

Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production

White Paper - Characterizing the Effect of NGNP Operating Conditions on the Uncertainty of Meeting Project Cost and Schedule Objectives

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1. BACKGROUND

The Very High Temperature Reactor (VHTR) is one of the advanced reactor concepts within the internationally-supported Generation IV program. Because of its design features and design maturity, the VHTR was selected by the U.S. Department of Energy as the U.S. Generation IV design concept for the Next Generation Nuclear Plant (NGNP). Other countries, including Russia, Japan, South Korea, China, South Africa, and France are also developing this technology, and large-scale deployment of VHTR technology is a realistic element of future energy-growth scenarios. For electricity production, General Atomics (GA) has developed the Gas Turbine Modular Helium Reactor (GT-MHR) concept (see Fig. 1), which operates with a helium coolant-outlet temperature of 850°C and a thermal efficiency of 48% using a direct Brayton cycle Power Conversion System (PCS). For hydrogen production and other processheat applications, heat is transferred through an intermediate heat exchanger (IHX), and it is desirable to operate the VHTR core with higher coolant outlet temperatures in the range 900°C – 950°C to compensate for temperature drops through the IHX and maintain high thermal efficiency and competitive economics.



Figure 1. GT-MHR Concept and Core Layout

Passive safety is one of the fundamental requirements for the VHTR. Passive safety features include (1) ceramic, coated particle fuel that maintains its integrity at high temperatures during normal operation and Loss of Coolant Accidents[•] (LOCAs); (2) an annular graphite core with high heat capacity and large surface area for heat transfer in the radial direction that limits the temperature rise during a LOCA; (3) a relatively low power density that helps maintain acceptable temperatures during normal operation and accidents; (4) an inert helium coolant, which reduces circulating and plateout activity; and (5) a negative temperature coefficient of reactivity that ensures control of the reactor for all credible reactivity insertion events. During a LOCA, the decay heat is conducted through the graphite to the vessel. The heat is transferred from the vessel by thermal radiation and natural convection to a passive Reactor Cavity Cooling System (RCCS). The fuel, the graphite, the primary coolant pressure boundary, and a low-pressure vented containment building provide multiple barriers to the release of fission products.

This paper provides an assessment of the potential cost and schedule risks associated with the key operating conditions currently under consideration for the NGNP. The most significant risks are associated with selection of a coolant outlet temperature in excess of approximately 900°C and design choices that would require use of a higher-temperature, high-alloy steel for the Reactor Pressure Vessel (RPV).

2. IMPACTS OF OPERATING CONDITIONS ON NGNP DESIGN

Operating parameters that have a significant impact on NGNP design include the thermal power level, primary coolant inlet temperature, primary coolant pressure, and primary coolant outlet temperature. These parameters are discussed below with regard to their primary impacts on NGNP design.

Reactor Thermal Power Level

Thermal power levels ranging from 250 MW to 600 MW are being considered for the NGNP prototype. The GA and other NGNP vendor teams have recommended the thermal power level for the NGNP prototype be the same as that of a single module in a commercial-scale, multi-module plant. This approach essentially eliminates any technical and regulatory concerns regarding scale-up of the nuclear heat source for commercial applications. For a GT-MHR module, a thermal power of 600 MW corresponds to the maximum power level that can be achieved within the constraints of passive safety and an RPV diameter that is within the current

^{*} For MHRs, a LOCA is referred to as a Low Pressure Conduction Cooldown, and a Loss of Flow Accident (LOFA) is referred to as a High Pressure Conduction Cooldown. For both events, conduction of decay heat through the graphite and other reactor internal components is a key factor in determining the temperature response of the fuel, which typically includes a slow heatup phase followed by a slow cooldown phase after the decay heat rate drops below the heat removal capacity of the RCCS.

experience base of RPV manufacturers. The primary impacts of thermal power level on the NGNP design are discussed below.

<u>RPV and Reactor Internals Design</u>. GA has developed passively safe MHR designs with annular, prismatic-block cores at thermal power levels ranging from 350 MW to 600 MW. Table 1 provides a comparison of the RPV design parameters for the 350 MWt and 600 MWt concepts. As indicated in Table 1, the RPV dimensions for a 600 MWt module are not significantly greater than those for a 350 MWt module. Because of its higher operating temperature, the allowable stresses for the 600 MWt RPV are lower, which translates into thicker wall sections and greater weight (1328 t vs. 728 t). If a 350 MWt RPV operated under the conditions shown in Table 1 for the 600 MWt RPV, the wall thickness and weight would be approximately the same as those for the 600 MWt RPV. An alternative RPV design for MHRs with higher temperature design points is to use SA-508/533 steel and incorporate design measures (e.g., active vessel cooling) to ensure the RPV operates at temperatures within the ASME code limits. With this design, the 600 MWt RPV would have a wall thickness of approximately 0.165 m and the weight would be reduced to approximately 1000 t.

Parameter	350 MWt RPV	600 MWt RPV	
Application	Electricity production, steam cycle	Electricity production, direct Brayton cycle (GT-MHR)	
RPV Material	SA-508/533	9Cr-1Mo-V	
Design Temperature, °C	288	495	
Max. Operating Temperature, °C	210	474	
Primary Coolant Inlet/Outlet Temperatures, °C	258/687	490/850	
Design Pressure, MPa	7.2	8.0	
Operating Pressure, MPa	6.4	7.1	
RPV Outside Diameter (Shell), m	6.8	7.5	
RPV Outside Diameter (Flange), m	7.4	8.2	
RPV Thickness (Shell), m	0.133	0.216	
RPV Total Height, m	22.0 24.0		
RPV Weight, t	728	1328	

 Table 1. RPV Design Parameters for 350 MWt and 600 MWt MHR Concepts

<u>Design of Primary Heat Transport System</u>. Thermal power level can have a significant impact on design of the primary heat transport system. For the GT-MHR, a significant risk for commercialization is successful demonstration of the integrated PCS. A lower thermal power level would translate into a smaller turbomachine for power conversion, which could lower the risks associated with technology development. Capital costs of the PCS and other plant equipment would also be reduced. However, previous studies [Schwartz 1994] have shown significantly higher electricity production costs at lower power levels, which could be a major impediment to commercialization. The optimal thermal power for commercialization has not yet been established for process heat applications using an indirect cycle with an IHX. However, there are practical limitations for the size of heat exchangers used to transfer high-temperature heat. For a 600 MWt MHR module, recent evaluations indicate a single primary heat transport loop may be feasible if a compact, printed-circuit type IHX is used [GA 2008a]. However, the associated technology-development risks may be relatively high for this IHX concept. If a more conventional helical coil IHX were used, three 200-MWt primary heat transport loops would likely be required [GA 2008a].

Conclusions

- 1. Thermal power level is not expected to have a big impact on design and capital costs of the RPV and reactor internals.
- 2. Selecting a lower thermal power level for the NGNP can reduce the number of primary and secondary heat transport loops and the size of the IHX, circulators, and other components, which would reduce capital costs. Scale-up of the heat-transfer equipment should not pose a large risk for future commercialization. For example, scale-up of a compact IHX can be accomplished by adding additional IHX modules and increasing the size of the IHX vessel.

Primary Coolant Inlet Temperature

The primary coolant inlet temperature affects design of the RPV and reactor internals and the coolant velocity within the graphite fuel elements. In addition, for an indirect-cycle plant, the inlet temperature affects the design of the circulator and IHX.

<u>RPV and Reactor Internals Design</u>. For the GT-MHR, the inlet coolant flow is routed through riser channels between the core barrel and RPV (see Fig. 1). With this configuration, the design of the reactor vessel (especially materials selection) is driven in large measure by the design point selected for the coolant inlet temperature (see Table 1). As shown in Fig. 2, the MHR reactor internals can be designed to route the inlet flow through the Permanent Side Reflector (PSR) to provide additional thermal resistance between the inlet flow and RPV. As shown in Fig. 3, this configuration may allow use of SA-508/533 steel for the RPV if the inlet temperature is below about 490°C, assuming leakage flow to the annular space between the core barrel and RPV can be controlled [GA 2008b]. Based on previous studies [Richards 2007], a leakage flow of 2% will increase RPV temperatures by about 40°C (see Fig. 4). A Vessel Cooling System (VCS) can also be incorporated into the reactor internal design to ensure the RPV operates at temperatures below the ASME code normal-operation limit of 371°C for SA-508/533 steel.

<u>Cooling of Graphite Fuel Elements</u>. As indicated in Eq. (1), for a fixed thermal power level Q, the product of core ΔT and total coolant mass flow rate \dot{m} is constant. For NGNP, the outlet

temperature is expected to be a fixed design requirement, and a decrease in inlet temperature will increase core ΔT and lower \dot{m} . Hence, one of the constraints on the inlet temperature is ensuring adequate coolant mass flow to maintain fuel operating temperatures at acceptable levels. The impact of higher core ΔT and lower \dot{m} on peak fuel temperatures can be reduced if the core physics design is optimized to minimize power peaking factors, which helps to flatten the distribution of flow among the fuel columns. As indicated in Fig. 5, a 100°C decrease in inlet temperature results in an approximately 40°C increase in peak fuel temperature.

$$Q = \dot{m}C_{p}(T_{out} - T_{in}) = \dot{m}C_{p}\Delta T$$
(1)



Figure 2. RPV and Reactor Internals with PSR Coolant Risers and Vessel Cooling

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Figure 3. Predicted Peak RPV Temperatures with PSR Coolant Risers



Figure 4. Effect of Leakage Flow on Normal Operation RPV Temperatures



Figure 5. Effect of Coolant Inlet Temperature on Peak Fuel Temperature

<u>*Circulator Design.*</u> The circulator is located on the cold leg of the primary circuit, and coolant inlet temperature will have a direct impact on material requirements for the circulator blades. As shown in Fig. 6, circulator pumping power increases with temperature and decreases with pressure.



Figure 6. Circulator Pumping Power as a Function of Coolant Inlet Temperature

<u>IHX Design</u>. As indicated in Eq. (2), for a given IHX duty Q_{IHX} the product of the required heat transfer area A_t and overall heat transfer coefficient U_m of the IHX is inversely proportional to the log-mean temperature difference LMTD, which is defined by the differences between the primary and secondary temperatures at the IHX inlet (ΔT_{in}) and outlet (ΔT_{out}). As shown in Fig. 7, higher primary coolant inlet temperatures will result in larger LMTDs and smaller required heat transfer areas for the IHX.



Figure 7. Effect of Primary Coolant Inlet Temperature on IHX LMTD

Conclusions

- For reactor coolant inlet temperatures above approximately 490°C, an active VCS would likely be required in order to use SA-508/533 steel. Potential risks include additional technology development to support design and safety classification of a VCS (safetyrelated vs. investment risk). In principle, an active VCS should not impact the case for passive safety, since a SA-508/533 RPV could operate for extended periods with the VCS offline without exceeding damage limits. However, the VCS should be considered an investment protection system and should be designed for a high degree of reliability.
- 2. Coolant inlet temperature will be constrained in part by the requirement to provide adequate coolant mass flow to cool the graphite fuel elements. For an outlet temperature of 950°C and thermal power of 600 MW, the minimum acceptable inlet temperature is approximately 490°C. This core ΔT is 100°C higher than that for the GT-

MHR, which was designed for coolant inlet/outlet temperatures of $490^{\circ}C/850^{\circ}C$ [Shenoy 2006]. A core operating with higher ΔT (and lower coolant mass flow) may require design measures to optimize power distributions and core thermal hydraulics, and additional technology development may be required to confirm the benefits of these design measures. Possible examples include demonstration of lateral restraint mechanisms and sealing keys to reduce bypass flow.

- 3. Practical limitations on circulator size and operating temperature may have some impact NGNP design and technology development. Circulator blade materials with higher temperature capability will have to be developed for coolant inlet temperatures above approximately 350°C, but this does not appear to be a major issue. Circulators with pumping powers above about 6 MW may require additional technology development, but multiple circulators can be used on a single heat-transport loop, if necessary.
- 4. If the physical size and cost of the IHX pose significant risks, increasing the primary coolant inlet temperature is a viable option to address these risks (to reduce the LMTD and required heat-transfer area), provided the risks associated with higher inlet temperature (e.g., possible need for a VCS) are determined to be acceptable.

Primary Coolant Pressure

The primary coolant pressure determines in part the required thickness of the RPV and the power required for the circulator. Coolant pressure can also affect the lifetime of the IHX and the thermodynamics of process heat applications.

<u>*RPV Thickness*</u>. The required thickness t_{RPV} for the RPV can be estimated using the formula given in Section III, Division 1, Subsection NB of the ASME Code:

$$t_{\rm RPV} = \frac{{\sf PR}_{\rm i}}{{\sf S}_{\rm m} - 0.5{\sf P}} \tag{3}$$

where P = internal pressure, R_i = internal radius of the RPV, and S_m = ultimate tensile strength. At the temperatures and pressures of interest, $S_m >> P$ and the required RPV thickness is nearly directly proportional to the primary coolant pressure. Reducing pressure from 7 MPa to 5 MPa reduces the required vessel thickness by approximately 30%.[†]

[†] Operating at reduced system pressure would improve the feasibility for using 2.25Cr-1Mo (Grade 22) steel for the RPV [GA 2008b]. This material is included in Section III of the ASME code and was used for Japan's High Temperature Engineering Test Reactor (HTTR) pressure vessel [Tachibana 2004]. However, it should be noted that the manufacturer of forgings and plates for this pressure vessel (Japan Steel Works) has expressed reluctance about using this material for a commercial-scale VHTR, in part based on their experience with the HTTR pressure vessel.

<u>*Circulator Power.*</u> As shown in Fig. 6, the required circulator power varies inversely with pressure. Reducing pressure from 7 MPa to 5 MPa will increase circulator power by approximately 40%.

<u>IHX Lifetime</u>. Preliminary calculations performed by Toshiba Corporation [GA 2008a] indicate total system pressure may have a significant impact on the stress intensities in a compact, printed-circuit heat exchanger. For a differential pressure between the primary and secondary helium coolant of 0.1 MPa, the stress intensity at a primary coolant pressure of 7 MPa is predicted to be approximately 40% higher than at 5 MPa, which could have a significant impact on IHX lifetime.

<u>Thermodynamics of Process Heat Applications</u>. In general, it is desirable to minimize pressure gradients across IHX surfaces, and higher primary coolant pressures will generally translate into higher secondary coolant pressures, which in turn translate into higher fluid pressures within the process-heat application. Some process-heat applications may be more thermodynamically efficient at lower pressures, which must be factored into the design point selected for the primary coolant pressure. For example, the sulfur-iodine thermochemical water splitting process includes several fluid-vaporization steps that are more efficient at lower pressures. In contrast, the GT-MHR with a direct Brayton cycle PCS for electricity production favors higher system pressures for thermodynamic efficiency.

Conclusions.

- 1. Operating at lower system pressure can reduce risks associated with the RPV, especially with regard to manufacturability and weldability of thick sections.
- 2. Because the required power for the circulator varies inversely with system pressure, operating at lower system pressure would be more amenable to operating at lower reactor thermal power. For example, the required circulator power for a 600 MWt module at 7 MPa primary coolant pressure is approximately the same as that for a 400 MWt module at 5 MPa primary coolant pressure.
- 3. For an indirect cycle, higher system pressures may have a significant adverse impact on IHX lifetime that requires further evaluation.
- 4. Some process-heat applications favor operation at lower pressure, which could be a factor in determining the system pressure and thermal power rating for the reactor module.

Primary Coolant Outlet Temperature

The design setpoint selected for primary coolant outlet temperature will likely have the most impact on the uncertainties associated with meeting NGNP project cost and schedule objectives, especially with regard to the high-temperature metals required for the IHX and other high-temperature components. The outlet temperature also affects the peak fuel temperature and higher temperatures generally improve the efficiency of power production and process heat applications.

<u>IHX Material</u>. For operating temperatures in the 900°C – 950°C range, a number of materials have been considered for the IHX [Natesan 2006b], including Alloy 800H, Alloy 617 and Alloy 230. Of these materials, Alloy 800H is the only one currently approved for nuclear applications in Section III of the ASME codes. This material has been considered for the IHX and a significant amount of data at temperatures up to 1000°C have been compiled. The data showed some creep strength at high temperatures, but the slope of the curve in this higher temperature regime was steep and not very predictable.

The general consensus is that Alloy 617 and Alloy 230 are the two primary candidate materials for the IHX. At higher temperatures, Alloy 617 has slightly better properties. Previously, there were a number of problems associated with welding of Alloy 617, including stress induced cracking in the weld heat affected zone and cold worked areas, but these problems were resolved by using a post weld heat treatment.

Currently, neither Alloy 617 nor Alloy 230 is approved for use in Section III Class 1, 2 and 3 or in the high temperature NH section of the ASME Code. They are both approved at temperatures up to 982°C in Section VIII Div. 1. Table 2 provides the maximum allowable stresses from ASME Section II Part D Table 1 for Alloy 617 and Alloy 230 at 900°C and 950°C. Also included are the values for Alloy 800H.

Even for these super alloys, the allowable stress levels for Section VIII Division 1 are quite low in the temperature range 900°C – 950°C. Data will have to be obtained in order to develop a code case for nuclear applications. Furthermore, if the allowable stresses are further reduced because of Section NH rules and/or application of long-seam weld reduction factors, developing a viable high-temperature IHX design will become even more difficult. On a more positive note, Heatric Division of Meggitt (UK) Ltd. has successfully manufactured a diffusion-bonded printed circuit heat exchanger core using Alloy 617 [Li 2008]. However, design rules for these types of heat exchangers need to be established and incorporated into the ASME code.

ASME Product Specs	Allowable Stress 900°C	Allowable Stress 950°C	
SB 168 Plate Alloy 617	1.8 ksi	1.1 ksi	
SB 564 Forging Alloy 617	1.8 ksi	1.1 ksi	
SB 435 Plate Alloy 230	1.5 ksi	0.7 ksi	
SB 564 Forging Alloy 230	1.5 ksi	0.7 ksi	
SB 409 Plate Allov 800H*	0.86 ksi	Not permitted	
SB 564 Forging Alloy 800H*	0.86 ksi	Not permitted	

Table 2. ASME Section VIII Division 1 Allowable Stresses for Alloys 617, 230, and 800H

*All product forms have a 2.6 ksi maximum allowable stress at 760°C in ASME Section III Part NH.

Two other potential issues for Alloy 617 are its high cobalt content (~13%) and carburization. Although the IHX itself is not exposed to neutron flux, even low levels of corrosion or spallation of the IHX wetted surfaces could significantly increase the primary circuit circulating and plateout activity through production of Co-60 as the coolant passes through the reactor core. There are also concerns about carburization of Alloy 617 in an impure helium environment that require further evaluation [Johnson 1982].[‡] These issues were among the considerations for developing Hastelloy XR as the material for the HTTR IHX [Inagaki 2004]. Hastelloy XR has improved creep strength and corrosion resistance relative to Hastelloy X and is a viable material for the NGNP IHX. As part of the Generation IV collaboration between the U.S. and Japan, there is an ongoing effort to include this material in the ASME code. However, at 900°C, the allowable stress for Hastelloy XR are about 50% lower than that for Alloy 617 [Li 2008].

<u>Peak Fuel Temperature</u>. The coolant temperature is the boundary condition for determining the fuel temperature, and an increase in coolant outlet temperature generally results in a proportional increase in peak and overall fuel temperatures.

Conclusions.

Operation with a high coolant outlet temperature in the range 900°C – 950°C will likely
present the biggest technical challenge to NGNP. Codifying a suitable material for the
IHX and developing a viable IHX design with reasonable lifetime could pose a significant
risk for meeting an NGNP startup in the 2018 – 2021 time frame.

[‡] Other studies indicate that proper control of the CO partial pressure in the helium coolant can result in a stable, corrosion-resistant oxide layer at temperatures approaching 1000°C [Cabet 2008].

2. Higher coolant outlet temperatures will result in higher fuel temperatures. The impact of higher fuel temperatures on fuel performance and fission product release must be factored into the NGNP design, which could affect other design parameters, including selection of the reactor thermal power level.

3. MANAGEMENT AND QUANTIFICATION OF RISKS

GA strongly believes one of the best ways to manage cost and schedule risks for any design project is to ensure the design process and the associated technology-development programs are closely integrated. In addition, decision trees can be used to determine the best path for minimizing schedule delays and reducing costs, and decision trees can be combined with Monte Carlo simulations to quantify uncertainties. Both of these approaches are described below.

Integration of Design with Technology Development to Reduce Risks

GA uses the process illustrated in Fig. 8 to focus technology development on supporting a specific design. This approach minimizes the technical risk of the design and the associated technology-development costs, and is based on successful engineering development and demonstration programs conducted and managed by GA for DOE projects, including the commercial GT-MHR and the New Production Reactor, which was a 350 MWt concept with a steam-cycle PCS that was developed through the preliminary design phase.

The process begins by evaluating design requirements and reviewing existing design data from a variety of sources. Design assessments and trade studies are performed, eventually leading to key design selections and a technical baseline that meets all design requirements. It may be reasonable to revise one or more design requirements during the process if the overall impact is small. At this point, a design has been developed that meets all requirements, but requires some technology development to confirm assumptions upon which the design is based. Also, if necessary, the process allows for an early testing path to provide early confirmation of basic assumptions.

The technology development process begins with the design organization preparing design data needs (DDNs), which are formal project documents that include fallback positions in the event the testing programs do not produce acceptable results or the test could not be performed for budgetary or other reasons. The DDNs provide a concise statement of the required data and the associated schedule, quality, and accuracy requirements. In addition to preparing DDNs, the design organization also prepares Test Specifications that define the data requirements in more detail. The technology organization is responsible for developing Technology Development Plans and Test Plans for specific tests. The design and technology organizations

work together during preparation of the DDNs, Test Specifications, Technology Development Plans, and Test Plans.

The technology organization conducts the technology development programs and generates the design data. If feasible, the technology organization may integrate its activities with other (including international) programs in order to reduce costs. After the design data are obtained, the design and technology organizations work together to determine if the DDNs are satisfied. If the DDNs are satisfied, the key design selections and technical baseline are finalized and the design is completed. If a DDN is not satisfied, the most likely path forward is to adopt the fallback position, which could mean additional margin is added to a certain area of plant design in order to reduce technical risk. However, depending on the results of a specific test program, a more reasonable path forward may be to re-evaluate a key design selection and return to the design process. An Independent Review and Verification organization is established during the early stages of the design project to provide oversight of both the design and technology development processes.



Figure 8. Methodology for Integration of Design Process with Technology Development

Figure 8 also includes annotations to show how this process could be used for selecting the RPV material. For this example, it is assumed NGNP startup must occur by 2018 - 2021 and the NGNP must be able to operate with a helium coolant outlet temperature in the range 900°C - 950°C. One of the key long-lead items for the NGNP is the RPV and one of the key design selections that will determine whether or not an RPV can be supplied in time to support a 2018 - 2021 startup is the RPV material. The influence of RPV design on the overall NGNP design and operating conditions will depend in large measure on the design philosophy adopted for the RPV, which will be determined in large measure by schedule constraints. If the NGNP schedule is relatively tight, a risk-averse approach to RPV design will likely have to be adopted, and the NGNP RPV design will be similar to current LWR RPV designs in terms of materials, physical size, and operating conditions. Other aspects of NGNP design, including design of the reactor internals and the RCCS, must ensure the RPV is not exposed to conditions outside the envelopes established by Section III of the ASME code for nuclear pressure boundaries. As discussed previously, this design philosophy will likely result in a more complex reactor internals design to limit RPV temperatures and may also result in some constraints on NGNP design points, including the selection of primary coolant inlet and outlet temperatures. The required technology development for NGNP will then include DDNs to support these other aspects of NGNP design.

If the NGNP is less constrained by schedule, the overall NGNP design can be better optimized for a given application. With this design philosophy, the RPV design is not limited to using materials with an extensive manufacturing base, and the RPV design is less of a factor for determining acceptable operating conditions for the NGNP. This philosophy was used to develop the 600-MWt GT-MHR conceptual design [Shenoy 1996]. For the GT-MHR, the inlet temperature also has a significant impact on performance of the PCS. The design point of 490°C ensures high-efficiency operation of the PCS and acceptable operating conditions for an RPV manufactured from high-alloy steel with higher temperature capability. For the GT-MHR, Grade 91 steel (9Cr-1Mo-V) was selected as the material for the RPV, cross vessel, and PCS vessel, with the expectation that additional technology development would be required to fully qualify this material for the GT-MHR. As discussed in [GA 2008b], Grades 92, 22V and 23 steels are also good candidate materials for a higher-temperature RPV. Candidate materials for the RPV are also discussed in [Natesan 2006a].

In order to achieve a 2018 startup date, the RPV must be delivered to the construction site by about 2014. Since approximately 36 months are required to manufacture the RPV, the procurement specification must be delivered to the RPV manufacturer by approximately 2011, which means final design of the RPV must be completed in the same time frame. SA-508 (ring forgings) and SA-533 (rolled plates) have been used extensively for LWR RPVs. Table 3

provides a comparison of SA-508/533 and Grade 91 steels. The limited experience with Grade 91 and other high-alloy steels combined with the tight NGNP schedule will likely require a riskaverse approach to the RPV design and selection of SA-508/533 material for the RPV. However, use of a high-alloy steel should be a fallback position, and a programmatic decision should be made to develop design data for both materials. This decision is based in part on potential use of a high-alloy steel for follow-on commercial plants to increase design margins and provide greater flexibility for operation at different design points. As illustrated in Fig. 8, the DDNs for SA-508/533 and a high-alloy steel are put on an early testing path in order to minimize schedule risks. As discussed above, use of SA-508/533 steel will also require DDNs related to the reactor internal design to be satisfied (e.g., VCS DDNs and/or DDNs related to design modifications to reduce bypass flow). If these DDNs related to reactor internals are not satisfied. a possible path forward is to increase the coolant inlet temperature (to reduce the core ΔT and provide more flow to the fuel), which would require adopting the fallback position to use a highalloy steel and accepting some delay in the NGNP startup date. Alternatively, a decision could be made to lower coolant inlet and outlet temperatures to levels that would allow the use of SA-508/533 steel for the RPV.

Parameter Design Impacts		SA-508/533	Modified 9Cr-1Mo (P91)		
Nuclear RPV Experience		Used extensively for LWR RPVs.	Nuclear experience limited to piping and other thin-walled components.		
ASME Code Status	Schedule and	Section III, Subsection NB	Section III, Subsection NH.		
Required Technology Development	licensability.	Effects of helium impurities on mechanical properties and oxidation/corrosion.	Effects of helium impurities on mechanical properties and oxidation/corrosion. Manufacturability, properties, and welding of thick sections.		
Temperature Limits	Reactor internals design. RCCS design. Potential need for active VCS.	371°C for normal operation. 538°C for accident time periods up to 1000 h.	649°C		
Tensile Vessel thickness.		High.	High.		
Ring Forging Capability	Reduces required number of welds and ISI requirements.	Extensive experience for LWR RPVs.	No experience or current capability.		

Table 3. Comparison of SA-508/533 and Modified 9Cr-1Mo Steels for the NGNP RPV

Decision Tree Analysis to Determine Optimal Design Approach

The Microsoft Excel add-in TreePlan[§] was used to develop decision trees for selecting the RPV material. Decision trees can be formulated that include both decision nodes and event nodes that have multiple branches. Event nodes include assignment of a probability to each branch of the node. Two decision trees were developed for this study; one with an 850°C outlet temperature that minimizes the risks associated with selection of a super-alloy material for high-temperature components, and one with a 950°C outlet temperature that recognizes the technological risks associated with this high temperature but also recognizes the need for the NGNP to demonstrate a truly innovative technology. Figure 9 shows the decision tree for a coolant outlet temperature of 850°C. With the coolant outlet temperature fixed, this tree includes two decision nodes: (1) selection of the RPV material (SA-508/533 or high-alloy steel) and (2) selection of the coolant inlet temperature (390°C or 490°C).

[§] Information on TreePlan can be obtained from http://www.treeplan.com/.

Path 2 Path 3 Path 4 Path 5 Path 1 NGNP Start Date 2020 2019 2025 2020 N ~ N -3.5 42 2 1 VCS Not Req'd VCS Not Req'd VCS Not Req'd 0 N 0



Figure 9. Decision Tree for Selection of RPV Material (850°C Core Outlet Temperature)

Event nodes are associated with (1) the probability fuel temperatures are within acceptable limits for a higher ΔT core and (2) the probability a VCS is required with a 490°C inlet temperature and a SA-508/533 RPV. Based on previous design experience, there is high probability fuel temperatures will be within acceptable limits for a higher ΔT core, especially if the coolant outlet temperature is limited to 850°C, and this probability is set at 0.9. As indicated in Fig. 3, it should be possible to use SA-508/533 for the vessel material with a 490°C inlet temperature, provided leakage flow to the annular space between the core barrel and RPV can be controlled (see Fig. 4). However, the reactor internal design details need to be further developed to confirm whether or not a VCS would be required, and the probability for requiring a VCS with a 490°C inlet temperature is set at 0.5.

This decision tree includes the following schedule delays associated with the decision and event paths:

- A 5-year delay associated with developing and qualifying a high-alloy steel for the RPV.
- A 2-year delay associated with developing the design details and performing the associated technology development for a higher ΔT core. This delay is also assumed to be applicable to proving a VCS is not required with a 490°C inlet temperature.
- A 1-year delay associated with developing design details and resolving potential licensing issues for an active VCS.

These delays are assumed to be relative to a 2018 NGNP startup.^{**} For an 850°C outlet temperature, it is assumed the materials-related issues associated with the IHX and other high-temperature components can be resolved in a time frame that does not impact the NGNP schedule.

As shown in Fig. 9, there are 5 possible outcomes that lead to an acceptable design. To illustrate how the decision tree works, the branches associated with Path 2 are described below:

• The box containing a "1" in front of the first branch indicates selecting the upper branch (SA-508/533 steel for the RPV) leads to the best outcome in terms of minimizing schedule risk, because of the significant 5-year delay assumed for selecting a high-alloy RPV.

^{**} The final design of long-lead items such as the RPV must be completed before procurement specifications for these items can be released to potential vendors. For this reason, achieving startup of the NGNP by 2018 requires initiation of the formal design process as soon as possible, probably before the end of calendar year 2008.

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 The box containing a "2" in front of the decision node for the coolant inlet temperature indicates selecting the lower branch (490°C coolant inlet temperature) leads to the best outcome. This decision ensures acceptable fuel temperatures and leads to two acceptable designs with minimal schedule risk, one with an active VCS (Path 2) and one without an active VCS (Path 3).

There are uncertainties associated with each of the schedule delays and event probabilities discussed above. If these uncertainties can be estimated, the Microsoft Excel add-in RiskSim^{††} can be used to perform a Monte Carlo simulation of the decision tree. For this study, the event node probabilities are based on engineering judgment and fixed as constant values. However, the schedule delays are assumed to have lognormal distributions with the mean values and standard deviations shown in Table 4.

		Coolant Outlet Temperature				
		850°C		950°C		
Parameter	Mean	Std. Dev.	Mean	Std. Dev.		
Delay for High-Alloy Steel RPV (y)	5	2	5	2		
Delay for Super Alloy Development ^(a) (y)	0	0	5	1		
Delay for Reactor Internals Optimization (y)	2	0.5	2	0.5		
Delay for VCS Development and Licensing (y)	1	0.5	1	0.5		
Probability VCS Required with 490°C Inlet Temperature		0.5 0.5		0.5		
Probability Fuel Temperatures Acceptable with Higher Core ΔT		0.9 0.75		0.75		

 Table 4. Parameters Used for Monte Carlo Simulation of Decision Trees

(a) This delay is applied only for a 950°C outlet temperature if SA-508/533 steel is selected for the RPV. If a highalloy steel is selected for the RPV, it is assumed the development effort for both the high-alloy RPV and a super alloy for the IHX would proceed in parallel. For this case, the additional delay for developing both materials is assumed to be 1 y with a standard deviation of 0.5 y.

Figure 10 shows Monte Carlo simulation results for each of the five paths in Fig. 9 that lead to an acceptable outcome. The early startup date is defined as the mean minus one standard deviation and the late startup date is defined as the mean plus one standard deviation. If SA-508/533 steel is selected as the RPV material, Path 2 results in the least schedule delay with a mean NGNP startup date of 2019. If a high-alloy steel is selected as the RPV material, Path 5 results in the least schedule delay with a mean NGNP startup date of 2023. Figure 11 shows the cumulative probability distributions for these two paths.

Figure 12 shows the decision tree for a 950°C coolant outlet temperature, which includes a significant schedule delay related to IHX design, material development and qualification, and ASME codification. Because of this delay, the choice of RPV material has much less influence

^{††} Information on RiskSim can be obtained from http://www.treeplan.com/risksim.htm.

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on the NGNP schedule than was the case for an outlet temperature of 850°C. Figure 13 shows Monte Carlo simulation results for each of the five paths in Fig.12 that lead to an acceptable outcome. If SA-508/533 steel is selected as the RPV material, Path 3 results in the least schedule delay with a mean NGNP startup date of 2024. If a high-alloy steel is selected as the RPV material, Path 5 results in the least schedule delay, also with a mean NGNP startup date of 2024. Figure 14 shows the cumulative probability distributions for these two paths.



Figure 10. NGNP Startup Dates (850 °C Outlet Temperature)

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Figure 11. Cumulative Probability Distributions for NGNP Startup Date (850 °C Outlet Temperature)



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Figure 12. Decision Tree for Selection of RPV Material (950°C Core Outlet Temperature)



Figure 13. NGNP Startup Dates (950°C Outlet Temperature)



Figure 14. Cumulative Probability Distributions for NGNP Startup Date (950°C Outlet Temperature)

Figure 15 shows a comparison of cumulative probability distributions for the NGNP startup date for coolant outlet temperatures of 850°C and 950°C, assuming SA-508/533 steel is selected for the RPV material.



Figure 15. Cumulative Probability Distributions for NGNP Startup Date (SA-508/533 RPV)

4. **RECOMMENDATIONS**

Primary Coolant Outlet Temperature

Selection of a coolant outlet temperature in the range 900°C – 950°C will pose the biggest risk for the NGNP cost and schedule. However, from a programmatic perspective, technology innovation is a key selling point for the NGNP, and it is recommended the NGNP be designed to operate with a coolant outlet temperature in this range. The German AVR pebble-bed reactor operated successfully with a coolant outlet temperature of 950°C, and the JAEA HTTR completed extended operation with a coolant outlet temperature of 950°C in 2007. The primary risk associated with a high coolant temperature is developing and codifying a suitable super alloy for the IHX and other components exposed to very high temperature. This risk can be mitigated by assigning high priority to all of the DDNS for these materials and through early and frequent interaction with the appropriate ASME code committees and Nuclear Regulatory Commission (NRC) staff. Candidate super alloy materials include Alloys 617, 230, and Hastelloy-XR. In terms of high-temperature strength, Alloy 617 appears to be the best choice and the core for a compact heat exchanger has been successfully manufactured using this material. However, Alloy 617 has relatively high cobalt content, and there are concerns that corrosion or spallation of the IHX wetted surfaces could significantly increase the primary circuit circulating and plateout activity. Also, carburization is a potential issue for Alloy 617. The HTTR IHX was manufactured using Hastelloy-XR, and this material was developed in part to address the potential issues associated with Alloy 617. It is recommended that both Alloy 617 and

Hastelloy-XR be developed and codified as super alloys for high-temperature, nuclear applications. Because the NRC generally does not approve materials that are not already approved for use in the ASME code, it is very important to accelerate the technology-development and ASME code activities for these materials as much as possible.

RPV Material

It is recommended that SA-508/533 steel be selected as the material for the NGNP RPV. The primary advantage for SA-508/533 steel is its extensive experience base as the material used for current generation LWR RPVs. Use of a high-alloy steel with higher temperature capability would place less burden on optimizing the reactor internal design, but these materials pose a significant level of risk because of their very limited experience base for nuclear applications and/or lack of approval in Section III of the ASME code. With this choice, the efforts to mitigate risks can be focused on developing the super alloys discussed above, and on other potentially high-risk areas, including coated-particle fuel development. However, if SA-508/533 steel is selected as the RPV material, the NGNP design must ensure the RPV temperatures remain within ASME code limits, and should proceed along two parallel paths: (1) Operation with an inlet temperature of 490°C and design optimization to ensure acceptable fuel temperatures and to prevent leakage flow to the RPV; and (2) Operation with a more flexible inlet temperature in the range 490°C to 590°C with an active VCS. The first design path entails the risks associated with successful demonstration of the technology required to optimize the reactor internals design. The second design path may raise issues about demonstration of a design with full passive safety. In principle, an active VCS should not impact the case for passive safety, since a SA-508/533 RPV could operate for extended periods with the VCS offline without exceeding damage limits. However, the VCS should be considered an investment protection system and should be designed with a high degree of reliability. For NGNP, the reactor internals should be designed for reactor operation without a VCS, but a VCS should be incorporated into the design to mitigate the relatively high design and licensing risks associated with a prototype reactor operating at temperatures well in excess of those for current generation LWRs. During NGNP operation, RPV temperatures can be measured with the VCS online and offline to confirm whether or not a VCS is actually required. The availability of a VCS also allows demonstration of reactor cores operating with both high and nominal coolant ΔT . In addition to these two design paths, there should be a parallel technology-development program to develop an RPV material with higher temperature capability, which could be beneficial for future VHTR commercial plants. Candidate materials include Grades 91, 92, 22V, and 23 steels.

Thermal Power Level

It is recommended the thermal power level for the NGNP prototype be the same as that of single module in a commercial-scale, multi-module plant. This approach essentially eliminates any technical and regulatory concerns regarding scale-up of the nuclear heat source for

commercial applications. For a GT-MHR module, a thermal power of 600 MW corresponds to the maximum power level that can be achieved within the constraints of passive safety and an RPV diameter that is within the current experience base of RPV manufacturers.^{‡‡} However, some cost savings can be realized with a smaller-sized plant, especially if a full-scale module requires multiple heat-transport loops and a reduced-scale module can be matched to the requirements for a single heat-transport loop. Lower thermal power levels are also more amenable for operating at lower system pressure. Operating at lower system pressure will reduce the required thickness of the RPV, may significantly increase IHX lifetime, and is more favorable in terms of efficiency for some process-heat applications, including hydrogen production. However, if the decision is made to build the NGNP as a reduced-scale module, the NGNP must still be designed to demonstrate the key safety features of a full-scale module, in order to minimize the risks for future commercialization.

Overall Design Strategy

The final design of long-lead items such as the RPV must be completed before procurement specifications for these items can be released to potential vendors. For this reason, achieving startup of the NGNP by 2018 requires initiation of the formal design process as soon as possible, probably before the end of calendar year 2008. The schedule for design and technology-development work can be compressed to some extent by taking as much advantage as possible of work performed for previous MHR design concepts. For example, GA has completed work through the preliminary design phase for a 350 MWt MHR steam-cycle concept. The 600 MWt GT-MHR concept has also been developed through the preliminary design phase as part of the U.S. – Russian Federation collaboration on disposition of surplus weapons-grade plutonium.

5. NOMENCLATURE

- ANL Argonne National Laboratory
- ASME American Society of Mechanical Engineers
- DDN Design Data Need
- DOE U.S. Department of Energy
- GA General Atomics
- GT-MHR Gas Turbine Modular Helium Reactor
- HTTR High Temperature Engineering Test Reactor
- IHX Intermediate Heat Exchanger
- JAEA Japan Atomic Energy Agency
- LMTD Log Mean Temperature Difference
- LOCA Loss of Coolant Accident

^{‡‡} For commercial-scale process heat or steam applications, the optimum thermal power rating of a reactor module has not been determined, and could be less than 600 MW.

- LWR Light Water Reactor MHR Modular Helium Reactor NGNP Next Generation Nuclear Plant NRC Nuclear Regulator Commission PCS Power Conversion System PSR Permanent Side Reflector RCCS Reactor Cavity Cooling System RPV Reactor Pressure Vessel VCS Vessel Cooling System
- VHTR Very High Temperature Reactor

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