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NGNP Risk Evaluation of Major Components

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Table of Contents

Table of Contents
(continued)

Page

List of Tables

List of Tables
(continued)

Page

List of Tables
(continued)

Page

List of Tables
(continued)

Page

List of Figures

Page

1.0 PURPOSE

This report provides a risk characterization for five major components of the Nuclear Heat Supply System of the NGNP reactor. The five components evaluated are: the Vessel System, the Tubular IHX, the Compact IHX, and the Primary and Secondary Circulators. The study examines the effects of reactor operating conditions on these components with respect to a successful startup of the reactor in 2018. The study was conducted by an expert panel of engineers who used their qualified judgment to award a weighted score measuring the feasibility of the component against a predetermined set of operating conditions.

2.0 METHODOLOGY

The five major NGNP components evaluated are: the Vessel System, the Tubular IHX, the Compact IHX, and the Primary and Secondary Circulators. The evaluation used information provided by an expert panel, who considered the following four parameters for each of the five major components: availability, fabricability, qualification, and codification. The evaluation only considers primary materials and key issues for the five major components.

The method of evaluation uses a matrix to assign a percentage success score for each component parameter as a function of operating conditions. The output is a cumulative score for the likelihood of successfully building and operating each component for a startup of the NGNP reactor in 2018.

For each component, the materials of construction considered in the evaluation are those identified in the NGNP pre-conceptual design. Table 1 lists the components and materials.

Table 1. Major components and materials of construction

	Material	Material 2	Material 3	Material 4
Vessel System	Mod 9Cr1Mo	SA-508/SA 533	Cooled SA-508/SA 533	2.25 Cr Steel (Grade 22)
Primary Circulator	Standard Technology			
Secondary Circulator	Standard Technology			
IHX Tubular	Inconel 617	800H		
IHX Compact	Inconel 617	800H		

“Cooled” SA 508 / SA 533 option implies that the PWR material is used either with active cooling or with thermal protection of the vessel wall. For other material options, the design of the vessels is supposed to be identical to that proposed in the context of the pre-conceptual design.

The material used for the fabrication of the circulators is recorded in Table 1 as “Standard Technology”.

The NGNP circulators are expected to rely on existing technology. The circulator includes several different subcomponents including the impeller, motor, bearings, power supply, etc. Each of these subcomponents must be considered in evaluating the readiness of the circulator technology. The design materials for each part of the circulator are existing. Moreover, the technologies for each aspect of the circulator have been used in comparable applications. Of course, in some cases extrapolation of existing experience might be required.

For most conditions a likely candidate for the impeller would be Alloy 718. Other existing alloys are available if higher temperatures are required. Magnetic bearings have been used for other comparable rotating machinery such as gas compressors. Large motors certainly exist. Variable frequency power supplies exist. The main issue that must be resolved is the integration of these elements into a component optimized for the design conditions. Depending on the size of the circulator extrapolation of some technologies may be required.

2.1 Operating Conditions Considered for Each Component

The following operating conditions are considered in this risk assessment:

Core inlet temperature	350 – 500°C
Core outlet temperature	750 – 950°C
Core power levels	250 – 650 MWt
Primary coolant pressure	5 – 9 MPa

The risk assessment associates specific operating parameters with effects on the material behavior of each component. These associations are shown in Table 2. For the primary and secondary circulators, the circulator power is used to measure the feasibility of the component. The relationship between different operating parameters is later qualified in the interaction of components section.

Table 2. Operating parameters that affect major NGNP components

	Core Inlet Temp	Core Outlet Temp	Core Power Level	Primary Coolant Pressure
Vessel System	X		X	X
Primary Circulator	X			X
Secondary Circulator	X			X
Tubular IHX		X	X	
Compact IHX		X	X	

2.2 Parameters to be Considered in Risk Assessment

The task specification requests an evaluation of each reactor component for the following parameters to determine the percentage chance of successful operation for the range of operating conditions:

- Availability. Identified materials selected for the component manufacture are available or can be developed to meet the project schedule.
- Fabricability. Required fabrication processes are available or can be developed to meet the project schedule.
- Qualification. The generic qualification of the material and the qualification of the component design to confirm the adequacy of the design and the required capability of the materials.
- Codification. The selected materials meet suitable codes and standards or suitable codes and standards can be developed to meet the project schedule.

2.3 Risk Matrix for Major Components

A matrix of operating conditions was established for each major reactor component. The matrix considered each of the four parameter's individually when assessed against a predetermined set of plant operating conditions. Table 3 is an example of one of the matrix cells.

The final size and complexity of the risk evaluation matrix depends on the number of operating parameters that effect a component's performance. This results in either a two- or three-dimensional matrix, shown in Figures 1 and 2, respectively.

Table 3. Example of evaluation matrix for assessing parameters versus inlet temperature

Parameters →

Operating Conditions →

Outlet Temp °C	Availability	Fabricability	Qualification	Codification
750				
800				
850				
900				
950				

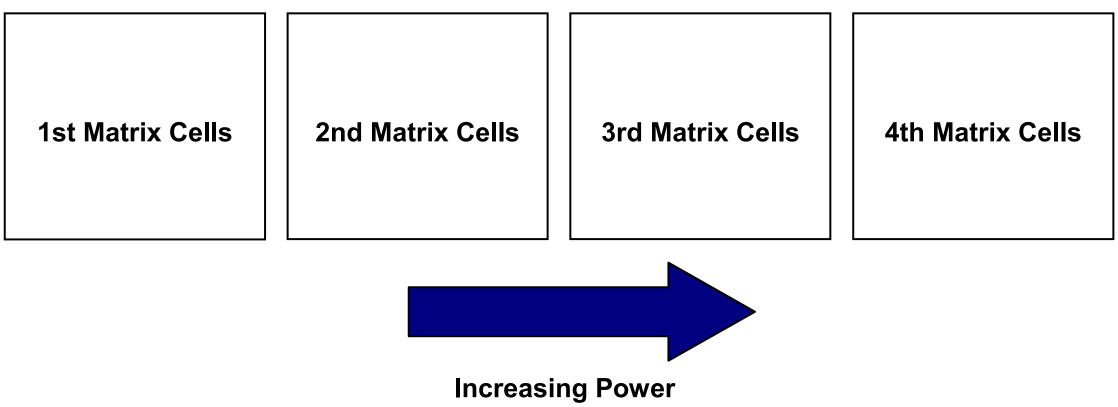

Figure 1. Two-dimensional matrix for two variables

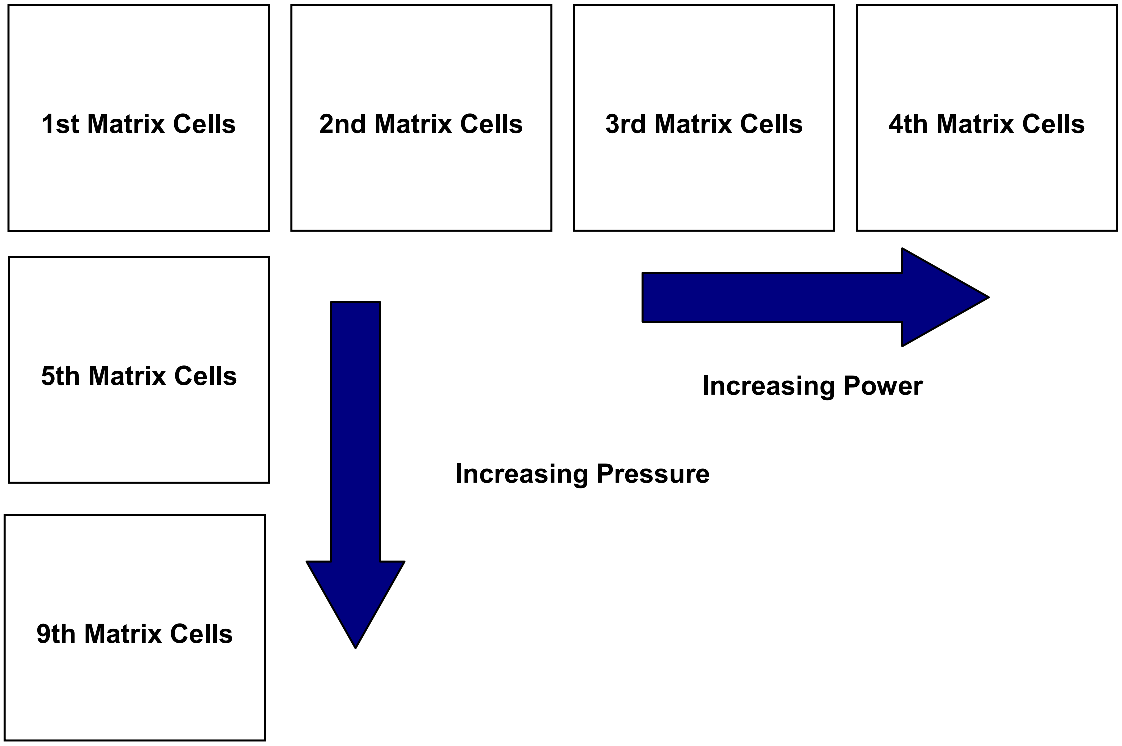

Figure 2. Two-dimensional risk matrix for three variables

An evaluation matrix is repeated for each material considered for the major components.

2.4 Parameter Scoring Used in Risk Assessment

Table 4 shows the categorical scoring method used for the probability of success for each parameter in the risk assessment. The scoring categories are kept intentionally broad during this initial phase of the risk qualification.

Table 4. Parameter scoring used in the risk assessment

100% Successful	Factor being considered will certainly not limit NGNP startup by 2018
90% Successful	Factor being considered is very unlikely to prevent NGNP startup by 2018
70% Successful	Factor being considered is unlikely to prevent NGNP startup by 2018
50% Successful	Factor being considered could prevent NGNP startup by 2018
30% Successful	Factor being considered is likely to prevent NGNP startup by 2018
10% Successful	Factor being considered is very likely to prevent NGNP startup by 2018
0% Successful	Factor being considered will certainly prevent NGNP startup by 2018

2.5 Identified R&D Requirements for NGNP Components.

During the initial phase of NGNP pre-conceptual design, the research and development needs of each component were discussed and explained. This information is summarized in Appendix A.

2.6 Expert Panel

A panel of experts conducted the review of the components and provided data for the evaluation matrix. Table 5 lists the members of the expert panel.

Table 5. Members of expert panel convened to review component operation

	Panel Lead	**Participant**	**Participant**	**Participant**
Vessel System	Bernard Riou	Lewis Lommers		
Circulator Primary	Lewis Lommers	Eric Breuil	Bernard Riou	Robert Zimmerman
Circulator Secondary	Lewis Lommers	Eric Breuil		
IHX Tubular	Kevin McCoy	Don Kim	Lewis Lommers	Bernard Riou
IHX Compact	Kevin McCoy	Don Kim	Lewis Lommers	Bernard Riou
Interaction of Components	Lewis Lommers			

2.7 Overall Feasibility for 2018

The overall feasibility score for 2018 defines a component's design feasibility, based on the proposed operating conditions, to meet the required date of 2018 as measured by the four parameters requested by the customer, e.g., availability, fabricability, qualification, and codification.

2.8 Overall Feasibility for 2021

The overall feasibility score for 2021 was awarded by the expert panel on the completion of the feasibility evaluation for 2018. The panel considered the effect of an extra three years on the availability, development, and design of the components. This quantitative assessment assumed that funds for development work and design would be available to progress the feasibility of the component under consideration. In almost every case this extra three years increased the probability of success of the component compared to the 2018 date.

2.9 Weighting of Results to Obtain Overall Feasibility Factor

For each component the four parameters were evaluated and awarded a score based upon a predetermined set of reactor operating conditions. Several methods were evaluated to combine the scores to allow the final assessment of the overall design feasibility for 2018. After much deliberation, it was determined that the most appropriate method was to take the lowest score of the four parameters being considered.

3.0 KEY ASSUMPTIONS

The following key assumptions apply:

- The basic NGNP configuration is an indirect steam cycle.
- Electric drive circulators are used.
- IHXs have been assessed assuming He on the secondary side.
- Appropriate funding is available to support required actions for qualification and codification.
- Availability assumes that actions to reserve slots for long-lead components are timely. In particular, the vessel forging order will be placed at the end of 2008.
- Material of construction for the RPV is the same as the IHX vessel.
- Operating temperature for the secondary circulator will be 50 ^{o}C less than the corresponding temperature of operation for the primary circulator.

4.0 RISK EVALUATION

4.1 Intermediate Heat Exchangers (IHX)

The IHXs are part of the primary heat transfer system (PHTS) and act as the point of interaction between the primary and secondary circuits. For the AREVA NGNP design concept, two IHX designs are proposed (Reference 1, Section 6.3):

- Tubular IHX for the Power Conversion System (PCS)
- Compact IHX for heat supply to the hydrogen production plant

The IHX design requirements are (Reference 1, Appendix A):

- Tubular IHX
  - Lifetime of 20 years
  - Effectiveness of ≥89%

- Compact IHX
  - Lifetime of 5 years
  - Effectiveness of ≥94%

4.2 Risk Assessment for the Tubular IHX

The proposed NGNP pre-conceptual design has two tubular IHX based on the helical coil concept with a tube diameter of 21 mm (2.2 mm wall thickness). The proposed concept is a first-of-a kind design due to its size and requirements on thermal effectiveness, leak-tightness, thermo-mechanical resistance, materials, reliability, and cost. The main components of the tubular IHX are (see Figure 3):

- Tube Plate
- Central Tube
- Hot Header
- Helix Tube Bundle

A special insulation system protects the bottom of the Tube Plate in order to minimize stress inside the plate during normal conditions.

The Central Tube has a removable insulation system to minimize stress inside the tube and thermal loss in the secondary coolant flowing from the Hot Header at the lower region of the IHX to the top of the IHX.

An insulated outer shroud separates the Helix Tube Bundle from the cold gas back flow to the bottom of the IHX. This shroud minimizes heat loss from hot flow areas inside the bundle to the cold gas area.

A special fiber insulation system insulates the Hot Header, which is covered by a liner. Together with the outer shroud of the Tube Bundle, these systems provide a special formed flow channel to get a nearly constant flow velocity inside the tube bundle.

The Hot Header is made out of a forging. The connection studs from the Hot Header to each tube are machined. With this design each tube welding is a normal circumferential welding and therefore easy to control with Ultrasonic Testing.

With regard to mechanical resistance, the IHX must take no part in the primary boundary function, which is ensured by the pressure vessel where the IHX is inserted. The IHX only has to withstand the pressure difference between the primary loop pressure and the secondary loop pressure. However, the IHX will have to withstand the full primary pressure (1 bar in the secondary loop) for a specified time duration.

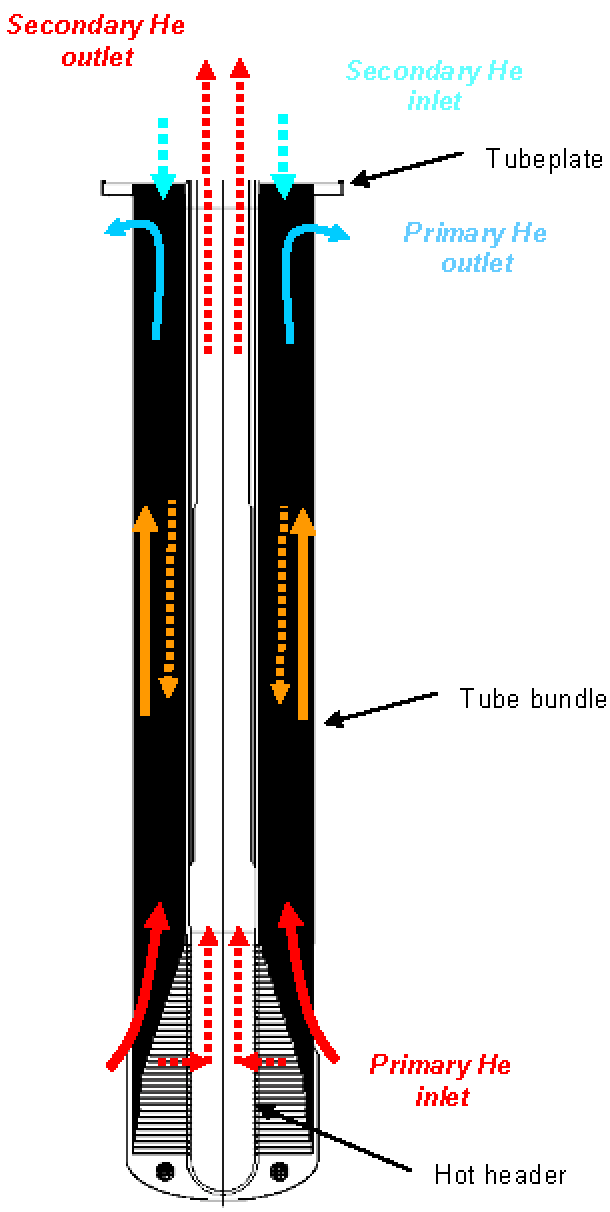

Figure 3. Tubular IHX concept

4.2.1 Parameter Assessment for the Tubular IHX with Alloy 617

Availability. Material of construction is available for this component.

Fabricability. The limiting component for the IHX is the Hot Header. Initial reviews suggest the manufacture of this component is within the capabilities of industry up to 300 MWt power range. A mockup of a similar header was built successfully for the KVK tests. Industrial experience also exists for fabricating helical coil tube bundles and welding 617 tubing.

Qualification. Alloy 617 over the temperature range 750 to 850°C should not be an issue. At higher temperatures environmental effects must be taken into account such as oxidation, carburization, and decarburization. There is, however, more design and operating experience with tubular heat exchangers compared to compact IHXs. Moreover, there is the added benefit of their design based on thicker walls, which can accommodate environmental effects. There is established experience fabricating helical coil tube bundles and welding 617 tubing. The evaluation matrix considers temperatures as high as 950°C, which is near the upper limit for qualification of this material.

Codification. Alloy 617 is considered straightforward at temperatures up to 850°C. At higher temperatures, new design methods may be needed. Approving these new design methods poses a codification risk that has been taken into account in the assessment

4.2.2 Probabilities of Success for Tubular IHX with Alloy 617

Table 6. Tubular IHX probabilities of success for Alloy 617 at 100, 150, 200, and 250 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	1.00	1.00	0.95	95	100
800	1.00	1.00	1.00	0.95	95	100
850	1.00	1.00	1.00	0.95	95	100
900	1.00	1.00	0.80	0.80	80	90
950	1.00	1.00	0.60	0.60	60	70

Table 7. Tubular IHX probabilities of success for Alloy 617 at 300 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	0.90	1.00	0.95	90	90
800	1.00	0.90	1.00	0.95	90	90
850	1.00	0.90	1.00	0.95	90	90
900	1.00	0.90	0.80	0.80	80	90
950	1.00	0.90	0.60	0.60	60	70

4.2.3 Risk Results for the Tubular IHX with Alloy 617

The percentage success results from the Year 2018 risk evaluation for the Tubular IHX with Alloy 617 are shown in Table 8 and Figure 4.

Table 8. Year 2018 percentage success for the Tubular IHX with Alloy 617

Inlet Temperature (^{o}C)	100 MWt	150 MWt	200 MWt	250 MWt	300 MWt
750	95	95	95	95	90
800	95	95	95	95	90
850	95	95	95	95	90
900	80	80	80	80	80
950	60	60	60	60	60

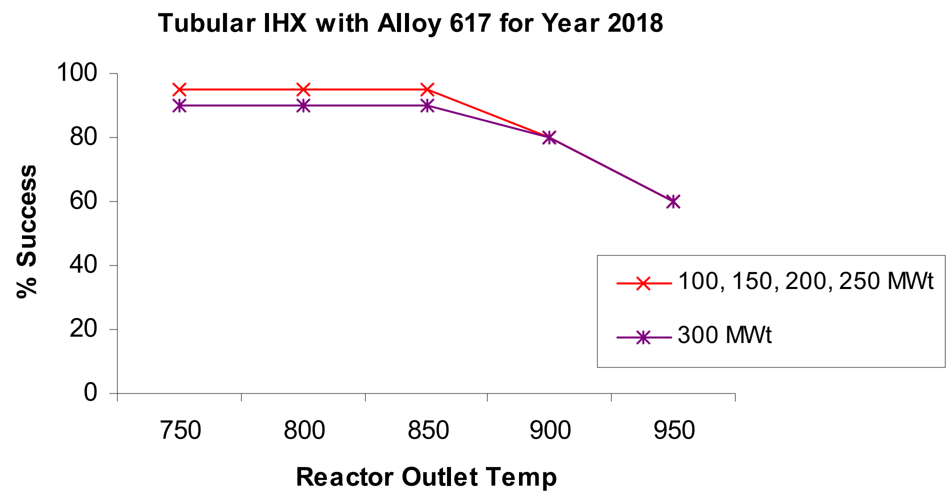

Figure 4. Year 2018 percentage success for Tubular IHX manufactured from Alloy 617

4.2.4 Parameter Assessment for the Tubular IHX with Alloy 800H

Availability. Materials of construction are available for this component.

Fabricability. Scores should be greater than or equal to those for Alloy 617 because Alloy 800H is more readily worked and welded than Alloy 617. The size required for the limiting component (the Hot Header) appears to be within manufacturers capabilities. The added design constraints of operating at higher reactor powers was determined to reduce the fabricability of the component slightly.

Qualification. The properties of Alloy 800H at a given temperature were taken to be comparable to the properties of Alloy 617 operating at a temperature 100°C higher.

Codification. Alloy 800H is in the ASME code for temperatures up to 760°C, so codification at 750°C is not in question. At higher temperatures, decreasing material performance raises questions about codification. By 900°C, strength and resistance to environmental degradation are poor, so Alloy 800 H should not be codified at 900°C or above.

4.2.5 Probabilities of Success for the Tubular IHX with Alloy 800H

Table 9. Tubular IHX probabilities of success for Alloy 800H at 100, 150, and 200 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF2021
750	1.00	1.00	1.00	1.00	100	100
800	1.00	1.00	0.80	0.80	80	90
850	1.00	1.00	0.60	0.60	60	70
900	1.00	1.00	0.00	0.00	0	0
950	1.00	1.00	0.00	0.00	0	0

Table 10. Tubular IHX probabilities of success for Alloy 800H at 250 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	0.95	1.00	1.00	95	95
800	1.00	0.95	0.80	0.80	80	90
850	1.00	0.95	0.60	0.60	60	70
900	1.00	0.95	0.00	0.00	0	0
950	1.00	0.95	0.00	0.00	0	0

Table 11. Tubular IHX probabilities of success for Alloy 800H at 300 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	0.90	1.00	1.00	90	90
800	1.00	0.90	0.80	0.80	80	90
850	1.00	0.90	0.60	0.60	60	70
900	1.00	0.90	0.00	0.00	0	0
950	1.00	0.90	0.00	0.00	0	0

4.2.6 Risk Results for the Tubular IHX with Alloy 800H

The percentage success results from the Year 2018 risk evaluation for the Tubular IHX with Alloy 800H are shown in Table 12 and Figure 5.

Table 12. Year 2018 percentage success for the Tubular IHX with Alloy 800H

Inlet Temperature (°C)	100 MWt	150 MWt	200 MWt	250 MWt	300 MWt
750	100	100	100	95	90
800	80	80	80	80	80
850	60	60	60	60	60
900	0	0	0	0	0
950	0	0	0	0	0

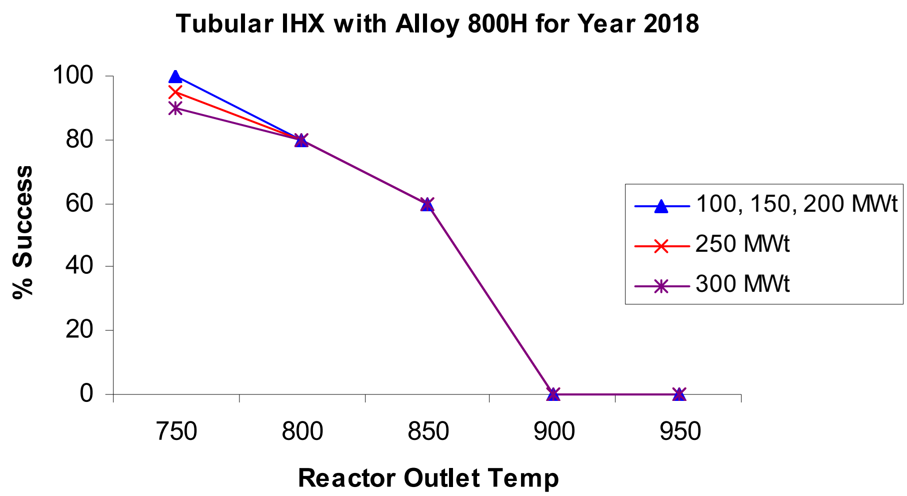

Figure 5. Year 2018 Percentage Success for the Tubular IHX manufactured from Alloy 800H

4.2.7 Comparison Between Alloy 617 and Alloy 800H for the Tubular IHX

A comparison of the Tubular IHX risk evaluation results for the percentage success with Alloy 617 versus Alloy 800H at 100 MWt is shown in Figure 6.

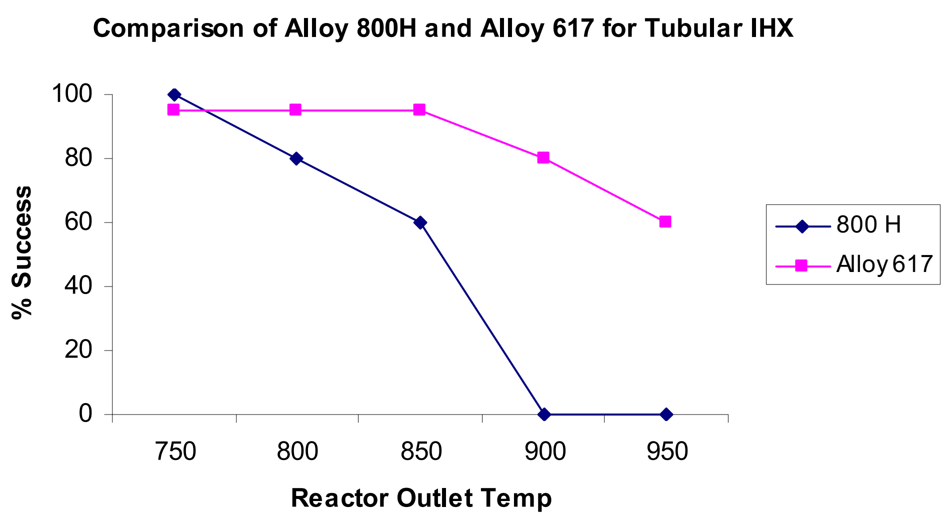

Figure 6. Comparison of % success for Tubular IHX with Alloy 617 vs. Alloy 800H at 100 MWt

4.3 Risk Assessment for the Compact IHX

Compact IHX technology is proposed for heat transport to the H2 plant. The following types of compact IHX can be envisioned for this application:

- Plate Machined Heat Exchanger
- Plate Fin Heat Exchanger
- Plate Stamped Heat Exchanger

These IHX concepts will be evaluated in the conceptual design phase. The Plate Stamped concept is regarded as the best candidate due to its less demanding bonding technology, and the risk assessment is based on this concept.

The parameters of the compact IHX are given in Table 13 (Reference 1, Section 6.3.3.1.2, Table 6-7). An approach temperature of 25ºC is selected to provide the higher temperature on the H2 plant side. Taking into account this approach temperature, evaluations show the volume necessary for compact IHX modules should be about 4 to 5 m^3 (module volume excluding pipes or headers). Therefore, six compact IHX modules would be required for such an application.

It is proposed to base the design on the “hot centre” concept, which has been developed by AREVA for commercial application. Figure 7 shows how this concept could be implemented for a 6-module IHX.

Table 13. Compact IHX parameters

	NGNP Compact IHX	
Desired thermal power	60	MWt
Primary fluid	He	
Secondary fluid	He	
Primary side (shell side)		
Inlet temperature	900	^oC
Outlet Temperature	500	^oC
Inlet pressure	5	MPa
Mass flow	29	kg / s
Secondary side (tube side)		
Inlet temperature	475	^oC
Outlet temperature	875	^oC
Inlet pressure	5.2	MPa
Mass flow	29	kg / s

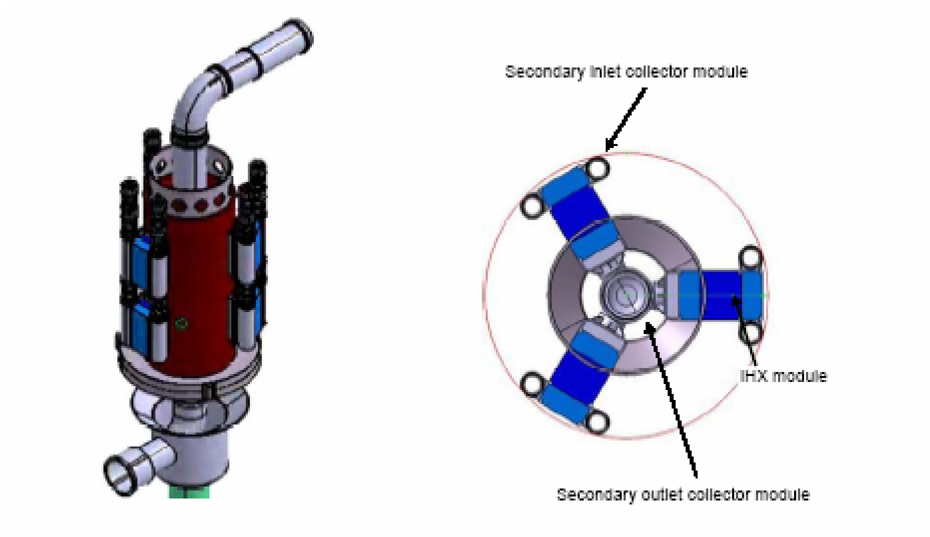

Figure 7. Compact IHX concept

4.3.1 Parameter Assessment for the Compact IHX with Alloy 617

Availability. The heat exchanger plates are standard forms. It is assumed that the central tube will be welded from curved plates, possibly with forged nozzles for connection to the heat exchanger modules. Curved plates and forged nozzles are standard forms.

Fabricability. The majority of the process for manufacturing the Compact IHX using Alloy 617 is available, however the sealing of the heat exchanger modules could benefit from additional studies. As the power of the reactor increased the score awarded for the fabricability of the component reduced correspondingly to take account of the lack of experience in fabricating the component for these conditions.

Qualification. Alloy 617 over the temperature range 750 to 850°C should not be an issue. At higher temperatures environmental effects must be taken into account such as oxidation, carburization, and decarburization. The impact of these effects is more severe for the thin sections of the compact IHX, higher stresses, reduced allowables and higher temperatures. The lack of experience with compact IHX added to the uncertainty at higher temperatures reduces the overall qualification score's for this component compared to the tubular design..

Codification. Alloy 617 is considered straightforward at temperatures up to 850°C. At higher temperatures, new design methodsmay be needed. Approving these new design methods poses a codification risk that has been taken into account in the assessment.

4.3.2 Probabilities of Success for the Compact IHX with Alloy 617

Table 14. Compact IHX probabilities of success for Alloy 617 at 60 and 100 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	0.90	0.90	0.95	90	90
800	1.00	0.90	0.90	0.95	90	90
850	1.00	0.90	0.80	0.95	80	90
900	1.00	0.90	0.50	0.80	50	60
950	1.00	0.90	0.30	0.60	30	40

Table 15. Compact IHX probabilities of success for Alloy 617 at 300 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	0.80	0.90	0.95	80	80
800	1.00	0.80	0.90	0.95	80	80
850	1.00	0.80	0.80	0.95	80	80
900	1.00	0.80	0.50	0.80	50	60
950	1.00	0.80	0.30	0.60	30	40

Table 16. Compact IHX probabilities of success for Alloy 617 at 600 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
750	1.00	0.60	0.90	0.95	60	60
800	1.00	0.60	0.90	0.95	60	60
850	1.00	0.60	0.80	0.95	60	60
900	1.00	0.60	0.50	0.80	50	60
950	1.00	0.60	0.30	0.60	30	40

4.3.3 Risk Results for the Compact IHX with Alloy 617

The percentage success results from the Year 2018 risk evaluation for the Compact IHX with Alloy 617 are shown in Table 17 and Figure 8.

Table 17. Year 2018 percentage success for the Compact IHX with Alloy 617

OutletTemperature (°C)	60 MWt	100 MWt	300 MWt	600 MWt
750	90	90	80	60
800	90	90	80	60
850	80	80	80	60
900	50	50	50	50
950	30	30	30	30

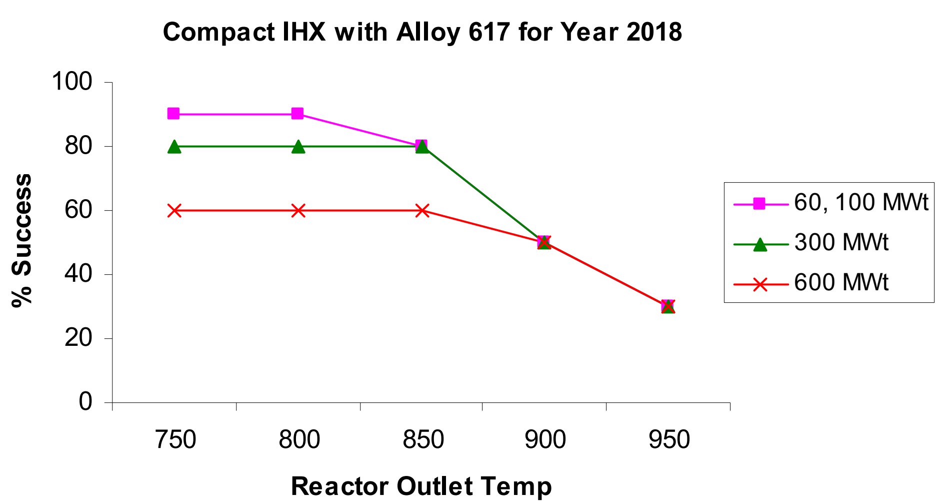

Figure 8. Year 2018 percentage success for Compact IHX manufactured from Alloy 617

4.3.4 Parameter Assessment for the Compact IHX with Alloy 800H

Availability. Material is available to manufacture the Compact IHX module.

Fabricability. The majority of the process for manufacturing the compact IHX using Alloy 800H is available. However, the sealing of the heat exchanger modules could benefit from additional studies. As the power of the reactor increased the score awarded for the fabricability of the component reduced correspondingly to take account of the lack of experience in fabricating the component for these conditions.

Qualification. The properties of Alloy 800H at a given temperature were taken to be comparable to the properties of Alloy 617 operating at a temperature 100°C higher.

Codification. Alloy 800H is in the ASME code for temperatures up to 760°C, so codification at 750°C is not in question. At higher temperatures, decreasing material performance raises questions about codification. By 900°C, strength and resistance to environmental degradation are poor, so Alloy 800H should not be codified at 900°C or above.

4.3.5 Probabilities of Success for the Compact IHX with Alloy 800H

Table 18. Compact IHX probabilities of success for Alloy 800H at 60 and 100 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018
750	1.00	0.90	1.00	1.00	90
800	1.00	0.90	0.80	0.80	80
850	1.00	0.90	0.60	0.60	60
900	1.00	0.90	0.00	0.00	0
950	1.00	0.90	0.00	0.00	0

Table 19. Compact IHX probabilities of success for Alloy 800H at 300 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018
750	1.00	0.80	1.00	1.00	80
800	1.00	0.80	0.80	0.80	80
850	1.00	0.80	0.60	0.60	60
900	1.00	0.80	0.00	0.00	0
950	1.00	0.80	0.00	0.00	0

Table 20. Compact IHX probabilities of success for Alloy 800H at 600 MWt

°C	Availability	Fabricability	Qualification	Codification	DF 2018
750	1.00	0.60	1.00	1.00	60
800	1.00	0.60	0.80	0.80	60
850	1.00	0.60	0.60	0.60	60
900	1.00	0.60	0.00	0.00	0
950	1.00	0.60	0.00	0.00	0

4.3.6 Risk Results for the Compact IHX with Alloy 800H

The percentage success results from the Year 2018 risk evaluation for the Compact IHX with Alloy 800H are shown in Table 21 and Figure 9.

Table 21. Year 2018 percentage success for the Compact IHX with Alloy 800H

Outlet Temperature (°C)	60 MWt	100 MWt	300 MWt	600 MWt
750	90	90	80	60
800	80	80	80	60
850	60	60	60	60
900	0	0	0	0
950	0	0	0	0

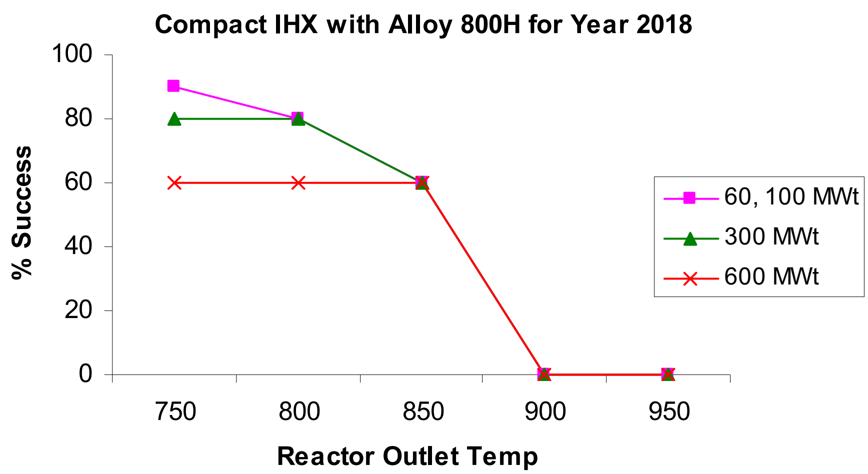

Figure 9. Year 2018 percentage success for Compact IHX manufactured from Alloy 800H

4.3.7 Comparison Between Alloy 617 and Alloy 800H for the Compact IHX

A comparison of the Compact IHX risk evaluation results for the percentage success with Alloy 617 versus Alloy 800H at 100 MWt is shown in Figure 10.

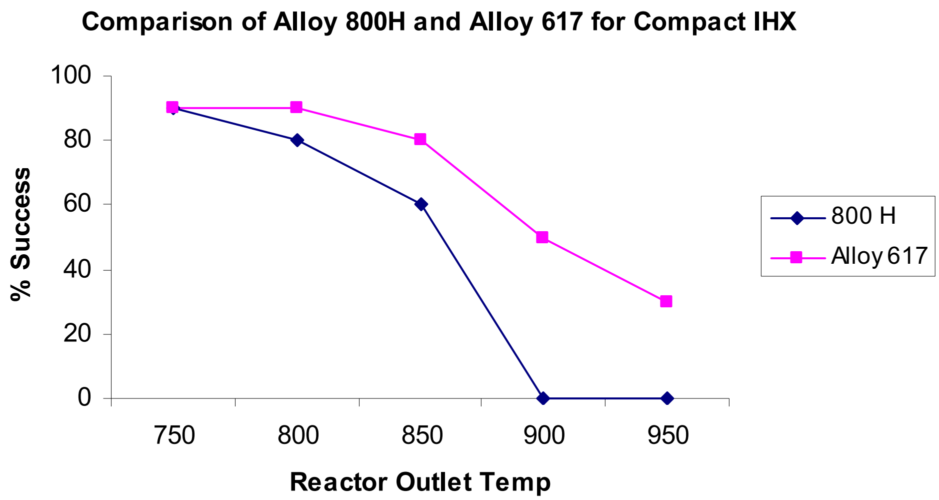

Figure 10. Comparison of % success for Compact IHX with Alloy 617 vs. Alloy 800H at 60 MWt

4.4 Circulators

The Main Helium Circulator (MHC) is part of the Primary Heat Transport System (PHTS). The required function of the MHC is to control the flow of helium to match the heat generation of the reactor core with the heat removal of the PHTS (Reference 1, Appendix A, Section 7.3.3.1).

The MHC has the following pre-conceptual design requirements, per Reference 1 (Appendix A, Section 7.3.3.1):

- Driven by electrical motors capable of rated and variable speeds
- Use of active magnetic bearings to avoid any lubricating product ingress in the primary circuit
- Use of thermal insulation to protect internal components by reducing heat migration due to primary system temperatures
- Minimum lifetime of 10 years
- Hydraulic characteristics as stable as possible over the required speed range without distinctive reversal points and without pronounced peak

For the NGNP, two types of circulators are envisaged (Reference 1, Section 6.3.1):

- Circulator for heat transport to the electric plant
- Circulator for heat transport to the H2 plant.

In the pre-conceptual design, the NGNP uses three circulators for heat transport to the electric plant (one for each tubular IHX vessel). These circulators have a power level around 8 MW and are within the gas circulator design feasibility. The use of two circulators should remain acceptable and would need no significant R&D or qualification needs. Using one single gas circulator is feasible but is beyond the present state of the art and would require significant development.

The gas circulator for the 60 MWt process heat loop is a smaller gas circulator (about 1.5 MW) and does not present any feasibility issues.

The following description is applicable to both types of circulators:

- The gas circulators are encapsulated, centrifugal, vertically mounted, and have the impeller mounted directly on the motor shaft. The circulator may hang from the bottom (reference option) or may rest on top of the IHX vessel without significant consequences on feasibility. Impellers are high efficiency and are matched aerodynamically to a radial diffuser, radial to axial bend, and a short annular diffuser.

- The gas circulator flow rate is controlled by speed control through an electrical motor driven by a variable frequency inverter.

- The motor is vertically mounted within the pressure vessel. Therefore, it is a submerged design and is separated from the IHX vessel by a thermal barrier plate devoted to minimizing the ingress of heat from the primary side into the motor compartment. There is a small clearance into this barrier at the impeller level to balance the pressure between main primary vessel and motor compartment.

- The motor compartment is cooled by a water / helium heat exchanger. A fan within the compartment ensures fluid circulation for an efficient heat transfer. Also helium injection into the cavity allows the maintaining of a slightly higher pressure into the compartment and can be used for cavity cooling at motor standby if required.

- The gas circulator is supported by radial and axial electro-magnetic bearings (EMB). Mechanical catcher bearings are set to support the machine in case of EMB failures.

There is no material issue concerning the gas circulators. High stresses expected at the impeller level should be solved by the selection of Alloy 718 as reference material. This material is identified as a suitable material due to its high strength and performance at elevated temperatures.

4.5 Risk Assessment for the Circulators

Core inlet temperature (or circulator gas temperature) affects circulator design at several levels.

First, core inlet temperature affects the selection of impeller material and the resulting allowable stress in the impeller design.

However, the big issue is the effect on circulator power. Circulator power is proportional to the product of the volumetric flow rate and the system pressure drop. Higher gas temperature results in lower density which requires a higher volumetric flow rate thus increasing the required circulator power for a given mass flow rate.

The circulator power is increased even further by the effects of high cold leg temperature on the overall primary circuit performance. Lower gas density requires higher velocity flows through all the primary components. This increases the pressure drop of the loop.

Moreover, for a given core outlet temperature, an increased inlet temperature reduces the coolant temperature rise in the core. Therefore, for a given core power level, the system mass flow rate must be increased which further increases the circulator volumetric flow.

Thus, there are three separate effects of the higher core inlet temperature on the circulator performance, each of which causes the required circulator power to increase. These are:

- Higher volumetric flow (for given mass flow rate)

- Higher system pressure drop (for given mass flow rate)

- Higher mass flow rate (for given core power level; this exacerbates the other two points)

4.5.1 Parameter Assessment for the Primary Circulator

The expert panel considered the following components in their assessment of the primary circulator:

Impeller	flow rate, temperature, size, shaft speed, coolant interactions smaller high speed larger low speed - radial
Motor	power level, speed, electrical environment
Bearings	weight, whether or not need to run on criticals
Rotor dynamics	a critical difficult area that will require optimization of motor and bearings
Barrier plate	temperature, load, insulation
Housing	pressure, penetration locations
Penetrations	motor drive power, bearing power, instrumentation, cooling water, purge helium
Seals	NA - shaft seal not required for primary circ w/ submerged motor
Inverter	size is an issue for the large inverters; high frequency is an issue for small circulators

Availability. At lower temperatures Alloy 718 would be available for manufacture. This alloy starts to creep at temperatures above 540°C. Based upon this characteristic, the availability of suitable materials for operations above 500°C is a concern to the expert panel and the score is reduced accordingly. However it should be noted the current basis of the design calls for the circulator to operate in the range of 350 to 550 °C. Higher temperatures were included in this particular case at the discretion of the panel.

Fabricability. The primary component of concern is the inverter. At lower temperatures, there is no significant problem foreseen and thus the component is scored relatively high. As the temperature increases, the requirement to switch from Alloy 718 is recommended. At higher temperatures, the score is reduced to account for the creep characteristics and the possible need to fabricate the impeller using alternate materials. However it should be noted the current basis of the design calls for the circulator to operate in the range of 350 to 550 °C. Higher temperatures were included in this particular case at the discretion of the panel.

Qualification. At lower temperatures and circulator power, the qualification of the materials is within the experience base. At increasing circulator power, concerns and issues about some of the components and design features reduces the score for the circulator. For high circulator power and high inlet temperatures, the stresses on some components and the experience base for the design are exceeded.

Codification. Codification is not an issue for the materials of construction over the proposed operating parameters.

4.5.2 Probabilities of Success for Primary Circulator

Table 22. Primary Circulator probabilities of success at 4 MWe

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	1.00	1.00	1.00	100	100
400	1.00	0.95	1.00	1.00	95	95
450	1.00	0.95	1.00	1.00	95	95
500	1.00	0.95	0.90	1.00	90	90
550	0.70	0.90	0.90	1.00	70	80

Table 23. Primary Circulator probabilities of success at 8 MWe

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	1.00	0.95	1.00	95	95
400	1.00	0.95	0.90	1.00	90	90
450	1.00	0.95	0.90	1.00	90	90
500	1.00	0.95	0.80	1.00	80	80
550	0.70	0.90	0.80	1.00	70	75

Table 24. Primary Circulator probabilities of success at 12 MWe

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	0.90	0.80	1.00	80	90
400	1.00	0.90	0.80	1.00	80	90
450	1.00	0.90	0.80	1.00	80	90
500	1.00	0.90	0.70	1.00	70	80
550	0.70	0.90	0.60	1.00	60	70

Table 25. Primary Circulator probabilities of success at 16 MWe

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	0.85	0.70	1.00	70	80
400	1.00	0.85	0.70	1.00	70	80
450	1.00	0.85	0.70	1.00	70	80
500	1.00	0.85	0.60	1.00	60	70
550	0.70	0.85	0.40	1.00	40	60

Table 26. Primary Circulator probabilities of success at 20 MWe

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	0.80	0.40	1.00	40	60
400	1.00	0.80	0.40	1.00	40	60
450	1.00	0.80	0.40	1.00	40	60
500	1.00	0.80	0.40	1.00	40	50
550	0.70	0.80	0.30	1.00	30	40

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4.5.3 Risk Results for the Primary Circulator

The percentage success results from the Year 2018 risk evaluation for the Primary Circulator are shown in Table 27 and Figure 11.

Table 27. Year 2018 percentage success for the Primary Circulator

Circulator Inlet Temperature (^{o}C)	4 MWe	8 MWe	12 MWe	16 MWe	20 MWe
350	100	95	80	70	40
400	95	90	80	70	40
450	95	90	80	70	40
500	90	80	70	60	40
550	70	70	60	40	30

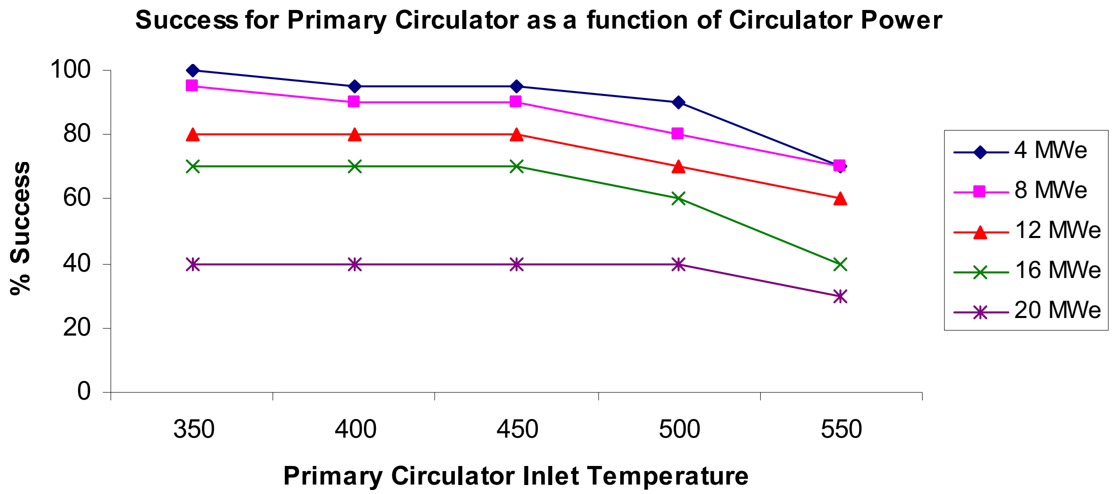

Figure 11. Year 2018 percentage success for Primary Circulator

4.5.4 Probabilities of Success for Secondary Circulator

The expert panel considered the following components in their assessment of the secondary circulator:

Impeller	flow rate, temperature, size, shaft speed, coolant interactions smaller high speed larger low speed - radial
Motor	power level, speed, electrical environment
Bearings	weight, whether or not need to run on criticals
Rotor dynamics	a critical difficult area that will require optimization of motor and bearings
Barrier plate	temperature, load, insulation
Housing	pressure, penetration locations

Penetrations	motor drive power, bearing power, instrumentation, cooling water, purge helium
Seals	feasibility of shaft seal, leakage, maintenance
Inverter	size is an issue for the large inverters; high frequency is an issue for small circulators

Availability. The secondary circulator operates at lower temperatures than the primary and as a result Alloy 718 is suitable material. It should be noted the current basis of the design calls for the circulator to operate in the range of 350 to 550 °C. Higher temperatures were included in this particular case at the discretion of the panel.

Fabricability. Confidence is high that manufacturing of the component is achievable in the temperature range considered. As the power of the inverter increases the fabricability score decreases slightly to reflect the risk associated with the additional engineering allowances of the higher power unit. It should be noted the current basis of the design calls for the circulator to operate in the range of 350 to 450 °C. Higher temperatures were included in this particular case at the discretion of the panel.

Qualification. At 4 MWe the qualification of the unit is not in question. As the power increases engineering challenges can be expected in several of the components that proportionally increase the risk for the circulator operating successfully. This is reflected in the reduced scoring for the circulator particularly at high power and high temperature regions. Nonetheless, the risk is reduced compared to the primary circulator, since it is more practical to use a non-submerged motor for the secondary circulator. Use of a non-submerged motor provides significantly more flexibility in motor design and bearing selection and design. This also makes rotor dynamics issues easier to manage. Electrical penetrations are also less limiting. As a result, while increasing size does affect secondary circulator feasibility, it is not as limiting as for the primary circulator. Therefore, for a given power level, the secondary circulator feasibility risk is lower than for the primary circulator, and higher secondary circulator powers can be considered.

Codification. For the operating range considered this was not considered an issue.

Table 28. Secondary Circulator probabilities of success at 4 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	1.00	1.00	1.00	100	100
400	1.00	0.95	1.00	1.00	95	95
450	1.00	0.95	1.00	1.00	95	95
500	1.00	0.95	1.00	1.00	95	95
550	1.00	0.90	0.90	1.00	90	95

Table 29. Secondary Circulator probabilities of success at 8 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	1.00	1.00	0.95	1.00	95	95
400	1.00	0.95	0.90	1.00	90	90
450	1.00	0.95	0.90	1.00	90	90
500	1.00	0.95	0.90	1.00	90	90
550	0.80	0.90	0.80	1.00	80	90

Table 30. Secondary Circulator probabilities of success at 12 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF2021
350	1.00	0.90	0.90	1.00	90	90
400	1.00	0.90	0.85	1.00	85	90
450	1.00	0.90	0.85	1.00	85	90
500	1.00	0.90	0.80	1.00	80	80
550	0.80	0.90	0.70	1.00	70	80

Table 31. Secondary Circulator probabilities of success at 16 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF2021
350	1.00	0.85	0.90	1.00	85	80
400	1.00	0.85	0.80	1.00	80	80
450	1.00	0.85	0.80	1.00	80	80
500	1.00	0.85	0.70	1.00	70	80
550	0.80	0.85	0.60	1.00	60	65

Table 32. Secondary Circulator probabilities of success at 20 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF2021
350	1.00	0.80	0.70	1.00	70	70
400	1.00	0.80	0.70	1.00	70	70
450	1.00	0.80	0.70	1.00	70	60
500	1.00	0.80	0.60	1.00	60	60
550	0.80	0.80	0.50	1.00	50	60

Table 33. Secondary Circulator probabilities of success at 24 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF2021
350	1.00	0.70	0.55	1.00	55	60
400	1.00	0.70	0.55	1.00	55	60
450	1.00	0.70	0.55	1.00	55	60
500	1.00	0.70	0.50	1.00	50	50
550	0.80	0.70	0.40	1.00	40	40

Table 34. Secondary Circulator probabilities of success at 28 and 32 MWe

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF2021
350	1.00	0.60	0.40	1.00	40	50 / 40
400	1.00	0.60	0.40	1.00	40	50 / 40
450	1.00	0.60	0.40	1.00	40	50 / 40
500	1.00	0.60	0.40	1.00	40	40
550	0.70	0.60	0.30	1.00	30	30

4.5.5 Risk Results for the Secondary Circulator

The percentage success results from the Year 2018 risk evaluation for the Secondary Circulator are shown in Table 35 and Figure 12.

Table 35. Year 2018 percentage success for the Secondary Circulator

Circulator Inlet Temperature (°C)	4 MWe	8 MWe	12 MWe	16 MWe	20 MWe	24 MWe	28 MWe	32 MWe
350	100	95	90	85	70	55	40	40
400	95	90	85	80	70	55	40	40
450	95	90	85	80	70	55	40	40
500	95	90	80	70	60	50	40	40
550	90	80	70	60	50	40	30	30

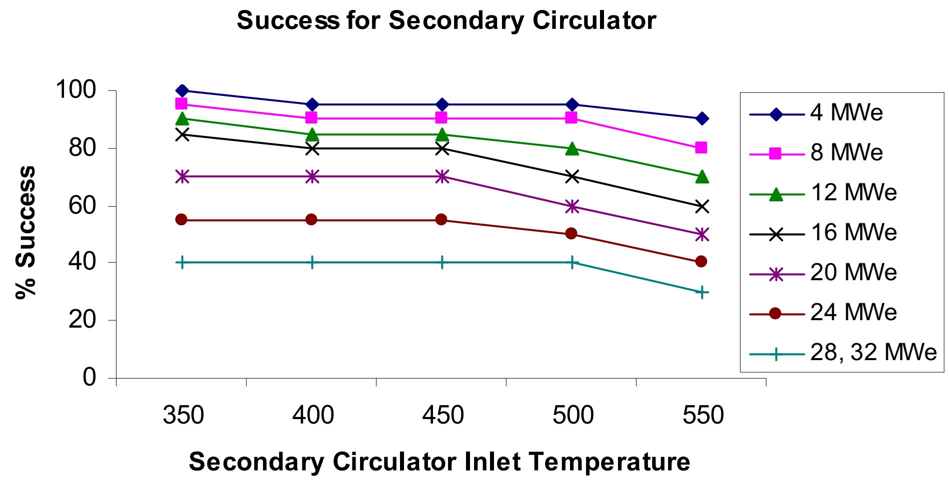

Figure 12. Year 2018 percentage success for Secondary Circulator

4.6 Vessel System

The Vessel System is composed of the vessels and supporting devices of the primary pressure boundary. This system is divided into the following subsystem:

- The Reactor Vessel
- The intermediate heat exchanger vessels
- The cross-vessels (one for each IHX vessel)

The vessels are designed to contain the heat transport medium (helium) inventory within a leak tight pressure boundary and to maintain the integrity of this pressure boundary.

The main component of the system is the Reactor Vessel. Its required functions are the following (Reference 1, Appendix A, Section 7.3.2.1):

- Provide core support and maintain its relative position to the control rods
- Provide decay heat and residual heat removal by radial conduction during conduction cooldown

- Designed for operation duration of 60 years

The approximate Reactor Vessel dimensions and weight are (Reference 1, Section 6.2.1.1):

- 25 meters high
- 7.5 meters in diameter
- 150 mm thick in the core belt line region
- 825 T total weight including 225 T for the cover head

The reference material for the Reactor Vessel and other components of the vessel system, based on pre-conceptual design work, was mod 9Cr-1Mo steel. Material selection issues have been revisited in reference 3 and the following summarizes the outcome of this work which is the basis for the risk assessment:

- The main issue associated to material candidates is linked to procurement. Whatever material is selected, the design of the Reactor Pressure Vessel will have to be made out of plates to be consistent with 2018 schedule. The few remaining forgings could be provided by JSW in time for start-up by 2018, subjected that the corresponding forgings could be switched with slots currently under negotiation at the time of the present report. Otherwise, a minimum two years delay for start-up should be anticipated, subjected to taking a decision in the very near term to reserve forging slots. Other forging suppliers could also be envisioned but should be limited to small size forgings of the RPV (such as nozzles) or at most some of the larger forgings of the IHX vessel.

- Procurement issues have been identified with mod 9Cr1Mo and it is recommended to pursue investigations to clarify, if this option is still viable.

- 2.25Cr 1Mo annealed (grade 22) could also be envisioned for the “hot” vessel option, but this material requires to increase the thickness by about 150% compared to other candidates. It must be clarified if mechanical properties expected for the thicker parts (flanges and nozzle ring) would still be acceptable.

- 2.25Cr 1Mo V is also considered as a good candidate for such an application, with expected reduced feasibility issues for welding compared to mod 9Cr1Mo. However, this material is not currently permitted for nuclear application according to the ASME code and the time required to qualify it for the NGNP is not expected to be consistent with NGNP schedule.

- No procurement issue has been identified with the PWR grade (SA 508 / SA 533 grades) and this material could be procured in the required dimensions for the NGNP. This material can not be used at elevated temperatures and its use for high core inlet temperature would require the implementation of active cooling system or thermal protection of the vessel system to ensure a wall temperature no greater than 350°C during normal operating conditions.

As a result, the following material options are considered for the risk assessment:

- Mod 9Cr1Mo

- SA 508 / SA 533

- SA 508 / SA 533 with implementation of active cooling system or thermal protection

- 2.25Cr1Mo (grade 22).

It is to be noted that the Reactor Vessel is not in direct contact with the helium at the core inlet temperature and is protected from return He by stagnant areas at the bottom, periphery, and top of the vessel. As a result the vessel temperature can be significantly lower than the core inlet temperature. This is not the case for the IHX vessel which will have to be insulated to limit heat losses. Risk assessment is performed assuming that the IHX vessel is at the core inlet temperature, except for the “cooled” SA 508 / SA 533 case which assumes that the active cooling system or thermal protection would cover the IHX vessels and cross vessels as well. Alternatively, it could be envisioned combination of two materials (one for the RPV and another for the IHX vessels) but this would require the use of heterogeneous welds with additional risks not addressed in the context of the present work.

Note finally that the RPV is supposed to operate in the negligible creep regime in order to avoid the implementation of a surveillance program covering the effect of irradiation and creep altogether and the risk assessment takes this requirement into account.

4.7 Risk Assessment for the Vessel System

4.7.1 Parameter Assessment for the Vessel System with mod 9Cr1Mo

Availability. Availability is the major concern for mod 9Cr1Mo. This material is currently used in the petrochemical industry, but for different operating conditions (at higher temperatures) and for other applications than pressure vessels (mainly for piping). Japan Steel Works has experience with this material (even though mainly for rotor application with slightly different chemical composition but their current facilities do not enable them to fabricate the forgings (even the smaller ones) that would be required for the NGNP. The design of the RPV could be made out of plate with no flange but this would require the availability of rolled plates and small forgings (for instance for the cross vessel nozzles). Possible suppliers have not yet been identified. The procurement of the flanges of the IHX vessel is however likely to be an issue. Procurement is supposed to be less of an issue at lower power levels and for lower primary pressure but it is not expected that they will be completely solved.

Fabricability. Actions have been performed by AREVA on the welding of thick sections of mod 9Cr1Mo. Actions have shown that welding is possible, even though optimization is still necessary to obtain all required material properties. Welding and associated post weld heat treatment is however considered as a possible issue for high pressure values.

Qualification. The material is considered as appropriate for the intended application, even though R&D is still required to fully understand the behavior of this material and complete its qualification.

Codification. The material is covered by ASME Section III but its use for RPV application would require extending subsection NH of the Code to heavy section forgings. The regulatory acceptance of this material may however be an issue, especially for higher core inlet temperature which would require an agreed upon definition of negligible creep conditions for the RPV and approved creep-fatigue design rules for the IHX vessels.

4.7.2 Probabilities of Success for the Vessel System with mod 9Cr1Mo

Table 36. Vessel System probabilities of success for mod 9Cr1Mo at 250 MWt and 5 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.50	0.80	0.90	0.80	50	60
400	0.50	0.80	0.90	0.80	50	60
450	0.50	0.80	0.90	0.80	50	60
500	0.50	0.80	0.90	0.70	50	60

Table 37. Vessel System probabilities of success for mod 9Cr1Mo at 350 MWt and 5 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.40	0.80	0.90	0.80	40	50
400	0.40	0.80	0.90	0.80	40	50
450	0.40	0.80	0.90	0.80	40	50
500	0.40	0.80	0.90	0.70	40	50

Table 38. Vessel System probabilities of success for mod 9Cr1Mo at 450 MWt and 5 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.30	0.80	0.90	0.80	30	40
400	0.30	0.80	0.90	0.80	30	40
450	0.30	0.80	0.90	0.80	30	40
500	0.30	0.80	0.90	0.70	30	40

Table 39. Vessel System probabilities of success for mod 9Cr1Mo at 550 and 650 MWt and 5 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.30	0.80	0.90	0.80	30	40
400	0.30	0.80	0.90	0.80	30	40
450	0.30	0.80	0.90	0.80	30	40
500	0.30	0.80	0.90	0.70	30	40

Table 40. Vessel System probabilities of success for mod 9Cr1Mo at 250 MWt and 6 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.40	0.80	0.90	0.80	40	50
400	0.40	0.80	0.90	0.80	40	50
450	0.40	0.80	0.90	0.80	40	50
500	0.40	0.80	0.90	0.70	40	50

Table 41. Vessel System probabilities of success for mod 9Cr1Mo at 350 MWt and 6 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.30	0.80	0.90	0.80	30	40
400	0.30	0.80	0.90	0.80	30	40
450	0.30	0.80	0.90	0.80	30	40
500	0.30	0.80	0.90	0.70	30	40

Table 42. Vessel System probabilities of success for mod 9Cr1Mo at 450 MWt and 6 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.20	0.70	0.90	0.80	20	30
400	0.20	0.70	0.90	0.80	20	30
450	0.20	0.70	0.90	0.80	20	30
500	0.20	0.70	0.90	0.70	20	30

Table 43. Vessel System probabilities of success for mod 9Cr1Mo at 550 and 650 MWt and 6 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.20	0.70	0.90	0.80	20	30
400	0.20	0.70	0.90	0.80	20	30
450	0.20	0.70	0.90	0.80	20	30
500	0.20	0.70	0.90	0.70	20	30

Table 44. Vessel System probabilities of success for mod 9Cr1Mo at 250 MWt and 7 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.30	0.80	0.90	0.80	30	40
400	0.30	0.80	0.90	0.80	30	40
450	0.30	0.80	0.90	0.80	30	40
500	0.30	0.80	0.90	0.70	30	40

Table 45. Vessel System probabilities of success for mod 9Cr1Mo at 350 MWt and 7 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.20	0.70	0.90	0.80	20	30
400	0.20	0.70	0.90	0.80	20	30
450	0.20	0.70	0.90	0.80	20	30
500	0.20	0.70	0.90	0.70	20	30

Table 46. Vessel System probabilities of success for mod 9Cr1Mo at 450, 550, and 650 MWt and 7 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.10	0.60	0.90	0.80	10	20
400	0.10	0.60	0.90	0.80	10	20
450	0.10	0.60	0.90	0.80	10	20
500	0.10	0.60	0.90	0.70	10	20

Table 47. Vessel System probabilities of success for mod 9Cr1Mo at 250 MWt and 8 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.20	0.70	0.90	0.80	20	30
400	0.20	0.70	0.90	0.80	20	30
450	0.20	0.70	0.90	0.80	20	30
500	0.20	0.70	0.90	0.70	20	30

Table 48. Vessel System probabilities of success for mod 9Cr1Mo at 350 MWt and 8 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.10	0.60	0.90	0.80	10	20
400	0.10	0.60	0.90	0.80	10	20
450	0.10	0.60	0.90	0.80	10	20
500	0.10	0.60	0.90	0.70	10	20

Table 49. Vessel System probabilities of success for mod 9Cr1Mo at 450, 550, and 650 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.00	0.50	0.90	0.80	0	0
400	0.00	0.50	0.90	0.80	0	0
450	0.00	0.50	0.90	0.80	0	0
500	0.00	0.50	0.90	0.70	0	0

Table 50. Vessel System probabilities of success for mod 9Cr1Mo at 250 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF2018	DF 2021
350	0.10	0.60	0.90	0.80	10	20
400	0.10	0.60	0.90	0.80	10	20
450	0.10	0.60	0.90	0.80	10	20
500	0.10	0.60	0.90	0.70	10	20

Table 51. Vessel System probabilities of success for mod 9Cr1Mo at 350 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.00	0.50	0.90	0.80	0	
400	0.00	0.50	0.90	0.80	0	
450	0.00	0.50	0.90	0.80	0	
500	0.00	0.50	0.90	0.70	0	

Table 52. Vessel System probabilities of success for mod 9Cr1Mo at 450, 550, and 650 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF2018	DF 2021
350	0.00	0.40	0.90	0.80	0	0
400	0.00	0.40	0.90	0.80	0	0
450	0.00	0.40	0.90	0.80	0	0
500	0.00	0.40	0.90	0.70	0	0

4.7.3 Risk Results for the Vessel System with mod 9Cr1Mo

The percentage success results from the Year 2018 risk evaluation for the vessel system are shown in Tables 53-56 and Figures 13-15.

Table 53. Year 2018 percentage success for Vessel System with mod 9Cr1Mo at 250 MWt

Inlet Temperature (°C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	50	40	30	20	10
400	50	40	30	20	10
450	50	40	30	20	10
500	50	40	30	20	10

Table 54. Year 2018 percentage success for Vessel System with mod 9Cr1Mo at 350 MWt

Inlet Temperature (°C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	40	30	20	10	0
400	40	30	20	10	0
450	40	30	20	10	0
500	40	30	20	10	0

Table 55. Year 2018 percentage success for Vessel System with mod 9Cr1Mo at 450, 550, and 650 MWt

Inlet Temperature (°C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	30	20	10	0	0
400	30	20	10	0	0
450	30	20	10	0	0
500	30	20	10	0	0

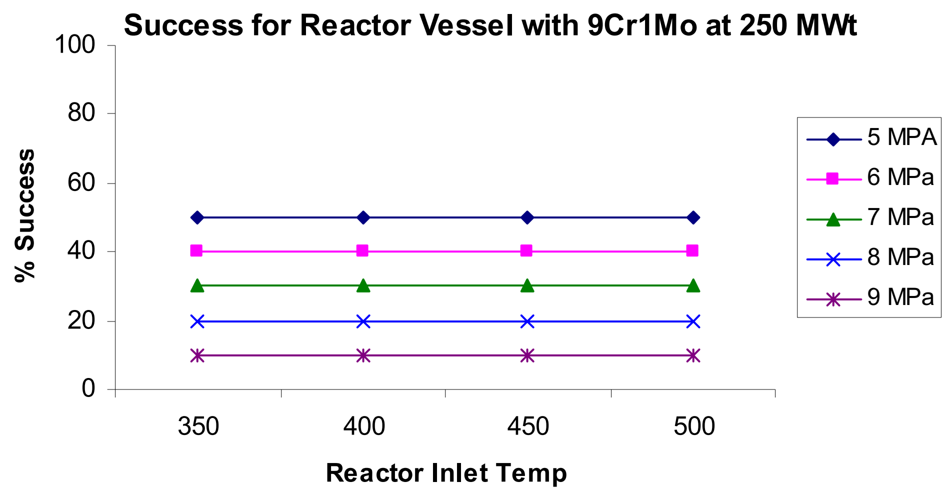

Figure 13. Year 2018 percentage success for Vessel System with mod 9Cr1Mo at 250 MWt

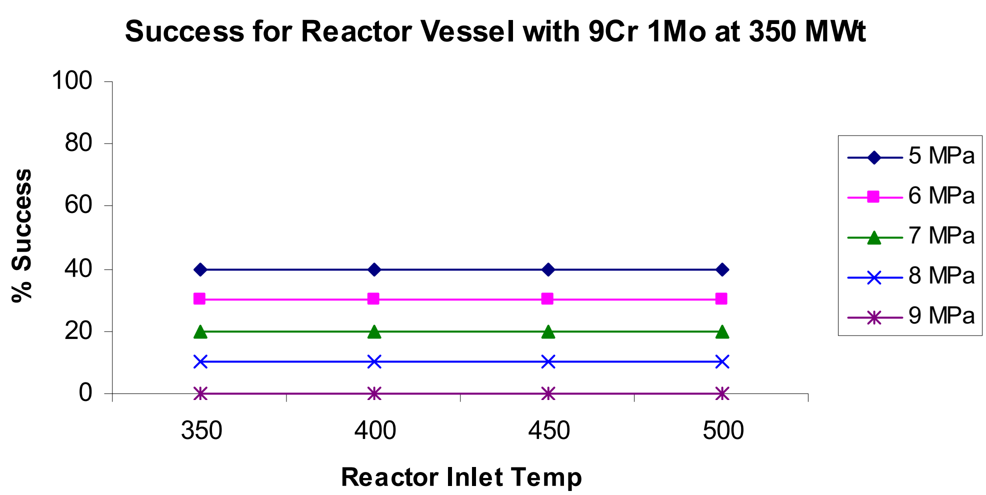

Figure 14. Year 2018 percentage success for Vessel System with mod 9Cr1Mo at 350 MWt

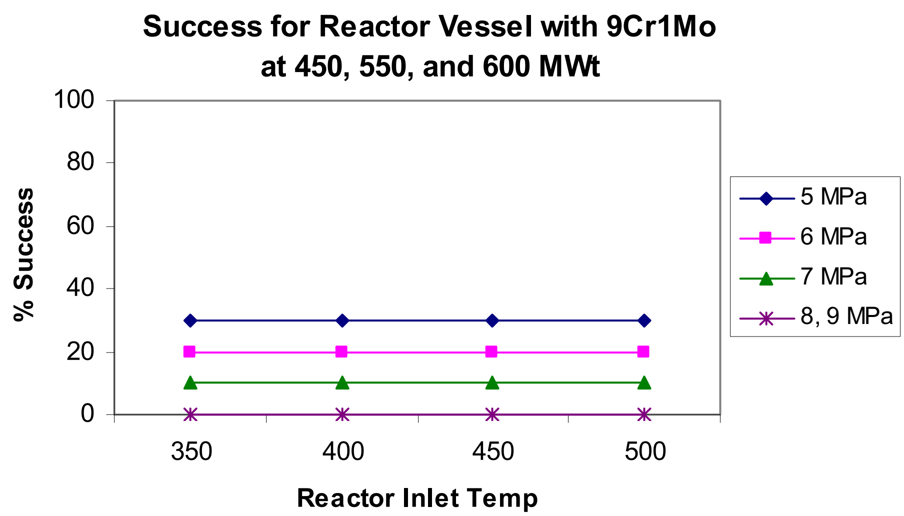

Figure 15. Year 2018 percentage success for Vessel System with mod 9Cr1Mo at 450, 550, and 650 MWt

4.7.4 Parameter Assessment for the Vessel System with SA-508/SA-533

Availability. It is considered that this material could be procured in time for start-up by 2018 subjected that the RPV be designed with extensive use of plates. A limited number of forgings could be procured from Japan Steel Works (JSW) if it could be envisioned to switch slots currently under negotiation to accommodate NGNP needs. Otherwise, forgings will need to be obtained from other sources and this means in particular that the RPV will need to be designed without flange (outside the capability of other suppliers). This design option can be envisioned but is not the preferred option.

For a design based on forgings only, the only supplier is JSW and their current lead time is not consistent with start-up by 2018 but should support a start-up by 2021. A decision has to be taken on the schedule target (2018 vs 2021) in order to decide which path in terms of fabrication options (either plates and forged or full forged design) has to be pursued. It is imperative that a decision is made to increase the chance of success, even with the 2021 target.

It is also expected that availability of plates or forgings could become an issue for large power level combined with high primary pressure.

Fabricability. No fabricability issues have been identified, even for high pressure values requiring thicker plates or forgings.

Qualification. This material is currently permitted up to 371°C in normal operation and up to 538°C in accident events under the conditions defined in ASME Code Case N499-2. An inlet temperature of 400°C could be envisioned for the RPV, based on the current design but the design of the cross vessels and the IHX vessels would need to be modified in order to limit the vessel temperature to 350°C during normal operation. The feasibility at 400°C is therefore rated as zero due to the impossibility to operate the IHX vessel at that temperature without design modification. Based on the current design, the feasibility of operating the RPV with 400°C core inlet would be about 50%

Codification. This material is extensively used for PWR application and no codification issue is expected, subjected to meeting the current temperature limitations of the ASME Code.

4.7.5 Probabilities of Success for the Vessel System with SA-508/SA-533

Table 56. Vessel System probabilities of success for SA-508 at 250, 350, 450, 550, 650 MWt and 5 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	100 / 95 (at 450-650 MWt)
400	0.90	1.00	0.00	0.00	0	0
450	0.90	1.00	0.00	0.00	0	0
500	0.90	1.00	0.00	0.00	0	0

Table 57. Vessel System probabilities of success for SA-508 at 250, 350, 450, 550, 650 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	100 / 95 (at 450-650 MWt)
400	0.90	1.00	0.00	0.00	0	0
450	0.90	1.00	0.00	0.00	0	0
500	0.90	1.00	0.00	0.00	0	0

Table 58. Vessel System probabilities of success for SA-508 at 250, 350, 450, 550, 650 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	100 / 95 (at 450-650 MWt)
400	0.90	1.00	0.00	0.00	0	0
450	0.90	1.00	0.00	0.00	0	0
500	0.90	1.00	0.00	0.00	0	0

Table 59. Vessel System probabilities of success for SA-508 at 250, 350 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	95
400	0.90	1.00	0.00	0.00	0	0
450	0.90	1.00	0.00	0.00	0	0
500	0.90	1.00	0.00	0.00	0	0

Table 60. Vessel System probabilities of success for SA-508 at 450, 550, 650 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90
400	0.80	1.00	0.00	0.00	0	0
450	0.80	1.00	0.00	0.00	0	0
500	0.80	1.00	0.00	0.00	0	0

Table 61. Vessel System probabilities of success for SA-508 at 250, 350 MWt and 9 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90
400	0.80	1.00	0.00	0.00	0	0
450	0.80	1.00	0.00	0.00	0	0
500	0.80	1.00	0.00	0.00	0	0

Table 62. Vessel System probabilities of success for SA-508 at 450, 550, 650 MWt and 9 MPa

^oC	Availability	Fabricability	Qualification	Codification	DF2018	DF 2021
350	0.70	1.00	1.00	1.00	70	80
400	0.70	1.00	0.00	0.00	0	0
450	0.70	1.00	0.00	0.00	0	0
500	0.70	1.00	0.00	0.00	0	0

4.7.6 Risk Results for the Vessel System with SA-508/SA-533

The percentage success results from the Year 2018 risk evaluation for the Vessel System with SA-508 are shown in Tables 63-67 and Figures 16-17.

Table 63. Year 2018 percentage success for the Vessel System with SA-508 at 250 MWt

Inlet Temperature (^oC)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	90	80
400	0	0	0	0	0
450	0	0	0	0	0
500	0	0	0	0	0

Table 64. Year 2018 percentage success for the Vessel System with SA-508 at 350 MWt

Inlet Temperature (^oC)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	90	80
400	0	0	0	0	0
450	0	0	0	0	0
500	0	0	0	0	0

Table 65. Year 2018 percentage success for the Vessel System with SA-508 at 450 MWt

Inlet Temperature (^oC)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	80	70
400	0	0	0	0	0
450	0	0	0	0	0
500	0	0	0	0	0

Table 66. Year 2018 percentage success for the Vessel System with SA-508 at 550 MWt

Inlet Temperature (^oC)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	80	70
400	0	0	0	0	0
450	0	0	0	0	0
500	0	0	0	0	0

Table 67. Year 2018 percentage success for the Vessel System with SA-508 at 650 MWt

Inlet Temperature (^oC)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	80	70
400	0	0	0	0	0
450	0	0	0	0	0
500	0	0	0	0	0

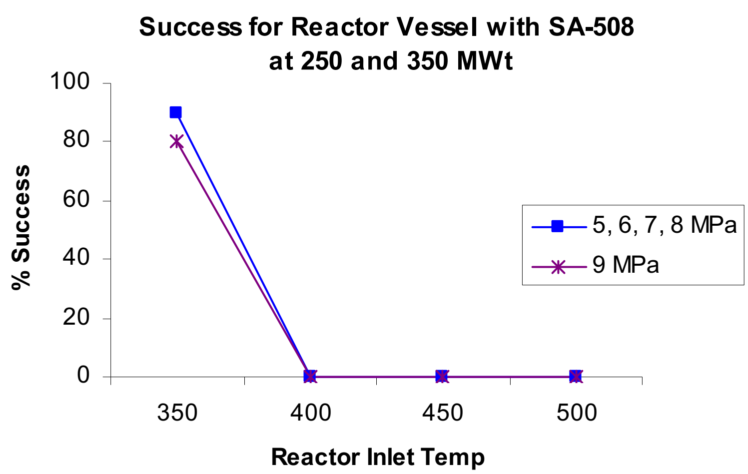

Figure 16. Year 2018 percentage success for Vessel System with SA-508 at 250 and 350 MWt

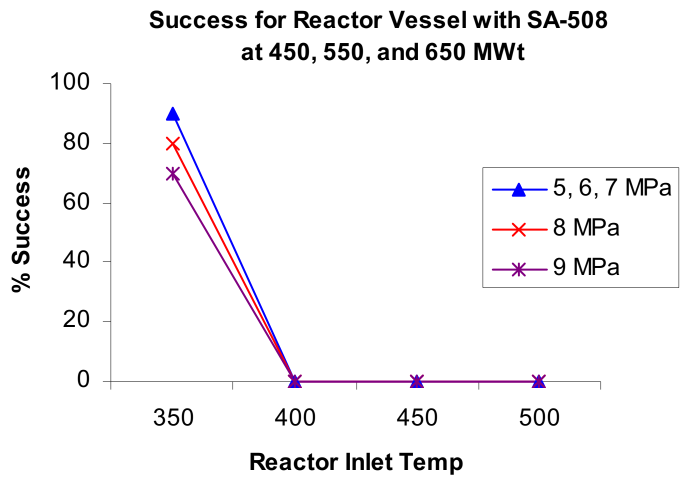

Figure 17. Year 2018 percentage success for Vessel System with SA-508 at 450, 550, and 650 MWt

4.7.7 Parameter Assessment for the Vessel System with cooled SA-508/SA-533

Availability, fabricability, qualification and codification for SA 508 / SA 533 material is supposed to be the same as that described in section 4.7.4. The only difference is linked to the implementation of active cooling or thermal protection of the RPV, cross vessels, and IHX vessels, which enables using the same material with higher core inlet temperatures. Such systems or new design features should guarantee acceptable temperatures at any point of the vessels and the qualification assessment addresses the risk associated to such systems.

Codification could become an issue for high power level combined with high core inlet temperature due to the risk to exceed the limit imposed by ASME Code Case N-499-2 on metal temperatures during conduction cooldown accident.

4.7.8 Probability of Success for the Vessel System with cooled SA-508/SA-533

Table 68. Vessel System prob. of success, cooled SA-508 at 250, 350, 450, 550 MWt and 5 MPa

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	100 / 95 (at 450-550 MWt)
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	1.00	60	70

Table 69. Vessel System probability of success, cooled SA-508 at 650 MWt and 5 MPa

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	95
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	0.80	60	70

Table 70. Vessel System prob. of success, cooled SA-508 at 250, 350, 450, 550 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	100 / 95 (at 450-550 MWt)
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	1.00	60	70

Table 71. Vessel System probability of success, cooled SA-508 at 650 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	95
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	0.80	60	70

Table 72. Vessel System prob. of success, cooled SA-508 at 250, 350, 450, 550 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	100 / 95 (at 450-550 MWt)
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	1.00	60	70

Table 73. Vessel System probability of success for cooled SA-508 at 650 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	95
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	0.80	60	70

Table 74. Vessel System probability of success, cooled SA-508 at 250, 350 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	95
400	0.90	1.00	0.95	1.00	90	95
450	0.90	1.00	0.80	1.00	80	85
500	0.90	1.00	0.60	1.00	60	70

Table 75. Vessel System probability of success, cooled SA-508 at 450, 550 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90
400	0.80	1.00	0.95	1.00	80	90
450	0.80	1.00	0.80	1.00	80	85
500	0.80	1.00	0.60	1.00	60	70

Table 76. Vessel System probability of success, cooled SA-508 at 650 MWt and 8 MPa

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90
400	0.80	1.00	0.95	1.00	80	90
450	0.80	1.00	0.80	1.00	80	85
500	0.80	1.00	0.60	0.80	60	70

Table 77. Vessel System probability of success, cooled SA-508 at 250, 350 MWt and 9 MPa

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90
400	0.80	1.00	0.95	1.00	80	90
450	0.80	1.00	0.80	1.00	80	85
500	0.80	1.00	0.60	1.00	60	70

Table 78. Vessel System probability of success, cooled SA-508 at 450, 550 MWt and 9 MPa

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.70	1.00	1.00	1.00	70	80
400	0.70	1.00	0.95	1.00	70	80
450	0.70	1.00	0.80	1.00	70	80
500	0.70	1.00	0.60	1.00	60	70

Table 79. Vessel System probability of success, cooled SA-508 at 650 MWt and 9 MPa

^{o}C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.70	1.00	1.00	1.00	70	80
400	0.70	1.00	0.95	1.00	70	80
450	0.70	1.00	0.80	1.00	70	80
500	0.70	1.00	0.60	0.80	60	70

4.7.9 Risk Results for the Vessel System with Cooled SA-508

The percentage success results from the Year 2018 risk evaluation for the Vessel System with cooled SA-508 are shown in Tables 80-82 and Figures 18-19.

Table 80. Year 2018 percentage success for Vessel System, cooled SA-508 at 250, 350 MWt

Inlet Temperature (^{o}C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	90	80
400	90	90	90	90	80
450	80	80	80	80	80
500	60	60	60	60	60

Table 81. Year 2018 percentage success for Vessel System, cooled SA-508 at 450, 550 MWt

Inlet Temperature (^{o}C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	80	70
400	90	90	90	80	70
450	80	80	80	80	70
500	60	60	60	60	60

Table 82. Year 2018 percentage success for Vessel System, cooled SA-508 at 650 MWt

Inlet Temperature (^{o}C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	90	90	80	70
400	90	90	90	80	70
450	80	80	80	80	70
500	60	60	60	60	60

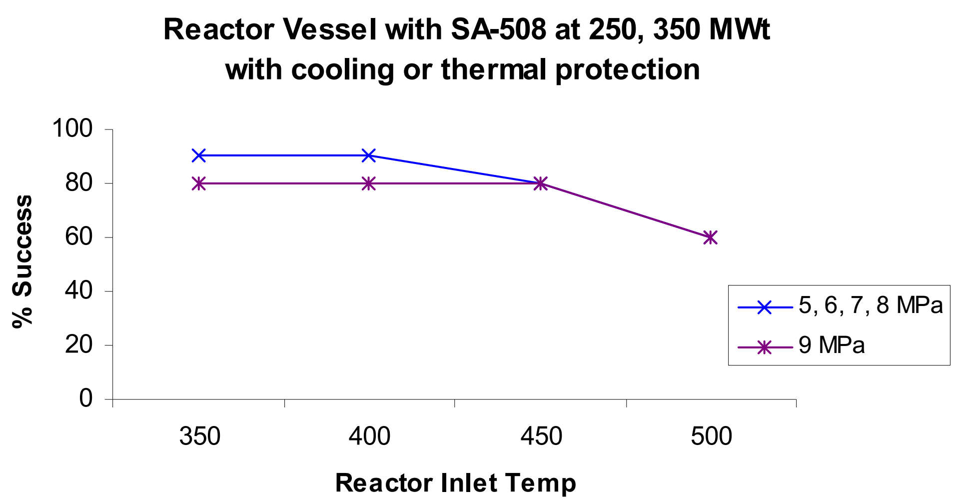

Figure 18. Year 2018 percentage success for Vessel System, cooled SA-508 at 250, 350 MWt

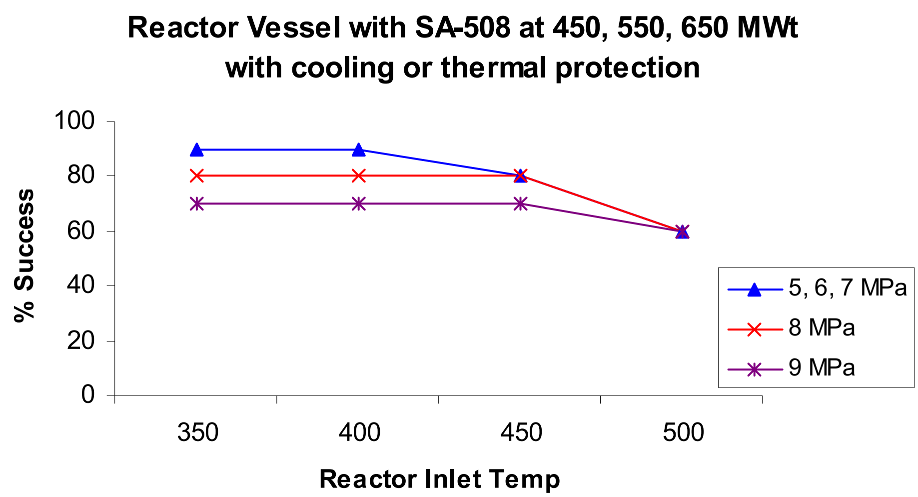

Figure 19. Year 2018 percentage success for Vessel System, cooled SA-508 at 450, 550, 650 MWt

4.7.10 Parameter Assessment for Vessel System with 2.25Cr1Mo

Availability. It is considered that this material could be procured in time for start-up by 2018 subjected that the RPV be designed with extensive use of plates. A limited number of forgings could be procured from Japan Steel Works (JSW) if it could be envisioned to switch slots currently under negotiation to accommodate NGNP needs. Otherwise, forgings will need to be obtained from other sources and this means in particular that the RPV will need to be designed without flange (outside the capability of other suppliers). This design option can be envisioned but is not the preferred option. As for SA 508 / SA 533, a decision has to be taken on the schedule target (2018 vs 2021) in order to decide which path in terms of fabrication options has to be pursued.

It is expected that procurement of plates or forgings would become an issue for high power levels and high primary pressure due to the expected reduction of mechanical properties for heavy section products.

Fabricability. Welding and post-weld heat treatment are feasible for lower pressure values but might be an issue for higher pressures.

Qualification. No qualification issues are identified up to 400°C core inlet temperature but it needs to be confirmed that the IHX vessel and cross vessel could support temperatures of 450°C and above.

Codification. The material is covered by ASME Section III up to 371°C under Subsection NB and up to 650°C under Subsection NH

4.7.11 Probability of Success for the Vessel System with 2.25Cr1Mo

Table 83. Vessel System probability of success with 2.25Cr1Mo at 250 MWt and 5 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.90	1.00	1.00	1.00	90	90
400	0.90	1.00	1.00	1.00	90	90
450	0.90	1.00	0.90	1.00	90	90
500	0.90	1.00	0.80	1.00	80	80

Table 84. Vessel System probability of success with 2.25Cr1Mo at 350, 450 MWt and 5 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90 / 85
400	0.80	1.00	1.00	1.00	80	90 / 85
450	0.80	1.00	0.90	1.00	80	90 / 85
500	0.80	1.00	0.80	1.00	80	80

Table 85. Vessel System probability of success with 2.25Cr1Mo at 550, 650 MWt and 5 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.70	1.00	1.00	1.00	70	70
400	0.70	1.00	1.00	1.00	70	70
450	0.70	1.00	0.90	1.00	70	70
500	0.70	1.00	0.80	1.00	70	70

Table 86. Vessel System probability of success with 2.25Cr1Mo at 250 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.80	1.00	1.00	1.00	80	90
400	0.80	1.00	1.00	1.00	80	90
450	0.80	1.00	0.90	1.00	80	90
500	0.80	1.00	0.80	1.00	80	80

Table 87. Vessel System probability of success with 2.25Cr1Mo at 350 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.70	1.00	1.00	1.00	70	70
400	0.70	1.00	1.00	1.00	70	70
450	0.70	1.00	0.90	1.00	70	70
500	0.70	1.00	0.80	1.00	70	70

Table 88. Vessel System probability of success with 2.25Cr1Mo at 450 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.70	0.90	1.00	1.00	70	70
400	0.70	0.90	1.00	1.00	70	70
450	0.70	0.90	0.90	1.00	70	70
500	0.70	0.90	0.80	1.00	70	70

Table 89. Vessel System probability of success with 2.25Cr1Mo at 550, 650 MWt and 6 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.60	0.90	1.00	1.00	60	60
400	0.60	0.90	1.00	1.00	60	60
450	0.60	0.90	0.90	1.00	60	60
500	0.60	0.90	0.80	1.00	60	60

Table 90. Vessel System probability of success with 2.25Cr1Mo at 250 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.70	0.90	1.00	1.00	70	
400	0.70	0.90	1.00	1.00	70	
450	0.70	0.90	0.90	1.00	70	
500	0.70	0.90	0.80	1.00	70	

Table 91. Vessel System probability of success with 2.25Cr1Mo at 350 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.60	0.90	1.00	1.00	60	70
400	0.60	0.90	1.00	1.00	60	70
450	0.60	0.90	0.90	1.00	60	70
500	0.60	0.90	0.80	1.00	60	70

Table 92 Vessel System probability of success with 2.25Cr1Mo at 450 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.60	0.70	1.00	1.00	60	60
400	0.60	0.70	1.00	1.00	60	60
450	0.60	0.70	0.90	1.00	60	60
500	0.60	0.70	0.80	1.00	60	60

Table 93. Vessel System probability of success with 2.25Cr1Mo at 550, 650 MWt and 7 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.50	0.70	1.00	1.00	50	50
400	0.50	0.70	1.00	1.00	50	50
450	0.50	0.70	0.90	1.00	50	50
500	0.50	0.70	0.80	1.00	50	50

Table 94. Vessel System probability of success with 2.25Cr1Mo at 250 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.60	0.70	1.00	1.00	60	60
400	0.60	0.70	1.00	1.00	60	60
450	0.60	0.70	0.90	1.00	60	60
500	0.60	0.70	0.80	1.00	60	60

Table 95. Vessel System probability of success with 2.25Cr1Mo at 350 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.40	0.70	1.00	1.00	40	40
400	0.40	0.70	1.00	1.00	40	40
450	0.40	0.70	0.90	1.00	40	40
500	0.40	0.70	0.80	1.00	40	40

Table 96. Vessel System probability of success with 2.25Cr1Mo at 450 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.40	0.60	1.00	1.00	40	40
400	0.40	0.60	1.00	1.00	40	40
450	0.40	0.60	0.90	1.00	40	40
500	0.40	0.60	0.80	1.00	40	40

Table 97. Vessel System probability of success with 2.25Cr1Mo at 550, 650 MWt and 8 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.30	0.60	1.00	1.00	30	30
400	0.30	0.60	1.00	1.00	30	30
450	0.30	0.60	0.90	1.00	30	30
500	0.30	0.60	0.80	1.00	30	30

Table 98. Vessel System probability of success with 2.25Cr1Mo at 250 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.40	0.60	1.00	1.00	40	40
400	0.40	0.60	1.00	1.00	40	40
450	0.40	0.60	0.90	1.00	40	40
500	0.40	0.60	0.80	1.00	40	40

Table 99. Vessel System probability of success with 2.25Cr1Mo at 350 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.20	0.60	1.00	1.00	20	20
400	0.20	0.60	1.00	1.00	20	20
450	0.20	0.60	0.90	1.00	20	20
500	0.20	0.60	0.80	1.00	20	20

Table 100. Vessel System probability of success with 2.25Cr1Mo at 450 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.20	0.50	1.00	1.00	20	20
400	0.20	0.50	1.00	1.00	20	20
450	0.20	0.50	0.90	1.00	20	20
500	0.20	0.50	0.80	1.00	20	20

Table 101. Vessel System probability of success with 2.25Cr1Mo at 550, 650 MWt and 9 MPa

°C	Availability	Fabricability	Qualification	Codification	DF 2018	DF 2021
350	0.10	0.50	1.00	1.00	10	10
400	0.10	0.50	1.00	1.00	10	10
450	0.10	0.50	0.90	1.00	10	10
500	0.10	0.50	0.80	1.00	10	10

4.7.12 Risk Results for the Vessel System with 2.25Cr1Mo

The percentage success results from the Year 2018 risk evaluation for the Vessel System with 2.25Cr1Mo are shown in Tables 102-104 and Figures 20-22.

Table 102. Year 2018 percentage success for Vessel System with 2.25Cr1Mo at 250 MWt

Inlet Temperature (°C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	90	80	70	60	40
400	90	80	70	60	40
450	90	80	70	60	40
500	80	80	70	60	40

Table 103. Year 2018 percentage success for Vessel System with 2.25Cr1Mo at 350, 450 MWt

Inlet Temperature (°C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	80	70	60	40	20
400	80	70	60	40	20
450	80	70	60	40	20
500	80	70	60	40	20

Table 104. Year 2018 percentage success for Vessel System with 2.25Cr1Mo at 550, 650 MWt

Inlet Temperature (°C)	5 Ma	6 MPa	7 MPa	8 MPa	9 MPa
350	70	60	50	30	10
400	70	60	50	30	10
450	70	60	50	30	10
500	70	60	50	30	10

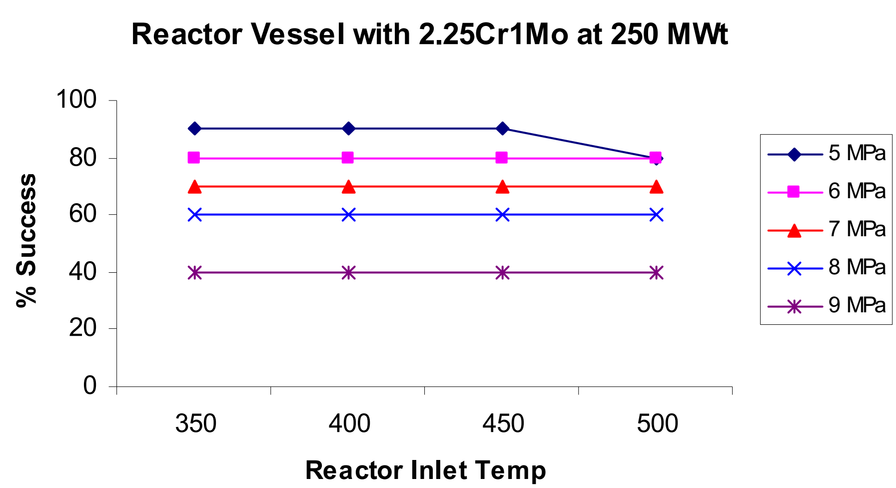

Figure 20. Year 2018 percentage success for Vessel System with 2.25Cr1Mo at 250 MWt

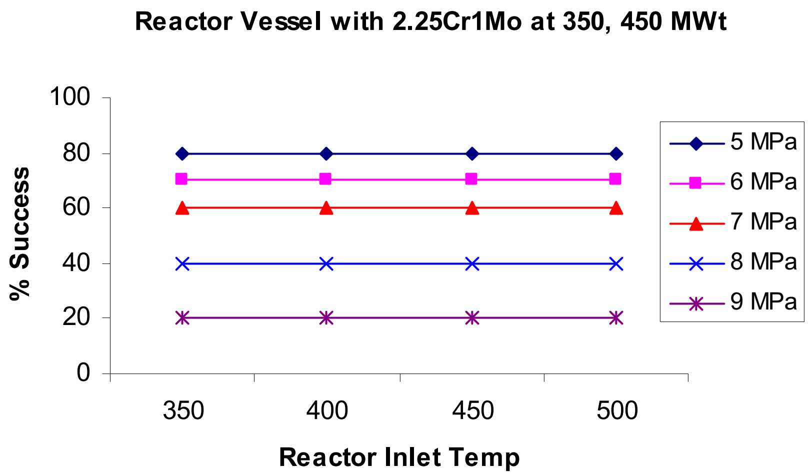

Figure 21. Year 2018 percentage success for Vessel System with 2.25Cr1Mo at 350, 450 MWt

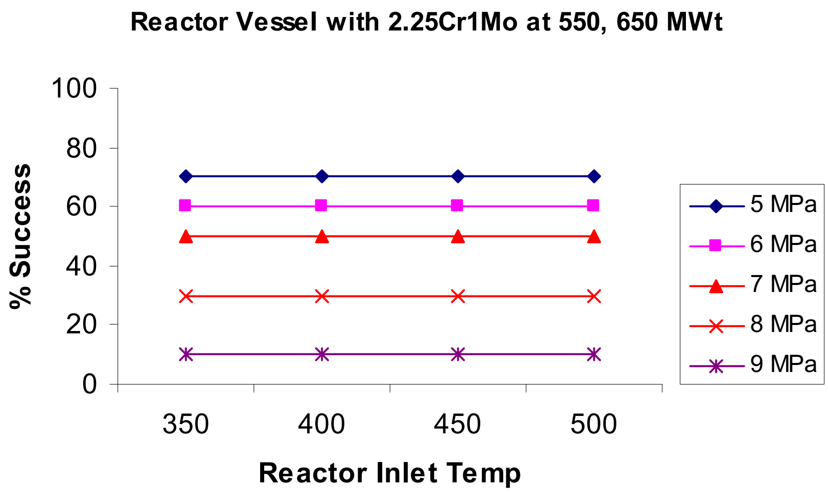

Figure 22. Year 2018 percentage success for Vessel System with 2.25Cr1Mo at 550, 650 MWt

4.8 Parameter Interrelationships and Risk Considerations

The risk associated with each key NGNP component is controlled by one or more of the main parameters selected for the design as discussed in the preceding sections of this report.

The risk associated with the main components can be expressed functionally as

$S_{RPV} = f(Matl_{RPV}, T_{in}, Q_{Rx}, P)$

$S_{IHX} = f(Matl_{IHX}, Type_{IHX}, T_{out}, Q_{IHX})$

$S_{PC} = f(T_{in}, W_{circ1})$

$S_{SC} = f(T_{in}, W_{circ2})$

where

$Matl_{IHX}$ is IHX material type

$Matl_{RPV}$ is vessel system material type

P is the system pressure

Q_{IHX} is the individual IHX power level

Q_{Rx} is the reactor power level

S_{IHX} is the confidence that the IHX will be available to support the project schedule

S_{SC} is the confidence that the secondary circulator will be available to support the project schedule

S_{PC} is the confidence that the primary circulator will be available to support the project schedule

S_{RPV} is the confidence that the vessels will be available to support the project schedule

T_{in} is the core inlet temperature

T_{out} is the core outlet temperature

$Type_{IHX}$ is the type of IHX (compact or tubular)

W_{circ1} is the power of each primary circulator

W_{circ2} is the power of each secondary circulator

However, two additional types of relationships are necessary to characterize the collective resulting risk for the plant containing these components.

One of these additional sets of relationships includes those necessary to define the relationship between the independent parameters in the above functional relationships to the key parameters which define the plant. Specifically, Q_{IHX}, W_{circ1}, and W_{circ2} are to be obtained from Q_{Rx}, T_{in}, T_{out}, and P, which are the key defining parameters.

The second type of additional relationships includes those which define allowable combinations of the key defining parameters. These relationships affect the impact on the collective performance of the system of components rather than the impact on a specific component. For example, it is easy to select an inlet temperature that is acceptable for the vessel system and at the same time select an outlet temperature that is acceptable for the IHX. However, it is not necessarily true that this combination of inlet and outlet temperature is acceptable for the overall system. While the key components of the system may be individually acceptable, the system may not be able to operate at the specified point.

In the HTR system, the first main system limitation is implicitly covered by the circulator feasibility. Some potential configurations will result in unacceptably large flow rates. The resulting estimate of circulator risk will eliminate such configurations.

The second main system limitation is the impact on core design feasibility. Some combinations of inlet and outlet temperature make it very difficult to develop an acceptable core design. An extra constraint must be imposed in order to identify these undesirable configurations.

The third limitation is linked to RPV feasibility which is a trade off with circulator feasibility.

4.8.1 Individual Loop Parameters

The main defining parameters for the plant define the reactor system. However, the IHX and circulator constraints must consider the conditions of an individual heat transfer loop. The following relationships provide the relationship between the plant parameters and the individual loop parameters. An indirect cycle configuration is assumed in which there is a one-to-one correspondence between primary and secondary loops and in which each primary loop has one circulator and one IHX and each secondary loop has one secondary circulator.

$$Q_{IHX} = Q_{Rx} / n$$

where

n is the number of loops.

The circulator power is ignored in this evaluation.

Additional relationships provide the individual loop mass flow rates.

$$m_{Rx} = Q_{Rx} / (T_{out} – T_{in}) / c_p$$

and

$$m_{loop} = m_{Rx} / n$$

4.8.2 Circulator Power Estimate

Circulator power is estimated from the loop mass flow rate, circulator inlet temperature, system pressure drop, and pressure using the conventional compressor formula. The general relationship for circulator power is

$$W_{circ} = J_{circ} \cdot V_{circ} \cdot \Delta P_{syst} / \eta_{circ}$$

where

J_{circ} is the circulator power margin factor (including design evolution) (= 1.5)

η_{circ} is the circulator efficiency (= 0.85)

V_{circ} is the volumetric flow at the circulator (= f(T_{in}, P, m_{loop}))

ΔP_{circ} is the system pressure drop

The circulator power margin is recommended to be 1.5 at this early stage of design in order to allow for uncertainty and design evolution.

The system pressure drop will vary depending on a number of design parameters. However, assuming that the geometry of the system is consistently scaled with the system power level, a simple relationship is possible scaling from a reference pressure drop based on reference conditions.

$$\Delta P_{circ} = \Delta P_{ref} \cdot (\rho_{avg,ref} / \rho_{avg}) \cdot (m_{loop} / m_{loop,ref})^2 \cdot (Q_{Rx,ref} / Q_{Rx})^2$$

ρ_{avg} = average coolant density around loop

$\approx P/2R_{He} \cdot (1/T_h + 1/T_c)$

An additional adjustment would also be required if the number of loops is different in the reference concept and the alternate concept of interest. The impact of the number of loops on the primary circuit pressure drop is minor since the core dominates the pressure drop. However, it would be significant for the secondary circuit.

The same relationship is used to calculate both the primary and secondary circulator powers. In doing so, the densities, loop flow rates, and reference parameters are taken for either the primary or secondary loop as appropriate.

Having calculated the circulator power, it can be used to assess the circulator success probability based on the data presented previously.

4.8.3 Constraint Due to Core Design Feasibility

Next the temperature constraint necessary to ensure core design feasibility is provided. This constraint states the impact of potential inlet and outlet temperature combinations on core design feasibility. Specifically, the probability that the core designers will be able to develop a suitable core design which meets fuel temperature constraints is estimated.

This evaluation is assumed to be independent of design power level as long as core geometry is adjusted as necessary for different power levels in order to maintain average power density and to ensure consistent conduction cool down performance.

The evaluation was performed by running an existing core hot channel model for a variety of different core inlet and outlet temperature combinations. The resulting peak fuel temperatures were evaluated to judge the likelihood that an acceptable design could be achieved to ensure acceptable fuel temperatures at the final design stage.

The results are presented Table 105 below in the form of probability of successful core design for each inlet/outlet temperature combination. For example, with an inlet temperature of 350°C and a core outlet temperature of 800°C, the confidence that an acceptable core design is feasible is very high (98%). Conversely, with an outlet temperature of 900°C and an inlet temperature of 450°C, the confidence that an acceptable core design could be achieved is only 43%.

Table 105. Core feasibility temperature constraint

Core Design Feasibility Matrix

T_{in} \ T_{out} °C	700	750	800	850	900	950
300	100	100	91	0	0	0
350	100	100	98	58	0	0
400	100	100	100	87	0	0
450	100	100	100	96	43	0
500	100	100	100	100	82	0
550	100	100	100	100	94	16
600	100	100	100	100	100	77

4.8.4 Overall Plant Risk Assessment

The preceding sections have developed the required relationships linking the key component parameters, the next step is to evaluate the overall plant success probability.

With the preceding parameter interrelationships established, it is possible to estimate the overall risk to project success schedule due to the major components based on the key parameters which define the plant. For the indirect steam cycle concept, these parameters include:

- Reactor power level
- Core inlet temperature
- Core outlet temperature
- System pressure
- Number of loops
- IHX approach temperature
- Vessel system material
- IHX material

Based on these parameters, the individual success confidence level can be calculated for the vessel, the IHX, the primary circulator, the secondary circulator, and the core design.

Various approaches can then be considered to integrate these individual success probabilities into an overall level of confidence in the success of the total plant schedule. The simplest approach is to simply take the product of the individual component probabilities, although that would generally be overly conservative. More sophisticated statistical approaches might be considered to specifically assess the uncertainty in project schedule. For example, a detailed evaluation of the best estimate schedule could be established for each component as a function of the relevant independent variables and the appropriate uncertainty bands determined. These could then be combined statistically to determine the overall best estimate project schedule and uncertainty range. This would provide a more realistic assessment of the actual confidence in meeting the 2018 startup target. However, such an approach is far beyond the scope of this task.

5.0 SAMPLE OVERALL RESULTS

Several potential plant configurations have been evaluated. The sample overall results are summarized in Table 105. These results should not be viewed in absolute terms, since they are based on a number of subjective parameters, and the supporting models are very simple. Nonetheless, the comparison of the relative values does provide interesting insights.

Note that in these cases the schedule risk associated with the secondary circulator was ignored. While the risk associated with this component is not negligible in some cases, it is not independent of the primary circulator risk, since many relevant concerns affect both components. Therefore, it would be overly conservative to include both terms in the product of the individual probabilities.

Hence, the overall success probability shown is simply the product of the individual success probabilities for the vessel, IHX, primary circulator, and core design, Table 107.

Case A represents the current AREVA NGNP reference design. The overall confidence is indicated to be only 18%. Several factors contribute to this, but the dominant one is the current risk perceived for a 9Cr vessel. This is largely driven by the need to obtain key forgings with the required heat treatment and the total amount of welding required in the context of the desired aggressive schedule.

Case B represents the same reference concept but with a 2.25 Cr vessel. The vessel risk is perceived to be reduced significantly. However, significant welding will still required, and the availability of the 2.25 Cr vessel has not been examined as thoroughly as for the 9Cr vessel. Therefore, the 2.25 Cr vessel risk might be understated compared to the 9Cr risk.
Case C again represents the same case but with a cooled SA533 vessel. This concept has somewhat higher risk due to increased complexity. It also would increase plant cost, maintenance issues, and operational concerns. Nonetheless, it could offer some benefits in controlling technology risk.

Cases D and E represent reduced temperature plant concepts with two different vessel options. While not providing full VHTR performance, these concepts are expected to result in reduced risk.

Case F is a lower temperature steam cycle plant. The plant still includes an IHX with a secondary gas loop between the IHX and steam generator. However, the operating temperatures are typical of a simple steam cycle plant. The vessel and core design risks are reduced to very low levels. A small IHX risk remains, but it is minimal at these low temperatures. Nonetheless, the design complexity of the IHX and secondary loop remain.

Case G is a conventional steam cycle plant without any IHX. Risk associated with the IHX and secondary loop is completely eliminated. The residual schedule risk is due almost entirely to vessel procurement issues rather than technology issues.

Of course, detailed assessment of specific candidate concepts will ultimately be required to quantify project risk more precisely.

Table 106. Summary of sample cases

Case	A	B	C	D	E	F	G
Case Description	Ref VHTR w/ 9Cr vessel	Ref VHTR w/ 2.25Cr vessel	Ref VHTR w/ Cooled 508 vessel	Moderate temp w/2.25 Cr vessel	Moderate temp w/cooled 508 vessel	Indirect Cycle Steam	Simple Steam Cycle
Power (MWt)	565	565	565	600	600	600	600
Core Tin (C)	500	500	500	400	400	350	350
Core Tout (C)	900	900	900	850	850	750	750
Vessel Material	mod 9Cr	2.25 Cr	cooled SA508	2.25 Cr	cooled SA508	SA508	SA508
IHX	tube 617	tube 617	tube 617	tube 617	tube 617	tube 617	NA
Primary Circ Power (MWe)	7.70	7.70	7.70	4.51	4.51	5.48	5.48

Table 107. Percentage success probabilities for 2018 schedule for above referenced case

Case	A	B	C	D	E	F	G
Case Description	Ref VHTR w/ 9Cr vessel	Ref VHTR w/ 2.25Cr vessel	Ref VHTR w/ Cooled 508 vessel	Moderate temp w/2.25 Cr vessel	Moderate temp w/cooled 508 vessel	Indirect Cycle Steam	Simple Steam Cycle
Vessel	30	70	60	70	90	90	90
IHX	80	80	80	90	90	90	NA
Primary Circulator	90	90	90	95	95	100	100
Secondary Circulator	100	100	100	100	100	100	NA
Core Design	82	82	82	87	87	100	100
Overall Success	18	41	36	52	67	81	90

6.0 CONCLUSION

The design feasibility of five major components of the NGNP reactor for start-up in 2018 has been qualitatively evaluated by an expert panel assembled by AREVA. The evaluation considered the performance of each component against the four main considerations, namely, availability, fabricability, qualification and codification. The results of this study indicated that the design feasibility of the NGNP reactor may be achievable for 2018 with the reactor operating within a defined operating range. However, if operation at very high temperatures is a mandatory requirement then there is significant risk for the 2018 schedule.

The expert panel also considered the effect of an extra three years on the availability, development, and design of the components. This highly subjective assessment assumed that funds for development work and design would be available to progress the feasibility of the component under consideration. In almost every case this extra three years increased the probability of success of the component and the operating envelope of the reactor as a whole compared to the 2018 date.

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7.0 REFERENCES

1. 12-9051191-001, NGNP Preconceptual Design Studies Report, 6/22/07.

2. 51-9072396-000, NGNP Conceptual Design Studies Baseline document for Indirect Steam Cycle Configuration, April 2008.

3. 12-9076324-001, NGNP RPV and IHX Pressure Vessel Alternatives.

APPENDIX A: R&D NEEDS

A.1 VESSEL MATERIALS

The information in this section is from Reference 1 (Section 19.2.2.1).

The primary candidate for vessel materials is Modified 9Cr1Mo steel. Alloy 800H is considered for internal materials. Modified 9Cr1Mo is also a candidate only if the temperature is kept well below 750°C. As for the IHX, superalloys such as In617 or Haynes 230 are candidate materials.

Mod 9Cr1Mo has already been used in conventional power plants and is also supported by significant R&D test results from past Fast Reactor R&D programs. An HTR ANTARES R&D program has already been started to complete the required input data for the final selection and the qualification program.

For Mod 9Cr1Mo steel, the R&D needs, of "High Priority," include mechanical properties on heavy section products (base and weld metal), effects of aging and radiation, corrosion in helium environment, weldability, emissivity, negligible creep conditions, and creep fatigue. A specific test program on representative plates and forgings (including welded joints) will be required for component qualification. It has been estimated that the qualification of Mod 9Cr1Mo will take approximately 72 months and $4M due to the need of procuring a large forging.

Mod 9Cr1Mo is covered by the ASME code up to 371ºC in Subsection NB and beyond 371ºC in Subsection NH. Subsection NH does not currently cover heavy section products and needs to be updated to cover specific aspects of Mod 9Cr1Mo. Actions have already been launched in the context of the DOE/ASME Gen IV material project to provide basis for code development. R&D efforts to support this codification should be continued.

A.2 COMPONENTS

The information in this section is from Reference 1 (Section 19.2.3)

R&D needs have been identified for the Circulators, IHX (Tube), and IHX (Plate) as follows:

- Circulators

  Circulators up to 4 MWe have already operated in HTR reactors. The test program is dedicated to component qualification during the commissioning phase rather than as an R&D task. Planned tests ("Low Priority") include:

  - Air tests of the impeller (at scale 0.2 to 0.4).
  - Helium tests of magnetic and catcher bearings.
  - Tests of the circulator shutoff valve.
  - Full scale integrated tests.

- IHXs

  The R&D inputs are based on two IHX concepts: Tubular IHX for 193 MWt power conversion and Plate IHX for 60 MWt loads for hydrogen plant loop.

  Small test facilities up to 1 MWt are available. Large test facilities of about 10 MWt will need to be designed and built (Risk D-015). It is estimated that it will require $20M and 30 months to build a 1 MWt test loop and $80 to $120M to build and test a 10 MWt test loop: $72M to $112M for the facility, $1M for the test article, and $7M for the test.

- Tubular IHX

  The Tubular IHX design is based on the extrapolation of past German experience. NGNP requirements lead to high temperature operation with an innovative secondary fluid mixture of helium and nitrogen. Feasibility concerns include module size, temperature level, corrosion / nitriding, manufacturing, and assembly, which are not state of the art).

  Tubular IHX R&D needs of “High Priority” include:

  - Tests to confirm fabrication feasibility (tube bending, tube welding, nozzles on hot header, ISIR and assembly, etc).
  - Corrosion and nitriding tests on base and coated materials in a representative environment.
  - Fabrication of representative IHX mock-ups from thermo-hydraulic and manufacturing point of views.
  - Testing in representative helium and helium-nitrogen environments is recommended.
  - The current plan is to use a full scale mock-up for component qualification. The need for intermediate testing on sub-scale mock-ups is deemed unnecessary provided that manufacturing issues are sufficiently addressed.

- Plate IHX

  The feasibility of the plate IHX is a concern and a reduced lifetime is expected. Primary concerns are temperature level, corrosion, manufacturing, and thermal-mechanical resistance.. The plate IHX R&D needs, which are “Medium Priority”,” include:

  - Development of visco-plastic model (material data-base to be completed)
  - Corrosion tests on base and coated materials in a representative environment
  - Development of manufacturing techniques (fusion welding, diffusion bonding, brazing and forming)
  - Tests on representative IHX mock-ups from both thermo-hydraulic and manufacturing point of views (diffusion bonding, brazing, ISIR).

  A three step approach is recommended for component qualification, these are:

  - Tests in air with sub-scale mock-ups
  - Tests in helium with sub-scale mock-ups (about 1 MWt test loop). These tests will provide a basis for recommendations on which type of concept should be used for the NGNP
  - Final qualification on a full scale mock-up (at least for the channels and the plates) on a large test facility (around 10 MWt).

APPENDIX B: ACRONYMNS

Acronyms:

AFS AREVA Federal Services

ASME American Society of Mechanical Engineers

Cr Chromium

DOE Department of Energy

EMB Electro Magnetic Bearing

He Helium

H_2 Hydrogen

HTR High Temperature Reactor

IHX Intermediate Heat Exchanger

JSW Japan Steel Works

Kg/s Kilograms per second

m Meters

m^3 Cubic meters

MHC Main Helium Circulator

Mod Modified

mm Millimeters

MPa Mega Pascals

MW Mega Watt

MWe Mega Watt Electric

MWt Mega Watt Thermal

N_2 Nitrogen

NA Not Applicable

NGNP Next Generation Nuclear Plant

PCS Primary Control System

PHTS	Primary Heat Transfer System
Pout	Outlet Pressure
RPV	Reactor Pressure Vessel
PWR	Pressurized Water Reactor
R&D	Research and Development
Tout	Outlet Temperature