased conversion. That means higher temperatures will result in smaller process volumes due to a reduction in the amount of unconverted materials that need to be recycled. Smaller process equipment means a reduction in capital cost. The effect of temperature on the conversion yield of the sulfuric acid decomposition reaction is illustrated in Figure 3-3 [6]. The figure also shows the affect of pressure on conversion. In the range of likely operating temperatures, yield benefits significantly from increased temperature, particularly at higher pressures.

Table 3-1 summarizes the evaluation of the temperature requirement for the hydrogen production process. Process efficiency requires a minimum of 800°C (which translates to 850°C at the reactor outlet). However, process yield considerations suggest a higher temperature in order to provide reasonable capital equipment costs for the process recycle loops, etc. Therefore, a process temperature near 850°C is preferred to provide margin. At very high temperatures, the feasibility of process equipment may decrease unacceptably unless ceramic components are assumed. Thus, from the hydrogen process perspective, a peak process temperature in the range of 850-875°C is recommended.

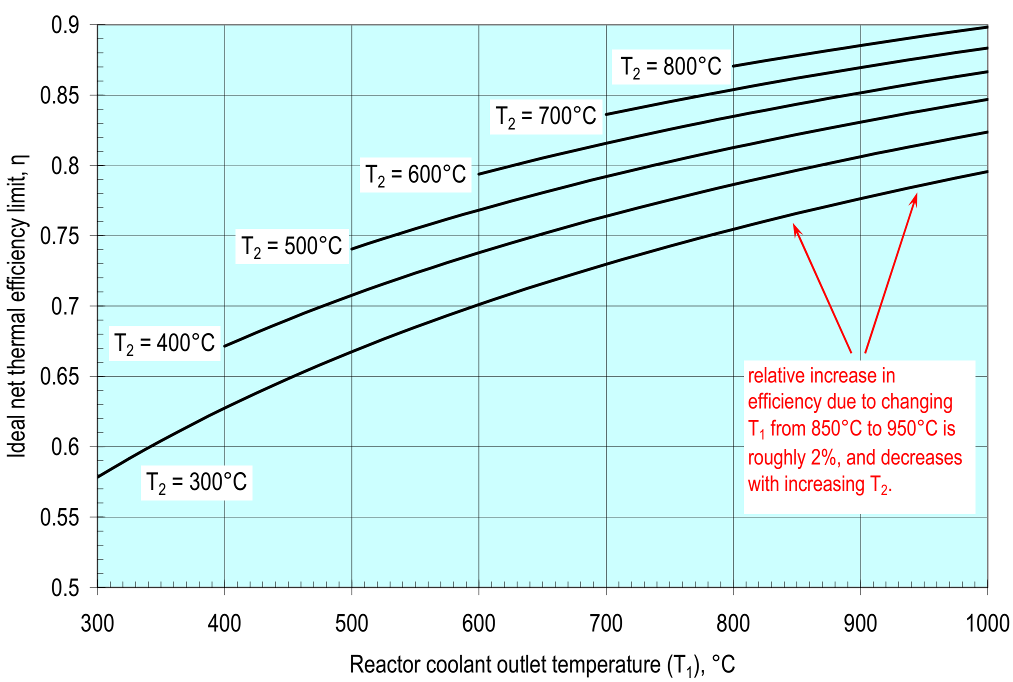


Figure 3-1: Ideal Thermochemical Hydrogen Production Efficiency Temperature Sensitivity

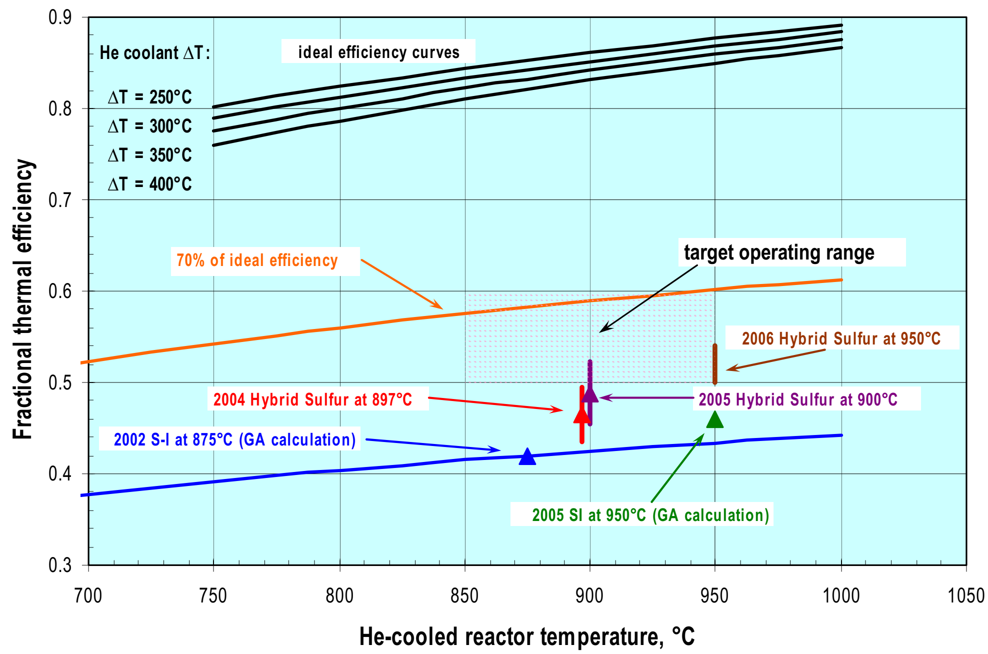


Figure 3-2: Efficiency of "Real" Sulfur Cycles As Function of Temperature

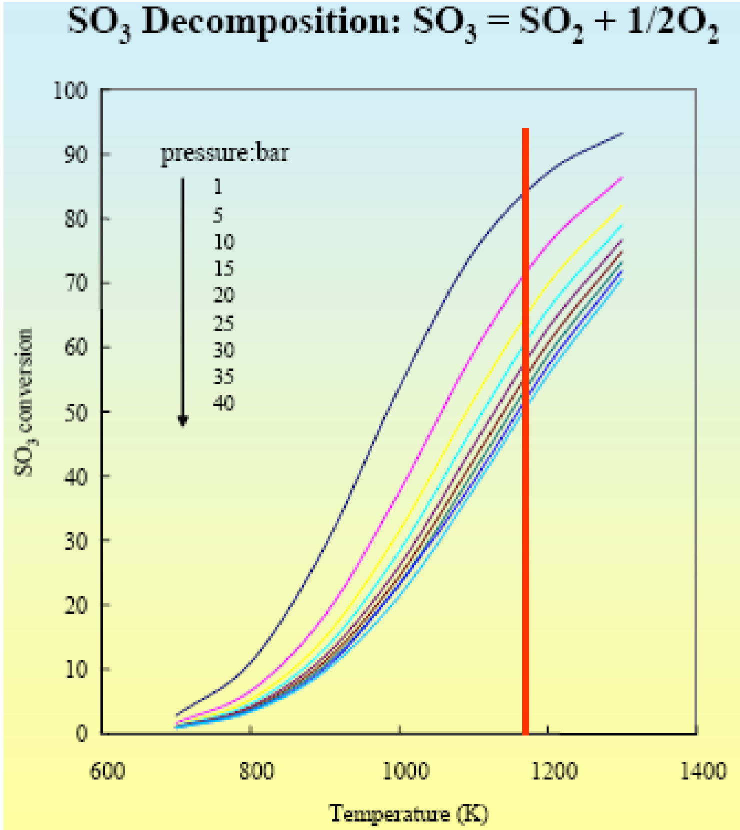


Figure 3-3: SO_3 Decomposition Equilibrium as a Function of Temperature and Pressure

Table 3-1: Summary of S-I Process Performance Temperature Needs

Reactor Outlet Temperature	Assumed H_2 Process Temp	H_2 Process Performance
950°C	900°C	Very Good
925°C	875°C	Good
900°C	850°C	Good
875°C	825°C	OK
850°C	800°C	Marginal

3.1.2.2 Nuclear Heat Source Feasibility Considerations for Reactor T_{out}

The NHS feasibility concerns due to increased reactor outlet temperature are associated with three main parts of the system:

- Core design
- Hot duct
- IHX

The ceramic support structures are not sensitive to high temperatures. Therefore, changes to the reactor outlet temperature would not change affect these structures except for the possible thickening of the graphite between the reactor outlet plenum and the metallic core support structure, which is only a design detail.

3.1.2.2.1 Core Design Considerations for Reactor T_{out}

The main effect of modified reactor outlet temperature on the core design is the need to control operating fuel temperatures. A higher core outlet temperature will result in higher operating fuel temperatures, if the core design is not modified to compensate for the higher temperature. Changes in operating fuel temperature may affect fuel performance including normal operating releases as well as subsequent accident performance or the fuel qualification. Greater operational release could result in higher circulating activity and increased primary circuit component plateout unless the compensating helium purification improvements are implemented.

If operating releases increase, maintenance could be more challenging due to increased contamination of some components. This is a greater concern for direct cycle systems, since the higher maintenance gas turbine would be contaminated. It is less important for indirect cycles, but it is still an issue. Thus, increased operating fuel temperatures could require compensating adjustments in other systems, possibly including greater coolant purification, more complex maintenance procedures, and increased safety margins. Obviously it is desirable to minimize the need for such adjustments to the reference ANTARES concept.

The goal for AREVA's NGNP design is to avoid a significant increase in peak operating temperature from the reference ANTARES core design.

The key to controlling operating fuel temperatures is appropriate core design optimization. Modern light water reactor (LWR) cores are highly optimized to control local power generation, burnup, and fuel temperature margins. Similar techniques and design tools can be applied to modern prismatic HTR cores. Prismatic core layouts allow optimization of the fuel loading to control peak operating temperatures through variations in burnable poison, fuel particle packing fraction, and fuel enrichment.

While sophisticated core designs offer the potential to reduce peak fuel temperatures substantially, they may also increase fuel design and fabrication costs, just as they do for LWRs. However, as is the case in commercial LWRs, the cost is justified to achieve both increased fuel operating margins and increased fuel cycle flexibility.

In addition, the reactor inlet temperature would also be increased to compensate for the increased outlet temperature. Due to the thermal hydraulics of prismatic core design, this will minimize any increases in peak fuel temperature, although average temperatures will increase. This tradeoff is beneficial, since particle fuel performance variability with temperature is very non-linear. Generally, the overall performance is governed by only a small fraction of the fuel which is at the highest operating temperatures. This area will be addressed further as part of the reactor inlet temperature evaluation in Section 3.2.

In the future, advanced fuel forms such as ZrC coated particles may be beneficial in providing improved performance at substantially higher temperatures. This would require less optimization for temperature control and greater design flexibility. However, these fuel forms are not expected to be ready for deployment in the 2018 timeframe. Therefore, the current design approach does not rely on them.

3.1.2.2.2 Hot Duct Considerations for Reactor T_{out}

The hot duct channels the hot reactor outlet coolant from the reactor outlet plenum to the IHX. The hot duct generally consists of a metallic pressure boundary which is protected by an internal thermal liner. It is the thermal liner that is actually exposed to the hot gas. Similar structures are used to transport the out secondary gas from the IHX outlet. An example of a hot duct and liner concept developed for a previous HTR project is shown in Figure 3-4.

Since the hot duct is protected by an internal thermal liner, the integrity of the thermal liner is the main question associated with hot duct feasibility. The metallic pressure boundary or support tube carries the main loads while operating at only moderate temperature. The cover plates in the thermal liner are normally under very low stress, but they are directly exposed to the reactor outlet temperature. The effects of hot streaks and transient variation must also be taken into account.

The main impact of the reactor outlet temperature on the hot duct is in the selection of the thermal liner cover plate material. Metallic plates can be considered for a nominal reactor outlet temperature up to about 900°C. Ceramic plates would be used for higher temperatures.

Historically, cover plates of Alloy 800H were specified for HTR concepts with reactor outlet temperatures in the range of 750-850°C. More advanced alloys might be considered for somewhat higher temperatures. High temperature designs use ceramic cover plates for insulation. Both graphite and composite liner systems have been developed as illustrated in Figure 3-5. In the 1980s, ceramic hot duct concepts were tested in high temperature service conditions (Figure 3-6).

The result of this experience is that hot duct feasibility is not an issue, even at reactor outlet temperatures of 950°C. The selection of the appropriate hot duct concept and liner material is a design optimization issue.

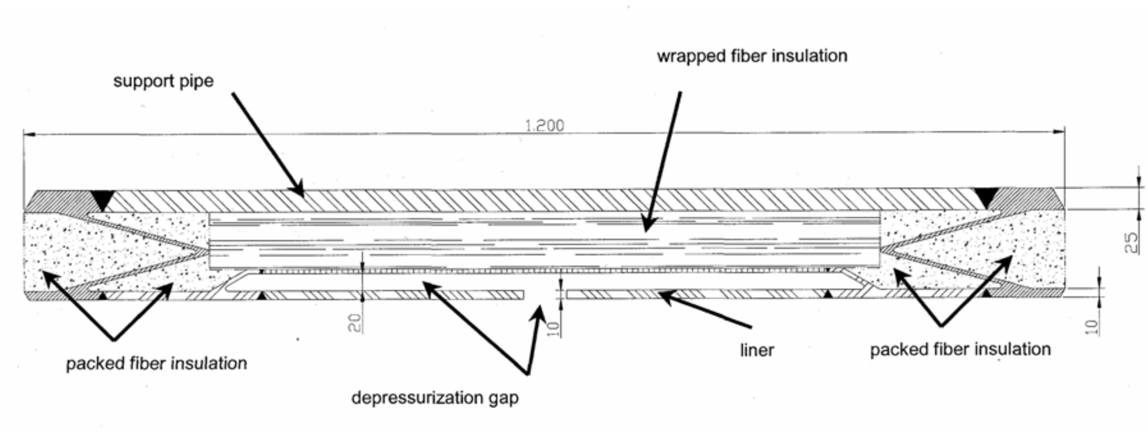


Figure 3-4: Hot Duct with Metallic Liner Concept

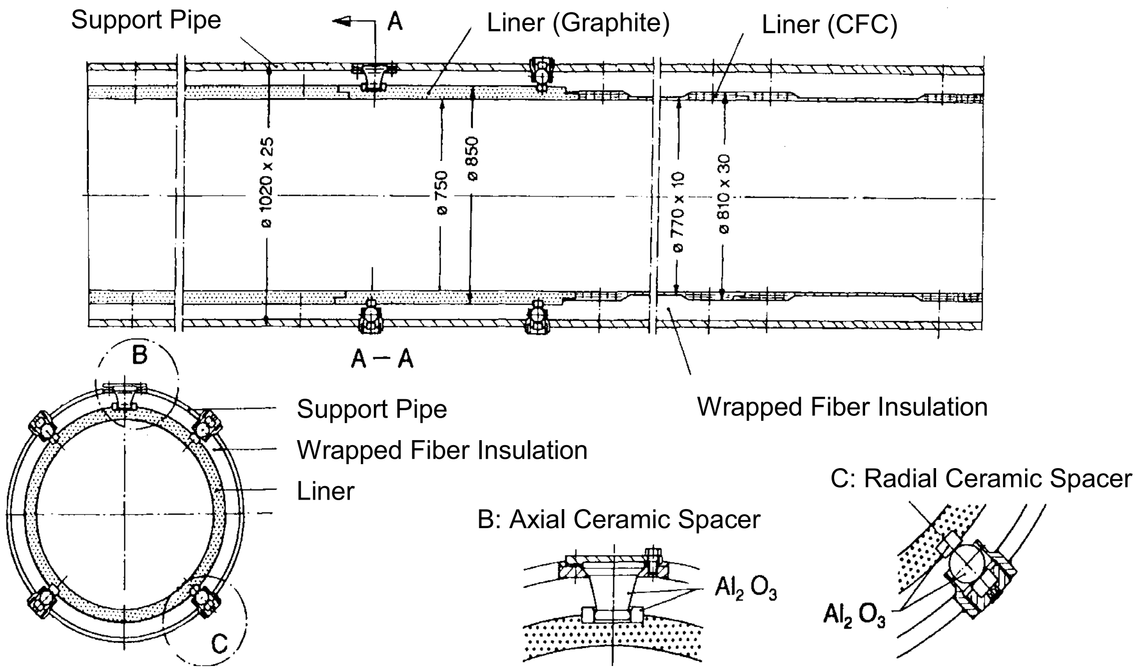


Figure 3-5: Graphite and Composite Ceramic Hot Duct Liner Concepts

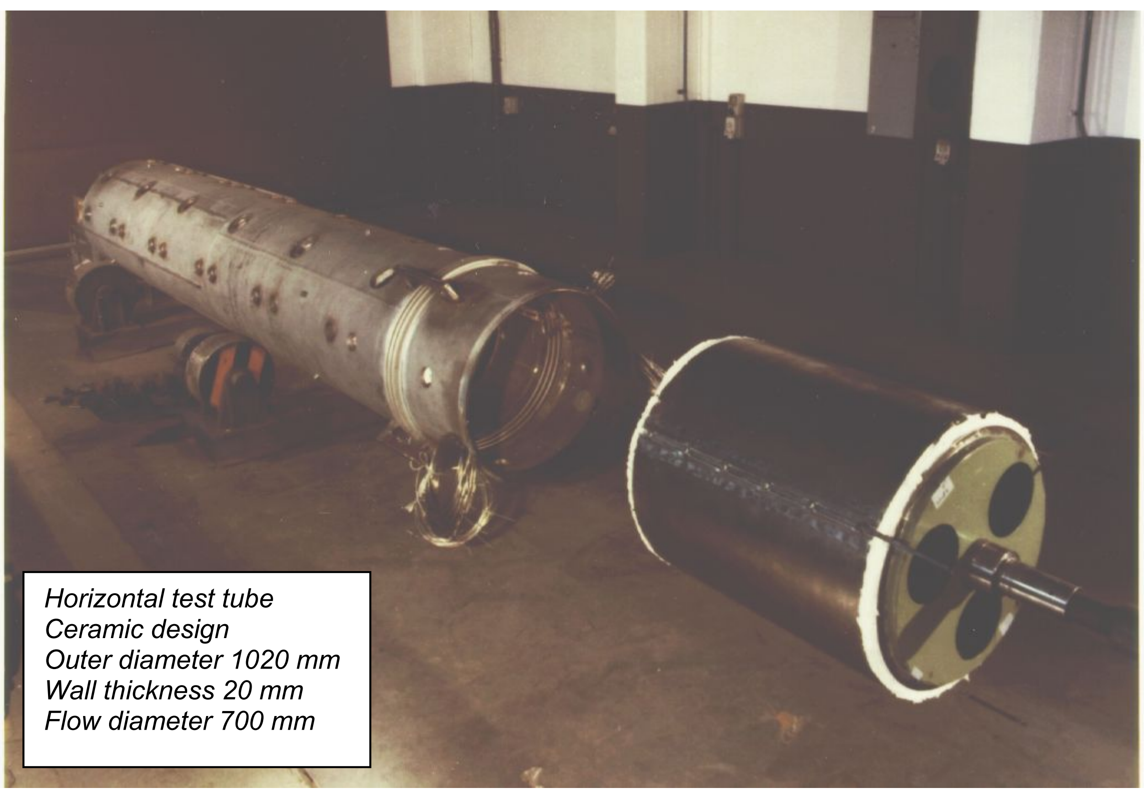


Figure 3-6: Ceramic Hot Duct and Liner Demonstration Element

3.1.2.2.3 IHX Considerations for Reactor T_{out}

The IHX is a key component. The NGNP IHX transfers heat from the primary coolant to the intermediate heat transport loop for use in the hydrogen process. With an indirect cycle PCS, the IHX also transfers the remaining reactor heat to the electricity generating system. In a commercial VHTR, the IHX must transfer all of the reactor output to the heat user.

Both compact heat exchanger and tubular IHX concepts are being considered for VHTR applications. The tubular heat exchangers are related to conventional shell and tube heat exchangers. They commonly use a helical coil tube bundle with the secondary coolant flowing in the tubes and the primary coolant flowing over the bundle in a counterflow arrangement. Tubular IHX concepts are relatively robust and they have been demonstrated at high temperature, but they require a large heat transfer volume. A variety of compact heat exchanger concepts such as plate-fin are also being considered. They require much less heat exchanger volume than tubular concepts, although internal ducting connecting individual modules uses up some of the space savings. Compact heat exchangers offer significant potential, but they have not been demonstrated in the required high temperature service regime.

The IHX feasibility depends directly on the reactor outlet temperature. The IHX heat exchange surface is a primary coolant boundary surface that must accommodate the reactor outlet gas without any thermal protection. The IHX is the only metallic component which must do this. In the future, ceramic heat exchangers may be developed which are optimized for these conditions, but they are not expected to be available in the time frame of the NGNP or early commercial VHTR plants.

Advanced high temperature alloys such as Inconel 617 and Haynes 230 are being considered for IHX fabrication. However even these alloys are approaching their practical limits at the anticipated IHX operating temperature. The strength of the base material decreases rapidly as the temperature goes to 900°C and above. Figure 3-7 illustrates allowable stresses for Inconel 617 as a function of temperature based on a previous ASME code case that was never pursued. The allowable stresses for reasonable component lifetimes are only a small fraction of their value at lower temperatures.

Bonding techniques are also limited at these temperatures. Welding is possible but it is primarily applicable to tubular IHX designs. Compact heat exchanger IHX designs typically rely on diffusion bonding or brazing to fabricate the heat exchanger core. Unfortunately, diffusion bonding or welding can have an adverse effect on the base material, due to the high temperature thermal soak required for the diffusion process. Brazing capability for high temperature service has to be demonstrated, and it is difficult to ensure consistent brazed joints through the heat exchanger core.

IHX feasibility is also strongly linked to the required component lifetime. Increasing temperature adversely affects both IHX design feasibility and design lifetime. Figure 3-8 provides a better view of the strong dependence of component lifetime on temperature for In-617 in the high temperature regime based on the KTA (German design code). A temperature increase of from 850°C to 950°C results in either a reduction in lifetime by more than a factor of 10 or a reduction in design stress by more than a factor of 3. Considering that designing for 850°C is already not easy, this poses a significant challenge.

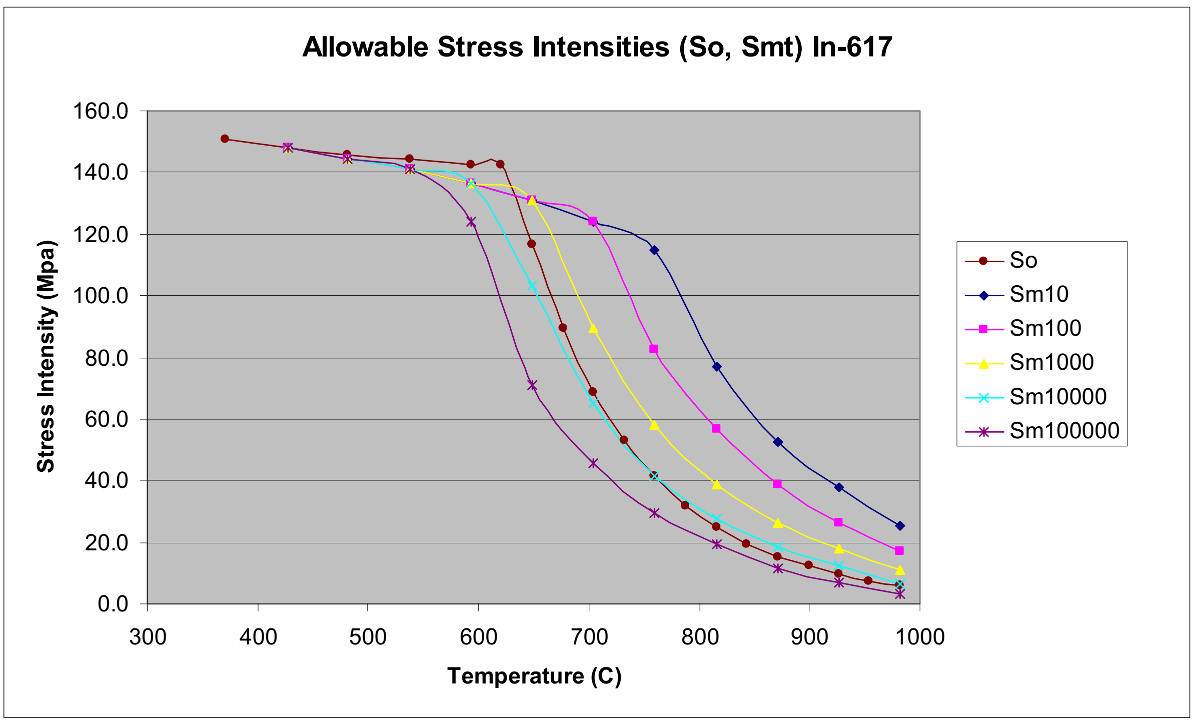
Corrosion concerns also increase at higher temperatures. Primary side metallic corrosion concerns include oxidation, carburization, and decarburization. The specific behavior is governed by very small quantities of impurities in the primary coolant. On the secondary side the same issues exist, although the impurity concentrations may differ due to the absence of the large carbon inventory present on the primary side. For the CCGT secondary system, which will likely use a mixture of nitrogen and helium to simulate air, nitriding must also be considered.

Corrosion is normally more significant at high temperatures. Strategies to control and manage corrosion in HTR systems are being evaluated by AREVA and others. In general, corrosion is viewed to be a manageable problem in the temperature regime being considered within this study. However, the corrosion problem may be more serious for very thin sections such as those in compact heat exchangers. Therefore, tubular IHX designs may offer an advantage in greater corrosion resistance. Anticipated corrosion management strategies may also be easier to implement in tubular IHX geometries. It is AREVA's view that the use of thin section compact heat exchangers at temperatures of 900°C and above may present greater corrosion management difficulties.

IHX feasibility as a function of temperature is summarized in Table 3-2. The feasibility depends on the type of IHX. Tubular IHXs have been demonstrated at high temperature, while compact IHXs have not been demonstrated in VHTR conditions. Current design efforts have faced greater challenges adapting compact heat exchangers to high temperature conditions. Compact heat exchangers have been applied successfully in the recuperator market, but the IHX application requires significantly higher temperatures and it is much less leak tolerant. Tubular heat exchangers provide greater design margin and flexibility in adapting to the required IHX conditions. The feasibility also depends on the intended environment due to corrosion considerations. In general, helium environments are expected to be more benign.

In helium-to-helium service, the tubular IHX is considered feasible over the full temperature range considered in this study. The compact heat exchanger is considered feasible at 850°C and moderately feasible at 900°C. In helium-to-nitrogen/helium service, the tubular IHX is considered feasible up to 900°C, but feasibility declines as temperature increases beyond that point. Compact heat exchangers are not believed to be very feasible at 900°C or above in helium-to-nitrogen/helium service.

Of course heat exchanger performance in terms of size and effectiveness is also a consideration. Tubular IHXs are expected to have longer lifetime but higher initial cost. The recommendation of tubular or compact IHX will be further discussed in Section 3.4.



(based on previous draft In-617 code case)

Figure 3-7: Candidate Inconel 617 Allowable Stresses

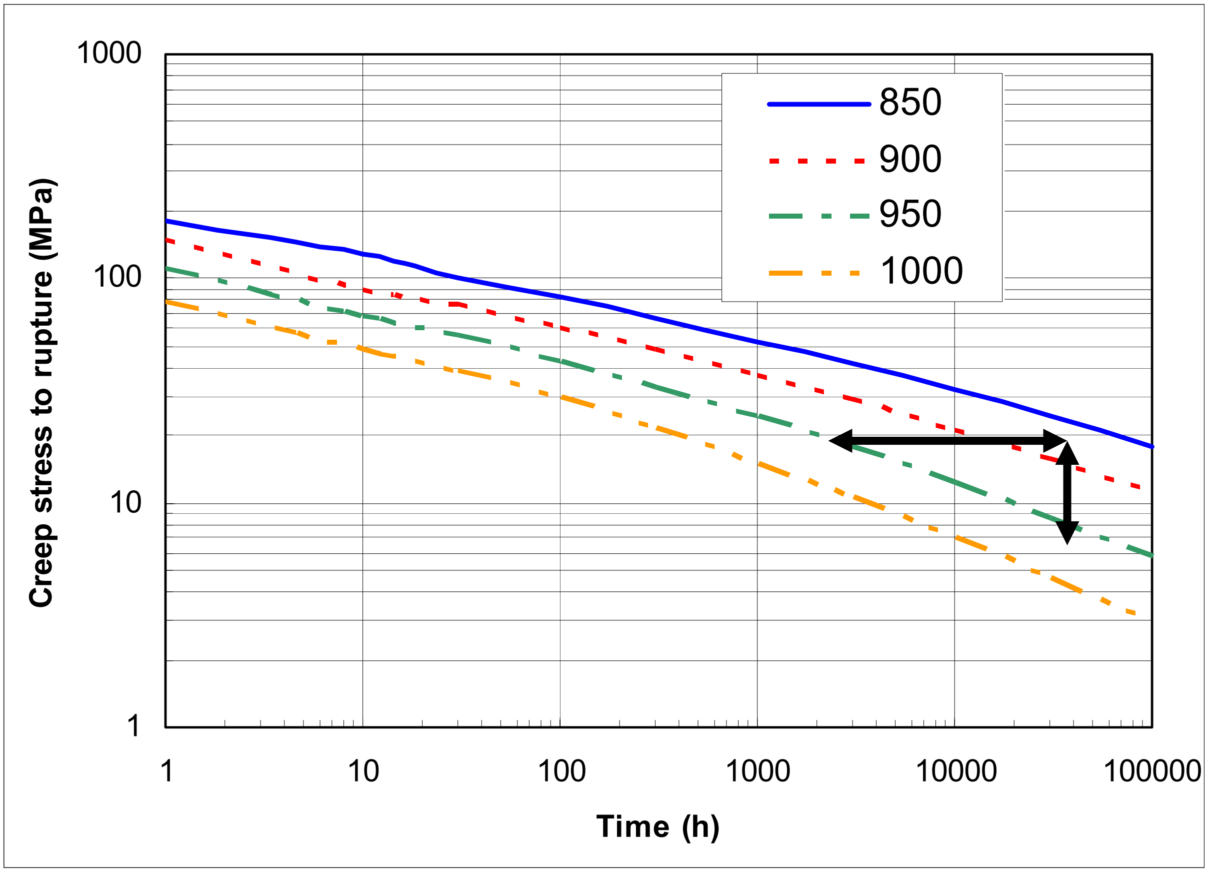


Figure 3-8: Creep Rupture Stress for In-617 (S_r curve KTA base metal)

Table 3-2: Summary of IHX Feasibility

Reactor Outlet Temp (°C)	Compact HX Feasibility		Tubular HX Feasibility	
	He/He	He/N-He	He/He	He/N-He
950	Low	Low	Good	Low
925	Low	Low	Good	Moderate
900	Moderate	Low	Good	Good
875	Good	Moderate	Good	Good
850	Good	Moderate	Good	Good

3.1.2.3 Other Considerations for Reactor T_{out}

The feasibility of the PCS is not impacted by reactor outlet temperature over the range of interest in this study. Air breathing turbines routinely operate at much higher temperatures under more adverse environmental conditions.

The performance of Brayton topping cycles is temperature dependent. Increasing the reactor outlet temperature from 850°C to 900°C translates into an increase in turbine inlet temperature from 800°C to 850°C. This change alone would be expected to give a 1.5-2.0% increase in cycle efficiency (e.g., 47% to 49%). This would suggest a preference for higher operating temperatures. However, around this temperature range, there is a threshold where turbine cooling will be required. Thus, the need for turbine cooling might reduce the efficiency increase to about 1%.

Overall, PCS considerations do not result in a strong preference for reactor outlet temperature. There is a slight preference for higher temperatures, but this is overshadowed by the NHS feasibility concerns at high temperature.

Cost factors are evaluated to see if they have a strong influence on the reactor outlet temperature decision. For the NHS cost, the main factors affected by increased reactor outlet temperature are IHX design and fabrication costs and any indirect impact on the system resulting from corresponding increases in reactor inlet temperature. While IHX feasibility varies significantly over the temperature range of interest, the actual variation in cost over that range is not expected to be important in terms of the overall plant cost when compared to the corresponding impact on system performance.

The PCS costs are not impacted significantly.

The impact of higher temperatures on the heat transport loop cost was not assessed. This impact would be expected to be comparable to the impact on the hot duct, but at a slightly reduced temperature. Cost of the heat transport loop might increase slightly due to the potential need for larger piping or higher temperature. Higher temperature materials might also be required in the hydrogen plant, but these costs would be expected to be compensated for by reduced equipment sizing due to increased conversion efficiency at higher temperature.

3.1.3 Reactor Outlet Temperature Issue Conclusion

The impact of the reactor outlet temperature on the evaluated considerations is summarized in Table 3-3. Two main factors, the hydrogen plant performance and the NHS feasibility, clearly dominate this decision. The hydrogen plant performance is marginal at a process temperature of 800°C. It is somewhat better at 825°C, but a process temperature of 850°C or above is really preferred to ensure acceptable performance. By comparison the NHS is clearly feasible up to a reactor outlet temperature of 900°C, but feasibility is less certain above that temperature. The resulting overlap in these ranges suggests 900°C as the obvious recommendation.

The other considerations identified do not provide a significant basis to modify this recommendation. The PCS concept is compatible with any of the temperatures considered, and the variation in net PCS performance is not strong. In terms of required R&D and schedule risk, most of the temperatures considered would require a very aggressive schedule in order to achieve NGNP startup in 2018, but success should be possible given adequate resources. However, if a reactor outlet temperature of 950°C were selected, it could prove to be extremely difficult to meet the desired startup date. Commercial applicability of any of the proposed temperatures would be good, although an outlet temperature of 850°C might have slightly less market flexibility (albeit with likely earlier market penetration).

Therefore, a reactor outlet temperature of 900°C is recommended. This confirms the initial AREVA NGNP preconceptual design baseline.

Table 3-3: Summary of Reactor Outlet Temperature Considerations

Reactor Outlet Temperature	Importance as Discriminator	850°C	875°C	900°C	925°C	950°C
Assumed H_2 Process Temperature		800°C	825°C	850°C	875°C	900°C
H_2 Performance	HIGH	Marginal	OK	Good	Good	Very Good
NHS Feasibility	HIGH	Very Good	Good	Good	Low	Very Low
PCS Performance	low					
R&D/Schedule/Risk	low					
Plant Cost	low					
Commercial applicability	low					

3.2 Issue 2 – Evaluation of Reactor Inlet Temperature

The second decision to be addressed is the reactor inlet temperature. A summary of the issue is reviewed in the following subsection. The next subsection provides the evaluation of the discriminating considerations. Then the conclusion for this decision is summarized in the final subsection on this decision.

3.2.1 Summary of Reactor Inlet Temperature Issue

Key question:

"What is the recommended reactor T_{in}?"

Range of options:

Overall range 400-600°C with emphasis on 500°C, 525°C, and 550°C.

Major considerations:

Nuclear heat source feasibility

Other discriminators:

PCS performance

Hydrogen plant performance

3.2.2 Assessment of Reactor Inlet Temperature Considerations

The reactor inlet temperature impacts the reactor design in several ways. The core design is affected in terms of the temperature rise across core and the normal operating fuel temperatures. The system response during conduction cooldown accidents is strongly influenced by the operating reactor inlet temperature, since it determines the initial temperature of the reflectors and the active core. Circulator performance is also affected by the IHX outlet/reactor inlet temperature.

Metallic internals such as the core barrel are not strongly affected by the reactor inlet temperature, since they are typically governed by conduction cooldown temperatures. Normal operating temperatures are generally less challenging than the accident temperature. Therefore, the metallic internals temperatures should be acceptable, assuming fuel and vessel accident temperatures do not increase significantly.

3.2.2.1 Core Design Considerations for Reactor T_{in}

For a given reactor outlet temperature and power and flow distribution, the reactor inlet temperature determines both the average and the peak operating fuel temperature. HTR core design is somewhat counter-intuitive in that, while reducing the core inlet temperature decreases the average core temperature, it actually raises the peak core temperature. This is due to the inevitable non-uniform radial power distribution.

Figure 3-9 illustrates this principle for a hypothetical VHTR core with no lateral mixing. In this example, the core outlet temperature is 1000°C, and that is the exit temperature for the average coolant channel, regardless of the inlet temperature. However with a Radial Peaking Factor (RPF) of 1.3, the temperature rise in the theoretical “hot” channel is 1.3 times the average. Therefore, in the case with the lower inlet temperature, if the RPF is 1.3, the 1.3 multiplier applies to a larger nominal temperature rise, and the outlet temperature of the hot channel actually increases.

A broader comparison of peak fuel temperature as a function of inlet temperature is provided in Figure 3-10 for different RPF and bypass flow values.

Because of this characteristic, when the core outlet temperature is increased, a corresponding increase in the core inlet temperature is beneficial to minimize any increase in peak fuel temperatures. For the AREVA NGNP design, the recommended reactor outlet temperature of 900°C corresponds to a 50°C increase in the reactor outlet temperature compared to the reference ANTARES design. In order to minimize the increase in peak fuel temperatures, a larger increase in inlet temperature is suggested. A minimum 500°C reactor inlet temperature is recommended from the core design perspective. This represents a 100°C increase from the current reference ANTARES inlet temperature, and a 50°C reduction in the core temperature rise.

In order to assess the adequacy of this change, a scoping fuel temperature calculation was performed using a simple model to evaluate the normal operating fuel temperature fractional distribution for operation 500°C inlet and 900°C outlet. The results in Figure 3-11 indicate that the estimated peak fuel temperature is in the vicinity of 1250°C. During conceptual design more detailed calculations will be required which will include the effects of cross flow and lateral conduction as well as uncertainty analysis. These factors are somewhat offsetting, since cross flow and lateral conduction will each decrease the calculated peak fuel temperatures while uncertainties will likely increase them. It is anticipated that acceptable fuel temperatures will result.

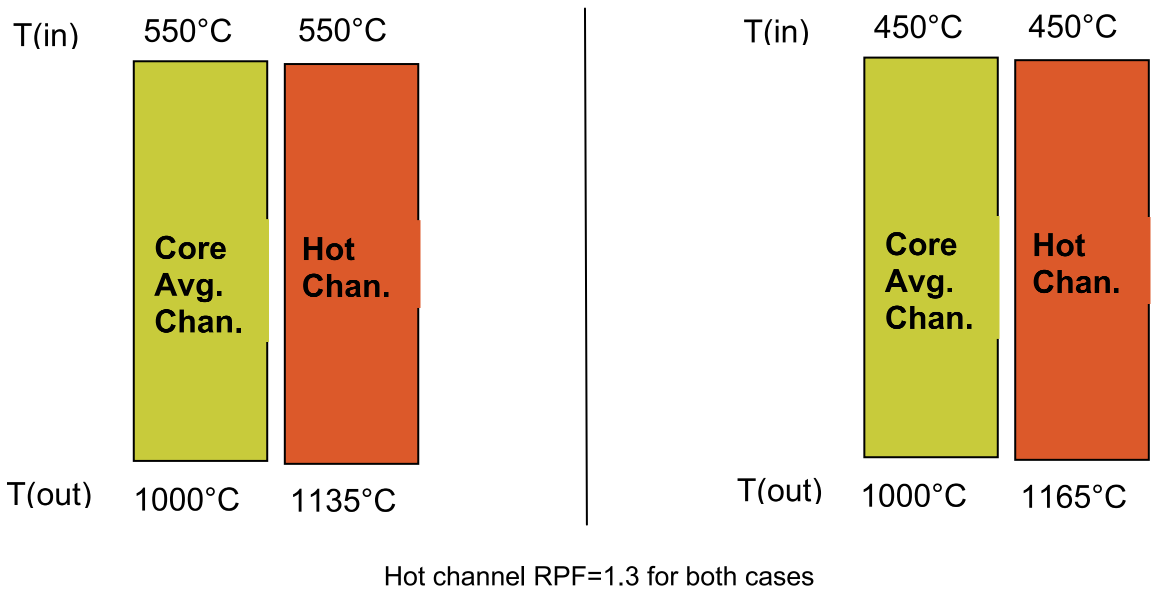


Figure 3-9: Sensitivity of Core Outlet Temperature for Average and Hot Channels In Hypothetical VHTR

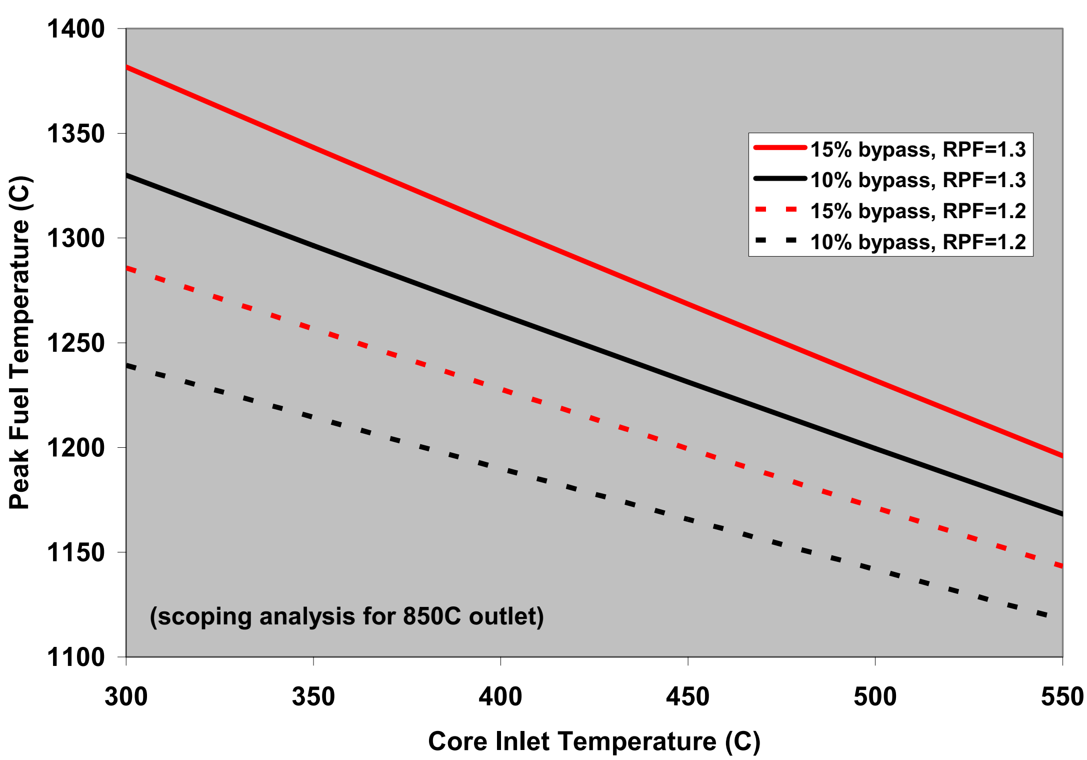


Figure 3-10: Sensitivity of HTR Peak Fuel Temperature to Core Conditions

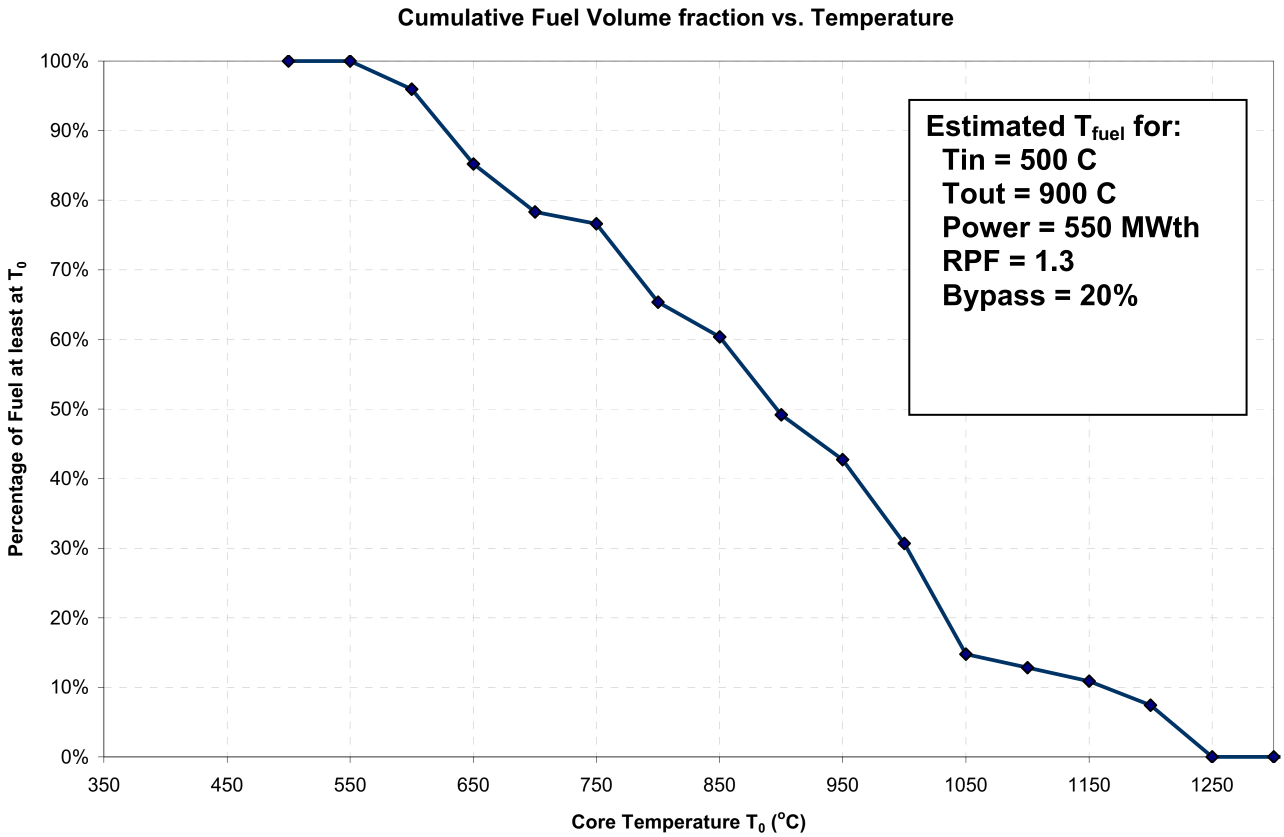


Figure 3-11: Estimated Core Fractional Temperature Distribution

3.2.2.2 Vessel Considerations for Reactor T_{in}

The effect on the vessel operating temperature is an important factor in assessing the impact of increased reactor inlet temperature. The vessel operating temperature is determined by a balance between internal heat flux and external heat flux. The internal heat flux comes from convection due to primary coolant on the inner surface of the vessel and from thermal radiation from the core barrel. The external heat flux comes from the convection and thermal radiation to the Reactor Cavity Cooling System (RCCS). Under equilibrium conditions, the reactor vessel temperature will go to the value that exactly balances these heat fluxes. If the heat flux on the inside surface of the vessel increases or decreases, then the vessel temperature will have to increase or decrease to drive more or less heat to the RCCS.

The main factor in the relationship between vessel temperature and core inlet temperature is whether or not the main coolant flow sweeps the inner surface of vessel. If so, then the core inlet temperature will dominate the vessel temperature. On the other hand, if the coolant in contact with the vessel is stagnant, then the vessel temperature will be largely controlled by the thermal radiation coming from the metallic internals. The latter is the case for the adapted ANTARES design, since the reactor inlet flow is contained within a shroud integral to the core barrel. Stagnant helium separates the internals and the inner surface of the vessel.

AREVA's goal is to keep the reactor vessel within negligible creep regime. For modified 9Cr-1Mo, this is somewhere in the range of 400 to 450°C. This range is relatively conservative, and operation at a through wall temperature in the vicinity of 425°C would likely be acceptable. For SA508, the current code limit is 371°C. This is a hard limit so additional margins to cover transients and operational uncertainties would have to be provided, resulting in a more likely upper bound for the nominal operating point of 350°C.

There are several approaches to controlling the vessel temperature during normal operation:

- Maintain low reactor inlet temperature

  If the reactor inlet coolant temperature is maintained below the creep regime temperature limit, then the issue is eliminated. However, this imposes unrealistic constraints on the core designer and on the hydrogen production process interface.

- More detailed thermal analysis and material characterization

  Due to the convective heat transfer film temperature drop and the temperature gradient within the vessel, the vessel will always be at a lower temperature than the coolant, even with direct contact. Detailed heat transfer calculations can be performed to precisely quantify this. In addition, better characterization of the boundary of the negligible creep regime might allow reductions in current design margins.

- Provide limited thermal protection

  Modest internal protection (e.g., baffles, radiation shields, thermal insulation) may provide significant vessel temperature reduction under operating conditions. Such protection would have a moderate impact on conduction cooldown accident performance. However the impact would mostly be on the vessel temperature (beneficial decrease) and core barrel (slight increase within limits). The peak accident fuel temperature is not strongly coupled to the vessel and only very slight increases would be expected.

Active cooling of the vessel provides another alternative. However, this option is not preferred. It undermines the HTR passive cooling strategy and it increases parasitic heat loss during normal operation. It also increases complexity and it has the potential to reduce plant availability in the event of cooling system failure.

3.2.2.3 Conduction Cooldown Considerations for Reactor T_{in}

Normal reactor inlet temperature affects conduction cooldown peak fuel temperature. The large heat sink formed by the inner and outer reflectors plays a major role in limiting peak fuel temperatures during conduction cooldown. Since the reactor inlet temperature sets the initial temperature of these reflectors at the start of the transient, an increase in inlet temperature has a direct bearing on the amount of heat the reflectors can absorb. This results in higher peak fuel temperatures during conduction cooldown unless compensating changes are made to the design.

The peak fuel temperature during depressurized conduction cooldown (DCC) is a function of several parameters including core geometry, initial temperature, initial reactor power level and resulting decay heat production, and the irradiation history of the core graphite and the resulting impact on effective thermal conductivity. The NGNP is designed to avoid significant fuel failure during DCC by preventing the peak fuel temperature from significantly exceeding an accident temperature guideline of 1600°C. If the reactor inlet temperature (and hence the initial core temperature) is increased, the most straightforward compensating design is to reduce the normal operating power level slightly to maintain DCC performance. This avoids the need for significant redesign of the core geometry and the need for a larger core annulus. It also maintains the flexibility to provide higher power levels in other applications with lower operating temperatures.

Detailed conduction cooldown conditions have not been performed yet for the NGNP configuration and operating conditions. Nonetheless, DCC performance has been estimated using existing sensitivity analyses. Figure 3-12 estimates the maximum allowed power level as a function of reactor inlet temperature. For a given core inlet temperature, the indicated power level is expected to provide peak DCC temperatures near the 1600°C guideline. The figure is based on anticipated NGNP conditions and it includes an estimate of the required conservatisms for uncertainties and design margins. Based on this analysis, a reactor inlet temperature of 500°C would permit a nominal power level of 565 MWth, and a temperature of 525°C would permit 560 MWth.

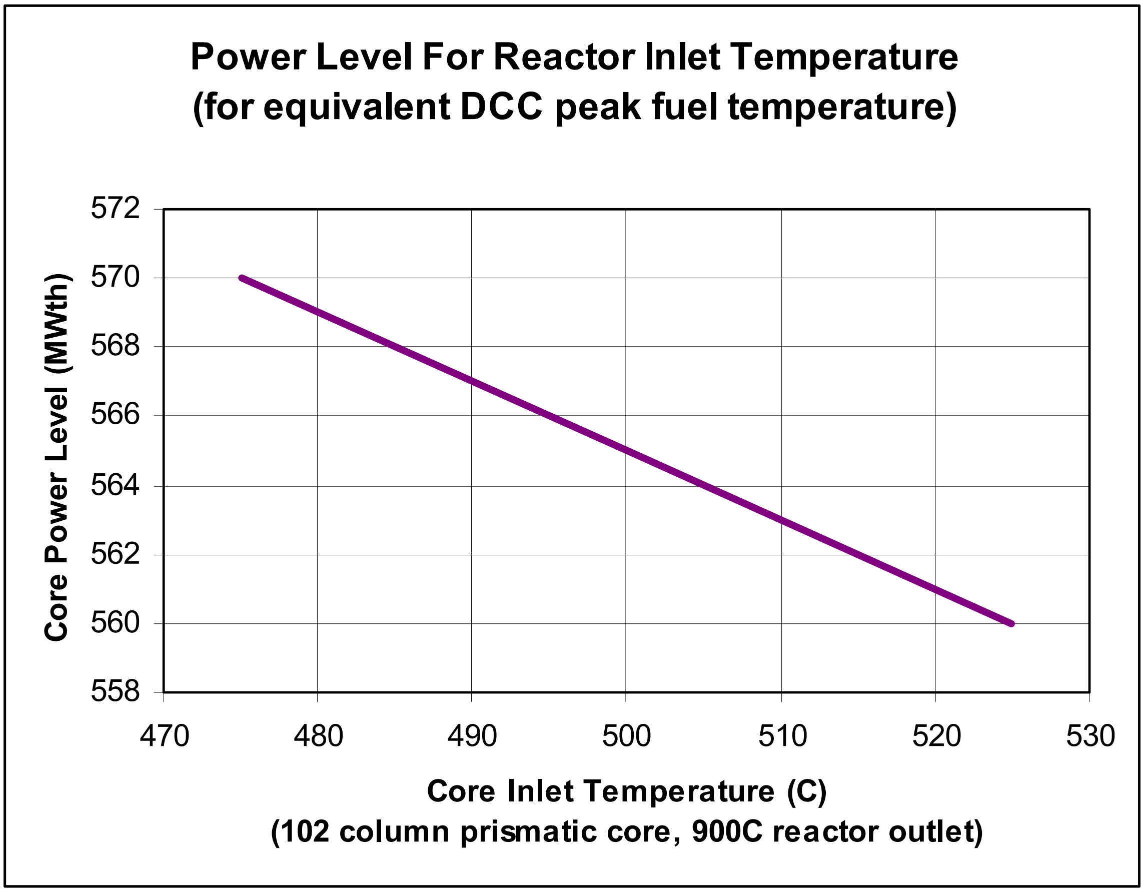


Figure 3-12: Permitted Power Level for Equivalent DCC Performance

3.2.2.4 Circulator Considerations for Reactor T_{in}

As the reactor inlet temperature is increased the required circulator power will increase slightly. For a given power level, reducing the core temperature rise results in increased mass flow. This results in increased pressure drop and a need for higher pumping power. The reference ANTARES configuration uses a single main primary coolant circulator. However, for NGNP conditions, multiple circulators would likely be required due to the increased power requirement.

A higher reactor inlet temperature also reduces the gas density at the circulator. This may adversely affect circulator performance. Higher coolant temperature in the vicinity of the circulator may also require increased thermal protection and cooling for motor cavity.

The basic feasibility of the circulator is not a concern in the anticipated range of operating conditions. Adequate materials are available to allow design for operation to above 500°C. However, the need for multiple machines will have to be considered in light of anticipated technology development. This will be addressed further in Section 3.4.

3.2.3 Reactor Inlet Temperature Issue Conclusion

Based on these considerations, the reactor inlet temperature recommendation is 500°C. This confirms the existing AREVA NGNP design baseline.

The increased reactor outlet temperature necessitates a larger increase of the reactor inlet temperature in order to maintain fuel temperatures within the desired range. Hence, the increase in outlet temperature from 850°C to 900°C suggests a corresponding increase in inlet temperature from 400°C to 500°C.

At temperatures above 450°C, thermal protection for vessel may be required. However, very modest thermal protection is expected to be adequate at 500°C, and any impact on accident fuel temperatures is expected to be negligible.

With an increased core inlet temperature, a slight reduction in nominal reactor power (about 6 % compared to the reference ANTARES) compensates for increased heat sink temperature during accidents.

The circulator feasibility is not challenged by higher reactor inlet temperatures. However, the increase in cold leg temperature does increase the likelihood that multiple circulators could be required to deliver the required pumping power.

The hydrogen production process also exhibits a preference for slightly higher return temperatures in the 550°C range.

The key point is that a reactor inlet temperature of 500°C provides greater core design margin.

3.3 Issue 3.1 – Evaluation of System Configuration – Parallel or Series

The next decision has two parts. This section examines the first of those, which is whether the system configuration for heat supply to the hydrogen process should be in parallel or series with the heat supply to the PCS. A summary of the issue is reviewed in the following subsection. The next subsection provides the evaluation of the discriminating considerations. Then the conclusion for this decision is summarized in the final subsection on this decision.

3.3.1 Summary of Parallel or Series Issue

Key question:

> "Should the H2 and PCS heat loads be in series or parallel?"

Range of options:

> Parallel hydrogen process IHX and PCS, or
>
> Series hydrogen process IHX and PCS

Major considerations:

Hydrogen plant and PCS performance

- Plant efficiency
- Maneuverability
- Availability
- Maintainability

NHS feasibility

Other discriminators:

Operating flexibility

Flexibility for component testing

3.3.2 Assessment of Parallel or Series Considerations

The most important consideration for this study is what the temperature range is over which the hydrogen process requires energy. The two options are shown in Figure 3-13. If the hydrogen process requires energy only within a narrow high temperature band, perhaps from 800 to 850°C, then a series configuration would be advantageous. However, if the hydrogen process requires energy over a broad range, perhaps from 500 to 800°C, then a parallel configuration would be better.

3.3.2.1 Energy User Temperature Requirements

Anticipated high temperature hydrogen production plants are complex facilities requiring heating and cooling of a number of fluid streams at various temperatures. This is true for both S-I and HTE processes. The specific energy management strategy for a particular hydrogen plant depends on the detailed process configuration. Most of the energy needs within the plant can be met through heat recovery where higher temperature streams which must be cooled are used to heat lower temperature streams. The net heat consumption that cannot be met in this way must be supplied by an external heat source such as the NHS for direct nuclear hydrogen production.

Generally, practical hydrogen processes require external heat over a relatively broad range of temperature. A typical composite heating and cooling curve for an S-I plant with a process temperature of 900°C is shown in Figure 3-14. As the composite curves show, high temperature heat is needed to preheat the vaporized sulfuric acid at temperatures from about 550°C to 700°C, and to drive the endothermic decomposition reaction at temperatures above 700°C. This means that the high-temperature heat demand can be satisfied with heat delivered over a range of about 350°C, to maximize efficiency. For example, if the supply temperature is 850°C, the return temperature need not be any less than 500°C.

Thus, range of heat input for the S-I process is of the same order as the reactor operating temperature range. This suggests a parallel arrangement. This is important, since dedicated commercial hydrogen plants will have to use energy over full reactor temperature range for practical system designs. The fact that the hydrogen process is not limited to a narrow range of energy consumption means that such dedicated plants are feasible.

The PCS energy usage temperature spectrum is also important. Maximum PCS performance is achieved using the full reactor temperature range. Conventional gas turbine technology can readily accommodate full reactor (or IHX) outlet temperature, so there is no incentive to place a separate high temperature heat load upstream of the PCS. Again, this suggests a parallel arrangement.

3.3.2.2 Operational Flexibility Considerations and System Configuration

Operational flexibility is greater for parallel loop configurations. This includes both control for normal plant maneuvering and response to upsets and other transients. In a parallel system, the primary coolant flow rate to the IHX supplying each heat load can be controlled independently. This allows the power and temperature range of each load to be matched. This flexibility is available during both normal operation and transients.

In a series configuration, the primary coolant flow rate is the same to both heat loads. Therefore the individual heat loads can only be varied by modulating the flow rate on the secondary side of each IHX, and this is only a weak control. It allows control of the heat load, but it gives little ability to control the secondary temperature. The inlet temperature control to the upstream heat load is primarily the reactor outlet temperature, while the primary temperature control for the downstream heat load is simply the outlet temperature of the upstream process. Neither of these is a particularly effective control.

In a parallel configuration, the heat load to each load can be adjusted independently through the primary coolant flow rate. This, combined with the control of flow rate on the secondary side of each IHX, allows both the secondary heat load and temperature to be varied more independently.

For example, if it is desired to reduce the temperature supplied to the hydrogen process, the only way to accomplish this with the series configuration is to reduce the reactor outlet temperature. However, this will also significantly reduce the performance of the PCS. With the parallel configuration, the primary flow rate to the hydrogen process IHX can be reduced significantly while maintaining a higher secondary flow rate. This will provide a reduced process inlet temperature, without affecting the PCS inlet temperature or performance.

Since the hydrogen process and the PCS are not tightly coupled in the parallel configuration, the need for careful coordination of startup of the individual subsystems is minimized. It is not necessary to start up the NHS, PCS, and hydrogen plant simultaneously. Moreover, load changes in either the PCS or the hydrogen plant need not affect the other system.

More importantly, load rejection for the hydrogen plant does not have a large impact on the PCS in the parallel plant configuration. The circulator in the hydrogen plant branch of the primary circuit would be tripped following the hydrogen plant loss-of-load, and PCS operation would continue unaffected.

However, in the series configuration, loss of hydrogen plant load would result in a step increase in temperature for the PCS. The system has no simple way to mitigate the loss of upstream load, because the core heat capacity is very large and the core outlet temperature can not be decreased rapidly, regardless of any rapid reduction in reactor power. Therefore, in the series configuration, the PCS must be designed for the full reactor (or IHX) outlet temperature regardless of plant configuration to accommodate transients.

Similarly, with the parallel configuration, PCS load changes do not significantly affect the hydrogen process. For either direct or indirect Brayton cycle systems, changes in electricity generation require significant changes in primary coolant flow rate and pressure distribution. In the series system it is very difficult to decouple the hydrogen process from these effects.

3.3.2.3 Testing Flexibility and System Configuration

Parallel configurations also offer significantly more flexibility for future testing of alternate plant equipment with minimal modification of other plant systems. Series configurations result in tight interfaces between the hydrogen process heat supply and the PCS. This includes both hardware interfaces within the primary circuit and process condition and control interfaces.

With a parallel configuration, it is relatively simple to test different process IHX designs and circulators. Since the process IHX loop is not directly integrated into the PCS loop, it can more easily be designed to accommodate alternate components for testing. Again, the flow rates and temperatures can be controlled independently in the parallel configuration in order to accommodate the needs of the alternate equipment in future test programs.

In addition, a parallel configuration may permit special high temperature demonstration operating modes. This is an important potential advantage that would not be possible with a series configuration. The idea would be to operate the reactor at very low power supplying heat only to the hydrogen plant.

The system might be configured to permit low power operation using only hydrogen plant IHX loop. The PCS IHX loop would be shut down and out of service. Reduced power operation (e.g., 10% reactor power) could allow significantly higher outlet temperature without adversely affecting the core. Fuel temperatures would still be within normal operating limits, and safety margins would be maintained due to the low decay heat associated with reduced power operation.

With operation in this mode, temporary demonstration testing with reactor outlet temperatures 1000°C may be achievable.

The PCS IHX loops would not be affected except for possible recirculation of hot gas local hot duct region immediately adjacent to the reactor outlet plenum.

However, operation in this mode would significantly affect the hydrogen plant IHX lifetime. Nonetheless, this would provide valuable hydrogen process performance data, and it would provide an excellent means of testing future ceramic IHX concepts in actual reactor service conditions.

More detailed analysis and design will be required during conceptual design to fully understand the range of testing possible in this mode.

3.3.2.4 Control of Parallel Heat Loads

The flexibility to match the required power to each heat load is achieved using the circulator and shutoff valve in each loop. The flow rate through each loop is controlled accurately using the variable speed circulator for that loop. A variety of control schemes are possible, but a typical scheme would be to monitor the outlet temperature on the secondary side of the IHX and use the deviation from the temperature setpoint as a bias in the circulator speed control.

If heat supply to one load is to be suspended (e.g., for electricity only operation), then the circulator is shut down for the circuit being taken out of service. A reverse pressure differential then exists across the shutdown loop due to the other loop(s) remaining in service. The loop shutoff valve or "flapper" valve in the shutdown loop closes passively due to both gravity and the reverse pressure differential, thus preventing significant backflow through the shutdown loop. Thus, high temperature isolation valves are not required for loop shutdown.

This approach has been used successfully in previous multi-loop HTR plants such as Fort St. Vrain and THTR, and it was the standard design approach for larger multi-loop HTR concepts such as the U.S. DOE 2240 MWth Steam Cycle/Cogeneration design [7].

3.3.2.5 Separate IHXs for Hydrogen Plant and PCS

It has been assumed that heat is not supplied to both the hydrogen production process and the electricity generating system through the same IHX. As an alternative, one could envision a different configuration in which a single IHX is used to supply both the hydrogen process and the PCS with a common secondary fluid carrying heat to both applications. (The alternative of a composite IHX heating two separate fluid streams is really two IHXs that are tightly coupled, but functionally somewhat separable.) In theory the use of a single shared IHX might result in a more compact primary circuit and greater operational flexibility as fluid could be shifted between loads to meet demand. However, there are several difficulties with implementing such a shared IHX concept in a real system, and it is more practical to use separate IHXs for most applications.

There are several reasons that separate IHXs are preferred.

First, different secondary fluids are preferred for each heat load. In the AREVA NGNP concept, the PCS is based on an indirect CCGT. This system uses a nitrogen-based fluid as a surrogate for air so that air-breathing gas turbine technology can be directly applied. For high temperature heat transport to the hydrogen process, helium is preferred for its better heat transfer properties. Moreover, in future more advanced systems other fluids such as molten salt may be attractive for heat transport.

Second, even if both systems used helium as the secondary coolant, it would be desirable to keep the fluid streams separate due to the fundamentally different dynamics of the two systems. The high temperature heat transport loop works best as a constant inventory system. For any PCS involving a Brayton cycle, substantial pressure variations would be expected during load following operations and even just in normal turbomachine load control. It is preferred not the expose the heat transport loop to these variations.

Having separate systems also provides greater flexibility for future missions to demonstrate alternate IHX and heat transport equipment in the IHX supporting the hydrogen process demonstration. These demonstrations might eventually include ceramic IHX concepts and alternate heat transport fluids. The use of separate systems means that the PCS interface with the primary circuit need not be affected by such missions.

Finally, having separate systems helps to isolate contaminants such as process fluids from the hydrogen production process within individual systems.

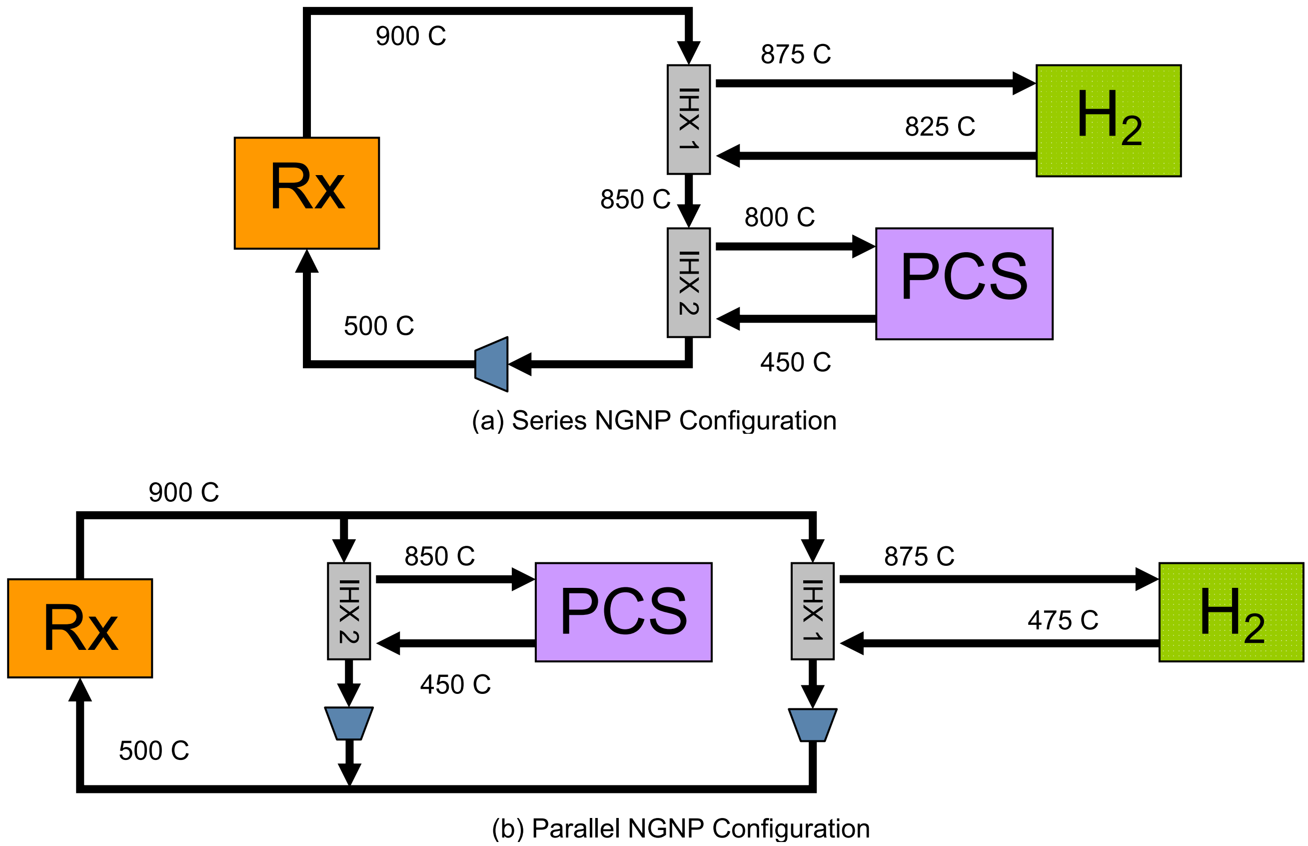


Figure 3-13: NGNP Configuration Options – Series or Parallel

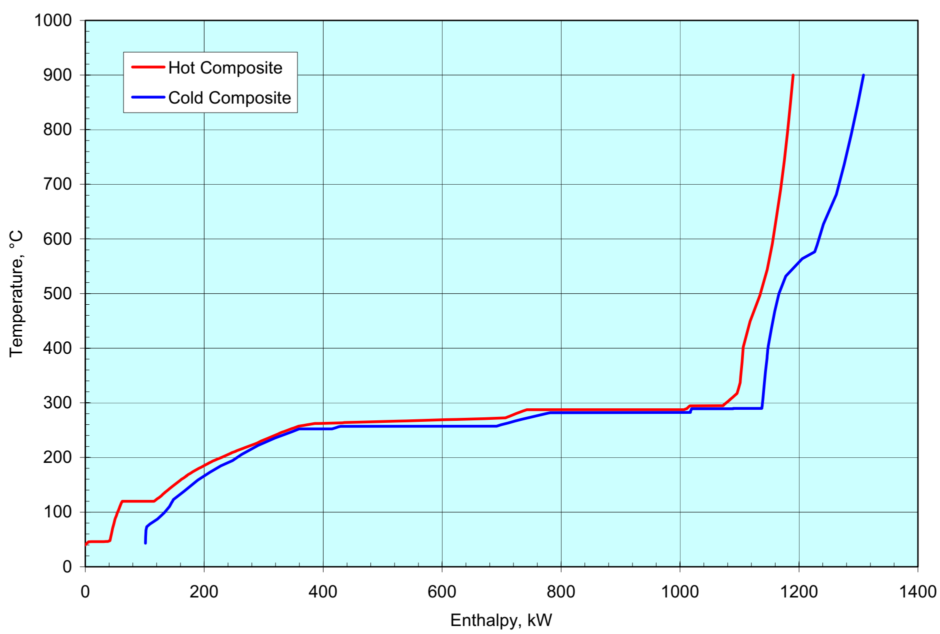


Figure 3-14: Composite Heating and Cooling Curves for the Sulfur-Iodine Process

3.3.3 Parallel or Series Issue Conclusion

The parallel system configuration is selected based on the considerations evaluated.

The parallel configuration is most compatible with the energy needs of both the hydrogen process and the PCS. The parallel system is also the most technically feasible. It has the most manageable operational characteristics. It also provides increased operational flexibility for future testing and demonstration missions.

3.4 Issue 3.2 – Evaluation of System Configuration – Number of Loops

Next, the second part of the system configuration question is examined. This section evaluates how many loops the primary system should have. A summary of the issue is reviewed in the following subsection. The next subsection provides the evaluation of the discriminating considerations. Then the conclusion for this decision is summarized in the final subsection on this decision

3.4.1 Summary of Number of Loops Issue

Key question:

> "How many loops should the system have?"
>
> For the parallel system configuration, main issue is the number of loops required to support the PCS. A separate dedicated loop is assumed for the hydrogen process.

Range of options:

> 1-4 loops

Major considerations:

> NHS feasibility
>
> Plant cost

Other discriminators:

> Plant performance
>
> Operating flexibility

3.4.2 Assessment of Number of Loops Considerations

The number of loops is a complicated question. It really includes four different parts:

- Number of cross vessels,
- Number of IHXs,

- Number of circulators, and
- How they are arranged

A single loop is acceptable, if the design is feasible with one cross vessel, one IHX, and one circulator. Otherwise, some form of multiple loop configuration is required.

A single PCS is used regardless of the number of primary loops. Existing air breathing turbines are adequate to handle the full anticipated output of a single NHS module. If multiple IHX loops are included, the secondary coolant lines are merged into a common header to supply the turbine inlet.

It is assumed that the NGNP will demonstrate multiple hydrogen production processes, with the likelihood that at least two processes might be supplied by the NHS at the same time. Single high temperature heat transport loop will carry heat to the hydrogen production demonstration facility where it will be provided to the hydrogen process(es) being demonstrated in the facility. This is the most logical approach, since the hydrogen production processes would most likely be located at some distance from the NHS and in relatively close proximity to one another. The high temperature heat transport loop would be operated at a temperature adequate to support the current process being demonstrated with the higher process temperature requirement. It would not be economical to build multiple heat transport loops to the hydrogen production area, each with a separate interface with the NHS.

3.4.2.1 Assessment of Number of Cross Vessels

The biggest impact of the number of cross vessels on the NHS design is the change in cross vessel size. When multiple cross vessels are used, the flow per cross vessel is reduced as is the vessel diameter. The cross vessel diameter is determined by the required diameter of the inner hot duct, the thickness of the hot duct thermal liner and support tube, the width of the outer cold duct flow annulus, and the thickness of the cross vessel wall. When the flow per vessel is reduced, both the hot duct diameter and the cold duct annulus thickness are reduced. An initial sizing evaluation was performed to estimate the cross vessel outer diameter for one, two, and three loops:

- 1 loop – 2.5 m
- 2 loop – 1.85 m
- 3 loop – 1.55 m

The cross vessel to the IHX dedicated to hydrogen production might be significantly smaller than this.

The potential reduction in cross vessel diameter has several ramifications for the NHS design. A key impact is on the reactor vessel ring where the nozzles to attach the cross vessels are located. The cross vessel diameter determines the size of the corresponding nozzles on the reactor vessel and hence the size of the nozzle forgings. Vessel fabrication is simpler if a single full ring forging can be produced containing the cross vessel nozzle(s). The size of such a ring forging is determined by the height of the nozzle. However, current fabrication limits determine the maximum ingot and forging size that can be obtained. It is feasible to obtain a full ring forging for the three cross vessel (1.55 m) configuration including all three nozzles. However, it is uncertain whether a single ring forging large enough for the single or two loop nozzles can be obtained in the near term. Single nozzle forgings can be obtained up to the size of a single cross vessel. A vessel can be fabricated using individual nozzle forgings and rolled plate, but it is simpler to have a single ring forging.

Adopting a multiple cross vessel configuration could have a small safety impact, since multiple cross vessels may increase the cross vessel failure probability. However, the theoretical rupture size would be smaller, reducing blowdown rates, thrust loads, and internal loadings during blowdown. The net impact is expected to be small but beneficial, since cross vessel failure is considered as a beyond design basis event. Given that the cross vessels would continue to be designed to the vessel code, that classification would not likely change and the resulting assessment would be less severe.

The reduction in hot duct diameter resulting from using multiple cross vessels would also reduce the reactor outlet plenum height. This would result in direct cost savings for graphite, reactor internals, the reactor vessel, and the reactor building. It would also provide increased margin against buckling of the core support posts.

Considering all of these factors, multiple cross vessels are preferred for both vessel fabrication and core outlet plenum height considerations. Either single or multiple loop cross vessel configurations are feasible.

3.4.2.2 Assessment of IHX Size Limitations

The recommended number of IHXs is determined primarily by IHX size limitations.

Compact heat exchangers require a modular approach. The size of a “single” IHX tends to be limited by how many modules can be connected together within a single IHX vessel.

Tubular heat exchangers are limited by the physical size of the tube bundle necessary to obtain the required heat transfer surface with reasonable primary and secondary side pressure drops. Tubular IHX capacity usually depends on the fluid. For the anticipated NGNP heat load, three loops would be required for PCS using a nitrogen-helium mixture in a tubular IHX. Two loops would be adequate for a commercial hydrogen plant using helium as the secondary heat transport fluid.

A tubular IHX heat transfer core is usually significantly larger than a compact heat exchanger, but less internal manifolds and piping is required for the tubular IHX. In addition, the vessel to house a tubular IHX is significantly smaller than compact IHX vessel. Of course, multiple such vessels would be necessary for the tubular.

Table 3-4 provides a comparison of key characteristics of compact and tubular IHX concepts. In general, tubular heat exchangers are more robust than compact heat exchangers, and they are more maintainable. Compact heat exchangers are expected to have lower initial capital cost, but they will also have shorter lifetimes and potentially higher maintenance costs.

Tubular IHX concepts are more maintainable, because individual tubes can be tested, inspected, and plugged. For compact IHX concepts, entire IHX modules would have to be replaced in the event of an IHX failure or leak. This requires a longer outage including opening of the IHX vessel for module replacement.

Another important point is that large tubular heat exchangers have been demonstrated in HTR IHX service environments. 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, is shown in Figure 3-15. Substantial development is underway on compact heat exchangers for high temperature applications, but no compact IHX concepts have been demonstrated in HTR service conditions.

The initial conclusion regarding the selection of IHX concept is that a tubular IHX is the preferred overall technology for NGNP conditions. As discussed in Section 3.1.2.2, the compact heat exchanger IHX is not judged to be feasible for the main PCS heat transfer interface in the required NGNP timeframe. In addition, the compact heat exchanger component lifetime under NGNP conditions is a concern.

In the context of the NGNP’s role as a commercial demonstrator, it is important to remember that the tubular IHX is well suited to a commercial hydrogen plant configuration. For a commercial hydrogen plant using helium as the intermediate heat transport fluid, two loops should be adequate using tubular IHXs. The cost of such a system has not been evaluated, but it is likely the lowest cost system.

For NGNP conditions with a nitrogen-helium mixture on the secondary side of the PCS, three loops are required for tubular IHXs. This is because the indirect cycle CCGT is being operated at hydrogen plant temperatures.

The situation is somewhat different for the NGNP hydrogen plant IHX. This IHX is expected to be substantially smaller than the PCS IHX. Therefore, it is expected to be more practical to design a more robust compact heat exchanger configuration, even if the design is not fully optimized economically. In addition, the hydrogen process IHX will likely be designed for ready replacement in order to support future testing of alternate IHX concepts.

The resulting IHX technology recommendation is two-fold:

- Three tubular IHXs for large PCS loops
- Modular compact IHX for hydrogen loop with change out capability to demonstrate alternate concepts

This strategy is intended to maximize reliability for the PCS IHX while allowing advanced performance development and demonstration in the smaller hydrogen IHX.

3.4.2.3 Assessment of Circulator Size Limitations

Circulator size constraints determine the number of primary circulators that are needed. A commercial size HTR (i.e., approximately 500-600 MWth) requires approximately 15 MWe of circulator pumping power with a prismatic core. (Significantly more would be required for a pebble bed core due increased flow resistance.) This value may increase slightly due to NGNP conditions.

As part of AREVA's ANTARES program, various circulator suppliers were previously queried to determine the upper bounds on a practical circulator size. There are several factors which limit circulator size including rotor dynamics, impellor aerodynamics, rotor stress, motor electrical design, etc. The existing experience of probable vendors will support machines in 4-5 MWe range. This is the limit of current experience. A machine in the 12-15 MWe range is believed to be feasible by the vendors. However, significant development would be required, and they are not prepared to formally commit to such a machine today.

Therefore, it is recommended to base the NGNP preconceptual design on using three main primary circulators for the PCS heat supply and one smaller primary circulator for heat supply to the hydrogen loop IHX. This is based on the current circulator technology status and the target NGNP deployment schedule.

3.4.2.4 Assessment of IHX Vessel Considerations

The number of IHX loops will determine the number of IHX vessels, so the ramifications on the IHX vessel design are also considered.

While compact IHX concepts allow all IHX modules to be placed in a single IHX vessel, the resulting vessel is comparable in size to the reactor vessel. As a result, the compact IHX vessel requires on-site fabrication at landlocked sites (such as INL).

Multiple vessels are required for tubular IHXs, but these vessels are smaller. Therefore, vessels for multi-loop tubular IHX are transportable by land. These vessels are smaller in diameter, and they have a smaller wall thickness compared to the compact IHX vessel. This reduces the material requirements and fabrication cost for the individual vessels substantially. The cost of each tubular IHX vessel is expected to be less than half the cost of the compact IHX vessel.

Given that circulator power may be limiting for a single loop configuration and that a multiple loop arrangement facilitates the use of multiple circulators, a multiple loop configuration will likely have more circulator power margin. This means that the optimization between system pressure and system pumping power will likely arrive at a lower system pressure. Therefore, the whole system would benefit from a reduced operating pressure. This will reduce the reactor vessel cost and fabrication difficulty.

3.4.2.5 Summary of NHS Considerations for Number of Loops

The major NHS feasibility issues are summarized in Table 3-5 for configurations with one, two, and three main PCS loops.

For the cross vessel(s), the three cross vessel configurations is clearly feasible. The one and two cross vessel configurations are feasible provided that a welded vessel nozzle ring is acceptable.

For the IHX, a compact IHX would be required for a single loop configuration, and this is not judged to be ready for deployment in 2018. For a two loop configuration, a tubular IHX would work with helium secondary fluid, but not with the nitrogen-helium mixture used in the CCGT secondary circuit. For the three loop configuration, a tubular IHX is feasible with the nitrogen-helium mixture.

For the circulator, a single circulator is not expected to be available by 2018. A half size circulator for two loop operation may be achievable by 2018, but it would be a stretch from current technology. A one third size circulator could be supplied based on current technology.

The IHX vessel is feasible for any of the considered configurations. The vessel for the single loop system has a slight disadvantage, since it would require on-site fabrication.

Overall, a single loop configuration for heat supply to the NGNP PCS is theoretically possible with major development effort, but it is probably not achievable by 2018. For a commercial hydrogen production plant, a two loop configuration is probably achievable in the near-term using helium as the heat transport fluid.

For the NGNP demonstration mission, the best configuration from the NHS feasibility perspective is with three loops supplying heat to the indirect CCGT (and a 4th loop for the hydrogen production process).

3.4.2.6 Economic Considerations for Number of Loops

In assessing the number of loops, the main consideration balancing NHS feasibility is the plant economics. It is a question of fewer larger components versus a larger number of smaller components. Table 3-6 summarizes the relevant economic factors qualitatively. The two main economic factors are initial IHX capital cost and IHX component lifetime. These two factors largely offset one another.

The compact IHX concept required for the single loop configuration is expected to be significantly cheaper than the tubular concept. However this advantage is of limited value, since the concept would probably not be ready for full size deployment in the required NGNP timeframe.

Conversely, the tubular IHX is expected to have a significantly longer lifetime under NGNP conditions. This is due to lower design stresses, thicker wall sections, and a more easily optimized configuration. Required component replacement intervals could differ by as much as a factor of three or four for the two IHX concepts.

Most other factors are of secondary importance. The circulator cost is expected to be slightly lower for a single large machine, although feasibility is questionable. Vessel cost is considered to be largely a wash between the two concepts. The need for less on-site fabrication and a reduced reactor outlet plenum height are slight advantages for the multi-loop configuration. The building cost may be slightly higher for the multi-loop configuration due to a larger footprint.

Better maintainability and availability are expected for the multi-loop system, although these are only qualitative estimates at this time.

Overall, it is hard to draw a clear conclusion one way or the other from this economic evaluation. The results in Table 3-6 suggest perhaps a slight advantage for the multi-loop configuration although the assessment is certainly very qualitative.

A slightly more quantitative assessment was performed to compare the cost difference of the single loop compact IHX configuration to the multiple loop tubular IHX configuration. The results were again largely inconclusive, since one configuration or the other was judged to have a 2-4% overall cost advantage, depending on how the IHX capital cost and replacement interval and cost were estimated. (A more detailed estimate of the selected concept will be performed as part of the remaining preconceptual design studies work scope.)

What is clear is that the multiple loop configuration does not appear to have a large cost disadvantage as might have been anticipated.

3.4.2.7 Other Considerations for Number of Loops

One other consideration regarding the number of loops should be touched upon briefly. That is the point that multiple loops offer greater operational flexibility. In particular, the use of a robust tubular IHX in a multiple loop configuration may permit elimination of the Shutdown Cooling System. The regulatory implications of this decision have not been investigated, but the potential savings should be investigated further as part of future NGNP design activity.

Table 3-4: Key Comparison of Compact and Tubular IHX Concepts

Compact Heat Exchanger IHX	Tubular IHX
Compact heat exchanger (CHE) IHX can use single loop (with multiple modules)	Tubular requires multiple loops
	Tubular is more robust
	Tubular is more maintainable • Individual tube testing • ISI • Tube plugging without IHX removal
CHE may have higher operating costs • Shorter lifetime • Repair requires module replacement outage	Tubular may be more expensive initially • More IHX material • More vessels

Figure 3-15: Tubular IHX Built and Tested for PNP

Table 3-5: NHS Feasibility Issues for 1, 2, and 3 Main Loops

	1	2	3
Cross Vessel	Forging*	Forging*	OK
IHX	CHE Reqd.	Tubular w/ He	Tubular w/N_2
Circulator	By 2018?	Stretch	Current
IHX Vessel	Onsite Fab?	OK	OK

* Individual nozzle forgings are feasible for 1 and 2 cross vessel configurations, but full vessel nozzle ring forging probably not feasible.

Table 3-6: Economic Considerations for Single vs Multiple Loop Configurations

	Single Loop CHE IHX	3 loop Tubular IHX
IHX Cost (+ = lower cost)	+++	
IHX Lifetime (+ = longer life)		+++
Circulator Cost (+ = lower cost)	+	
System pressure (+ = lower P)		+
Vessel Cost (+ = lower cost)	=	=
Reduce On-Site Fabrication (+ = factory fabrication)		+
Reduce Outlet Plenum Height (+ = lower plenum height)		+
Building Cost (+ = lower cost)	+	
Maintainability		+
Availability		+

3.4.3 Number of Loops Issue Conclusion

Table 3-7 summarizes the comparison of the important factors in the decision on the number of loops (and the related decision on IHX type). The feasibility of the single loop system is judged to be low, primarily due to doubts about the compact IHX and large circulator feasibility in the required NGNP timeframe. In contrast, the feasibility of the multiple loop system based on the tubular IHX and smaller circulator is expected to be ready for deployment in the near-term.

The plant capital cost is judged to be better for the single loop system, primarily due to the lower IHX cost. However, the operating cost of the multiple loop system is expected to be better, because the tubular IHX is predicted to have a significantly longer service lifetime. Plant operability is also better for the multiple loop configuration.

Therefore, the three loop configuration (+ hydrogen process loop) is recommended for the NGNP. This selection maximizes feasibility and minimizes schedule risk. It also maximizes operational flexibility and maintainability. Any increase in plant cost is compensated by significantly reduced risk. Figure 3-16 shows the recommended arrangement schematically, including three loops supporting the single PCS and one loop supporting the hydrogen plant.

This recommendation is also fully compatible with future two loop commercial hydrogen plants.

More specific recommendations from the preceding discussion support this overall recommendation. These include:

- Separate cross vessels are preferred for each loop
- Tubular IHXs are recommended for large PCS loops
- Compact IHX is recommended for hydrogen loop with change out capability to demonstrate alternate concepts
- Separate circulator is recommended for each loop

Table 3-7: Overall Comparison of Single Versus Multiple Loops

		Single Loop Compact IHX	3 Loop Tubular IHX
NHS feasibility	HIGH	Low	High
Plant capital cost	HIGH	Good	OK
Plant operating cost	low	OK	Good
Plant performance - Maintainability - Availability	low	OK	Good
Operating flexibility	low	OK	Good

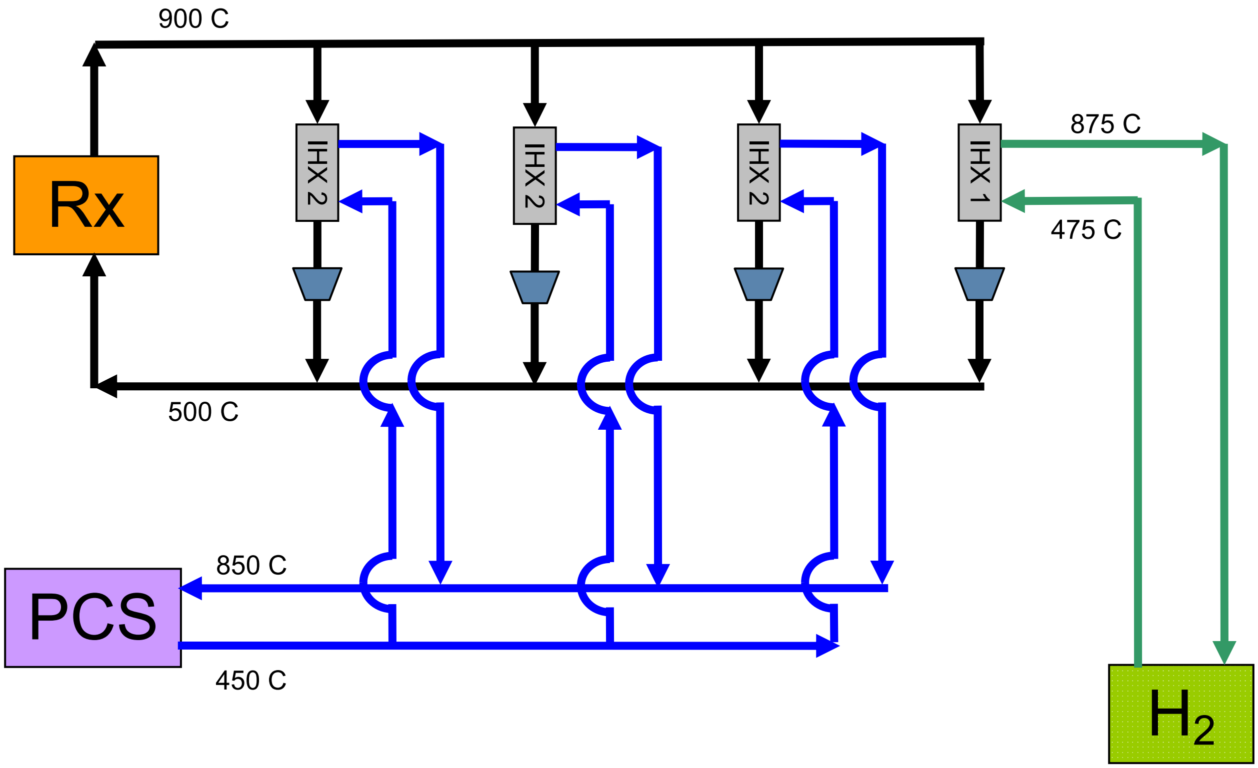


Figure 3-16: Schematic of preferred 4-loop configuration

3.4.4 Recommended Loop Arrangement

With the selection of a multiple loop configuration, a decision must be made on the recommended arrangement for the loops.

At the outset of this study, four basic arrangement types were considered as shown in Figure 3-17 through Figure 3-20. These configurations result from the number of cross vessels and IHX vessels to be used. The reference arrangement in the Design Baseline [1] was Option C (Figure 3-19).

There are two main considerations in the selection of the new NGNP loop arrangement. The first is the recommendation from the preceding sections for the number of IHXs, circulators, and cross vessels. The second is the impact of the configuration on building size and cost. A secondary consideration is how well the proposed NGNP configuration supports the deployment of future commercial plants.

Given the recommendation to use multiple cross vessels, Option D is preferred. The use of three main cross vessels in Option D (plus one for the hydrogen loop) provides somewhat improved vessel nozzle ring fabrication capability compared to the two vessels in Option C. This is reinforced by the recommendation to use a separate circulator for each loop. In Option C a hub separates each pair of IHX vessels. If each pair of IHXs was to be supported by a shared circulator, then this hub would have provided a convenient circulator mounting location.

However, with dedicated circulators attached to each IHX vessel, this hub only adds additional design complexity. The simplest design solution is the completely independent loops of Option D.

Support of the IHX vessels along the cross vessel axis is also more straightforward for Option D.

Originally it had been assumed that Option C might have an advantage in compactness compared to Option D. However, evaluation of the arrangement has not born this out. At the current level of detail, the two options are indistinguishable. Option C does increase the primary circuit complexity, since two IHXs must be connected to a single cross vessel.

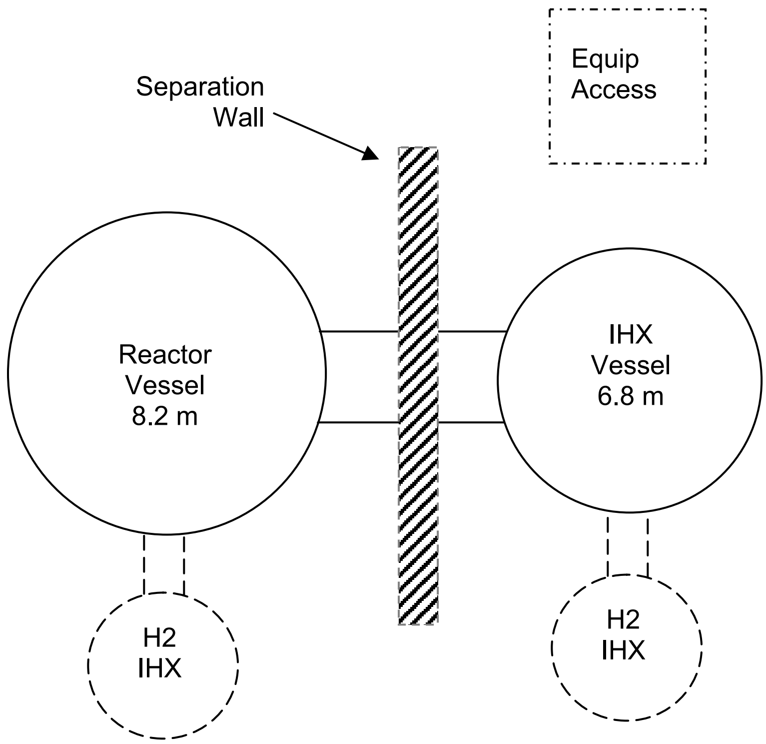
Option B was considered as an early alternative to the single IHX vessel with compact heat exchangers. The close arrangement of four tubular IHX's was intended to be compatible with the building footprint of Option A. Option B would also allow four IHXs to share a single cross vessel and possibly a single circulator. However, Option B does require a significant increase in complexity to connect the ducts from four IHX vessels to a single cross vessel. In addition, in order to provide a compact arrangement, Option B does not provide significant separation between IHX modules. This eliminates any benefit of physical separation between redundant systems, and it complicates maintenance.

The Option D building size is slightly larger than for Option A, but this disadvantage applies only to the NGNP. As shown in Figure 3-21, for a three loop commercial electricity plant or a two loop commercial hydrogen plant, the building design is smaller than the Option A layout. (Note that the diameter shown for the two loop configuration may not be practical, since it does not allow significant space for other utilities and access paths within the structure. The actual size might be closer to the three loop layout.)

Of course, this is a very preliminary analysis. Building cost is more complex than simply the diameter of the building. Nonetheless, this initial comparison suggests that the Option A arrangement does not have a significant building cost advantage.

The Option D configuration also provides the greatest fidelity to the anticipated commercial plant configurations in terms of operational characteristics. This will allow demonstration of anticipated loop control strategies and plant protection schemes in the NGNP plant.

Hence the recommended arrangement is Option D with completely independent loops. This is a change for the existing baseline [1].

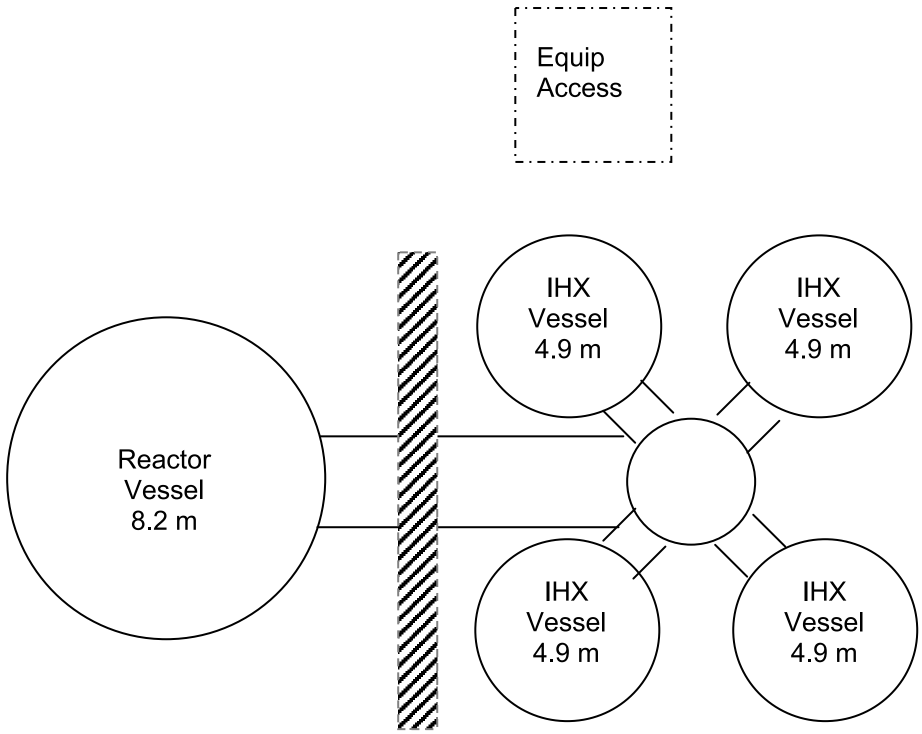


Circulator on bottom of IHX vessel

Possible IHX for Hydrogen Plant shown with dashed lines

Option	Cross Vessels	IHX Vessels	Circulators	H_2 Plant IHX Location
A-1	1	1	1	Integral in IHX vessel
A-2	1	1	2	Integral in reactor vessel
A-3	1	2	TBD	adjacent to PCS IHX vessel
A-4	2	2	2	Separate IHX vessel and cross vessel

Figure 3-17: Loop Arrangement Option A – Single Loop with Compact IHX



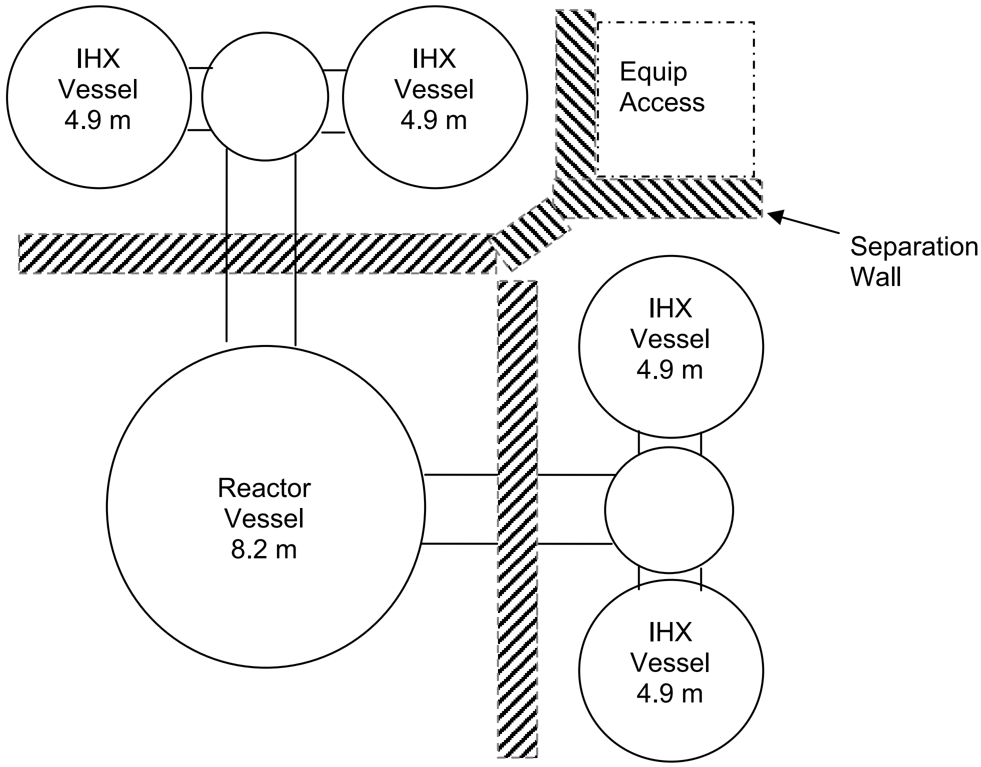
Assume 3 IHX provide heat to PCS

Assume 1 IHX provide heat to H_2 Plant *

Option	Cross Vessels	IHX Vessels	Circulators	Circulator Location
B-1	1	4	1	Central IHX Dist Hub
B-2	1	4	2	Header between IHX pairs
B-3	1	4	4	Bottom of IHX Vessel

* H_2 Plant IHX vessel may be smaller than PCS IHX vessels

Figure 3-18: Loop Arrangement Option B – Single Cross Vessel with Multiple Tubular IHXs



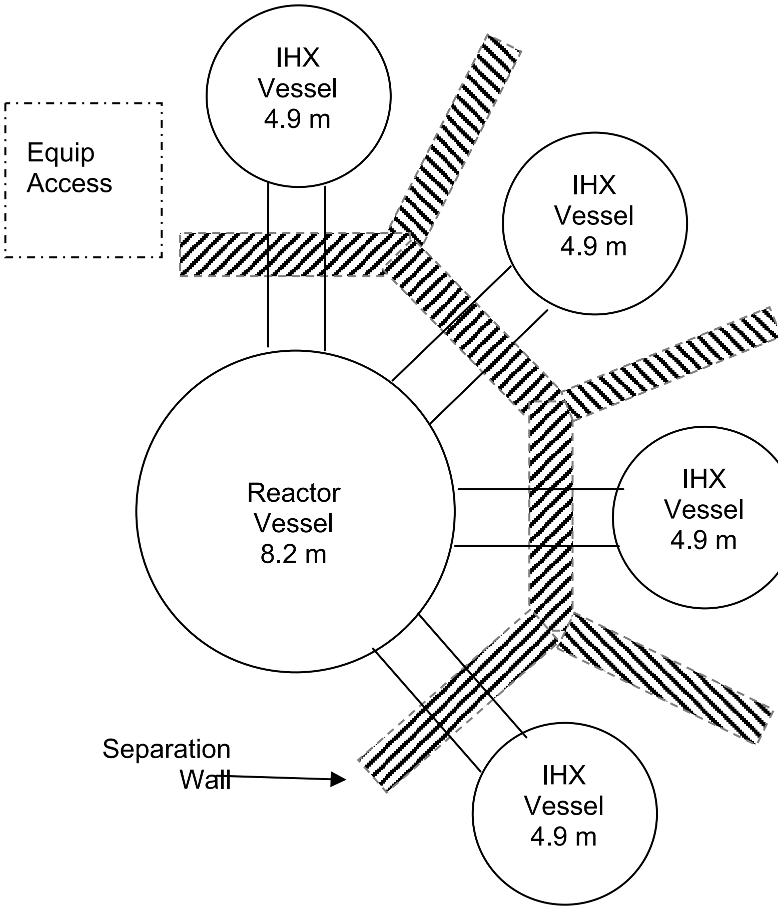
Assume 3 IHX provide heat to PCS

Assume 1 IHX provide heat to H_2 Plant *

Option	Cross Vessels	IHX Vessels	Circulators	Circulator Location
C-1	2	4	2	Header between IHX pairs
C-2	2	4	4	Bottom of IHX Vessel

* H_2 Plant IHX vessel may be smaller than PCS IHX vessels

Figure 3-19: Loop Arrangement Option C – Double Cross Vessels with Two Pairs of Tubular IHXs



Assume 3 IHX provide heat to PCS

Assume 1 IHX provide heat to H_2 Plant *

Option	Cross Vessels	IHX Vessels	Circulators	Circulator Location
D-1	4	4	4	Bottom of IHX Vessel

* H_2 Plant IHX vessel may be smaller than PCS IHX vessels

Figure 3-20: Loop Arrangement Option D – Four Tubular IHXs and Four Cross Vessels

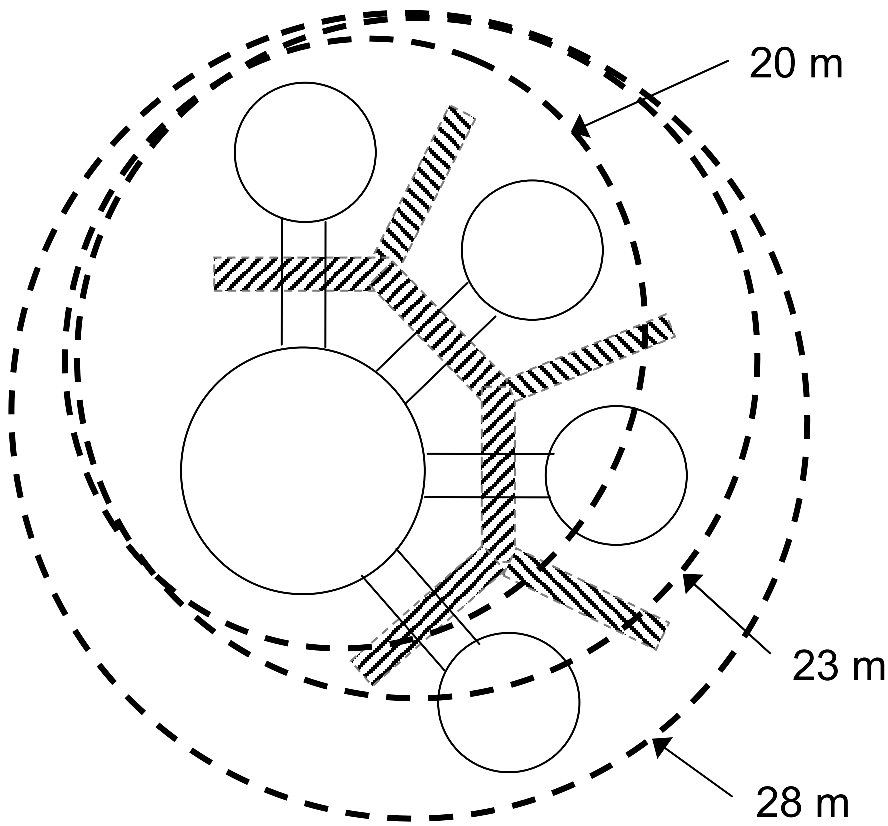


Figure 3-21: Reactor Building Outline Comparison for 2, 3, and 4 Loop Arrangements

3.5 Issue 4 – Evaluation of Secondary Temperatures

The next decision to be addressed is what the secondary loop temperatures should be. A summary of the issue is reviewed in the following subsection. The next subsection provides the evaluation of the discriminating considerations. Then the conclusion for this decision is summarized in the final subsection on this decision.

3.5.1 Summary of Secondary Temperatures Issue

Key question:

"What is the secondary side T_{hot} and T_{cold}?"

Range of options:

IHX approach temperatures between 25-50°C

Major considerations:

Hydrogen process performance

PCS performance

Component cost

Other discriminators:

NHS feasibility

3.5.2 Assessment of Secondary Temperatures Considerations

The evaluation of the secondary temperatures is primarily a tradeoff of improved plant performance weighed against the cost of increased IHX effectiveness. System performance can improve significantly if heat is delivered to the process or PCS at higher temperature. However, the IHX cost also increases significantly as higher effectiveness is specified.

To some extent, this question is the other side of the reactor outlet temperature question examined in Section 3.1. In the reactor outlet discussion, the approach temperatures in the IHX were assumed as given values. In this discussion, the reactor outlet temperature is assumed as a boundary condition and the incentive for modifying the approach temperature is examined. In a sense, the evaluation of the secondary temperature question is intended to confirm the assumption made in setting the reactor outlet temperature.

With a reactor outlet temperature of 900°C, the PCS and hydrogen plant will operate somewhere in the 800-900°C range. System performance can improve significantly with increased heat delivery temperature in this range. As discussed in Section 3.1, the PCS performance improves modestly within this range. The hydrogen process performance is expected to improve more significantly, so it offers a greater incentive for a reduced approach temperature.

The approach temperature between the primary and secondary fluid depends on the IHX effectiveness. In order to achieve a 50°C approach temperature such that the hot secondary fluid leaving the IHX is at 850°C, an IHX effectiveness of 89% is required. For a 25°C approach, the required effectiveness increases to 94%. A key point which makes this difference very significant is that, for high effectiveness heat exchangers, small improvements in effectiveness typically require large increases in surface area. An increase in effectiveness from 89% to 94% would approximately double the size and cost of an IHX.

Thus, it does not make sense to significantly increase the effectiveness for the PCS loop IHX. The anticipated performance benefit is not that large, but the cost of increasing the effectiveness would be significant for the large tubular IHXs with nitrogen-helium on the secondary. The size of the PCS IHX necessitates controlling cost.

For the hydrogen production IHX, the benefit of increasing the effectiveness and the resulting process heat delivery temperature is greater. Moreover, this IHX is smaller, so the overall cost of improving the effectiveness is not as significant. The small IHX for hydrogen production provides a greater incentive for pursuing high effectiveness.

3.5.3 Secondary Temperatures Issue Conclusion

Based on the assessment in the preceding section, the secondary temperatures will be kept at their current baseline values. This corresponds to an approach temperature of 50°C in the PCS IHX, with a relatively conservative 89% effectiveness, and an approach temperature of 25°C in the hydrogen production IHX, with a more aggressive 94 effectiveness.

The PCS secondary system temperatures are:

- T_{hot} (PCS supply) = 850°C
- T_{cold} (PCS return) = 450°C

This will provide good PCS performance, and it provides a reasonable effectiveness goal for the large IHX.

The temperatures in the High Temperature Heat Transport Loop which carries heat to the hydrogen plant are:

- T_{hot} (Heat transport loop supply) = 875°C
- T_{cold} Heat transport loop return) = 475°C

The hydrogen process performance characteristics encourage higher temperatures, and the more aggressive effectiveness goal is reasonable for the smaller IHX.

The recommended conditions are for the NGNP demonstration plant. An obvious question would be what the recommended conditions should be for a dedicated commercial hydrogen production plant. A detailed answer to that question is not available but one would anticipate a compromise in which reactor, IHX, and hydrogen process design and performance margins are reevaluated to develop the optimized solution. One might anticipate a solution in which the reactor outlet temperature is increased by a few degrees, the IHX effectiveness is slightly above 90%, and the hydrogen process is further optimized, resulting in good overall performance without placing an unacceptable burden on any specific part of the overall system. The fact that pure helium would be used in the high temperature heat transport loop would certainly help. Of course, the first commercial plant would benefit from the additional knowledge obtained in the NGNP development and demonstration program.

3.6 Issue 5 – Evaluation of System Pressure

The final decision to be addressed is the primary and secondary coolant pressures. A summary of the issue is reviewed in the following subsection. The next subsection provides the evaluation of the discriminating considerations. Then the conclusion for this decision is summarized in the final subsection on this decision.

3.6.1 Summary of System Pressure Issue

Key question:

"What are the primary and secondary system pressures?"

Range of options:

Overall range 4.0-8.0 MPa with emphasis on 5.0 MPa, 5.5 MPa, 6.0 MPa, and 6.5 MPa

Major considerations:

Operating cost

Plant cost

Other discriminators:

NHS feasibility

Secondary system performance

3.6.2 Assessment of System Pressure Considerations

In the simplest sense, determination of the primary coolant pressure is an optimization exercise which attempts to balance the vessel cost with the system pumping power. Increasing pressure generally increases vessel cost and reduces pumping power requirements.

The vessel cost includes the actual capital cost of the primary coolant vessels as well as the development and fabrication issues that are either minimized or exaggerated as a function of increasing system pressure. It also includes any operational costs associated with increased surveillance requirements due to higher system pressure.

The main element of the pumping power is the electrical power required to drive the circulator in indirect cycle systems or the shaft power required to drive the compressor in direct Brayton systems. However, several other factors are implicitly included in the pumping power. Systems with higher pumping power also require larger circulators or compressors which increases capital cost. As circulator size increases, technology development and feasibility issues may also arise.

The impact on cycle performance varies differently for different power conversion systems. Optimization of system pressure has a more fundamental effect on direct cycle systems than on indirect systems, although all systems are affected to one degree or another.

For indirect cycle systems, the pressure difference across the IHX can be important in determining the operating stress in the IHX and the corresponding component lifetime. A slight pressure bias across the IHX is preferred to avoid locations that are nearly perfectly balanced and therefore frequently crossing back and forth from tension to compression. The direction of this bias is normally dependent on the optimization of stress in the IHX and on the impact of potential leaks and the transport of contaminants from one fluid stream to the other.

For the NGNP preconceptual design based on the adapted ANTARES HTR concept, the system pressure does not have a significant impact on the fundamental characteristics of the system. Therefore, only a brief qualitative assessment of system pressure has been performed. More detailed optimization calculations will be necessary during the Conceptual Design phase.

The key difference between the reference ANTARES concept and the AREVA NGNP preconceptual design is the decision to use multiple loops in the NGNP. The resulting availability of multiple circulators leads to optimization at a lower primary pressure than the ANTARES. The ANTARES reference primary coolant pressure was 6.0 MPa, and the recommended NGNP pressure is 5.0 MPa. The use of a lower pressure reduces vessel cost and it reduces fabrication difficulties. This is beneficial for 2018 startup at the INL site.

3.6.3 System Pressure Issue Conclusion

The recommended NGNP primary coolant pressure is 5.0 MPa.

The secondary coolant pressure is essentially balanced with the primary circuit. A slight bias (perhaps 0.1 MPa) will be imposed between the two circuits to make the long-term stress regimes more predictable. For the PCS the system pressure would likely be set slightly above the primary pressure in order to minimize stress in the hot end of the IHX and to minimize contamination of the PCS circuit in the event of an IHX leak. For the heat transport loop to the hydrogen plant, the possible presence of contaminants in the circuit due to potential process heat exchanger leaks in the hydrogen plant must be considered. In each case, detailed analysis will be required to optimize the pressure bias for each of the secondary loops.

3.7 Review Overall Consistency of Results

Having completed the initial evaluation of each of the decisions to be made, it is necessary to review the initial results to make sure that in the aggregate the results are reasonable and self-consistent. Since most of the later decisions depend to some extent on the prior decisions, it is important to review them to make sure that the initial decisions still make sense in light of the final outcome. The following questions are addressed with this purpose in mind:

Is the reactor outlet temperature of 900°C still reasonable considering that it indirectly requires an inlet temperature of 500°C?

> Yes. The 900°C hot end temperature provides good performance, and the 500°C cold end temperature can be reasonably accommodated without adversely impacting core flow distributions, etc.

Do the selected parameters and configuration result in a reasonable system?

> Yes, all key elements are feasible, and the level of technical difficulty is reasonably balanced within the system.

Is the recommended concept compatible with 2018 deployment?

> Yes, assuming prompt action is taken on design, development, and procurement.

Does the concept support hydrogen process development?

Yes, the dedicated loop providing heat to the high temperature heat transport loop provides significant flexibility. It provides a way to test alternate components and it can support a range of temperature and operational conditions without adversely impacting electricity generation.

Does the concept support direct commercialization?

Yes, the rugged system design based on near-term technology and reasonable performance requirements provides a good foundation for rapid commercial deployment following initial NGNP demonstration.

The selection of the parallel configuration for PCS and hydrogen process heat loads provides best support for future commercialization, since dedicated commercial plant will have to directly match process and reactor inlet and outlet temperature inderface.

The selected approach allows results in reasonable requirements for key component and a well balanced overall system. The emphasis on maintainable technologies will allow rapid transfer to a commercial environment.

4.0 RESULTS AND CONCLUSIONS

The main results and recommended operating conditions for the NGNP are provided in Section 4.2. First, more general conclusions are provided in Section 4.1.

4.1 General Conclusions

A 900°C reactor outlet temperature provides a good balance between hydrogen production process performance and NHS feasibility

A 500°C reactor inlet temperature provides a reasonable core temperature rise without severe consequences on the rest of the design.

The multiple loop configuration addresses several otherwise difficult development challenges, and leads to designs based on existing experience and near-term technology for all key components.

The recommended concept is well suited to future commercial hydrogen plants. Two loops with tubular IHXs are expected to be adequate for transferring the full reactor output to a hydrogen production facility, potentially resulting in reduced system cost compared to a single loop compact heat exchanger configuration. The selected configuration is also most easily adapted to future advanced heat transport systems such as the use of molten salt.

4.2 Summary of Results and Recommendations

The following parameters are recommended for use in the NGNP preconceptual design:

- Reactor outlet temperature — 900°C
- Reactor inlet temperature — 500°C
- System configuration — H2 and PCS in parallel
- Number of loops — 4 loops
3 with tubular IHXs for PCS
1 with compact IHX for H2
- Secondary temperatures — 450-850°C for PCS (50°C approach)
475-875°C for H2 (25°C approach)
- System pressure — 5.0 MPa

It is further recommended that these parameters be reconfirmed early in the conceptual design phase in order to take into consideration the final results of the preconceptual design studies and any modification of mission requirements at the beginning of the next project phase.

5.0 REFERENCES

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APPENDIX A: IMPACT OF HIGH TEMPERATURE HEAT TRANSPORT STRATEGY ON PRIMARY AND SECONDARY CYCLE CONCEPT

A.1 High Temperature Heat Transport Alternatives

The Primary and Secondary Cycle Concept Study has assumed that an intermediate heat transport loop using high pressure helium would be used to transport the heat to be provided to the hydrogen production process facilities. This is an effective means of high temperature heat transport which presents the most straightforward interface with the NHS for service in the 850-900°C temperature range with minimal basic technology development.

The study also assumes an indirect cycle CCGT using a nitrogen-helium gas mixture as adapted from the reference ANTARES design as the basis for the PCS.

It is important to keep in mind that several alternatives to these assumptions exist which may have significant advantages depending on the specific plant mission requirements and design constraints. The evaluation of these alternatives falls most clearly under the High Temperature Heat Transport Special Study and the Power Conversion System Special Study, and it is clearly outside the scope of the Primary and Secondary Cycle Concept Study. Nonetheless, these alternative approaches could have significant impacts on the decisions made within this study if they had been adopted as the reference assumptions at the beginning of the study. Moreover, these alternatives may present important opportunities for future technology deployment, and it is not the intent of the study to discourage them from being further evaluated.

Some of the most obvious alternatives to high pressure helium include the following:

- Molten salt
- Liquid metal
- Chemical energy transfer
- High temperature steam
- Electrical energy supply
- Hybrid systems

A.2 Effectiveness of Heat Transport Alternatives

- Molten salt – Has the potential to significantly reduce pumping power and piping cost by allowing low pressure operation. It has good high temperature capability.
- Liquid metal – Similar characteristics as molten salt, although high temperature capability is not quite as good.
- Chemical energy transfer – Proposed in the past as a means to transfer the energy at ambient temperature. NHS heat exchanger drives high temperature endothermic reaction and products are cooled regeneratively prior to transport to user facility. Energy is released at user facility in inverse exothermic reaction. Systems have been evaluated for specific applications in the past. Substantial component and system development work would be required to deploy a system for current applications.

- High temperature steam – This is the most mature thermal energy transfer technology. High temperature steam is routinely transported over significant distances, potentially alleviating the challenge of locating the NHS and hydrogen production facility in close proximity to one another. However, the maximum temperatures achievable are not as high as high pressure helium and molten salt (perhaps 600°C). Use of high pressure steam for thermochemical hydrogen production would require modification of currently envisioned systems or adoption of processes with lower temperature requirements than S-I.

- Electrical energy supply – The most convenient form of energy supply is electrical heating. This simplifies the design of both the process equipment and the NHS interface. The key drawback is the substantial loss in efficiency due to the electricity generation process. Using HTRs offers the potential to increase this efficiency, but it is still a significant loss compared to the ideal of direct thermal energy transfer.

- Hybrid systems – The most attractive approach may ultimately be a system that combines elements of more that one of the above concepts. Mature systems will likely take this route to minimize some of the difficulties associated with individual approaches and achieve the best optimized system. This is one of the areas of AREVA's internally funded research.

A.3 Impact of Heat Transport Alternatives on Nuclear Heat Source

- Molten salt –Trace heating of all piping, heat exchangers, and components would be required, including the IHX. Significant material compatibility questions remain to be resolved. The issue of pressure balance within the IHX could be a serious problem. The issue of molten salt leaking into the primary system must also be resolved.

  Molten salt is not viewed as ready for deployment in the NGNP and probably not in the initial wave of commercial plants.

- Liquid metal – Similar concerns as molten salt. Material compatibility data may be more widely available, but remaining issues still preclude near term deployment.

- Chemical energy transfer – Significant development and analysis would be required to assess the impact of such a system for NGNP. Significant effort would be anticipated in developing the required heat exchanger/chemical reactor for interfacing a proposed application with the primary circuit of current reactor concepts. Safety implications of large scale chemical reactions on secondary side of NHS heat exchanger would have to be evaluated with the regulator.

  Chemical energy transfer systems are perhaps the least ready for deployment due to the required development.

- High temperature steam – Production of high temperature steam using HTRs is well established technology, having been the focus of numerous design studies and having been demonstrated successfully in several previous plants. In general, NHS design constraints are relaxed significantly, because reactor operating temperatures are somewhat lower, and because the IHX is replace by a steam generator which is more robust. The issue of water ingress would have to be reintroduced into the safety analysis space, but existing approaches used to resolve this issue in the past would be expected to be adequate. (Note that the water ingress issue is not the serious circulator water bearing issue that plagued Fort St. Vrain.)

High temperature steam supply is the most readily available technology and could accelerate deployment of the NHS.

- Electrical energy supply – The impact of this approach on the NHS depends on which generating technology is employed. If a Rankine system is used, the issues are almost identical to the high temperature steam option. If a Brayton or CCGT is used, then other considerations are introduced.

- Hybrid systems – The impact on the NHS obviously depends on which options are adapted in the hybrid approach. If a combination of high temperature steam and electricity were selected, then there would be no impact on the NHS, since the NHS product would be steam in either case.