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NGNP with Hydrogen Production IHX and Secondary Heat Transport Loop Alternatives

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		p. 43	Clarification on welding process
		p. 174	Paragraph deleted
		p. 207	Table title clarified
		p. 208	HTS configuration matrix for direct steam cycle added
		p. 219 to 222	Table numbering corrected and Table 5-19 added
		p. 223	Total plant cost reduction corrected
		p. 240 to 241	Appendix B added

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1.0 INTRODUCTION

This study is carried out in the context of the Next Generation Nuclear Plant (NGNP) project. It follows activities carried out in 2007 during the preconceptual design studies and is aimed at providing additional information to support the selection of key parameters and technologies for the NGNP (e.g., reactor power, gas outlet temperature, IHX design and materials, etc).

This study will characterize the advantages and disadvantages and technical risks of the potential alternatives for the intermediate heat exchangers (IHXs) to Power Conversion System (PCS) and H_2 plant, secondary heat transport loop to PCS and Steam Generator Unit, including materials, design configuration, fabrication, operation, maintenance, in-service inspection, and means for periodic replacement. The study will also provide specific recommendations for the IHX design(s), primary and secondary loop configurations, SGU design and materials.

The report is split into 3 sections:

- IHX design alternatives
- Material alternatives
- Heat Transport System (HTS) configuration

The study also considers the impact of varying NGNP design and initial operating conditions (power level, core inlet and outlet temperatures, primary pressure) on the conclusions of the evaluations.

2.0 BACKGROUND AND ASSUMPTIONS

The Preconceptual Design Studies Report (PCDSR, ref. 20) was prepared based on the Combined Cycle Gas Turbine (CCGT) concept adopted by the ANTARES project. A configuration was proposed using multiple tubular IHX with the objective of providing at the same time electricity and very high temperature heat. It was however acknowledged that the steam cycle could be the best path forward for near-term deployment of HTRs.

The present study is primarily based on the indirect steam concept which differs from the conventional steam cycle concept by the addition of an Intermediate Heat Exchanger between the Nuclear Heat Source (NHS) and the Steam Generator (see figure 2-1). The study is performed as previously assuming direct production of Helium at very high temperature (900-950°C) to feed a H_2 production facility. The Trade Study on Primary and Secondary cycle concept (ref. 119), carried out in the context of the Preconceptual Design Studies, recommended IHX in parallel and this option is still considered as valid.

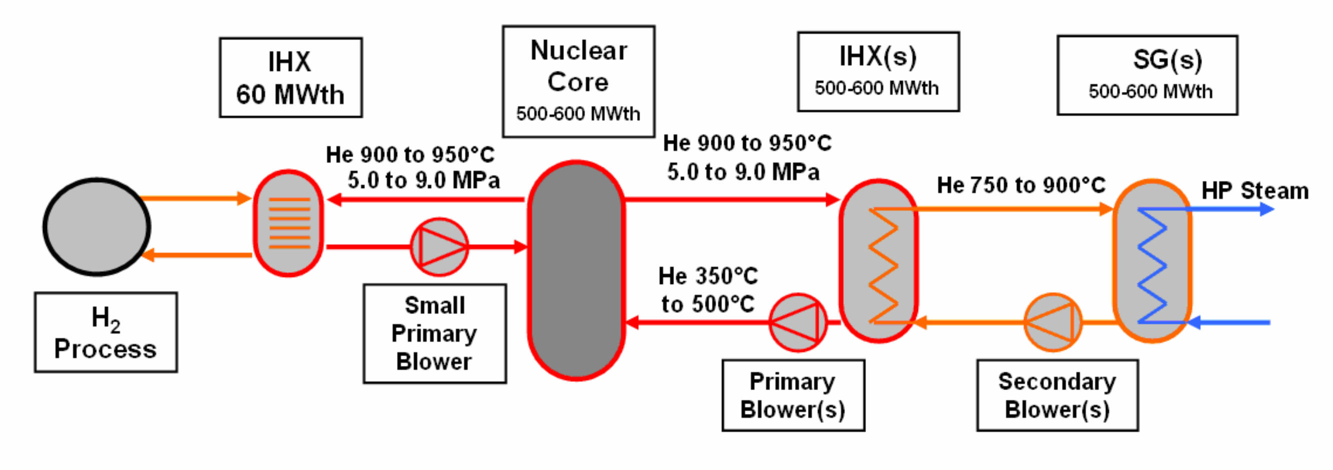


Figure 2-1 NGNP configuration considered in this study

The main aspects of this configuration are:

- The large power loop (500-600 MWth) is dedicated to the production of High Pressure steam for electricity production. Heat is transferred from the NHS to a secondary circuit through IHX(s). In case of the use of the tubular IHX concept, a two or three loop design could be envisioned

- The intermediate circuit between the IHXs and the SGUs provides an additional confinement barrier as compared to a configuration in which the SGUs would be directly connected to the NHS. It is remarkable that in this configuration, the transients that the IHX has to withstand at secondary side are smoothed as compared to the CCGT (Combined Cycle Gas Turbine) option.

- One test scale IHX (60 MWth) is dedicated to an experimental loop including a hydrogen production unit. This loop is also seen as a way to experiment an innovative concept of IHX like a metallic plate type IHX. A reduced lifetime of 5 years of operation is considered as acceptable for this IHX due to the low availability expected for this test loop.

- Helium is used in primary and secondary circuits. This allows high thermohydraulic performances for the IHX thanks to the good coolant properties of Helium as compared to other gases. In addition, the use of Helium eliminates the nitriding problem that appears when using a Helium/Nitrogen mixture at secondary side for the CCGT option.

One important assumption in carrying out this work and in particular the Heat Transport System configuration study is the objective of beginning initial operation of NGNP in 2018.

3.0 IHX DESIGN ALTERNATIVES

3.1 Scope of work

This work is aimed at comparing the characteristics and development requirements for the candidate IHX designs. This comparison will include shell and tube, plate-fin, compact and other potential heat exchanger designs.

This work will be performed in two steps. The first step will identify the different concept alternatives and will provide a comparison table.

Based on this evaluation, two concepts will be selected and a comparison will be performed on the following factors:

- Current state-of-the-art and the steps necessary to extend the state-of-the-art to meet NGNP requirements
- Status and current planning for design, lab-scale, pilot-scale, and engineering-scale testing of the candidate designs
- Fabricability issues
- Operational issues
- Maintainability of modules or entire heat exchanger
- Replaceability of modules or entire heat exchanger
- Ability to detect leak or material failures and the consequence of leak or material failures during operation
- The impact of environmental effects (e.g., potential for dust clogging, accumulation, erosion and fouling, Tritium transfer)
- The identification of required in-service-inspection requirements and the impact of these requirements for each design and the practicality in meeting those requirements
- Required material strength properties
- Risks.

For the initial NGNP configuration the comparison should assume that the secondary fluid will be gaseous, (e.g., helium, helium/nitrogen). The work should also consider, however, the identification of alternative environments and will comment as to whether material compatibility issues should be expected.

This evaluation will finally evaluate as to whether each alternative would be compatible with a “two-stage” IHX design.

3.2 IHX concept alternatives

This study lists as extensively as possible the different concepts of IHX that could be envisioned for an application at high temperatures such as NGNP. A judgment is stated on the feasibility of each concept considering the range of operating conditions specified in section 2.

3.2.1 Tubular IHX

The tubular IHX concept consists of a helical coil tube bundle. Even if being a first of a kind for a large scale HTR, tubular heat exchangers are already used in conventional industries and benefits from a significant test experience in nuclear industries namely:

- Tests of a 10 MWth mock-up (He/He) in the KVK facility in Germany by INTERATOM in the frame of the PNP project. This mock-up was coupled to a conventional heat source reaching outlet gas temperatures of up to 950°C.

- Operation of a 10 MWth IHX (He/He) in Japan by JAERI. This IHX was coupled to the HTTR nuclear reactor reaching outlet gas temperatures of 850°C for normal operation and up to 950°C for a limited duration.

The current state of the art is estimated to be around 150 MWth (with an approach temperature of around 50°C) but could be extended to NGNP conditions with a 2 or 3 loop design.

Alloy 617 is the preferred candidate for this concept in order to benefit from the German experience. With this alloy, it is however considered that a corrosion risk by impure helium exists at primary and secondary sides, due to expected operation at 900°C and above. Nevertheless, the tube wall (about 2 mm) is the thickest as compared to the other concepts which makes this concept comparatively less sensitive to corrosion.

As regards thermomechanics, the tube bundle design is the most favorable to accommodate the thermal expansion and to spread the gradients over long lengths. But with temperatures of 900°C or 950°C, the limits of the material resistance with respect to creep will have to be checked.

The tubular IHX is the most feasible concept to transfer the heat to the Power Conversion System.

3.2.2 Metallic compact IHXs

Plate type IHXs are seen as the most promising compact IHXs concepts. From the thermohydraulic point of view, 600 MWth can be housed in a single pressure vessel.

Metallic plate type IHXs are used as "class 3" components in many nuclear applications but the technology and the materials are not the same as those required for applications at high temperatures. There is no commercial plate type IHX for high temperatures (≥650°C which requires the use of high temperature nickel base alloys) in operation today but numerous developments are carried out in the conventional industries. So, their manufacturability and their ability to withstand the pressure and thermal loads as well as the corrosion by impure Helium during a significant lifetime at high temperatures have to be demonstrated.

For NGNP, the 60 MWth test loop is seen as a way to start operating with an innovative metallic plate IHX at low power.

Each concept consists of elementary modules disposed in a pressure vessel with an arrangement depending on the concept. Each module is composed of a stacking of plates between which the primary and secondary fluids flow in channels. The hydraulic diameter of these concepts is relatively small (the larger being 2.6 mm for the Plate Stamped Heat Exchanger) which enables high heat transfer coefficients.

The modules are radially arranged in the IHX pressure vessel around a central pipe which collects the hot secondary gas (hot center).

Remark: Due to the concept of using a set of elementary modules, it is not obvious that a 60 MWth IHX is much more feasible than a 600 MWth IHX. The simplest approach to reduce the overall power is to reduce the number of modules but each of them operates independently, so that the difficulties remain unchanged. On the other hand, housing a smaller power in the pressure vessel allows some design modifications of each module which will be investigated further.

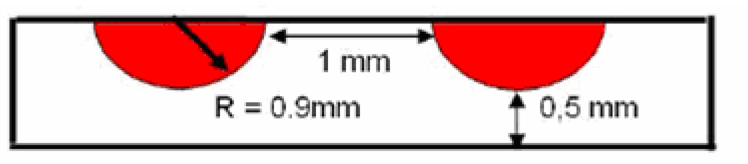
Two candidate alloys have been selected for these concepts, namely Alloy 617 and Alloy 230.

Details about each concept are given thereafter.

3.2.2.1 Plate Machined Heat Exchanger (PMHE)

The plate type IHX PMHE concept is based on the assembling of nickel alloy plates. The plates (thickness of about 1.4 mm) are provided with channels machined using high speed machining, electrochemical etching or chemical attack. The plates are then assembled using diffusion bonding to make a module.

The geometry of a plate is shown hereunder



Tests have shown that obtaining a satisfying geometry is difficult due to the complexity of providing the precise shape of the channels with the selected processes (mechanical, electrochemical or chemical etching). Keeping the inter channel surface plane enough for diffusion bonding is also challenging.

Besides, due to the high pressure used in the diffusion bonding phase, the shape of the channels undergo some additional deformations.

On the mechanical point of view, the stiffness provided to each module by the diffusion bonding assembly leads to high stress levels induced by thermal deformations during normal operation. Therefore, it is considered as very challenging to bring down these stresses by design improvements to values compatible with a prolonged utilization at high temperatures, even for 5 years of operations.

3.2.2.2 Plate Fin Heat Exchanger (PFHE)

Several concepts of PFHE have been studied. Both of them consist of a set of modules, each of them composed of a stacking of plane plates separated by fins that provide channels and improve the heat exchange. Several options are proposed for the fins design including wavy, straight or serrated fins. The fins are brazed on the plates for both concepts.

The fins thickness (≤0.2 mm) is regarded as a serious concern regarding corrosion by impure Helium. It is reckoned that the whole thickness of the fins would be subject to internal oxidation after a limited lifetime if no coating is applied on the material.

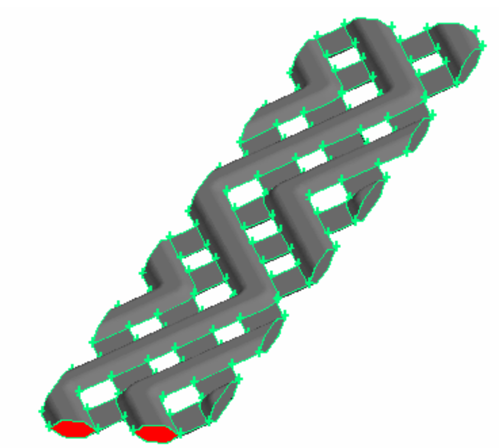
In addition, some difficulties have been encountered regarding brazing of the fins onto the plates.

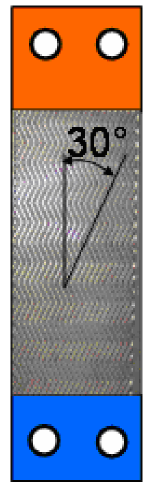
Lastly, as well as for the PMHE concept, the stress levels calculated do not seem to be compatible with the expected lifetime and temperatures.

For these reasons, the PFHE is not seen as a promising concept for NGNP.

3.2.2.3 Plate Stamped Heat Exchanger (PSHE)

The PSHE concept consists of a set of modules, each being composed of a stacking of plates stamped with corrugated channels. The plates are stacked in such a way to cross the channels of two consecutive plates and, therefore, to allow the different channels to communicate through the width of the plate as shown on the left below. A general view of a plate is shown hereunder.





The assembly of the plates together is performed by welding on the edges of the plates only. No joint is performed in the active part of the plates, which gives to the module a relatively good flexibility. Therefore, this concept accommodates the thermal stresses better than the two other concepts of plate IHXs.

However, the stress levels with the current design are still too severe to justify even a lifetime of 5 years. Design improvements are needed and seem possible in order to reduce the thermal stresses notably.

The location of the welded joints is also favourable to inspection, even if this remains a difficult question.

The welding process which seems to be the most relevant is laser due to its capability to perform narrow-gap joints and, therefore, to avoid the overlapping of the welds of two consecutive plates. Laser welding still require development for such an application but other processes could be envisioned if optimisation of laser is not successful.

Lastly, the thickness of the PSHE plates is the largest among the metallic plate type IHX (1.5 mm) which means that it is the most favourable concept regarding material resistance to corrosion issues.

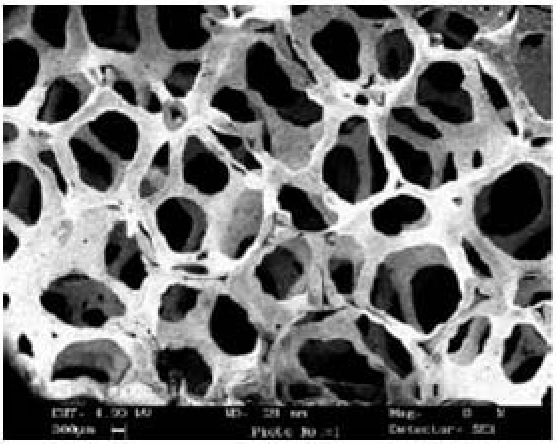
These reasons lead to consider the PSHE concept as the most promising among the plate IHXs, even if challenging design improvements are still needed.

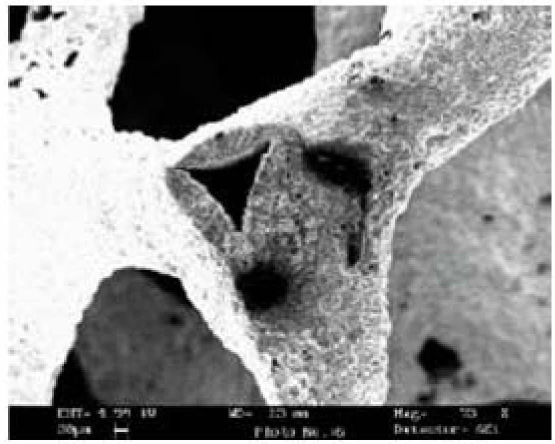
3.2.3 Innovative concepts

This part concerns some particularly innovative concepts of heat exchangers. Therefore, the technical risk linked with the important development effort requested for each of them is considered as high.

3.2.3.1 Foam IHX

The concept is based on a stacking of plates separated by metallic foam. The barrier between the fluids is constituted by the separated plates and the fluids flow through the foam. It is a new technology for heat exchanger application.





Several concerns have been identified regarding this type of IHX concept:

- The pressure losses induced by the foam are particularly high.
- The loss of small fragments of the foam is hardly avoidable.
- The geometry of the foam leads to an increased risk of clogging by graphite dust.

Besides, the performance increase that was expected from the foam has not been clearly proven.

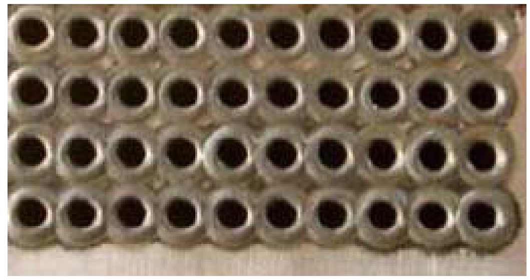
To conclude, this concept seems to present too many issues to support NGNP operation in 2018.

3.2.3.2 Capillary IHX

A "conventional" concept with thread tubes between two tube-plates with external shell including bellows has been investigated. The diameter of the tubes is of 2 mm to 3 mm.

This kind of heat exchangers is currently being developed at industrial scale. The small size of the tubes allows a compactness gain but some difficulties arise at the same time:

- The vibration risk is increased so that the supporting system shall be very performing.
- The number of tubes reaches very high values, which notably increases the complexity of the manufacturing and the cost of the IHX. Notably, assembly by narrow gap welding is required.
- The technological works are mainly based on technological feasibility tests like tube to tube-plate by laser techniques. The results confirm the feasibility for limited thickness of the plate (small mock-up shown here under).



An open issue could be to adopt a new technology based on two networks of thread tubes flooded in a material , like a melted material or a powder compacted by HIP (Hot Isostatic Pressure), and the collectors are drilled.

But the maturity of this concept seems too weak to support NGNP operation in 2018.

3.2.4 Ceramic IHX

The development of IHXs made of ceramic is still at the research stage. The UNLV (University of Nevada, Las Vegas) and the CEA notably are working on this innovative concept.

Ceramic development are either tubular or plate IHXs (mostly PFHE for the ceramic plate IHXs). Their resistance to aggressive environment is remarkable and they can operate at very high temperatures such as 1000°C. But the fragility of ceramic makes this concept difficult to design so that it is not seen as mature enough to support NGNP operation in 2018.

3.2.5 Comparison of IHX concepts

The following table provides a high level comparison of the different IHX concept alternatives.

	Maturity	Stress behavior	Sensitivity to corrosion	Compactness
PMHE	Numerous developments in conventional industry	High stress levels. 5 years lifetime seems very challenging	Sensitive	26 MW/m^3
PFHE	ditto	High stress levels. 5 years lifetime seems very challenging	Very sensitive	24 MW/m^3
PSHE	ditto	Challenging but best stress accommodation among the plate IHXs	Sensitive	35 MW/m^3
Tubular IHX	Industrial components in operation	Limit of state of the art	Better than plates but still sensitive	0.4 MW/m^3
Foam IHX	R&D	No results	Very sensitive (loss of fragments risk)	Comparable to other plate IHXs
Capillary IHX	Industrial developments	No results	Very sensitive	Better than classical tubular IHX
Ceramic IHX	R&D	Difficult design because of fragile behavior	Resistant	Comparable to other plate IHXs

The tubular IHX concept is the one which is considered as the most robust and mature at the same time. Design adaptations are required to use this concept for NGNP in a 2-or 3-loop configuration but development seem to be consistent with 2018 start-up. The tubular IHX concept is recommended for the IHX to PCS.

Among the plate IHX, the PSHE concept is considered as the most promising. Therefore, this concept is recommended for the 60 MWth test loop of NGNP. It is however underlined that some challenging design improvements are still needed for this concept to support NGNP operation by 2018.

Based on this pre-evaluation, sections 3.4 and 3.5 provide additional assessments of the tubular and PSHE concepts. Section 3.3 provides the status of current testing.

3.3 Status and current planning for testing of IHX concepts

The purpose of this section is to report various tests on IHX candidate designs. There are numerous tests/researches taking places regarding IHX designs whether tubular designs or compact plate-type designs. The tests are design, lab-scale, pilot-scale or engineering-scale type. This document take a look at what kinds of tests are performed, what the results are, what the future plans are if any etc.

This section provides a summary of component testing in a first part, then summarizes tests carried out in the context of manufacturing feasibility.

3.3.1 Component testing of Tubular IHX

There are a couple of facilities that have tested tubular IHXs. One is KVK test facility in Germany and the other is JAERI (Japan Atomic Energy Research Institute) test facility in Japan.

3.3.1.1 KVK Test Facility

Tubular IHXs were tested in the KVK facility in the context of the PNP project. Two types of tubular intermediate heat exchanger were studied during 1985 – 1988. One was the helical-tube IHX and the other was the U-tube IHX. The IHXs were representative of 125 MW thermal power and delivered secondary side helium of 900°C at 40 bars. The helical-tube IHX was tested for a period of 5200 hours while the U-tube IHX was tested for more than 4000 hours. Specific tests were also carried out on the hot header of the helical-tube IHX. The components were tested in steady state operation and transient conditions. Following describes detailed tests and their results for each component.

3.3.1.1.1 Helical Tube IHX

The helical-tube IHX was fabricated by Steinmuller/Sulzer consortium and was tested between October 1986 and June 1988 for a period of 5200 hr whereof 2200hr at 950°C. Operating data and materials are shown in Figure 3-2.

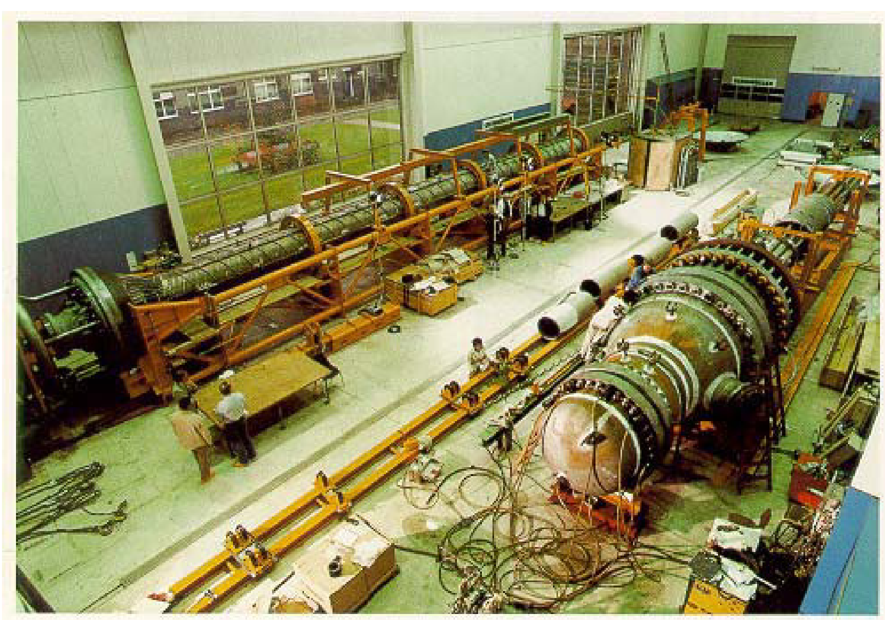


Figure 3-1 View of 10MWth Mock-up for KVK Facility

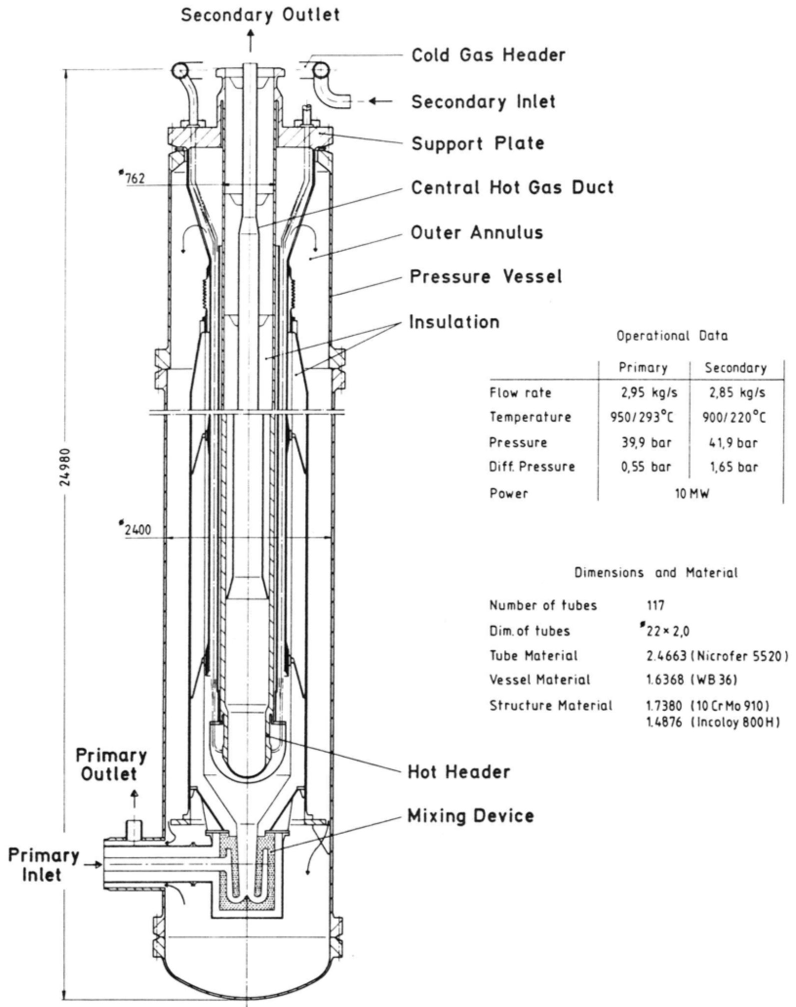


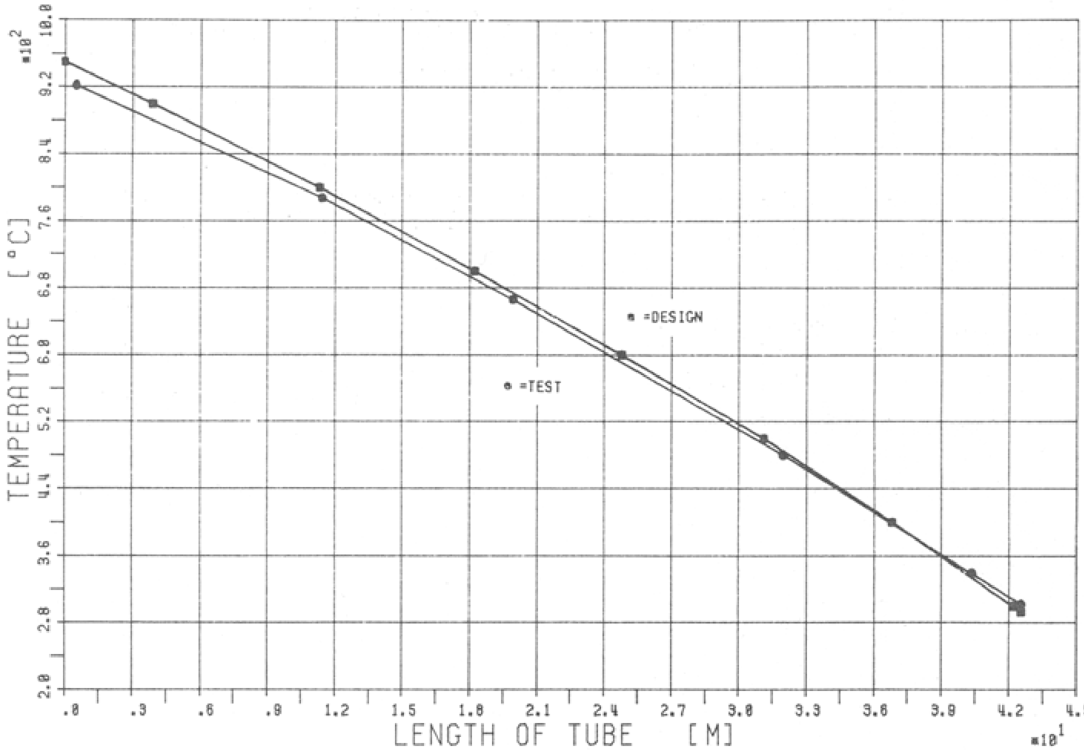
Figure 3-2 Helical Tube IHX

The heated gas (950^{o}C) enters into the primary inlet at the bottom of the IHX, passes the mixing devices and heats up the cold tube bundle in upward counter flow. The primary outlet temperature is 293^{o}C. The hot header is located further down compared to the U-tube IHX and is shielded with thermal shock sheet from sudden fluctuation of the temperatures. Conversely, the cold (200^{o}C) helium enters into toroidal shape gas header and gets heated to 900^{o}C at the outlet. The tested IHX has 117 helical tubes with a length of 43m. Many experiments were done with the IHX and Table 3-1 shows the list of tests performed. The materials that were used for the IHX is alloy 800H and Nicrofer 5520 (Ni-based alloy) for the exchange tubes.

Table 3-1 Various Testing

Experiment		% Power	Temperature
Stationary	Startup	40-100%	Up to 950°C
	Min. Power	30%	950°C
	Max. Power	105%	950°C
	Long-term testing at nominal load	100%	950°C/200hr
	Long-term testing at partial load	40%	950°C/300hr
cyclic	Startup/Shutdown	0-100%	950°C 1K/min
	Long-term operation (200 cycles)	40-100%	No details provided
	450°C-900°C-450°C, 1hr holding	No details provided	5K/min
Accident	Quick change of primary inlet temperature	100%	950°C-750°C

The Table below shows the results obtained from the Helical tube testing with various conditions (see above table). The temperature profile of the tube bundle illustrates that the empirical data and calculated data are very consistent each other. Also, the inlet and outlet temperatures and pressures, flow rates and heat transfer values are close between the empirical data and the calculated data.



PRIMARY HELIUM TEMPERATURE PROFILE OF THE HELICAL HEAT EXCHANGER

LOAD 100 %		PRIMARY SIDE DESIGN	PRIMARY SIDE TEST	SECONDARY SIDE DESIGN	SECONDARY SIDE TEST
TEMPERATURE	[°C]				
• INLET		950	951	220	221
• OUTLET		293	295	900	907
PRESSURE	[bar]	39.9	40.1	43.6	43.7
PRESSURE DROP	[bar]	0.16	0.15	1.67	1.28
MASS FLOW RATE	[kg/s]	3.00	3.01	2.90	2.90
HELIUM VELOCITY	[m/s]	14.7	14.6	56.9	56.3
OVERALL HEAT TRANSFER		DESIGN		TEST	
COEFFICIENT	[W/m² K]	526		538	
HEAT TRANSFER	[MW]	10.24		10.28	

Table 3-2 Results of helical heat exchanger testing

3.3.1.1.2 U-Tube IHX

The 10 MWth U-tube IHX made by Balcke-Durr has been tested between April 1985 and April 1986 for a period of 4700 hr whereof 1500 hr at 950°C.

The cross-sectional view of the basic design is shown below.

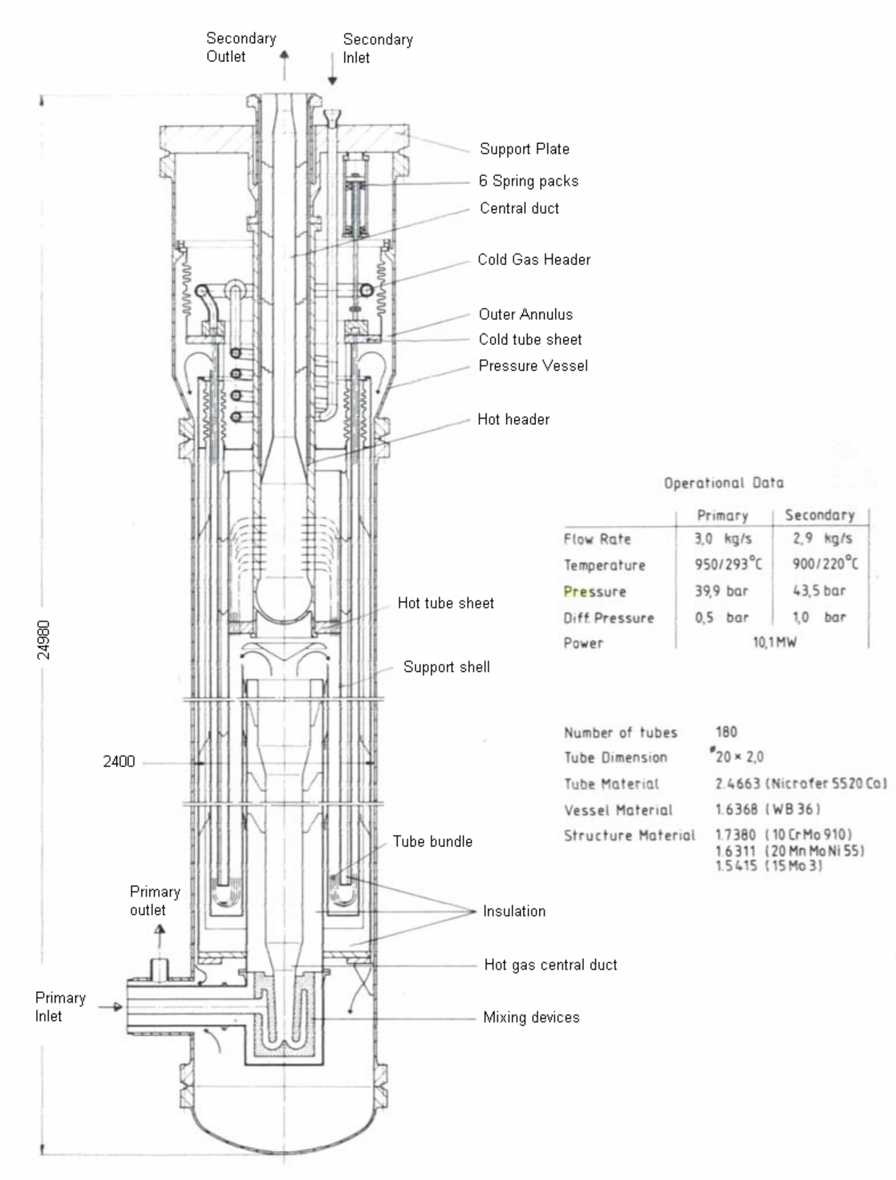


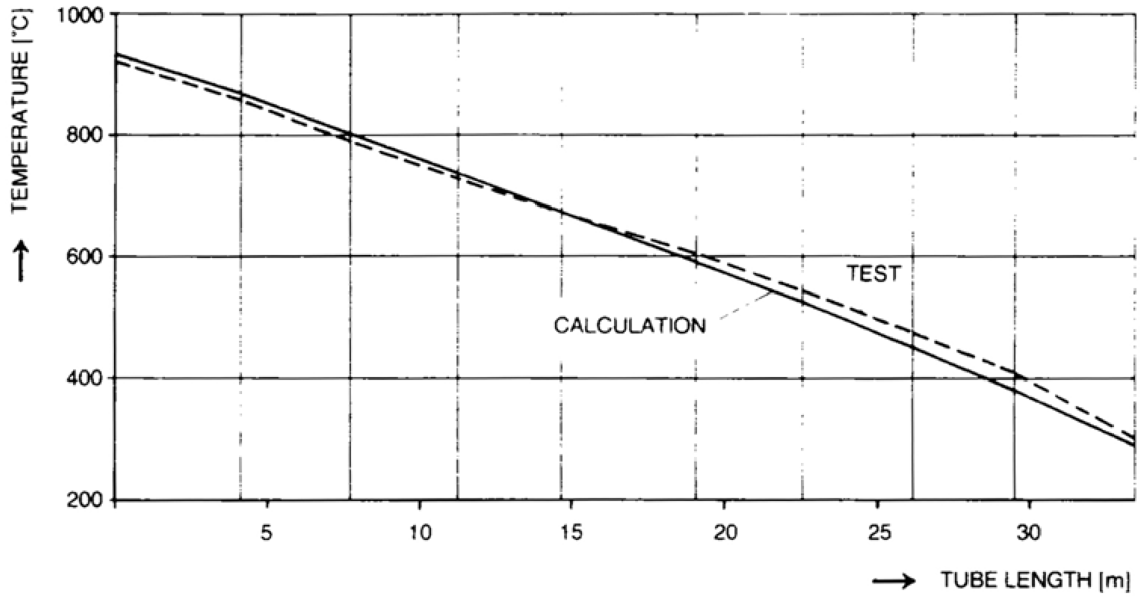
Figure 3-3 U-Tube IHX

Similar to the helical tube IHX, the heated gas of 950°C enters the bottom of the IHX, runs through the hot gas central duct and heats the cold tube bundles (220°C inlet temperature) in counter flow at the annulus region. Since the IHX vessel wall sees much cooler temperature (about 293°C), this configuration allows to use conventional a low alloy, high temperature steel for the vessel material. 180 tubes are arranged in the six flow channels which are equally disposed over the circumference. A range of tests have been done on the U-tube IHX and a table below describes the details.

Table 3-3 Various Testing for U-tube IHX

Experiment		% Power	Temperature
Stationary	Startup	25-100%	Up to 950°C
cyclic	Starup/Shutdown	0-100%	950°C 1K/min
	Change of He mass flow	No details provided	No details provided
	650°C-950°C-450°C, 1hr holding	No details provided	No details provided
	Hot standby and hot start-up at nominal load	No details provided	No details provided
Accident	Fast temperature decrease	No details provided	50K/min
	Fast temperature cycles	No details provided	+/- 5K/min
	Fast reduction of He mass flow	No details provided	No details provided
	Depressurization (5bar/s)	No details provided	No details provided

The Table below shows the results obtained from the U-tube testing with various conditions (see above table). The temperature profile of the U-tube bundle illustrates that the empirical data and calculated data are very consistent each other. Also, the inlet and outlet temperatures and pressures, flow rates and heat transfer values are close between the empirical data and the calculated data.



TEMPERATURE PROFILE OF THE U-TUBE HEAT EXCHANGER

LOAD 100 %		PRIMARY SIDE DESIGN	PRIMARY SIDE TEST	SECONDARY SIDE DESIGN	SECONDARY SIDE TEST
TEMPERATURE	[°C]				
• INLET		950	950	220	217
• OUTLET		293	306	900	894
PRESSURE	[bar]	39.9	40.0	43.6	43.3
PRESSURE DROP	[bar]	0.50	0.40	1.0	0.86
MASS FLOW RATE	[kg/s]	3.0	2.97	2.9	2.71
HELIUM VELOCITY	[m/s]	17.6	17.5	45.6	42.6
OVERALL HEAT TRANSFER		DESIGN		TEST	
COEFFICIENT	[W/m² K]	446		442	
HEAT TRANSFER	[MW]	10.24		9.53	

Table 3-4 Results of U-tube heat exchanger testing

3.3.1.1.3 Hot Header

The cylindrical hot header is the highest loaded component. This component is directly related to the safety because it has to assure the primary loop tightness after the design accident (e.g., the rupture of the secondary loop duct). To investigate the structural integrity of the header during the normal and accident conditions, a full size header (170 MWth) was built and installed in a different set (i.e., stand-alone mock-up set) and three tests have been performed.

- Creep buckling tests of the first-time inserted
- Creep fatigue tests by temperature cycles to realize a material fatigue equivalent to 140000 hr of the reactor operation
- Creep buckling tests with fatigued structure material

The main data of the three steps are summed up in the table below.

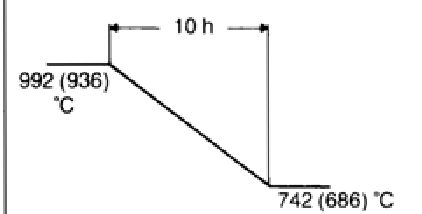
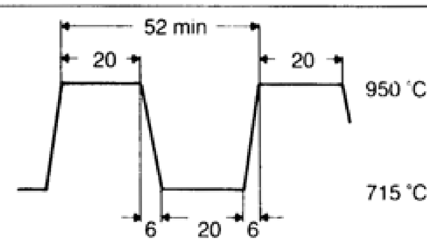
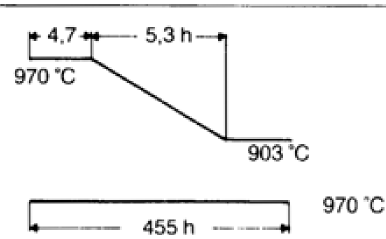
	T [°C]	Δp [bar]	$\dot{T}$ [k/min]	
CREEP BUCKLING TEST	936 ↓ 686 992 ↓ 742	43 43	− 0,42 − 0,42	
FATIGUE TEST (656 Cycles)	950 ↓ 715 ↓ 950		± 40	
CREEP BUCKLING TEST	970 ↓ 903 970	43 43 40	0 − 0,21	

Table 3-5 Hot Header Main Test Parameters

Creep Buckling Tests with Non-Fatigued Material

First, the test component had already been pre-deformed during its fabrication to an ovality of about 1% to enforced the starting condition for the creep buckling process. The hot header was heated up to 936°C and was exposed to pressure difference of 43 bar for 10 hr. During the period, the temperature of the helium was decreased from 936°C to 686°C. The deformations during the test have been recorded at 6 different locations. With a little higher temperatures (from 992°C to 742°C), 2nd creep buckling tests have been performed in similar fashion. Following photo is a hot header after the creep buckling tests. The results are not available.

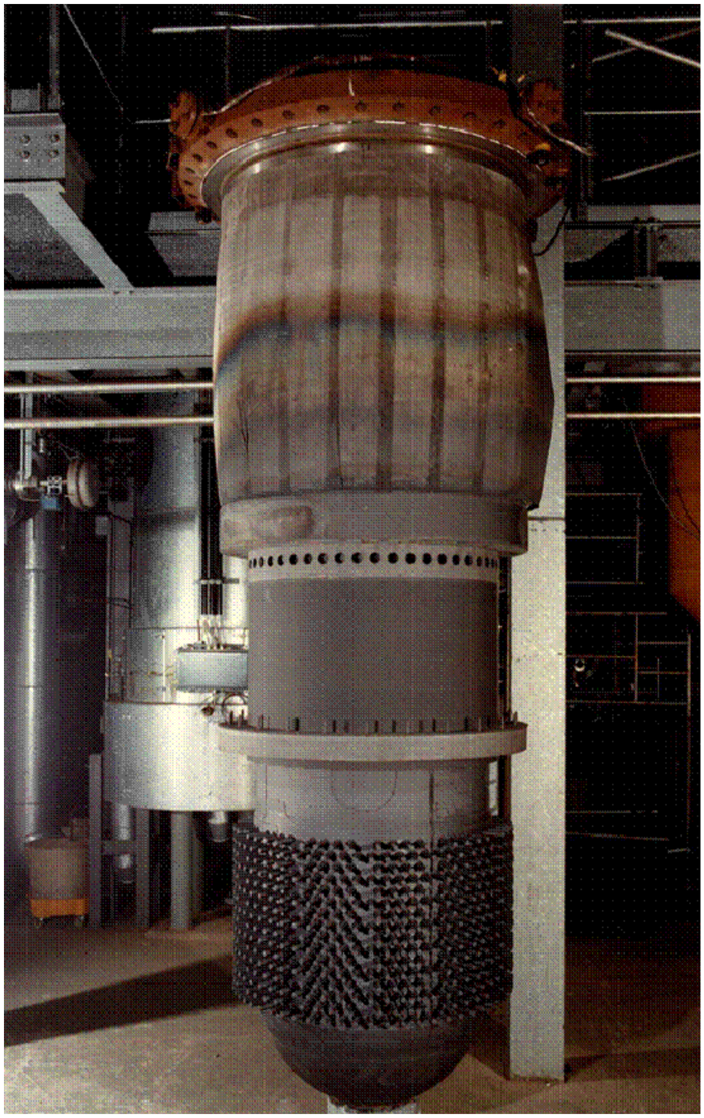


Figure 3-4 Hot Header after Creep Buckling Test

Creep Fatigue Test

For this test, helium was run from top of the test vessel and exited through the 864 tube nipple penetrations during fall 1984 and the end of 1985. A total of 656 temperature cycles (See above table for the fluctuations) have been performed. The temperatures was decreased from 950 °C to 715 °C with 40K/min then held constant fro 20 min and the temperature was increased to 950 °C with 40k/min then held constant for 20 min. The data has been collected during that period. The results are not available.

Creep Buckling Test with Fatigued Material

For this test, at a helium temperature of 970°C and a pressure of 43 bar, the hot header has been depressurized after 5 hours. Then, it was cooled down to 903°C over 5.3 hr. After that, the header went through another round of depressurization with longer period 9455 hr). After that, the test object was further examined for creep buckling with 970 °C and a constant pressure difference of 40 bar during a period of 455 hr. The results are not available.

3.3.1.2 HTTR / HENDEL

The HTTR (High Temperature Testing Reactor) reached first criticality in November 1998, full power at 850°C in December 2001 and high temperature at 950°C in April 2004 (Ref. 120). One of the HTTR's key high temperature components is an IHX. The IHX is a 10 MW vertical counter flow type heat exchanger much like the KVK helical IHX type. This IHX was coupled to the HTTR nuclear reactor reaching outlet gas temperatures of up to 950°C. The general cut-out view of the IHX is shown in Figure 3-5.

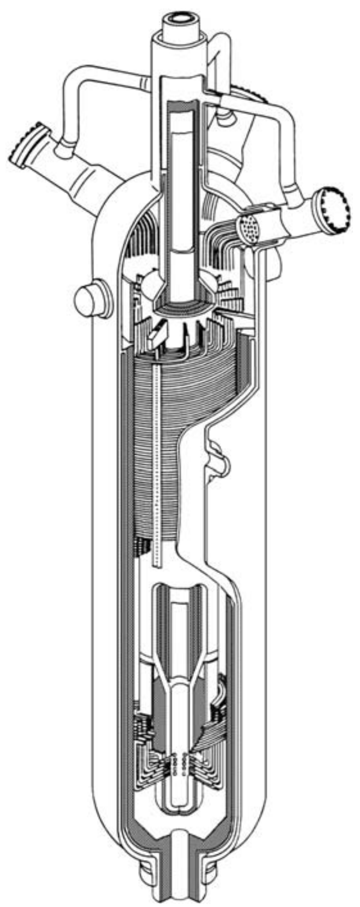


Figure 3-5 JAERI Tubular IHX Design

Other noteworthy parameters are tabulated in Table 3-6 below.

Table 3-6 JAERI Tubular IHX Parameters

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

Several experimental and analytical studies (Ref. 121) were carried out to confirm the structural integrity of the IHX. The five tests are as follows:

1. creep collapse of the tube against external pressure
2. creep fatigue of the tube against thermal stress
3. seismic behavior of the tube bundles
4. thermal hydraulic behavior of the tube bundle
5. in-service inspection technology of the tube.

3.3.1.2.1 Creep collapse of tube against external pressure

A test of creep collapse of the tube against external pressure (4 MPa) and high temperature was performed due to postulated depressurized secondary circuit. A test tube of 2-4mm thick and 400mm in length (31.8 mm OD) was exposed to a pressure of 5-6 MPa at 950°C. It has shown that the collapse times are proportional to the thickness of the tube. It also showed that the collapse time became shorter with initial ovality increased and wall thickness decreased. A FEM model using a Norton-type creep constitutive of Hastelloy XR confirmed that the FEM model reasonably predicted the collapse time. Although many cracks were observed on the surface of the collapsed tubes, the leak tightness was maintained.

3.3.1.2.2 Creep fatigue of tube against thermal stress

Since the lower connecting tube would be subjected to thermal stress caused by the difference of thermal expansion and temperature between the hot header and the tube, a test was done to the weld conjunction. A full scale mockup, composed of hot header and several tubes representing the lower sections of different angles, was simulated for the thermal expansion at high temperature (950°C). The center pipe was moved such as to simulate thermal expansion stress @ 950°C. The displacement between the hot header and the support, the displacement rate and holding time at the maximum displacement were 50mm, 120mm/hr and 10 min, respectively. The test was run more than 10000 times. Obviously, the test was more severe than the actual operating conditions and a crack was observed at the welding position between the stub and the connecting tube. Also, a fracture was discovered at the parent material of the lower elbow. With the obtained data, a Garofalo type creep constitutive equation is established. The results from a FEM model using the above mentioned constitutive equations showed that there were significant differences between the predicted and experimental life time (10-100 times of safety factor). Therefore, it is concluded that using such constitutive equations are very conservative compared with the experimental results.

3.3.1.2.3 Seismic behavior of tube bundle

The seismic test was carried out using a partial model of the tube bundle to focus on examining the vibration behavior induced. A partial tube bundle of 54 tubes was shaken to the estimated strongest earthquake for the HTTR. The analytical results gave very good agreement with the experimental ones despite amplitude of input acceleration.

3.3.1.2.4 Thermal hydraulic behavior of tube bundle

An experimental study was performed to investigate the flow-induced vibration of the tube bundle due to the flow velocity of the tube and the heat transfer characteristics on forced convection of outside of the tube and radiation by radiative plates. The same partial model with 54 tubes was used for this test. No abnormal vibration was observed in the test conditions. Also, it was concluded that the radiative plates have the advantage of promoting heat transfer despite the increase of pressure drop.

3.3.1.2.5 In-service inspection technology of tube

An in-service inspection (ISI) of the tubes was carried out with eddy current testing (ECT). This is to detect the discontinuities in the base metal as well as the welded joints. The ECT probe has a differential and self-induction type of coil arrangement because it is required to travel in helically coiled tubes and this design reduces the influence of the curvature of the tubes. The test results showed some discrepancies between the actual depths of discontinuities and the ECT probe data. The test results showed the predicted depths were different from the actual ones by about 18%. As for the welded joints, the inspection performance was lower (difference about 20 %) compared with the base-metal. Also, it is found that there are some small discontinuities undetected with this method. There were some rather significant discrepancies discovered between the actual data and the predicted ones. An improvement of the ECT on ISI seems necessary.

3.3.2 Component testing of compact IHX

Tests are being performed in the context of the RAPHAEL project (6^{th} European Framework program) on PMHE with stainless steel material in helium environment (HEFUS 3 loop in Italy) at high temperature (~500^{o}C). The purpose of the tests are to compare the data with previous collected data in air and to compare the performances with manufacturing predictions. There are two tests: hydraulic test and thermal test. The hydraulic tests measure pressure drop of inlet and outlet of IHX due to different mass flow rates. The object of this test is to determine a friction law as a function of Re number. The thermal tests measure inlet and outlet temperatures due to different mass flow rates. This is to establish a thermal law as a function of Re number. There are two groove types used: straight groove (hot side) and wavy groove (cold side). So far what is concluded is that it is feasible to carry out to determine hydraulic law with maximum mass flow (~0.1 kg/s). For thermal tests, working temperature has to be limited to get significant Re number at moderated DP. The test results are planned to come out at the end of April, 2008.

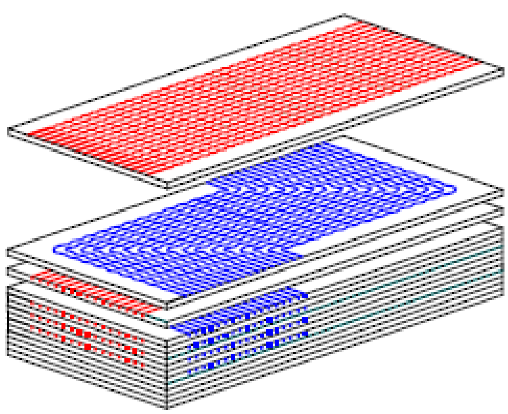


Figure 3-6 PMHE Mock-up Plate

3.3.3 Manufacturing feasibility tests

While various manufacturing tests on plate-type heat exchanger have been conducted by CEA within ANTARES program, other institutes have also been conducting various tests on this type of IHX. Following is a summary of tests on the compact IHXs being performed or plan to perform.

3.3.3.1 PMHE

3.3.3.1.1 CEA

Diffusion bonding tests performed by CEA are encouraging but need to be improved. Welding tests on Haynes 230 at Chalon Technical Center were not satisfactory. Tests on high speed machining are encouraging but machining speed and lifetime of drill could be improved. Electrochemical etching is still not satisfactory with degradation mark.

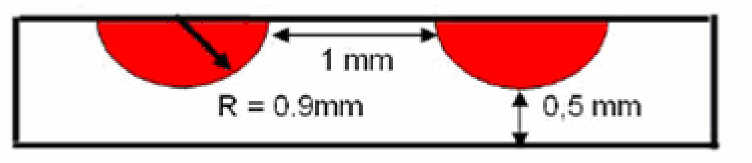


Figure 3-7 A Sample of PMHE

3.3.3.2 PFHE

3.3.3.2.1 MHI

At MHI, several tests have been done focusing on high temperature strength and inelastic behavior (Ref. 122). Tensile, creep and fatigue tests of the brazed plate-fin model were carried out. The influence of the braze filler metal thickness on the tensile strength was experimented. A 30mm x 10mm of test specimen (three layers, two fin plates and three solid plates) made of Hastelloy X was examined. Fins (0.25 mm) and plates (0.5 mm) were brazed in a vacuum condition. Several brazing filler materials, brazing temperatures and brazing filler thicknesses were experimented. The specimens were subjected to a tensile loads and the results of the deformation, strains and short term creep were investigated. The results showed that higher brazing temperature rendered a rounder fillet which leads to lesser stress concentration. When the brazing filler thickness is between 80-100 μm, it gave the highest tensile strength.

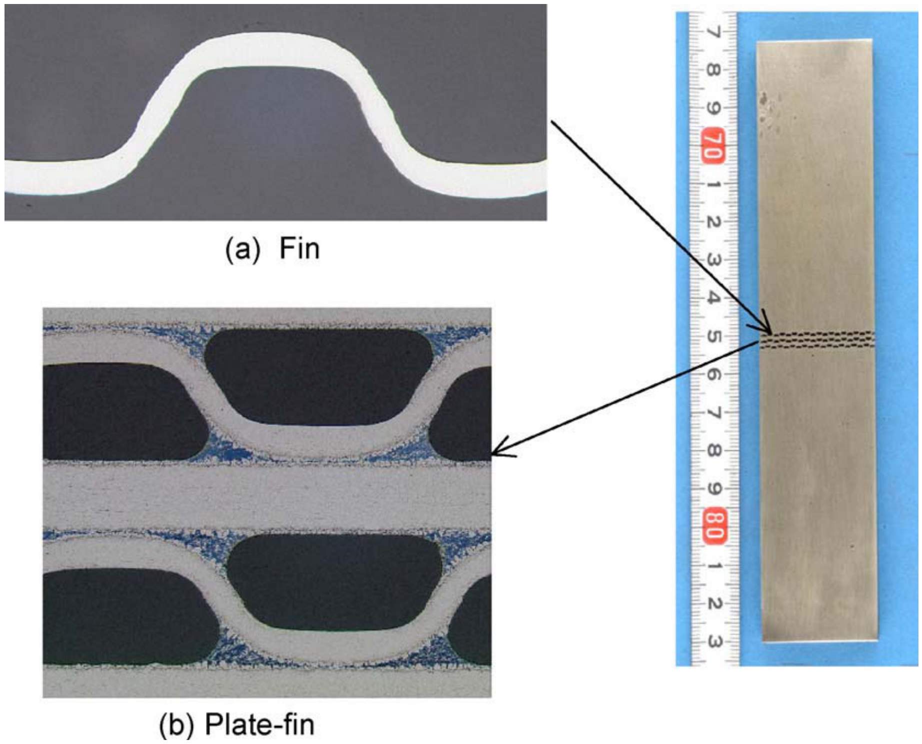


Figure 3-8 Test specimen of Plate-Fin model at MHI

3.3.3.2.2 JAERI

Normally, brazing is the choice of the welding for a plate fin type compact heat exchanger (PFHE). For the purpose of long duration, the reliability of brazing is insufficient. JAERI (Ref. 123) has been developing the PFHE with diffusion welding between plates and fins. The tensile and creep strength are reported to be superior to those in the brazing especially high temperature region. It has conducted a small scale test for the PFHE and the results showed that reliability of the diffusion welding is very high.

3.3.3.3 PSHE

No major feasibility issue has been shown with PSHE concept. Laser welding appears promising for the plate assemblies. However, tests must continue to solve some difficulties (porosities, liquation). Welding by plasma could be a backup solution. The preferred material for PSHE is inconel 617, mainly due to its better stamping capability and better weldability than Haynes 230. Even though bigger thickness (1.5 mm) is a favorable factor against corrosion, it is not sufficient to ensure an acceptable lifetime

Figure 3-9 A sample of PSHE

3.4 Current state-of-the-art and the steps necessary to extend the state-of-the-art to meet NGNP requirements

This section presents the current state-of-the-art for the tubular IHX and plate stamped compact IHX assessed to be viable candidate for the NGNP and describes the steps necessary to extend the state-of-the-art to meet NGNP requirements.

3.4.1 Tubular IHX

3.4.1.1 State of the art of the Tubular IHX

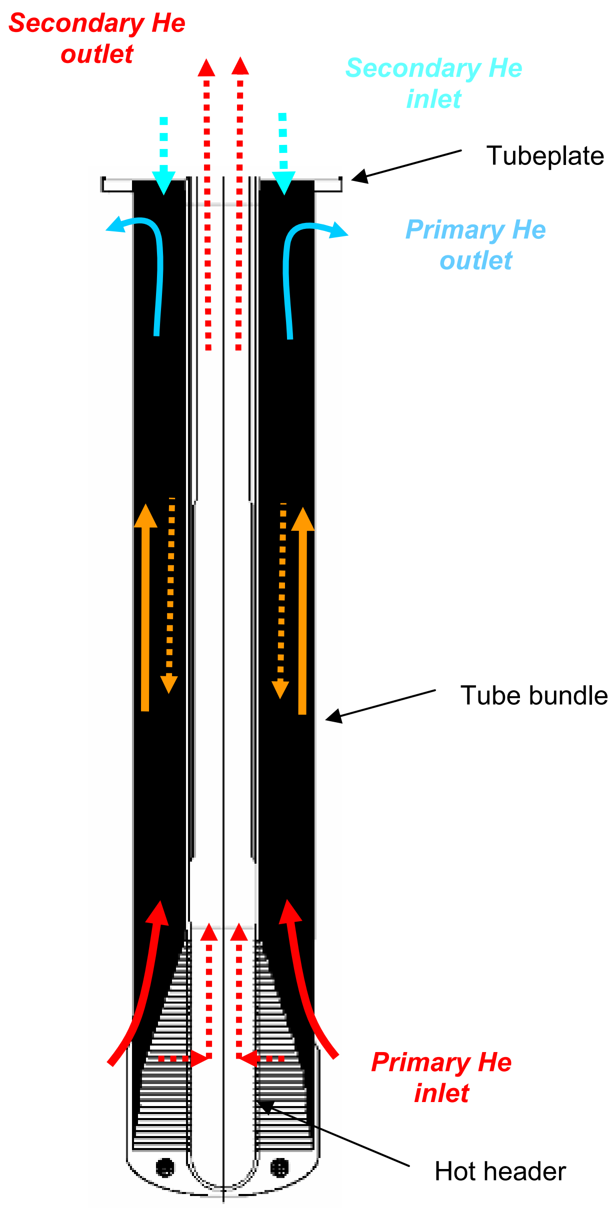


Figure 3-10 Typical flow of the tubular IHX

The basic characteristics of the tubular (helical type) IHX is that the primary side of thermal energy is transferredto the secondary side by means of convective heat transfer through the tubular wall. Typical flow of the IHX (see figure 3-10) is that hot He (900-950^{o}C) enters through the bottom part of the IHX and heats up the tubes as it flows upward and exits out through periphery annulus while relatively cold He (about 500^{o}C) runs downward through the tubes from the top, gets collected at the hot header and pass back through outlet at the top. The tubes are purposely coiled to maximize the heat transfer area as well as to minimize the strain caused by thermal expansion. One ends of tubes are attached to the tube plate while the other ends of tubes are attached to the hot header (i.e., hot gas collector). To keep the pitch distance between the tubes even, spacer grids are there to support the tubes. The function of the hot header is to collect the heated gas centrally from the secondary tubes. Other than the heat exchanged areas, IHX is outfitted with insulation for better thermal efficiency.

The current tubular IHX design is based on a German design. To deliver the nuclear process heat to a coal gasification process or to split methane in a steam reformer, an IHX design was developed in the name of PNP program. The German IHX design had a possible thermal power of 125 MW and had a capability of delivering secondary side helium of 900^{o}C at 40 bars. To investigate the IHX design, a mock-up IHX was modeled and tested at the KVK testing facility (See Section 3.3.1.1). The mock-up helical-tube IHX was fabricated by Steinmuller/Sulzer consortium and has been tested between October 1986 and June 1988. The mock-up model was capable of 10MW thermal power with 117 tubes but still delivering 900^{o}C of He at the secondary side. Figure 3-11 shows the picture of the mock-up hot header (including the extruding nozzle) which was used for creep buckling test. The table below shows the key parameters of the design.

Table 3-7 Parameters of tubular IHX

		KVK Tubular IHX
Power (MWth)		10 MWTh (representative of 125 MWth)
Flow Rate (kg/s)	Primary	2.95
	Secondary	2.85
Temperature (^{o}C)	Primary (Tin/Tout)	950/293
	Secondary (Tin/Tout)	200/900
Pressure (bar)	Primary	39.9
	Secondary	41.9
Pressure Difference (bar)	Primary	0.55
	Secondary	1.65
Number of tubes		117
Length (m) / diameter (mm) of tube		43/22
Materials		Alloy 800H/ Nicrofer 5520 (Alloy 617)

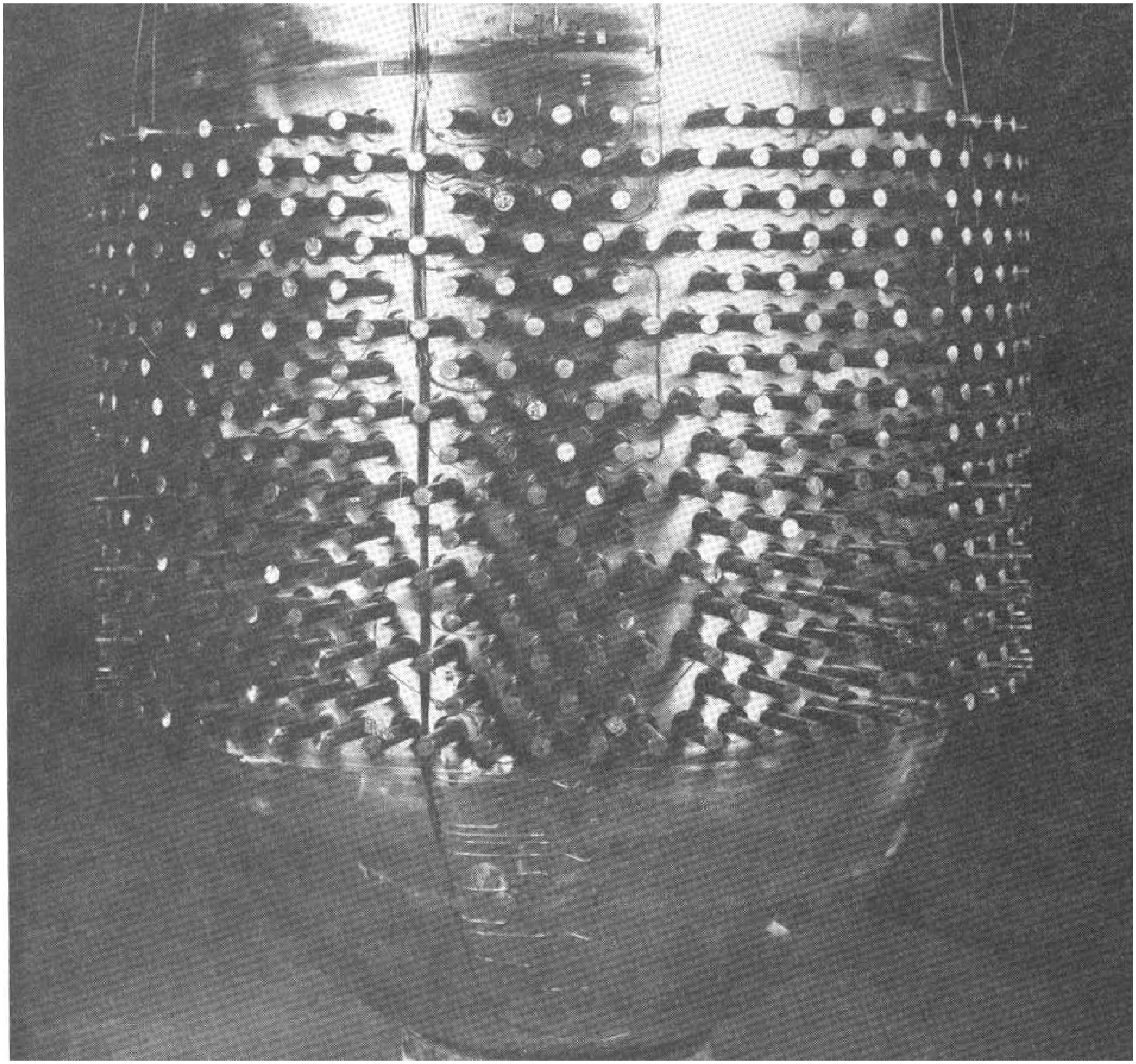


Figure 3-11 Hot Header of the Test Component at KVK

3.4.1.1.1 Thermo-hydraulic Issue

In spite of having advantages of larger heat transfer area and reduced thermal strain due to thermal expansion, there are some disadvantages related to the helical tubes. Since a number (more than 2500 tubes expected for the NGNP design) of tubes are packed in a relatively small area (the size of the hot header is about 1.2m in diameter and about 4m in height), this arrangement tends to create rather eccentric flow and possibly cause flow-induced-vibration.

Following lists some of the issues related to the thermo-hydraulic aspect:

- Misdistributions in the tube bundle between outer and inner rows – As the length of the tubes of the outer row is greater than those of the inner row, the pressure drop on the outer row is higher than the one of the inner row. This induces a lower mass flow and a lower temperature as a consequence.
- Gyration effect – The effect of a higher gyration in the inner rows due to smaller radius leads to a higher pressure drop.
- By-pass flow – There is a possibility of by-pass flow between the outer row and the outer shroud of the hot side of the primary circuit. This induces higher flux and hence higher pressure drop and higher temperature.
- FIV - Since the tubes are tightly packed together, a flow-induced-vibration (FIV) might occur. The FIV can be caused by any turbulent flow.

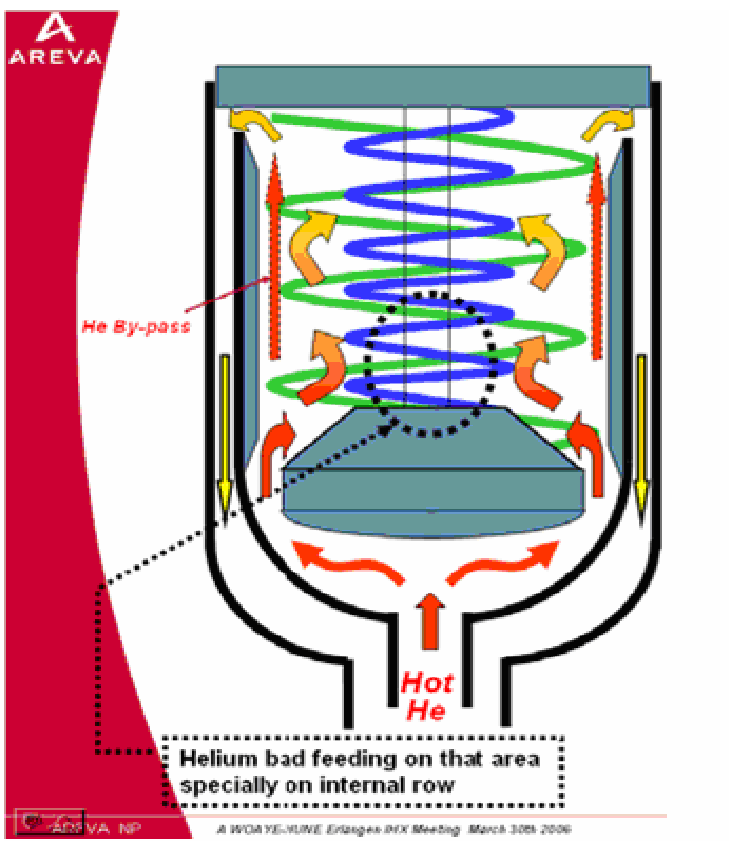


Figure 3-12 Misdistribution

3.4.1.1.2 Thermo-mechanical Issue

The helical tubes and the other parts (especially hot header) of the IHX structures have to reside in a very high temperature (more than 800°C) environment within the life time. Since the material strength lessens (creep) with high temperature and elapsed time, all affected components' structural integrity due to the creep behavior have to be examined. There are two characteristics of the creep behavior: creep buckling (collapse) and creep fatigue. Following lists the issues for the critical parts of the IHX

- Creep behavior of tubes – The tubes at the primary and secondary side will be in direct contact with the heat transfer medium (He) which is in very high temperature for the duration of life.

- Creep behavior of the hot header – It is a large forged component which is subject to high temperature during the life span.

- Tube plate – This component is in relatively lower temperature (about 350°C) but it has to support the whole tube bundle weight and withstand thermal expansions during the transients. Moreover, the connections between the tube plate and the tubes are welded joints which can be potentially weak area.

- Nozzles of the tubes to the hot header – Along with the hot header, these will be at high temperature thus subject to creep. These connections also have to share the thermal expansion loads.

3.4.1.1.3 Seismic Issue

Massive in weight but thin (about 2.3mm in thickness) tubes are only supported by the tube plates, the hot header and other supports. In case of an earthquake event, the tubes can be damaged and thus possibly alter primary boundary leak-tightness. Following is the list of concerns regarding to the seismic condition:

- Possible tube failure by seismic condition

3.4.1.1.4 Material degradation

One of the concerns about the behavior of the high nickel-based alloy (e.g., Alloy 617) is its ability to keep its mechanical properties under the postulated IHX environment for the expected lifetime of 20 years. The heat transfer medium for both primary and secondary sides is helium gas which is an inert gas but, due to the impurities, the material is subject to corrosion. Even though the thickness of the tube is about 2.3mm, it is essential to assure that the corrosion does not fall short of life span. The study of this phenomenon requires numerous long term tests to understand the specific behavior of the chosen material under IHX atmosphere and is therefore a serious concern.

On the other hand, various researches have been done regarding the coating technique on the tubes. However, coating of long, thin and curved tubes are still needed to be developed. Furthermore, even if coating of the long tubes can be achieved, the coating of the welded sections has to be performed in the assembly line and that can not be overlooked.

- Corrosion on tubes

- Coating techniques on tubes

- Coating the welded sections

3.4.1.1.5 Manufacturing of the IHX

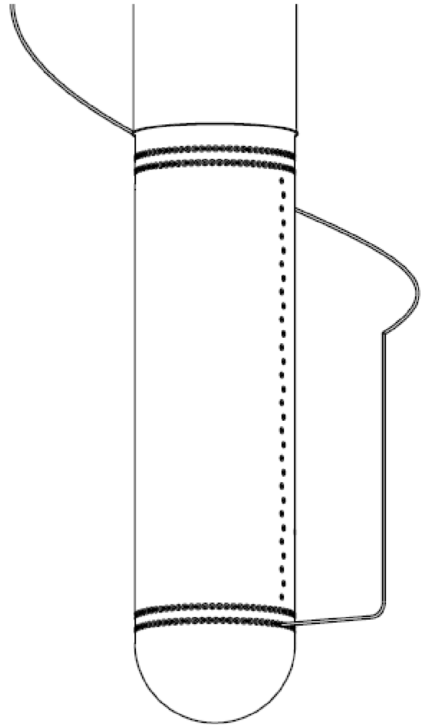


Figure 3-13 Hot Header

Forging of the hot header

One of the concerns regarding the IHX manufacturing is to forge the hot header (about 1.2m in outer diameter and more than 4m in height). In the mid-eighties, in the frame of the German PNP project, a firm, VDM, experimented such a large scale production. With various difficulties (issues of electroslag remelting, upset forging, forging mandrel etc), they were able to make a large hot header (1.05/.78m in diameter, 4.4, height and weighs about 17 tons). However, the expected dimension for the NGNP design might be more than the one produced by VDM. Manufacturing hot header made of nickel base alloy (e.g., alloy 617) is not going to be easily feasible both technically and economically. Currently, there are few manufacturers (Wyman Gordon etc) who can make such a large scale forging. However, they are somewhat limited by the maximum ingot size, selection of material, heat treatment capacity, lead time etc. More over, there is an economical risk involved in case the finished hot header does not qualify for the required material specifications.

Assembling of the tube bundle

Knowing that tubes needed to be welded at each end to the tube plate and to the hot header, the assembly of the tubes (possibly more than 2500 tubes) may be a difficult task. Whether the tube is a seamless one or welded with several pieces, the difficulty will be to bend the joints at the level of the hot header and the tube plate because the access will be limited. In fact, if the tubes are not manufactured directly to the total length (seamless pipe about 30m), one or more tube to tube welds will have to be made hence takes the assembling processes longer. Looking at the KVK mock-up, the tubes were welded together from 4 standard lengths to a total length of around 45m. Also, putting a support between each tube might not be easy task either. The assembling procedure has not been examined yet. One can expect some difficulties with the high number of tubes. A specific study should be performed in order to establish the most suitable assembling process and to confirm the feasibility of the assembling of the tubular IHX. The expected number of tubes that can be welded onto the hot header is assessed to be more than 2500. One other concern might be to maintain the helical tube-to-tube distance. Since tubes are tightly crammed and there are constant turbulent flow surrounding them, there should be means to keep those tubes separate so as to minimize tube abrasion.

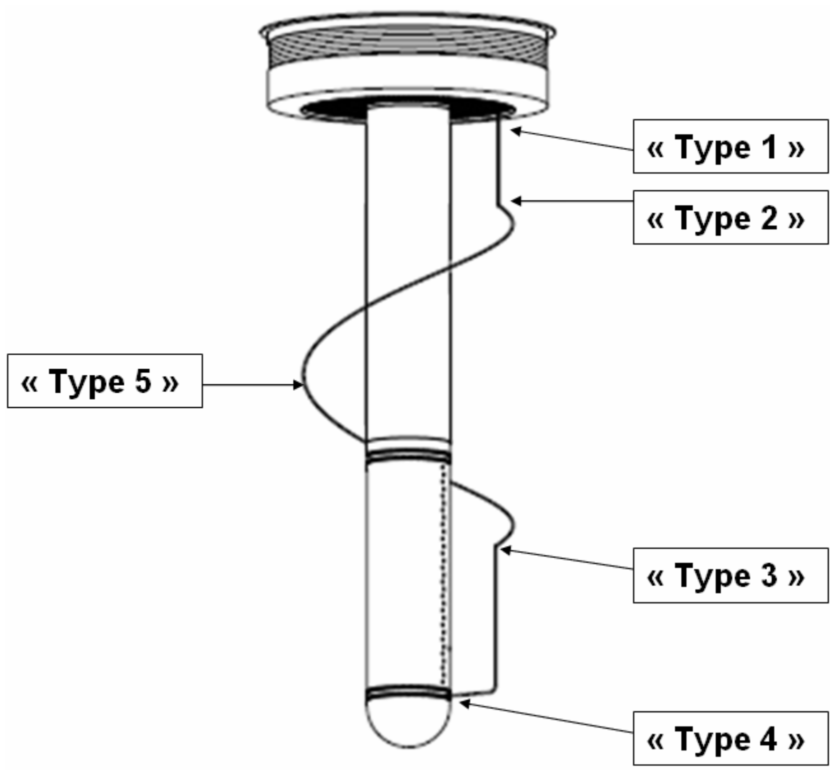


Figure 3-14 Five Types of Welds

Bending of the tubes

The tubes will have to be preformed (bended) while being inserted into the IHX. The critical parameter is the angle of the gyration of the tube to be achieved. This angle depends on the helix angle and on the diameter of the tube layer. Also, the bending process has to assure the smooth tube surface.

Welding

Assuming that a helical tube consists of 4 pieces of tubes (See Figure 3-14), the straight tube (e.g., returning area, Type 3) will have to be welded to the helical part of the tube. So, two welds have to be performed in the lower section of the IHX. According to the German experience, the welds can be performed with GTAW (Gas Tungsten Arc Welding) with a rotating torch inside the tube. In this case, a cover gas at the other side is needed. Ring grooves will be machined on the surface of the collector in order to make a tube to tube weld easier. The most difficult welds to perform seem to be the welds of lower section (connection between curved section and straight section, type 3 from Figure 3-14) because the access is difficult and the torch has to be introduced inside the tube through the opening at the wall of the hot header and then through the bow and along a total distance of about 3 meters. Then, the torch should be able to turn around by a mean of a suitable mechanical device. Furthermore, to ease the tubes' pre-stress after welding tubes, a post weld heat treatment (PWHT) may be considered. One concern in doing so might be to find a large enough furnace to handle the long IHX tubes.

3.4.1.2 Development and Schedule

Even though the NGNP design is based on the German design which was tested in the mid-eighties and some of the test results might not be available, it still is a proof that the tubular IHX can be run and is a viable option to meet the requirement of 2018 operation. Furthermore, it is to be noted that a large scale mock-up (10MWth) has been tested. To meet the requirement of 2018 operation, there are a few tests performed based on the need of the size of the test: lab scale test, small scale test and full scale test (about 30 MWt in a component test facility). Depending characteristics of the tests, several tests can be performed simultaneously or needed to be run separately. Following are the key tests or developments toward meeting the goal.

3.4.1.2.1 Thermo-hydraulic

The actions that are recommended to confirm thermo-hydraulic aspects of the design (e.g., minimize pressure drop, reduce FIV etc) are as follow.

- Confirm that the effect of the tube misdistribution is negligible.
- Confirm that the gyration effect of tube curvature is negligible.
- Validate values of by-pass flow at the periphery of the primary side.
- Confirm that FIV effect is negligible.

3.4.1.2.2 Thermo-mechanical

The actions that are recommended to confirm the thermo-mechanical aspects of the design (creep fatigue test etc) are as follow.

- Conduct a test for creep buckling (collapse) of the tubes against external pressure
- Conduct a test for creep fatigue of the tubes
- Conduct a test for creep buckling (collapse) of the hot header against external pressure
- Conduct a test for creep fatigue of the hot header including the nozzle connection
- Perform a test to study the connection between the tube plate and the tubes.

3.4.1.2.3 Seismic

The action that is recommended to improve seismic loading aspect of the design is as follow:

- Conduct a test under the representative seismic loads

3.4.1.2.4 Material degradation

The actions that are recommended to improve the life time of the material are as follow:

- Development of a protective coating of the tubular IHX - The coating should provide an efficient protection against corrosion in base metal and welded joints.
- Demonstration of its ability to withstand thermal cycling

3.4.1.2.5 Manufacturing

The actions necessary to qualify the manufacturing aspects of the IHX component are as follow:

- Qualify the tube bending process
- Qualify the welding technique which can be used for welding the tubes to the plate and the hot header
- Develop a process which can optimize assembling of the tube bundles
- Demonstrate procedure of the ISI and tests them on the full scale mock-up test
- Demonstrate the tube repair and tube plugging techniques

3.4.1.2.6 Schedule

To execute the afore-mentioned developments or tests to meet the requirement of 2018 operation, a detailed schedule has to be made in a timely manner. Especially, one has to consider the possibility of the iterative process of a development and to consider the availability of the testing facilities.

Milestones of the schedule

First step which is needed to be completed before development of an assembling techniques is to finish the coating development. If the coating technique is available, then it needs to be included in the assembling processes. Otherwise, best corrosion resistant material has to be selected.

Procurement of the mock-ups is needed to be completed (needs about 30 months lead time) by the end of 2010 for the lab scale and small scale tests.

A 2-year of duration (2011-2012) will be used for the various tests for each sub-components (hot header and tubes). In the mean time, a full scale mock-up is built for the full scale (30MWth) mock-up test (expected completion year of the full scale test facility is the end of 2012).

The test module will go through various conditions (thermally, mechanically and hydraulically) for about 2 years. During this period, the structural integrity of the tubular IHX is tested. ISI (in-service inspection) is performed while in testing.

The order of the IHX for the NGNP is needed to be placed by middle of 2012 to make the delivery by the end of 2014. It takes about two years to manufacture the IHX.

Requirement for meeting the goal

The full scale mock-up testing facility is needed by the end of 2012. Also, all the necessary tests are needed to be done by the end of 2014 which will give appropriate time for the manufacturing the final IHX design.

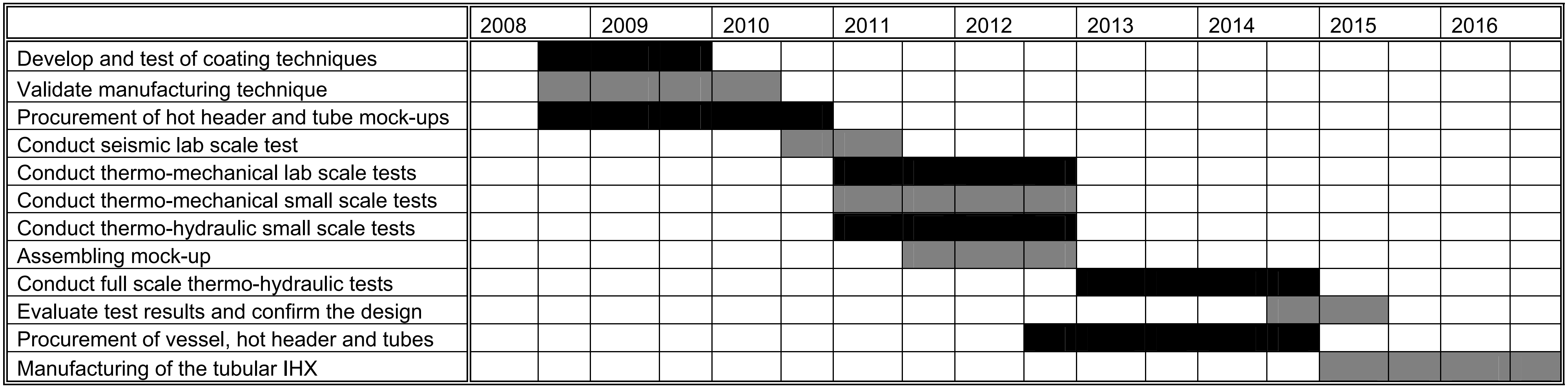
Possible road block of meeting the goal

Development of coating techniques has been carried out in many industries. However, coating of the long and curved tubes and maintaining under very hot temperatures were not part of the techniques. One and half years of development might not be enough. There is a good chance that the development might not be completed by the end of 2009.

Development of tube welding and tube bending might take longer than expected schedule because the number of tubes is more than the German design hence much tighter area to weld and bend.

As pointed out previously, the full scale mock-up testing facility is needed to be built by the end of the 2012 and the facility is ready for tubular IHX testing. This one is the most significant decision factor for meeting 2018 goal. Also, the schedule is underlined that there is no significant structural damage during the tests which leads to significant model modification.

Schedule of development, testing and manufacturing is shown next page.


2008
2009
2010
2011
2012
2013
2014
2015
2016
Develop and test of coating techniques
Validate manufacturing technique
Procurement of hot header and tube mock-ups
Conduct seismic lab scale test
Conduct thermo-mechanical lab scale tests
Conduct thermo-mechanical small scale tests
Conduct thermo-hydraulic small scale tests
Assembling mock-up
Conduct full scale thermo-hydraulic tests
Evaluate test results and confirm the design
Procurement of vessel, hot header and tubes
Manufacturing of the tubular IHX

3.4.2 PSHE

From the different concepts of metallic compact IHXs developed by AREVA NP, the PSHE (Plate Stamped Heat Exchanger) is considered as the most promising one for NGNP. However, this concept is currently out of the state-of-the-art for application at high temperatures and important design improvements, material tests, manufacturing tests and mock-up tests are still needed to support a NGNP deployment in 2018. The fact that the PSHE is an innovative concept leads to prefer using it only for the 60 MWth Hydrogen test loop.

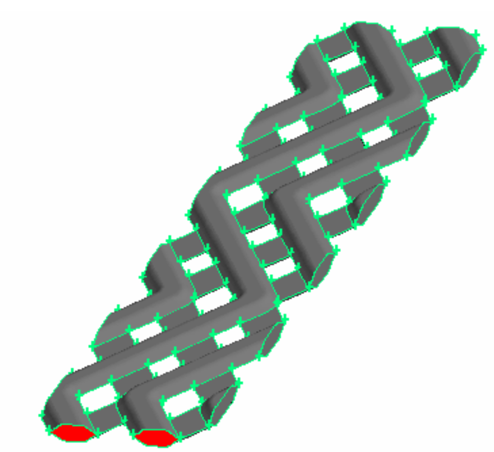
So this document focuses on the current state-of-the-art of the PSHE IHX for a use with He/He, 60 MWth, and the steps necessary to extend the state-of-the-art to meet NGNP requirements to support NGNP operation in 2018.

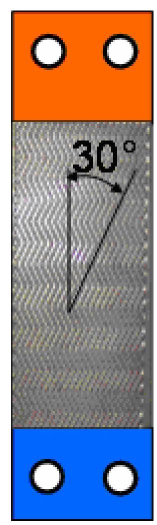
3.4.2.1 State of the art of 60 MWth PSHE compact IHX

3.4.2.1.1 Overall description

A PSHE IHX is composed of set of small modules (power of 5 to 10 MWth) disposed in a pressure vessel. The modules are radially arranged in the vessel around a central pipe which collects the hot secondary gas (hot center). This is illustrated in Figure 3-15

Each PSHE elementary module is composed of a set of stacked plates. Each plate is stamped with corrugated channels. The plates are stacked in such a way to cross the channels of two consecutive plates and, therefore, to allow the different channels to communicate through the width of the plate as shown on the left below. A general view of one plate with integrated headers is shown on the right.





The flow paths of the primary and secondary He coolants are illustrated in Figure 3-16 and Figure 3-17.

The assembly of the plates together is performed by laser welding on the edges of the plates. Welded joints are also needed inside the secondary headers but no weld is performed in the active part of the plates which provides the modules with a relative flexibility as compared to the other plate IHX concepts (PMHE has diffusion bonding joints and the PFHE fins are brazed onto the plates).

Figure 3-15 ARRANGEMENT OF THE MODULES IN THE PRESSURE VESSEL

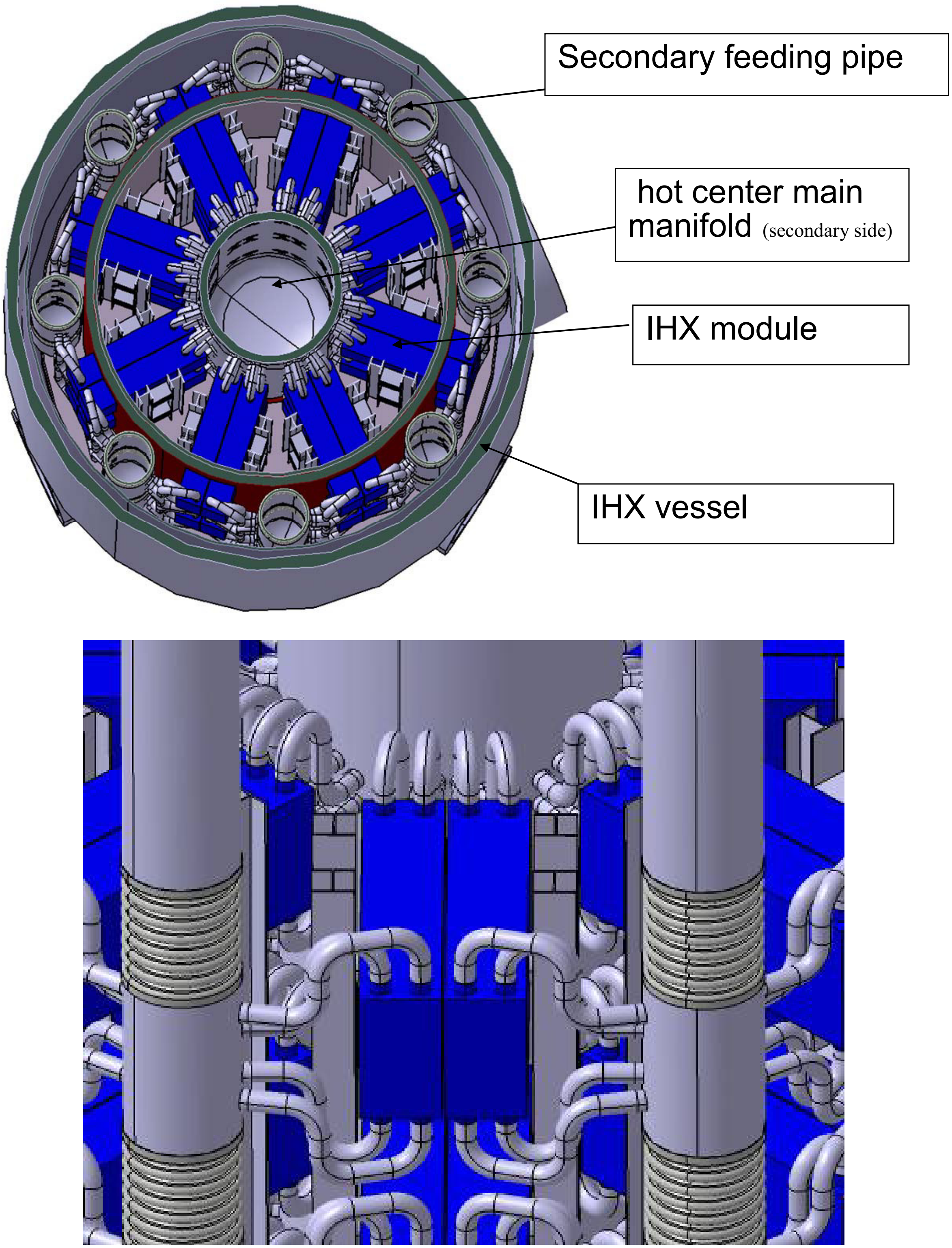


Figure 3-16 FLOW PATHS IN A PSHE MODULE

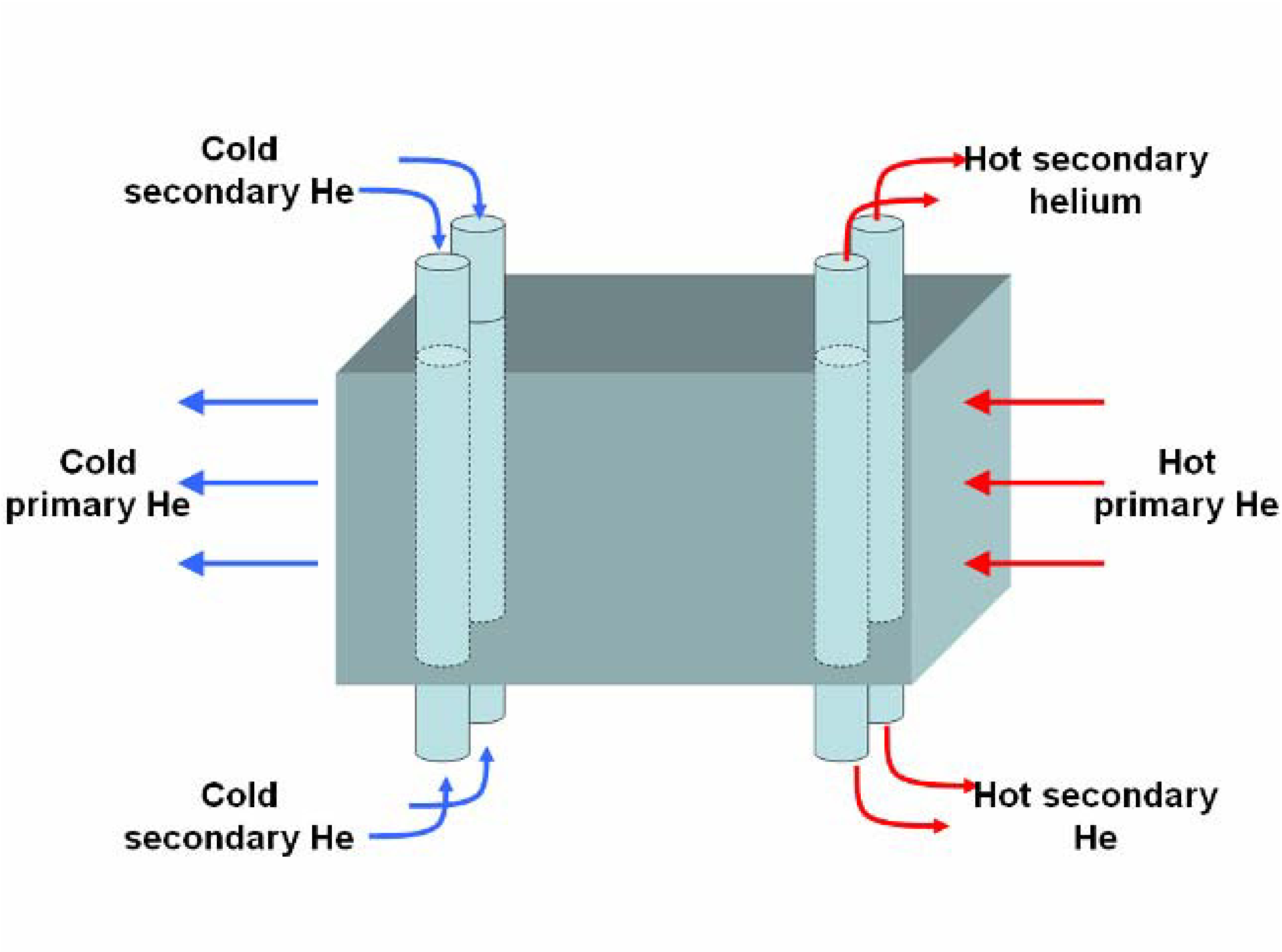
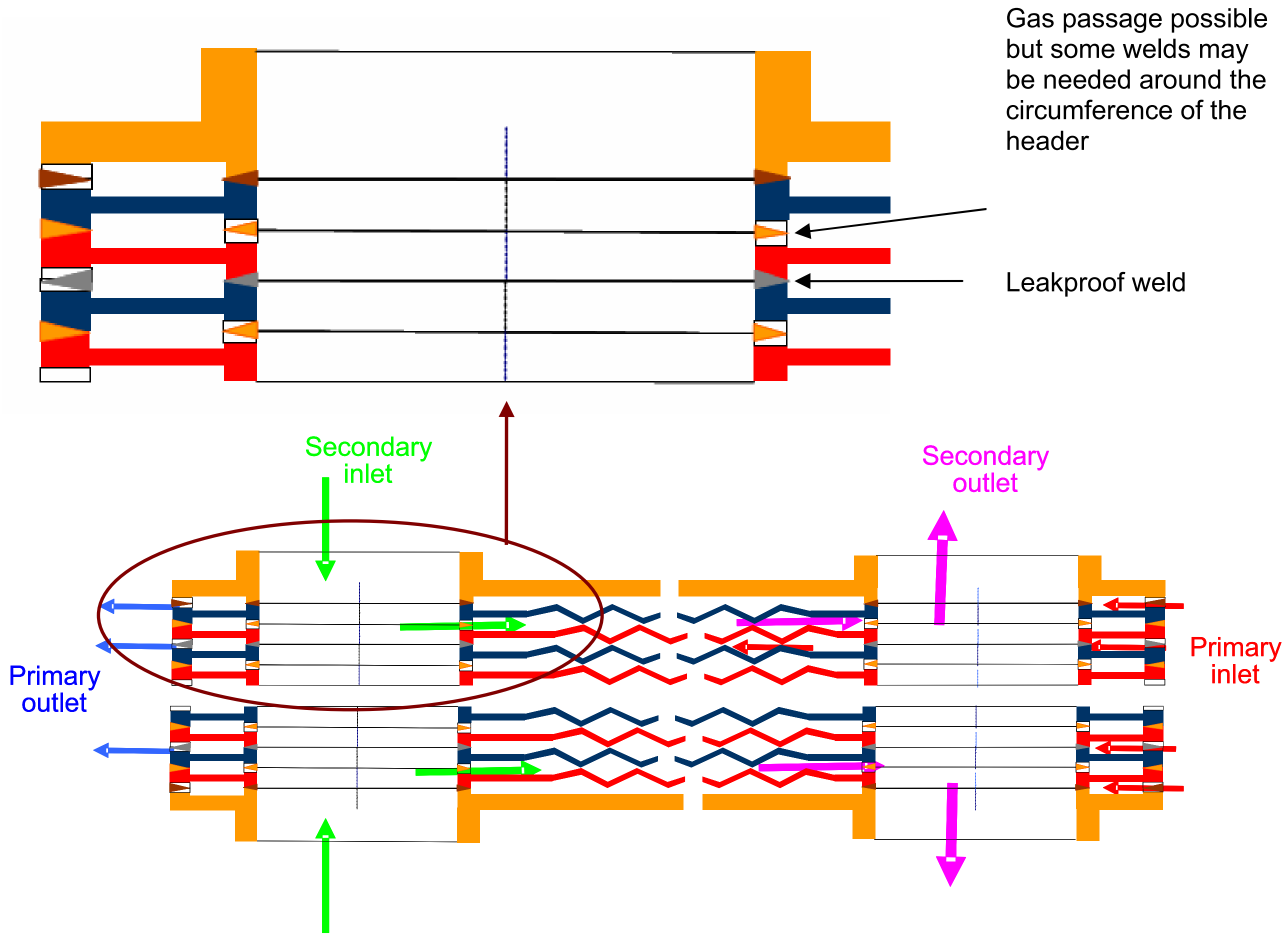


Figure 3-17 DETAIL OF FLOW PATHS AND WELDED JOINTS IN A PSHE MODULE



3.4.2.1.2 Thermohydraulic design

Correlations for the thermohydraulic design of PSHE have been established on the basis of tests (in air on a single interplate) and CFD to assess the pressure drop coefficients and the heat exchange coefficients.

It is concluded that the expected performances can be reached with a satisfying level of confidence. The expected efficiency is reachable (0.9) and the pressure drop can be limited to values of about 2% of the inlet pressure.

The misdistribution risk is assessed to be limited for the following reasons:

- Module width is reduced (300 mm as compared to a length of more than 1000 mm),
- Fluids channels are communicating which allows fluid balance within the inter-plates width,
- Despite the integrated pipe headers presence on module extremities and the corrugations angle (30°), no abrupt flow direction change is designed within the plate channels,
- Primary side He flows straight trough the module,
- Inlet and outlet flow windows are wide and U shape flow path is retained for secondary side when entering or exiting via the pipe headers,
- The secondary Helium exit pipe header section is adjustable to compensate the static pressure unbalance along inlet and outlet pipe headers. In addition, this potential unbalance pressure is low as compared to the pressure drop along the active part of the plates, so that the mass flow should not be significantly impacted.

3.4.2.1.3 Thermomechanic design

Results for a full scale IHX (600 MWth)

FEM calculations of the thermomechanical behavior of a full scale PSHE IHX (600 MWth) have raised some important issues of lifetime due to the severe loads due to the compactness of the concept and to the high temperatures at stake, even for a use with primary helium at 850°C.

A start up from cold state to normal operating condition has been simulated on the basis of the thermohydraulic calculation results with a primary helium temperature of 850°C and an approach temperature of 50°C.

It should be highlighted that, regarding codes and standards, the section NH of ASME provides no official rules for Inconel 617. The code case for alloy 617 that has been written in the eighties has stayed at the draft state. So design rules currently available are not appropriate and more realistic (and probably less pessimistic) rules will need to be developed to justify such a component.

However, the results are the followings:

The important thermal gradients obtained in the hot headers area are responsible for high stresses that limit the lifetime to values of a few thousands of hours due to creep damage with the latest design at 850°C (relaxation model was Armstrong Frederick which is quite conservative).

At 900°C, the situation would be even worse.

A margin study has been performed in order to define the potential gain and the parameters that could worsen the results.

The following parameters can have a positive influence on the results:

- Decrease of the temperature
- Improvement of the behavior law (an increase on the lifetime by a factor 10 is obtained when changing the relaxation model from Armstrong-Frederick to Norton)
- Some design modifications (reduced height, collector arrangement, flow deflectors…)

It is underlined that the creep curves are strongly not linear so that a small decrease of the stress can multiply the lifetime by significant factors.

On the other hand, the following parameters can have a negative influence on the results:

- The effect of the history which has not been accounted for
- Effect of transients (only nominal conditions have been taken into account)
- Difficulty to evaluate local effects (geometry, thermal effects…)
- Canal evaluation: up to now, only the global behavior of the block has been studied and no information is available concerning the local behavior of the block
- No weld coefficients are taken into account in this analysis which could worsen the results if the welds had lower properties than the base material.

The effects of the pressure loading have not been well assessed because the model was not appropriate. A local model would be necessary. Nevertheless, the pressure difference between the primary and the secondary circuits is low and shouldn't be a problem during nominal conditions.

Considering the results obtained during nominal conditions, the cyclic behavior of the block hasn't been evaluated in this study.

As a conclusion, even if the material data are too weak to have a clear view on the reachable lifetime with the PSHE concept, some significant difficulties are expected in the light of the first evaluations of the lifetime due to severe creep damage.

Possible improvement due to a limited power (60 MWth)

It should be underlined that the effect of the overall power of the IHX is of low importance regarding thermomechanics because the modules operate in parallel and practically independently. Changing a 600 MWth plate IHX for a 60 MWth plate IHX mainly consists in reducing the number of modules without avoiding any thermomechanical issue. So the small scale of the 60 MWth IHX is not seen as a strong argument that would justify an enhance feasibility of the compact IHX at reduced scale (60 MWth) as compared to full scale (600 MWth) with regard to thermomechanics.

However, some design modifications are possible in order to decrease a bit the stresses at the price of a lower compactness (important parameter for the full scale IHX but not for the small scale one). But if the design is changed as compared to a full scale design, it will be more difficult to use the 60 MWth IHX as a qualification component for a large scale plate type IHX, whereas the extrapolation seems easy if the design is not changed. The following design modifications would be positive to increase the lifetime, even if penalizing the compactness of the IHX:

- Decrease of the height of each module and use of more modules (easy to realize without changing important design parameters). It has been demonstrated by FEM calculation that a reduced height can significantly decrease the thermal stresses by giving the module some more flexibility. It is reckoned that dividing by 2 the height of the modules results in a gain of about a factor 2.5 on the lifetime.

- Limit the thermal gradients by increasing the length of the modules and decreasing the heat exchange coefficients. This option would however call into question most of the parameters of the current design, probably including the radial arrangement in the pressure vessel. In addition, decreasing the heat exchange coefficients requires decreasing the velocity of the gas by increasing the hydraulic diameter (loss of compactness). But the rate of flow would probably become transitional and the effect on the heat exchange coefficients can not be predicted yet because the correlations in this geometry have been established for a turbulent rate flow. Lastly, the high stress levels obtained in the FEM simulations are much localized in the header areas so that it is not obvious that such a design modification would result in big improvement of lifetime.

- Use of a “two-stages” IHX with a tubular helical bundle for the highest temperatures (more complex arrangement). This solution presupposes giving up the idea of qualification of a plate IHX at high temperatures but could be a compromise if the difficulties with plate IHX prove to be too challenging.

It can also be mentioned that the isolation valves needed for the 60 MWth IHX have much less stringent requirements in terms of performance than the valves associated with the full-scale IHX. So the approach that consists in relying on the isolation valves to ensure the confinement seems more appropriate in this case. This might be an argument in a view of decreasing the safety level of the small component as compared to the full-scale one which would allow relaxing some requirements in terms of qualification and controls.

3.4.2.1.4 Material issues

Corrosion by the primary impure Helium remains a challenge for the plate-type IHX at temperatures above 800°C, which could require developing specific measures like a protective coating.

For PSHE, the higher plate thickness (1.5 mm) is a favorable factor in comparison with the other plate-type IHX concepts but does not seem sufficient to ensure an acceptable impact of corrosion.

A protective coating could provide the required protection. Such a solution still needs to be entirely developed and validated, including:

- Selection of the coating material,

- Development of the coating process, with emphasis on ensuring the homogeneity of the coating and its compatibility with the forming and welding processes (a post assembly coating technique seems mandatory),
- Demonstration of integrity of the coating over the IHX lifetime when subjected to thermomechanical cyclic loadings.

3.4.2.1.5 Manufacturing issues

The manufacturing of a module consists of three main steps: machining of the plates, stamping of the plates and assembling them together.

Machining of the plates

A first assessment of the feasibility of the industrial realization of machining has been performed. The design has been significantly changed since then but the detailed analysis of the results indicates that the machining process still needs optimization in order to reduce the delay of realization for a large size IHX. In the case of a 60 MWth IHX, this delay should be reasonable.

It is however underlined that the design of the header zones are not well defined today, and that this design could strongly impact the time needed for machining.

Stamping of the plates

The second step provides the serrated corrugations on the plates by stamping. The tests performed on this process with Inconel 617 have shown encouraging results. Some optimizations are still required in order to avoid section reductions and therefore local stress intensification source. An example of a section of stamped plate is shown hereunder.

Welding of the plates

The last step is the welding of the plates on their edges and welding of some parts of the secondary headers (still to be defined). The welds inside the secondary headers are expected to be performed from the inside with a rotating welding device.

The leakproof welds are well defined (all around the circumference of the secondary header and on the lateral borders of the plate on primary side and on every borders of the plate on secondary side). But some additional welds may be needed for mechanical sustain of the header zones (notably at secondary side) and for potential flow deflectors that would optimize the gas flow in order to reduce the thermal stresses. These additional welds would however have no leakproof requirement.

As a consequence of the small thickness of the plates, narrow gap welding by laser is the reference option considered for the welded joints. Tests have been performed with laser welding for the joints situated on the edges of the pates.

However, some minor metallurgical imperfections have been detected in the welded joints, the impact of which still has to be studied in details.

Some ways of improvement of the welding process have been identified, including changing the welding process or enlarging the joints.

The inspection of these welds is still a difficult question. It is needed to define the best controls that can be performed and the safety classification of the IHX modules that would be acceptable for NRC.

3.4.2.2 Development schedule

Document No. 12-9072397-000 “NGNP Component Test Facility” recommends the use of three test loops to support NGNP development:

- A “small” loop for Conceptual Design (power of about 100 kWth)
- A “representative” loop for Preliminary Design (power of about 1 MWth)
- A “large scale” loop (CTF for Component Test Facility) for Final Design (power of 30 MWth).

The three loops would be used for various components of the facility including the IHX.

A requirement is that the IHX should be available on site by the end 2016 to support NGNP operation in 2018. This timeframe is considered as very short in a will to qualify a compact plate-type IHX.

For this reason, two schedules are proposed. Schedule 1 seems more realistic but no test of the IHX on the CTF is planned. Schedule 2 includes tests on CTF but is considered as very optimistic.

3.4.2.2.1 Main development steps

The main steps that have been identified as necessary to extend state-of-the-art so that PSHE meet the NGNP requirements are listed thereafter. The remarks in brackets assume that CTF tests can be performed (Schedule 2).

It is assumed that the different mock-ups are composed of a stacking of a limited number of full-size plates. Thus, machining and stamping can be validated at full size and potential flow misdistributions through the width of the plates are accounted for from the start of the development on the “small” mock-up.

The “small” mock-up would consist in a very limited number of plates (<10). The representative one would consist of about 30 to 40 plates when the full scale module comprises between ~180 and ~350 plates respectively for a 5 MWth or a 10 MWth module.

Thermohydraulics

- Design optimization in order to limit the thermal gradients (CFD),
- Tests of performances (heat exchange and pressure losses) at high temperature on small and then representative mock-up [Final validation on CTF],
- Study of the feeding between the plates on representative mock-up (the small one would consist in too few plates) [Final validation on CTF would have a significant added value as the representative mock-up has a reduced number of plates],
- Leak tightness tests in Helium on representative mock-up [Final validation on CTF].

Thermomechanics

- Design optimization in order to limit thermal stresses (FEM in parallel to the corresponding CFD task),

- Characterization of Inconel 617 and development of high temperature design rules (including development of specific constitutive equations and associated set of parameters). This work would be performed on samples. Using controlled Helium as the one of the representative loop to account for environmental effects is preferable because tests in air are quite conservative.

- Mechanical tests on small mock-up, representative mock-up [and CTF] to justify the structural integrity of the module when subjected to the thermomechanical loads (pressure and thermal transients). This item would be split into two kinds of tests:

  – The rupture pressure of the assembly would be determined on the representative loop with a 1 MWth mock-up (which should have a sufficient number of plates to be representative of the full size module regarding this item). This test need to reach the rupture of the module and needs the corresponding security equipments. Performances tests (heat exchange and pressure losses) under nominal conditions can be performed before this test on the same mock-up.

  – Resistance to thermal cycling (creep fatigue) can be studied on the representative loop on the basis of the Design Duty Cycles, still to be defined. Another dedicated representative mock-up will be needed for these tests. The creep fatigue phenomena can be accelerated by increasing a bit the temperature. However, this operation requires verifying that the creep regime does not change and that the environmental effects do not change significantly. The stresses can also potentially be increased a bit by slight modification the design. In order to be able to extrapolate the results, FEM in parallel would be needed (modeling would be validated by test results and would be used to extrapolate the results to the actual geometry). [For creep fatigue tests, the CTF would have an important added value because the stress repartition is very sensitive to the height of the module. Thus, even if means of extrapolation can be imagined, relying only on the tests on representative mock-up (as in Schedule 1) presents an increased risk regarding licensing of the compact IHX].

- Design of the supporting system and of the collecting pipes for secondary Helium. Tests on representative mock-up [and CTF].

Material interaction with Helium environment

- Development of a protective coating. The coating should provide an efficient protection against corrosion in base metal and welded joints and maybe also against tritium permeation (efficiency on the base metal may be sufficient due to area effect),

- Demonstration of its ability to withstand thermal cycling on samples and then on representative mock-up [and CTF],

- Demonstration of its uniformity everywhere necessary in the IHX on representative mock-up (including thermal cycling phase) [and CTF],

- Determination and qualification of suitable non destructive controls compatible with the coating (on samples). Tests on representative mock-up [and CTF].

Manufacturing

- Optimization of the stamping and machining processes (quality and speed),
- Definition of the welding parameters. Tests would be performed on samples and small mock-up. [If tests on CTF can be performed, the welding parameters can be adjusted until the manufacturing of the full scale mock-up]. Welding of the edges and of the headers will need separate works (orbital welding for the headers and linear for the edges).
- Characterization of the welded joints behavior (on samples).

Key items

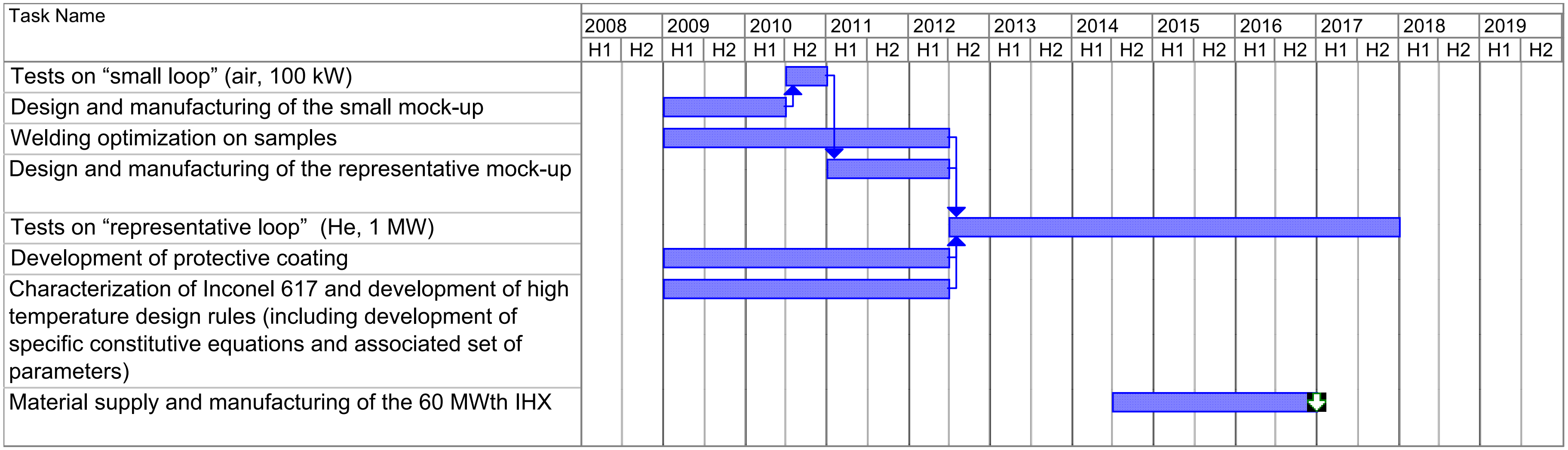
The items that are considered to be the most challenging and time consuming are:

- The justification of the lifetime of the IHX when subjected to thermomechanical loads in representative conditions, including design optimization and final characterization of Inconel 617 behavior (including welded joints) when subjected to creep and cyclic loads. [CTF tests would have an important added value with regards to this item, significantly reducing the technical risk]
- The development of a coating that meet stringent requirements of uniformity and reliability [Deposition of the coating may be more difficult on the full scale module so that tests on CTF would have an added value regarding this item].

Remark: The key parameter in these two points is the temperature. The corresponding technical risk decreases fast when the temperature decreases. The two points seems manageable for a “low” core outlet temperature (750°C) but an important technical risk is foreseen for a high core outlet temperature such as 900°C or 950°C.

3.4.2.2.2 Schedule 1 for compact IHX development

In Schedule 1, presented on next page, tests are performed on only two loops: the “small” one and the “representative” one. This means that no full scale qualification is planned and that the results of the tests on the 1 MWth loop are assumed to be sufficiently representative of the full scale IHX to start NGNP operation with the compact IHX on the 60 MWth test loop.



SCHEDULE 1 FOR NGNP COMPACT IHX DEVELOPMENT

Milestones of the schedule

A first step in the welding optimization should be completed by the end 2009 in order to manufacture the small mock-up with a satisfying geometry, stress resistance and leak tightness. The final optimized welding parameters should be decided before middle 2012 so as to manufacture the representative mock-up with those optimized joints (expected to be weak points).

It is preferable to start the design of the representative mock-up only when the results of the small mock-up tests are available in order to benefit from them and to adapt the design if needed.

The development of the protective coating should be completed before starting the manufacturing of the representative mock-up in order to be tested at representative scale on this mock-up. If these tests are not satisfying, it will be necessary to build another mock-up after further optimization of the coating technique.

The tests on the representative loop may need less time than stipulated in Schedule 1. It may be possible to completed these tests in about three years and a half (six month for performance tests and rupture pressure determination and three years for creep fatigue tests) but if design modifications are needed or if the tests need more time for any reason, the finalization of the tests can be performed in parallel to the manufacturing of the mock-up.

In any case, the material supply and the manufacturing of the mock-up need to begin less than two years after the beginning of the tests on representative loop. This strategy is risky because very limited adjustment of the design is possible if the tests on representative loop are not satisfying.

Requirements about the loops

The time needed to get the test facilities ready and the compatibility with this schedule still has to be checked.

It has to be underlined that the CTF is needed anyway for qualification of other components than IHX, even if not included in this schedule.

Level of qualification of the compact IHX concept

It is reckoned that up to 16 modules can be radially arranged on a single height level around the hot center and working in parallel. For the 60 MWth test loop IHX, a set of modules disposed on a single level should be sufficient. So qualification of a single module is considered as sufficient to be fully representative of the 60 MWth IHX (the risk of misdistribution between the modules is practically excluded).

In this schedule, mock-up tests are performed until a power of 1 MWth in Helium. This power can not be considered as fully representative of a full size module (5 to 10 MWth) notably because the height of the module has a significant influence on the stress levels. But the questions concerning manufacturing, thermal performances, leak tightness, protective coating and erosion can be dealt with thanks to that component.

In order to be representative of the full-scale module, it is conceivable to increase a bit the test temperature and to increase a bit the stresses by slight design modifications but these techniques are not easy to implement, so that tests with a full scale module on CTF would be more relevant.

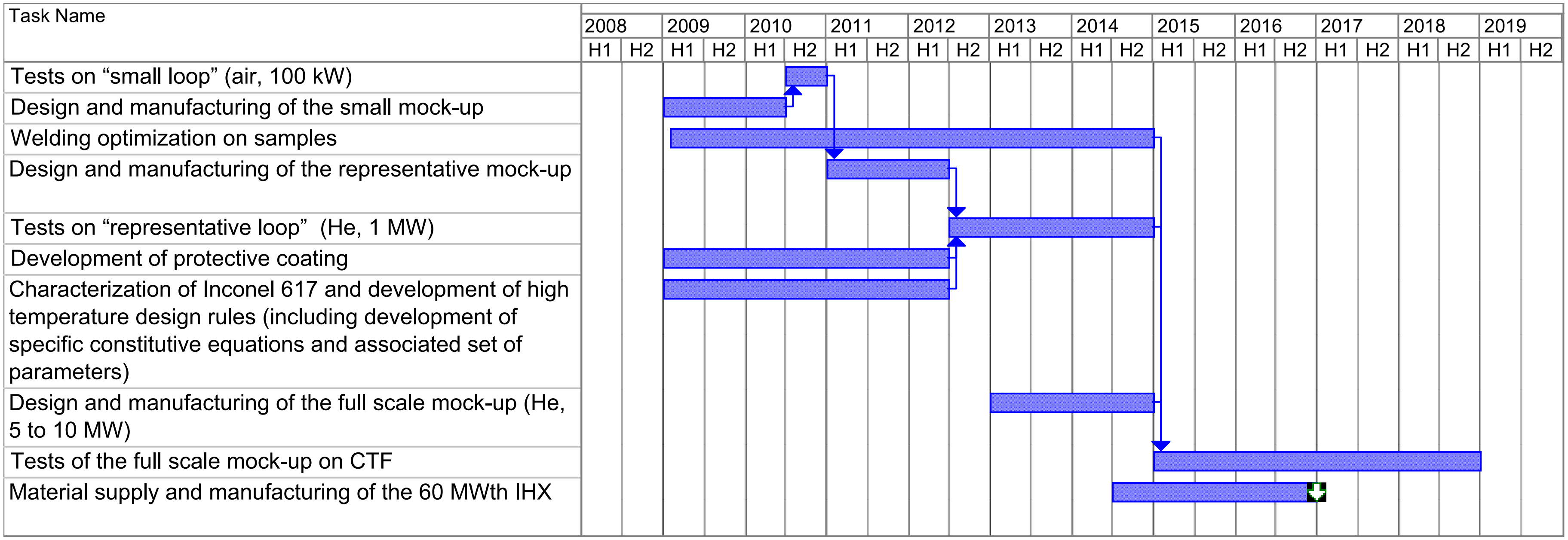
So, in Schedule 1, the compact IHX modules are tested in conditions as representative as possible but not at full scale. The operation of the IHX on the NGNP 60 MWth test loop should therefore be considered as a final qualification based on the important but not fully sound results of the representative loop tests. This strategy is risky and could threaten licensing of the IHX.

However, the reduced power of this loop leads to think that the isolation valves can have high performances and could therefore be considered as a sufficient confinement barrier, provided that an efficient leak detection system is implemented (the $P_1 < P_2$ configuration is not favorable regarding that topic because leak detection by activity is not possible). In this case, the IHX could be classified as a non safety component and the final qualification of the plate modules on the nuclear reactor could be acceptable as regards safety.

In that case, a 60 MWth tubular IHX would need to be provided either to work in parallel with a single qualification compact IHX module (5 to 10 MWth) or as a fall-back component in case of failure of the 60 MWth compact IHX (composed of 6 to 12 modules).

3.4.2.2.3 Schedule 2 for compact IHX development

Schedule 2, presented on next page, includes a test campaign on CTF, in addition to the tests planned in Schedule 1.



SCHEDULE 2 FOR NGNP COMPACT IHX DEVELOPMENT

Milestones of the schedule

The same milestones as for Schedule 1 are needed, except that the welding optimization can be continued until manufacturing of the full scale mock-up.

A weak point of this schedule is the overlapping of the design phase of the full scale mock-up with the tests on representative loop, which limits the feedback from these tests on the design of the full scale mock-up.

Assuming that the material supply needs one year, the manufacturing of the IHX starts at the same time as the qualification tests. So only the feedback of 2.5 years of representative tests would be available at the time of the manufacturing of the IHX, which remains a risky strategy.

Three years may be sufficient for the qualification tests but further testing can be performed if additional information can still be gathered.

Requirements about the mock-ups and loops

As in Schedule 1, the time necessary to get the facilities available has not been checked. Moreover, the CTF that appears only in this Schedule 2 (even if necessary anyway for other components qualification), needs a particularly important timeframe (assessed to ~5 years) to be designed and constructed due to its large power. Therefore, no feedback from the representative tests will be available during the design of CTF which is not favorable to minimization of technical risk in the development of CTF.

In addition, the tests needed on the loops and notably on the CTF to qualify other components has not been taken into account.

Level of qualification of the compact IHX concept

If this schedule can be complied with, the qualification of the IHX will be fully completed by the end 2018 for starting operation of NGNP as required by the NGNP schedule.

But one should note that the technical risk associated to this schedule is important due to the overlapping of several tasks that should better be performed one after another to benefit from the feedbacks of the different tests. The fact that the compact IHX is an innovative concept should lead to provide margins in the schedule in order to adjust the design all along the development steps which is not the case in Schedule 2.

3.4.2.2.4 Conclusion on the reference development schedules

Two schedules are proposed for the compact IHX development program for NGNP.

In Schedule 1, no final qualification is planned before 2018 but long term tests on the representative loop can be performed and potentially extrapolated to full scale IHX. There is limited overlapping of the tasks but relying on tests limited to 1 MW is risky as regards licensing of the component.

In Schedule 2, a final qualification is planned before 2018 but the timeframes to perform the tests are very limited and the overlapping of the tasks is significant, so that design optimization by feedback of the tests all along the development program is difficult. This is not favorable to the development of an innovative concept such as compact plate-type IHX.

In both cases, an important technical risk has been identified due to limited timeframe until delivery of the IHX planned by the end 2016.

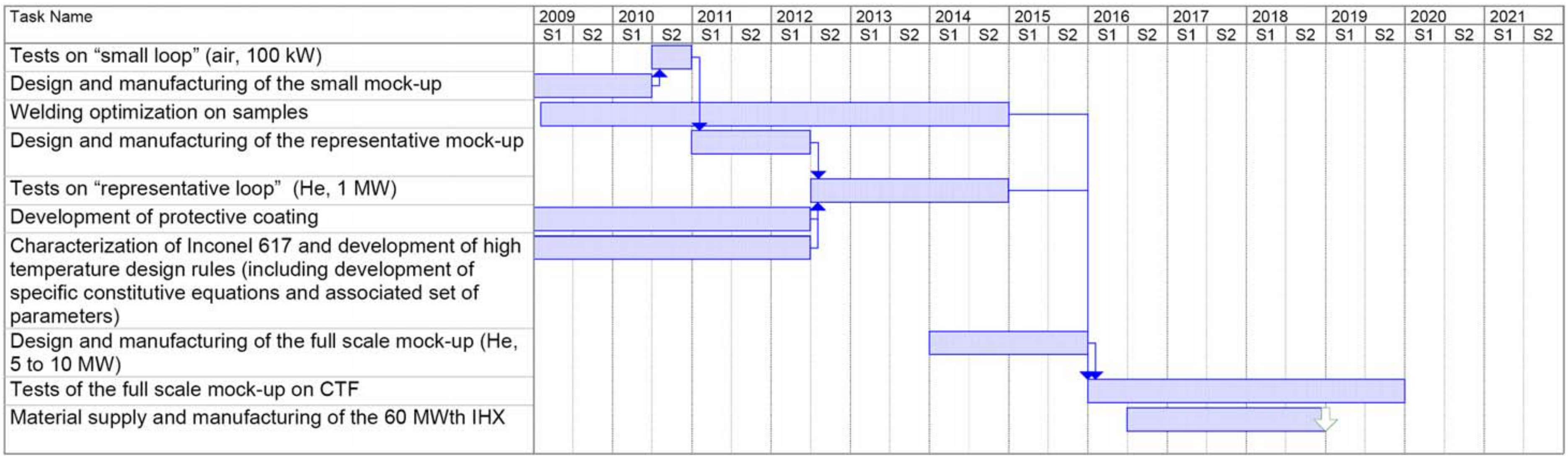
The IHX development program is at least on the critical path, if not oversaturated. Any delay in the development of a loop or in any test may endanger the whole schedule and consequently the whole NGNP schedule. The possibility to access to other helium loops (see Document No. 12-9072397-000 “NGNP Component Test Facility”) can help securing the NGNP schedule, all the more that not all tests require the most stringent conditions that can be provided by the representative loop or the CTF.

3.4.2.2.5 Ways of minimization of the risk

Due to the high technical risk foreseen for the compact IHX schedule, an alternative strategy is proposed.

It is estimated that delaying the starting of the 60 MWth test loop would have limited consequence on the NGNP schedule. The hydrogen process unit may indeed be available later than the starting of the PCS 2018 deadline.

If we assume that the end 2016 deadline for the availability of the compact IHX on the test loop can be postponed, the risk of the compact IHX schedule can be strongly reduced. Therefore, an alternative schedule is proposed (Schedule 3) which is considered as more realistic and satisfying in terms of design optimization possibility and licensing risk limitation.



ALTERNATIVE SCHEDULE 3 FOR NGNP COMPACT IHX DEVELOPMENT

Schedule 3 is based on Schedule 2 except that the overlapping of the tasks is reduced. Notably, feedback of the tests on representative loop is possible, which is much more favorable to design optimization. In this schedule, the compact IHX qualification should be completed by the end 2018 (three years should be sufficient for the qualification tests but further testing until the end 2019 can be performed if additional information can still be gathered).

An additional benefit of Schedule 3 is that the risk of overlapping of the CTF tests campaigns of tubular and compact IHXs is strongly reduced.

If it does not seem acceptable to postpone the starting of the 60 MWth test loop, the possibility to start operating NGNP with a tubular IHX on the test loop can also be considered (the tubular concept has to be qualified anyway in accordance with the 2018 deadline for the PCS). In this case, the tubular IHX would be replaced by the compact IHX as soon as its qualification is fully completed.

In any case, it is proposed to provide a large enough pressure vessel on the 60 MWth loop in order to house either a tubular or a compact IHX. This would allow either to start NGNP operation with a tubular IHX to provide more time for qualification of the compact one, or to replace the compact IHX by a tubular IHX in case of failure of the first one.

Remark: Such a pressure vessel would be of a size comparable to the ones of the PCS IHXs because the tubular IHX needs a length independent to the power but proportional to the inlet/outlet temperature difference and the diameter requirement due to the compact IHX follows the same dependence.

3.5 Comparison of Tubular IHX and PSHE concepts

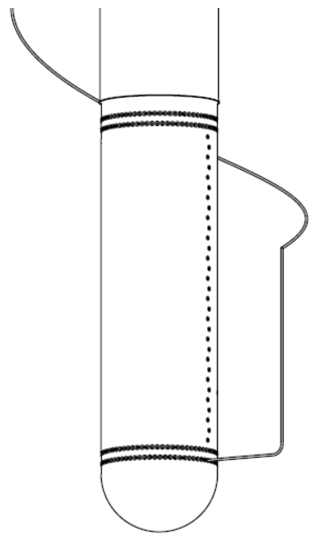
3.5.1 Feasibility of tubular IHX

3.5.1.1 Manufacturing issues

High numbers of tubes are foreseen for the NGNP tubular IHXs (>2500 when the past German IHX were designed with ~1500 tubes). So the size of the main components will have to be increased.

3.5.1.1.1 Hot header manufacturing

The main interrogation about the tubular IHX manufacturability concerns the hot header (see hereunder). This piece collects the whole hot secondary gas flow coming from the bundle and exiting the IHX.



The cylindrical hot header is the highest loaded component of the tubular IHX and it is outstandingly important for the safety because it has to assure the primary loop tightness after the design accident, the rupture of a secondary loop duct.

Therefore, it is considered that this component should be forged so as to avoid welded joints in it.

It should be checked that the hollow needed for this component can be forged by a manufacturer with the sufficient diameter and thickness to connect the whole tube bundle. Past experience suggest that the forging may be challenging for the number of tubes expected for the NGNP tubular IHXs.

The arrangement of the tube connections onto the header needs to be defined (pitches, machining of nipples) so as to define the density of tubes that can be fitted on the header and its size as a result.

3.5.1.1.2 Other components

Notably the tube plate and the supporting system feasibility could be impacted by a too large number of tubes.

3.5.1.2 Operational issues

The tubular IHX concept generates less thermal gradients than the compact IHX so that more transients can be tolerated in comparison.

It should however not be considered that important margins will be available in terms of lifetime.

The indirect steam cycle configuration should however be favorable as regards transients as compared to the combined cycle configuration.

3.5.1.3 Dust clogging

In dry atmosphere, it has been assessed that a graphite dust grain is typically of a size of about Ø=1µm and that if $3Ø<D_H$ (D_H=hydraulic diameter), then no fouling should be expected. So the risk of dust clogging is negligible in a tubular IHX (primary side outside the tube bundle and distance between two tube walls is at least 10 mm).

For tubular IHX, even in case of accidental entry of water and of agglomeration of the grains, it seems highly unlikely to face any clogging issue.

3.5.1.4 Maintainability

As for the compact IHX, maintenance may be needed in order so avoid graphite dust accumulation in the circuits. However, the tubular IHX design seems to be less prone to dust accumulation because the primary circuit has a very large passage section (outside the bundle).

If a "cleaning" of the IHX is however needed, it still has to be completely defined and the demonstration should be done that no deleterious interaction with the IHX material (possibly including protective scale) is possible and that polluting element release after cleaning can be ruled out.

3.5.1.5 Ability to detect leak

As for the compact IHX configuration, the leak detection does not seem easy because fluids at both sides are nearly identical and activity detection is not possible due to the pressure arrangement.

The ability to localize the leaky tube in case of leak detection is an important requirement. This function can hardly be ensured by a leak detection system and the inspection of each tube one by one seems to be necessary in case of leak detection (e.g. thanks to eddy currents probe as evoked in section 3.5.1.6 below).

3.5.1.6 In-service-inspection requirements and possibilities to detect material failures

Again, the ISI requirements are not clear today and the definition of the safety classification of the IHX is necessary to define the ISI requirements.

The tubular IHX however offers inspection possibilities because of its simpler design than the compact IHX.

The German experience has shown that eddy current tests can be performed from the inside of the tubes by the mean of a manipulator.

The remotely controlled manipulator had to be transported through the central duct downwards to the hot header to position a testing sensor via a TV camera. The sensor was then transported by the cable into the tube that must be checked.

3.5.1.7 Replaceability / repair

In case of failure of a tube, and providing that the faulty tube is localized, it can be sealed on site, resulting in a marginal loss of power and stop of the leak. This operation is however relatively complex and needs to be studied in detail.

Replacement of a single tube seems conceivable in workshop but there is *a priori* no need to do so (sealing a single tube has marginal consequences) except in case of failure of a large number of tubes.

3.5.1.8 Erosion

The order of magnitude of the primary helium velocity is ~10m/s (~20m/s for the compact IHX). On the other hand, the heat exchange area is increased (~3500m^2 against ~2500m^2) but the orders of magnitude are not that different.

So, a comparison *a priori* of the two concepts is not possible and, as for the compact IHX, further investigations are needed in order to demonstrate the acceptability of the IHX concept as regards this topic.

3.5.2 Feasibility of PSHE

3.5.2.1 Manufacturing issues

The manufacturing of a module consists of three main steps: machining of the plates, stamping of the plates and assembling them together. Information on those three steps is given in section 3.4.2.1.5.

3.5.2.2 Operational issues

The plate-type IHX concepts generates by nature higher thermal gradients due to reduced thicknesses, increased compactness and boundary effects than simpler tubular IHXs. This results in important damage induced by transients on the component.

Thus, the component is hardly tolerant to transients so that the flexibility of the plant operation modes could be limited by the compact IHX.

3.5.2.3 Dust clogging

In dry atmosphere, it has been assessed that a graphite dust grain is typically of a size of about Ø=1µm and that if $3Ø<D_H$ (D_H=hydraulic diameter), then no fouling should be expected. So the risk of dust clogging is considered as negligible in PSHE modules (D_H=1.5mm).

However, in case of accidental entry of water, the grains could agglomerate which still has to be checked.

3.5.2.4 Maintainability

Periodic maintenance of the IHX will probably be needed in order to avoid accumulation of graphite dust coming from the NHS in the modules.

A chemical process may be needed in order to periodically remove the dust from the channels. In that case, this process should have limited interaction with the material surface. In addition, cleaning of the channels would probably be needed in order to remove any chemical element that could remain in the IHX and then pass into the primary and secondary Helium.

Such a process still has to be entirely defined and its required frequency has not been evaluated either.

A much easier process would be to blow a powerful flow of Helium into each of the modules so as to drag along the graphite dust out of the channels. The efficiency of such a technique has however to be proved and the erosion risk should be assessed.

It should be underlined that maintenance to avoid dust clogging could have an impact on the availability of the IHX. In this perspective however, the use of the compact IHX on the test loop is favorable regarding the maintenance possibility of the IHX due to limited availability requirement of this loop.

3.5.2.5 Ability to detect leak

In normal operation, the primary pressure is lower than the secondary one so that a leak would result in an entry of secondary helium into the primary circuit. As a result of the impact of the coolants on the materials, the primary and secondary helium impurities will need to be tightly controlled in order to reach the most benign atmosphere in both circuits. So the compositions of the two coolants will need to be very close.

3.5.2.5.1 Activity detection

Activity detection is considered as the easiest and the most performing mean of leak detection.

However, leak detection based on activity release is not possible in normal operation because of the pressure arrangement.

If leak from primary circuit to secondary one should be controlled (assuming depressurization of secondary circuit for any reason), activity detection is recommended because of its high performances.

3.5.2.5.2 Chemical detection

For normal operation, the use of a tracer artificially added in the secondary circuit could be a mean of leak detection from secondary circuit to primary one. Such a tracer would need to have several features. The following requirements would be in favor of a large quantity of tracer in secondary circuit:

- To be rapidly detectable
- To leak as much as Helium molecules into small defects

A tradeoff would need to be found with the following requirements (in favor of a small quantity of tracer in secondary circuit):

- Not to affect the thermal performances of secondary Helium
- To have a negligible role as regards oxidation of the material of the IHX and of the other components of the secondary loop.
- To have acceptable interaction with the NHS in case of leakage

In a first approach, such leak detection is considered as complicated.

3.5.2.5.3 Pressure/temperature variations detection

Pressure variation monitoring on both primary and secondary sides is of interest for control of the pressure difference between primary and secondary circuits at least at nominal operation. The nominal pressure difference should be defined within a range so as to avoid corrective actions for normal variations of pressure due to the circulators. For an abnormal pressure difference value the discrimination between an IHX leak and other events as inadvertent discharge on one side or whatever is not easy.

For temperature detection, a rather small IHX leak should probably lead to thermal local effects which are globally integrated in the mean temperature seen by the temperature sensors set at outlet of both IHX sides. The induced variations could possibly be small and should not significantly be discriminative for the IHX leak detection.

Pressure or temperature use for IHX leak detection has also the drawback of measurement uncertainty and shifting.

3.5.2.5.4 Conclusion

In normal operation, leakage detection by activity control is not possible due to the arrangement $P_2>P_1$. On the other hand, it can be envisioned for detection of leakage from primary to secondary side in case of pressure reversal for any reason.

Chemical detection of leakage from secondary to primary circuit seems conceivable but the choice of the tracer is delicate and it is not demonstrated that sufficient performances can be reached.

Pressure or temperature control does not seem to be performing enough to detect small leaks.

Leakage detection is easier to implement in an arrangement with $P_1>P_2$ thanks the high performances of activity detection.

3.5.2.6 In-service-inspection requirements and possibilities to detect material failures

Definition of the safety classification of the IHX is necessary to define the ISI requirements.

If a detailed ISI is finally required for any safety reason, the compact IHX should have little capability to be inspected in detail. So the stress should also be laid on the performances of the other devices that play a role in the confinement barrier function (leakage detection system and isolation valves).

In that perspective, the pressure arrangement $P_1<P_2$ which leads to difficulties to find a leakage detection system easy to implement and performing is not favorable in a will to relax the ISI requirements on the compact IHX. Even if the natural leak in normal operation is from secondary to primary circuit (favorable to confinement barrier function), a small IHX failure is difficult to detect rapidly in this configuration.

In case of detection of a failure by the leak detection system, the process should be:

− To localize the failure (in which module, and where in the module).

− To explain the reasons of the leakage in order to exclude the potential generic feature of the default.

− If this generic concern is confirmed or enough likely all of the modules should be inspected in detail in the faulty zone.

Localization of the failure is a challenge for the compact IHX.

Determining which module is leaky seems difficult. If the leakage detection is based on chemical detection by tracer, localization of the leaky module is not practicable. For a leakage detectable by activity, localization needs to be demonstrated.

Localization of the failure in a leaky module needs inspection in factory with all the constraints linked to activity.

It has to be underlined that the PSHE concept recommended for the compact IHX does not include any joint in the active part of the plates, as opposed to PFHE and PMHE concepts (respectively assembled by brazed fins and diffusion bonding joints between plates). Welded joints are localized all along the borders of the plates and inside the secondary headers which allows potential access as opposed to the other concepts for which inspection of the joints in the active zones is excluded.

However, the inspection of the border welded joints does not seem easy as access is only available from the outside. This may limit the quality of the practicable controls. The concept does not seem to be adapted to perform these inspections on-site.

The secondary header welded joints inside the modules offer only access from one side as well. But there are additional difficulties. The secondary inlet or outlet pipes need to be removed and a dedicated rotating device with a probe is needed in order to inspect the welds. This operation can not be performed on-site.

Access to the inlet/outlet header pipes outside the modules may be possible by introducing a remotely controlled manipulator equipped with a probe into the central secondary hot pipe.

As a conclusion, complete inspection of the compact IHX is probably not practicable on-site and the quality of the control may be limited due to limited access of the welded joints (one side only). Nevertheless, PSHE is the best compact plate-type IHX concept regarding ISI due to the access provided to the welded joints (limited but not null as in the other concepts).

3.5.2.7 Replaceability / repair

The risk of failure of the IHX should be taken into account (especially for the innovative concept of compact IHX) and the needs to repair also. Main concerns are the leaks and the weak points are essentially the welds. But due to the very high temperatures at significant pressures in the current NGNP configuration, it cannot be excluded either at this stage the possibility that the IHX could fail at base metal level.

The replaceability of the IHX depends on the following topics:

- Capability of repairing internal parts

This is not possible in the IHX vessel. Even in factory, repairing is questionable. It can however be noted that, as regards repairing of welded joints, PSHE has an advantage on the other compact plate-type IHXs because of the relative accessibility of its welds.

- Capability to repair headers and manifolds

Some possibility may exist in the IHX vessel through the central hot duct but the accessibility is limited.

- Capability to repair the connections of IHX internal parts to headers

Some possibility may exist but remain to be proved (same difficulty of accessibility).

- Contamination level sufficiently low to allow repair using reasonable means

- Decontamination capability

The repairing capability of a PSHE module appears very limited and replacement should probably be preferred in most cases.

3.5.2.8 Erosion

The coolants are flowing in the IHX at velocities of about ~20 m/s in each circuit and they are conveying solid impurities. So the IHX material could be eroded. In fact, it is estimated that the risk could only exist on the primary side where graphite dust coming from the NHS is present in the coolant.

It is considered that the higher risk related to erosion is the cobalt tearing off. Cobalt is an element that can easily be activated by radiations from the NHS. Therefore, it is avoided in NHS internals. Alloy 617 contains a relatively high content of cobalt (~12%) so that if an important quantity of cobalt was torn off the alloy, then the contamination of the primary circuit would be greatly increased as a consequence of activation of cobalt particles passing through the NHS.

This topic should still be investigated so as to find erosion laws that would be able to account for the phenomena at stake in a NGNP IHX.

In the frame of GT-MHR investigations for a direct gas cycle (Brayton cycle), it has been shown that graphite particles of the primary circuit were not able to tear a significant quantity of cobalt off the turbine blades (with high content of cobalt). The velocities at stake were much higher but the erosion laws were specific to the leading edge of the turbine blades. In case of the IHX, the surface is much more important so that this topic requires complementary investigations.

A point that needs to be taken into account is the oxide scale at the surface of the alloy. Even if no protective coating is applied on the material, a passive layer of chromia (free of cobalt) is rapidly formed. This should be a very positive point so as to demonstrate that a negligible quantity of cobalt would be removed from the alloy as a result of erosion.

AREVA *a priori* considers that erosion is not a critical issue and that this risk is acceptable.

3.5.3 Comparison table

This table provides a comparison of the recommended compact IHX (PSHE) and the tubular IHX for the purpose of NGNP with indirect steam cycle.

	Compact IHX	Tubular IHX	Comments
Manufacturing issue	Laser welding difficult to adjust. The welding process could need to be changed.	Forging of the hot header seems difficult due to its large size, which notably implies a limited number of tubes	Even if the full scale tubular IHX may face some difficulties like the forging of the hot header, the existence of the 10 MWth mock-up shows that a sound experience exist on this topic (notably on the welded joints) whereas PSHE modules made of Inconel 617 have never been realized.

Lifetime for prolonged operation at 900°C	Challenging	Consistent with German experience	
Lifetime for prolonged operation at 950°C	Very challenging	Challenging	In KVK (Germany) or HTTR (Japan), 950°C was reached only for limited durations in tubular IHXs.
Operational issues	Very sensitive to transients	Sensitive to transients	In any case at 900°C, the components' lifetime can be strongly reduced if severe transients are applied on them. But due to the inherent difficulty to justify prolonged lifetime of the compact IHX, this concept should be considered as less tolerant to transients conditions than the tubular one.
Dust clogging	Low risk	Negligible risk. The primary coolant flows outside the tube bundle and the distance between two tube walls is at least 10 mm.	In case of accidental entry of water, the grains could agglomerate which still has to be checked. If this could be an issue for compact IHX, the risk for tubular concept is very limited by its design (primary circuit outside the tube bundle)
Maintainability	Periodic cleaning of the IHX to avoid dust clogging could be necessary and a process should be defined	Ditto compact IHX	The risk of dust clogging however is much more limited for tubular IHX.
ISI&R	Low inspectability. But among the other plate IHX, PSHE is the only one without totally hidden joints in active part of the modules	On-site inspection of the tubes (including welded joints) possible e.g. with an eddy current probe (access through the hot header).	For both concepts, the ISI&R requirements still need to be defined precisely regarding safety classification. Tubular IHX shows an important advantage regarding ISI&R.
Consequence of a leakage	As regards safety, the failure of a whole module has to be envisaged (about 1% of the mass flow)	The failure of a single tube has limited consequences (about 0.01% of the mass flow)	The tubular concept shows an important advantage regarding this topic.
Erosion	Velocities ~20 m/s. Area ~2500m^2	Velocities ~10 m/s. Area ~3500m^2	Erosion laws still need to be studied so as to demonstrate that the phenomenon is negligible. The velocity and area values comparison is not relevant to compare the two concepts regarding erosion.

3.5.4 Required material strength properties

The selected material for the IHX internals (especially tubes) is Alloy 617. In this section, the material's sensitivity toward high temperature is investigated herein. Note that the values shown in this section are for comparison only. Since there are some assumptions that need further verification, these do not represent the final results but rather show general trend.

Creep Fatigue

Tube is one of the most critical parts in tubular IHX. It is the thinnest part (about 2mm) of the component and is the place where vast thermal energy is transferred thus sees large temperature differences. The original design that the NGNP tubular IHX is based on had used 50K approach temperature (difference between primary inlet temperature and secondary outlet temperature). However, for the NGNP design, an approach temperature of 75K is envisioned. The higher approach temperature obviously leads to more severe thermal stress but renders other advantages such as lower inlet temperatures to SGU, smaller heat transfer area (i.e., shorter tube bundle length) thus leads to shorter tube length etc. Therefore, it is prudent to examine what the impacts are to the design life and strength of the material. Since transients are not defined at this stage, detailed thermo-mechanical stress calculation is not possible. But, with a simplified condition, one can still calculate thermal stresses and design life of the tube. In this study, two approach temperatures (50K and 75K) are examined (note that additional details are provided in section 5.4.1). This study assumes 9-month cycle and short shutdowns in between for the life span of 20 years. Using ASME Section NH, the results are as follows:

Table 3-8 Results of simplified analysis

	50K	75K
Total stress at inner wall in normal operation	16.6 Mpa	24.5 Mpa
Creep fatigue damage after 20 years	0.11	0.075

The results (see Table 3-8) show that based on current design baseline (75K), the thermal stresses have been increased compared to those of approach temperature of 50K. It's because increasing the approach temperature also increases the thermal gradients through the tube wall. But, the creep-fatigue damage has not been increased due mainly to the decrease of tube average temperatures. These results should not be considered as a general rule but they show at least that we should not necessarily expect a significant reduction of design life due to the increase of approach temperature. The creep fatigue damage from 75K of approach temperature is shown to be small enough to provide some flexibility to accommodate more severe transients, welded joint effect and environmental effect. However, this study did not take into account of other loadings such as weight, fluid forces etc. These will be taken care of in subsequent analytical phase. It is further to be noted that other calculations showed increasing the pitch distance on tubes can reduce thermal stresses. This could be used to further reduce creep-fatigue damage and therefore increase the design lifetime.

Effect of temperature

Increasing temperature adversely affects both IHX design feasibility and design lifetime. Figure 3-18 provides a better view of the strong dependence of component lifetime on temperature for Alloy 617 in the high temperature regime based on the KTA (German design code). A temperature increase of from 850°C to 950°C results in either a reduction in lifetime by more than a factor of 10 or a reduction in design stress by more than a factor of 3.

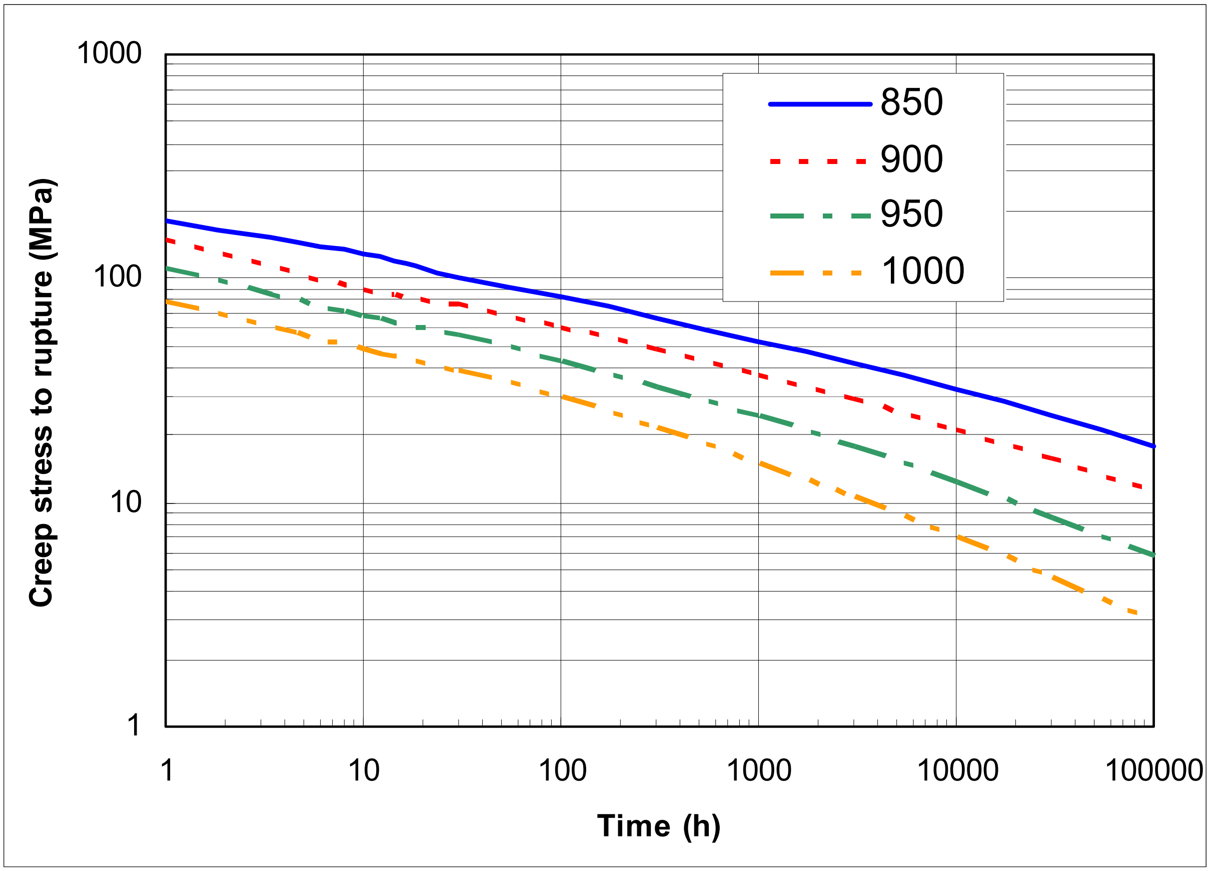


Figure 3-18 Creep Rupture Stress for Alloy 617 (Sr Curve KTA base metal)

In conclusion, Alloy 617's strength seems consistent with proposed operation at 900°C for 20 years. Operation at higher temperature would significantly affect the design life. The IHX's feasibility drastically changes to small change of temperature. It has shown that there are a few impacts of having a higher approach temperature of 75K as opposed to an approach temperature of 50K. The impacts are

- Improve the SGU feasibility
- Improve compactness and manufacturability of the IHXs
- Slightly improve the plant efficiency by easing the secondary helium blowing
- Possibly penalize the capability of the helix to accommodate thermal expansion

However, increasing the pitch between the tubes seems to be an efficient mean of increasing the lifetime for a given value of approach temperature. So it seems interesting to go for a rather high IHX approach temperature so as to benefit from the positive impacts and if necessary compensate the lifetime reduction by increasing the pitch between the tubes.

3.5.5 Risks

In PCDSR (Ref. 20), some key risks in many different areas were defined and assessed. In this section, the risks are revisited and reassessed with updates resulting from current project options. It is to be noted that only the risks related to the IHX issues will be dealt herein. Before going right to the summary assessment table, the terms and definitions related to the risk management need to be reminded and they are described in section 3.5.5.1

3.5.5.1 Assessment methodology

Risk assessment involves determining the probability of the occurrence of a risk (Table 3-9), assessing the consequences of this risk (Table 3-10), and combining the two to identify a probability/consequence (P/C) correlation score. This P/C score represents a judgment as to the relative risk level to the project as a whole. Based on the risk level, handling strategies are identified to appropriately respond to the risk.

Table 3-9: Probability of Occurrence

Qualitative	Quantitative	Criteria	Score
Very Unlikely	< 0.2	Will not likely occur anytime in the life cycle of the project or its facilities. The probability of occurrence is remote and less than 20%.	1
Unlikely	≥ 0.2 but < 0.4	Will not likely occur in the life cycle of the project or its facilities. The probability of occurrence is greater than or equal to 20% but less than 40%.	2
Likely	≥ 0.4 but < 0.6	Will likely occur sometime during the life cycle of the project or its facilities. The probability of occurrence is greater than or equal to 40% but less than 60%.	3
Very Likely	≥ 0.6 but < 0.8	Will likely occur sometime during the life cycle of the project or its facilities. The probability of occurrence is greater than or equal to 60% but less than 80%.	4
Most Likely	≥ 0.8 but < 1.0	Will occur sometime during the life cycle of the project or its facilities. The probability of occurrence is imminent and greater than or equal to 80% but less than 100%.	5

Table 3-10: Consequence of Occurrence

Qualitative	Quantitative	Criteria	Score
Negligible	< 0.1	Minimal or no consequences in project performance. No threat to project mission, environment, or personnel. Cost estimates not exceeded. Negligible impact on project mission.	1
Marginal	≥ 0.1 but < 0.3	Small reduction in project performance. Moderate threat to project mission, environment, or personnel. Cost estimates marginally exceed budget proposals. Potential adjustment to schedule/ milestones required that may affect the project mission.	2
Significant	≥ 0.3 but < 0.7	Significant degradation in project performance. Significant threat to project mission, environment, or personnel. Cost estimates significantly exceed budget. Significant adjustment to schedule with resulting milestone changes that may affect the project mission.	3
Critical	≥ 0.7 but < 0.9	Project objectives cannot be achieved. Serious threat to project mission, environment, or personnel. Cost estimates seriously exceed budget. Excessive schedule changes unacceptably affecting the project mission.	4
Crisis	≥ 0.9 but < 1.0	Project objectives cannot be achieved. Catastrophic threat to project mission, environment, or personnel. Cost estimates unacceptably exceed budget. Project mission cannot be completed; failure imminent.	5

3.5.5.2 Risk Management Results

3.5.5.2.1 Compilation of Identified Risks

The results of the risk identification step produced clear statements of risk with corresponding bases in three main categories:

- Design (4 risks identified), and
- Licensing (1 risk identified).

These risks are compiled in Table 3-11 along with mitigation strategies or specific tasks, as necessary, to lower probabilities of occurrence and/or reduce consequences. Top or key risks within these categories are discussed in the next section.

3.5.5.2.2 Key Risks for the IHXs

In applying the Risk Management approach described above, two areas emerge as presenting the greatest risk to the IHX design of the NGNP project. These "key" risk areas are discussed below. These areas have the highest unmitigated probability/consequence (P/C) scores, and as such, need to be targeted for immediate action and monitoring by management.

- Corrosion of IHX materials

  Due to the He impurities, the internal components are susceptible to the corrosion. To mitigate this risk, following actions can be taken

  - Develop on coating techniques
  - Decrease in-service temperature and pressure condition to use Hastelloy X or XR

- Codification of IHX materials

  IHX material needs to be codified in time for the 2018 operation. To mitigate this risk, following action can be taken

  - Interact with ASME and NRC management to encourage modification of the ASME code.

Table 3-11: NGNP Project Risk Summary

Risk ID No.	Risk Title	Description of Risk	Initial Risk			Approach	Management Strategy	Residual Risk		
			Prob	Cons	P/C			Prob	Cons	P/C
Design										
D-003	Corrosion of IHX materials	HTR past experience highlighted issues associated to oxidation (including internal oxidation), carburization and decarburization of In 617 under He plus impurities. The alloy is affected in depth, so the consequences of the material degradation are more important when the plate or exchange tubes are thin.	4	3	5	Mitigate	Assess the feasability of a protective surface treatment of the IHX material (coating). Decrease in-service temperature and pressure conditions to use Hastelloy X or XR instead of 617 or 230 alloy.	2 1	3 3	3 2
D-011	Plate IHX design feasibility (60 MW He/He loop)	Plate IHX feasibility (with a lifetime > 10 years) is a concern due to: temperature level, corrosion, manufacturing, and thermomechanical resistance.	5	2	4	Mitigate	Urgent to launch an R&D program: For corrosion tests on base and coated materials, For thermohydraulic correlations tests, For IHX representative mock-ups, For development of a visco-plastic model			

Risk ID No.	Risk Title	Description of Risk	Initial Risk			Approach	Management Strategy	Residual Risk		
			Prob	Cons	P/C			Prob	Cons	P/C
							(material database to be completed), and For manufacturing (diffusion bonding, brazing, ISIR). Reduce design life of 5 years for compact IHX.			
							Potential alternatives to mitigate the risk: 1) Reduce the design lifetime	3	2	2
							2) Fall back option with a tubular IHX on the 60 MW loop	2	2	2
							3) Fall back option with a tubular IHX at lower temperature in consistency with the steam cycle option to combined cycle.	1	2	1

Risk ID No.	Risk Title	Description of Risk	Initial Risk			Approach	Management Strategy	Residual Risk		
			Prob	Cons	P/C			Prob	Cons	P/C
D-012	Tubular IHX feasibility	Tubular IHX feasibility is a concern due to: size of the module, temperature level, corrosion, manufacturing, assembly (which are out of the state of the art)	3	3	4	Mitigate	Urgent to launch R&D program: For tube bending, tube welding, ISIR and assembly, For corrosion tests on base and coated materials, For thermohydraulic test to assess more accurately the correlations to be used in order to optimize the design, and For IHX representative mock-ups.			
							Potential alternatives to mitigate the risk: 1) Reduced lifetime target (< 20 years): IHX replacements are planned more frequently.	2	3	3
							2) Reduced size of the IHX module to fit with the state of the art from manufacturing point	2	3	3

Risk ID No.	Risk Title	Description of Risk	Initial Risk			Approach	Management Strategy	Residual Risk		
			Prob	Cons	P/C			Prob	Cons	P/C
							of view. 3) Fall back option to combined cycle option with a steam cycle at lower temperature that leads to feasible SG instead of IHX.	1	3	2
D-015	Large He Test Facility	A large He test facility (about 10 MW) is needed to do prototype testing of NHS components (valves, IHX, hot gas duct). Since such a facility does not exist, it must be built. Failure to complete the facility in time to do prototype testing would delay NGNP startup or could result in unacceptable plant performance if the NGNP was started up without prototype component testing.	2	3	3	Monitor	Monitor.	2	3	3

Licensing										
L-005	Codification of internal and IHX materials	ASME update to incorporate internal materials (alloy 800H is the prime candidate) and IHX material (617 or 230) is not developed in time or modifications proposed for these materials are not approved by the NRC.	2	4	5	Mitigate	Increase the presence within ASME Sub-Committees. Interact with ASME and NRC management to encourage the involvement of the NRC as early as possible in the process of modification of the ASME Code. Continue effort on R&D to support the Code modifications.	1	4	3

Legend	
Prob =	**Probability of Occurrence**
Cons =	**Consequence of Occurrence**
P/C =	**Probability/Consequence Correlation Score**
Risk Score	**Action**
≥ 9	Avoid the risk through alternative approach, if possible.
6, 7 or 8	Identify measures to minimize the probability of the Risk occurring (and actively manage those measures) and steps to mitigate the consequences should the Risk occur.
4 or 5	Identify steps to mitigate the consequences should the Risk occur.
2 or 3	Monitor the Risk.
1	Accept the Risk.

3.6 Identification of alternative secondary fluid environments

3.6.1 Introduction

The reference design for the NGNP uses helium as both the primary and secondary coolant. Being a gas, helium has a low volumetric heat capacity, and it is therefore necessary to circulate large volumes of it through the heat transport loops. At first glance, liquids appear to be an attractive alternative, offering the potential of reduced pumping power and IHX size. However, the significant differences in properties between helium and liquids mean that other aspects of the heat transport system will also be affected. This section discusses some of those differences and how their use as a secondary coolant might affect the design of the NGNP.

The coolants considered are sodium and molten salts, both of which have been used previously in nuclear reactor systems. Other liquid metals are considered unsuitable because of their incompatibility with high-temperature nickel alloys (Ref. 7). For each coolant, four topics are considered: the useful temperature range, the effect of the coolant on corrosion of piping and other structural components, the means required for chemistry control, and other chemical considerations such as toxicity and chemical reactivity.

3.6.2 Sodium

Sodium has been used as both a primary and a secondary coolant in a number of reactors, including experimental, demonstration, and commercial-scale fast-spectrum reactors (Ref. 1). Interest in sodium as a reactor coolant dates from the 1950s (Ref. 2). As a result there is a substantial body of knowledge and experience related to engineering of systems containing liquid sodium.

3.6.2.1 Temperature Range

The melting and boiling points of sodium are 98 °C and 882 °C, respectively (Ref. 3). Because the melting point is above ambient temperature, some design feature must be included to ensure that the sodium remains liquid even when the reactor is shut down. It would be preferable to have a design that would allow the sodium to be drained for maintenance and decommissioning.

The boiling point of sodium is slightly below the proposed operating temperatures for the NGNP. A recommended equation for vapor pressure (Ref. 3) predicts the vapor pressures of sodium at 900 and 950 °C to be 0.119 and 0.182 MPa, respectively. These values are well below the pressures being considered for the secondary loop. The sodium loop would therefore need a pressurizer to maintain a pressure balance between the primary and secondary sides at the IHX. Designing a sodium loop to operate safely at high temperatures and high pressures would pose a significant challenge, because a breach of the pressure boundary would result in a large volume of reactive sodium spray.

3.6.2.2 Corrosion

Corrosion of structural materials in liquid metals has been studied extensively. The following forms of corrosion have been cataloged (Ref. 4).

- Dissolution of the solid metal surface (general corrosion).

- Interaction between the solid and liquid phases to form intermetallic layers and solid solutions.
- Selective dissolution of alloying elements from the surface and subsurface of the solid metal, where the removal rate is generally controlled by either volume or grain boundary diffusion processes.
- Interaction between the solid metal and impurities in the liquid (e.g., O_2, H_2, N_2, C) to form oxidized and internally oxidized surfaces, solid solutions, or precipitated phases.

General corrosion is discussed here and interaction with impurities is discussed in the section on chemistry control. The other forms are considered to be less important but should also be evaluated if sodium is to be seriously considered as a coolant.

Corrosion of piping and other structural components has generally not been a problem for sodium-cooled reactors (Ref. 5). However, the coolant temperatures used in sodium-cooled reactors have generally not exceeded 575 °C (Ref. 1); those being considered for the NGNP are substantially higher. Bailly et al. (Ref. 5) also note that for "nickel alloys, the corroded layer is about twice that of austenitic steels for alloys with 40 % nickel, but is more influenced by the sodium oxygen content. At higher nickel concentrations, this value increases and becomes unacceptable at 50 % nickel." The composition of alloy 617 is nominally 54% nickel (Ref. 6).

At least one early evaluation noted that the corrosion performance of nickel alloys that contain iron, chromium, and molybdenum is "good" for exposure to liquid sodium at 800 °C (Ref. 7). Good performance was defined as a corrosion rate of less than 0.025 mm/yr. However, the same source also warns that the evaluations "represent for the most part only a limited number of relatively small-scale laboratory tests. It should not be assumed that the same numerical rates would apply in larger-scale heat-transfer systems" (Ref. 7). Figure 3-19 clarifies one possible reason for differences in corrosion behavior. At the coolant temperatures expected for NGNP, the solubilities of iron and chromium are both well above 10 ppm, and the solubility of nickel is nearly 10 ppm. All of the solubilities have substantial temperature dependence, and there would be a large difference between the temperatures of the sodium as it leaves the IHX and as it leaves a steam generator. As a result, metal from the piping or other structural components could be dissolved in the hot portions of the secondary loop, then carried to the cold portions and precipitated there. Corrosion of structural components by liquid sodium is therefore a significant concern for the NGNP.

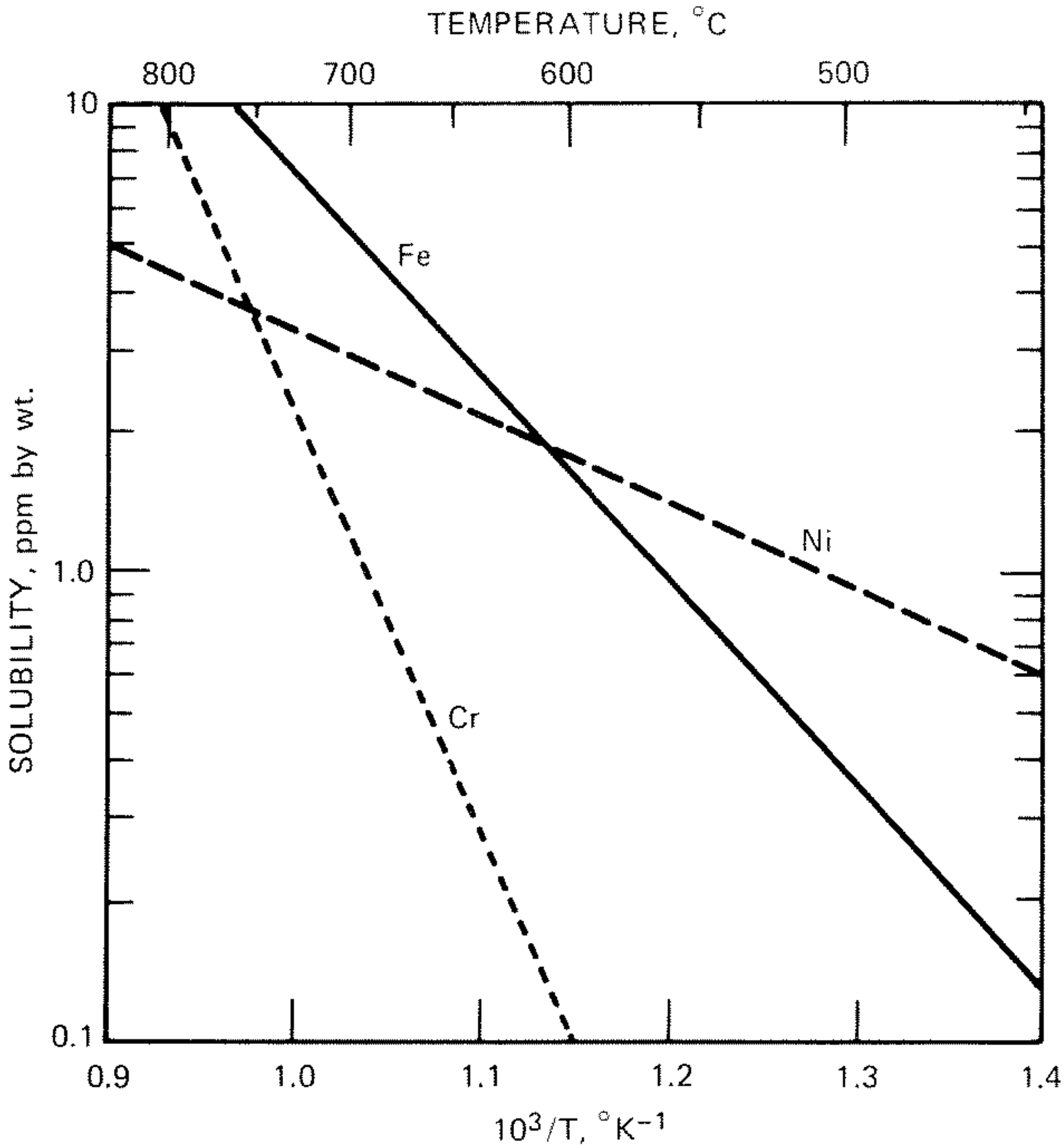


Figure 3-19 Solubility of iron, nickel, and chromium in oxygen-free sodium (from Ref. 8)

3.6.2.3 Chemistry Control

Oxygen is significant in promoting the corrosion of steels in liquid sodium. Iron and steel react with dissolved oxygen according to the following reactions (Ref. 9):

$3Na_2O(l) + Fe(s) \rightarrow (Na_2O)_2{\cdot}FeO(s) + 2Na(l)$

$2Na_2O(l) + Cr(s) \rightarrow NaCrO_2(s) + 3Na(l)$.

(The reactions above follow the notation of Ref. 9 in using "$Na_2O(l)$" as a shorthand for sodium with dissolved oxygen. Liquid Na_2O would not be present.) The latter reaction can be controlled by maintaining the oxygen concentration in the sodium at less than about 3 ppm (Ref. 9). On a thermodynamic basis, nickel-base alloys would be expected to be more resistant to this type of corrosion because nickel is more noble than iron or chromium. That view is supported by Olander's observation that dissolution of "pure nickel is unaffected by the oxygen content of the liquid metal" (Ref. 8). However, it was noted earlier that the dependence of corrosion rate on oxygen content is stronger for nickel alloys than for austenitic stainless steels (Ref. 5), so corrosion rates apparently reflect effects other than thermodynamics.

Oxygen is controlled in current sodium-cooled reactors by cold trapping. The solubility of oxygen in sodium varies strongly with temperature, rising from about 1 ppm at 120 °C to about 2700 ppm at 600 °C (Ref. 8). In cold trapping, a small amount of sodium is diverted from the heat transport system, cooled to just above the melting point, and passed through porous, sintered stainless steel or layers of fine stainless steel screen (Ref. 10). The cold trap causes crystallization of Na_2O on the stainless steel (Ref. 4). Currently available methods of oxygen control are expected to be sufficient for the NGNP as well.

3.6.2.4 Other Chemical Considerations

It is well-known that sodium is chemically reactive. At sodium-cooled fast reactor plants, the amount of sodium present is so large that leaks appear to be nearly inevitable. A recent report (Ref. 11) notes that "There have been small sodium leaks (and small fires) at essentially every sodium-cooled reactor plant built; in some cases, several of them." Sodium would be less prevalent in the NGNP because it would be used only as a secondary coolant, but its chemical properties would still need to be considered in designing for accidents. If the sodium is used to heat a steam generator, the designer must consider the possibility of sodium or water leaks. In addition, water and carbon dioxide could not be used to control fires because both react violently with sodium (Ref. 10; Ref. 2). The use of sodium as a secondary coolant is therefore expected to add significant complexities to the design of the NGNP.

3.6.3 Molten Salts

Work on molten salts in nuclear reactor systems dates to the 1950s. Several experimental reactors using molten salts were developed and operated at Oak Ridge National Laboratory; the reactors included the Aircraft Reactor Experiment, the Molten Salt Reactor Experiment, and the Molten Salt Breeder Reactor (Ref. 12). These reactors used molten salts not only as coolants but also as fuels. Other possible uses for molten salts are (1) as a primary coolant for use with solid fuel and (2) as a secondary coolant. It is the latter use that is being considered for the NGNP.

The following criteria have been established (Ref. 13) for selecting reactor salts:

- The ability to dissolve useful quantities of fissile and fertile material
- A small thermal neutron capture cross section
- Stability under intense radiation
- Chemical stability at high temperatures
- Low melting temperatures and low volatility
- Compatibility with high-temperature alloys.

The first criterion is applicable only to fuel salts, and the second and third apply to fuel salts and salts used as primary coolants. The remaining criteria apply to all three uses. Much of the recent work at on molten salts Oak Ridge National Laboratory has focused on their application as primary coolants, but some work has also considered salts as secondary coolants (Ref. 14) and is directly applicable to the NGNP. The candidate coolants are all mixtures of salts because the individual salts have unacceptably high melting points, whereas mixtures have melting points that can be substantially lower.

The candidate salts considered at Oak Ridge for use as secondary coolants fall into four sets (1) alkali metal fluoride salts, (2) ZrF_4-bearing salts, (3) fluoroborate salts, and (4) chloride salts. BeF_2-bearing salts had previously been considered as primary coolants (Ref. 12) but were excluded in Ref. 14 because of their toxicity. In contrast, chloride salts are included even though they had previously been excluded as primary coolants because of the large neutron capture cross section of ^{35}Cl and long half-life of ^{36}Cl (Ref. 15).

Compositions of candidate salt mixtures are listed in Table 3-12. Vertical position within the table is chosen roughly by melting point. Salts that were deemed to be too corrosive or volatile, that included oxygen, or that included heavy halides or mixed halides were excluded (Ref. 14).

Table 3-12 Compositions (in mole percent) and melting points for possible secondary coolant salts (Ref. 14)

Alkali Metal Fluoride	ZrF_4-Bearing	Fluoroborate	Chloride
	NaF-ZrF_4 (59.5-40.5) 500°C		
LiF-NaF-KF ("FLiNaK") (46.5-11.5-42) 454°C	LiF-NaF-ZrF_4 (42-29-29) 460°C	KF-KBF_4 (25-75) 460°C	NaCl-$MgCl_2$ (63-37) 475°C (58-42) 445°C
	LiF-NaF-ZrF_4 (26-37-37) 436°C	RbF-$RbBF_4$ (31-69) 442°C	KCl-$MgCl_2$ (68-32) 426°C
	NaF-RbF-ZrF_4 (33-24-43) 420°C		
			LiCl-KCl-$MgCl_2$ (9-63-28) 402°C
	KF-ZrF_4 (58-42) 390°C	NaF-$NaBF_4$ (8-92) 384°C	NaCl-KCl-$MgCl_2$ (20-20-60) 396°C
			LiCl-KCl (59.5-40.5) 355°C
			LiCl-KCl-$MgCl_2$ (55-40-5) 323°C
			LiCl-RbCl (58-42) 313°C

3.6.3.1 Temperature Range

The salt mixtures listed in Table 3-12 all have melting points well above ambient temperature, so the secondary loops will require auxiliary heating systems to keep the salt from solidifying when the reactor is shut down. If the salt remains in the secondary loop during inspections and maintenance, there will be significant challenges in designing electronic equipment that can operate in such a hot environment. It would therefore be highly desirable to have a design that would allow the salt to be drained for maintenance and decommissioning.

Most of the salt mixtures have low vapor pressures (about 15 kPa or less) at 900 °C (Ref. 14). The one exception is the NaF-$NaBF_4$ mixture, with a gas pressure of about 1.3 MPa. That pressure is still less than the expected operating pressure for the secondary loop of the NGNP, so it is probably acceptable.

3.6.3.2 Corrosion

The fluoride and chloride salts are effective fluxes and will readily dissolve oxide layers on the surfaces of piping and other structural components. Corrosion of metals is therefore better understood in terms of the solubility of the constituents of the metal parts rather than the properties of a passivating layer. Especially for the fluoride salt mixtures, the solubility of the metals can be discussed in terms of the free energies of formation of various salts. The preferred situation is to have coolant salts that are highly stable, that is, have strongly negative free energies of formation, and to use structural materials composed of elements that yield fluorides with free energies of formation that are substantially less negative. In that case, the cations in the salt (Na^+, etc.) compete very strongly for the available fluoride, whereas cations derived from the structural materials (Cr^{2+}, etc.) compete much more weakly. If the structural material cannot obtain fluoride ions, it remains as a metal rather than dissolving as a fluoride. The same considerations apply to chloride salt mixtures. Free energies of formation for selected fluorides and chlorides are provided in Table 3-13. (Note that the free energies of formation in Ref. 14 are given incorrectly as positive numbers; the actual values are all negative.)

It will be noted from Table 3-13 that, when compared to the fluoride salts, the chloride salts have much smaller differences in free energy between the coolant salts and the salts derived from structural materials. On this basis, chlorides would be expected to be more corrosive than fluorides. Additional study would be needed to confirm that conclusion (Ref. 14).

It will also be noted from Table 3-13 that chromium fluoride has the most strongly negative free energy of formation among the fluorides from structural materials. It would therefore be expected that alloys with a low chromium content would be more resistant to fluoride corrosion than alloys with a larger chromium content. Such effects were observed in early tests and led to the development of Hastelloy N for the Molten Salt Reactor Experiment (Ref. 12). Hastelloy N has a chromium content of 7%, whereas alloys 617, 230, and X have minimum chromium contents of about 20%.

Corrosion of piping and other structural components is also affected by the redox potential of the salt, with low (reducing) potentials generally being favorable. The salts themselves may limit the application of such a strategy for corrosion control. For example, ZrF_4 could be reduced to zirconium if too low a redox potential is imposed. The recommendation of Ref. 12 is to consider the ZrF_4-bearing salts with only mildly reducing conditions and LiF-NaF-KF with strongly reducing conditions.

It may be impractical to make a helium-to-salt heat exchanger from Hastelloy N. Its oxidation resistance in air is said to be “good”, with “promise for continuous operations at temperatures up to 1800°F (982°C)” (Ref. 16), but resistance to corrosion in primary helium is not known. In addition, the creep rupture strength of Hastelloy N appears to be substantially below that of alloy 617 (Ref. 16; Ref. 17). A clad material might offer a design solution, but such a product is not currently available.

Table 3-13 Free energies of formation for selected fluorides and chlorides (Ref. 14)

Cation Species	Free Energy of Formation, kcal/mol of halide element	
	Fluoride	Chloride
(Cations in salt mixture)		
Mg^{2+}	---	−124
Li^{+}	−125	−84
Na^{+}	−112	−81.6
K^{+}	−109	−87.4
Zr^{4+}	−96.9	---
(Cations from structural materials)		
Cr^{2+}	−75.2	−71.4
Fe^{2+}	−66.4	−58.2
Ni^{2+}	−55.3	−49.9

3.6.3.3 Chemistry Control

Salts supplied by manufacturers are apt to contain undesirable impurities, notably moisture and oxides. To prevent corrosion of structural components, the salts will need to be purified before use in a heat exchanger. Purification was studied during the early development of molten salt reactors, and the preferred method of purification for fluoride salts is sparging with HF and H_2, which removes moisture, oxides, chlorides, and sulfur (Ref. 12). Sparging may be followed by treatment with active metals to reduce the redox potential. Because HF removes chloride, an alternative method would be needed for chloride salts.

Experimental studies of corrosion have taken significant precautions to control the chemistry of test loops. One test (Ref. 18) used two separate salt supplies, one for cleaning the loop and one for the actual test. Cleaning of the loop was done as follows:

> Prior to the start of testing, the Hastelloy N loop was cleaned of residual oxides and other surface contaminants in two steps. First, the loop was flushed and then filled with argon/4% hydrogen, held at 850°C for two hours and then allowed to cool in an argon/4% hydrogen environment. Secondly, the loop and one of the salt supplies was heated to 550°C and the salt pushed into the loop by pressurizing the salt supply vessel with helium. The loop was then heated to 650°C and maintained at temperature overnight. The next day, the salt was allowed to flow back into its salt supply vessel.
>
> Following the above procedure, the loop was then filled with the working salt from the second salt supply vessel.

The test loop was sealed during the tests, so it was not necessary to actively control its chemistry. A working IHX would presumably have pumps with shaft seals that could leak, so some means of maintaining the salt chemistry would be needed.

3.6.3.4 Other Chemical Considerations

The fluoroborate salts, such as $NaBF_4$, tend to decompose at high temperatures, and the "vapor pressure" mentioned above is primarily due to the pressure of BF_3, produced by the reversible reaction

$$NaBF_4 \leftrightarrow NaF + BF_3(g)\ .$$

Decomposition of $NaBF_4$ poses challenges for several reasons (Ref. 14). First, it is toxic. Second, it reacts with moisture to form hydrogen fluoride, which is both corrosive and a chemical hazard. Moisture must be strictly excluded from the secondary loop. Third, local depletion of BF_3 from the salt mixture would result in an excess of NaF and therefore an increased melting point and risk of plugging. Fourth, cover gases, such as those that would be present in a pressurizer, must be controlled to prevent release of BF_3. These challenges tend to put the fluoroborate salt mixtures at a disadvantage with respect to the other mixtures.

Molten fluorides do not react violently with air or water (Ref. 18; Ref. 15), and chlorides are expected to have similar properties. It is therefore expected that design for accidents will not require elaborate considerations of the chemical properties of molten salt.

3.6.4 Conclusions

Although the use of sodium or molten salts as secondary coolants may not have been decisively ruled out, several significant or even severe challenges have been identified for each of these coolants. For sodium, some of the primary challenges are as follows:

- The design must ensure that the sodium remains liquid even when the reactor is shut down.
- The operating temperatures would be well above those at which sodium has been used in the past.
- A breach of a pressurized sodium loop would result in a large volume of reactive sodium spray.
- Corrosion of structural components is a significant concern.
- The chemical reactivity of sodium must be considered when designing steam generators or fire suppression systems.

For molten salt, some of the primary challenges are as follows:

- The design should allow for the salt to be drained for maintenance and decommissioning.
- For some salts, additional study of corrosion is needed.
- A structural material with sufficient creep rupture strength, combined with corrosion resistance in primary helium and molten salt, must be developed.
- Some means for cleaning the secondary loop before operation and maintaining the salt chemistry must be provided.
- If fluoroborate salts are used, the design must accommodate the decomposition of salts to form BF_3 gas.

3.7 Two-stage IHX design

3.7.1 Introduction

The purpose of this section is to document all possible types of two-stage IHXs and evaluate them based on the feasibility. "Two-stage" IHX is the IHX with two independent modules connected in series in one or two vessels. The first stage would be a high-temperature module with a limited expected lifetime, but that is easily replaceable. The first stage would feed the second stage which would operate at a lower temperature with longer expected lifetime. Both stages can have the same conceptual IHX types or different conceptual IHX types with the objective to optimize the overall lifetime and compactness.

This section evaluates the pros and cons for different kind of 2-stage IHX.

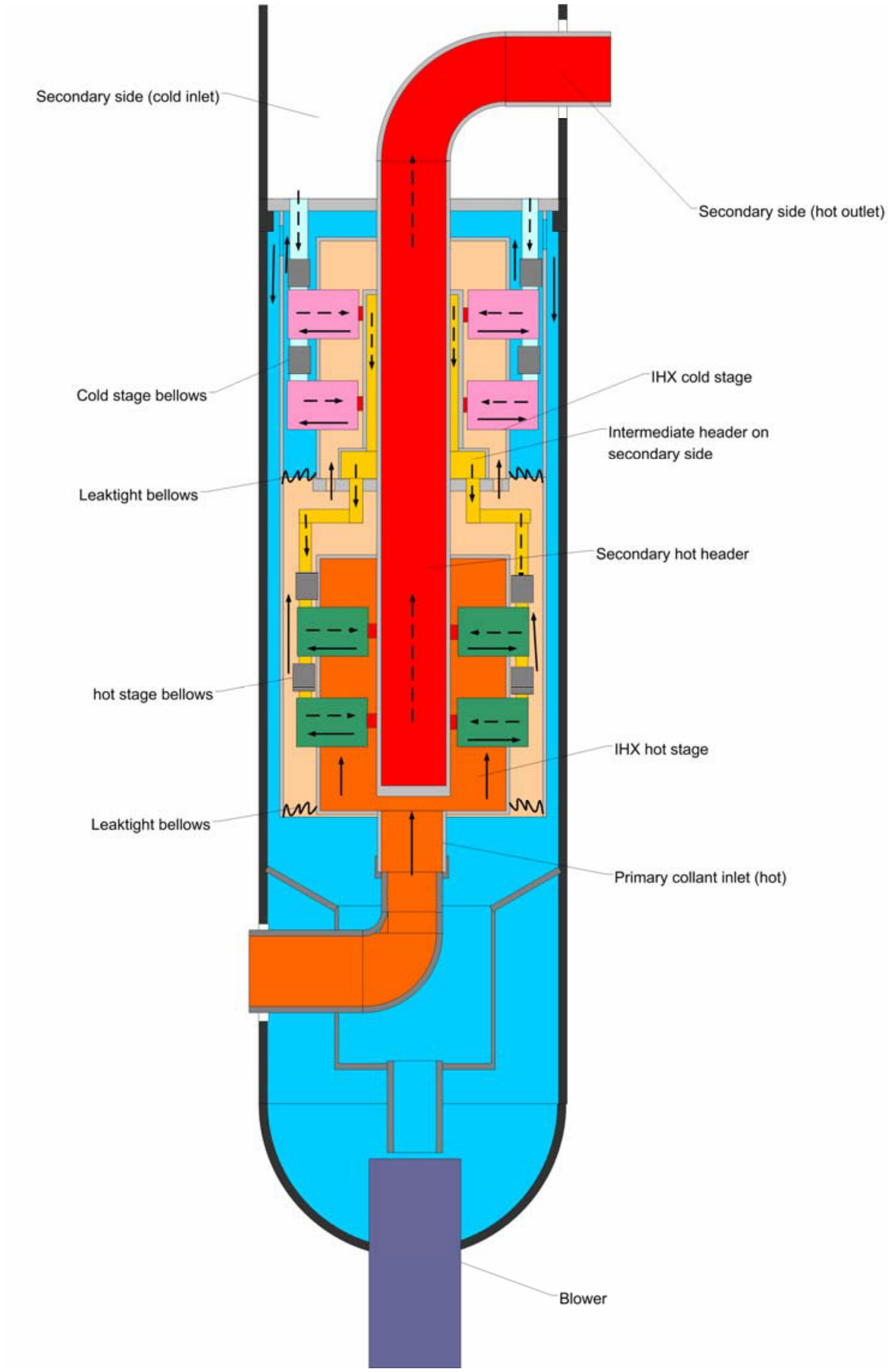
The arrangements evaluated are:

- 2 stage IHX in one vessel:
    - Plates/Plates heat exchanger for both cold and hot stages,
    - Tubes/Tubes heat exchanger for both cold and hot stages,
    - Plates/Tubes heat exchanger for respectively cold and hot stages,
    - Tubes/Plates heat exchanger for respectively cold and hot stages.
- 2 stage IHX in two vessels:
    - Arrangement independent of the kind of heat exchanger retained.

3.7.2 2-STAGE IHX IN ONE VESSEL

Plates/Plates IHX

The preliminary arrangement proposed for this 2-stage IHX is based on “Hot center” arrangement:



With the proposed arrangement, the hot side is at the bottom of the IHX package. In the case that the hot side has a shorter life time than the cold, it is necessary to remove the complete set of IHX modules for maintenance (but it is the same for 1-stage IHX).

Regarding repairing of the IHX, it could be envisaged to "cut" or disconnect only the hot side and to replace the hot stage modules, without modification on cold side.

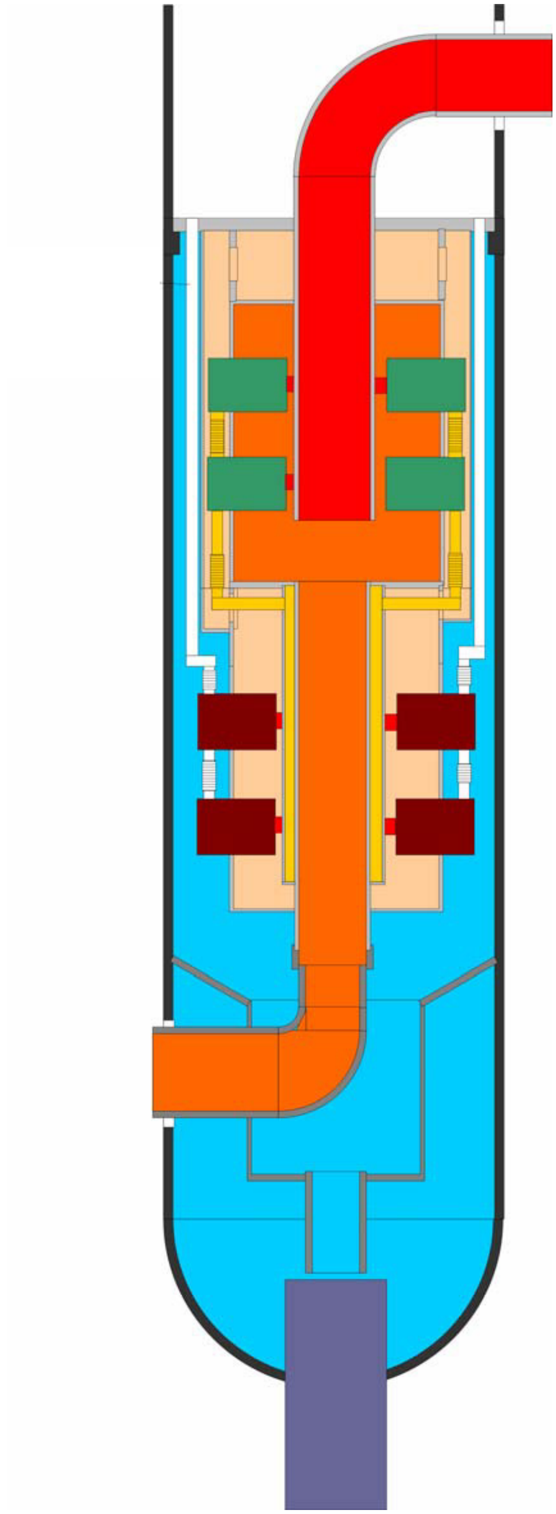
It could be also envisaged to have a design with smallest modules on hot side than on cold side, so as to enhance the life time of the hot side. But in this case the global height is augmented because the number of modules and therefore of levels is increased.

The weak points of the concept are mainly:

- Taller IHX vessel compared to 1 stage IHX. Since the operating temperatures of 1 stage are reduced, the active length (for the heat exchange) is reduced so as to be adapted to the temperatures. Consequently, the length of the modules is divided by 2 (height is kept the same as for 1 stage IHX) and therefore the number of "IHX levels" is doubled so as to conserve the global heat exchange area. That is why the height of IHX package is at least doubled compared to 1-stage IHX,
    - Expected overall dimensions for 1loop IHX:
        - Height: about 40m with blower and IHX vessel cover head,
        - Diameter: about 5.5 m,
- For the thermal expansions, it is necessary to foresee elbows on the secondary pipes, as for 1 stage reference design. But, with the hot IHX stage, the elbows are bathed with hot coolant. Design modification as the addition of expansions loops on the secondary pipes could be envisaged but the expected impact is an increase of the overall dimensions.

The plates/plates design doesn't present major advantage compared to the 1 stage arrangement (less compact, hot bellows) except the fact that the hot side could be designed slightly different from the cold side and could be replaced without a change on cold side.

An alternate design with the hot stage at the top is given by the following figure.

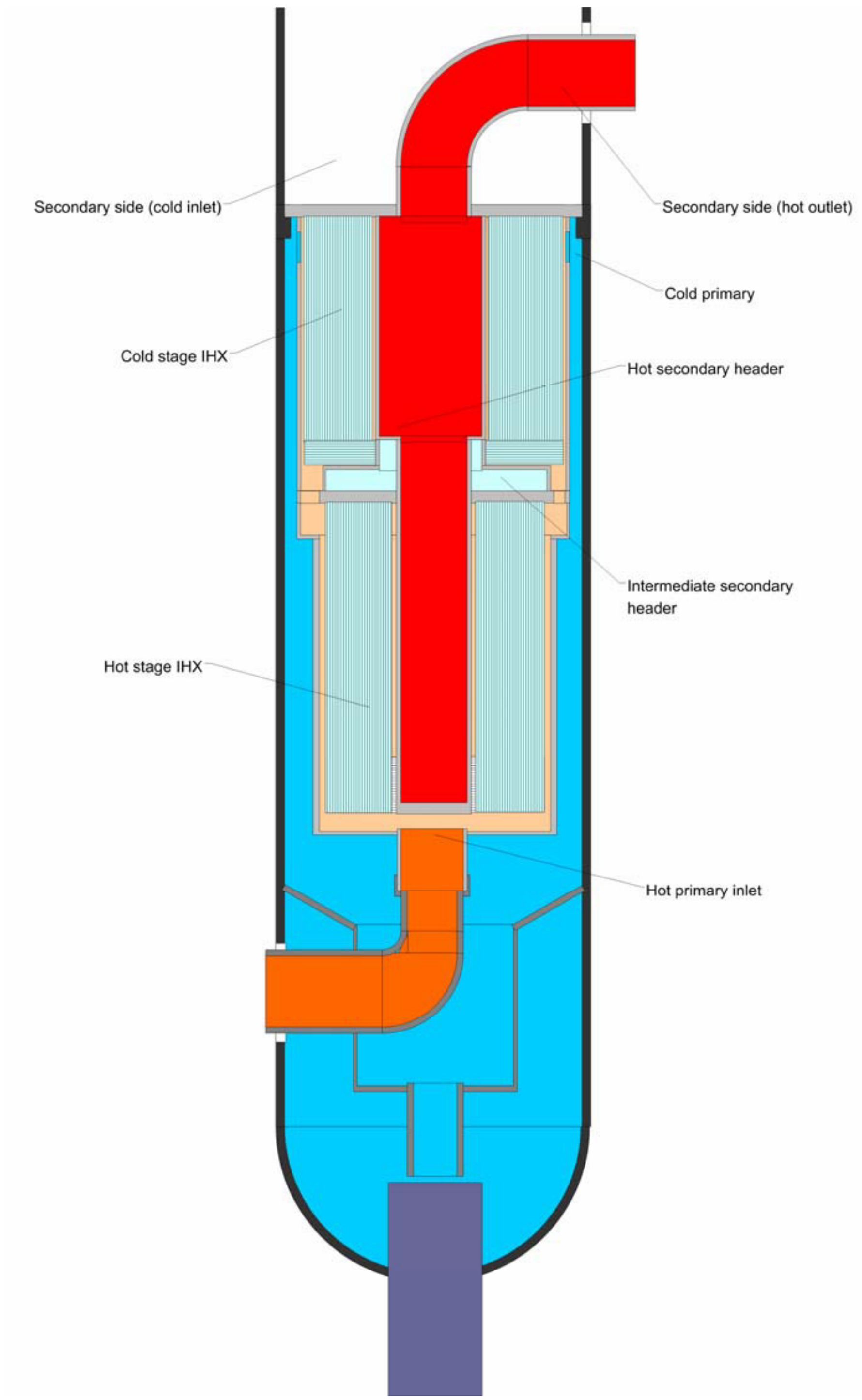


This design has mainly the same pros and cons as the 2-stage plates/plates IHX with the hot stage at the bottom. Besides, compared to the hot stage at the bottom design, this proposal is expected to have a bigger diameter because the cold secondary coolant needs to be guided to the bottom. The impact onto the diameter is an increase of about 600-800mm.

Tubes/Tubes IHX

The 2 stages of the tubular IHX are based on the 1-stage tubular IHX design, that is to say secondary coolant inside the tubes collected by the central hot header.

With the proposed design, the hot and cold stages are separated on the secondary side by an intermediate header.



With this design, the main advantage compared to the 1 stage reference design is that the cold side material could different from hot side (example, stainless steel on the cold side and nickel alloy on the hot side) for a similar life time of the 2 stage. Consequently, this concept could have a cost impact.

Main weak points:

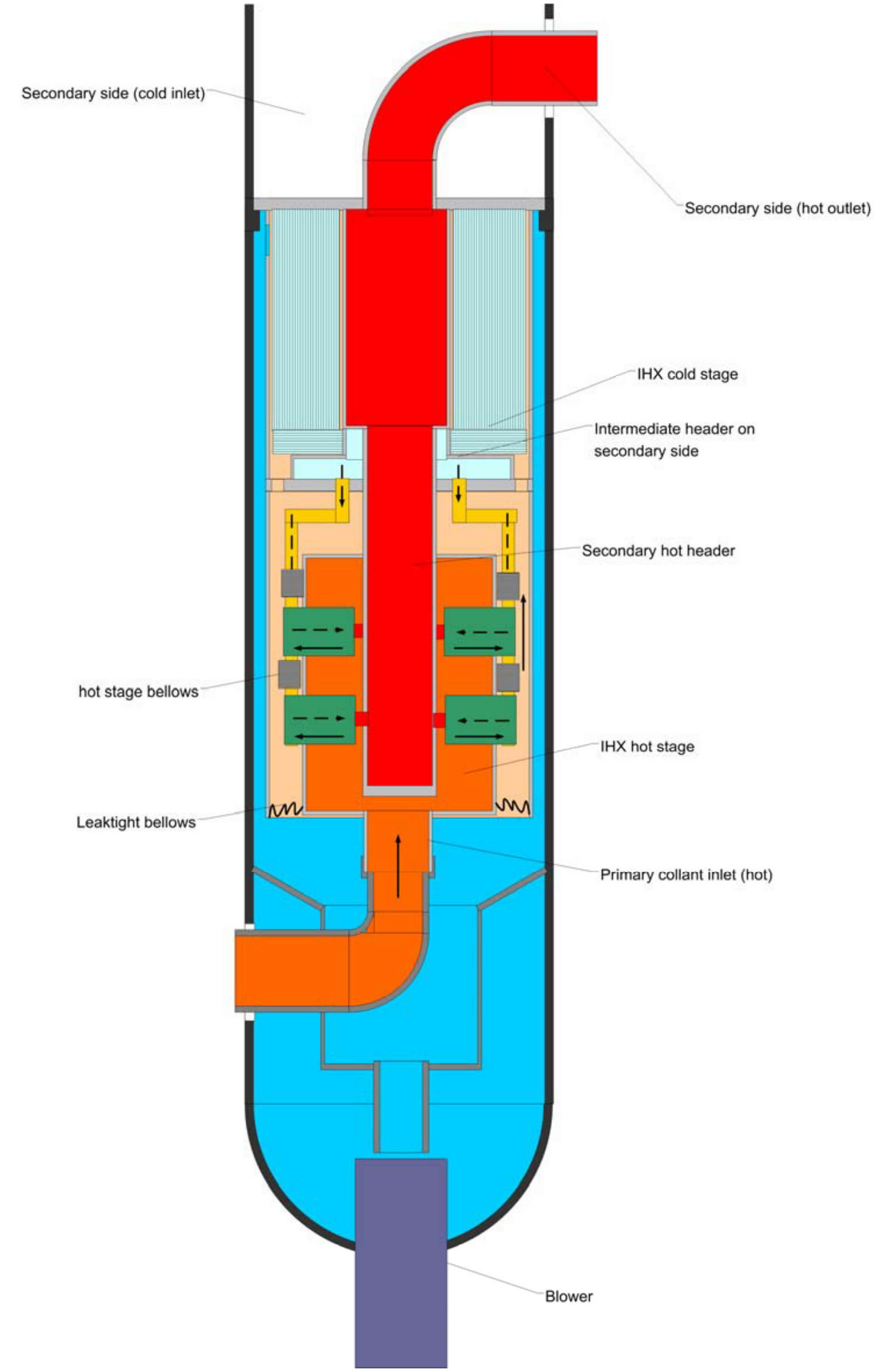
- Thermal expansions have to be managed on the intermediate header and at the connection with the hot header,
- Taller than the 1 stage IHX:
    - To collect the coolant at the intermediate stage header, it needs additional length of about 4-5m,
- The intermediate header and the associated intermediate tubular plate are structure at elevated temperatures.

An alternate to this proposal could be to perform a 1 stage IHX with the cold part of the tubes manufactured with stainless steel and the hot with nickel alloy. The tubes could be manufactured with a bimetallic weld.

Tubes/Plates IHX

This design is a "mix" between the 2 precedent arrangements.

In this case the hot side is performed with plates IHX.



Considering analysis done for the previous arrangements, it could be retained that the advantages of this concept are:

- Possibility to perform the cold stage tubular IHX with stainless steel (cost save impact),
- If the hot side has a shorter life time than the cold, it is necessary to remove the IHX package for maintenance (but it is the same for 1 stage IHX) and it could be envisaged to “cut” or disconnect only the hot side and to replace the hot stage modules, without modification on cold side.

The diameter of the vessel is expected to be about 5.5m.
The height is expected to be about 40m with the blower.

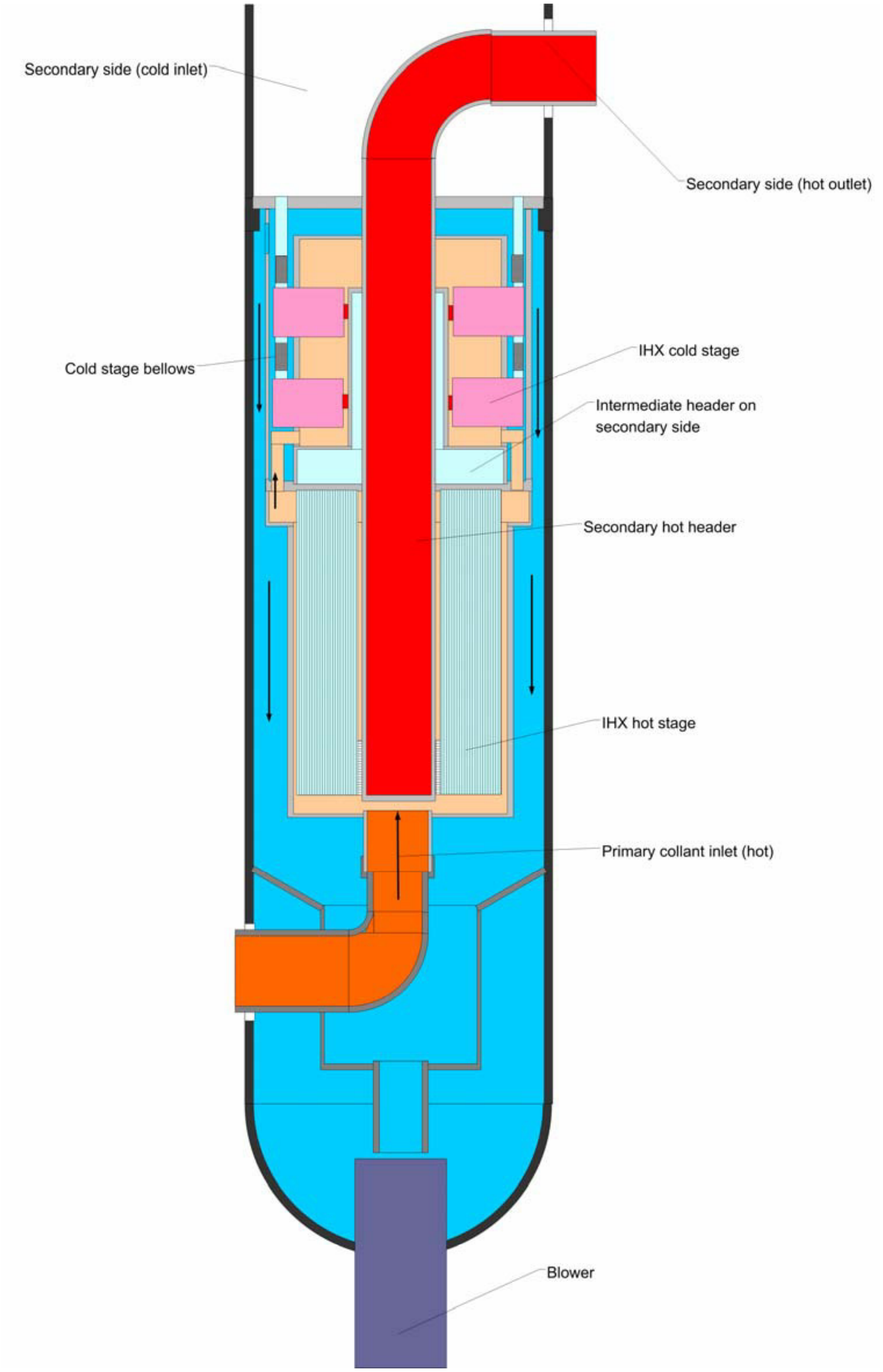
Main weak points expected are:

- The hot stage is performed with plates IHX and to cope with the thermal expansions, it is necessary to implement bellows that will work at high temperature,
- The life time between the hot and the cold stages might be different (plates IHX with a shorter life time),
- Pressure drops on secondary side are expected to be increased compared to 1 stage IHX.

Plates/Tubes IHX

This arrangement is an alternate to the precedent proposal.

The plates IHX are used for the cold stage.



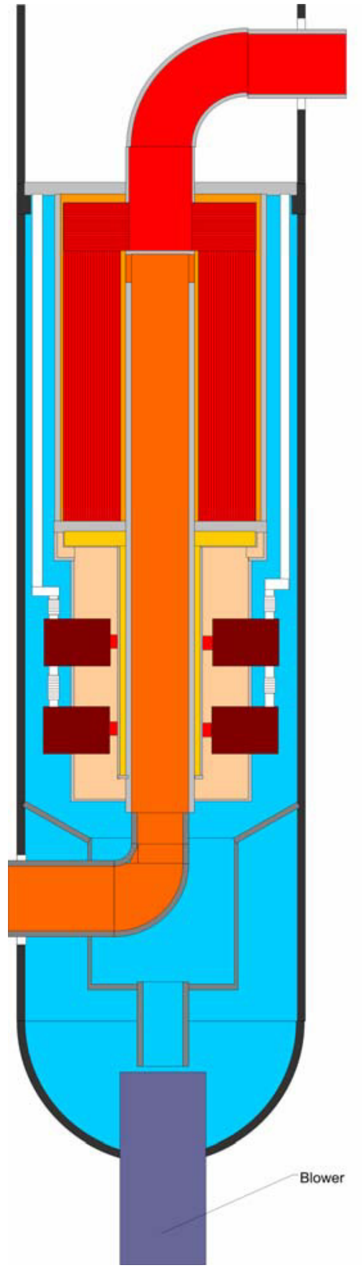
With this arrangement, the main advantages are:

- Use of plates IHX on the cold side for compactness and tubes IHX on the hot side because they are expected of a better life time than plates IHX at high temperatures:
  - Life time enhanced compared to the 1 stage plates IHX,
  - Compactness enhanced compared to 1 stage tubes IHX since the 600MWth could eventually performed with 1 vessel instead of 4.
- The design can cope with thermal expansions and the bellows are not working at high temperatures.

On the other hand, the weak points are expected to be:

- The expected height is about 40m,
- Pressure drops are expected to be more important on secondary side, compared to the 1 stages design.

An alternate design with the hot stage at the top is given by the following figure.



This design has mainly the same pros and cons as the 2 stage IHX with the hot stage at the bottom. Furthermore, compared to the hot stage at the bottom design, this proposal is expected to have a bigger diameter because the cold secondary coolant needs to be guided to the bottom. The impact onto the diameter is an increase of about 600-800mm.

Preliminary evaluation

The preliminary evaluation purpose is to compare the different arrangement, especially regarding gains (or not) compared to 1 stage designs.

	Compactness	Life time	Cost savings	Repairing & maintenance	Design	Operating – Pressure drops
Plates/Plates	Expected larger than 1 stage plates IHX	No major gains on life time are expected because the hot side is performed with plates IHX that would limit the life time. Hot stages IHX submitted to less important thermal gradients compared to 1 stages design.	No gains	Same as for the 1 stage IHX design to remove the IHX modules from the IHX vessel. But possibility to change only the hot stage (but complex to perform).	More complex design with the addition of intermediate header. Bellows working at high temperature are necessary.	Same order of magnitude as 1 stage design expected (plates IHX design).
Tubes/Tubes	Expected larger than 1 stage tubes IHX	Same life time expected as the 1 stage tubular IHX	Eventual cost savings if the cold stage could be performed with stainless steel tubes.	Same as for the 1 stage IHX design to remove the IHX modules from the IHX vessel. But possibility to change only the hot stage (but complex to perform).	More complex design with the addition of intermediate header. Design alternate with 1 stage manufactured with 2 materials tubes to be check.	Same order of magnitude as 1 stage design expected (plates IHX design).
Tubes/Plates	Height expected larger than 1 stage plates IHX	No major gains on life time compared to the 1 stage plates IHX since the hot stage is performed with plates IHX. Hot stages IHX submitted to less important thermal gradients compared to 1 stages design. But little gains are expected if a special design is performed for the hot side (but not considered significant enough).	Eventual gains on the cold side if the tubes are manufactured with stainless steel.	Same as for the 1 stage IHX design to remove the IHX modules from the IHX vessel. But possibility to change only the hot stage (but complex to perform).	More complex design with the addition of intermediate header. Bellows working at high temperature are necessary.	More important pressure drops on the secondary side compared to the 1 stages design if the 600MWth are put into one vessel, because of the flow rate through tubes.
Plates/Tubes	Overall dimensions expected larger than for 1 stage plates IHX, especially regarding the height.	Gains on life time are expected compared to the 1 stage plates IHX because the hot side is done with tubular IHX. The life time is expected between the 1-stage plates IHX and 1-stage tubular IHX (much closer to the tubes IHX).	No cost saving expected	Same as for the 1 stage IHX design to remove the IHX modules from the IHX vessel. But possibility to change only the hot stage (but complex to perform).	More complex design with the addition of intermediate header.	More important pressure drops on the secondary side compared to the 1 stages design if the 600MWth are put into one vessel, because of the flow rate through tubes.

General comment:

If the need in outlet temperature would be increased (over 900°C), with 2 stages IHX design it could envisage to perform a dedicated hot stage manufactured with ODS tubes or ceramic plates IHX. But these kinds of heat exchangers still need R&D to be adapted to this application.

For bi-metallic design (as example, stainless steel – nickel alloy), it will be necessary to take provisions and precautions so that "cold" stage always stay "cold" to avoid any deterioration by the elevated temperatures.

Plates/Tubes IHX analysis

1 loop analysis

The arrangement that is expected to be the most promising of the Pates/Tubes IHX because it could be possible to manage a better compactness compared to 4 tubes IHX (1 stage design) and a better life time compared to the 1 stage plates IHX.

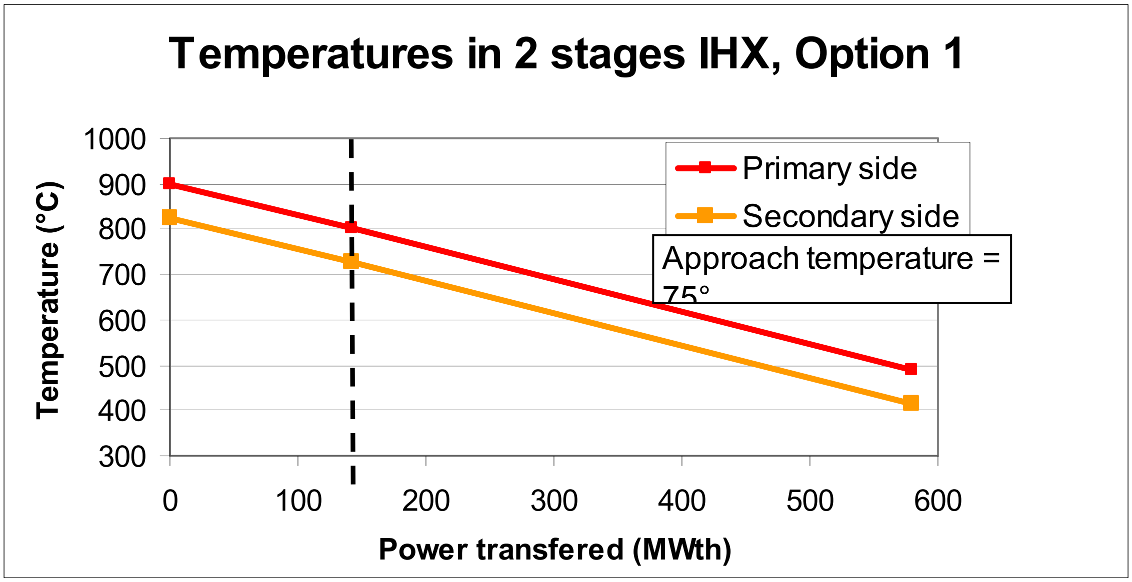
Therefore, a more detailed analysis regarding the arrangement has been performed with regards to the objective to conserve 1 IHX vessel.

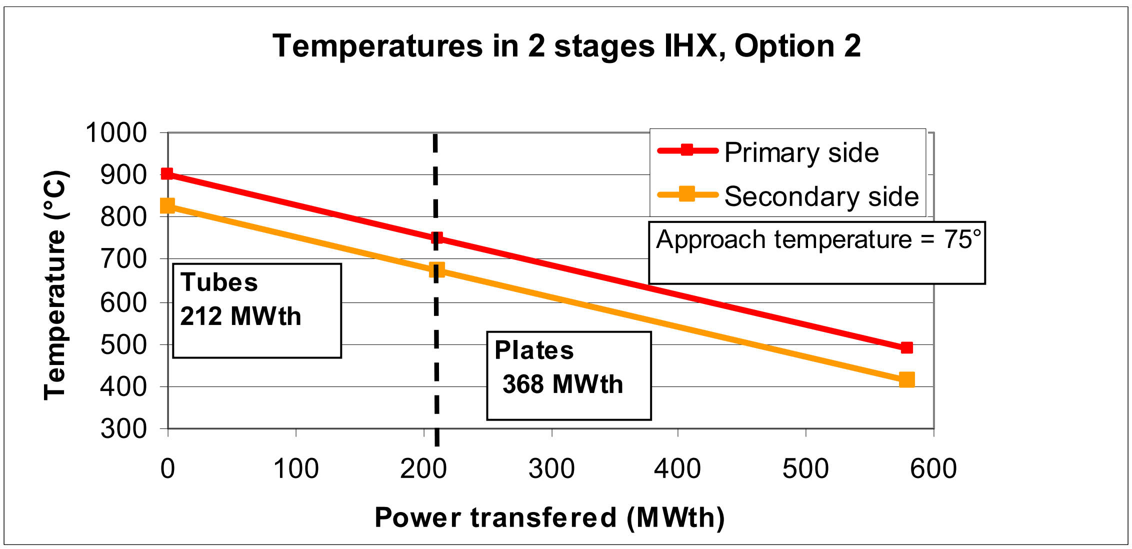
This section investigates a configuration in which a single 580 MWth loop with an IHX housed in a single pressure vessel would be used.
The coolants temperatures (Helium at both sides) have not been changed (primary Helium from 900°C to 490°C and secondary Helium from 415°C to 825°C).

This IHX would be a “two-stages IHX” comprising a helical coiled tube bundle and a compact plate-type IHX in series, the tube bundle working in the high range of temperature so as to allow an important lifetime of the IHX.

The following tables give assessments of the design parameters that would be needed for each stage of the two-stages IHX. The blower (16 MWth) has been assumed feasible, even if its feasibility in primary helium is disputable.

Two options have been considered in this study. Option 1 corresponds to an intermediate temperature (between tubular and compact stages) of 800°C whereas in Option 2, this temperature is of 750°C. The arrangement of the IHX and the boundary temperatures of the two options are given on the last page of this document. The drawing of the arrangement shows two levels of compacts IHX but calculations have shown that a third level would be necessary.


Temperatures in 2 stages IHX, Option 1
Primary side
Secondary side
Approach temperature = 75°
Temperature (°C)
1000
900
800
700
600
500
400
300
0
100
200
300
400
500
600
Power transfered (MWth)


Temperatures in 2 stages IHX, Option 2
Primary side
Secondary side
Approach temperature = 75°
Tubes
212 MWth
Plates
368 MWth
Temperature (°C)
1000
900
800
700
600
500
400
300
0
100
200
300
400
500
600
Power transfered (MWth)

Tube bundle

Parameter	Value for option 1	Value for option 2
Primary side:		
T_{in}(°C)	900	900
T_{out}(°C)	800	750
Secondary side:		
T_{in}(°C)	725	675
T_{out}(°C)	825	825
$\Delta T=T_{in}-T_{out}$ (°)	100	150
Approach temperature (°)	75	75
Power (MWth)	141	212
Mass flow (kg/s)	272	272
Maximum velocity allowed at the level of the thermal insulation of the secondary header (m/s)	60	60
Corresponding diameter of the critical section (m)	1.55	1.55
Corresponding ID of the hot header (m)	1.53	1.53
Number of tubes	2940	2940
Pressure drop at secondary side (bar)	2.3	3.4
Bundle height (m)	2.5	3.7
Length of the tubes (m)	5.7	8.6
External diameter of the bundle (m)	3.6	3.6
Circumference of the bundle (m)	11.3	11.3

Plate IHX

Parameter	Value for option 1	Value for option 2
Primary side:		
T_{in}(°C)	800	750
T_{out}(°C)	490	490
Secondary side:		
T_{in}(°C)	415	415
T_{out}(°C)	725	675
$\Delta T = T_{in} - T_{out}$ (°)	310	260
Approach temperature (°)	75	75
Power (MWth)	439	368
Mass flow (kg/s)	272	272
Number of modules per level	16	16
Number of levels	3	3
Number of modules	48	48
Number of plates per module	170	170
Height of a module (m)	1.03	1.03
Active length of the modules (m)	0.47	0.40
Length of the modules (m)	~0.8	~0.7
Pressure drop at secondary side (bar)	0.48	0.39

Estimations for the whole IHX

Parameter	Value for option 1	Value for option 2
Pressure drop at secondary side (bar)	>2.8	>3.8
Diameter of the pressure vessel (m)	~5.5	~5.3
Height of the pressure vessel (m)	40	41

Synthesis

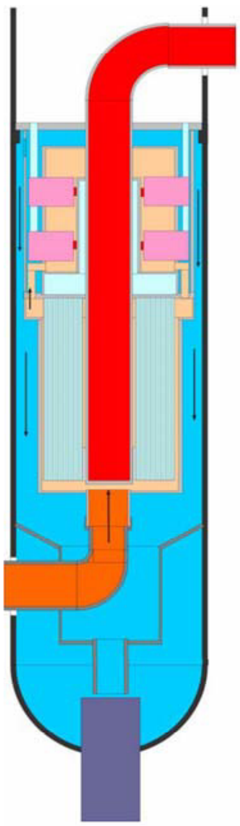
The 580 MWth two-stage IHX main parameters have been assessed.

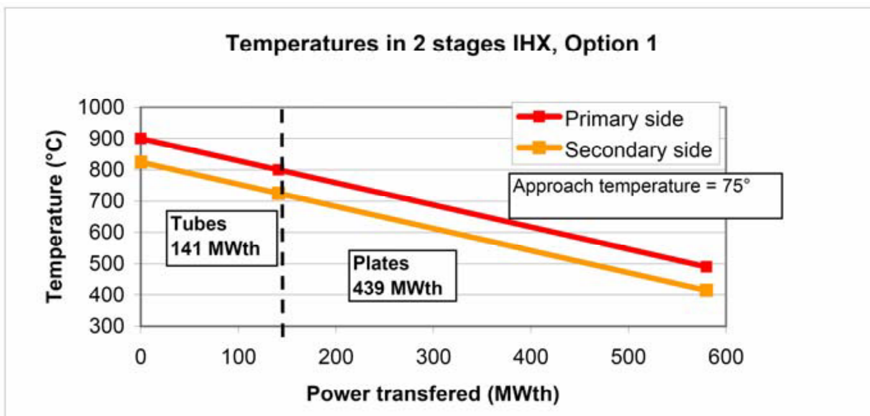
Several challenging items have been identified considering the feasibility of such an IHX:

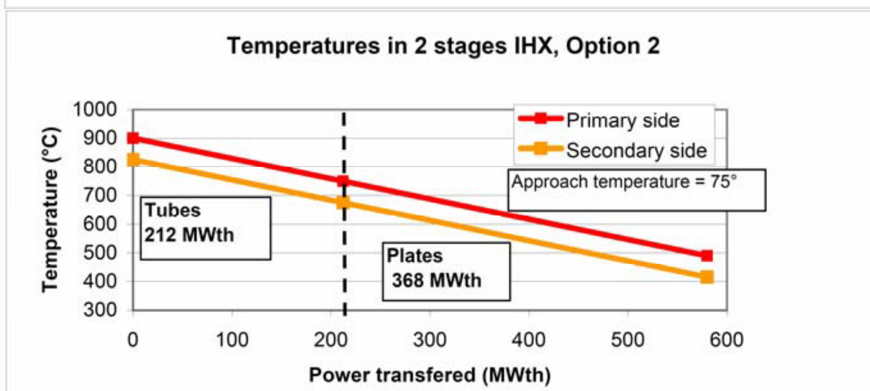
- The pressure drops at secondary side can hardly be reduced under 0.3 MPa and, as a consequence, secondary blower feasibility issues can be foreseen. Option 1 is the most favorable one considering this point (0.3 MPa as compared to 0.4 MPa for Option 2).
- The design of the tubular IHX has been deeply changed as compared to the state-of-the-art. The ability of such a short bundle to accommodate the thermal stresses has to be checked.
- The feasibility of the hot header is questionable as the number of tube is of 2930 and the inside diameter imposed by velocity limitation inside secondary header is of ~1.5 m.
- The compact IHX feasibility should be greatly enhanced by this design but a compact IHX at 800°C or even 750°C would still need to be demonstrated. Option 2 is the most favorable regarding this point (maximum temperature=750°C as compared to 800°C for Option 1).
- The complexity of the pressure vessel is largely increased so as to manage the superimposition of the two stages.
- The size of the vessel may also be problematic (about 40m including the blower).

2 loops analysis

This paragraph investigates the potentiality to use a “two-stage” 290 MWth IHX housed in a single pressure vessel in each of the two loops. These IHXs would consist of a helical coiled tube bundle and a compact plate-type IHX house in a single pressure vessel and disposed in series, the tube bundle working in the higher range of temperature so as to allow an important lifetime of the IHX.
The coolants temperatures (Helium at both sides) have not been changed (primary Helium from 900°C to 490°C and secondary Helium from 415°C to 825°C). The following tables give assessments of the design parameters that would be needed for each stage of these “two-stage” IHXs.
Two options have been considered in this study. Option 1 corresponds to an intermediate temperature (primary Helium between tubular and compact stages) of 800°C whereas in Option 2, this temperature is of 750°C. The arrangement of the IHX and the boundary temperatures of the two options are given hereunder.







Tube bundle

Parameter	Value for option 1	Value for option 2
Primary side:		
T_{in}(°C)	900	900
T_{out}(°C)	800	750
Secondary side:		
T_{in}(°C)	725	675
T_{out}(°C)	825	825
$\Delta T = T_{in} - T_{out}$ (°)	100	150
Approach temperature (°)	75	75
Power (MWth)	71	106
Mass flow (kg/s)	136	136
Maximum velocity allowed at the level of the thermal insulation of the secondary header (m/s)	60	60
Corresponding diameter of the critical section (m)	1.10	1.10
Corresponding ID of the hot header (m)	1.07	1.07
Number of tubes	2130	2880
Pressure drop at secondary side (bar)	1.0	1.3
Bundle height (m)	2.1	2.2
Length of the tubes (m)	4.9	5.1
External diameter of the bundle (m)	2.95	3.35
Circumference of the bundle (m)	9.3	10.5

Plate IHX

Parameter	Value for option 1	Value for option 2
Primary side:		
T_{in}(°C)	800	750
T_{out}(°C)	490	490
Secondary side:		
T_{in}(°C)	415	415
T_{out}(°C)	725	675
$\Delta T = T_{in} - T_{out}$ (°)	310	260
Approach temperature (°)	75	75
Power (MWth)	219	184
Mass flow (kg/s)	136	136
Number of modules per level	16	16
Number of levels	2	2
Number of modules	32	32
Number of plates per module	170	170
Height of a module (m)	1.03	1.03
Active length of the modules (m)	0.40	0.33
Length of the modules (m)	~0.7	~0.6
Pressure drop at secondary side (bar)	0.30	0.24

The sum of the pressure drops and evaluations of the pressure vessel dimensions are provided in the following table.

Estimations for the whole IHX

Parameter	Value for option 1	Value for option 2
Pressure drop at secondary side (bar)	>1.3	>1.6
Diameter of the pressure vessel (m)	~4.7	~4.5
Height of the pressure vessel (m)	35	37

Synthesis

The main parameters of a configuration with two loops, each comprising a “two-stage” IHX have been assessed. The feasibility of this configuration is greatly enhanced as compared to the “two-stage” one loop configuration. The concept also shows some advantages as compared to the reference configuration with two tubular IHXs. The pros and cons of the two loops “two-stage” IHX configuration are listed thereafter:

Pros:

Changing the high temperature stage independently is possible thanks to the “two-stage” configuration.

The 0.2 MPa maximal value for the secondary side pressure drops given by the NGNP Conceptual Design Studies Baseline Document can be complied with. Margins are even available without using such a large number of tubes as in the reference tubular configuration. So this configuration is favorable as regards feasibility of the tube bundle (fewer tubes are needed, notably in Option 1) and also of the blowers (reduced size) and of the plant efficiency (less electricity needed to blow the secondary Helium).

The diameter of the hot header can be reduced as compared to the reference configuration (from ID~1.23m to ID~1.10m) which is favorable regarding its forging feasibility. In Option 1, the number of tubes is of 2130 which is particularly favorable to the sizing of the hot header (limited length needed).

The compact IHX feasibility should be greatly enhanced by this design but a compact IHX at 800°C or even 750°C is still to be demonstrated. Option 2 is the most favorable regarding this point (maximum temperature=750°C as compared to 800°C for Option 1).

Cons:

There is no compactness improvement as compared to the reference configuration (estimated height~33 m, vessel diameter~3.6m) due to the need of more headers (penalizing the height) and the larger diameter needed to implement the compact stage.

The design of the tubular IHX has been deeply changed as compared to the state-of-the-art. The ability of such a short bundle to accommodate the thermal expansions has to be checked.

The complexity of the pressure vessel is largely increased so as to manage the superimposition of the two stages. This is unfavorable to assembly procedure and ISI notably.

The potentiality to use a more conventional alloy for the compact IHX (cost reduction) is questionable as the maximum temperature in the compact IHX is still of 800°C to 750°C respectively for Option 1 and Option 2. In this two loops configuration, Option 2 seems to be the most interesting for this reason but if an edge effect exists regarding change of the material under 750°C, it may be more interesting to chose Option 1 with a compact IHX made of high temperature alloy (e.g. Alloy 617) to reduce the pressure losses so as to enhance the plant efficiency, providing that the lifetime of the compact IHX can be sufficient at 800°C.

To conclude, as compared to the fully tubular IHX or fully compact designs, the feasibility of the tube bundle is improved (lower number of tubes and smaller hot header) and the pressure drops at secondary side can be decreased without using a very high number of tubes (enhanced efficiency). The compact IHX is subject to lower temperature which is favorable in terms of lifetime.

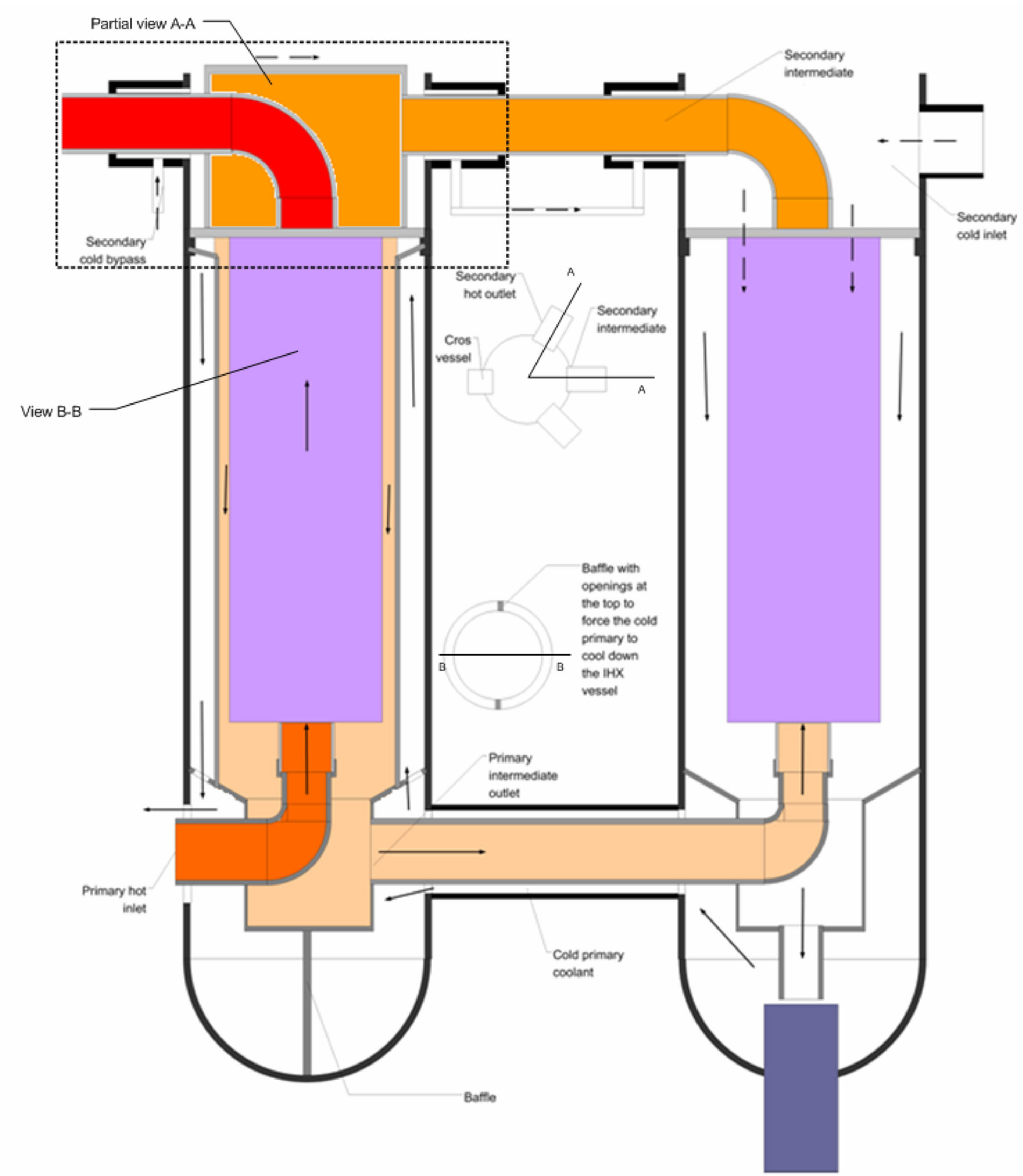
However, the compactness is not improved as compared to the tubular IHX and the maximum temperature of the compact stage is still high (750°C for the most favorable option regarding this point) so that a cost reduction thanks to the use of a more conventional alloy is questionable.

So, the interest of the two loops “two-stage” IHXs configuration does not appear obvious when taking into account the increased complexity of the “two-stage” concept.

3.7.3 2-STAGE IHX IN TWO VESSELS

The 2 vessels arrangement is independent from the kind of IHX used.

The proposed arrangement has been perform with the objective to conserve a “cold” temperature on the vessels respectively for primary and secondary sides.



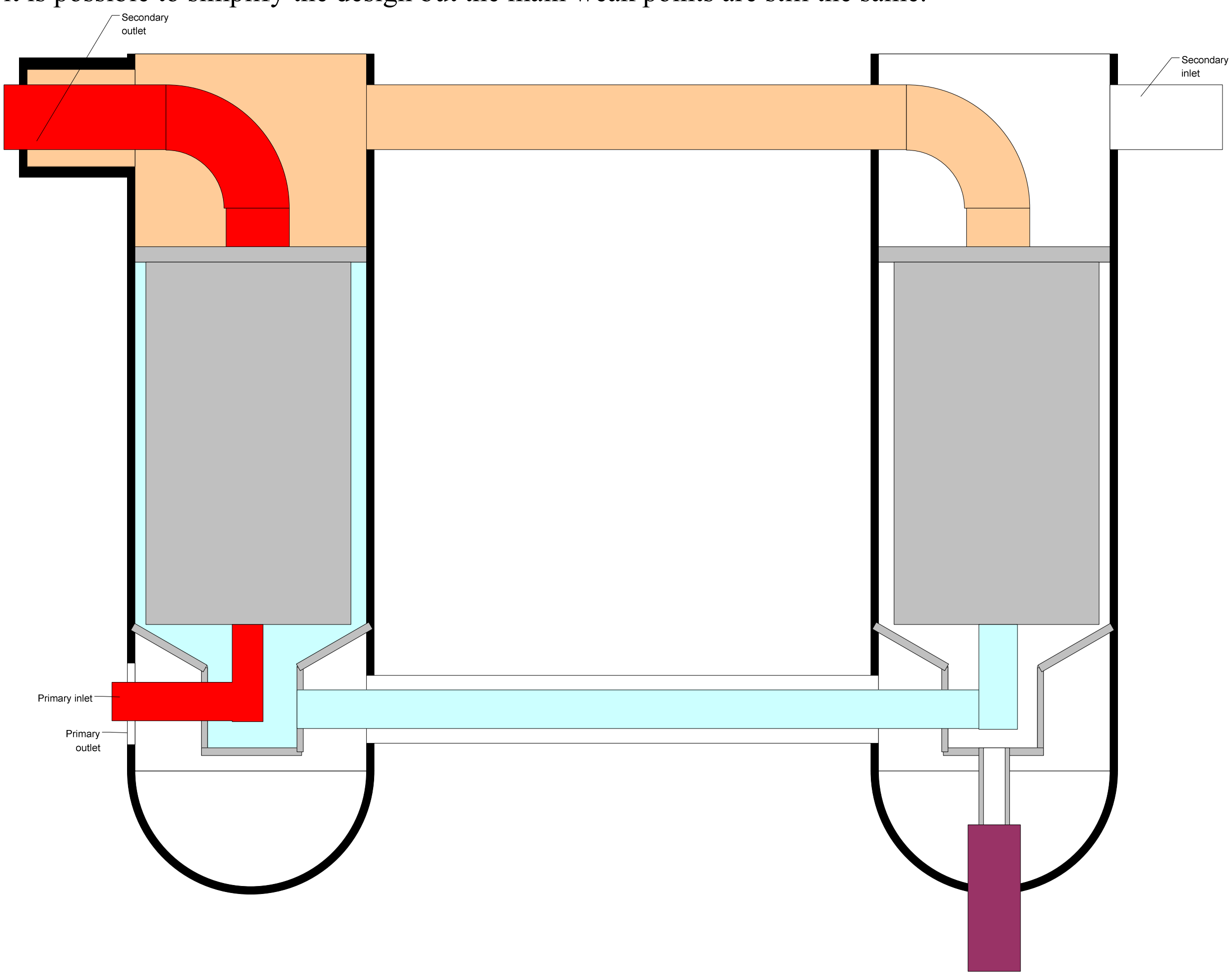
The main advantages of this kind of arrangement are:

- Same design for Plates or tubular IHX,
- Easier to change one stage for maintenance
- Possibility to replace a tubular stage by a plate stage,
- Height of vessel reduced but diameter expected the same as for 1 stage design,

The weak points are mainly:

- Complex coolant flow path so as to cool down the vessels with cold fluid (less complex without "cooled vessels"),
- Due to the coolant flow path, the design is therefore much more complex,
- Vessels supporting more complex especially regarding thermal expansion,
- Impact on general arrangement and civil work (cost of the primary containment expected much more important than 1 IHX vessel per loops).
- Expansion loop or elbows are expected necessary on secondary side to cope with thermal expansions

If the cooling of the vessels is performed with insulation inside the vessel + external active cooling system it is possible to simplify the design but the main weak points are still the same.



In both cases, the 2-stage IHX in one vessel appears to be the less complex arrangement mainly regarding the coolants flow path and the impact onto the lay out.

4.0 MATERIAL ALTERNATIVES

4.1 Scope of work

This task will identify and evaluate alternative materials for the IHX, including as a minimum the following:

- Review of the recommendations of the reactor vendor's PCDR/PCDSR
- Identification and review of relevant prior studies (e.g., ANL evaluations of materials for RPV and IHX, NUREG/CR-6824-ANL-02/37, ANL/EXT-06-45 and -46)
- Status of and planning for the demonstration of candidate material properties in thick and thin sections
- Status of and planning for codification of the material (and associated welding, bonding or other fabrication processes) for the expected operating conditions
- The impact of environmental effects (e.g., corrosion potential due to fluid contaminants, Tritium transfer)
- Fabricability and welding or other bonding techniques of the candidate materials in the required configurations.
- Other issues and requirements (low activation requirements, etc)
- Availability of the material with the requisite properties from quality suppliers in the time frame to support NGNP operation in 2018.

This task will also identify a course of action required for longer-term material development to support the use of NGNP as a test facility for demonstration of evolving and emerging technologies.

This task will provide finally recommendations in terms of material selection.

4.2 Review of Materials Selection for Hot Section of IHX

The primary coolant of the NGNP is potentially subject to radioactive contamination by the core. To isolate the radioactivity and minimize radiation doses to personnel, intermediate heat exchangers (IHXs) have been proposed as a means for separating the primary circuit of the NGNP from the power conversion and hydrogen generation systems. The IHXs pose significant engineering and fabrication challenges because (1) some components will be exposed to very high temperatures, (2) large amounts of heat must be transferred from the primary to the secondary coolant, and (3) the requirements for reliability and leak-tightness are stringent.

This section reviews previous efforts on materials selection for the IHX and discusses classes of materials that might compete with those selected previously. It then compares the properties of the leading candidate materials to determine whether recent information would suggest that a change is in order. The conclusion is that there is no recent information that would require a change in the materials for the hot section of the IHX.

4.2.1 Identification of Alternative Candidates

4.2.1.1 Recommendations of Reactor Vendors

AREVA, General Atomics, and Westinghouse, who are the three reactor vendors working on the NGNP project, have all prepared preconceptual designs for the NGNP that include IHXs. Each vendor has made a materials selection for the hot section of the IHX. All three selected alloy 617. This section briefly describes the arrangement of IHXs and the materials selection proposed by each vendor. The selections are reviewed to determine whether additional information has come to light that might cause reconsideration of the selection. The primary focus is on alloys 617, 230, and XR. The IHX designs are described briefly, and the primary issues in materials selection are discussed.

4.2.1.1.1 AREVA

AREVA (Ref. 19) has proposed a multiloop reactor system, with one compact IHX dedicated to the hydrogen production system and three tubular (shell-and-tube) heat exchangers dedicated to the power conversion system. The number of tubular heat exchangers is subject to change, dependent on fabricability and economics. The reactor outlet temperature could be as high as 950 °C. The compact heat exchanger is assigned about 60 MW (thermal), and the balance of the reactor output is distributed among the shell-and-tube heat exchangers. AREVA has specified alloy 617 as the preferred material for the hot section of the IHXs, with alloy 230 as an alternative (Ref. 20). Alloy XR is mentioned as a possible alternative material if corrosion in hot helium proves to be a problem. Ceramics are apparently considered to be promising but impractical at this time.

The primary coolant is helium, and the initial design was that the two types of IHXs would have different secondary gases: the compact IHX would use helium as the secondary gas, but the tubular heat exchangers would use a helium-nitrogen mix. That gas was chosen because the intent was to use the secondary gas to drive a gas turbine, and helium-nitrogen would allow air-breathing gas turbine technology to be used.

4.2.1.1.2 General Atomics

General Atomics (Ref. 21) has proposed a two-loop design. There is one compact IHX with a capacity of 65 MW (thermal). The remainder of the output of the reactor is supplied directly to a gas turbine. The reactor outlet temperature is still subject to refinement; temperatures of 850 °C and 950 °C are both discussed in the report. In either case, the primary and secondary gases are both helium. Alloy 617 is the only material suggested for the hot portions of the IHX.

4.2.1.1.3 Westinghouse

Westinghouse has selected a one-loop design with two heat exchangers in series (Ref. 22). The first heat exchanger reduces the temperature of the primary gas from the reactor outlet temperature, approximately 950 °C, to about 850 °C; at that temperature it is delivered to the second heat exchanger. (The report does not appear to be entirely consistent in its temperature selections. A different section gives a maximum temperature of 760 °C for the low-temperature heat exchanger. The reason for choosing that temperature is “to allow the use of established ASME Section III materials” such as alloy 800H.) Both heat exchangers would use a compact design. The reference material for the high-temperature heat exchanger is alloy 617, with alloy 230 identified as an alternative, although it is recognized that the internals of the high-temperature heat exchanger will require periodic replacement if these alloys are used. Ceramics for heat exchangers are considered to be impractical but to warrant aggressive development.

4.2.1.2 Other Alternatives

The three reactor vendors appear to be in surprising agreement concerning heat exchanger materials; all have identified alloy 617 as the primary candidate, and two have identified alloy 230 as the first alternative. Other materials suggested by the vendors include alloy XR and "ceramics", presumably silicon carbide. The composition limits of alloy 617, 230, X, and XR are provided in Table 4-1.

Alloy 617 was selected in Germany for hot helium systems because of its mechanical properties at elevated temperature. Alloy 230 has elevated temperature properties comparable to those of alloy 617, but the cobalt content of alloy 230 is significantly lower than in alloy 617.
Both materials contain significant percent of chromium (22%), with Mo, Mn, Co, Al, Fe, Ti…as minor alloying elements.
The main differences in composition are:

- a significant quantity of cobalt in alloy In617 (10-15%)
- a significant level of tungsten in alloy H230 (14%) instead of a significant level of molybdenum in alloy 617
- the presence of a small quantity of titanium in In617 (up to 0.6%) and a higher level of aluminium (around 1% in In617 instead of 0.4% in Haynes 230).

Alloy XR is a refinement on alloy X, with generally tighter composition limits that were chosen to improve particular aspects of alloy performance (Ref. 23). In particular, alloy XR has a minimum manganese content of 0.75%, which promotes the formation of a protective layer of the oxide $MnCr_2O_4$. A minimum silicon content of 0.25% is specified. Alloy XR also restricts the aluminum and titanium contents to 0.05% and 0.03%, respectively, to suppress internal oxidation and intergranular attack. Finally, alloy X requires a minimum cobalt content of 0.50%; that limit is removed for alloy XR. Removing the lower limit on cobalt is helpful in applications where a significant neutron flux is present; it controls the activation of ^{59}Co to ^{60}Co.

Alloy XR-II is a further refinement on XR, which appears to provide increased creep rupture strength. Boron content was found to have a significant effect on the creep rupture lifetime of alloy XR, with increased boron contents found to improve the creep rupture properties. However, weld cracking was found to be unacceptable if the boron content was greater than 0.007%. Boron contents of 0.004 to 0.007% were found to be optimal.

Austenitic stainless steels and NiFeCr alloy such as Alloy 800H cannot be used for long term in impure helium at 900°C and above because of environment effects (the protective chromium oxide layer would be destroyed). In addition their creep resistance at high temperatures exceeding 900°C is very low.

Silicon carbide is promising because of its high thermal conductivity and resistance to creep, but it is not considered to be technologically mature enough for the large parts to be used in the NGNP (Ref. 20).

Oxide dispersion strengthened (ODS) alloys might also be considered for the IHX. ODS alloys have promising creep rupture performance, but there are concerns about long-term microstructural stability, oxidation resistance, and joining. Finding a commercial supplier will also be difficult. Two former suppliers (Special Metals and Plansee) have discontinued production of ODS alloys, and a third (Dour Metal of Belgium) has gone out of business. It is concluded that it would be difficult to obtain and qualify ODS alloys for use in a reactor that is to begin operation in 2018.

Ni-Cr-W alloys have been the subject of substantial study in Japan. Alloy 230 (13 to 15% W) could be considered as a member of this class of alloys, but the Japanese effort has focused on alloys with even higher tungsten contents, as evidenced by a patent (Ref. 24) for alloys with 15 to 24% W. At least one Ni-Cr-W alloy has a projected creep rupture lifetime of over 100000 hours at 9.8 MPa and 1000 °C (Ref. 25). Weld cracking of these alloys still poses a problem for fabrication, however.

Development continues on additional materials, such as alloy 740 (Ref. 26). This Ni-Cr-Co alloy has substantially greater creep strength than alloy 617, at least at temperatures up to 800 °C (Ref. 27). This material is probably not sufficiently mature for deployment in a reactor by 2018, but it may be useful for later design changes.

Table 4-1 Compositions of candidate materials for IHX (in weight %)

	617		230		X		XR	
	min	max	min	max	min	max	min	max
Ni	44.5		remainder		remainder		remainder	
Fe		3.0		3.0	17.0	20.0	17.0	20.0
Cr	20.0	24.0	20.0	24.0	20.5	23.0	20.5	23.0
Co	10.0	15.0		5.0	0.5	2.5		2.5
Mo	8.0	10.0	1.0	3.00	8.0	10.0	8.0	10.0
W			13.0	15.0	0.2	1.0	0.2	1.0
C	0.05	0.15	0.05	0.15	0.05	0.15	0.05	0.15
Cu		0.5						0.50
Si		1.0	0.25	0.75		1.00	0.25	0.50
Mn		1.0	0.30	1.00		1.00	0.75	1.00
P				0.030		0.04		0.04
S		0.015		0.015		0.03		0.03
Ti		0.6						0.03
Al	0.8	1.5	0.200	0.50				0.05
La			0.005	0.050				
B		0.006		0.015				0.01

4.2.2 Primary Issues in Materials Selection

4.2.2.1 Core Outlet Temperature

Core outlet temperature is probably the most important design variable that affects selection of materials for the hot section of the IHX. The materials discussed here are those that are considered to be suitable for application at temperatures above about 750 °C. At lower temperatures, additional materials are available. An example is alloy 800H, which is currently approved under ASME Code Section II Subsection NH for use up to 760 °C (Ref. 28).

Outlet temperatures as high as 1000 °C have been discussed but are considered to be beyond the current capability of metallic materials (Ref. 29). It has been recommended that the outlet temperature be limited to 900 °C. Temperatures up to 950 °C may be considered, though that is apt to be at the expense of a reduced lifetime for the affected components (Ref. 29).

4.2.2.2 Creep Rupture

Data on creep rupture are available for alloys 617, 230, X, and XR. Figure 4-1 shows the data for alloys 617 and 230. For temperatures up to 850 °C, these alloys have comparable strengths (Ref. 28), with some investigators noting a slightly better creep rupture strength for alloy 230 over the temperature range from 700 to 850 °C (Ref. 27). At 950 °C, however, alloy 617 has better strength at long lives (> 3000 hours) (Ref. 28). Alloys X and XR appear to have somewhat lower creep rupture strengths; in rough terms, the stress/time performance of alloy 617 at 950 °C is comparable that of alloy X at 900 °C. Alloy 617 therefore has an advantage over the other alloys in that it can be used either in thinner sections or at higher temperatures.

The composition refinements of alloy XR-II allow it to approach the creep rupture performance of alloy 617. Similar refinements of the composition of alloy 617 (Refs. 27, 28) may also provide some benefit.

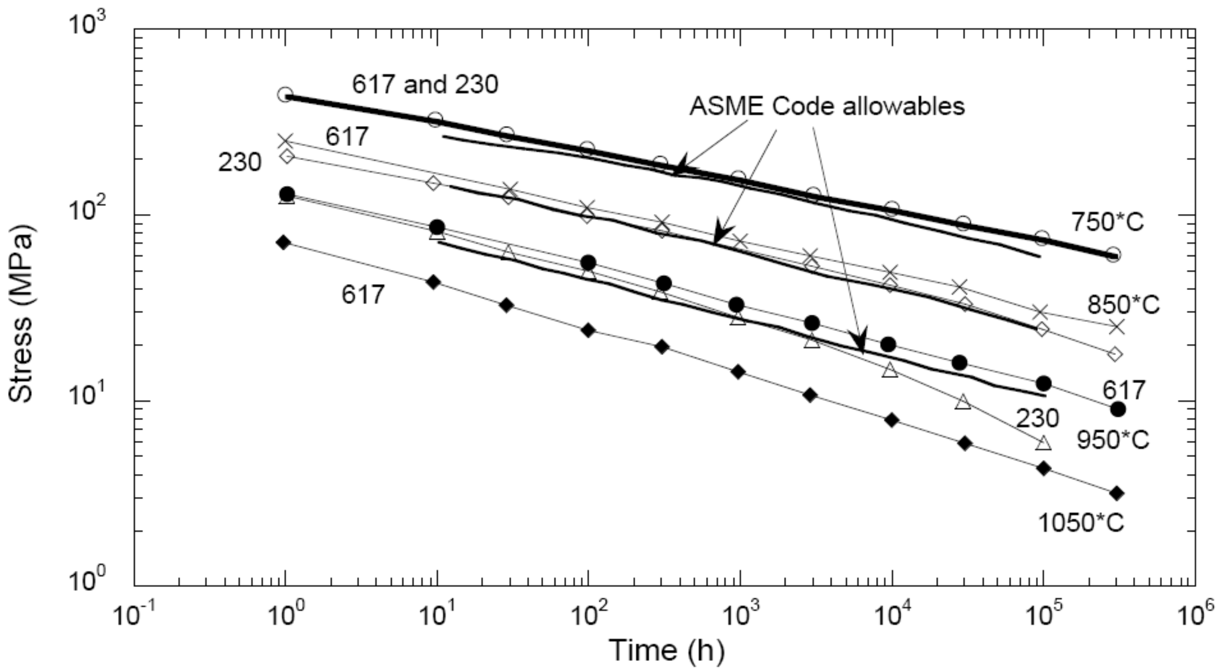


Figure 4-1 Creep-rupture strength of alloys 617 and 230 as a function of temperature and time to fail (Ref. 28)

4.2.2.3 Weldability

All of the candidate alloys are weldable, though in each case precautions are necessary to prevent hot cracking, and difficulty in welding is sometimes encountered. Welding becomes more difficult as thickness increases. Haynes International reports that alloy 230 has been successfully welded in thicknesses up to 76 mm, and Hoback et al. discuss welding of alloy 230 plates 50.8 mm thick by GMAW (Ref. 30). Alloy 617 is considered to be easier to weld than alloy 230. Alloys X and XR should be similar in weldability.

4.2.2.4 Microstructural Stability

All of the candidate alloys are primarily solid-solution strengthened materials. Ref. 28 states that alloy 617 "retains toughness after long-time exposure at elevated temperatures and it does not form embrittling phases such as, sigma, mu, chi, or Laves." Because it contains aluminum and titanium, alloy 617 may under some conditions form γ', a strengthening phase (Ref. 28).

Alloy 230 shows a reduction in room-temperature tensile elongation from about 50% to about 35% after 8000 hours of high-temperature exposure (650−871 °C) (Ref. 28). Aging did not produce sigma, mu, or Laves phases (Ref. 28). However, additional data are still needed on long-term stability (Ref. 28).

Alloy X (and therefore presumably alloy XR as well) does not appear to be as microstructurally stable as the other two candidates. Ref. 28 notes that "Above ≈700 °C, Alloy X can form topographically close-packed phases like sigma, mu, and Laves phases. These phases can embrittle the material and result in property degradation."

4.2.2.5 Corrosion

Nickel-base alloys are typically designed for oxidation resistance in air, and in that environment they form protective oxide layers on their surfaces. In a less oxidizing environment, such as that in the NGNP, the oxygen potential is lower and the oxide may not be protective. The alloy may then carburize or internally oxidize (and become brittle) or may decarburize (and lose strength).

Alloy XR was developed from alloy X in order to improve the resistance to corrosion in a reactor helium environment. The improvement was found to be significant at 1000 °C but not at 900 °C. Thus the improvements appear to be significant only at temperatures where alloy XR has insufficient strength.

There is insufficient information to predict the relative corrosion behavior of the candidate alloys. However, it appears that it is practical to maintain an atmosphere that will produce a protective oxide layer; at 950 °C, the required partial pressure of carbon monoxide is 150 μbar (15 Pa). It appears that the required pressure would be lower at lower temperatures.

It has been proposed that aluminide coatings could be applied to the surfaces of the IHX components in order to improve their resistance to oxidation (Ref. 20). No reason was found that such coatings should be more effective on one alloy than another.

4.2.2.6 Codification

Alloys 617, 230, and X are all listed in the ASME Boiler and Pressure Vessel Code, Section II, but none is approved for use under Section III.

A draft code case has been prepared for alloy 617, but it has not been approved, and it is not clear that the draft code case would provide adequate flexibility (Ref. 29). Long term data on alloy 230 appear to be inadequate, and most data on alloy XR appear to be restricted to a Japanese database that is generally not available to U.S. developers (Ref. 29).

4.2.3 Summary and Conclusions

Almost all evaluations indicate that alloy 617 should remain the reference material for the IHX:

- All three reactor vendors that are participating in the NGNP project selected alloy 617 as their reference material.
- Alloy 617 has acceptable performance for reactor outlet temperatures up to 900 °C or higher.
- At high temperatures, alloy 617 has longer creep rupture lifetimes than alloys 230 or XR.
- Alloy 617 is considered easier to weld than alloy 230.
- Alloys 617 and 230 have better long-term microstructural stability than alloy XR.
- Any of the alloys will require review before it is approved for use under Section III of the ASME Boiler and Pressure Vessel Code.

Alloy XR is better than alloy 617 in terms of resistance to corrosion in reactor helium at high temperatures. However, that advantage is not significant because it is only applicable at temperatures where the alloy lacks sufficient strength.

4.3 Status of and planning for the demonstration of candidate material properties in thick and thin sections

This section reviews the knowledge items related to IHX material alternatives and acquired through the HTR R&D program, including specific recommendations (if any) regarding materials, component design or environment specifications. The main material characteristics and properties to be assessed with regard to HTR project requirements in terms of operating conditions, component design and fabrication, are:

- The material mechanical resistance,

- The effects of primary side/secondary side environments on the material behavior,

- Forming and joining aptitude.

The aim is to identify R&D needs for materials qualification with regard to NGNP requirements, and to propose an action program. When possible the facilities that would be required for material testing will be listed.

The evaluation is provided for material which could be envisioned at very high temperature (900°C and above).

4.3.1 NGNP Project requirements for IHX material

4.3.1.1 IHX component

Several IHX Designs are studied. The different concept characteristics are summarized hereafter:

IHX concept	Wall thickness
Tubular	2.2 mm
Plates	0.2 mm (PFHE minimal value) to 1.5 mm (PSHE)

The expected IHX life time is 20 years for the tubular IHX and 5 years for the plate IHX

4.3.1.2 IHX operating conditions

The NGNP coolant is helium in both primary and secondary circuits.
The IHX operating conditions are summarized hereafter:

	Primary side : helium		Secondary side : helium	
	temperature	pressure	temperature	pressure
IHX inlet	900°C to 950°C	50 bar (90 bar in direct cycle)		55 bar
IHX outlet	500°C		up to 850°C depending on application	

4.3.2 Mechanical properties

4.3.2.1 Background

Preliminary Characterization has been performed on

- Bars (30 to 50 mm Ø),
- Sheets (2 mm thick),
- Plates (25 mm thick),

The effect of products shape highlighted: better tensile and medium term creep strength for small thickness/diameter products, due to better microstructure control during fabrication. As a consequence:

- Comparison between alloy 230 and alloy 617 must be made on similar product form,
- Characterization must be performed on the different product types to be used in order to define the different average values, the design data being possibly the most pessimistic ones.

4.3.2.2 Knowledge statement

Tensile properties
A large scatter of tensile data was found for 617 due to a large range of product forms. Fewer results are available for 230, but, in comparison, it seems that the yield and the tensile strengths of 230 are higher than those for 617 up to 850°C, and that the differences become negligible at higher temperature. Recent results performed on same kind of product for both 617 and 230 (bars) confirm this trend.

Creep properties
For alloy 230, the producer database indicates a creep stress to rupture slightly lower than that of alloy 617 at 750°C, 850°C and 950°C, but the first results of the program on alloy 230 show stress to rupture at 850°C up to 4000 hrs and at 950°C up to 2000 hrs similar to the average data of alloy 617. At 950°C for times greater than 5000 hrs, the result of alloy 230 seems lower than the mean trend of alloy 617. More precise comparative data for longer time and at higher temperature are necessary to clarify the possible differences between the long term design data of the two alloys at very high temperature. In addition, the comparison indicated above is applicable even to a grade of alloy 230 practically free of cobalt (Co = 0.3%).

In the case of thin sheets for plate IHX, it seems that the stamping operation has a detrimental effect on creep strain rates and probably on creep strength.

Toughness
Before ageing, Charpy impact values of alloy 230 at room temperature are much lower than those of alloy 617 (i.e. 80 J to compare to 270 J).

Ageing effects
As regards ageing effects, the testing program covering the 750-950°C range has started. The first results up to 1000 hrs of ageing for alloy 617 indicate no significant shift in tensile and yield strengths. Ductility and impact toughness are significantly lowered with the following notable trends:

- The shifts in ductility and impact toughness are very significant, but as the values are high in the as-delivered condition, they remain higher than those of alloy 230 at least after 1000 hrs of ageing.
- The shifts in ductility and impact toughness do not systematically increase as the ageing temperature is increased.

Therefore for evaluation and comparison of end of life properties, it will not be possible to accelerate the effects by an increase in ageing temperature. Consequently, durations up to 15 000 hrs are foreseen in the testing program.

The same trend of a comparable reduction of impact values at 700°C, 750°C and 850°C as for alloy 617 is also seen for alloy 230, for which properties after 5000 hrs of ageing are already available, as well as a trend to healing at 950°C.

Fatigue endurance
Preliminary results (850°C air data) indicate a better endurance of alloy 230 between 1000 and 100 000 cycles). Clarification of effects of frequency, hold times (tensile or compressive) and environment (air, vacuum, helium) on fatigue and creep-fatigue endurances is a major item for IHX material confirmation.

4.3.2.3 R&D needs for qualification

To complete material data base for modeling (behavior law) further efforts should concern:

- Long term ageing and creep tests
- Effect of stamping on creep properties
- Cyclic behavior
- Creep-fatigue interaction (Air, vacuum, He)

4.3.3 Environmental effects

Chemically neutral, pure helium has no effect on materials. However, an industrial helium atmosphere cannot be totally free from impurities. Impurities come from various sources such as reaction of air or humidity (in case of air ingress) with the graphite core, out-gassing of reactor material. In the primary circuit these impurities are: O_2, H_2O, H_2, CO, CO_2, CH_4. Even in small quantities, they may have interactions with the materials: oxidation leading to the formation of an external oxide layer but also internal oxidation; bulk carburization or decarburization of the materials. These phenomena can become of importance at high temperature and may result in a loss of the mechanical properties of materials. Internal oxidation can lead to a reduction of creep strength particularly when aluminum oxides are formed at the grain boundaries. Carburization can increase the creep strength and reduce the toughness resulting in embrittlement of the material. Inversely, carbide depleted zone lost its initial mechanical properties (strength loss). Such consequences can become unacceptable especially for thin sections like IHX heat transfer surfaces. For thick sections, corrosion effects can be taken into account through thickness allowances.

The following paragraphs provide a summary of issues to provide the context for the required development program. Further detailed information is provided in section 4.5.

4.3.3.1 Background

Numerous long term corrosion data on high temperature materials are available from former HTR experience. Particularly, information on In617 has been compiled from the large research program performed in the frame work of German HTR. Corrosion tests have been carried out up to 50 000 hours in the range of 700 to 950°C. The effects of impure helium/metal interactions have been assessed in terms of carbon take-up (twice the initial carbon content), external oxide scale, internal oxidation and depth of the carbide depleted zone.

It can be shown that nickel-base alloys can become very sensitive to impure helium effects at high temperature, above 800°C. Based on improved PNP-Helium experience on In617 (mainly 10 000 h and up to 50 000 hours at 800°C), extrapolation up to 200 000 hours (assuming that the corrosion effects follow a parabolic type law) leads to relatively large corrosion depths (internal oxidation and particularly carbide depleted zone could reach several hundred of µm) that would not be acceptable with regard to IHX thin wall thickness considering the long lifetime of the component. The most restrictive parameter appears to be the carbon take-up. The chromium oxide layer has a limited protection capability.

It should be outlined that there is a very large scatter in the data depending on heats and thermo-mechanical treatment. Thus one can expect possible improvement of the material corrosion resistance by a structural optimization through fabrication processes and chemical composition.

A theoretical assessment of the HTR environment (equilibrium, kinetic of reactions) has been performed by Quadakkers, Brenner, Graham in the 70s and 80s. The theory shows that corrosion is influenced by the following main parameters: oxygen partial pressure, carbon monoxide partial pressure, carbon activity, chromium activity, temperature, which determines oxidation and carburization/decarburization processes. Thus environmental effects on the material behavior will be of importance in the alloys selection.

4.3.3.2 Knowledge Statement

4.3.3.2.1 Impure Helium effects - Role of impurities

It can be shown, according to theoretical analysis developed by Quadakkers from phase stability diagrams of NiCr alloys, that the effects of gas impurity interactions on these alloys, particularly oxidation, carburization/decarburization phenomena, are minimized in a range of impurity concentrations. These concentration limits define the so called “benign atmosphere”. Particularly the CO concentration should be high enough to prevent from the “micro-climate reaction” (as called by Brenner) that leads to the destruction of both the oxide layer and internal carbides (i.e massive decarburization).

Atmosphere Specifications (primary helium)
Based on the benign atmosphere defined from Quadakkers’ phase stability diagrams regarding NiCr alloys, AREVA-NP has proposed specifications for the helium impurity content in the HTR primary circuit for temperatures up to 950 or 1000°C. This recommendation deals with H_2O, H_2, CO, CH_4, N_2 level:

- $P(H_2O)/P(H_2)$ level (in relation with oxygen potential) to allow the formation of an external oxide layer

- CO partial pressure higher than a critical value to avoid "micro-climate" reaction

- $P(CH_4)/P(H_2O)$ ALARA to limit carburization

It also takes into account the graphite behavior in impure helium which leads to define an upper H_2O content, based on past experience.

A limit value is proposed for N_2, based on former HTR atmosphere (PNP).

Scope of (ANTARES) R&D program
The aim of the R&D program regarding the effects of environment on IHX materials was to confirm the validity of the recommended atmosphere for the two pre-selected material candidates, to assess the influence of main parameters (excessive temperature or lack of CO), to select the most appropriate materials, and if possible to optimize the materials in order to further reduce the environmental effects. This work has been carried out together by AREVA-NP, CEA and EDF through a concerted R&D program for providing all data required for the selection and the qualification of materials in the frame of AREVA-NP (ANTARES) project.

Behavior in benign atmosphere
In benign atmosphere, internal oxidation is mainly controlled by CO partial pressure, whereas long term oxidation behavior is controlled by H_2O partial pressure.

It has been demonstrated that for a given CO content in impure helium, there is a critical temperature limit above which the surface chromium oxide layer becomes unstable and is destroyed due to the reaction with bulk carbon, the so called "micro-climate reaction", leading to massive decarburization of the material. In addition the material is no longer protected against internal oxidation attack. This temperature limit increases when the CO content increases.

The safety region has been determined for In617 and H230 alloys in terms of critical temperature and CO partial pressure.

In617/H230 comparison
In617 and H230 alloys exhibit similar behavior with regard to critical Temperature and CO partial pressure.

An 800 hour test in benign atmosphere at 950°C (CEA) showed apparent greater resistance of H230 compared with In617, since H230 exhibits slightly thinner oxide layer and less internal oxidation attack at grain boundaries. However it should be noted that H230 shows a tendency to spalling at the top surface of the oxide scale. Internal oxidation would be enhanced by higher aluminum and titanium content in In617. Longer exposure tests are needed to confirm these tendencies.

For both materials it has been confirmed that a tight control of the HTR primary helium is required.

Influence of helium environment on mechanical behavior
The mechanical behavior of In617 under helium and vacuum environments has been compared through low-cycle fatigue and stress relaxation tests carried out at 850 and 950°C.

It has been shown that specimens often exhibit higher fatigue life endurance with equal strain range in simulated HTR helium environment than in air. However, more investigations are still required for a better understanding of the influence of helium on crack formation and crack propagation

Other materials (Hastelloy X, ODS)

The behavior of different potential material candidates for IHX (In617, H230, Hastelloy X and some ODS type alloys) has been compared through corrosion tests carried out in impure helium (benign atmosphere) at 950°C for about 800 hours (CEA test).

It could be noted that the two ODS alloys (PM1000 and 6025) and then Hastelloy X appear to have better oxidation resistance than In617 and H230. However they have not been pre-selected because of low mechanical properties for Hastelloy X and forming/welding difficulties for ODS.

Hastelloy X has been further developed in Japan to become Hastelloy XR to improve both oxidation resistance and creep properties.

Other Potential solutions

Material optimization has been proposed to improve the corrosion resistance of IHX materials in HTR environments.

It is expected that internal oxidation attack could be decreased by reducing the aluminum and titanium content of alloy In617 within the range of its composition specifications. The influence of these elements was to be studied on small ingots with

- reduced Ti and Al at the minimum values specified by ASTM/ASME standards
- value of Ti and Al as low as possible
- Ti and Al contents similar to those of existing industrial heats,

in order to assess the benefit of a particular composition before validation of the industrial feasibility.

Since chromium oxides that develop at the surface of In617 and H230 do not seem to be protective enough against corrosion (either in impure helium or in nitrogen base atmospheres), another potential solution is to protect the material by surface treatment or coating. Especially aluminum base coatings allow the formation of an external aluminum oxide layer which is known to be very protective against corrosion at high temperature. Note that the low aluminum content of In617 and H230 does not allow the formation of an external continuous aluminum oxide scale.
Some coating techniques have already been tested: Aluminum-base paint, PVD coating combined with diffusion annealing and aluminide (AlNi) CVD coating. The aluminide scale provides an aluminum “reservoir” for the formation of a protective alumina scale on the external surface. Preliminary tests have been carried out by AREVA-NP-NTCC-F on a limited number of In617 coated specimens (NiAl CVD coating) showing a remarkable corrosion resistance in severe conditions (in both helium and nitrogen environments). However the integrity of the coating under IHX HTR operating conditions (large range of temperatures, cyclic thermo-mechanical stresses induced by temperature transients, very long lifetime) still has to be demonstrated.

Aluminum base coatings are now considered as the most relevant potential solution. However, the validation of these solutions would still require a significant test program. In particular, the long term behavior (aluminum "reservoir" capability), the thermal behavior (coating/substrate interdiffusion) and the thermo-mechanical fatigue resistance (spalling, cracking) should be assessed.

Moreover the feasibility of coating techniques at an industrial scale should be assessed, taking into account the implementation constraints and control possibilities. The coating process should be compatible with the IHX size, geometry and fabrication procedure (plates concept is preferred compared with tubes). The CVD technique appears to be more convenient to implement than PVD techniques as it can be applied to an assembled component. CVD technique has moderate cost compared with PVD techniques.

4.3.3.2.2 Effect of nitrogen (HTR secondary gas in the case of the Combined Cycle Gas Turbine concept or as helium impurities or due to air entrance)

The effect of nitrogen has been investigated through AREVA-NP, CEA and EDF concerted program in the frame of ANTARES project. This program aimed to assess the nitriding risks on IHX materials in the ANTARES secondary circuit atmosphere which composition was 80% N_2-20%He by mass. Nitriding leads to material embrittlement due to the formation of internal nitride precipitates. This can become unacceptable especially for thin sections like the IHX heat transfer surfaces.

The nitriding kinetics and the nitrogen diffusion coefficient have been measured in both materials through tests carried out in a reducing nitrogen atmosphere in the temperature range 800-1000°C. The protective effect of an external oxide layer has been assessed through tests carried out at 800°C (up to 1000 hours) and 900°C (up to 3000 hours) in an oxidizing nitrogen atmosphere (industrial grade nitrogen) on specimens pre-oxidized or not.

Exposure to reducing nitrogen at 800 and 900°C leads to very severe nitriding attack. Both In617 and H230 are affected by nitriding, even if H230 exhibits better resistance due to lower content of nitride forming elements. At 900°C, the Cr_2O_3 oxide layer, which forms on both materials either during pre-oxidation treatments and/or when exposed to oxidizing nitrogen, is not protective enough to prevent nitriding. Increasing the temperature is an aggravating factor. These results are in accordance with the literature and German specialist experience. Moreover, an internal discontinuous oxidation (aluminum oxide) is observed below the external oxide layer, H230 alloy being less sensitive than In617.

The nitriding risk is likely to preclude the use of chromia-forming alloys such as In617 or H230 for IHX (plates or tubes design) if exposed to nitrogen-base atmosphere for the expected IHX lifetime.

Potential solutions have been identified: maintaining a specified amount of oxidizing species in nitrogen (this solution is restricted to the use of H230 alloy and, provided that the operating temperature is limited i.e ≤800°C[1]), providing an aluminum-based coating, using more nitriding resistant materials (alumina-forming materials). However the chances of success of these solutions are still to be demonstrated: the integrity of protective layer (whether oxide or coating) over the IHX lifetime under thermo-mechanical cycling, industrial feasibility of coating process on IHX, formability and weldability of alumina-forming materials.

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[1] After short duration test at 800°C, nitrogen seems to be confined in the oxide scale of H230. But this has not been confirmed through longer tests and the integrity of the oxide scale over the whole IHX life time should be demonstrated.

Nevertheless the nitriding risk in nitrogen-base atmosphere has been considered as not acceptable and AREVA-NP's current position is to use another secondary gas.

The effect of nitrogen as gas impurities is expected to be insignificant. However the effect of nitrogen partial pressure has not been investigated. The limit of nitrogen content should be assessed in terms of nitrogen partial pressure, temperature and duration, particularly in the secondary circuit because of potential contamination (accidental air, water ingress) and taking into account the capabilities of the purification means.

4.3.3.2.3 Tritium permeation issue

Tritium is produced in the HTR reactor and is likely to diffuse through metallic walls of components due to the high diffusivity of hydrogen isotopes. This phenomenon can become significant due to high operating temperature. Depending on the applications, the tritium permeation issue can become of importance particularly for gas production application (as hydrogen cogeneration application) since the tritium migration from the primary circuit via the IHX can lead to the contamination of the product gas. In the past, German investigators estimated the product gas contamination to be below the maximal allowable tritium content of the product gas required by German standard expected in 1985, based on PNP-500MW_{th} reactor conditions (for which tritium source has been estimated to be 562 $Ci.year^{-1}$ at equilibrium). More recently, GA estimated the tritium permeation rate through an MHR-HEATRIC plate IHX design (5230 m^2) to be 930 $Ci.year^{-1}$.

Tritium permeation is controlled by gas/solid diffusion laws, the main influencing parameters being the temperature and the impeding factor of the oxide scale at the metal surface, which acts as a permeation barrier. The oxide scale may reduce the permeation rate by several orders of magnitude (up to a factor of 1000). Coatings are also expected to reduce tritium permeation.

Other parameters having an influence on the permeation rate through the IHX are the upstream tritium and hydrogen partial pressures in the primary circuit.

A lot of data is available about tritium permeation through Incoloy 800H, Hastelloy X-XR, Inconel 617, from German experience (1980's) and from Japanese tests with the HTTR.

The best impeding factors have been obtained on Ni-20-25Cr alloys such as IHX material candidates but there is substantial scatter in the values, depending on the metal composition and on oxidation conditions.

To assess the tritium contamination level of the hydrogen product, it would be necessary to assess the tritium source in the HTR primary circuit.

More investigations would be required to assess the oxide (or coating) impeding performance (hydrogen permeation tests on oxidized IHX candidate materials) and resistance and self-healing capability in conditions representative of HTR operating conditions including thermo-mechanical cycling conditions.

Depending on the HTR applications, the tritium permeation issue could lead to recommendations about the helium impurity content and purification systems, the reactor operating conditions, the material pre-treatment, the IHX design, the graphite purity and the helium inventory in order to reduce the tritium source.

4.3.3.3 Facilities inventory

The facilities used or built under the ANTARES R&D program to study the environmental effects on mechanical and corrosion behavior of materials are listed in the following table:

Facility	Characteristics	
	Uniform corrosion	
Le Creusot TGA facility	Symmetric Thermo-Gravimetric Apparatus (short tests) or furnace (long duration tests) up to 1600°C Wide range of gas concentration (down to ppm) controlled by a Gas Chromatograph (GC) Low water vapor level controlled by cryogenic trap and mirror hygrometer (H_2O detection limit:0.3ppm)	AREVA-NP-NTCC-F
Le Creusot Ageing facility	Furnace (2 furnaces, up to 1200°C) Wide range of gas concentration (down to ppm) controlled by a gas chromatograph Low water vapor level controlled by cryogenic trap and mirror hygrometer (H_2O detection limit:0.3ppm)	AREVA-NP-NTCC-F
Le Creusot thermo-cycling facility	Lamp Furnace (up to 1200°C) Control of the heating kinetics (up to 40K/s) Control of the environment (gas and water level concentration)	AREVA-NP-NTCC-F
CORALLINE facility	Furnace (2 furnaces, up to 1050°C) Chromatograph, mirror hygrometer (H_2O detection limit:1.3ppm)	CEA
CORINTH facility	Furnace (4 test sections, up to 1500°C, 2 different atmospheres) Chromatograph, mirror hygrometer (H_2O detection limit:0.3ppm)	CEA
ESTEREL facility	Furnace (up to 1050°C) IR Gas analysis, Mirror hygrometer (H_2O detection limit:1.3ppm)	EDF
	Effect of environment on creep	
CORSAIRE facility	Creep under impure helium or nitrogen 900°C, 2kN load cell	CEA
FLAMENCO facility	Creep strength at low stress 1000°C, 20 MPa bending device, laser deflection measurement	CEA
Creep/Low cycle fatigue facility	1100°C, 35 kN tension-compression LCF device	CEA

Similar facilities would have to be built in the context of NGNP or an agreement would have to be reached to secure access to those facilities for NGNP testing.

4.3.3.4 R&D needs for qualification

According to the work described above it appears that further efforts should concern:

- a better understanding of the environment/material interaction,
- the optimization of the material microstructure
- the implementation of coatings with assessment of their performance.

4.3.3.4.1 Improvement of the understanding environment/material interaction

This action includes:

- Characterization of oxidation and carburization in the HTR benign environment
  - Assessment of the effect of H_2O content on the critical behavior of materials
    - Effects on the critical temperature
    - Evaluation of the kinetics of degradation
  - Assessment of the effect of CH_4 content on the critical behavior of materials:
    - Effects on the critical temperature
    - Evaluation of the kinetics of degradation
  - Characterization of the long term behavior of materials in primary environment.
- Characterization of the material behavior in the secondary side NGNP environment
  - Determination of a benign secondary side environment
  - Assessment of the effect of accidental air entrance (N_2, O_2, H_2O, CO_2)

4.3.3.4.2 Optimization of material microstructure

The optimization of the material microstructure may consist in evaluating the influence of different metallurgical parameters on the corrosion behavior. This task requires the acquisition of tubes, sheets and plates, the characterization of the microstructure and of the mechanical and corrosion behavior in representative HTR environment (for short and long exposure) to assess respectively the impact on material mechanical properties and behavior.

4.3.3.4.3 Implementation and assessment of coatings

This task consists of:

- Selection of some coatings taking into account their characteristics (deposit composition, structure, thickness) and their potential performance (high temperature corrosion resistance, low interdiffusion and Kirkendall effect, no spalling, good adherence to the substrate) in relation with available coating processes (CVD, PVD, thermal spraying or others). The selection should take into account the coating industrial implementation and control possibilities.
- Fabrication of coated specimens and characterization.
- Long term behavior of coated specimens to assess their performances: ageing tests, corrosion tests in representative HTR helium atmosphere and tests under thermo-mechanical cycling stresses.

4.3.3.5 Proposed R&D action program

Proposed action program and planning are summarized in the following table.

Actions	Work type	Available facilities	Required time (estimation)
Improvement of environment/material interaction understanding			
Characterization of corrosion in helium benign environment			
Role of H_2O and CH_4	Corrosion tests (TGA+GC) and metallurgical characterization PhD Thesis for example	AREVA-NP-NTCC-F, CEA	3-4 years
Long term corrosion behavior	Long term exposure (>10 000 hrs)	AREVA-NP-NTCC-F, CEA	5 years
Material behavior in secondary side NGNP environment			
Definition of a benign secondary side environment (oxidizing species, gas composition…) within the secondary side specifications	Short and long exposure corrosion tests (TGA+GC) and metallurgical characterization	AREVA-NP-NTCC-F, CEA	3-4 years
Effect of accidental air entrance in the secondary side	Corrosion test (TGA+GC) and metallurgical characterization	AREVA-NP-NTCC-F, CEA	1 year
Material behavior simultaneously exposed to representative primary/secondary environments	Definition of a specific test for long duration exposure	AREVA-NP-NTCC-F	2 years
Tritium permeation issue			
Determination of the NGNP reactor tritium source	Study/calculation		2 months
Assessment of the tritium rate through the IHX and of the expected contamination level in the product gas	Calculation		4 months
Assessment of the impeding performance of oxide layer or coating	Hydrogen isotopes permeation tests on oxidized or coated IHX candidate material specimens (see below)	To be identified	2 years
Optimization of material microstructure			
Review of long term previous work	Bibliographic study	AREVA-NP, CEA	3 months
Acquisition of sheets, tubes and plates	Characterization (carbides)	Industries and laboratories (identified but to follow up)	6 months
Assessment of material performance	Ageing tests in environment (> 10 000 h) Mechanical tests Critical corrosion tests Characterization	AREVA-NP-NTCC-F	3 years

Development and assessment of coatings			
Selection of some coating composition and processes	Bibliographic study +consultation with coating industries or laboratories	AREVA-NP, CEA	3 months
Assessment of the feasibility of the selected coating processes (to be performed in parallel to the determination of the coating performance)	Fabrication Characterization	CEA, other laboratories or industries (to be identified)	6 months
Evaluation of the technological and economical cost for the industrial production	Study	AREVA-NP	6 months
Assessment of coating performances	Ageing tests in environment (> 10 000 h) Corrosion tests in representative helium Thermo-mechanical tests Characterization	AREVA-NP-NTCC-F, CEA, EDF	2-4 years
Assessment of the corrosion behavior of welded zones			
Assessment of the corrosion behavior of welded zones in HTR environment	Ageing tests in environment (> 10 000 h) Corrosion tests in representative helium Thermo-mechanical tests Characterization	AREVA-NP-NTCC-F, CEA	2-4 years

It should be underlined that the whole program would require a significant investment in order to perform parallel tasks.

4.3.4 Forming and joining

4.3.4.1 Knowledge statement

4.3.4.1.1 In617 and H230 forming and joining

Preliminary forming tests (Erichsen tests) have not detected a significant difference between In617 and H230 concerning formability. Their formability seems similar to or better than that of austenitic stainless steels.
Preliminary welding works have shown that GTAW (TIG) and SMAW (covered electrodes can be used for In617 but a risk of hot cracking exists and should be avoided by optimization of the welding process). In the case of H230 GTAW (TIG) (and may be GMAW) appears to be the only possible process. In the case of TIG H230 weldments, the bad point is a very low tensile ductility.
Preliminary brazing works have shown that

- Brazing at a temperature lower than the solution annealing temperature of the base metal was not satisfactory (poor wettability and formation of brittle phases of high hardness at interfaces).

- In the case of brazing at a temperature higher than the solution annealing temperature of the base metal, a brazing metal can be selected for satisfactory wettability, limitation of brittle eutectic phase must be carried on (Si content, optimization of thickness of brazing).

- Brazing of H230 seems a little bit easier than brazing of In617.

Some preliminary work has also been performed on diffusion bonding with pressure, temperature and hold time as relevant parameters to be optimized. Diffusion bonding, like brazing at a temperature exceeding the solution annealing temperature of the base metal, produces new phases with microstructures and mechanical properties different from those of the initial materials.

4.3.4.1.2 Forming and joining other materials

ODS: the main drawback of ODS alloys is the fact that they cannot be formed. So the IHX design should be adapted to industrial fabrication limits: feasible shapes and sizes (thickness, width and length) to be defined with the producers.
Other difficulties are:

- the feasibility of efficient nondestructive detection of defects[2] which can significantly alter the material properties (leak tightness in case of thin sheets)

- welding. Fusion welding is not possible because oxides are rejected from the melted matrix. The solutions for joining ODS material would be diffusion bonding or brazing. But the diffusion bonding and the brazed joints are likely to be affected by an efficiency factor, which would reduce the allowable stress limit of the base material. It is not sure that such factors will be compatible with the design of very high temperature components.

4.3.4.2 R&D needs for qualification

Further efforts should concern:

- Continuation of optimization of In617 weldability

- Search for suitable welding parameters for H230 (with Haynes?)

- Weldment stress rupture factors

- Characterization of the corrosion behavior of the welded zone (HAZ and welded metal)

4.4 Status of and planning for codification of the material

4.4.1 Introduction

In the frame work of high temperature or very high temperature reactor development, experiments and studies have been undertaken in the past (1980 – 1992) in order to provide design data for NiCrCoMo Alloy 617. These works were mainly performed in U.S. and Germany. The results are summarized in references 127 and 128. They cover mainly the same properties as used for elevated temperatures design following the subsection NH of ASME III (formerly Code Case N47).The purpose of this note is to point out :

- The main discrepancies in these design data
- The lack of reliable data to cover some types of damages
- The inadequacy of constitutive equations to evaluate stress-strain-time behavior of the material

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[2] Voids, pores, ceramic inclusions that are not easily detected and quantified by nondestructive techniques

- The Code and standard status of other high temperature superalloys candidates.

4.4.2 Characterization of UNS alloy 6617 in the 1980 years

The summarized data of references 127 and 128 provide only minimum temperature dependent values of:

- Yield strength
- Tensile strength
- Creep stress to rupture
- Pure fatigue curves are also given in reference 127 (design fatigue curves) and in reference 128 (average endurance curves)

4.4.2.1 Tensile properties

At temperature up to 800°C for yield strength and up to 500°C for ultimate tensile strength, the KTA minimum values are higher than those from the Code Case. This can be related to the differences in specified tensile properties at room temperature:

	ASME	KTA and EN 10302 standard
Yield strength (MPa)	≥ 240	≥ 270
Tensile strength (MPa)	≥ 655	≥ 700

At more elevated temperatures, the ASME minimum values appear to be higher than the KTA values. When minimum tensile strength data are compared to experimental data, Code Case minimum values do not show margins at temperatures from 750°C to 950°C whereas KTA minimum values show margins at temperatures from 500°C to 950°C.

Concerning minimum yield strength data, it seems that the Code Case values show larger margins with the experimental results than the KTA minimum values.

In addition to the differences in initial data base (shape and size of semi finished products which have been tested), in the statistical treatment used to derive minimum values, a specific high temperature effects should be taken into account. It is the strain rate dependence of the tensile properties. This effect will be discussed later but it must be indicated that the Code Case data are announced for a strain rate of 5.10^{-3} min^{-1} (8.10^{-5} s^{-1}) and the KTA data for 10^{-4} s^{-1}.

4.4.2.2 Time independent allowable stress limit S_m

The differences in minimum values of tensile properties produce differences in time independent allowable stress limits S_m.

In Code Case, it was proposed to reduce the value of S_m at high temperatures by using a factor 2/3 instead of 0.9 at temperatures exceeding 1200°F (649°C). The 800°C S_m value is actually reduced by 30%. But the values from 850°C to 950°C are not affected as they are dependent on minimum values of the tensile strength and not on minimum values of yield strength.

4.4.2.3 Creep properties and stress to rupture

As for tensile strength, lower minimum stress to rupture curves are given by KTA. The discrepancy is larger as the time is longer or the temperature is higher. As previously, Code Case minimum values of stress to rupture do not show clear margins compared to experimental data at temperatures from 800°C to 1000°C. In addition, the remark that the discrepancy is larger as the time is longer or the temperature is higher, means that the treatment of data for average and minimum values in extrapolated conditions, has an effect on design data. These was partially recognized in derivation of data in reference 127 which are limited to 100,000 h whereas data in subsection NH of ASME III are extended to 300,000 h.

4.4.2.4 Fatigue data

After application of factors 20 and 2 in order to compare average endurance data and design fatigue data, no important discrepancies have been found between KTA in air data and Code Case data for pure fatigue. The KTA design data however are limited to 3000 cycles which is too short to cover the design needs. In addition KTA provide average fatigue endurance data in helium at 750°C and 850°C, which are significantly longer in number of cycles than air data. At 950°C, the difference between air and helium fatigue data disappears above around 3000 cycles. Additional experiments in fatigue and creep fatigue areas should take account of the representative He environment

4.4.3 Application of design rules of subsection NH to very high temperatures

As mentioned in introduction, design rules and corresponding design data in references 127 or 128 are similar to those of subsection NH of ASME III. Several comments have been made in relation to the extension of subsection NH to service conditions of VHTR. First type of comments is related to the very high temperature and can be extended to any Ni superalloys. They are :

- Important strain rate dependence of tensile properties (yield strength, flow stress for a given plastic strain, ultimate tensile strength)
- Lack of a clear distinction between time independent (elastic plastic) behavior and time dependent (creep) behavior
- Near zero strain hardening in tensile behavior leading to small elongations at maximum stress
- Other softening effects (in cyclic behavior for example)

An effect which is more specifically related to alloy 617, is the reduction in toughness due to thermal aging.

These effects have been recognized by the Task Force Very High Temperature Design (Reference 129) which reported to the Subgroup on Elevated Temperature Design. The Task Force has examined the following possible failure modes:

- Ductile rupture from short-creep rupture term loadings,
- Creep rupture for long-term loadings
- Creep-fatigue failure
- Gross distortion due to incremental collapse and ratcheting
- Buckling due to short-term loadings
- Creep buckling due to long-term loadings
- Loss of function due to excessive deformation

- Non ductile rupture.

The last point is related to the degradation of toughness due to aging.

Taking account of the very high temperature effects and concerning the prevention of failure modes listed above, reference 129 points out the following features of the Draft Code Case as compared with subsection NH of ASME III :

- Full inelastic analysis accounting for rate dependence and creep effects for analysis associated with level D service limits.
- Inelastic analysis based on unified constitutive equations for temperatures above 649°C (an example of such constitutive equations is detailed in reference 129).
- Lower load for level D service limits (70%).
- Modification of the derivation of S_m (as mentioned previously and apparently efficient at 800°C but not at 850, 900 or 950°C).
- Modification of the derivation of St stress for the onset of tertiary creep not taken in account because increasing strain rate is observed very early in constant load creep tests at 982°C.
- Limitation at 649°C of the provisions proposed in appendix T of subsection NH for strain and fatigue limits
- Exclusion of alloy 617 for bolting
- Exclusion of cold worked material

These last two points are related to aging effect on toughness and to possible recrystallisation effect on strengths.

4.4.4 Data and rules for design at very high temperature: main shortages in the case of alloy 617

4.4.4.1 Tensile curves and tensile properties

The data at different strain rates can be derived from reliable constitutive equations. But such equations will not cover correctly the strain rate dependence of ultimate tensile strength which enters in some loading limit (level D). A particular formulation of strain rate dependence of ultimate tensile strength is needed.

4.4.4.2 Creep properties

A first point is to obtain a representative data base: Besides the number of casts and the number of data, the tests must include products representative in shapes and dimensions. Bars of 1 inch or 25 mm in diameter are commonly used in test programs. Tubes of similar diameters and more than 2 mm thick, have probably similar properties, but the properties of very thin sheets or foils have to be checked in relation to the design of IHX. The effect of the fabrication process needs also to be checked in relation to the exclusion of cold worked materials.

Derivation of properties from a satisfactory data base is easier to perform. Nevertheless, consensus from a working group is necessary on two points:

- Determination of average data allowing reasonable extrapolation in time and temperature among methods which all are quite satisfactory for conditions covered by the tests of the data base.

- Derivation of minimum values from average values (the practice seems to lower the data by 1.65 times standard deviation in US and by 2 times standard deviation in Europe).

The decision to exclude onset of tertiary creep from stress limit determination means that the observed increasing strain rate is not due to creep damage initiation : This point must be proven.

4.4.4.3 Constitutive Equations

The task of selection and validation of such equations needs material specialists as well as specialists of codified data and inelastic analyses. The domain of validity in temperature, stress or strain level and time must be clarified and compared to the design needs. This task will probably result in specific complementary tests programs. The task has been performed many times but at lower temperature and using the data of a particular heat. From the past experience, the hard point is to adjust the constitutive equation parameters to an average behavior of a particular, clearly identified grade of alloy.

4.4.4.4 Ratcheting and strain limits

Reference 129 has pointed out that extension of strain limits above 649°C needs to be validated and that simplified ratcheting analysis procedure do not exist at such temperatures. To mitigate these deficiencies, tests on mock up and benchmark exercises are probably necessary.

4.4.4.5 Fatigue and creep-fatigue

In reference 129, this point was identified as the biggest short coming of the draft Code Case and of subsection NH of ASME III: « rather than generate more data to characterize creep-fatigue of alloy 617 in terms of linear damage which is widely recognized to be inadequate, a basic effort is needed to identify and experimentally validate a more fitting damage theory».

Recent studies on modified 9Cr1Mo confirm this opinion. The decrease in fatigue life at elevated temperatures when cycle frequency is reduced or when hold time is introduced can be due to the environment as well as to a creep effect. If the environment effect is dominant, it is hopeless to correlate the reduction in fatigue cycles number to the creep damage. Similar complex interaction of fatigue cycling, of environment and of creep effects on inelastic strain as well as of creep damage, is likely to occur in alloy 617 at very high temperature as:

- Creep fatigue behavior in Ni base alloy is known to be environment dependent (case of alloy 718).
- High temperature accelerates softening effects as well as interaction with the environment.
- Conclusions from comparison of air and helium fatigue data seem to be temperature dependent.

4.4.4.6 Thermal aging effects

The effect of thermal aging needs to be clarified in order to evaluate end of life value of toughness, as extensive decrease of impact Charpy V values have been observed after aging of alloy 617. The difficulty will arise from a non monotonic influence of temperature and time or from some kind of healing effect in a particular time and at some temperatures, as observed in some Ni alloy above 750°C. In this case acceleration of aging effect by increasing temperature is not justified and cannot be used for end of life toughness data prediction. A full analysis of the different aging mechanisms should be performed.

End of life tensile strength should also be evaluated in connection with level D service analysis. The evaluation has also to take account of a probable rate effect. Available data at 750, 850 or 950°C are after too short-term aging for any end of life prediction.

4.4.5 Status of candidate materials for intermediate heat exchangers of HTR

The following table gives the status of possible IHX material candidate within ASME code.

UNS number	ASTM standard for sheet and plates	Maximum temperature in ASME VIII-1	S (MPa) (650 °C)	S (MPa) θ_{max}	Alloy designation
N06617	SB168	900 °C (1 650 °F)	117	11.7	Alloy 617, Inconel 617, Nicrofer 5520 Co
N06002	SB435	900 °C (1 650 °F)	78	8.3	Alloy X, Hastelloy X, Nicrofer 4722 Co
N06230	SB435	900 °C (1 650 °F)	108	8.3	Alloy 230, Haynes 230
R30556	SB435	900 °C (1 650 °F)	94	11	Haynes 556
N08330	SB536	900 °C (1 650 °F)	32	3.3	Alloy 330, Nicrofer 3718
N08810	SB409	900 °C (1 650 °F)	51	5.9	Alloy 800 H, Incoloy 800 H, Nicrofer 32204

It is to be noted that from the above table, alloy 800H is the only one currently permitted for nuclear applications.

Weldability and availability of other joining techniques such as brazing or diffusion bonding for non pressure retaining assemblies, are important criteria for the selection of an IHX material. But the present knowledge of these technologies is too restricted to guide the selection.

4.4.6 Conclusion

A task force for rules and data for design at very high temperatures of components in alloy 617 should cover the following tasks:

- Tensile and creep properties and allowable stress limits (material specialists and code experts)
- Constitutive equations (material specialists and inelastic analysis experts)
- Strain evaluation and ratcheting (inelastic analysis experts, code experts and high temperature testing experts)
- Creep- fatigue (material specialists, code experts, and high temperature environment experts)
- Thermal aging effects (material specialists and fracture toughness testing experts)

The difficulty of very high temperatures design is enhanced by

- The low level of stress limit which can be less than 10 MPa to be compared to 100 MPa in the range of validity of subsection NH.

- The uncertainty of constitutive equations in low stress and high temperature conditions which, conversely, are expected to produce strain and stress evaluations ten times more precise than in the range of validity of subsection NH.
- The enhancement of environmental effects

4.5 Impact of environmental effects

4.5.1 Corrosion in He environment

4.5.1.1 Introduction

Past experience from Helium Gas Cooled Reactors indicates that the primary coolant gas will inevitably contain residual impurities (CO, H_2O, H_2 and CH_4) in the range of tens to few hundreds of µbars [31]. Due to the very low level of impurity and to the very high gas flow velocity, the gas phase is not in a thermodynamic equilibrium [32, 33] and gas/metal interactions may be regarded as independent [32, 34]. Since the 70's, numerous studies have been conducted on the corrosion behavior of structural materials in typical primary side HTR environments. Depending on temperature and gas composition, interactions between metallic alloys and gaseous species may lead to oxidation (external/internal), carburization or decarburization [32, 34-39]. For a given temperature service condition, the formation of a long term corrosion resistant oxide layer relies on the definition of a "benign" atmosphere with an oxidation potential controlled by the P_{H_2O}/P_{H_2} ratio and an adequate control of the concentration of carbon-bearing gases. Nevertheless, for a given P_{H_2O}/P_{H_2} ratio, the existence of a critical temperature/carbon monoxide partial pressure relationship, defining a domain where the chromium-rich surface layers are no longer stable, has been pointed out [32, 34, 37-39]. For a given CO partial pressure, the critical temperature, T_A, corresponds to the upper boundary of coexistence of the native oxide scale with the carbon from the alloy. Above $T_{A,}$ the so-called "microclimate" reaction occurs leading to a mutual destruction of oxides and carbides producing CO until either the total reduction of the external chromium rich oxide layer or removal of all the accessible carbon.

If the atmosphere plays a significant role in the long term behavior of IHX structural materials, the role of minor alloying elements is also of major importance due to their solid solution strengtheners role and their potential influence on the corrosion behavior of the material (especially regarding the internal corrosion).

The present IHX concepts are highly demanding for structural materials since very thin metallic sheets must be mechanically resistant and leak-tight at high temperature for an extensive lifetime, typically 20 years. Accordingly, the environmental damage must be limited, and it is necessary to understand the specific corrosion mechanisms of IHX candidate alloys in both primary and secondary HTR environments in order to achieve the optimum chemistry control of both environments. In addition, alternative protective solutions such as coatings may be considered.

4.5.1.2 High temperature Corrosion of Ni-Cr alloys in impure helium

4.5.1.2.1 Characteristics of the VHTR helium

HTR primary coolant will inevitably contain some impurities coming from the outgassing of adsorbed species out of the structural components, from air-ingresses during maintenance and refueling, and from in-leakages [31]. Among these impurities some are reactive and may interact with the core graphite and metallic elements leading to an alteration of their properties. Experience from helium-cooled reactors [33, 40] allows the estimation of the contamination level (Table 4-2).

	H_2	H_2O	CO_2	CO	CH_4	N_2
DRAGON	2	0.1	0.04	1	0.3	1.2
AVR	30	3	10	30	-	
Peach Bottom	20	<1	-	1	1.5	1.5

Table 4-2 Impurity contents (in Pa) in experimental helium-cooled reactors [33, 40]

Nitrogen was demonstrated to be fairly inert in the very low concentrations present in HTR Helium and does not significantly contribute to corrosion [41]. Major active impurities are water vapor and permanent gases such as H_2, CO, CH_4 and may be divided in oxidizing (H_2O and CO) and carburizing (CO, CH_4) species. The specific nature of the HTR environment relies on the very low level of impurities ranging from tens to hundreds of µbar that reduce the probability of gas/gas interactions. Consequently, as expressed by Brenner [34], the HTR environment may not be described by the classical thermodynamic approach.

4.5.1.2.2 Gas/metal surface reactions in impure helium

Because of the low impurity contents, the collision probability between gaseous molecules is very low and the gas phase does not achieve equilibrium [32, 33]. In absence of any metallic surface, it has been verified that, up to 1050°C, no measurable change of the environmental composition occurs. Considering that the gas phase is not in thermodynamic equilibrium, it is assumed that the gas/surface reactions can be regarded as independent [32-34]. Therefore, the following set of possible equations between one helium impurity and the metallic surface has been established:

- Oxidation of the metal by the water vapor

$$y\ H_2O\ (g) + Me\ (s) = MeOx\ (s) + y\ H_2\ (g) \quad (1)$$

- Decomposition of the methane on the metallic surface

$$CH_4\ (g) = C\ (s) + 2\ H_2\ (g) \quad (2)$$

- Reaction of the water vapor with carbon from the alloy

$$H_2O\ (g) + C\ (s) \rightarrow CO\ (g) + H_2\ (g) \quad (3)$$

- Decomposition of the carbon monoxide with metal oxidation

y CO (g) + Me (s) → MeOx (s) + y C (s) **(4)**

where Me (s) is a metallic alloying element that can be oxidized at the low oxygen potential prevailing in the VHTR helium such as Al, Si, Ti, Mn, Cr… (Fe, Co, Ni… cannot be oxidized or carburized in the given HTR conditions) and MeOx is the corresponding oxide. Above equations have been expressed in terms of carbon in solution C (s) instead of internal carbides (as Cr_3C_2 or $Cr_{23}C_6$), so it is assumed that carbides and C (s) are in equilibrium within the substrate, according to:

$Cr_{23}C_6$ (s) = 6 C (s) + 23 Cr (s) **(5)**

High temperature resistance of Ni-Cr alloys relies on the formation of a "protective" chromium-rich surface oxide scale that must be adherent, dense, and slow-growing. As a consequence, the following conditions must be respected in a "benign" HTR environment [32, 34, 37, 39]:

- In the absence of oxygen in the primary HTR environment, the oxygen potential defined by the P_{H_2O} / P_{H_2} ratio must be oxidizing with respect to chromium,

- Carbon-bearing gasses have to be tightly controlled: carbon monoxide partial pressure must be high enough to avoid the "micro-climate" reaction (discussed below) and the CH_4/H_2O ratio must be kept as low as possible.

Due to the possible occurrence of simultaneous reactions, carbon exchanges between the metal and the atmosphere cannot be completely avoided and may not only modify the surface corrosion products (oxides and/or carbides), but also cause in-depth changes in the alloy microstructure. One can expect either carburizing effects leading to embrittlement effects due to the coarsening of internal carbides [36] or decarburization triggering the dissolution of the internal carbides, which can lower the creep properties of carbide-strengthened alloys [42]. Several authors have attempted to describe and rationalize the surface reaction in high temperature helium and the most accurate approaches were given by Brenner [32, 34] and Quadakkers [37, 43, 44]. The major interest of such approaches relies on their ability to offer a "direct" prediction of the behavior of Ni-Cr based alloys in HTR environment by a graphic representation. These representations are based on the stability diagram of chromium oxide and carbides as a function of the impurity content. Brenner has proposed a mapping of the corrosion behavior of a chromia-forming alloy in the form of Ternary Environmental Attack (TEA) diagrams expressed as function of P_{CH_4} / S, P_{H_2O} / S, and P_{CO} / S where $S = P_{CH_4} + P_{H_2O} + P_{CO}$. The major interest of the representation proposed by Quadakkers that is expressed as function of carbon and oxygen activity (a_c and P_{O_2}) leads in its ability to describe the different behavior domains in a unique "stability diagram" at a given temperature (Figure 4-3).

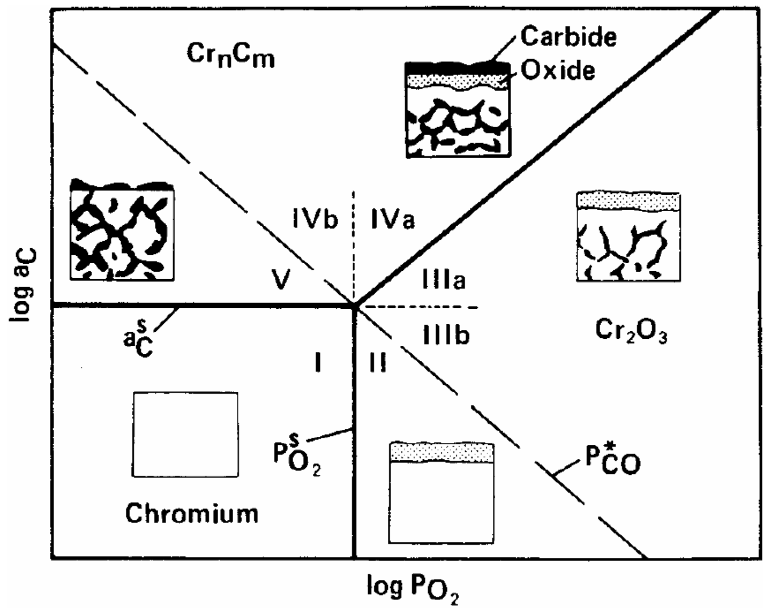


Figure 4-3 - Identification of the different regions of the stability diagram and corresponding types of behaviour of Ni-Cr based alloys [37, 43, 44].

In the stability diagram, 7 different domains have been identified:

- Region I: metallic chromium is stable; no protective oxide will be formed and severe decarburization will occur,

- Region II: chromium oxide is stable ($P_{O_2} > P_{O_2}^s$) but a severe decarburization is expected due to the low carbon activity,

- Region V: carbon activity is high ($a_C > a_C^s$) and the oxidation potential is too low to allow the oxidation of chromium; a strong carburization will occur,

- Region IVb: due to the high carbon activity, carburization may occur. As a function of the porosity of the carbide surface layer, oxidation may also happen below the carbide layer if the pores are small enough to avoid any renewal of the gas phase, leading to a local decrease of the carbon activity to a_C^s and increase of the oxygen potential $P_{O_2}^s$.

- Region IVa: chromium carbide is stable and, since $P_{O_2} > P_{O_2}^s$, a chromium oxide film may develop below the carbide film,

- Region IIIa: chromium oxide is stable, leading to the formation of a continuous oxide film but, due to the high carbon activity, chromium carbides are expected to form below the oxide film where the oxygen activity is low. The formation of the oxide film is expected to limit the carburization process.

- Region IIIb: the oxide is stable and the carbon activity is too low for the chromium carbides to be stable. However, according to Quaddakers, the material behavior will depend on the porosity of the oxide scale. Severe decarburization may occur in case of the formation of a porous oxide scale, whereas any formation of an oxide scale with small pores will impede any rapid renewal of the gaseous environment. In this case, the local oxidizing potential is expected to decrease to $P_{O_2}^s$, inducing a local increase of the carbon activity which inhibits any decarburization or even causes a slow carburization.

At a given temperature, region III, which requires a partial pressure of carbon monoxide that exceeds P^*_{CO}, is considered to be the safest region regarding the material degradation. As a consequence, the benign atmosphere requires a partial pressure of carbon monoxide higher than the critical value P^*_{CO}, an oxygen activity large enough to allow the formation of a stable chromium oxide layer and the lowest possible P_{CH_4}/P_{H_2O} ratio.

Below the critical carbon monoxide partial pressure or at higher temperatures, previous works [32, 34, 37-39] have pointed out that the chromium-rich protective oxide layers are no longer stable. For a given P_{CO} in the helium coolant, the critical temperature, T_A, corresponds to the upper boundary of coexistence of the native oxide scale with the carbon from the alloy. Above $T_{A,}$ the so-called "microclimate" reaction occurs leading to massive decarburization and reduction of the external oxide scale rich in chromium inducing a production of CO, according to the following reaction that is formally the back equation of Eq. (4):

$$\mathbf{MeOx\ (s) + y\ C\ (s) \xrightarrow{T>T_A} y\ CO\ (g) + Me\ (s)} \qquad \mathbf{(6)}$$

Brenner [32, 34] emphasized the major influence of the P_{CH_4}/P_{H_2O} ratio: a low P_{CH_4}/P_{H_2O} will lead to a regeneration of the oxide together with massive decarburization while a high ratio will lead to extensive carburization. The exact scheme of Eq. (6) is still under discussion in order to take into account that solid/solid reactions are unlikely to happen for kinetic reasons [32, 34, 35, 37, 38]. On nickel-chromium base alloys [35, 38, 45-49], it is now clearly established that the higher P_{CO} is in the gas environment the higher is T_A. From an operational point of view, Eq. (6) proceeds until either all the oxide or all the carbon is removed, if the parameters remain constant. Consequently, the temperature of the helium has to be adjusted and monitored to avoid any "microclimate" reaction.

4.5.1.3 High Temperature reactivity of Ni-Cr base alloys

4.5.1.3.1 Behavior in Benign Atmosphere

Since the 70's, the detrimental consequences of the overall corrosion process on the long term material behavior have been established [32, 34-39]. Depending on temperature and gas composition, interactions between metallic alloys and gaseous species may lead to strong carburization (region V), severe decarburization (region I and II) or combined carburization/oxidation with the formation of a non protective (region IV) or protective (region III) oxide layer as identified in Figure 4-3. A benign HTR environment may therefore be defined consisting of controlling the oxidation potential and the carbon activity above a given critical carbon monoxide partial pressure. However, long term experiments in "benign" atmospheres have demonstrated that the formation of the chromium oxide layer will not prevent other unwanted corrosion effects. Among the deleterious effects that have been characterized, the following have to be considered with attention due to their impact on the material properties:

- The occurrence of internal oxidation (rich in aluminum) which may affect the adherence of the oxide scale and induce a depletion of strengthening elements,
- The occurrence of a carbide free zone close to the metal/oxide interface due to the depletion in chromium subsequent to cationic oxidation process;
- The increase of the carbon content, which is one of the most deleterious potential effects.

Based on such considerations, specific studies have been launched to offer a better understanding of the fundamental parameters controlling the formation of the external oxide scale and the concomitant corrosion effects. To investigate the oxidation mechanisms of IHX candidate alloys in typical primary atmosphere (containing little or no methane), short-term oxidation studies have been carried out following procedures derived from past experiments [38] in dedicated test facilities that allow adjusting most of the key parameters of the environment such as impurity levels, temperature, and gas flow rate [50].

In presence of the two oxidizing species, H_2O and CO, typical short term oxidation behaviors are presented in Figure 4-4. A significant amount of carbon monoxide is initially consumed during the heating up of the specimen [38, 48]. The CO consumption reaches a maximum when the isothermal plateau starts, then smoothly decreases and finally stabilizes at very low rate. Moreover, it may be pointed out that the higher the water vapor content in helium, the lower the CO consumption and the thicker the oxide layer [51, 52]. It is thus assumed that carbon monoxide initially takes part in the oxidation but after a while the oxidation by CO becomes negligible compared to the one governed by water vapor. In the first stage of oxidation, CO and H_2O may be considered as competitors with respect to the oxidation of the alloy even if the oxidation process remains mainly governed by the water vapor contained in the environment. It is worth noticing that oxidation by CO will deposit some carbon at the reaction site according to Eq. (4). Moreover, tests with a low P_{CH_4}/P_{H_2O} ratio (≈10) illustrates that the carbon take up is mainly due to CO [52]. So, as low as oxidation by CO may be, it has to be clearly controlled due to the its potential carburizing character, which may play a significant role when considering long periods corresponding to the IHX lifetime.

As a consequence, optimizing the helium composition inside the "benign" domain of the stability diagrams requires that we understand the quantitative role of both CO and water vapor (and to some extent the oxidizing potential) on the long term corrosion behavior of Ni-Cr alloys in order to evaluate their relative influence on the material degradation (carbon uptake, depth of the carbide free zone). The exact role of the oxidizing potential on the morphology of the chromium oxide layer and on its ability to inhibit any CO consumption, and consequently any carbon uptake, over long periods still has to be clearly established.

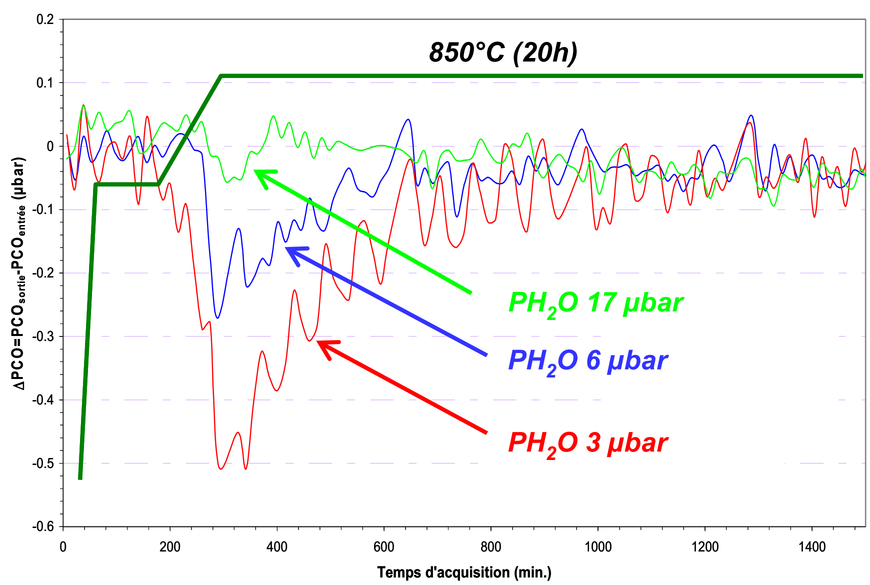


Figure 4-4 – Evolution of the CO consumption as a function of time for constant value of P_{CO} = 15µbar and P_{H_2} = 140µbar for IN617 specimens [51].

As already expressed, chromium is the only major alloying element which is likely to oxidize in low oxidizing Helium environment. Since minor alloying elements as aluminum, silicon, manganese and titanium are also expected to oxidize, they are likely to influence the oxidation kinetics of chromium and consequently its "protective" character. Metallurgical characterization of the corrosion products illustrates that minor elements also participate actively to the oxidation process [45]. For industrial alloys, the surface oxide consists of a continuous chromium rich oxide layer. For Alloy 617 (0.4wt.% Ti), titanium is detected in the oxide layer preferentially above alloy grain boundaries. Manganese (0.5wt.% Mn in Alloy 230) is detected on the upper part of the Alloy 230 oxide scale, forming a spinel $Mn_xCr_{(3-x)}O_4$, phase irrespectively of the alloy grains or grain boundary regions whereas the inner oxide layer consists of pure chromia. The Mn superficial enrichment, also observed at high temperature in air [53] and for other chromium rich nickel base alloys [54], is related to a diffusion coefficient of Mn ions hundred times larger than that of Cr ions themselves in chromia at 900°C [55, 56][3].

Underneath the chromium rich oxide layer, a discontinuous internal aluminum rich oxide develops (enriched in silicon in the case of H230). Finally, aluminum intergranular oxidation is observed deeper in the alloys. Just below the oxide surface it has been shown that Cr and, to some extent, Al depleted zones are formed.

As the role of minor elements, typically Al and Ti, is of major importance due to their role of solid solution strengtheners and their active participation to the corrosion behavior of the material, specific attention has to be paid to their effective role on the oxidation mechanism. On Ni-Cr base alloys the influence of alloying elements is much stronger on low Cr alloys. For Ni-10Cr alloys, the addition of Ti (up to 3.4 wt.%) alone or in combination with Al (up 4 wt.%) increases the resistance to carburization whereas the effect of Al is deleterious to the material, inducing severe internal oxidation and carburization at 1173K [57]. Shindo *et al.* [58] have demonstrated that industrial alloys containing a rather high level of Ti in addition to Al may resist carburization better in carburizing environments. In oxidizing environments, the higher Al, Ti alloys exhibit good decarburization resistance but offer poor oxidation resistance, as both elements tend to oxidize internally and Ti seems to increase the growth rate of the chromium oxide scale. In the case of IN617, the oxide scale composition reflects the potential influence of such minor elements on the oxidation behavior in impure He environment. Ti (0.4wt.%) is detected in the oxide layer preferentially above alloy grain boundaries, whereas Al (1.0wt.%) internally oxidizes mainly at grain boundaries beneath the chromia scale [45]. As internal oxidation may be deleterious to the corrosion resistance of the material, the influence of Al on the behavior of IHX candidate alloy has been investigated by using direct comparison between industrial alloys and model alloys [59]. These works have shown that oxidation by CO strongly depends on the Al content: the higher the aluminum content, the higher the consumption peak (Figure 4-5).

[3] The presence of $MnCr_2O_4$ spinel oxide is also known to reduce the high temperature volatility of chromia

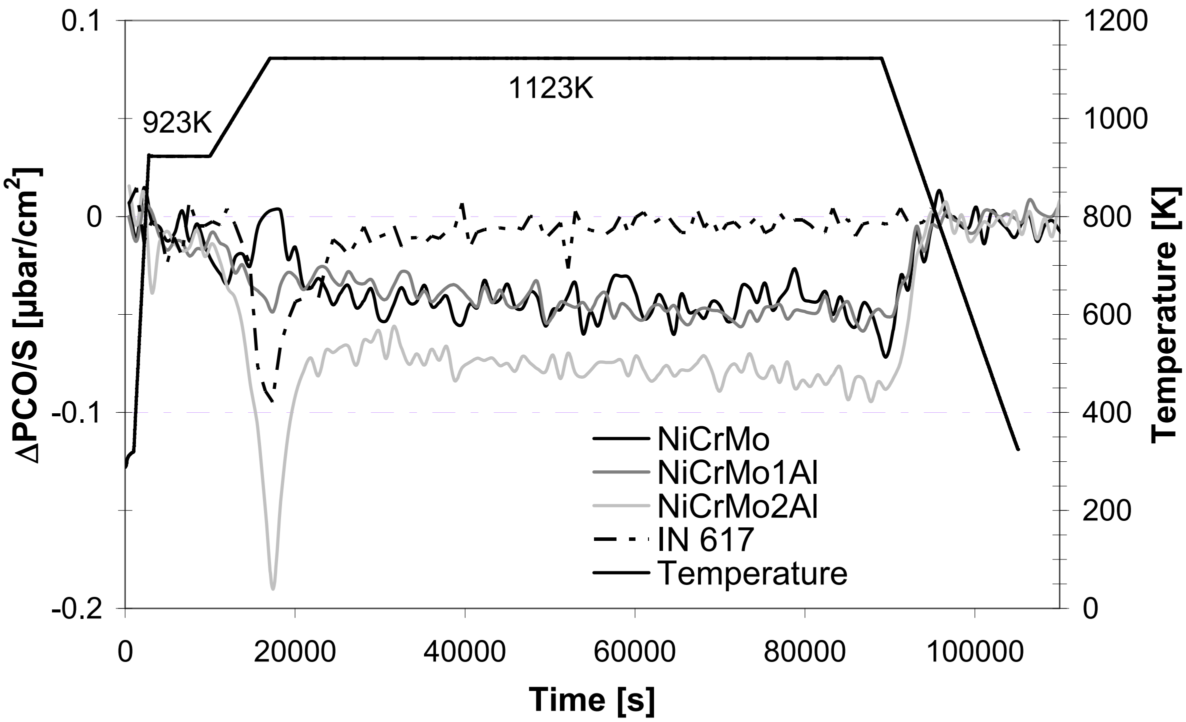


Figure 4-5 – Temperature program and influence of the Al content on ΔP(CO) as a function of time during testing in HTR environment: P_{CO} = 14µbar, P_{H_2} = 140µbar, P_{H_2O} = 6.5µbar [59].

When considering the oxidation mechanism, two reactions have to be considered and are competitive, at least in the preliminary stage of oxidation. H_2O seems mainly to react at the environment/oxide interface to form the Cr-rich oxide layer (enriched in Mn and Ti as a function of the alloying elements), whereas CO seems to be related to an oxidation process at the metal/surface interface involving mainly minor elements (Al) and to some extent Cr. A thermodynamic approach allows understanding the difference of reactivity between the two oxidizing gases and the alloying elements. It may be calculated that the affinity of CO for Cr exhibits a strong dependence on the Cr activity conversely to H_2O with Cr [52]. When considering the kinetics of CO reaction, it has been shown that CO consumption rate gradually decreases as a function of time and consequently as a function of the external oxide scale growth which decreases both the interfacial reaction area and the activity of oxidizing elements. The CO consumption rate is expected to decrease (and consequently any C ingress to the matrix would also decrease) as long as the external oxide scale keeps its protective character. The impact of the environment on the corrosion behavior of IHX candidate materials also depends on the alloy composition. A proposed scenario to account for the oxidation by CO may be the following: a primary direct oxidation mechanism occurs at the metal/oxide interface with reactive elements Al, Si and Cr and, after the building of the uniform and nano-porous external oxide scale, a quasi-stationary process may occur controlled by both interfacial reactions and the diffusion rates of minor elements.

Under very specific conditions, in very dry atmospheres[4], Graham [60] has mentioned the possibility of forming continuous Al_2O_3 external scale on Alloy 617 while no internal Al oxidation occurs. In such conditions, the oxidation potential is low enough to avoid oxidization of chromium. Whatever the interest of forming an endogenous Al_2O_3 oxide scale, two critical points have to be considered: first, the amount of Al in the base metal is too low to provide a "reservoir" to rebuild any protective barrier in case of spallation or cracking and, second, the required water level is not compatible with industrial application. Accordingly, a safe HTR environment for Alloy 617 cannot rely on the formation of an alumina layer at very low water content but must rely on the formation of a chromia layer at higher water levels.

4.5.1.3.2 Oxide layer stability

For a given temperature service condition, the formation of an oxide layer with long term corrosion resistance relies on the ability to form a continuous and "protective" oxide layer for the expected life-time of the component. Any alteration of the oxide scale will have a detrimental impact on the materials due to the re-building of the oxide scale following mechanisms described previously. Beside any spallation effect, numerous works [32, 34, 37-39] have pointed out the occurrence of a critical temperature, T_A, defining limiting conditions where the chromium-rich surface layer is no longer stable in a benign HTR environment. The occurrence of the so-called "micro-climate" reaction, Eq. 6, induces a characteristic production of CO. The origin of the production of carbon monoxide cannot be explained only by reactions involving water vapor or methane as the water vapor in the gas is very limited (and cannot account for the total amount of produced CO), and the microclimate reaction has been observed in CH_4-free atmospheres. Moreover, reactivity tests on model alloys [46], with or without carbon, have proven that the reduction of the oxide scale is controlled by the carbon coming from the alloy as described by Eq. (6). The deleterious character of such reaction is illustrated by the mass loss of the sample, corresponding to a reduction of the surface oxide layer, which is directly correlated to the CO outgassing. The influence of the gas composition on T_A is illustrated in Figure 4-6 and may be synthesized as follows: the higher the level of carbon monoxide in the gas phase, the higher is T_A. Based on metallographic characterizations, it has to be noted that the reduction of the oxide scale mainly affects chromium oxide rather than titanium and manganese rich oxides, which may explain why Alloy 617 and Alloy 230 show a similar dependence. Based on the assumption that T_A is the equilibrium temperature of Eq. (6), Quadakkers [38] proposed the following relation:

$$K_6(T_A) = \frac{\left(\frac{P(CO)}{P_{total}}\right)^3 .a(Cr)^2}{a(C_{(s)})^3} \quad (7)$$

where K_6 is the equilibrium constant of Eq. (6) and the chromium oxide activity taken as unity. A further common assumption consists in considering that the carbon in solution is in equilibrium with the carbides. For $M_{23}C_6$ type carbides, the carbon activity in the alloy is determined by:

$$a(C_{(s)}) = \frac{K_5(T_A)^{\frac{1}{6}}}{a(Cr)^{\frac{23}{6}}} \quad (8)$$

[4] At 950°C, the P_{O_2} equilibrium partial pressure between Cr and its oxide is close to 10^{-24} atm, corresponding to a P_{H_2O}/P_{H_2} ratio close to 10^{-4}, whereas the equilibrium pressure between Al and its oxide is close to 10^{-36} atm corresponding to a P_{H_2O}/P_{H_2} ratio close to 10^{-10}.

The combination of Eqs. (7) and (8) allows defining a direct relation between T_A and P_{CO} where the only unknown parameter is the chromium activity at the scale/alloy interface. Figure 4-6 plots log[P_{CO}] as a function of 1/T_A. for both Haynes 230 and IN617 [37, 38, 46]. Because the chromium activity depends on the temperature [61], experimental results do not follow exactly the curves for constant a(Cr); the lower the temperature, the higher is a(Cr).

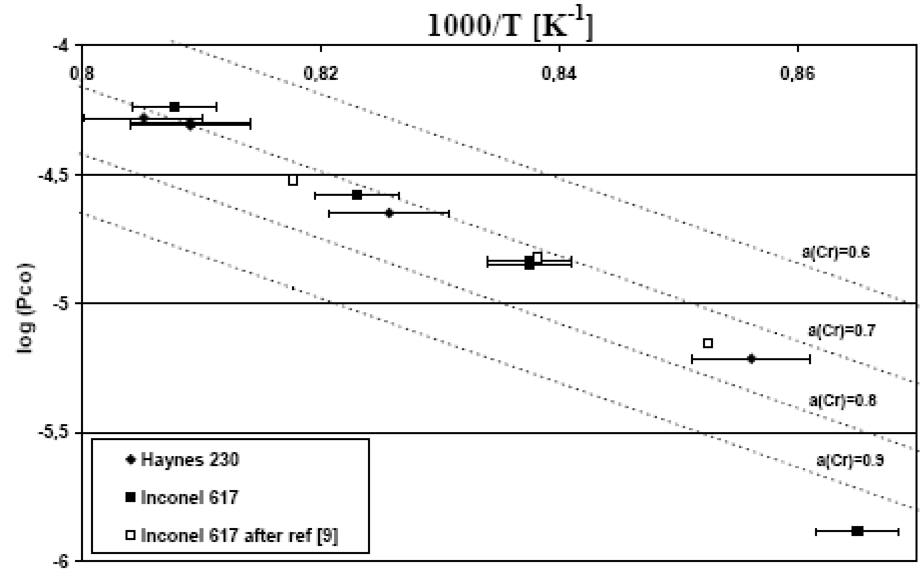


Figure 4-6 - Logarithm of P_{CO} in the gas phase as a function of 1/T_A [46]

Other studies tend to demonstrate that the occurrence of the "microclimate" reaction depends on P_{H_2O} [62]: the higher the water vapor, the lower is T_A, whereas no significant effect of P_{CH_4} has been observed [63]. Reactivity tests performed on aged materials emphasized the beneficial character of such ageing treatment on T_A [52]. Such ageing effects have to be extensively studied to identify the influence of long term exposure on the carbon/chromium activity and consequently on T_A. As emphasized by Brenner [32, 34], the consequences of this reaction rely on the P_{CH_4}/P_{H_2O} : in methane free atmospheres the reduction of the oxide layer comes together with a depletion of carbon beneath the scale while in methane rich environment carburization may be encountered. Recent studies have clarified the role of minor elements on the corrosion behavior of Ni-Cr base alloys in such carburizing conditions above T_A [64]. Inconel 617 demonstrates a better carburization resistance than Haynes 230 and Hastelloy X due to the development of a thin alumina scale in conditions where the external chromia scale is totally reduced following Eq. (6). Moreover, it has to be noted that in very weakly oxidizing atmospheres [60], the formation of a thin protective Al_2O_3 scale on Inconel 617 will raise T_A to very high values (above 2200°C). However, forming an endogenous alumina scale to improve corrosion resistance is inconsistent with the expected service conditions and due to the low level of Al in the alloy (see section 4.5.1.3.1).

Whatever the effect, carburization or decarburization, the HTR environment must fulfill a further criterion in order to secure a long lifetime of the IHX material: for a given CO level in the helium coolant, the temperature must stay below T_A (in other words at a given service temperature, P_{CO} in the gas phase must be higher than a critical value) to avoid any alteration of the material mechanical properties. During the operational period of the power plant, the other key parameter to account for is the chromium depletion and consequently the evolution of a(Cr).

4.5.1.4 Assessments for Corrosion Protection

It has been clearly established that the chromium rich oxide formed on Ni-Cr base alloys offers limited protection against corrosion in representative HTR environments. Moreover, for industrial processes, the use of chromia-forming alloys is generally limited to in-service temperatures lower than 1000°C due to the reactive evaporation of chromium oxide in presence of high partial pressure of O_2 [65]. In very high temperature industrial processes, one of the best endogenous protections against corrosion is the ability of a material to form an external continuous, compact and adherent aluminum oxide scale (α-Al_2O_3). It is commonly considered that the optimum aluminum content is close to 4-5%: higher levels will alter the mechanical properties and the formability of the alloy whereas lower levels will not produce a fully protective alumina scale. As the aluminum contents of Alloy 617 and Alloy 230, respectively 1 and 0.4%wt, are far from the protective threshold to form a protective alumina scale, coating type solutions may be proposed. In aeronautical and gas turbine industry, there has been extensive R&D to develop exogenous protection against high temperature oxidation. Treatments include enrichment of the metal surface by diffusion of aluminum (aluminizing processes) and overlaying the metal with an aluminum-base coating [66].

4.5.1.4.1 Aluminizing processes of Ni base alloys

A way to enhance the resistance of Ni base alloys in oxidizing environments is to enrich the surface of the alloy in aluminum by thermo-chemical processes. Diffusion coatings can be applied by a variety of Chemical Vapor Deposition (CVD) techniques; the most widely used are pack cementation [67-69] and gas phase coating. The phase composition and properties of the coating layer (and subsequent potential damage at the metal/substrate interface such as the formation of Kirkendall porosity) depend on the process parameters (raw material, temperature, duration) and on the material composition. For pack cementation techniques, one of the key parameters is the “activity” of the pack: “low activity” processes are characterized by outward diffusion of Ni from the substrate to form a β-NiAl phase at high temperature; whereas “high activity” treatments are driven by the inward diffusion of Al at lower temperature leading to the formation of Al rich β-NiAl phase or Ni_2Al_3 (Figure 4-7). Due to the possible formation of the Ni_2Al_3 brittle phase, “high activity” pack cemented materials have to be heat treated to transform Ni_2Al_3 to β-NiAl.

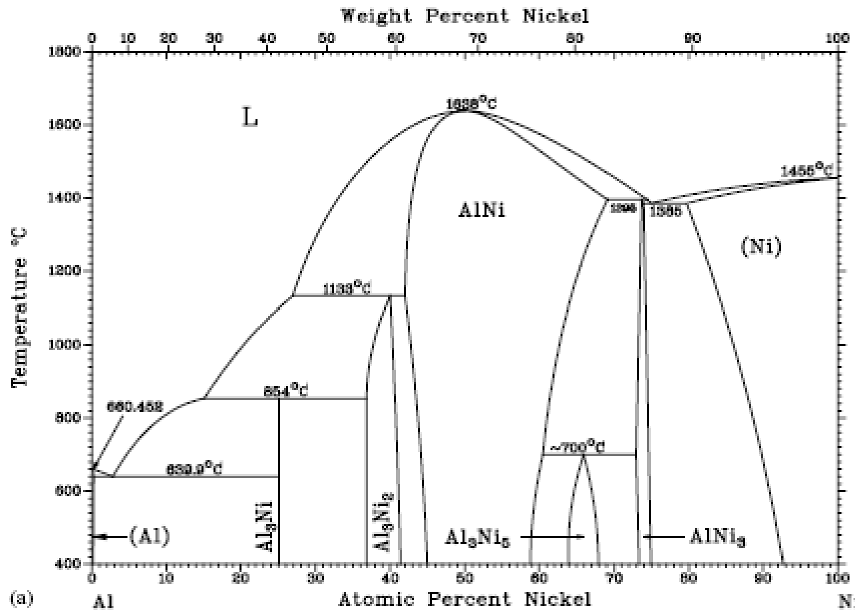


Figure 4-7 - Aluminum-nickel phase diagram [67]

The aluminized layer thickness is generally between 30 and 100 µm. When exposed to even a weakly oxidizing environment, the NiAl phase of the coating form a thin, continuous and protective Al_2O_3 scale. Damage to the aluminized layer may occur by loss of the continuity due to the consumption of protective elements or by inter-diffusion of the aluminum layer with the substrate. Aluminum diffusion towards the surface to form the alumina scale leads to β-NiAl depletion. Moreover the difference in diffusion rates between elements (Al, Ni, Cr) from each side of the coat/substrate interface may be responsible for the formation of Kirkendall pores. Also the aluminide layer can suffer cracking and spalling because of differences in thermal expansion coefficients of the aluminide layer and the substrate as shown on NiAl pack aluminized Hastelloy X submitted to cyclic oxidation tests at 1100°C [68]. It has to be noted that the presence of chromium and/or cobalt in the coating is known to promote the formation of an alumina scale with a much lower amount of aluminum than in simple aluminide coatings [70]. Chromium also enhances the transformation of θ-Al_2O_3 to α-Al_2O_3 during high temperature oxidation and thus improves the adherence and decreases the oxidation kinetics of the alumina scale [71].

4.5.1.4.2 Aluminum based coatings

Thermal spraying and Physical Vapor Deposition (PVD) processes are among the most common ways to apply aluminum-base coatings. In thermal spraying processes, the material to be deposed is melted and sprayed on the surface to be coated. The deposits have high adherence and low porosity. Generally PVD processes rely on the vaporization of the material to be deposed and are carried out under vacuum. Vaporization is obtained by thermal evaporation or it can be assisted by electrical arc, plasma (Ion Plating), sputtering (ionic bombardment), Electron Beam, Laser, Electron Beam – Physical Vapor Deposition (EB-PVD), or Low Pressure Plasma Spraying (LPPS). EB-PVD are known to give better quality coatings. For high temperature applications (Ni/Co base alloys), the deposit composition is typically M-Cr-Al-Y (X) with M=Ni or Co and X is an active element. Whereas aluminizing treatments are limited by thermodynamic and kinetic constraints, the composition of aluminum coatings mainly depends on the composition of the deposit source. Thus it can be more easily adapted to the considered application and have a better corrosion resistance. PVD coatings are generally thicker than aluminized layers obtained by diffusion. However, coatings may also be damaged by inter-diffusion phenomena at operating temperatures higher than 1000°C [66]. The oxidation resistance and the adherence can be enhanced by controlled pre-oxidation of the coating or, when possible, by the application of a diffusion barrier or Thermal Barrier Coating (TBC) that can lower inter-diffusion rates and thus reduce the Kirkendall porosity [72].

The cost is about 2 to 4 times higher than pack cementation treatments and PVD techniques are carried out in controlled atmosphere and pressure and require complex robotic handling to overlay the entire surface of the piece homogeneously. Moreover, compared with PVD coatings, diffusion coatings are well bonded to the substrate and generally have better adherence.

The addition of platinum or active or rare earth elements such as Si, Y, Zr, Hf, Ce, Ta, Re, La, is known to improve significantly the oxidation resistance and/or the adherence of the oxide scales of Ni-Cr or Ni-Cr-Al system. The beneficial effect of platinum is attributed to its ability to stabilize the β-NiAl phase. Recent comparative experiments have explained the fact that the presence of platinum significantly enhances the oxidation resistance and the adherence of the coating submitted to isothermal and thermal cycling test in air at 1150°C up to 250h [73]. The addition of active elements or rare earths such as Si, Y, Zr, Hf, Ce, Ta, La, Re, induces a modification of the diffusion processes leading to better oxidation resistance and improves the adherence of oxide scales. Other alloying elements such as titanum have a deleterious effect on the scale adherence on Ni-base alloys. Ti is reported to cause spalling by diffusion towards the coating/metal interface at high operating temperatures in MCrAlY coatings of gas turbine blades [74]. Some refractory elements such as W, Mo, V, are also undesirable either because they oppose the healing layer formation by decreasing the diffusion of Al, Cr and Si or because their oxides are generally non protective.

4.5.1.4.3 Role of protective coatings in HTR environment

Recent investigations on coated materials allow initial comparisons between two different protective systems under HTR representative conditions [75]. To address the specific needs of the future IHX, tests were performed on TBCs whose duplex structure, consisting of a bond-coat topped with a ceramic layer, is designed to decrease the substrate temperature. Isothermal exposures were carried out up to 1000 hours at 950°C in impure helium for the following coated materials: Alloy 800H/NiCrAl(Y)/ZrO_2(Y) and Alloy 800H/NiAl(Pt)/ZrO_2(Y). Two bond-coats were investigated: NiCrAl(Y) was sprayed by Air Plasma Spray (APS) while vapor phase aluminization process was used for the NiAl(Pt) bond-coat type.

The fabrication route of the NiCrAl bond-coat leads to the formation of a heterogeneous structure characterized by alumina precipitation together with intermetallic phases. On the NiAl(Pt) coated sample, it has been shown that an alumina layer has grown at the Partially Stabilized Zirconia (PSZ)/bond-coat interface. The bond-coat itself consisted of two zones:

- An outer zone formed by the diffusion of Ni from the substrate and Al supplied by the process and characterized by a gradient of Al and Pt content from the PSZ/outer bond-coat zone interface to the outer/inner bond-coat interface,
- An inner zone, composed of β-(Ni,Pt)Al precipitates in a γ solid solution. The substrate has also been significantly depleted in Ni while a small amount of Al has diffused in the substrate.

It was demonstrated that the chromium oxide is unstable in the studied atmosphere, the surface scale consisting of both titanium rich oxide and chromium rich carbide together with aluminium and titanium internal oxidation. When focusing on the bond-coat and the matrix behavior after high temperature exposure to impure helium, one can identify significant differences between the two tested materials:

- For the APS bond-coated specimen, a Thermally Grown Oxide (TGO) has developed at the PSZ/bond-coat interface. The NiCrAl bond-coat structure was modified with a significant decrease of the Al and Ni content and the probable precipitation of α-Cr phases. In the base metal, nickel and aluminium enrichment was detected together with a depletion of iron and, to a lesser extent, chromium.
- For the Alloy 800H/NiAl(Pt)/ZrO_2(Y), cracks were observed in the alumina scale formed during the process after 500h exposure. After 500h, the outer bond-coat zone has reached a stationary chemical composition while in the inner zone, β-(Ni,Pt)Al, γ phase and chromium rich carbides were identified. The base metal was largely depleted in nickel and enriched in aluminium.

From this original study, it may be concluded that the growth of an adherent alumina scale at the PSZ/bond-coat interface of the Alloy 800H/NiCrAl(Y)/ZrO_2(Y) sample seems to offer a better corrosion resistance than the other specimen which is characterized by the occurrence of cracks within the alumina scale formed during the process and precipitation of chromium rich carbides in the inner bond-coat zone.

4.5.1.5 Conclusion

Behavior in benign environment:

The role of the environment on the corrosion behavior of Ni-Cr alloys in an impure helium environment is highly documented. Depending on temperature and gas composition, interactions between metallic alloys and gaseous species may lead to strong carburization, decarburization or combined carburization/oxidation. Based on such considerations, rationalized descriptions of the material behavior as a function of the temperature and the gaseous environment have been used to define a benign HTR atmosphere. The benign atmosphere requires a partial pressure of carbon monoxide higher than the critical value P^*_{CO}, an oxygen activity large enough to allow the formation of a stable chromium oxide layer and the lowest possible P_{CH_4} / P_{H_2O} ratio to avoid any massive carburization of the material.

Despite of the tight control of the environment, undesired collateral corrosion effects are expected. These include internal oxidation, the formation of a carbide free zone and the increase of the bulk carbon content after long term exposure. It has been demonstrated that a competition between carbon monoxide and water vapor is expected in the very first steps of oxidation, while after few hours the oxidation kinetics are mainly controlled by water vapor. The role of minor elements, especially aluminum, on the first steps of the oxidation process has been clearly identified: the higher the aluminum content, the higher the carbon monoxide consumption peak. Moreover, the role of carbon monoxide on the carbon uptake up of the material in the HTR benign environment has been identified. However, the quantitative roles of both CO and water vapor on the long term corrosion behavior of Ni-Cr alloys still have to be investigated in order to quantify their relative influence on the material properties (carbon uptake, depth of the carbide free zone) and to optimize the benign environments with regard to the carburization process.

Oxide scale stability:

In addition to the tight control of the benign atmosphere, any temperature excursion above the critical temperature T_A has to be avoided in order to preserve the integrity of the material. Above T_A, the so-called "microclimate" reaction occurs, leading to massive decarburization of the material, reduction of the external oxide scale rich in chromium, and production of CO. The gas composition significantly affects T_A: increasing the level of carbon monoxide in the gas phase increases T_A, while increasing the water vapor content slightly decreases T_A; no significant effect of P_{CH_4} on T_A has been observed. The value of

T_A is controlled by the chromium activity at the scale/alloy interface and by the presence of minor oxidizable elements, especially aluminum and it has been demonstrated that the variation of T_A as a function of carbon monoxide partial pressure is similar for both Alloy 617 and Alloy 230.

Long term behavior assessment:

Among the points that still have to be investigated, one of the most critical relies on the assessment of the effect of H_2O content on the behavior of materials and to some extent on the oxidizing potential. The characterization of the long term behavior of materials in a different primary environment has to be investigated in order to quantify the respective role of the helium impurities on the corrosion behavior (carbon uptake, carbide free zone, internal oxidation, T_A).

In addition, the characterization of the material behavior in the secondary side NGNP environment has to be investigated. Due to the absence of graphite, the nature of the impurities will differ from the typical primary side environment: relative absence of CO, low level of CH_4, potential presence of O_2… A definition of a typical NGNP secondary side environment may be necessary in order to avoid deleterious phenomena such as severe decarburization in case of absence of CO and a weakly oxidizing environment. Moreover, the presence of a protective chromium oxide layer on the secondary side may be necessary to limit the decarburization processes which will probably result in the monitoring of ingress of oxidizing species. As the nature of the oxidizing species may affect the long term behavior of the material, specific studies have to be done to select the most efficient. Indeed, it has been demonstrated that the oxidation kinetics of chromia-forming alloys in a highly oxidizing atmosphere is significantly different if water or oxygen are the oxidizing species: the parabolic rate constant is higher in water vapor than in oxygen environment. In addition, it has been demonstrated on ferritic stainless steels that oxides grown in water vapor are more adherent than those grown in oxygen due to the nature of point defects responsible of mass transport in oxide [76]. Moreover, future work should focus on the corrosion behavior of typical IHX geometry samples in either primary or secondary HTR environment in order to evaluate potential shape effects. Tests should include a large number of specimens. Due to the potential influence of metallurgical effects on the corrosion behavior, which may be responsible for the wide scatter of carburization behavior detailed by Graham [60] on IN617, special attention has to be paid to the optimization of the metallurgical parameters of the candidate alloys.

Alternative protective solutions

As the aluminum contents of Alloy 617 and Alloy 230, respectively 1 and 0.4%wt, are far from the threshold for forming a protective alumina scale, coating type solutions may be proposed. The most common techniques for controlling high temperature oxidation of Ni or Co-base alloys are:

- aluminizing, which is a diffusion process performed by CVD techniques;
- aluminum-base coatings produced by thermal spraying or PVD techniques.

Initial results on Alloy 800H base TBC materials have shown that the growth of an adherent alumina scale at the APS bond-coat seems to offer better corrosion resistance than Vapor Phase Aluminization, which is characterized by the occurrence of cracks within the alumina scale formed during the process and precipitation of chromium rich carbides in the inner bond-coat zone. Almost no studies have evaluated the corrosion behavior of coated materials in impure helium. In order to validate such technology solutions, complementary investigations will be necessary to assess their durability. Coating type solutions have to demonstrate their ability to resist spallation and time-temperature dependant phenomena such as inter-diffusion of coating and substrate elements. Other aspects to be considered are the application of the coating to an IHX of large size, geometry and fabrication (welding), and the control of the coating quality (continuity, homogeneity...).

4.5.2 Tritium transfer

4.5.2.1 Introduction

Tritium is produced in the HTR and is likely to diffuse through metallic walls of components (especially through thin walled components such as the IHX) due to the high diffusivity of hydrogen isotopes. This phenomenon can become significant due to high operating temperature. Tritium permeation issue can be important particularly for gas production applications (such as hydrogen cogeneration) since the tritium migration from the primary circuit via the IHX can lead to the contamination of the product gas. Considering this risk, the potential for tritium contamination of the NGNP product hydrogen should be assessed.

Tritium diffusion phenomenology and available data are described hereafter.

4.5.2.2 Tritium source

As in other nuclear reactors, tritium is produced in the HTR core by ternary fission and by activation reactions with impurities and with boron contained in control rods. Lithium contained in HTR graphite components and He-3 isotope present in the HTR helium coolant are two other tritium sources specific to HTR.

Only a fraction of tritium produced in the core is released into the primary coolant:

- ✓ Tritium produced by ternary fission is mostly retained in fuel particles by the fuel particle coating. It could be assumed that only defective fuel particles release tritium in the coolant,
- ✓ Tritium produced from boron could be conservatively assumed to be totally released,
- ✓ Tritium from lithium impurities is partially dissolved in the graphite,
- ✓ Tritium from He-3 is directly produced in the helium primary coolant.

It can be noted that the graphite reflector may have sorption capacity with regard to tritium release.

Tritium production and release into the HTR primary circuit have been calculated and reported for the PNP-500MW plant (77) and AVR (78). It appears that the main contribution to the tritium in the primary coolant comes from He-3 - 70% of the total release rate during the first year and 35% at equilibrium.

The main part of the tritium in the primary coolant is removed by the helium purification system. Thus only a part of the tritium would permeate through the HTR-IHX.

The tritium concentration on the primary side would result from the equilibrium between the tritium release rate from the core and the tritium elimination rate in the purification system for the primary helium.

4.5.2.3 Description of gas permeation phenomena

The permeation of gaseous hydrogen isotopes through a metallic wall involves several steps:

- dissociative chemisorption at the metal surface (dissociation of the diatomic gas molecule and adsorption as atoms)
- dissolution into the metallic matrix
- diffusion in the bulk metal
- desorption
- re-combination of atoms into molecular gas

The resulting permeation rate is governed by the rate controlling step, which is the slowest step.

At high temperature, the hydrogen-permeation rate tends to be controlled only by diffusion and not by surface processes for most of the metals. When the process is limited by the diffusion mechanism, the permeation rate obeys classical diffusion equations (Fick's laws):

$J = D \cdot (C_1 - C_2) / e$

J : steady state permeation rate through the metal wall

D : gas diffusion coefficient in the metal

e : wall thickness

C_i : dissolved gas concentration in the metal

For diatomic gas such as hydrogen, the concentration of the dissolved gas can be expressed by Sievert's law if the gas is dissolved atomically in the metal:

$C_i = Ks \cdot P_i^{1/2}$

Ks : gas solubility in the metal (Sievert constant)

P_i : gas partial pressure on each side of the wall

Permeation tends to be controlled by gas/solid diffusion mechanism when the upstream gas pressure is significantly higher than the downstream gas pressure. In this case the permeation rate is proportional to the square root of the gas partial pressures on each side of the wall.

$J = Pe. (P_1^{1/2} - P_2^{1/2}) / e$

Pe = D . Ks, metal permeability with regard to the gas

Pe and D increase significantly as the temperature increases according to an Arrhenius law:

$Pe = Pe_0 \cdot \exp(-Q_{Pe}/R.T)$

$D = D_0 \cdot \exp(-Q_D/R.T)$

Pe_0, D_0 : constants

Q_{Pe}, Q_D : activation energies in $J.mol^{-1}$

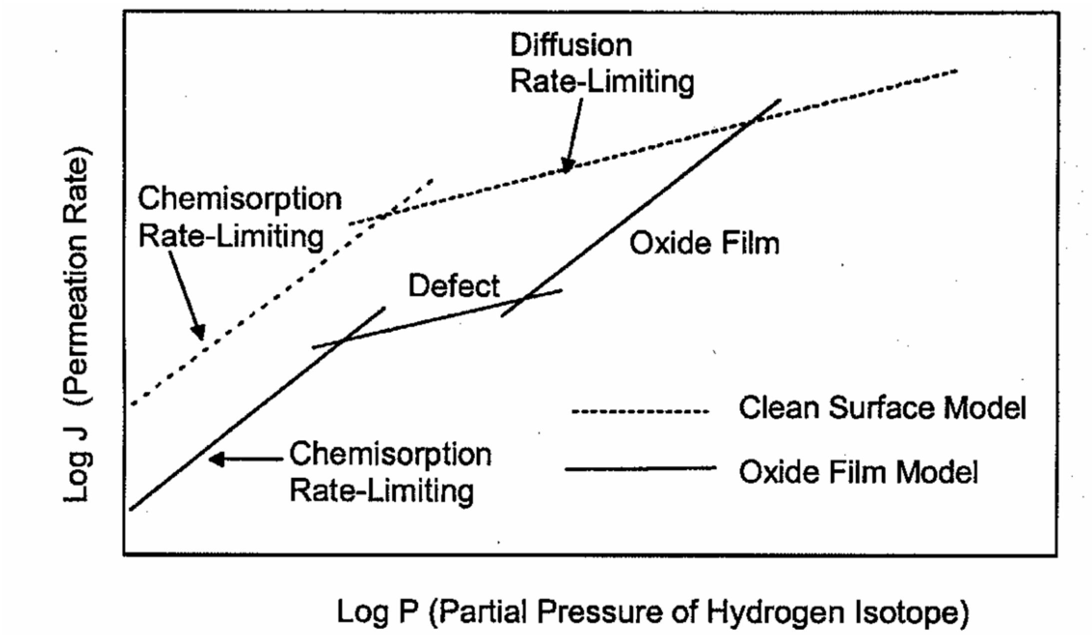
$R = 8.314\ J.K^{-1}.mol^{-1}$, gas constant

T: temperature in K

When the process is limited by surface phenomena, the permeation is governed by chemisorption. This is the case for low gas partial pressure, a very thin metal wall or in the presence of an oxide layer or coating film on the metal surface. In this case the gas permeation rate dependence with regard to the gas partial pressure tends to become linear (the permeation rate becomes proportional to the first power of the gas partial pressure) (79)(80)(81)(82)(83).

The overall permeation behavior through a metallic wall is shown qualitatively in figure 4-8.

Figure 4-8 Rate-limiting steps for permeation



In presence of an oxide scale (acting as a good inhibitive barrier) the permeation rate follows a linear dependence on the hydrogen partial pressure for relatively high hydrogen partial pressures and returns to half power dependence for lower hydrogen partial pressures (81)(83)(84). Half power dependence has been observed by German researchers (81) over a wide hydrogen pressure range from 10^{-10} to 1 bar on austenitic alloys (taking into account the influence of the oxide layer). The pressure dependence of permeation over a given range of pressures also depends on the characteristics of the oxide film.

Hydrogen isotope permeation through HTR-IHX

When hydrogen isotopes simultaneously exist in the gas, the thermodynamic equilibrium between the different isotopes (protium, deuterium, tritium) in the gas phase must be taken into account. The equilibrium between both protium (H) and tritium (T) to be considered is:

$H_2 + T_2 \leftrightarrow 2\,HT$

If protium is preponderant with regard to tritium concentration, as is expected in the primary circuit of HTR, it can be shown that tritium is mainly in the form of HT. In this case, and assuming that the partial pressure of all hydrogen isotopes is negligible on the IHX secondary side, the tritium steady state permeation rate J_T can be expressed as (77):

$J_T = Pe_T \,.\, [\, P_{HT} / (P_{H2})^{1/2}] / e$

Thus the tritium permeation rate is proportional to the HT partial pressure whereas it increases as the H_2 partial pressure decreases.

4.5.2.4 Bibliographic data on hydrogen isotopes permeation

4.5.2.4.1 Available data on hydrogen isotopes permeation in HTR

In the 1980's, German investigators estimated the contamination of the PNP product gas (Substitute Natural Gas) to be within the allowable tritium content of the product gas required by the German standard expected at that time, based on German prototype plant PNP-500MW$_{th}$ conditions (77)(85). The permeation rate calculation is based on German experimental tritium permeation data through the IHX and other heat exchanger materials (Incoloy 800H, Hastelloy X and Inconel 617), assuming that the main part of the tritium is removed by helium purification systems on both primary and secondary sides.

The calculated value of the tritium permeation rate through the Heat Exchanger of the Modular Helium Reactor (GT-MHR reactor system) coupled to a Hydrogen production Plant (86) would be about 29.5 μCi/s (= 930 Ci.year^{-1}). This source term will be used to assess the hydrogen product gas contamination and to determine if coolant purification is required on the secondary loop in order to reduce the tritium concentration in the hydrogen product gas to acceptable levels.

Hydrogen/tritium permeation tests have been carried out in Japan in the scope of Hydrogen production program in the Japanese High Temperature engineering Test Reactor (HTTR) (87) in order to obtain tritium permeation data, to examine the effect of hydrogen isotopes simultaneously existing in the gas, to assess the protective effect of a coating film (such as an oxidation film) on hydrogen/tritium permeation, and to develop a calculation code. Permeation data have been obtained on Hastelloy XR (82)(88).

4.5.2.4.2 Permeability coefficients data

Numerous values and expressions for diffusion and permeation coefficients of hydrogen isotopes in metals are reported in the literature (77)(79)(82)(88)(89)(90)(91)(92).

Some permeation coefficient values (permeability) of tritium in austenitic alloys and nickel base alloys (Incoloy 800H, Inconel 617, Hastelloy X) are compiled on figure 2, both on bare or oxidized metals (77).

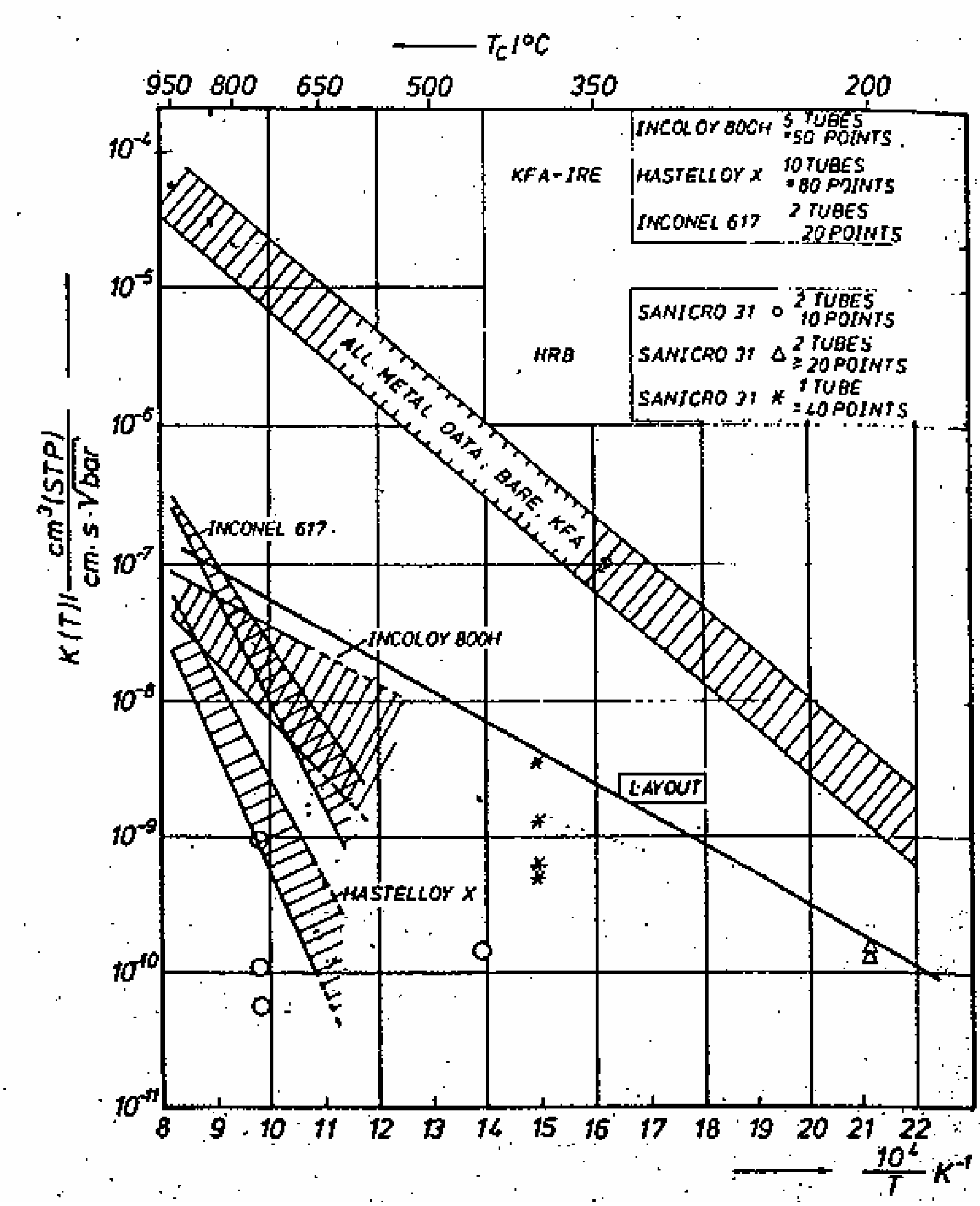


Figure 4-9 Tritium permeability for PNP-heat exchanger materials

4.5.2.5 Permeation barrier to limit tritium diffusion

The permeation rate through a metallic wall can be significantly reduced in presence of a surface scale, such as an oxide layer grown in-situ or obtained by specific pre-treatment. The protective effect of the oxide scale is expressed by the impeding or inhibitive factor defined as the ratio of the permeation rate through the bare surface to the permeation rate through the surface covered by an oxide scale. This impeding effect depends on the nature and structure of the oxide, the relative oxide/wall thicknesses, the pressure and the temperature. The alloy composition would be important since it determines to some extent the nature and the structure of the oxide layer and thus the impeding effect with regard to permeation. The nature and the structure of the oxide also reflect the conditions under which the oxide was formed: temperature, oxidation potential, oxidation rate. The initial surface state of the material may also have an influence.

The oxide scale should be dense, continuous, and adherent.

The favorable impeding effect of the oxide scale is expected to be advantageous in comparison with the impact on heat transfer.

4.5.2.5.1 Impeding factor data for oxides grown on austenitic alloys

The effect of oxide barriers on tritium permeation rate has been investigated as part of the German PNP experimental program for heat exchanger materials (Inconel 617, Hastelloy X and Incoloy 800H) (77).

Whereas the permeation rate in bare (unoxidized) metal is little influenced by the material composition, the presence of oxide scale may reduce the permeation rate by orders of magnitude, with more scatter depending on the metal nature as shown on figure 4-9 for alloys of interest. In the presence of oxide scale, a stronger temperature dependence of the permeability is observed for Inconel 617, Hastelloy X and Hastelloy XR (82).

From this figure, impeding factors higher than 100 for Inconel 617 and about 1000 for Hastelloy X can be evaluated at 950°C. For these two materials, the impeding factor increases as the temperature decreases.

According to German authors (81) the optimal permeation barriers are oxide scales (chromium oxide) grown in oxidizing atmospheres on Nickel-base alloys having 20-25% chromium content.

4.5.2.5.2 Influence of the "scaling temperature" of the oxide on its impeding effect

It is important to distinguish between the temperature at which the scale was created and grown (the "scaling temperature") and the temperature at which the permeation rate is measured (the "annealing temperature"). Depending on the scaling temperature, the impeding factor may vary significantly (84).

4.5.2.5.3 Influence of the oxygen potential on the oxide impeding effect

The effect of oxygen potential on the impeding factor of oxide scale should be of importance, but this effect is still not clearly understood. The role of H_2O and H_2 partial pressures on the oxide impeding factor has been studied but contradictory results are reported.

4.5.2.5.4 Oxide scale behavior under transient conditions

Oxide scales may be damaged especially during thermal transient conditions: start-up and shut-down of the plant. Thus it is necessary to assess the temperature cycling resistance of the oxide scales and the effect on tritium permeation. The behavior of oxide scales under thermal cycling between room temperature to 950°C has been investigated for Incoloy 800H, Inconel 519, Inconel 617 and Hastelloy X (81)(84). Damage may occur in the cooling phases and its effects (increased tritium permeation rate) arise during the restart of the plant. At high temperature, cracks and other defects can be healed, and the oxide scale regenerates in a short time, after which the permeation returns to the rate observed before thermal cycling.

4.5.2.5.5 Specific surface treatments

Reducing the tritium permeation rate by means of specific pre-treatment or coating could be useful during the reactor start-up phase, during which the oxide scale is forming or regenerating and there is not a sufficient permeation barrier. Pre-oxidation treatments have been shown to contribute to reducing the permeation rate (80)(81). According to German authors (80)(84), a Hydrogen anneal pre-treatment of steel alloys before oxidation would have a beneficial effect as a pre-cleaning of the metal surface, allowing the formation of good chromium oxide scale as a permeation barrier. Other types of surface pre-treatments (chemical or mechanical) were shown to have minor influence.

Some specific coatings are expected to reduce the permeation rate by a factor over 1000. Alumina-rich coatings and alternative coatings (e.g. Erbium oxide) obtained by various deposition techniques have been investigated in the frame of the EU Fusion Program in order to assess their effectiveness as hydrogen permeation barriers (93). Alumina-rich coatings (Al_2O_3) appeared to be the most promising solution with regard to chemical, physical and metallurgical parameters of coatings together with technological and economical aspects of the deposition techniques (CVD, hot dip aluminizing) and have been considered as a reference coating.

4.5.2.6 NGNP specificities

In order to assess the potential contamination level of the hydrogen product gas, the tritium permeation rate through the IHX should be determined taking into account NGNP specificities, especially (considering the NGNP design recommended by AREVA-NP):

- The high operating temperature (900 to 950°C at IHX primary side inlet) knowing that tritium permeation rate dramatically increases as the temperature increases.

- The presence of alumina-rich coating such as recommended against corrosion will be beneficial since it is expected to reduce significantly the tritium permeation rate.

- Neither the nature of secondary fluid (helium) nor a higher pressure in the secondary side pressure (55 bars) than on the primary side (50 bars) are likely to have a significant effect on the tritium permeation rate which is controlled by tritium/hydrogen partial pressures. However the purification level is of importance with regard to tritium permeation since it determines the tritium/hydrogen partial pressures.

- The impact of IHX design should be assessed taking into account that the whole tritium permeation rate through the IHX is proportional to the IHX surface/thickness ratio. Thus the thinner the wall thickness the higher the tritium rate. However it can be noted that the impact of the IHX design is limited compared with the impeding effect of oxide/coating layer.

4.5.2.7 Conclusion

Due to its atomic size and to its solubility in the metals at high temperature, tritium is likely to diffuse through the thin walls of an HTR-IHX. The main influencing parameters for tritium permeation rate are the IHX heat transfer surfaces temperature and the properties of oxide scales acting as impeding permeation barriers.
A lot of data is available about tritium permeation through Incoloy 800H, Hastelloy X-XR, Inconel 617, from German experience (1980's) and from Japanese tests for the HTTR.

Among the nickel-base alloys such as HTR-IHX candidate materials and more generally austenitic alloys, the material composition would have little influence on the permeation rate through the bare metal, whereas the oxide scale formed on such metals may reduce the permeation rate by several orders of magnitude with an important scattering of values depending on the metal composition and on oxidation conditions. Impeding factor up to 1000 can be expected but more investigations would be required in order to relate the oxide quality (thus its impeding effect) to operating conditions representative of NGNP and to NGNP-IHX material (metal composition, initial surface state of the metal, pre-oxidation conditions). Moreover the oxide resistance and self-healing capability should be assessed particularly under thermal cycling conditions. Coatings type solutions are also expected to reduce tritium permeation.

Other parameters having an influence on the permeation rate through the IHX are the upstream tritium and hydrogen partial pressures - to be defined for NGNP. The tritium permeation rate is proportional to the upstream tritium partial pressure. To a lesser extent, the hydrogen concentration has an opposite influence on the tritium permeation rate since the permeation is inversely proportional to the square root of the hydrogen partial pressure.

Also, the IHX heat transfer surfaces thickness has a limited influence compared with the effect of the temperature and of a good permeation barrier.

In conclusion, the tritium permeation diffusion rate through the IHX should be determined in order to assess the potential contamination level of the hydrogen product gas. For this, data about the tritium source in the NGNP core are needed. More investigations would be required to assess the oxide (or coating) performance with regard to hydrogen permeation, resistance and self-healing capability. The results could lead to recommendations about:

- the gas composition and purification systems (optimal tritium/hydrogen partial pressures and oxygen potential to minimize permeation rate and ensure oxide formation),

- the reactor operating conditions (maximal temperature, cooling down procedure to avoid oxide damage),

- the material pre-treatment (pre-oxidation or specific surface treatments),
- and to a lesser extent about:

- the IHX design (optimal wall thickness with regard to permeation and thermal performance, IHX surface size),

- the graphite purity (lithium impurities) and the helium inventory, in order to reduce the tritium source.

4.6 Other issues and requirements

The level of activation under the reactor core irradiation is expected to be very low and without any consequence on the selection of alloy 617 (with 12% of cobalt content). This statement is consistent with past experience (HTR-Module with tubular IHX in alloy 617, GT-MHR).

Contamination by plate-out (deposit of active particles on the IHX surface) is still an issue for any alloy.

4.7 Availability of Material for Hot-Section Components for IHX from Quality Suppliers

4.7.1 Introduction

The tubular and compact IHXs will require a variety of parts made from temperature-resistant materials, including small-diameter and large-diameter tubing, plates of varying sizes and thicknesses, and a forged hemispherical head. Joining these parts will require welding materials. This section discusses the availability of the various forms of these materials and the risks in procuring them. Manufacturers of temperature-resistant materials are listed and the availability of materials in each of the required forms is discussed. In some cases, the design of the IHX may be limited by the capacity of available production facilities.

4.7.2 Suppliers

To limit the required effort, the search for materials suppliers was primarily focused on those in the U.S.

Table 4-3 lists four nickel alloys that are of interest for the IHX and six materials suppliers that provide at least one of the alloys. The ASTM specifications to which they provide the materials were taken from company literature (Refs. 6, 17, 23, 94 to 107). The actual products may not include all the forms listed in the ASTM specifications. For example, Special Metals produces alloy 230 plate according to ASTM B435 but not sheet or strip.

None of the six suppliers mentions Hastelloy XR or XR-II in its literature, so these alloys do not appear to be commercially available at present. Both of these are refinements on alloy X, with generally tighter composition limits that were chosen to improve particular aspects of alloy performance (Ref. 23). Materials manufacturers are generally able to control compositions much more closely than is required by the ASTM specifications, so unless XR and XR-II are protected by patents, it is expected that suppliers of alloy X could also provide these alloys.

The U.S. suppliers with the best coverage of IHX alloys are Haynes International and Special Metals, so interactions with suppliers have primarily been with these two. The discussion is generally limited to alloys 617 and 230, which are the most promising for high-temperature IHX applications. Production of large-diameter tubing was also discussed with a forging company, Wyman-Gordon.

Table 4-3 Specifications, forms, and suppliers for IHX alloys

Designation	ASTM Specification	Form	ATI Allvac	G. O. Carlson	Electralloy	Haynes Int'l	Metals	p VDM
UNS N06230	B366	Wrought Fittings				X	X	
Haynes 230	B435	Plate, Sheet, Strip				X	X	
	B564	Forgings				X	X	
	B572	Rod				X	X	
	B619	Welded Pipe				X	X	
	B622	Seamless Pipe, Tube				X	X	
	B626	Welded Tube				X	X	
UNS N06617	B166	Rod, Bar, Wire				X	X	X
Alloy 617	B167	Seamless Pipe, Tube				X		X
W.Nr. 2.4663	B168	Plate, Sheet, Strip				X	X	X
Nicrofer 5520 Co	B472	Billets, Bars				X		
	B546	Electric Fusion-Welded Pipe					X	X
	B564	Forgings				X	X	X
UNS N08810	A240	Plate, Sheet, Strip					X	
Alloy 800H	A480	Plate, Sheet, Strip					X	
W.Nr. 1.4876	B163	Seamless Tube	X				X	X
W.Nr. 1.4958	B366	Wrought Fittings					X	
Nicrofer 3220 H	B407	Seamless Pipe, Tube	X				X	X
	B408	Rod, Bar	X		X		X	X
	B409	Plate, Sheet, Strip	X	X			X	X
	B514	Welded Pipe					X	X
	B515	Welded Tube	X				X	X
	B564	Forgings	X		X		X	X
	B751	Welded Tube					X	
	B775	Welded Pipe					X	
	B829	Seamless Pipe, Tube					X	
	B906	Plate, Sheet, Strip					X	
UNS N06002	B366	Wrought Fittings				X	X	
Alloy X	B435	Plate, Sheet, Strip	X	*		X	X	X
Alloy HX	B472	Billets, Bars				X		
W.Nr. 2.4665	B572	Rod	X		X	X	X	X
Nicrofer 4722 Co	B619	Welded Pipe				X	X	X
	B622	Seamless Pipe, Tube				X	X	X
	B626	Welded Tube				X	X	X
	B751	Welded Tube					X	
	B775	Welded Pipe					X	
	B829	Seamless Pipe, Tube					X	

*G. O. Carlson sells alloy HX but does not mention a specification

4.7.3 Small-Diameter Tubing

The current design for the tubular IHX calls for heat transfer tubing with an outside diameter of 21 mm and a wall thickness of 2.2 mm. This size is similar to NPS ½ SCH 10 pipe (21.3 mm outside diameter, 2.1 mm wall thickness). Because of the similarity in sizes, it is likely that producers of NPS ½ SCH 10 pipe could also provide tubing of the size specified for the IHX, or that the IHX could be redesigned to use NPS ½ SCH 10 pipe. Because the IHX would require a large amount of tubing, specification of a nonstandard size is not considered to be a significant obstacle.

Tubing may be classified as either seamless or welded. Seamless tubing is produced, for example, by extrusion or by extrusion followed by various working steps such as drawing or pilgering. Seamless tubing has a uniform wrought microstructure throughout. Welded tubing is produced from strip that is formed to shape. After welding, the tubing may be cold worked. In some cases, tubing is "bead reduced", that is, worked very lightly so that only the weld bead is deformed (Ref. 108). Because it is apt to have a nonuniform microstructure, bead reduced tubing is not recommended for use in the IHX.

In contrast to bead reduced tubing, "cold reduced" or "welded-and-drawn" tubing is worked after welding so that the entire volume of the metal is deformed. Cold reduced tubing is heat treated after the cold working step. Such tubing does not qualify as seamless, but the working and heat treating cause recrystallization of the weld zone and result in a microstructure that is similar to that of a wrought product.

Small-diameter welded-and-drawn tubing may be produced either in cut lengths or as a continuous coil. Cut lengths are typically limited to about 12 m in length (Ref. 109). They may be acceptable, or even preferable, if the heat transfer tubing is to be butt welded, with a highly temperature-resistant alloy at the hot end of the IHX and a less temperature-resistant (and less costly) alloy at the cold end. A continuous coil is probably preferable if the entire length of a heat transfer tube is to be made from one alloy, because fewer welded joints are necessary. In either case, forming a helical heat transfer tube will involve some deformation of the tubing, so a stress relieving heat treatment is recommended.

Small-diameter tubing of alloys 617 and 230 is a standard product and is not considered to pose significant procurement risks.

4.7.3.1 Haynes International

Haynes International currently provides both seamless and welded-and-drawn tubing of the required size in alloy 230 only. The tubing would be provided as straight random lengths, 3 to 7.3 m in length. It is possible that similar tubing could be provided in alloy 617.

The production rate is about 3050 m per month. For alloy 617 NPS ½ SCH 10, that is about 3100 kg per month, so 100000 kg of tubing would require about 32 months.

It may also be possible to have Haynes produce strip and send it to a tube manufacturer for conversion into welded-and-drawn tubing.

4.7.3.2 Special Metals

Special Metals produces seamless tubing of alloy 800H in sizes down to NPS ¾, but it does not produce small diameter tubing of alloys 617 or 230. Their suggested approach is to use welded-and-drawn tubing. Special Metals would produce cold-rolled strip that would be suitable for producing pipe of a size similar to NPS ¾ or 1. The strip would be sent to a tube manufacturer, which would form the strip, autogenously weld it to form tubing, draw the tubing to the desired size, and anneal it.

One limitation to this approach is that Special Metals does not produce alloy 230 strip, so it would not be possible to produce welded-and-drawn tubing from that alloy.

Special Metals estimates that it could produce 100000 kg of alloy 617 strip for tubing in about 16 weeks, with shipping to begin about 11 weeks after receipt of the order.

There are numerous tube manufacturing companies. Special Metals noted that Pressure Tube Manufacturing specializes in small diameters such as that to be used for the IHX. Conversion of strip to tubing is considered to have a short lead time.

4.7.4 Large-Diameter Seamless Tubing

The current design for the tubular IHX calls for the hot header to be made from a forging. Two steps are considered: production of an ingot or other suitable forging stock, and forming of the tubing. This section includes a discussion of ingot suppliers and forging.

Nickel-base alloys tend to segregate during solidification (Ref. 110), producing variations in composition that degrade performance. Segregation would be severe if the melted alloy were simply cast in a mold. To help control segregation and alloy composition, various advanced melting techniques are used, including vacuum arc remelting, vacuum induction melting, and electroslag remelting. These techniques are well developed and allow the production of large ingots that have closely controlled compositions throughout. Forging or other working after solidification further improves the material by refining the microstructure and reducing microscopic segregation.

Seamless tubing has been produced from nickel alloys by open-die forging and by extrusion. Both approaches are discussed here.

The experience from the KVK tests in the early 1980s is that alloy 617 can be forged into large tubes but only with difficulty (Ref. 110). For the KVK tests, a very large cylindrical ingot (17000 kg) was upset to half its original length, forged back to its original length, then upset again. The ingot was pierced, then cooled and dressed to remove folds and tears. Finally, it was stretched and widened to its final shape. The forging was done by open-die methods, and the manufacturer apparently started by producing smaller forgings and then worked up in size. In spite of that cautious approach, “problems were encountered with widening and stretching, as the available tools, i.e., the forging mandrels were breaking due to insufficient strength. This problem was overcome by forging in the upper forging temperature range, which necessitated frequent reheating.” The KVK forgings were produced by VDM.

An alternative approach, which was apparently not available at the time of the KVK work, is to form the tubing by extrusion (Ref. 111). The process is shown schematically in Figure 4-10. A cylindrical ingot is heated to the forging temperature and then upset inside a cylindrical form or “pot”. With the pot still in place, a piercing punch is pressed through the ingot. The ingot is supported by a two-piece pedestal during piercing, and the central part of the pedestal is withdrawn near the end of the piercing process. As a result, the punch can travel completely through the ingot, ejecting a plug at the end of its stroke. The hollow is then moved to a different press, where a mandrel is placed through the opening, and a die is pressed down to extrude the hollow into a large-diameter tube.

Production of large-diameter seamless tubing by extrusion is considered to be preferable to production by open-die forging, primarily because extrusion is an established process and is in regular use. In contrast, open-die forging is apparently not in regular use and requires many more steps. It is expected that a significant development effort would be needed to reestablish expertise. Only a few forging shops have the large presses required for open-die forging of tubing, and it may be difficult to find one that would be interested in such work.

The two suppliers that produce the largest seamless tubing (NPS 26 and larger) are Wyman-Gordon in the U.S. (and Scotland) and Mannesmann in Germany. Only Wyman-Gordon was contacted for this study.

Most of the length of the hot header will be devoted to the attachment of heat transfer tubes. Besides the tube attachment area, some additional length will be required at the ends of the header for thickness transitions and welds. The length of the tube attachment area is determined by the number of tubes to be attached, the outside diameter, and the areal density of the tubes. The KVK tests provide an indication of the areal density that can be achieved. The tubes had an outside diameter of 22 mm (Ref. 112), and each tube was surrounded by an annular groove with a width of 8 mm (Ref. 112), so the outside diameter of the annular grooves was 38 mm. Figure 4-11 shows a detail of the hot header (Ref. 112), from which it is concluded that the center-to-center spacing of the tubes is about 53 mm. If it is assumed that the tubes were arranged in an equilateral triangular array, the tube density is about 400 m^{-2}. If the same density can be achieved for NGNP, the hot header can be fairly short. For example, with 3000 tubes and a header with a diameter of 1100 mm, the tube attachment area would be slightly more than 2 m long.

Welding the heat transfer tubes to the header is a significant challenge. Although the individual welds are relatively small and the stock is thin, there are many welds to be made, inspected, and tested, and close spacing of the tubes will require the that welding equipment fit between the tube being welded and the tubes that were welded previously. Repair of a weld after the IHX has been in service would be particularly difficult, and it may be necessary to simply plug the heat transfer tube.

There are limitations and risks related to the production of large-diameter seamless tubing. Size limitations for Wyman-Gordon are provided below; these are set by the design of the equipment and should be considered as hard limits. Within those limits, the specific dimensions to be used for the hot header must be evaluated by Wyman-Gordon to determine whether production is feasible and would result in a suitable wrought structure. There is also a risk due to lack of experience. Wyman-Gordon has worked with a variety of nickel alloys, including alloys 600 and 800H but not 617. However, they have bid on an order for alloy 617 pipe (Ref. 113) and are working with Special Metals to produce it.

4.7.4.1 Haynes International

Haynes International produces ingots of alloys 617 and 230. The standard diameter for the ingots is 508 mm for alloy 617 and 406 mm for alloy 230, but larger sizes (up to 660 mm) could be produced. An order of 30000 kg of ingots could be produced in about 13 to 14 weeks.

4.7.4.2 Special Metals

Special Metals produces ingots of alloys 617 and 230 by either vacuum arc remelting or vacuum induction melting followed by electroslag remelting. Either process can produce ingots of over 13000 kg, which is larger than Wyman-Gordon’s preferred size (see below). The standard product is a round ingot, produced by the second process, with a diameter of 530 mm. Production of 30000 kg of ingots is estimated to require 12 to 16 weeks from time of order.

4.7.4.3 Wyman-Gordon

Wyman-Gordon forges large-diameter seamless tubing at its plants in Houston, Texas and Livingston, Scotland. The plant in Houston has two presses with capacities of 14000 and 35000 tons (Ref. 111). The smaller of the two is used for potting (upsetting) and piercing, whereas the larger is used for extrusion. The plant in Livingston has presses of similar capacity.

There are various size limitations that need to be considered. The maximum outside diameter is limited to 1219 mm (Ref. 111) or possibly 1194 mm (Ref. 113). The minimum outside diameter is on the order of 250 mm (Ref. 113) and therefore should not be a significant constraint. Wall thicknesses of up to 178 mm have been produced (Ref. 113). The minimum wall thickness is about 16 mm (Ref. 111) for smaller pipe. The maximum length that can be extruded is about 18 m (Ref. 113), but the maximum length that Wyman-Gordon can heat treat is about 13.5 m (Ref. 111).

The maximum length is also limited by the size of the initial ingot. Wyman-Gordon prefers to limit the ingot mass to about 11000 kg. Material loss during processing is estimated to be 10% to 15%. As a point of reference, an alloy 617 tube with an outside diameter of 1100 mm, a wall thickness of 100 mm, and a length of 4000 mm would have a mass of about 10500 kg.

Lead time for production of pipe is currently about 30 months (Ref. 113), but the final design need not be specified until 12 months before the scheduled production date. Wyman-Gordon normally charges a 30% penalty for contract cancellation before material is ordered, a 60% penalty for cancellation after material is ordered but before manufacturing starts, and 100% after manufacturing starts.

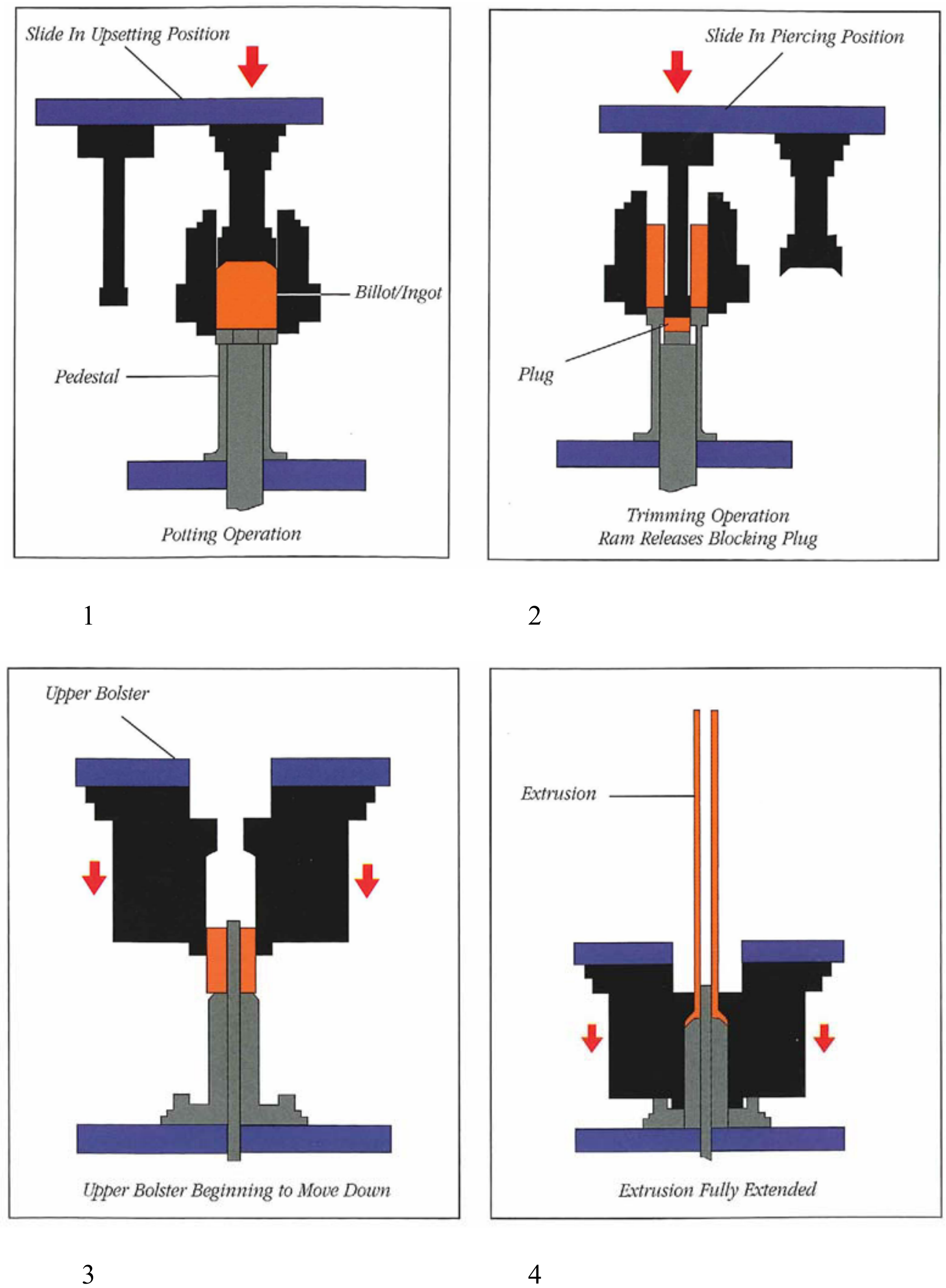


Figure 4-10 Tube extrusion process (from Ref. 111)

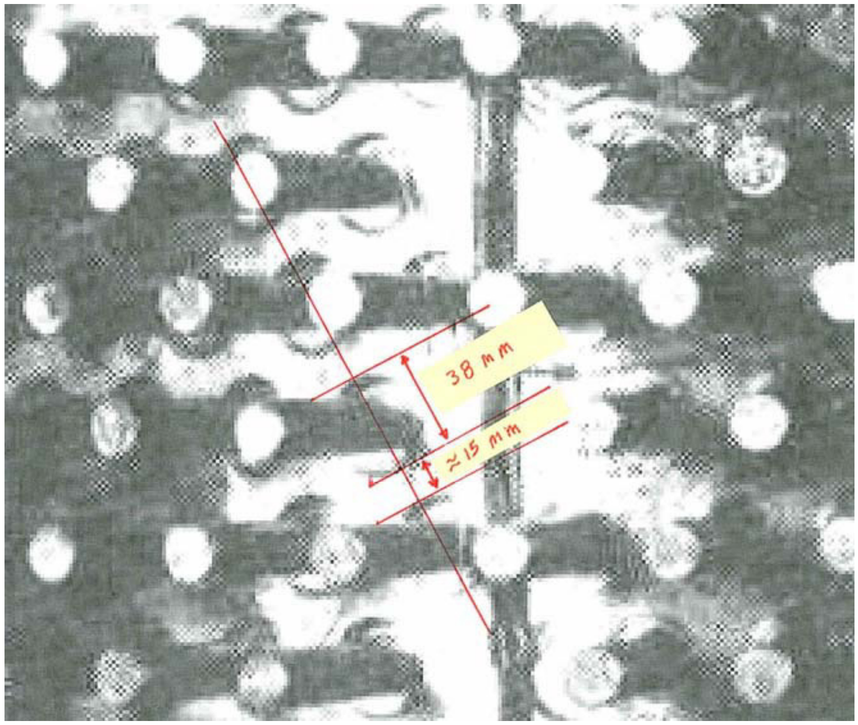


Figure 4-11 Detail of hot header from KVK tests (from Ref. 112)

4.7.5 Plates for Fabricating Large-Diameter Tubing

The tubular and compact IHXs both include large-diameter central tubes. These may be fabricated as seamless tubing by using the methods described above. An alternative is to fabricate them from curved plates. Longitudinal welds in the hot header would be undesirable because they would probably be necessary to avoid attaching heat transfer tubes to the weld metal of the hot header, and the areas without heat transfer tubes would disrupt the symmetry of the primary gas flow. In contrast, longitudinal welds in the central tube would be substantially less disruptive and could probably be tolerated.

The central tubes will be rather long (about 12 m for the tubular heat exchanger), so it is probably not feasible to form a single curved plate that would run the entire length of the central tube. Instead, curved plates should be joined by longitudinal welds to form lengths of tubing, and the lengths should then be joined to form the central tube. It would not be advisable to make the circumferential welds first because it would be difficult to maintain straightness over the entire weldment.

The central tube may use different materials at different elevations, according to the service temperature at a given elevation. In that case, the effects of mismatches in thermal expansion should be considered.

The central tube for the compact heat exchanger differs from that for the tubular heat exchanger in that it will be attached to numerous heat exchanger modules, with several modules attached around the central tube at a given elevation. It is recommended that the attachments be made near the middle of a plate (or away from the ends of a length of seamless tubing), that is, away from any longitudinal or circumferential welds.

For the tubular heat exchanger, it may be desirable to have a central tube that is larger in diameter than the hot header. An increased diameter would allow space for insulation inside the central tube while maintaining an acceptably low gas speed. If the angle of taper is kept small, it would probably be acceptable to form and weld a tapered section and to weld the tapered section to the cylindrical parts. For larger angles of taper, it would be preferable to forge the curved plates so that, when welded together, there would be short cylindrical sections at the ends and a tapered section in the middle.

Within the size limitations of the mills, plate is a standard product, and there is little procurement risk.

The hot sections of the heat exchangers are large weldments and are produced from heavy materials. There is some risk of weld cracking and welding distortion. The alloy producers describe alloy 617 as "readily formed and welded by conventional techniques" (Ref. 17) and alloy 230 as having "excellent forming and welding characteristics" (Ref. 99). It has also been stated that alloy 230 has been welded in thicknesses up to 76 mm, and that alloy 617 should be easier to weld than alloy 230. Despite such claims, it would be appropriate to consider tests to determine whether long, heavy-section welds can be made with acceptable quality and levels of distortion. The alloy suppliers provide substantial guidance on welding (Refs. 99, 114, 115).

Welding distortion may cause ovality of tubing that is fabricated from curved plates, but rerounding should help to reduce the distortion.

4.7.5.1 Haynes International

Haynes International provides plate in alloys 617 and 230 with widths up to 1828 mm and a maximum mass per piece of at least 2700 kg. More massive pieces may be possible. Alloy 617 can be produced up to 50 mm thick, and alloy 230 can be produced up to 38 mm thick. Haynes has worked with partner companies to form plate into tubing. Production of 30000 kg of plate would require 22 to 28 weeks.

4.7.5.2 Special Metals

Special Metals provides plate in alloys 617 and 230 in thicknesses up to 60 mm and widths up to 2438 mm, with a maximum mass per piece of 3400 kg. Production of 30000 kg of plate is estimated to require 18 weeks. If multiple shipments are desired, the first could occur 16 weeks after order.

4.7.6 Plates for Compact IHX

Several types of compact heat exchangers have been considered. All the designs use a stack of sheets or plates to define the flow paths for the primary and secondary gases. Confusingly, the material used for heat exchanger plates is sufficiently thin that alloy producers describe it as sheet rather than plate.

A plate fin heat exchanger uses a thin, corrugated foil to define the flow paths. Because of the thinness of the foil, the requirements for material performance are severe. Loss of chromium to the scale, internal oxidation, carburization, or decarburization could quickly change the chemistry of the materials and degrade their performance. For this reason, plate fin heat exchangers are not recommended.

Plate stamped and plate machined heat exchangers use more substantial plates that, as their names suggest, have stamped or machined grooves to define the flow channels. These designs are preferred because the thicker plates provide a reservoir of material that is less rapidly depleted or degraded by reactions with the primary and secondary gases.

Because of the temperature gradient from the hot end to the cold end of the heat exchanger, plates that are initially rectangular will become slightly trapezoidal during operation. A more serious design challenge is to control thermal gradients in directions perpendicular to the gas flow, which could result from variations in flow. The blocky shape of a compact heat exchanger offers little flexibility to accommodate such thermal stresses.

The edges of the plates must be reliably sealed together to avoid mixing of the primary and secondary gases. The sealing could be done by welding, brazing, or diffusion bonding. A development effort is probably needed to ensure that large compact heat exchangers can be adequately sealed and that the joints will not leak after some time in high-temperature service.

Sheet and strip of alloys 617 and 230 are standard products and do not pose a significant procurement risk.

4.7.6.1 Haynes International

Haynes International could produce 25000 kg of cold-rolled alloy 617 or 230 sheet in about 24 to 28 weeks. The material could be supplied as coils, large flat sheets, or cut-to-size sheets. The maximum width is 1220 mm. The maximum length of a flat sheet is 6.1 m.

4.7.6.2 Special Metals

Special Metals could produce 25000 kg of cold-rolled alloy 617 sheet in about 12 weeks. The material could be supplied as coils, large flat sheets, or cut-to-size sheets. The maximum width is 1219 mm.

Special Metals does not produce alloy 230 as sheet or strip.

4.7.7 Hemispherical Head

The design for the hot header includes a hemispherical head, which would be forged from a circular plate. It seems conservative to assume that a head of diameter d could be forged from a plate of diameter $\pi d/2$. In light of the available widths for plate (2438 mm), a head with a diameter of at least 1.5 m should be possible. That is larger than the maximum diameter for seamless tube, so the hemispherical head should not pose a size limitation.

For information on plate suppliers, see the section above on plates for large-diameter tubing. Obtaining the plate does not appear to pose a significant procurement risk.

No forging shops have been contacted, but Haynes International did not report any concerns about the feasibility of producing the head. The forging will require large dies, and manufacturing the dies may be the longest step in production.

4.7.8 Welding Supplies

For gas-tungsten and gas-metal arc welding, the recommended filler material for alloy 617 is AWS A5.14 ERNiCrCoMo-1, which has the same composition as the base metal (Ref. 17).

Haynes International recommends alloy 230-W (AWS A5.14 ERNiCrWMo-1) for gas-tungsten and gas-metal arc welding of alloy 230 (Ref. 99). The composition of alloy 230-W is similar to that of alloy 230.

In contrast, Special Metals recommends either alloy 230 or 617 as the filler for these welding processes (Ref. 102).

The welding supplies for alloys 617 and 230 are standard production items and do not pose a significant procurement risk.

4.7.8.1 Haynes International

Haynes International manufactures "Haynes 230-W filler wire" as its recommended filler for alloy 230 (Ref. 116). Haynes also appears to manufacture "Haynes 617 filler wire" for alloy 617 (Ref. 117).

4.7.8.2 Special Metals

Special Metals manufactures "Inconel Filler Metal 617" as its recommended filler for alloy 617 (Ref. 118). It does not appear to produce a filler metal for alloy 230.

4.7.9 Conclusions

Manufacturing the hot sections of the IHXs poses several challenges. Notable among these are forging the hot header, welding the many heat transfer tubes to the hot header, and assembling the central tube, hot header, and hemispherical head into a single weldment. Limitations of available manufacturing facilities will limit the diameter of the hot header and, if it is to be made of seamless tubing, the central tube. However, no limitations were found that would prevent construction of the IHXs.

5.0 HEAT TRANSPORT SYSTEM (HTS) CONFIGURATION

5.1 Scope of work

The task will identify and evaluate the alternatives for the NGNP heat transport system (HTS) configuration. This action reconsiders the Trade Study on Primary and Secondary Cycle concept in light of new NGNP requirements. The task will include the following:

- Recommend and provide bases for the number and configuration of the primary and secondary loops that comprise the HTS including the Steam Generator (SG). This shall consider the NGNP design requirement that the HTS include at least two primary and secondary loops and the recommended design of the IHX and the impact if any on the configuration and sizes of the Reactor Pressure Vessel.
- The type, size and rating of the circulators
- The size of the steam generator.
- The need for, and if required, the type and size of primary isolation valves.
- The need for, and if required, the type and size of secondary isolation valves.
- Current state-of-the-art for candidate circulators and valves and the steps necessary to advance the state-of-the-art to meet NGNP requirements.
- Current state-of-the-art for candidate SGs and the steps necessary to advance the state-of-the-art to meet NGNP requirements.

The current state-of-the-art for IHXs and additional steps necessary are already covered in section 3.4 and those results are taken into account in the present task.

The work will also include an update of the Capital costs and O&M costs of the NGNP FOAK based on the proposed configuration.

5.2 Study Assumptions

This study will consider an indirect steam cycle facility with an IHX separating the primary circuit from the SG. The expected applications for the system remain the same as that evaluated in Reference 1, that is, combined electricity production and heat supply to an experimental hydrogen production facility. We have explicitly not considered cycles directly coupling the SG to reactor, even though such configurations likely have major advantages.

The following system parameters were previously recommended by the Preconceptual Design NGNP Primary and Secondary Cycle study (Reference 119) for the indirect combined cycle gas turbine configuration:

- Reactor outlet temperature: 900°C
- Reactor inlet temperature: 500°C
- System configuration: H2 and PCS in parallel
- Number of loops: 4 loops
    - 3 with tubular IHXs for PCS
    - 1 with compact IHX for H2
- Secondary temperatures:

- 450-850°C for PCS (50°C approach)
    - o 475-875°C for H2 (25°C approach)
- System pressure: 5.0 MPa

In addition to these values, the overall reactor power was recommended to be 565 MWth by the Preconceptual Design NGNP Power Level trade study (Reference 125). The power requirements for the hydrogen production facility were recommended to be 60 MWth.

In light of the revised system configuration (indirect steam cycle rather than indirect combined cycle) several of these parameters will be re-examined.

The first three parameters, namely the reactor inlet and outlet temperatures and the loop configurations, as well as the overall reactor power level, are assumed to remain unchanged. In addition, the system parameters specific to the hydrogen system will also remain unchanged, as will the decision to use tubular heat exchangers for the IHXs (which is supported by the results of section 3.5).

The remaining parameters will be re-examined. Specifically, the main questions to be answered become:

- What are the IHX secondary side inlet and outlet temperatures (which also define the gas-side steam generator inlet and outlet temperatures)?
- What are the steam generator water/steam-side inlet and outlet temperatures?
- How many loops are required for heat transport to the PCS, assuming that the PCS must be designed to handle the entire thermal output of the reactor at full power.
- What should be the pressure of the primary and secondary systems?
- Should isolation valves be included in the HTS system. If so, where should these valves be located?

5.3 Summary of Results – HTS System Schematic Representation

This section presents an overview of the newly selected NGNP HTS system configuration, based on the analyses and evaluations conducted as part of the AREVA study of the NGNP Heat Transport System. The detailed discussion of the issues that lead to this configuration are addressed in the subsequent sections.

The recommended configuration resulting from the current Conceptual Design Study evaluation of the HTS configuration is:

<u>System Configuration</u> – Indirect Steam Cycle

This is the system configuration that AREVA has been directed to consider as a basis for this study. In the context of this study, an indirect steam cycle is taken to be a system wherein an IXH is used between the reactor and the steam generator and a secondary gas loop is used between the IHX and the steam generator.

<u>Reactor Power</u> – 565 MWth

This was the reactor power recommended by the original NGNP Power Level Trade Study. No information developed by the current study provided a strong reason to change this value. In particular, the temperature boundary conditions which lead to this power level are unchanged (see below).

Reactor Outlet Temperature – 900°C

This was the reactor outlet temperature recommended by the original NGNP Primary and Secondary Cycle Trade Study. No information developed by the current study provided a strong reason to change this value. The assumed requirements of hydrogen production processes are unchanged, and 900°C continues to represent the best balance between NHS feasibility and hydrogen process performance.

Reactor Inlet Temperature - 500°C

This was the reactor inlet temperature recommended by the original NGNP Primary and Secondary Cycle Trade Study. No information developed by the current study provided a strong reason to change this value. For the assumed reactor outlet temperature, this inlet temperature provides the best balance between reactor feasibility, process performance, and circulator requirements.

PCS IHX Type - Tubular

This was the IHX type recommended in the original NGNP Primary and Secondary Trade Study. Even under the changed PCS conditions of this study, the benefits of this more robust IHX remain and are confirmed by the results of section 3.5.

PCS IHX Approach Temperature - 75°C

This approach temperature represents a balance between the IHX design considerations (including tube stresses, unit lifetime, etc.) and the design considerations for the steam generator. The IHX design for the 75°C approach temperature has approximately 3000 tubes, a tube bundle height of about 8 meters, and a secondary side pressure drop of 0.2 MPa.

Hydrogen Process IHX Type - Compact

This was the IHX type recommended in the original NGNP Primary and Secondary Trade Study. No information developed by the current study provided a strong reason to change this value.

Hydrogen Process IHX Approach Temperature – 25°C

This was the IHX approach temperature recommended in the original NGNP Primary and Secondary Trade Study. This value was chosen to provide the maximum flexibility in supporting development of various hydrogen production technologies. No information developed by the current study provided a strong reason to change this value.

Steam Generator Helium Inlet Temperature - 825°C

As above, this temperature represents a balance between the IHX and steam generator design considerations. This inlet temperature is well within the acceptable range identified by MHI for this value.

Number of Loops – 2 (plus smaller Hydrogen process loop)

Based on the designs of the IHX and steam generators, the HTS system will require two loops.

Primary System Pressure – 5 MPa

This pressure has been selected based on initial assessment of the limitations imposed by reactor vessel fabrication issues, specifically the ability to provide forgings and plates above certain thicknesses. It is expected that this value may be increased based on more detailed assessment of the RPV fabrication issues and a coolant pressure trade study considering circulator feasibility, circulator power, RPV feasibility, and RPV cost. This trade study should be planned for early conceptual design, as soon as data on forging availability becomes available.

Secondary System Pressure – 5.5 MPa

This pressure is specified to limit primary system leakage in the event of a penetration of the IHX tubes, while limiting the stresses on those tubes during operation.

Primary Circulator Power – 8 MW each

This circulator power is estimated to be the maximum required based on the primary system fluid parameters. This estimate is believed to be conservative. Refinement of the system pressure and imposition of more representative uncertainties may lower the power requirements.

Secondary Circulator Power – 16 MW each

This circulator power is estimated to be the maximum required based on the secondary system fluid parameters. This estimate is believed to be conservative. Refinement of the system pressure and imposition of more representative uncertainties may lower the power requirements.

PCS Isolation Valves - Steam and Feedwater Side of Steam Generator Only

No isolation valves are needed on the helium loops to support the plant safety case and operational issues for anticipated operational modes.

Hydrogen Process Loop Isolation Valves - Hot and cold isolation valves at the exit of the compact IHX vessel

Secondary isolation valves for the H_2 process heat transport loop are included based on the regulatory uncertainty regarding the need to isolate a primary system loop with potential access to the environment coupled with the inability to inspect the compact IHX.

Reactor Building Configuration

The proposed reactor building layout, based on the recommended HTS system configuration, is depicted in Figure 5.1. This layout is discussed fully in section 5.4.5 of this report.

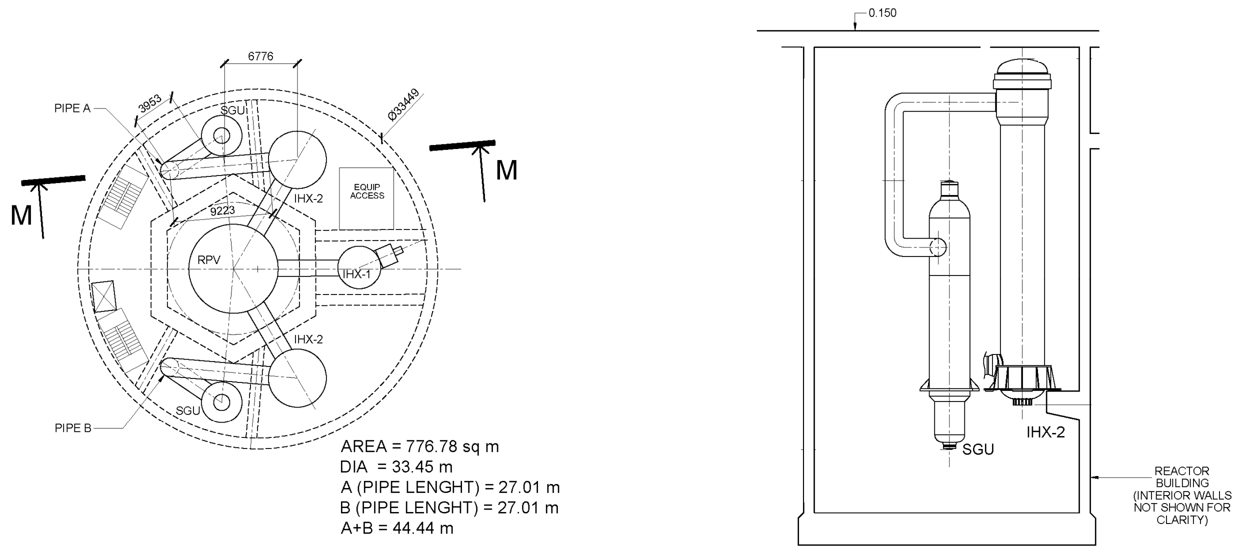


Figure 5-1 Proposed Reactor Building Layout

5.4 System Configuration Evaluations

In the process of establishing the final configuration of the HTS, several basic trade-offs need to be considered between the major components. Once these trade-offs are assessed and the basic configuration is defined, detailed descriptions of the components can be developed.

5.4.1 Steam Generators and IHXs

One trade-off involves the designs of the IHXs and the Steam Generators. Given the constraints placed on the NGNP system, it is not possible to have both of these components operate within previously-demonstrated optimal temperature regimes. As such a balance must be maintained between demonstrated IHX performance, characterized by high secondary side outlet temperatures (low approach temperature for the heat exchanger) and demonstrated steam generator performance, characterized by lower gas-side inlet temperatures.

Impact of Varying the Approach Temperature in the Current NGNP Configuration

The current NGNP configuration is presented in Figure 5-2 hereunder.

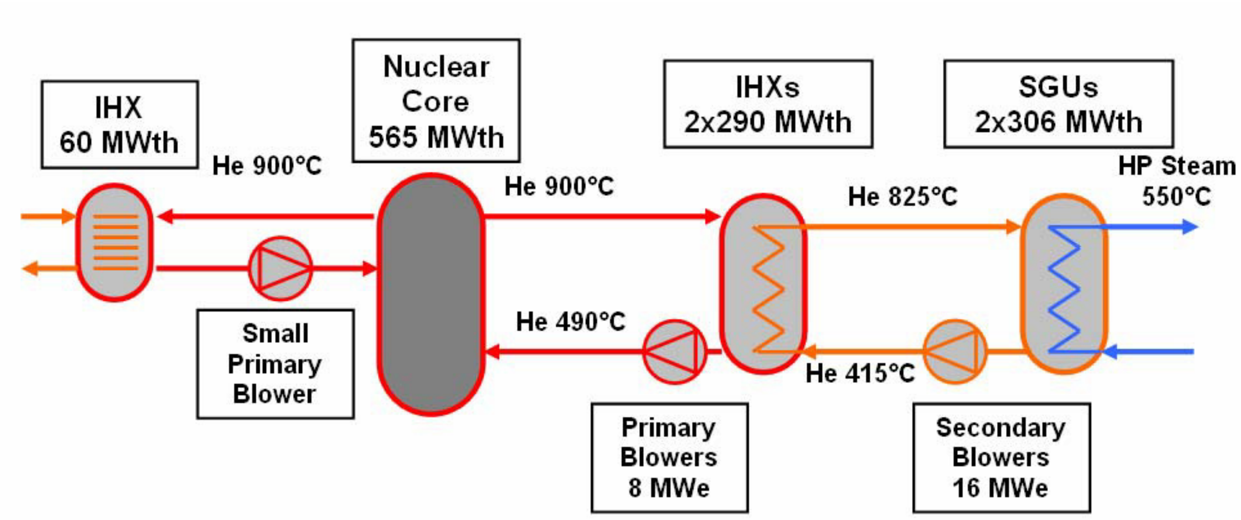


Figure 5-2 NGNP configuration (April 2008)

This section analyzes how the IHXs secondary outlet temperature can be changed, assuming that the reactor outlet temperature is kept at 900°C and that the steam temperature at the outlet of the SGs is kept at 550°C. The primary to secondary temperature difference is assumed constant all along the IHX tubes.

If the IHX secondary outlet temperature is decreased, the effectiveness of the IHXs will decrease because of the higher approach temperature but the approach temperature of the SGs will decrease which compensate the first effect in terms of overall plant efficiency. Thus, since the temperature of the SG outlet does not change, the efficiency of the steam cycle as a whole will not change as a function of the IHX secondary outlet temperature.

So, in a global sense, varying the approach temperature of the IHX has no impact on the plant efficiency.

The main impacts of varying the IHXs approach temperature concern:

- The design of the IHXs and SGs,
- The thermal loadings in the IHXs and the SGs,
- The necessary power of the circulators (colder Helium is easier to blow). Through this effect, increasing the approach temperature of the IHX actually slightly increases the overall plant efficiency.

The first two points are detailed below.

Impact on the components design

The feasibility of the SGs is very sensitive to the helium inlet temperature, because the steam comes out of the SG at a temperature of about 550°C regardless of the inlet temperature (steam becomes supercritical above this temperature which raises important technical challenges).

Discussions with MHI designers indicated that they considered SG designs with helium inlet temperatures between 750°C and 850°C to be feasible, though to varying degrees. Table 5.1 provides a summary of their assessment of the relative feasibility of designs within this temperature range.

Points Evaluated	**Steam Generator Design Condition – He Inlet / He Outlet**		
	750°C / 350°C	**800°C / 400°C**	**850°C / 450°C**
Representativeness of the conditions for a "standard" commercial direct steam cycle concept (in particular, when is a change in technology necessary?)	The most economical advantage for the following reasons, a) Pressure Vessel material of the Primary System can be Mn-Mo steel, which is used in LWRs. b) R&D is minimized c) Technical risk is minimized by the lower temperature of the helium hot leg.	Moderate economical advantage for the following reasons, a) Pressure Vessel material of the Primary System can be 21/4 CrMn-1Mo steel, which is used in the JAEA HTTR. b)Moderate R&D required c) Moderate technical risk	Lowest economical advantage for the following reasons, a) Pressure Vessel material of the Primary System needs to be 9Cr-1Mo, used in fossil power plants. b) Higher R&D required c) Highest technical risk
R&D Required	a) Application of ASME NH Code for tubes of SH and RH of SG.	a) Application of ASME NH Code for pressure vessel and tubes of SH and RH of SG.	a) Application of ASME NH Code for tubes of SH and RH of SG. b) Development of pressure vessel material of 9Cr-1Mo alloy steel.
Expected Lifetime of 40 years	Easy	Fair	Possible
Expected maximum power level per SG	Approximately 300 MWth Restriction based on capacity of MHI work shop	Approximately 300 MWth Restriction based on capacity of MHI work shop	Approximately 300 MWth Restriction based on capacity of MHI work shop
Ability to produce SGs to support a 2018 startup	Easy	Fair	Possible if the material development can be started soon.

Table 5-1 MHI Assessment of Steam Generator Relative Feasibility

Based on this assessment, a high approach temperature in the IHXs is favorable to the SGs feasibility.

As for the IHX, initial dimensioning of the tube bundle gives the features in Table 5.2 for the tube bundle with approach temperatures of 50°K and 75°K (two loops are assumed in each case).

Parameter	50°C approach	75°C approach	Comments
IHX Power (MWth)	**290**	**290**	
Primary side:			The temperatures at primary side are assumed to be imposed by the NHS, so they are kept constant.
T_{in}(°C)	**900**	**900**	
T_{out}(°C)	**490**	**490**	
Secondary side:			
T_{in}(°C)	**440**	**415**	
T_{out}(°C)	**850**	**825**	
Mass flow (kg/s)	**272**	**272**	The mass flows of primary and secondary sides are equal.
Number of tubes	**3544**	**2966**	The number of tubes is a limiting parameter in terms of feasibility of the bundle, mainly due to limited area on the hot header. State-of-the-art covers up to 2200. 3544 is considered as very challenging.
Pressure drop at secondary side (bar)	**1.9**	**1.8**	With a pressure drop of ~2 bar at secondary side of the IHXs, each loop needs a ~16 MWe blower which represents 5.5% of the total electric power of the PCS. But reducing this pressure drop requires a higher number of tubes which raises feasibility issues.
Bundle height (m)	**11**	**7.8**	
Length of the tubes (m)	**26**	**18**	
External diameter of the bundle (m)	**3.8**	**3.5**	

Table 5-2 Main Design Parameters of Helical Tube Bundles for $T_{approach}$= 50°K or 75°K

Assuming that the secondary pressure drop limitation (~2 bar) should be strictly observed, the main impact of going for a 75°K approach temperature as compared to the 50°K design is to reduce the number of tubes from the very challenging number of 3544 to 2966 (still slightly beyond past experience but more favorable). The height of the bundle is also decreased and the vessel diameter as well.

So, increasing the approach temperature is favorable in terms of compactness and manufacturability of the IHX.

Impact on lifetime of the components

Accommodation of thermal stresses by the helical bundle

The counterpart of increasing the approach temperature is a change of the thermo-mechanical behavior of the tube bundle. Going for a shorter helix (higher approach temperature) leads to reduce the capability of the bundle to accommodate thermal expansion. This effect has not been quantified however.

This topic needs an evaluation based on a finite element calculation of the behavior of at least one complete helical tube including the connections to the tube plate and the hot header.

Impact of the stresses through the wall

Increasing the approach temperature also increases the thermal gradients through the tube wall. This could be considered as favorable for the choice of a low approach temperature as regards lifetime but, on the other hand, the tube average temperature decreases as well with a high approach temperature (primary temperatures are kept constant) so that the creep strength of the material is improved. In addition, creep relaxation induces edge effects. So the impact of increasing the approach temperature on lifetime is strongly non linear.

Thus, a detailed analysis for each set of operating parameter is necessary to conclude on the impact of varying the approach temperature on the lifetime.

Results of ASME 2007 Section NH analysis for five design options

Simplified analyses according ASME 2007 B&PV Section NH have been performed for 5 options of operating conditions in which the approach temperature is varied from 50K to 100K. Based on a basic duty cycle history made of series of 9 months operating conditions interrupted by short shut-downs, the fatigue damage turns out to be negligible but the creep damage is not and should be life limiting in an analysis comprising all the loadings (weight, fluid forces, loads from support are neglected) and all the cycles (including incidental ones).

The five options considered in this analysis differ by:

- The approach temperature (temperature difference through the tubes' wall assumed constant all along the tubes),
- The pitch between the tubes, which is taken as either equal to the one used in the past German designs or with the pitch increased by 20%,
- The pressure losses on the secondary side which are equal to ~2 bar in every option except Option 5 for which it is decreased to 1.5 bar (decreasing those pressure losses is favorable as regard feasibility of the blowers and plant efficiency).

Option 1 and Option 2 correspond to the two designs presented in Table 5.2.

The results are presented in Table 5.3 and Table 5.4 hereunder.

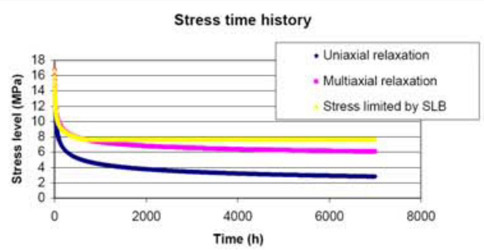
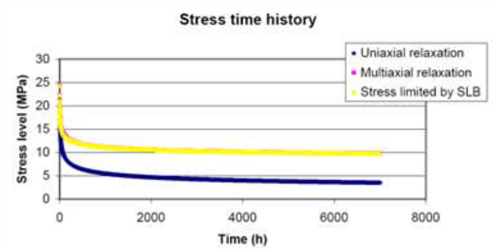
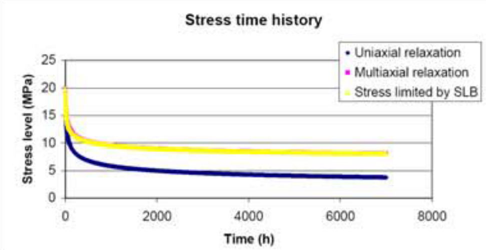
	Option 1	Option 2	Option 3
Precision on the design	Tapproach=50K with German pitches. ΔP_2=2,0 bar	Tapproach=75K with German pitches. ΔP2=2,0 bar	Tapproach=75K with enlarged pitches (factor 1,2). ΔP2=2,0 bar
Outer diameter of the tube bundle (m)	3,7	3,44	4,15
Height of the bundle (m)	11	7,8	9,6
Number of tubes	3544	2966	3203
Total stress at inner wall in normal operation before relaxation (MPa)	16,6	24,5	20
Inner wall temperature (°C)	870,4	854,7	849,3
Temperature used for the analysis (°C)	871	855	850
SLB reached?	Yes, very early in the cycle	Yes but very late in the cycle -> negligible influence	Yes, early in the cycle
Creep damage after 20 years	0,11	0,075	0,039
Stress time history			

Table 5-3 Results for Option 1, Option 2 and Option 3

Note: SLB denotes Steam Line Break in the above stress time history plots.

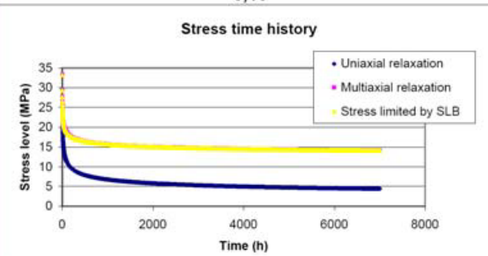
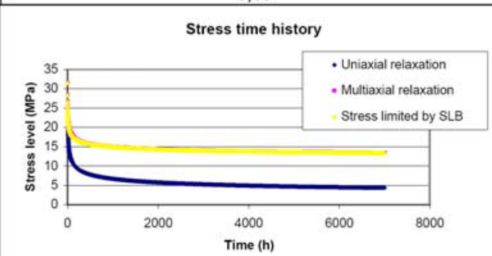
	Option 4	Option 5
Precision on the design	Tapproach=100K with German pitches. ΔP_2=2,0 bar	Tapproach=100K with German pitches. ΔP_2=1,5 bar
Outer diameter of the tube bundle (m)	3,3	3,4
Height of the bundle (m)	6,3	6
Number of tubes	2561	2829
Total stress at inner wall in normal operation before relaxation (MPa)	33,2	31,5
Inner wall temperature (°C)	838,9	839,6
Temperature used for the analysis (°C)	839	840
SLB reached?	No	No
Creep damage after 20 years	0,18	0,15
Stress time history		

Table 5-4 Results for Option 4 and Option 5

The relaxation curves are obtained as follows (according ASME 2007 Section NH):

A uniaxial relaxation calculation is performed on the basis of the initial stress level which is the total stress at normal operation. The multiaxial relaxation is deduced through a multiaxiality factor. Then the multiaxial relaxation is limited by S_{LB} (based on primary stresses that cannot relax). The damage is then calculated on the basis of the curve called "stress limited by S_{LB}".

5.4.1.1 Comparison between $T_{approach}$= 50°K and 75°K

Option 1 ($T_{approach}$= 50°K) appears to be worse than Option 2 and Option 3 ($T_{approach}$= 75°K) as regards lifetime. Option 2 is better than Option 1 (with a lower number of tubes) but the increase of the pitches in Option 3 (still with $\Delta T_{approach}$= 75°K and an "intermediate" number of tubes) leads to an additional gain of lifetime.

It should be noted that a strong edge effect exists due to the S_{LB} limitation for relaxation. This effect is unfavorable to Option 1. The initial stress is indeed lower for Option 1 but the S_{LB} limit is quickly reached so that the stress level stays at a level comparable with the one of Option 2 but at a sensitively higher temperature, which leads to a higher damage.

To illustrate this point, Table 5.5 hereunder gives the damage values when the S_{LB} value is decreased by 20% or 30%. These assumptions are reasonable since the material data on relaxation and the rules are still not very sound. Option 1 becomes as good as Option 3 in this case.

Relaxation limit taken into account:	**Damage for Option 1:**	**Damage for Option 2:**	**Damage for Option 3:**
S_{LB}	**0.11**	**0.075**	**0.039**
0.8*S_{LB}	**0.04**	**0.070**	**0.025**
0.7*S_{LB}	**0.026**	**0.070**	**0.025**

Table 5-5 Impact of changing the S_{LB} value

In addition, in incidental conditions, higher stresses than in normal operation may occur. If the pressures remains approximately constant but the secondary stresses become higher, then the S_{LB} (function of primary stresses) remains at the same level but the initial stress level (S_j) of the relaxation curve increases. Once more, the ranking between the solutions can be changed as illustrated below.

Initial stress level S_j taken into account:	Damage for Option 1:	Damage for Option 2:	Damage for Option 3:
S_j	**0.11**	**0.075**	**0.039**
1.2*S_j	**0.11**	**0.13**	**0.047**
1.3*S_j	**0.11**	**0.17**	**0.055**

Table 5-6 Impact of changing the initial stress level value

As a conclusion, the ranking of the first three options regarding lifetime ("$T_{approach}$= 75°K better than $T_{approach}$ =50°K") should be taken with care because it is sensitive to the edge effect of the relaxation limitation.

On the other side, it can be stated that increasing the pitch between the tubes (of 20% in this example) do have a significant and positive influence on the lifetime at the price of a reasonable increase of the pressure vessel (21% in this example).

Comments about $\Delta T_{approach}$= 100°C

In Option 4 and Option 5, the approach temperature is increased again up to 100K. When comparing them to Option 2 and Option 3 ($T_{approach}$= 75°K), the edge effect which is observed for comparison between $T_{approach}$ =50°K and 75°K no more holds, so that the lifetime decreases (the temperature decrease of the inner wall induced by lower secondary temperature is largely compensated by the increase of the thermal gradient through the tube).

$T_{approach}$= 100°K allow reducing the number of tubes (enhanced manufacturability) and lowering the pressure drop at secondary side but seems challenging regarding thermomechanics because far from state-of-the-art (e.g. $T_{approach}$= 50°K in the past German designs).

In addition, the height of the bundle reaches relatively low values so that its capability to compensate thermal expansion may be questionable. Again, this topic needs a finite element calculation of a whole helical tube behavior.

Conclusion on the impact on lifetime

Non-monotonous and strongly non-linear effects on lifetime calculation according ASME 2007 Section NH have been identified. With the set of operating conditions taken for the analyses, the best lifetime is obtained with $T_{approach}$= 75°K as compared to 50°K and 100°K. This singularity is due to the edge effect induced by the stress relaxation limitation (S_{LB}). It is reckoned that this is very specific to the arbitrary choice of the cycle being considered.

So it is difficult to draw a general conclusion about the effect of increased approach temperature on lifetime but it is reckoned that the higher lifetime found for $T_{approach}$= 75°K than 50°K is the result of a singularity which is not representative of the general trend which is a decrease of the lifetime when the approach temperature increases.

However, it has also been shown that increasing the pitch between the tubes results in limiting the thermal gradient through the tube at the price of a reasonable increase of the pressure vessel diameter. This could be a means to increase the approach temperature without too much penalizing the lifetime.

Conclusion

It has been shown that increasing the approach temperature leads to:

- Improved SGUs feasibility,
- Improved compactness and manufacturability of the IHXs,
- Slightly improved plant efficiency by reducing the secondary helium pumping power,
- Non-monotonous and strongly non-linear effects on lifetime calculation according ASME 2007 Section NH. It is however reckoned that the general trend is a decrease of the lifetime when the approach temperature is increased,
- Reduced capability of the helix to accommodate thermal expansion (additional negative impact on lifetime).

The NGNP indirect steam cycle configuration has the particularity of having a plant efficiency limited by the SGUs steam outlet temperature (~550°C) despite the high NHS outlet temperature (900°C).

The other impacts that have been identified have been shown positive except in terms of lifetime which is the hard point of high temperature IHXs. On this point, it is difficult to draw a general conclusion but it is reckoned that the general trend is that a high approach temperature penalizes the lifetime.

However, increasing the pitch between the tubes seems to be an efficient mean of increasing the lifetime for a given value of $\Delta T_{approach}$. So it is recommended to go for a rather high IHX approach temperature so as to benefit from the positive impacts and to compensate for the lifetime reduction by increasing the pitch between the tubes.

5.4.2 Number of HTS Loops and Heat Exchanger and SG Design Details

A second trade-off involves the number of recommended loops required for heat transport to the PCS. This is a function of, first, the maximum feasible sizes of the IHX and steam generators, than the economics of the use of smaller loops.

In the preceding discussions regarding the relationships governing the selection of the IHX approach temperature, and resulting SG helium inlet temperature, a two loop configuration was assumed for the loops required for heat transport to the PCS. The basis for this assumption was limitations on both heat exchanger units that preclude consideration of a single loop design on a schedule consistent with the NGNP startup date of 2018.

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

The size limitations considered for the SG are based on current constraints in the MHI fabrication facilities. Expansion of these fabrication capabilities, or fabrication at alternate facilities, may be ultimately possible, but may impact operations by 2018. In light of the more restricting limitations on the IHX, pursuing details of the maximum feasible SG size available in time to support the NGNP does not seem warranted should a “one IHX and SG per loop” model be desired. Implementation of a PCS system design which contains an equal number of IHXs and SGs, segregated into individual loops, is recommended to avoid the design and operational complexities associated with shared components.

The potential economic benefit of selecting a PCS deign with more loops, for example three 200 MW loops rather than two 300 MW loops, was considered in a qualitative study by MHI. This study considered potential fabrication cost, efficiencies, or lifetime benefits against expected higher reactor building volumes and piping lengths. The results of the study indicated no significant benefits to pursuing a higher number of loops used for heat transport to the PCS.

IHX Design Details

Table 5.7 provides the detailed parameters of the tubular IHX for a two loop design.

		NGNP Tubular IHX
Desired Thermal Power	MW	290
Primary fluid		He
Secondary fluid		He
Primary side (shell side)		
Inlet Temperature	°C	900
Outlet Temperature	°C	490
Inlet pressure	MPa	5
Pressure loss	MPa	0.02
Mass flow	kg/s	136
Secondary side (tube side)		
Inlet Temperature	°C	415
Outlet Temperature	°C	825
Inlet pressure	MPa	5.5
Pressure loss (only for the bundle area)	MPa	0.2
Mass flow	kg/s	136
Geometry		
Outer Tube diameter	mm	21
Inner Tube diameter	mm	16.6
Tube wall thickness	mm	2.2
Conductivity of tube	W/(m.K)	23
Number of tubes		2966
Helix angle	°	25.38
Diameter of first coil	m	1.5
Helix inner diameter (inner wall)	m	1.478
Helix outer diameter (outer wall)	m	3.5
Length of tubes (developed)	m	18.3
Tube bundle height	m	7.8
Heat exchange area	m^2	3567

Table 5-7 Tubular IHX Parameters (per loop)

SG Design Details

An overall description of a SG that meets all of the requirements discussed in the preceding sections, including a helium inlet temperature of 825°C and a two loop PCS system concept, is presented in Figure 5.3 and Table 5.8, below.

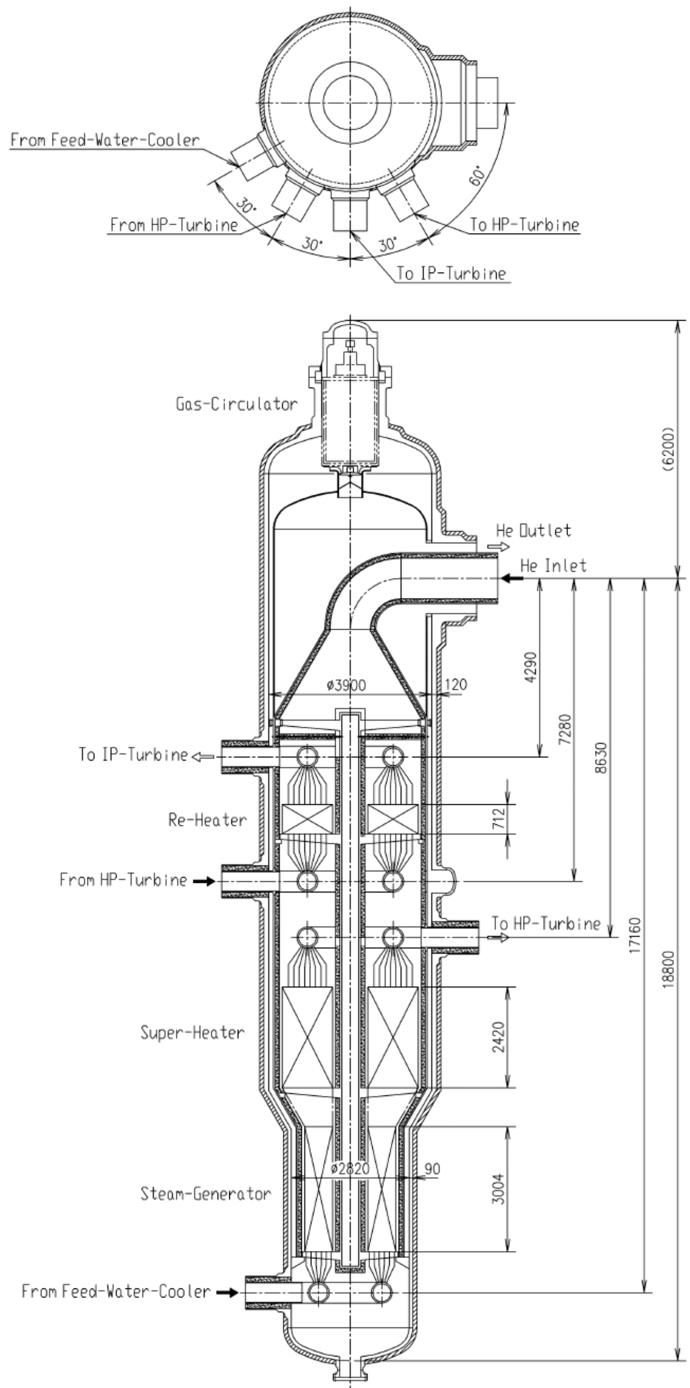


Figure 5-3 Proposed Steam Generator Design Overview

Table 5-8 Proposed Steam Generator Design Overview

Item			Unit	Specification	
General condition					
	Equipment name			Steam Generator	
	Type			Helical coil type	
	Number		(-)	1	
	Heat Transfer duty		MW	306.0	
Design condition				Shell side	Tube side
	Fluid			Helium gas	Water/Steam
	Flow Rate		kg/s	140.3	118.4/100.7
	Inlet Pressure		MPa	5.5	17.2
	Pressure drop		MPa	< 0.06	< 0.76
	Inlet Temperature		℃	825.0	281.5
	Outlet Temperature		℃	405.0	566/538
Dimension					
	Outer Shell (Cir.+RH+SH+SG)	Inside Dia.	mm	4,140	
		Thickness	mm	120	
		Height	mm	Approx. 25,000	
	Heat transportation	Outer Dia.	mm	3,400/2,320	
		Inner Dia.	mm	700	
		Height(sub cooling and evaporator zone)	mm	3,004	
		zone)	mm	2,420	
		Height(re-heating zone)	mm	712	
Material					
	Outer shell		-	2 1/4 Cr -1 Mo Steel	
	Heat transfer tube	(Sub cooling and Evaporator zone)	-	2 1/4 Cr -1 Mo Steel	
		(Super heating zone)		Alloy 800H	
		(Re-heating zone)		Alloy 800H	
	Insulator		-	Ceramics Fiber	
Weight			ton	420	

5.4.3 Primary and secondary System Pressures and Circulators Design

A third trade-off involves the pressure of the primary and secondary systems. In general, this is a balance between the fabricability and cost of the reactor vessel, which must be made thicker for higher pressures, the circulators, which must be larger for lower pressures, and the pumping power cost which is higher for lower pressures.

At the time of the writing of this report, the maximum reactor vessel thickness that it is feasible to fabricate has yet to be established. Therefore, for the purposes of providing a fairly conservative evaluation of this design trade-off, a primary system pressure of 5 MPa has been assumed. This pressure requires a minimum reactor vessel thickness of 230mm (in the nozzle ring) to meet appropriate design limits, which appears to be reasonably achievable.

In order to minimize creep impacts on the IHX tubes, and thereby increase the lifetime of the unit, the pressure differential between the primary and secondary systems has been limited to 0.5 MPa. Using this value, the secondary system pressure is set at 5.5 MPa to provide a slight overpressure to mitigate radionuclide releases in the event of a small tube leak within the IHX. Such a strategy will tend to reduce occupational exposure and potentially reduce operational and maintenance costs for the NGNP plant.

Selection of these low system pressures requires specification of high powered circulators for both the primary and secondary systems. Preliminary calculations, including conservative uncertainties, indicate that circulator powers of approximately 8MW and 16MW will be required for each loop of the primary and secondary systems, respectively. These values represent the estimated maximum circulator powers that may be required. The combination of potentially increased system pressures, through increased reactor vessel thicknesses, and detailed circulator designs including reasonable uncertainties should significantly reduce these required powers.

Discussions with circulator vendors that supported the development of the AREVA ANTARES design indicate that even at these maximum powers, provision of circulators should be feasible. Table 5.9 provides general details of a series of example circulator designs that meet these power requirements.

Single blower option	**High efficiency**	**Low efficiency**
Impeller diameter (m)	1.9	1.31
N (rpm)	3000	4250
Diffuser diameter (m)	3.9	2.325
Power (MW) with margin	15.6	16.8
Blades shape	backward inclined	radial

Two blowers option	**High efficiency**	**Low efficiency**
Impeller diameter (m)	1.418	0.998
N (rpm)	4000	5500
Diffuser diameter (m)	2.91	1.8
Power (MW) with margin	7.6	8.2
Blades shape	backward curved	radial

Table 5-9 Example Circulator Design Summaries

5.4.4 Need for, and Potential Location of, Isolation Valves

The purpose of this section is to examine the need for isolation of major flow paths in the indirect steam cycle configuration for the NGNP with a small (10%) heat transport loop for process heat application such as a hydrogen production plant. The heat transport fluid to hydrogen production plant is helium through a compact IHX and to the power conversion system through helical tube-and-shell IHXs and steam generators. The nuclear island main components are located underground with vented[5] reactor building design.

Discussion of Needs

Before identifying the need and proposing possible locations for isolation valves for this HTR configuration, the following questions must be answered. The response to these questions will form the basis and support the recommendation of the HTR isolation valves.

1. Why is isolation valve required?
2. Do HTRs need isolation valves?
3. The issue of ASME code requirements
4. If required, where should isolation valves be located?

Why is an isolation valve required?

From a regulatory perspective an isolation mechanism to contain radionuclides is required whenever there is a significant possibility of release of radionuclides to the environment. The high temperature reactors use high performance TRISO particle fuel. It is expected that during normal operation circulating activity of the primary system loop is such that it can be discharged to the atmosphere without exceeding site boundary dose limits.

From the operation and maintenance perspective an isolation mechanism is required if portions of a system must be taken out of service while other sections are in operation or maintained in a standby condition.

From the availability and economics perspective an isolation mechanism is needed to limit loss of inventory if it is technically practical and economically justified.

The current regulatory framework requires double isolation on the primary pressure boundary auxiliary penetrations to limit loss of coolant inventory in case of a pipe break. However the primary circuit itself is not isolated. In LWR technology, a loss of primary inventory leads to overheating events that could potentially cause core uncover and degradation scenarios. Furthermore, isolation devices are also required for containment penetrations to limit the possibility of containment bypass in case of radionuclides release into the containment.

So, the purposes of isolation devices (valves for pipes) are two fold:

- To reduce the possibility of inventory lose or
- To reduce the possibility of radionuclides bypassing the reactor containment

[5] In a large depressurization accident the initial inventory of primary Helium is discharged (i.e. vented) to the atmosphere (without filtration).

Do HTRs need isolation valves?

The HTR is a new technology and regulatory requirements for licensing such technology have not been established. Nevertheless, the need for containment of radionuclides is technology neutral, and if there is a barrier such as a reactor building or primary pressure boundary the function of which is to stop radionuclides dispersion, then any penetration through such barrier must be isolatable upon detection of conditions for potential release or bypass scenario.

Unlike the LWR technology the HTR primary coolant functions to transport heat generated in the core to the secondary side for distribution and use. Thus, in HTR technology the primary coolant is not a major contributor to core neutronics, heat generation, or accident decay heat removal. Therefore, a loss of primary inventory is only an economical and system availability concern and not a nuclear safety issue.

Unlike the current requirements for radionuclides retention measures the HTR technology must release the primary helium inventory to the environment to eliminate the driving force behind the subsequent delayed releases. Because of the TRISO particle fuel operating performance, this is possible in HTR technology and should be allowed.

Following the initial release, reactor building penetrations must be closed and remain closed to contain any delayed releases, however, no driving force is available from the primary side for such release but there could be high pressure systems available in the secondary side or the steam cycle that must be isolated from the primary side.

In HTRs where should isolation valves be located?

From the safety and regulatory view and given acceptable fuel performance; the HTR primary pressure boundary auxiliary penetrations should not need isolation devices. However, primary system pressure boundary isolation will be required for other reasons such as maintenance and system availability and economic factors. Such factors should also drive the need for the reliability of such isolation which will drive the need for single or double isolation mechanisms.

However, containment building penetration will require isolation to limit delayed releases and impact of higher pressure systems (i.e. secondary circuit or steam cycle) on the depressurized primary.

The issue of ASME code requirements.

The current ASME code that governs the LWR pressure vessel design and manufacturing which is endorsed by the NRC requires inspection of pressure boundary welds and double isolation between piping class boundaries. The HTR pressure vessel built to existing ASME Section III code requirements must provide double isolation between code class boundaries.

Licensing view on the need for isolation valves

Based on several years of HTR licensing pre-application interaction with the NRC, it has become evident that commercial HTRs will not use existing LWR regulations for licensing. If HTR technology becomes commercially viable thus many HTR are ordered, new HTR specific or technology neutral licensing rules will be needed. However, the first few HTRs will be licensed with the existing regulations (mostly LWR specific). This licensing path will require requests for specific exemptions for each rule by providing technical justification.

Recommendations:

HTR pressure vessel and primary pressure boundary - if an exemption is not requested then existing rules apply. This leads a requirement for double isolation on all primary pressure boundary penetrations that represent ASME Section III code class boundaries.

The compact IHX providing process heat to the hydrogen plant is a unique device; its heat transfer surfaces are not readily accessible for inspection, therefore an isolation valve may be required on the secondary circuit of the compact IHX. Given the current regulatory uncertainty, coupled with the fairly small size of these valves, the prudent path would be to include these values.

The tubular IHX heat transfer surfaces are inspectable so no isolation valve would be required for the tubular IHX side. However, a reliable depressurization mechanism may need to be designed for the secondary circuit and the steam cycle to prevent re-pressurization of the primary system and the reactor building following the initial depressurization. Otherwise, the steam cycle and the secondary circuit may need to be isolated from the primary loop and the reactor building to eliminate re-pressurization and delayed release. Since a re-pressurization event has not been defined for an HTR at this time, the most appropriate recommendation that can be made is that such letdown or isolation may be required after further study of the pertinent event sequences and discussions with the regulator.

HTR reactor building – It is imperative that exemption from the current LWR containment building requirements be requested and granted. This means that HTR reactor building will be a low pressure containment building. However, any penetrations in the containment building must be isolated following the initial release to eliminate the inadvertent release of delayed radionuclide from the reactor building.

In summary, AREVA recommends the following configuration of isolation valves:

- No isolation valves on the primary helium lines

- No isolation on the secondary helium lines

- Isolation on the steam and feedwater lines since such valves would be relatively cheap and would forestall arguments regarding water ingress

- Isolation on lines between the compact IHX and the hydrogen system to forestall arguments regarding interactions with the hydrogen system fluids, and to provide a demonstration of high temperature isolation valves at a smaller scale.

5.4.5 Building Layout

This section provides an evaluation of the impacts of the proposed PCS system configuration on the layout of the reactor building. There are two somewhat linked considerations that must be reflected in the building design. The first is the support strategy employed for the major system components. The second is the placement of the steam generators either within or outside the reactor building. Minimization of the building size for the resulting configuration and component placement as close together as practical will be pursued to reduce the cost of the reactor building and primary and secondary ductwork and piping.

The consideration that drives the selection of a support strategy for the major PCS system components (Reactor Vessel, IHXs, and SGs) is thermal expansion. Figures 5.4 and 5.5depict the relative magnitudes of this expansion. These figures are only intended to show the relative magnitude of potential thermal expansions and are based on a simplified configuration that does not depict the final conditions. The values shown in these figures are based on thermal expansions for mod 9 Cr material assuming 450°C temperature increase from room temperature for all structures. Connections between components are short, straight runs of pipe.

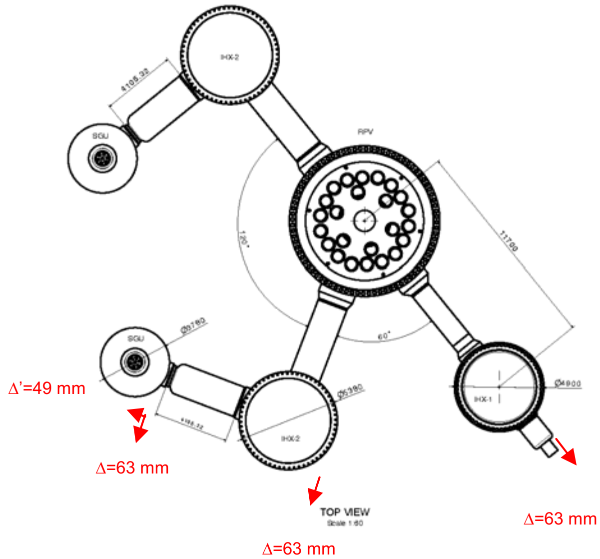


Figure 5-4 Estimated PCS Thermal Expansions – Top View

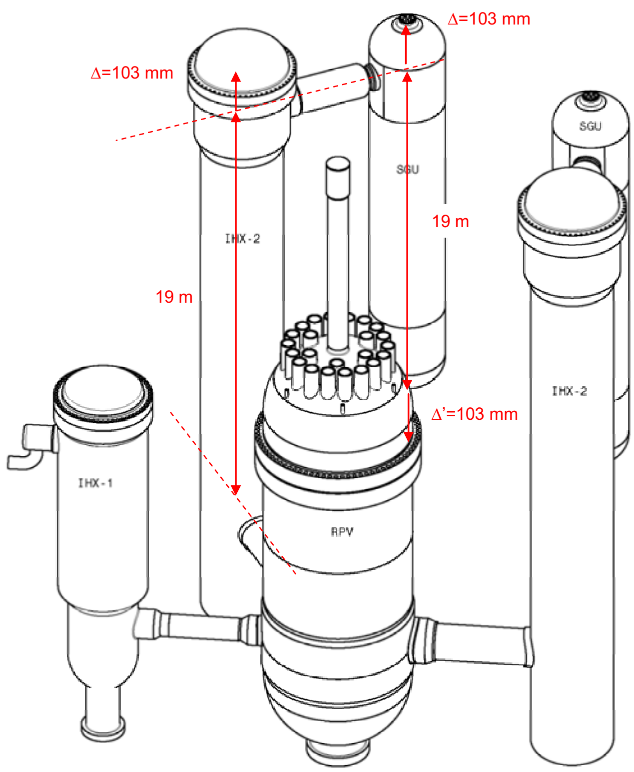


Figure 5-5 Estimated PCS Thermal Expansions – Plan View

These results indicate that there is significant relative motion of the components during temperature changes, which makes close-coupling impractical. The suggested support strategy is as follows

- The reactor vessel will be considered the fixed point in the system. It will be supported at the level of the cross duct.
- The IHX will also be supported at the level of the cross duct. In that configuration, the IHX moves only laterally with respect to the reactor vessel. As such, a simple sliding support can be used.
- The steam generator must be de-coupled from the IHX, otherwise a support system with three degrees of freedom would be required. As such, the Steam generator is linked to the IHX utilizing a long, looped duct configuration, a “flexible pipe”. The steam generator will be supported at the level of the cross duct as well, to limit axial expansion differences with the IHX.
- Snubbers and keys will be used as appropriate to limit lateral displacement during seismic events.

Based on this strategy, an assessment of the optimal placement of the SGs was conducted. It was determined that placement of the SGs outside of the reactor building would be expected to have significant cost drawbacks relative to placement inside, including much longer duct runs than required to support thermal expansion and an increased potential for the need of isolation valves on the secondary helium lines. Since these helium ducts will be very large diameter concentric ducts, any additional length will add significant cost, as will isolation valves for such a complex pipe. These costs were estimated to significantly exceed the costs of a larger reactor building diameter required to contain the SGs inside.

Figure 5.1 depicts the proposed configuration of the major reactor building components. The layout of the secondary helium duct has not been optimized, but a similar layout is expected to provide sufficient flexibility to limit duct thermal expansion stresses.

5.4.6 Conclusions

The above discussed assessments and evaluations support the choice of a heat transport system configuration for the HGHP that has the attributes listed in Table 5-10.

Table 5-10 Recommended HGHP Heat Transport System Attributes

Reactor Power	565 MWth
Reactor Outlet Temperature	900°C
Reactor Inlet Temperature	500°C
PCS IHX	Tubular helical coil 75°C Approach Temperature 0.2 MPa pressure drop on the secondary side 900°C Inlet / 490°C Outlet Temperature
Hydrogen Process IHX	Compact (25°C Approach Temperature) 900°C Inlet / ~500°C Outlet Temperature
SG Helium Inlet/Outlet Temperature	825°C/415°C
Number of Loops	2 (plus smaller Hydrogen process loop)
Primary System Pressure	5 MPa (may be increased based on more detailed assessment of the RPV fabrication issues)
Secondary System Pressure	5.5 MPa
Primary Circulator Power	8 MWe each
Secondary Circulator Power	16 MWe each
PCS Isolation Valves	Steam and Feedwater Side of Steam Generator Only
Hydrogen Process Loop Isolation Valves	Hot and cold isolation valves on secondary side connections of the compact IHX vessel

5.5 HTS operating condition matrix based on variable parameters

The HTS Configuration Matrix examines the impact of four variables on the feasibility of the heat transport system portion of the NGNP power conversion system. These variables are:

- Reactor Outlet Temperature
- Reactor Inlet Temperature
- Reactor Power
- Primary System Pressure

For each combination of these variables, a qualitative assessment of the impact on various HTS parameters is provided. These parameters are:

- Primary Circulator Power
- Secondary Circulator Power
- IHX Concept
- IHX Material
- RPV Material
- Fuel Performance
- Number of Required HTS Loops
- Steam Generator Feasibility

Each parameter assessment is given a color in the matrix to indicate its impact on system feasibility and ability to meet the NGNP startup goal of 2018. These colors and their connotations are:

- Green – Feasible using currently available technologies
- Yellow – Feasible, but some additional R&D is necessary for implementations
- Red – Not feasible, either due to technological limitations or schedule impacts.

The specifics of each parameter assessment are provided below.

Primary and Secondary Circulators

Total primary and secondary circulator power was estimated for each case and entered into the matrix. This value was not assigned a color. The number of circulators that are required per loop was calculated by dividing the total required circulator power by the number of loops to get the circulator power requirements for each loop, then adjusting the number of circulators per loop to keep the individual circulator power within the "Feasible" or "R&D Required" groups defined in Table 5-11. Circulator Power cell was assigned the color identified in the table and the Number of circulators per Loop cell was assigned Green for 1 circulator, Yellow for 2 circulators and Red for 3 or more circulators.

Primary Circulator Power	Secondary Circulator Power	Circulator Feasibility
P ≤ 8 MW	P ≤ 12 MW	Feasible – Green
8 MW < P ≤ 16 MW	12 MW < P ≤ 20 MW	R&D Required to Implement – Yellow
16 MW < P	20 MW < P	Avoid – Red

Table 5-11 Assessment of Circulator Powers

The Circulator Power Fraction was calculated by summing the total primary and secondary circulator powers, then dividing by the reactor power and an assumed overall efficiency of 45%. Power fractions of 15% or lower were assigned a Green designation. Power fractions from 15% to 25% were assigned a Yellow designation. Power fractions above 25% were assigned a Red designation.

IHX Concept

Based on the schedule limitations for the NGNP plant and the need to provide a reasonable component lifetime, it was judged that use of a compact IHX design was only feasible for inlet temperatures below 800°C, and that use at 800°C would be challenging by 2018. At temperatures above this range, a tubular IHX was judged to be necessary.

The matrix entries for the IHX Concept were rated Yellow for the compact IHX options based on the presumed R&D requirements for implementation of this technology. The entries for the tubular IHX were rated as Green due to the relative maturity of this technology.

IHX Material

IHX material assessments indicated that, for operation at or above 800°C core outlet temperature, Inconel 617 or its equivalent would be required. At 900°C, use of this material would require some additional qualification work. For operation above 950°C the significant qualification work would be required to support use of Inconel 617, or an ODS or ceramic material would be required, though such materials could not be qualified in time to support a plant start-up by 2018. For operation 750°C or below, use of Inconel 625 or alloy 800 H would be possible.

Matrix entries for Inconel 625 or alloy 800 H at 750°C and Inconel 617 below 900°C were determined to be Green, based on the experience with these alloys. The entries for Inconel 617 at 900°C were made Yellow based on the additional qualification work needed at this temperature. The entries for Inconel 617 at 950°C and for the ODS or ceramic materials were determined to be Red, due to the inability to qualify such materials in time to support the NGNP schedule.

RPV Material

RPV material assessments indicate that, for core inlet temperatures above 400°C, the RPV material should be modified 9 Cr 1Mo. For core inlet temperatures at or below that value, use of SA 508 material could be considered (note that use of SA 508 could be envisioned with higher core inlet temperature, subject to implementing active cooling systems or passive thermal protection of the RPV wall). For core inlet temperatures between 350°C and 400°C, the relationship between the nominal core inlet temperature and the RPV material temperature under all appropriate conditions, and with the detailed design reflected, will need to be established to verify that SA 508 is an acceptable material choice. For core inlet temperatures at or below 350°C, there should be sufficient margin to reasonably expect Sa 508 is an acceptable material.

In additional to temperature considerations, use of the modified 9 Cr 1Mo material is limited by the ability to procure rolled plate for the nozzle ring, which is limited to 300mm in thickness. Considering that the thickness of the nozzle ring is 230 mm for a pressure of 5 MPa and assuming that the thickness is proportional to the pressure, a limiting primary system pressure of 6.5 MPa can be established

Based on these limits, the matrix entries for this parameter should be:

- Green for core inlet temperatures at or below 350°C based on past experience with SA508 material
- Yellow for core inlet temperatures between 350°C and 400°C, including 400°C, based on work needed to adequately define accurate RPV material temperatures
- Yellow for core inlet temperatures over 400°C and with primary system pressures below 6.5 MPa based on the work that remains to be done to qualify 9Cr 1Mo material for use.
- Red for core inlet temperatures over 400°C and with primary system pressures above 6.5 MPa based on the limits on rolled plate thickness.

Fuel

Expected maximum operational fuel temperatures were estimated for each of the cases. Matrix entries with fuel temperatures below 1250°C were given a Green rating based on the fairly large experience base indicating generally acceptable operation at these temperatures. Matrix entries with temperatures between 1250°C and 1350°C were given a Yellow rating based on the limited experience operating in this regime coupled with the potential for higher fuel initial quality levels which may be required to support such operation. Temperatures above 1350°C were given a Red rating based on indications that such operation may challenge the fuel's ability to support the required performance characteristics.

Number of Loops

The number of loops required was assigned based on the estimated maximum feasible size of 300 MWth for a tubular IHX and 600 MWth for the compact IHX. Matrix entries were rated based on a qualitative assessment of the cost and complexity of the number of loops as follows:

- 1 or 2 loops – Green
- 3 loops – Yellow
- 4 or more loops – Red

Steam Generator

Steam generator feasibility was assessed based on input from MHI regarding potential developmental costs and schedule impacts of various inlet temperatures. For this assessment, a 50°C approach temperature was assumed for the IHX, that is, the steam generator inlet temperature is 50°C below the reactor outlet temperature.

Steam generator inlet temperatures 700°C and below were rated Yellow since this temperature is consistent with current uses of the technology, however this low temperature may require larger units to meet heat transfer requirements and may impact the capability to provide reheat. Steam generator inlet temperatures between 700°C and 750°C, including 750°C, were rated Green since this temperature is consistent with current uses of the technology. Inlet temperatures between 750°C and 850°C, including 850°C, were rated Yellow based on the development work expected to bring the technology to the needed level in line with the NGNP schedule. Inlet temperatures over 850°C were rated Red based on the expectation that developing the needed technology in time to meet the NGNP schedule was impractical.

Summary Matrix

The detailed matrix developed using these rules is presented in Appendix A. A summary of this matrix is presented here as Table 5.12. For each cell in this summary matrix, the color is determined by the least feasible color in the summarized cells. For example, for a given set of temperatures, power and pressure, if one attribute is yellow and the other attributes are green, the summary cell is colored yellow.

Reactor Power 300 MWTh

Primary System Pressure 5 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 7 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 9 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Reactor Power 400 MWTh

Primary System Pressure 5 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 7 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 9 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Reactor Power 500 MWTh

Primary System Pressure 5 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 7 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 9 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Reactor Power 600 MWTh

Primary System Pressure 5 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 7 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Primary System Pressure 9 Mpa

Rx Inlet Temp- C / Reactor Outlet Temp - C	350	400	450	500	550
750					
800					
850					
900					
950					

Table 5-12 Summary HTS Configuration Matrix Summary (Indirect Steam Cycle)

The HTS configuration matrix was also studied in the case of the direct steam cycle concept, for which the primary helium is used to provide heat directly to a steam generator, without use of a secondary helium heat transport loop and attendant IHX. This study was based on 350°C and 750°C core inlet and outlet temperatures.

The detailed matrix developed for the direct steam cycle concept is presented in Appendix B. The matrix cell ratings were assigned in a fashion similar to the matrix for the indirect cycle configuration, with the following exception. Since there is no IHX and no secondary circulators, the appropriate cells have been colored gray, indicating no rating for these components.

A summary of this matrix is presented in Table 5.13.

Direct Steam Cycle Summary					
Reactor Power - MWth		300	400	500	600
Primary System Pressure - MPa	5				
	7				
	9				

Table 5-13 Summary HTS Configuration Matrix Summary (Direct Steam Cycle)

5.6 Current state-of-the-art for candidate circulators and the steps necessary to advance the state-of-the-art to meet NGNP requirements

This is a brief summary of the status of gas circulator technology available for supplying the helium heat transfer fluid for cooling high temperature gas cooled reactors. The design constraints on the gas circulator are: the gas temperature as it leaves the reactor core, the pressure drop produced as the fluid is pumped through the core and cooling loops, performance capability, reliability (which is a function of technical maturity) and cost. The maximum circulator shaft power requirement is a function of the most demanding duty (He flow rate at maximum reactor output) and the pressure drop through the reactor cooling loop.

Status of He Circulators operating experience

Over 200 gas circulators have been built and operated worldwide as part of the carbon dioxide and helium-cooled reactor programs. Reference 124 summarizes the status of circulator technology in 1987. The specialists at that meeting concluded:

- Two basic gas circulator designs were in use at that time. Simple and rugged radial flow compressors were used for reactors with large system pressure drops, such as the pebble bed reactors. Single stage axial flow compressors with radial compression were used with prismatic fuel core designs, which have inherently low pressure drops. All of the new design concepts presented at the meeting relied on submerged electric motors.
- The circulator bearings were considered critical components for developing larger machines. The specialists at that meeting concluded that future circulators for modular high temperature reactors would embody active magnetic bearings, because of the adverse experience with the ingress of lubricants from oil and water bearings into the core.

The circulator configurations chosen in the United States for gas-cooled reactor designs in the early 1990s were based on assessments of technology used in the Peach Bottom, AGRs, AVR, and THTR reactors. The evaluations performed for the New Production Reactor (NPR) and the Modular High Temperature Gas-Cooled Reactor (MHTGR) highlighted the following broad range of options based on prior experience:

1. compressor type (axial or radial flow)
2. drive type (external, steam turbine, submerged electrical motor)
3. bearing type (gas and oil lubricated, active magnetic bearings)
4. installation and integration (horizontal and vertical orientations)
5. flow control (variable geometry in fixed speed machine or variable speed blower)

The circulator configuration chosen for the NPR included a radial flow impeller, submerged motor drive, oil-bath bearings, and vertical installation above the steam generator. The design configuration selection for the MHTGR circulator was a single stage axial flow impeller, submerged electric motor, magnetic bearings, and vertical orientation above the steam generator. These two reactor programs had different programmatic requirements. In both cases the compressor impeller choice was made based on the pressure and flow volumes, aerodynamic efficiency, and reliability characteristics. The NPR program chose a 5.7 MW slow speed centrifugal impeller. The MHTGR program chose a 5 MW high speed two-stage axial flow compressor. In both cases the bearing design was matched to the rotor dynamic responses of the impeller and motor stator. The circulator drives chosen were submerged induction motors using solid state inverters to control the variable motor speed. This technology was demonstrated in the AGR reactors [5.25 MWe], AVR [220 KWe] and THTR [2.3 MWe] and was considered established technology. The major advantage of the submerged motor was that it eliminated the need for drive shaft penetrations in the primary coolant boundary. The Fort St. Vrain circulator [4.1 MWth] used an integrated system using steam turbines for normal service and a pelton wheel drive for upset conditions. A comprehensive hardware development program was planned for both reactor programs.

AREVA has conducted ongoing studies of compressor technology for high temperature reactor designs over the past 20 years. That experience formed the basis for the NGNP conceptual design studies and recommendations made for testing and qualification of the NGNP circulators. Outside the NGNP program, AREVA has evaluated the feasibility of circulators over a range of sizes. Both internal AREVA experts and external vendors indicate that circulators of up to 5 MW are clearly feasible and could be supplied readily. 8 MW are considered within the state of the art without significant R&D or qualification. 16 MW circulators are considered technically feasible but there are design integration limitations with some of the technologies which require additional development and testing.

Design Issues and Trade-Offs

AREVA studied various design and system integration issues in making its recommendation for the design of the primary heat transfer system. The main circulator design for the reactor module is based on limiting coolant pressure drop through the reactor cooling system at 100% power. The circulator design specifications given to the vendor determines the selection of subcomponent technologies, sizes, and configuration. Circulator designs that can use submerged electric motors are preferred, since this eliminates the need for a large shaft seal within the primary coolant boundary. The limitations and trade-offs between subcomponent design features was found to vary by circulator capacity. The vendors recommend that they test the full sized machine with air to confirm the operation of the integrated system (impeller, casing, bearings, motor and electronics).

Circulator Design considerations include:

Mechanical design – the design methods for static, dynamic and aerodynamic loads are well established. The rotor dynamics typically drives the final motor and bearing design. The 5 MW machine is well within the state of the art. Vendors are comfortable using their design methods to design the 8 MW machine but recommend confirmatory testing at their facilities. The vendors also feel that they can design a 16 MW circulators with existing methods but indicate that there will be considerable design iteration before an acceptable design solution is found.

Motor - the design methods and technology for designing a motor that can operate enclosed in a He environment is considered well within the state of the art. The detailed design requires coordination between the motor supplier, rotor and bearing designer. The conductor power supply for the 16 KW motor will be more challenging because of its high electrical current and the low dielectric properties in high temperature He. Factory acceptance testing of the motor/bearing assembly is recommended to confirm the design.

Electronics – the motor control circuit design are within the state of the art for the 5 and 8 MW circulators. Additional design and testing is required of the conductor and penetration arrangement for the 16 MW circulator.

Integration and layout issues: The configuration of each size circulator will depend on the integrated design solution for the motor, inverter, impeller, rotor, and magnetic bearings. In some cases, especially where subcomponent designs are unique, additional testing is required to verify the design and performance.

Maturity – whether the circulator will be available for installation in 2018 (or 2021) is the main consideration.

Recommended Design Features

The reference gas circulator concept for this study is an encapsulated centrifugal impeller, vertically mounted on the motor shaft. The gas circulator flow rate is controlled by speed control through an electrical motor inverter. The motor is mounted within the pressure vessel and is separated from the circulating hot He by a thermal barrier. 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 is cooled using a water cooling coil (with connections exterior to the pressure vessel). The cooling water pressure is maintained lower than the He pressure to ensure any leaks are from the He side to the water side or exterior. The gas circulator is supported by radial and axial magnetic bearings. Mechanical catcher bearings are set to support the machine in case the magnetic bearings fail. The impeller will be constructed of Alloy 718 because of its high creep strength at design temperatures.

Near-term (<5 year) Design, Development and Testing

AREVA surveyed vendors experienced in high speed blowers and gas circulators to identify near-term design, development and testing needs. The 5 MW circulator is within the current state of the art. Acceptance testing at the manufacturer's facility is recommended. Manufacturers generally test their machines with air at their own facilities and have design methods that will predict the performance with the working fluid (He in this case). Final qualification could be at the reactor itself. The 8 MW circulator is feasible using existing design methods and technology but additional testing is required to confirm the design solution. Although this size circulator could be available for a 2018 startup, there is a risk of delays caused by integration issues or technical difficulties.

Long-Term (>5 year) Research, Development, and Testing.

Based on the AREVA vendor survey it was concluded that the 16 MW circulator was at or near the limitations of magnetic bearing technology. Other areas identified as requiring long lead research and development included the power penetrations and conductors through the He filled circulator casing to the motor. A 16 MW circulator is not expected to be available by 2018.

5.7 Current state-of-the-art for candidate valves and the steps necessary to advance the state-of-the-art to meet NGNP requirements

5.7.1 Isolation Valve Requirements

As discussed in Section 5.4.4, the main functions of the isolation valve might include

- Retain coolant
- Retain radionuclides
- Support maintenance activity

The specific functions of the NGNP isolation valves will be determined based on the final NGNP configuration, operating strategy, and licensing position.

During normal operation, the valve stays open and it passes very hot helium.

The operating temperature of the coolant is about 900^{o}C and the operating pressure is about 5.5MPa in helium environment.

Figure 5-6 Manufacturing Isolation Valve

5.7.2 Design Challenges for High Temperature Isolation Valve

Unlike commercial/industrial valves, since it is in such a harsh environment, there are a few other issues that need to be considered for designing an isolation valve. The main concerns are

- Need to have a high temperature-resistant material (creep distortion etc)
- Need to have a proper sealing surface
- Need to have a appropriate insulation
- Need to have a suitable protection for moving parts (tribology)
- Need to have accurate control/actuation.

5.7.3 State-of-the-art Isolation Valve

In the 1980s, The German HTR program developed and tested a prototype (called DN 200, see figure below) of the hot gas valve. The valve was tested in the KVK's hot gas duct system for an extensive time at up to 900°C. The key design data are as follow:

Table 5-14 Isolation Valve (DN 20) Design Data

Medium	Helium
Design Temperature	950°C
Operating Temperature	900°C
Design Pressure	4.6 MPa
Operating Pressure	4.3 MPa
Flow Rate	3kg/s
Temperature of external housing	400°C
Total Length	2045mm
Max. Outer Diameter	1340mm
Connection Tube Diameter	200mm

In the course of the German HTR development project and the KVK testing, the following main design data and operating data were established for the secondary-side hot gas valves. Most of these specifications can be applied unchanged to NGNP if the secondary heat transfer gas is helium. For other heat transfer gases, all parameters would have to be reconfirmed during the conceptual design phase.

The prototype valve tests confirmed the required elements of high temperature valve technology including, valve body design and materials, flow channel materials, thermal insulation, valve seat and plug materials and operation, actuation systems, cyclic operation, etc. Thus the basic technology is already established.

Table 5-15 NGNP Valve Parameters

Operating pressure	41.9 bar
Hot gas temperature	900 ±18°C
Body design temperature (pressure boundary)	400°C
Helium mass flow	47.3 kg / s at 60 m/s
Temperature transient (start-up and shutdown)	± 2 K / min
Total closing time	≤ 5 s (time between start to close and the first contact between the sealing systems
Closing time for "gas tight"	Round about 3-5 min
Max. Δp across seat	42 bar
Max. Δp during opening and closing (maximum backpressure to be overcome)	3.5 bar
Leakage rate from both seats	1 mbar·l / s
Design lifetime	140,000 h
Prototype dimensions:	
Pressure-retaining pipe	Dia. 1,120 mm, t = 30 mm
Free flow cross section	Dia. 700 mm
Total length	2,400 mm

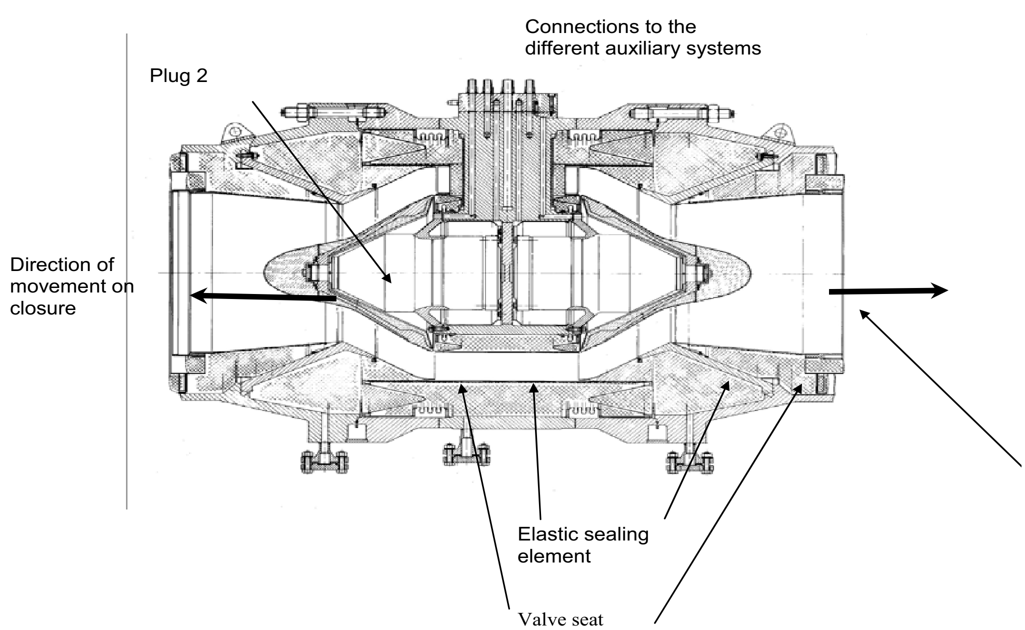


Figure 5-7 Double Acting Axial Valve

5.7.4 Steps necessary to meet NGNP requirements

The German isolation valve tests demonstrated that the NGNP isolation valve design will work and should be feasible for 2018 operation. However, some qualification tests of the isolation valve are necessary. A detailed qualification schedule has to be worked out. The two anticipated qualification steps are:

1) Elementary manufacturing tests to characterize the fiber insulation, assembly techniques, spacers, etc.
2) Full scale mock-up tests in a relevant helium environment.

These tests would cover:

a) manufacturing parameters,
b) depressurization tests,
c) pressure loss, heat loss, support tube temperature tests in a relevant helium environment,
d) leak-tightness tests of the valve,
e) closing and opening and
f) fatigue and creep-fatigue of specific areas.

5.8 Current state-of-the-art for candidate SG and the steps necessary to advance the state-of-the-art to meet NGNP requirements

Section 5.4.2 provides the design details of the Steam Generator (SG) envisioned for the NGNP. This design is considered as a first-of-a-kind due to higher inlet temperatures compared to what was designed and manufactured in the past. It is considered based on past experience that a design in the range of 400 to 450 MWt and up to 700°C is fully consistent with current state-of the art.

The re-heater and super heater tubes are the most critical part of the SG. It is considered that with a gas inlet temperature in the range of 750-850°C, the tube temperature can be maintained the same by adjustment of the exchange tube pitch. The material envisioned for the tubes of re-heater and super heater is Alloy 800H and it is expected that a design life of 60 years could be achieved with NGNP conditions.

With a gas outlet temperature above 371°C, the SG vessel will require a more resistant material than conventional Mn-Mo steel and the design will have to be based on 21/4Cr-1Mo or mod. 9Cr-1Mo steel.

Table 5.16 provides the risks identified and the corresponding verification plan. In general, minimization of those risks will be anticipated through analysis and/or experiments until completion of Basic Design (prior to Detail Design).

Figure 5.8 shows the SG development schedule for NGNP. The schedule is to be considered as a target because there are some uncertainties in the procurement of major forging materials and tubes.

No.	Verification Item	Completion date	Methodology of Verification			
			Analysis	Element test	Demonstration test by CTF	Commissioning test by NGNP
1	Thermal Hydraulic Performance	by the completion of BD	○	○	○	○
2	Flow induced vibration	by the completion of BD	○			
3	Flow stability and controllability of Water and Steam system	by the completion of BD	○		○	○
4	long term material test (Alloy 800H)	by the completion of BD		○		
5	Integrity of dissimilar material welding joint (Alloy800H/2-1/4Cr-1Mo)	by the completion of BD		○		
6	ISI equipment of tubes (If the ISI of tubes required)	by the commissioning test		○	○	○
	BD: Basic Design CTF: Component Test Facility ISI : In Service Inspection ○: Applicable Verification Process					

Table 5-16 Technical risks and Verification plan

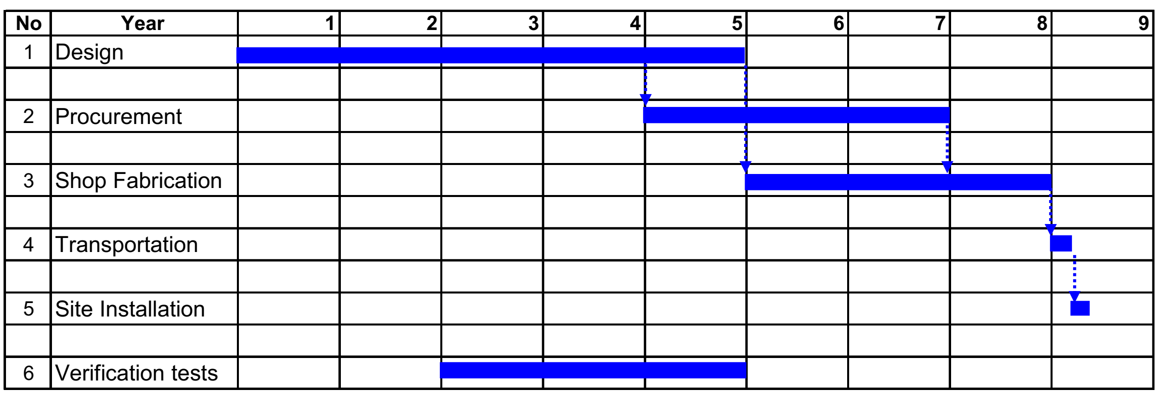


Figure 5-8 SG development schedule

5.9 Cost estimate of the NGNP FOAK

5.9.1 Capital Cost Estimate

5.9.1.1 Methodology, Basis and Assumptions

5.9.1.1.1 Methodology

The project scope and methodologies for this estimate were prepared from pre-conceptual design documents and discussions and meetings with the AREVA project team. A Statement of Work (SOW) and upper-level WBS provided by BEA were used to establish the structuring of the work. The estimate development was established using process equipment and system costs and labor costs from AREVA team members for the Nuclear Heat Plant (NHP), Power Conversion Plant (PCP) based on a current project and historical data.

The NPR-MHTGR Preliminary Design Balance of Plant (BOP) estimate is the basis for the NGNP BOP. BOP quantities and system costs, e.g., radwaste, steam and water, were used as is or modified to suit the NGNP design. Material costs from the NPR BOP estimate were escalated or current values were used where descriptions afforded the opportunity. Activity descriptions and costs are based upon these individual detailed item quantities.

Site work is scoped and quantified from the plot plan.

BOP labor hours were used as shown in the NPR estimate document or, if not shown, were added by cost estimating based on the description of the item. Labor hours from R. S. Means, Power Piping, Mechanical Contractors Association (MCA) and the National Electrical Contractors Association (NECA) were used. Current labor rates furnished as described below were applied.

Construction labor productivity adders were calculated using a “Construction Estimating Guidelines Labor Productivity Estimates” procedure. The procedure takes into account elements that affect labor. Some of the elements are: weather, craft variables, site logistics and third party oversight. Two adders were calculated for the project: one for nuclear grade work, i.e., the Reactor Vessel structure, and a second for all other work on the project.

Unit pricing, as required, was obtained from RS Means cost data books, “Trade Services Pricing” book, vendor quotes, vendor price lists and historical data. Local vendors were polled for preliminary quotes for removal of Basalt rock, supply of concrete, reinforcing steel and structural steel.

5.9.1.1.2 Basis

The cost estimate is to construct a Prototype (FOAK) Next Generation Nuclear Plant (NGNP) using Intermediate Heat Exchangers (IHX’s), Steam Generators (SG’s) and a standard Steam Turbine-Generator plant at the Idaho National Laboratory (INL) reservation at the New Production Reactor (NPR) Site. This estimate reflects a partnering of the AREVA, Inc. team, BEA, and DOE resources.

The project includes but is not limited to:

- A Nuclear Island (NI) consisting of the Vessels systems, Reactor Core and internals, IHX’s and SG’s for the PCS, an Intermediate Heat Exchanger (IHX) for a Hydrogen Plant (not in this work scope) and Hot Gas Transfer ducts;
- A Power Conversion System (PCS) consisting of a Steam Turbine and Generator and Ancillary Equipment and Piping;
- Balance of Plant (BOP) facilities consisting of clearing, grubbing and leveling, underground utilities, plant site security fence and guardrail, active vehicle barriers and Security Check Points, Secure Area triple-layer security fence, including passive and active detection and alarms, passive and active vehicle barriers, one main and one secondary entry point, all necessary structures and facilities for plant construction, operation and maintenance, and an electrical switchyard.

The H_2 plant was outside of the AREVA Team’s scope of work and is not covered in the present cost estimate.

An “onsite” fabrication shop for the assembly of reactor components and other large equipment not shippable in a single component is included in the work scope.

A five-mile transmission line to a local power grid and a 20-mile access road from an existing INL site road to the plant site is included per INL direction.

The Reactor Building structure and areas attached to the main structure for mechanical, electrical and other equipment and personnel is below grade and constructed of reinforced cast-in-place concrete. The Reactor

Building structure is enclosed with a steel structure (maintenance enclosure), with a 300-ton single failure overhead bridge crane. These structures shall be constructed to NQA-1 standards and appropriate seismic requirements.

A Basalt rock profile is within the Reactor Building area excavation depths of this structure and blasting will be employed for its removal.

Equipment removal access ports are provided in the at-grade top slab and a compartmentalized design is used to separate the reactor and each of the four IHX's. Various process and balance of plant systems for the reactor building are included.

Startup power is taken from the local grid and power generated by the project is sold to the grid. An emergency generator is provided for backup power.

Facility startup and commissioning, operating costs, R&D costs and decontamination, decommissioning and dismantlement (DD&D) costs are included. The NGNP plant will operate for 40 years.

The operating contractor provides level of effort (LOE) Construction Management and safety oversight and support, third party inspections, part-time LOE Project Management oversight, and procurement support of the bidding and contracting process.

Idaho Sales Tax of 6% is included for bulk materials and process equipment. Freight of 5% is included for bulk materials and process equipment, except PCS freight, which is a quoted ROM value.

INL provided a table with the majority of applicable craft wage rates. The rates are fully burdened with FICA, SUI, WC, etc. and also include a $19.00 per diem cost. Additional required rates are provided by the INL Site Labor Coordinator office in the "INEEL Site Stabilization Agreement" and current Appendix A rates. These wage rates expire May 31, 2007. Burdens are added to the SSA rates.

Contingency is included for: R&D, Design, License & Permit to Construct, Overall Site & BOP, Nuclear Heat Plant, Power Conversion Plant and Initial Ops. & Inspection.

At this time adjustments for commodity prices and exchange rates have not been performed for comparison with the PCDSR cost estimate.

5.9.1.1.3 Cost Estimate Assumptions

The proposed work scope will not exceed the activities and/or quantities as shown on the cost estimating detail sheets. The technical and functional requirements are included in the cost estimate for this work.

Project construction will begin in the third quarter of 2012 and the fieldwork will be completed in approximately 6 years. Craft labor will work a 4-10's workweek. The cost of overtime is not included.

All costs are in May 2007 dollars. Commodity price increases that may affect the plant cost have not been factored into the estimate.

The cost estimate does not consider or address funding restrictions. It is assumed that sufficient funding will be available in a manner allowing optimum usage of that funding as estimated and scheduled. The estimate does not include any monies for quality engineering or assurance reviews or input.

No allowances are included for any unknown existing underground utilities, for complications due to extreme weather or for the removal and transporting of contaminated soil.

The estimate assumes that a Construction Management team will supervise all construction of the site. A general contractor, in conjunction with Nuclear Island and Power Conversion equipment suppliers' representatives, will construct the project with subcontractors as needed.

Approximately 60% of the craft labor will be "travelers". The cost of "travelers" is included in the estimate as a 20% adder to the labor costs, direct labor and labor productivity adder.

Contractor indirect costs are included in the estimate as a percentage of total labor, direct labor and the labor productivity adder, without the 20% "travelers" adder. The indirect costs include mobilization, demobilization, field office staff, temporary facilities, construction equipment, insurance, bond and overhead and profit.

Once the project has been mobilized the work will proceed continuously until it has been completed. No others will utilize the project site and no delays from external forces (extreme weather conditions, catastrophic events, labor strikes, interveners (Greenpeace), "interested parties" (Native Americans, local residents), Congress, courts, etc.) will be encountered. Crews will demobilize from the project at the completion of construction and startup.

At this time, the cost estimate does not reflect any cost sharing or cost responsibilities between partners involved or risks to the operating contractor. Once the scope and agreements have matured, this estimate can be revised to reflect possible cost savings to the project.

5.9.1.2 R&D Costs

R&D costs are estimated to be $440 million in accordance with reference 126.

5.9.1.3 Licensing Costs

The licensing costs occur at all the phases of the project (Design, Construction, Initial Operations, Commercial Operations and Decommissioning). Licensing costs are taken from reference 126.

5.9.1.4 Design Costs

Costs for Conceptual and Preliminary designs on the one side and Final design on the other side are estimated to be $365.9 million and $299.3 million, respectively (consistently with reference 126).

5.9.1.5 Construction Costs

Construction costs are estimated to be $1,954.6 million. This figure covers the direct and indirect costs of Nuclear Heat Plant, Power Conversion Plant and Balance of Plant as described in Section 5.9.1.1. It is also based on spreadsheets and tables of required FTE's to perform construction tasks. These tasks include Project Management and System Integration; Waste Management; Environmental, Safety and Health; Security and Training. Licensing costs are also taken into account.

5.9.1.6 Startup and Testing Costs

Startup and Testing costs are estimated to be $447.2 million in accordance with reference 126.

Table 5-17 provides a summary of R&D, Licensing, Design, Construction and Startup and Testing costs. Table 5-19 compares current cost estimates with those performed during the pre-conceptual design phase (Ref. 126).

5.9.2 Prototype Nuclear System Operating Cost Estimates

5.9.2.1 Operating and Maintenance Costs

Plant operating and maintenance costs are estimated to be $ 75.3 million / Year. It is considered that O&M costs should not be affected by the change from CCGT to indirect steam cycle concept.

Plant operating and maintenance costs are summarized in Table 5-18.

5.9.2.2 Fuel Cycle Costs

Refuel costs have been provided by BWX Technologies based on reactor operating years, an 18 month refueling interval and 2,500 kg's of uranium per load.

Fuel fabrication facility costs are not included in the cost estimate.

5.9.2.3 Decommissioning Costs

Post-operations and DD&D costs are estimated to be $ 222.5 million in accordance with reference 126.

Decommissioning costs are summarized in Table 5-17.

Table 5-17: Summary of NGNP FOAK Plant Costs, without Operation Costs

WBS	Description	Costs, $Mil	% of Total
C.2	**Design (w/o H_2 plant)**	**1,139.6**	**30.7%**
C.2.22	R&D to Support Design	440.0	11.7%
C.2.32	Conceptual Design	127.4	3.4%
C.2.33	Preliminary Design	238.5	6.3%
C.2.34	Final Design	299.3	7.9%
C.2.41	License & Permit to Construct	34.5	0.9%
C.3	**Construction (w/o H_2 plant)**	**1954.6**	**51.9%**
C.3.42	License & Permit to Operate	87.5	2.3%
C.3.52.PM2	Project Management, Construction	54.0	1.4%
C.3.52.BOP	Overall Site & BOP	515.6	13.87%
C.3.52.NHP	Nuclear Heat Plant	1,012.5	26.9%
C.3.52.PCP	Power Conversion Plant	249.9	6.72%
C.3.52.H2P	Hydrogen Plant	-	-
C.3.62	Environment, Safety & Health	5.9	0.2%
C.3.64	Security	14.9	0.4%
C.3.66	Training	12.2	0.3%
C.3.68	Waste Management	2.3	0.1%
C.4	**Initial Ops & Inspection (w/o H_2 plant)**	**447.2**	**12.0%**
C.4.44	License & Permits to Operate	19.5	0.5%
C.4.62	Environment, Safety & Health	27.9	0.7%
C.4.64	Security	27.9	0.7%
C.4.66	Training	8.1	0.2%
C.4.72	Cold Start-up	23.9	0.6%
C.4.73	Hot Start-up	23.9	0.6%
C.4.74	Operate Plant	38.7	1.0%
C.4.75	Maintain Plant	36.9	1.0%
C.4.76	Shutdowns & Inspections	38.7	1.0%
C.4.77	Refuel	110.7	2.9%
C.4.78	Plant Modifications	49.5	1.3%
C.4.79	Waste Management	41.6	1.1%
C.6	**Post Ops & DD&D (w/o H_2 plant)**	**222.5**	**6.0%**
C.6.01	Program Management	4.5	0.1%
C.6.45	License & Permits to DD&D	9.2	0.2%
C.6.62	Environment, Safety & Health	16.7	0.4%
C.6.64	Security	41.9	1.1%
C.6.66	Training	10.4	0.3%
C.6.92	Plan DD&D Activities	37.8	1.0%
C.6.93	Defueling & Spent Fuel Management	16.2	0.4%
C.6.94	DD&D	45.5	1.2%
C.6.96	Long-Term Monitoring	21.6	0.6%
C.6.98	Waste Management	18.9	0.5%
C	**Total costs (w/o H_2 plant)**	**3,763.8**	
	Contingency	469.5	
C	**Total costs (w/o H_2 plant) w/Contingency**	**4,233.3**	

Table 5-18: NGNP FOAK Operation Costs, per Year (for 40 Year Life, without H_2 plant O&M costs)

WBS	Description	Costs, $Mil / year
C.5	**Operate Commercially**	**75.3**
C.5.11	Operations Management	0.9
C.5.44	Maintain License & Permits	5.8
C.5.62	Environment, Safety & Health	2.1
C.5.64	Security	6.6
C.5.66	Training	1.5
C.5.73	Commissioning & Start-up	6.4
C.5.74	Operate Plant	12.4
C.5.75	Maintain Plant	7.6
C.5.76	Shutdowns & Inspections	2.4
C.5.77	Refuel	22.5
C.5.78	Plant Modifications	4.3
C.5.79	Waste Management	2.9

Table 5-19: Comparison of Plant Costs

		NGNP PCDSR (Ref. 126), $Mil	NGNP indirect steam cycle, $Mil	Delta (%)
C.2	**Design**	**1,139.60**	**1,139.60**	**0**
C.3	**Construction (w/o H_2 plant)**	**1,966.00**	**1954.6**	**-0.6**
C.3.42	License & Permit to Operate	87.5	87.5	0.0
C.3.52.PM2	Project Management, Construction	54	54	0.0
C.3.52.BOP	Overall Site & BOP	540.9	515.6	-4.7
C.3.52.NHP	Nuclear Heat Plant	895.9	1,012.50	13.0
C.3.52.PCP	Power Conversion Plant	352.6	249.9	-29.1
C.3.52.H2P	Hydrogen Plant	-	-	-
C.3.62	Environment, Safety & Health	5.9	5.9	0.0
C.3.64	Security	14.9	14.9	0.0
C.3.66	Training	12.2	12.2	0.0
C.3.68	Waste Management	2.3	2.3	0.0
C.4	**Initial Ops & Inspection (w/o H_2 plant)**	**447.2**	**447.2**	**0.0**
C.6	**Post Ops & DD&D (w/o H_2 plant)**	**222.5**	**222.5**	**0.0**
C	**Total costs (w/o H_2 plant)**	**3,775.20**	**3,763.80**	**-0.3**
	Contingency	470.4	469.5	-0.2
C	**Total costs (w/o H_2 plant) w/Contingency**	**4,245.60**	**4,233.30**	**-0.3**

5.9.3 Cost Estimate Summary/Conclusion

A new configuration has been proposed for the indirect steam cycle concept. This configuration would result in a reduction of total plant costs by 0.3% compared to the CCGT concept studied during the pre-conceptual design phase. It has however to be mentioned that a refined cost estimate would be required to take into account the significant increase of commodity prices observed in the past few months.

It is considered at this stage that O&M cost estimate should not be affected by the change of PCS concept.

6.0 PROPOSED FUTURE STUDIES

The following lists items identified in the context of this work which would need to be further studied.

- Provide an integrated schedule of component testing to verify that the testing of critical components can be made in accordance with 2018 plant start-up
- Perform a detailed assessment of the RPV fabrication issues and a coolant pressure trade study considering circulator feasibility, circulator power, RPV feasibility, and RPV cost.
- Refine the HTS cost estimate to account for 2008 commodity prices

7.0 CONCLUSIONS

This study characterized the advantages and disadvantages and technical risks of the potential alternatives for the intermediate heat exchangers (IHXs) to Power Conversion System (PCS) and H_2 plant, secondary heat transport loop to PCS and Steam Generator Unit.

The tubular IHX concept is the one which is considered as the most robust and mature at the same time. This concept is recommended for the IHX to PCS.

It can be envisioned using a less robust IHX concept for the IHX to H2 plant due to the experimental nature of this loop. Among the compact IHX, the Plate Stamped Heat Exchanger concept is considered as the most promising and is recommended for the 60 MWth test loop of NGNP.

For both concepts, developments tasks and qualification are still needed and the report proposes actions to achieve qualification in due time.

Two-stage IHX concepts have been also studied. The most interesting configuration is the one with tubular IHX concept for the hot stage and a compact IHX concept for the cold stage. In that configuration, the feasibility of the tube bundle is improved compared to one-stage tubular IHX and the compact IHX would operate at lower temperatures which is favorable in terms of lifetime. The compactness is however not improved as compared to the one-stage tubular IHX and overall cost reduction would need to be questionable. So, the interest of the “two-stage” IHX configuration does not appear obvious when taking into account the increased complexity of the concept.

As far as material selection for IHX is concerned, it is considered that Alloy 617 is the material for which the characterization and codification is the most developed and it is recommended to select this material as the reference for IHX development. It is however to be recognized that this material is not necessarily the best in terms of corrosion resistance particularly at very high temperature and R&D actions are proposed to confirm that this material selection. It is in any case recommended to pursue R&D on alternative materials like Haynes 230 with low Co content. This type of material will be used for internal applications where the selection of alloy 617 would not be appropriate due to activation risks. For the longer term (beyond NGNP), ODS or ceramic could provide significant advantage and it is recommended to continue R&D on those materials for IHX application.

The report finally discussed alternatives for the Heat Transport loop configuration, based on the indirect steam cycle concept. The following configuration is proposed:

- Reactor Power: 565 MWth
- Reactor outlet temperature: 900°C
- Reactor inlet temperature: 500°C
- System configuration: H2 and PCS in parallel
- Number of loops: 3 loops
    - 2 with tubular IHXs for PCS (75°C approach temperature)
    - 1 with compact IHX for H2 (25°C approach temperature)
- Steam Generator helium inlet/outlet tempererratures: 825°C/ 415°C
- Primary pressure: 5.0 MPa

The cost estimate developed during the Pre-conceptual design has been updated to account for this new configuration. It is however recommended to refine this cost estimate based on 2008 commodity prices.

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APPENDIX A: HTS OPERATING CONDITION MATRIX FOR THE INDIRECT STEAM CYCLE CONCEPT

	Reactor Power 300 MWTh				
	Primary System Pressure 5 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	13	16	20	26	34
Nb of Pri. Circ. per Loop	1	1	2	2	3
Pri. Circ. Pwr. MWe	13.0	16.0	10.0	13.0	11.3
Total Sec Circ. Pwr - MWe	11	13	17	22	29
Nb of Sec. Circ. per Loop	1	1	1	2	2
Sec. Circ. Pwr. MWe	11.0	13.0	17.0	11.0	14.5
Circ. Pwr. Fraction	18%	21%	27%	36%	47%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1098 C Max. operational fuel temp.	1062 C Max. operational fuel temp.	11027 C Max. operational fuel temp.	992 C Max. operational fuel temp.	958 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	6	7	9	11	14
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	6.0	7.0	9.0	11.0	14.0
Total Sec Circ. Pwr - MWe	14	18	22	27	35
Nb of Sec. Circ. per Loop	1	1	2	2	2
Sec. Circ. Pwr. MWe	14.0	18.0	11.0	13.5	17.5
Circ. Pwr. Fraction	15%	19%	23%	28%	36%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	11181 C Max. operational fuel temp.	1145 C Max. operational fuel temp.	1110 C Max. operational fuel temp.	1075 C Max. operational fuel temp.	1040 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

	Reactor Power 400 MWTh				
	Primary System Pressure 5 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	17	21	27	34	46
Nb of Pri. Circ. per Loop	2	2	2	3	3
Pri. Circ. Pwr. MWe	8.5	10.5	13.5	11.3	15.3
Total Sec Circ. Pwr - MWe	14	18	23	29	39
Nb of Sec. Circ. per Loop	1	1	2	2	2
Sec. Circ. Pwr. MWe	14.0	18.0	11.5	14.5	19.5
Circ. Pwr. Fraction	17%	22%	28%	35%	47%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1125 C Max. operational fuel temp.	1088 C Max. operational fuel temp.	1052 C Max. operational fuel temp.	1017 C Max. operational fuel temp.	982 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	8	9	12	14	19
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	4.0	4.5	6.0	7.0	9.5
Total Sec Circ. Pwr - MWe	19	24	29	37	47
Nb of Sec. Circ. per Loop	1	1	1	1	2
Sec. Circ. Pwr. MWe	9.5	12.0	14.5	18.5	11.8
Circ. Pwr. Fraction	15%	18%	23%	28%	37%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1209 C Max. operational fuel temp.	1172 C Max. operational fuel temp.	1136 C Max. operational fuel temp.	1100 C Max. operational fuel temp.	1065 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

	Reactor Power 500 MWTh				
	Primary System Pressure 5 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	22	27	34	43	57
Nb of Pri. Circ. per Loop	1	1	2	2	2
Pri. Circ. Pwr. MWe	11.0	13.5	8.5	10.8	14.3
Total Sec Circ. Pwr - MWe	18	22	28	37	49
Nb of Sec. Circ. per Loop	1	1	1	1	2
Sec. Circ. Pwr. MWe	9.0	11.0	14.0	18.5	12.3
Circ. Pwr. Fraction	18%	22%	28%	36%	47%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1150 C Max. operational fuel temp.	1113 C Max. operational fuel temp.	1077 C Max. operational fuel temp.	1041 C Max. operational fuel temp.	1006 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	10	12	14	18	23
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	5.0	6.0	7.0	9.0	11.5
Total Sec Circ. Pwr - MWe	24	29	36	46	59
Nb of Sec. Circ. per Loop	1	1	1	2	2
Sec. Circ. Pwr. MWe	12.0	14.5	18.0	11.5	14.8
Circ. Pwr. Fraction	15%	18%	22%	28%	36%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1234 C Max. operational fuel temp.	1197 C Max. operational fuel temp.	1161 C Max. operational fuel temp.	1124 C Max. operational fuel temp.	1089 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

	Reactor Power 600 MWTh				
	Primary System Pressure 5 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	26	32	40	52	69
Nb of Pri. Circ. per Loop	2	2	2	2	3
Pri. Circ. Pwr. MWe	6.5	8.0	10.0	13.0	11.5
Total Sec Circ. Pwr - MWe	22	27	34	44	59
Nb of Sec. Circ. per Loop	1	1	1	2	2
Sec. Circ. Pwr. MWe	11.0	13.5	17.0	11.0	14.8
Circ. Pwr. Fraction	18%	22%	27%	36%	47%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1175 C Max. operational fuel temp.	1138 C Max. operational fuel temp.	1101 C Max. operational fuel temp.	1065 C Max. operational fuel temp.	1029 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	12	14	17	22	28
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	6.0	7.0	8.5	11.0	14.0
Total Sec Circ. Pwr - MWe	29	35	44	55	70
Nb of Sec. Circ. per Loop	1	1	2	2	2
Sec. Circ. Pwr. MWe	14.5	17.5	11.0	13.8	17.5
Circ. Pwr. Fraction	15%	18%	23%	29%	36%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1259 C Max. operational fuel temp.	1222 C Max. operational fuel temp.	1185 C Max. operational fuel temp.	1149 C Max. operational fuel temp.	1113 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

		Reactor Power 300 MWTh					Reactor Power 400 MWTh					Reactor Power 500 MWTh					Reactor Power 600 MWTh				
		Primary System Pressure 5 Mpa					Primary System Pressure 5 Mpa					Primary System Pressure 5 Mpa					Primary System Pressure 5 Mpa				
Reactor Outlet Temperature 850 C	Total Pri. Circ. Pwr. - MWe	5	6	8	9	11	7	8	10	12	15	9	10	13	15	19	10	12	15	18	23
	Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pri. Circ. Pwr. MWe	5.0	6.0	8.0	9.0	11.0	3.5	4.0	5.0	6.0	7.5	4.5	5.0	6.5	7.5	9.5	5.0	6.0	7.5	9.0	11.5
	Total Sec Circ. Pwr - MWe	13	16	19	24	29	17	21	26	31	39	22	26	32	39	49	26	31	38	47	59
	Nb of Sec. Circ. per Loop	1	1	1	2	2	1	1	1	1	1	1	1	1	1	2	1	1	1	2	2
	Sec. Circ. Pwr. MWe	13.0	16.0	19.0	12.0	14.5	8.5	10.5	13.0	15.5	19.5	11.0	13.0	16.0	19.5	12.3	13.0	15.5	19.0	11.8	14.8
	Circ. Pwr. Fraction	13%	16%	20%	24%	30%	13%	16%	20%	24%	30%	14%	16%	20%	24%	30%	13%	16%	20%	24%	30%
	IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
	IHX material	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1265 C Max. operational fuel temp.	1229 C Max. operational fuel temp.	1193 C Max. operational fuel temp.	1157 C Max. operational fuel temp.	1123 C Max. operational fuel temp.	1292 C Max. operational fuel temp.	1255 C Max. operational fuel temp.	1219 C Max. operational fuel temp.	1183 C Max. operational fuel temp.	1148 C Max. operational fuel temp.	1318 C Max. operational fuel temp.	1281 C Max. operational fuel temp.	1244 C Max. operational fuel temp.	1208 C Max. operational fuel temp.	1172 C Max. operational fuel temp.	1343 C Max. operational fuel temp.	1305 C Max. operational fuel temp.	1268 C Max. operational fuel temp.	1232 C Max. operational fuel temp.	1196 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	SG	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp
Reactor Outlet Temperature 900 C	Total Pri. Circ. Pwr. - MWe	5	6	7	8	10	6	7	9	11	13	8	9	11	13	16	9	11	13	16	20
	Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pri. Circ. Pwr. MWe	5.0	6.0	7.0	8.0	10.0	3.0	3.5	4.5	5.5	6.5	4.0	4.5	5.5	6.5	8.0	4.5	5.5	6.5	8.0	10.0
	Total Sec Circ. Pwr - MWe	12	14	17	21	25	16	19	23	27	34	20	24	28	34	42	24	28	34	41	50
	Nb of Sec. Circ. per Loop	1	1	1	2	2	1	1	1	1	1	1	1	1	1	2	1	1	1	2	2
	Sec. Circ. Pwr. MWe	12.0	14.0	17.0	10.5	12.5	8.0	9.5	11.5	13.5	17.0	10.0	12.0	14.0	17.0	10.5	12.0	14.0	17.0	10.3	12.5
	Circ. Pwr. Fraction	13%	15%	18%	21%	26%	12%	14%	18%	21%	26%	12%	15%	17%	21%	26%	12%	14%	17%	21%	26%
	IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
	IHX material	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1349 C Max. operational fuel temp.	1312 C Max. operational fuel temp.	1276 C Max. operational fuel temp.	1240 C Max. operational fuel temp.	1206 C Max. operational fuel temp.	1376 C Max. operational fuel temp.	1339 C Max. operational fuel temp.	1303 C Max. operational fuel temp.	1267 C Max. operational fuel temp.	1231 C Max. operational fuel temp.	1402 C Max. operational fuel temp.	1365 C Max. operational fuel temp.	1327 C Max. operational fuel temp.	1291 C Max. operational fuel temp.	1255 C Max. operational fuel temp.	1427 C Max. operational fuel temp.	1390 C Max. operational fuel temp.	1352 C Max. operational fuel temp.	1315 C Max. operational fuel temp.	1279 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	SG	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp

Reactor Outlet Temperature 950 C

	Reactor Power 300 MWTh					Reactor Power 400 MWTh					Reactor Power 500 MWTh					Reactor Power 600 MWTh				
	Primary System Pressure 5 Mpa					Primary System Pressure 5 Mpa					Primary System Pressure 5 Mpa					Primary System Pressure 5 Mpa				
Total Pri. Circ. Pwr. - MWe	4	5	6	7	9	6	7	8	10	11	7	9	10	12	14	9	10	12	14	17
Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Pri. Circ. Pwr. MWe	4.0	5.0	6.0	7.0	9.0	3.0	3.5	4.0	5.0	5.5	3.5	4.5	5.0	6.0	7.0	4.5	5.0	6.0	7.0	8.5
Total Sec Circ. Pwr - MWe	11	13	15	18	22	14	17	20	24	29	18	21	26	30	37	22	26	31	37	44
Nb of Sec. Circ. per Loop	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
Sec. Circ. Pwr. MWe	11.0	13.0	15.0	18.0	11.0	7.0	8.5	10.0	12.0	14.5	9.0	10.5	13.0	15.0	18.5	11.0	13.0	15.5	18.5	11.0
Circ. Pwr. Fraction	11%	13%	16%	19%	23%	11%	13%	16%	19%	22%	11%	13%	16%	19%	23%	11%	13%	16%	19%	23%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1432 C Max. operational fuel temp.	1395 C Max. operational fuel temp.	1359 C Max. operational fuel temp.	1323 C Max. operational fuel temp.	1289 C Max. operational fuel temp.	1460 C Max. operational fuel temp.	1423 C Max. operational fuel temp.	1386 C Max. operational fuel temp.	1350 C Max. operational fuel temp.	1314 C Max. operational fuel temp.	1487 C Max. operational fuel temp.	1449 C Max. operational fuel temp.	1412 C Max. operational fuel temp.	1374 C Max. operational fuel temp.	1339 C Max. operational fuel temp.	1512 C Max. operational fuel temp.	1474 C Max. operational fuel temp.	1436 C Max. operational fuel temp.	1399 C Max. operational fuel temp.	1363C Max. operational fuel temp.
Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

Reactor Power 300 MWTh						
	Primary System Pressure 7 Mpa					
	Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C	Total Pri. Circ. Pwr. - MWe	9	11	14	18	25
	Nb of Pri. Circ. per Loop	1	1	1	2	2
	Pri. Circ. Pwr. MWe	9.0	11.0	14.0	9.0	12.5
	Total Sec Circ. Pwr - MWe	8	10	12	16	22
	Nb of Sec. Circ. per Loop	1	1	1	1	2
	Sec. Circ. Pwr. MWe	8.0	10.0	12.0	16.0	11.0
	Circ. Pwr. Fraction	13%	16%	19%	25%	35%
	IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
	IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1098 C Max. operational fuel temp.	1062 C Max. operational fuel temp.	11027 C Max. operational fuel temp.	992 C Max. operational fuel temp.	958 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1
	SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C	Total Pri. Circ. Pwr. - MWe	4	5	6	8	10
	Nb of Pri. Circ. per Loop	1	1	1	1	1
	Pri. Circ. Pwr. MWe	4.0	5.0	6.0	8.0	10.0
	Total Sec Circ. Pwr - MWe	11	13	16	20	26
	Nb of Sec. Circ. per Loop	1	1	1	1	2
	Sec. Circ. Pwr. MWe	11.0	13.0	16.0	20.0	13.0
	Circ. Pwr. Fraction	11%	13%	16%	21%	27%
	IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
	IHX material	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	11181 C Max. operational fuel temp.	1145 C Max. operational fuel temp.	1110 C Max. operational fuel temp.	1075 C Max. operational fuel temp.	1040 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1
	SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

Reactor Power 400 MWTh						
	Primary System Pressure 7 Mpa					
	Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C	Total Pri. Circ. Pwr. - MWe	12	15	19	25	33
	Nb of Pri. Circ. per Loop	1	1	2	2	3
	Pri. Circ. Pwr. MWe	12.0	15.0	9.5	12.5	11.0
	Total Sec Circ. Pwr - MWe	11	13	17	21	29
	Nb of Sec. Circ. per Loop	1	1	1	2	2
	Sec. Circ. Pwr. MWe	11.0	13.0	17.0	10.5	14.5
	Circ. Pwr. Fraction	13%	16%	20%	26%	34%
	IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
	IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1125 C Max. operational fuel temp.	1088 C Max. operational fuel temp.	1052 C Max. operational fuel temp.	1017 C Max. operational fuel temp.	982 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1
	SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C	Total Pri. Circ. Pwr. - MWe	5	7	8	10	13
	Nb of Pri. Circ. per Loop	1	1	1	1	1
	Pri. Circ. Pwr. MWe	2.5	3.5	4.0	5.0	6.5
	Total Sec Circ. Pwr - MWe	14	17	21	27	34
	Nb of Sec. Circ. per Loop	1	1	1	1	1
	Sec. Circ. Pwr. MWe	7.0	8.5	10.5	13.5	17.0
	Circ. Pwr. Fraction	11%	13%	16%	21%	26%
	IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
	IHX material	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1209 C Max. operational fuel temp.	1172 C Max. operational fuel temp.	1136 C Max. operational fuel temp.	1100 C Max. operational fuel temp.	1065 C Max. operational fuel temp.
	Nb of loop	2	2	2	2	2
	SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

Reactor Power 500 MWTh						
	Primary System Pressure 7 Mpa					
	Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C	Total Pri. Circ. Pwr. - MWe	15	19	24	31	41
	Nb of Pri. Circ. per Loop	1	1	1	1	2
	Pri. Circ. Pwr. MWe	7.5	9.5	12.0	15.5	10.3
	Total Sec Circ. Pwr - MWe	13	16	21	27	36
	Nb of Sec. Circ. per Loop	1	1	1	1	1
	Sec. Circ. Pwr. MWe	6.5	8.0	10.5	13.5	18.0
	Circ. Pwr. Fraction	12%	16%	20%	26%	34%
	IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
	IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1150 C Max. operational fuel temp.	1113 C Max. operational fuel temp.	1077 C Max. operational fuel temp.	1041 C Max. operational fuel temp.	1006 C Max. operational fuel temp.
	Nb of loop	2	2	2	2	2
	SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C	Total Pri. Circ. Pwr. - MWe	7	8	10	13	16
	Nb of Pri. Circ. per Loop	1	1	1	1	1
	Pri. Circ. Pwr. MWe	3.5	4.0	5.0	6.5	8.0
	Total Sec Circ. Pwr - MWe	18	22	27	34	43
	Nb of Sec. Circ. per Loop	1	1	1	1	2
	Sec. Circ. Pwr. MWe	9.0	11.0	13.5	17.0	10.8
	Circ. Pwr. Fraction	11%	13%	16%	21%	26%
	IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
	IHX material	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1234 C Max. operational fuel temp.	1197 C Max. operational fuel temp.	1161 C Max. operational fuel temp.	1124 C Max. operational fuel temp.	1089 C Max. operational fuel temp.
	Nb of loop	2	2	2	2	2
	SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

Reactor Power 600 MWTh						
	Primary System Pressure 7 Mpa					
	Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C	Total Pri. Circ. Pwr. - MWe	19	23	29	37	49
	Nb of Pri. Circ. per Loop	1	1	2	2	2
	Pri. Circ. Pwr. MWe	9.5	11.5	7.3	9.3	12.3
	Total Sec Circ. Pwr - MWe	16	20	25	32	43
	Nb of Sec. Circ. per Loop	1	1	1	1	2
	Sec. Circ. Pwr. MWe	8.0	10.0	12.5	16.0	10.8
	Circ. Pwr. Fraction	13%	16%	20%	26%	34%
	IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
	IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1175 C Max. operational fuel temp.	1138 C Max. operational fuel temp.	1101 C Max. operational fuel temp.	1065 C Max. operational fuel temp.	1029 C Max. operational fuel temp.
	Nb of loop	2	2	2	2	2
	SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C	Total Pri. Circ. Pwr. - MWe	8	10	12	15	20
	Nb of Pri. Circ. per Loop	1	1	1	1	1
	Pri. Circ. Pwr. MWe	4.0	5.0	6.0	7.5	10.0
	Total Sec Circ. Pwr - MWe	21	26	32	40	52
	Nb of Sec. Circ. per Loop	1	1	1	2	2
	Sec. Circ. Pwr. MWe	10.5	13.0	16.0	10.0	13.0
	Circ. Pwr. Fraction	11%	13%	16%	20%	27%
	IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
	IHX material	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1259 C Max. operational fuel temp.	1222 C Max. operational fuel temp.	1185 C Max. operational fuel temp.	1149 C Max. operational fuel temp.	1113 C Max. operational fuel temp.
	Nb of loop	2	2	2	2	2
	SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

		Reactor Power 300 MWTh					Reactor Power 400 MWTh					Reactor Power 500 MWTh					Reactor Power 600 MWTh				
		Primary System Pressure 7 Mpa					Primary System Pressure 7 Mpa					Primary System Pressure 7 Mpa					Primary System Pressure 7 Mpa				
Reactor Outlet Temperature 850 C	Total Pri. Circ. Pwr. - MWe	4	4	5	7	8	5	6	7	9	11	6	7	9	11	14	7	9	11	13	16
	Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pri. Circ. Pwr. MWe	4.0	4.0	5.0	7.0	8.0	2.5	3.0	3.5	4.5	5.5	3.0	3.5	4.5	5.5	7.0	3.5	4.5	5.5	6.5	8.0
	Total Sec Circ. Pwr - MWe	10	12	14	17	22	13	15	19	23	29	16	19	23	29	36	19	23	28	35	43
	Nb of Sec. Circ. per Loop	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
	Sec. Circ. Pwr. MWe	10.0	12.0	14.0	17.0	11.0	6.5	7.5	9.5	11.5	14.5	8.0	9.5	11.5	14.5	18.0	9.5	11.5	14.0	17.5	10.8
	Circ. Pwr. Fraction	10%	12%	14%	18%	22%	10%	12%	14%	18%	22%	10%	12%	14%	18%	22%	10%	12%	14%	18%	22%
	IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
	IHX material	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1265 C Max. operational fuel temp.	1229 C Max. operational fuel temp.	1193 C Max. operational fuel temp.	1157 C Max. operational fuel temp.	1123 C Max. operational fuel temp.	1292 C Max. operational fuel temp.	1255 C Max. operational fuel temp.	1219 C Max. operational fuel temp.	1183 C Max. operational fuel temp.	1148 C Max. operational fuel temp.	1318 C Max. operational fuel temp.	1281 C Max. operational fuel temp.	1244 C Max. operational fuel temp.	1208 C Max. operational fuel temp.	1172 C Max. operational fuel temp.	1343 C Max. operational fuel temp.	1305 C Max. operational fuel temp.	1268 C Max. operational fuel temp.	1232 C Max. operational fuel temp.	1196 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	SG	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp
Reactor Outlet Temperature 900 C	Total Pri. Circ. Pwr. - MWe	3	4	5	6	7	4	5	6	8	9	6	7	8	10	12	7	8	10	12	14
	Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pri. Circ. Pwr. MWe	3.0	4.0	5.0	6.0	7.0	2.0	2.5	3.0	4.0	4.5	3.0	3.5	4.0	5.0	6.0	3.5	4.0	5.0	6.0	7.0
	Total Sec Circ. Pwr - MWe	9	10	12	15	18	12	14	17	20	25	14	17	21	25	31	17	21	25	30	37
	Nb of Sec. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Sec. Circ. Pwr. MWe	9.0	10.0	12.0	15.0	18.0	6.0	7.0	8.5	10.0	12.5	7.0	8.5	10.5	12.5	15.5	8.5	10.5	12.5	15.0	18.5
	Circ. Pwr. Fraction	9%	10%	13%	16%	19%	9%	11%	13%	16%	19%	9%	11%	13%	16%	19%	9%	11%	13%	16%	19%
	IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
	IHX material	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1349 C Max. operational fuel temp.	1312 C Max. operational fuel temp.	1276 C Max. operational fuel temp.	1240 C Max. operational fuel temp.	1206 C Max. operational fuel temp.	1376 C Max. operational fuel temp.	1339 C Max. operational fuel temp.	1303 C Max. operational fuel temp.	1267 C Max. operational fuel temp.	1231 C Max. operational fuel temp.	1402 C Max. operational fuel temp.	1365 C Max. operational fuel temp.	1327 C Max. operational fuel temp.	1291 C Max. operational fuel temp.	1255 C Max. operational fuel temp.	1427 C Max. operational fuel temp.	1390 C Max. operational fuel temp.	1352 C Max. operational fuel temp.	1315 C Max. operational fuel temp.	1279 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	SG	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp

Reactor Outlet Temperature 950 C

Reactor Power 300 MWTh	Primary System Pressure 7 Mpa				
Total Pri. Circ. Pwr. - MWe	3	4	4	5	6
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	3.0	4.0	4.0	5.0	6.0
Total Sec Circ. Pwr - MWe	8	9	11	13	16
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	8.0	9.0	11.0	13.0	16.0
Circ. Pwr. Fraction	8%	10%	11%	13%	16%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1432 C Max. operational fuel temp.	1395 C Max. operational fuel temp.	1359 C Max. operational fuel temp.	1323 C Max. operational fuel temp.	1289 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

Reactor Power 400 MWTh	Primary System Pressure 7 Mpa				
Total Pri. Circ. Pwr. - MWe	4	5	6	7	8
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.0	2.5	3.0	3.5	4.0
Total Sec Circ. Pwr - MWe	11	13	15	18	22
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	5.5	6.5	7.5	9.0	11.0
Circ. Pwr. Fraction	8%	10%	12%	14%	17%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1460 C Max. operational fuel temp.	1423 C Max. operational fuel temp.	1386 C Max. operational fuel temp.	1350 C Max. operational fuel temp.	1314 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

Reactor Power 500 MWTh	Primary System Pressure 7 Mpa				
Total Pri. Circ. Pwr. - MWe	5	6	7	9	10
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.5	3.0	3.5	4.5	5.0
Total Sec Circ. Pwr - MWe	13	16	19	22	27
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	6.5	8.0	9.5	11.0	13.5
Circ. Pwr. Fraction	8%	10%	12%	14%	16%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1487 C Max. operational fuel temp.	1449 C Max. operational fuel temp.	1412 C Max. operational fuel temp.	1374 C Max. operational fuel temp.	1339 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

Reactor Power 600 MWTh	Primary System Pressure 7 Mpa				
Total Pri. Circ. Pwr. - MWe	6	7	9	10	12
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	3.0	3.5	4.5	5.0	6.0
Total Sec Circ. Pwr - MWe	16	19	22	27	32
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	8.0	9.5	11.0	13.5	16.0
Circ. Pwr. Fraction	8%	10%	11%	14%	16%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1512 C Max. operational fuel temp.	1474 C Max. operational fuel temp.	1436 C Max. operational fuel temp.	1399 C Max. operational fuel temp.	1363C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

	Reactor Power 300 MWTh				
	Primary System Pressure 9 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	7	9	11	14	19
Nb of Pri. Circ. per Loop	1	1	1	1	2
Pri. Circ. Pwr. MWe	7.0	9.0	11.0	14.0	9.5
Total Sec Circ. Pwr - MWe	6	8	10	13	17
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	6.0	8.0	10.0	13.0	17.0
Circ. Pwr. Fraction	10%	13%	16%	20%	27%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1098 C Max. operational fuel temp.	1062 C Max. operational fuel temp.	11027 C Max. operational fuel temp.	992 C Max. operational fuel temp.	958 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	3	4	5	6	8
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	3.0	4.0	5.0	6.0	8.0
Total Sec Circ. Pwr - MWe	8	10	13	16	20
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	8.0	10.0	13.0	16.0	20.0
Circ. Pwr. Fraction	8%	10%	13%	16%	21%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	11181 C Max. operational fuel temp.	1145 C Max. operational fuel temp.	1110 C Max. operational fuel temp.	1075 C Max. operational fuel temp.	1040 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

	Reactor Power 400 MWTh				
	Primary System Pressure 9 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	10	12	15	19	25
Nb of Pri. Circ. per Loop	1	1	1	2	2
Pri. Circ. Pwr. MWe	10.0	12.0	15.0	9.5	12.5
Total Sec Circ. Pwr - MWe	8	10	13	17	23
Nb of Sec. Circ. per Loop	1	1	1	1	2
Sec. Circ. Pwr. MWe	8.0	10.0	13.0	17.0	11.5
Circ. Pwr. Fraction	10%	12%	16%	20%	27%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1125 C Max. operational fuel temp.	1088 C Max. operational fuel temp.	1052 C Max. operational fuel temp.	1017 C Max. operational fuel temp.	982 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	4	5	6	8	10
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.0	2.5	3.0	4.0	5.0
Total Sec Circ. Pwr - MWe	11	14	17	21	27
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	5.5	7.0	8.5	10.5	13.5
Circ. Pwr. Fraction	8%	11%	13%	16%	21%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1209 C Max. operational fuel temp.	1172 C Max. operational fuel temp.	1136 C Max. operational fuel temp.	1100 C Max. operational fuel temp.	1065 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

	Reactor Power 500 MWTh				
	Primary System Pressure 9 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	12	15	19	24	32
Nb of Pri. Circ. per Loop	1	1	1	1	2
Pri. Circ. Pwr. MWe	6.0	7.5	9.5	12.0	8.0
Total Sec Circ. Pwr - MWe	10	13	16	21	28
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	5.0	6.5	8.0	10.5	14.0
Circ. Pwr. Fraction	10%	12%	16%	20%	27%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1150 C Max. operational fuel temp.	1113 C Max. operational fuel temp.	1077 C Max. operational fuel temp.	1041 C Max. operational fuel temp.	1006 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	5	7	8	10	13
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.5	3.5	4.0	5.0	6.5
Total Sec Circ. Pwr - MWe	14	17	21	26	34
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	7.0	8.5	10.5	13.0	17.0
Circ. Pwr. Fraction	8%	11%	13%	16%	21%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1234 C Max. operational fuel temp.	1197 C Max. operational fuel temp.	1161 C Max. operational fuel temp.	1124 C Max. operational fuel temp.	1089 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

	Reactor Power 600 MWTh				
	Primary System Pressure 9 Mpa				
Reactor Inlet Temp	350 C	400 C	450 C	500 C	550 C
Reactor Outlet Temperature 750 C					
Total Pri. Circ. Pwr. - MWe	14	18	22	29	38
Nb of Pri. Circ. per Loop	1	1	1	1	2
Pri. Circ. Pwr. MWe	7.0	9.0	11.0	14.5	9.5
Total Sec Circ. Pwr - MWe	13	16	20	25	34
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	6.5	8.0	10.0	12.5	17.0
Circ. Pwr. Fraction	10%	13%	16%	20%	27%
IHX concept	Compact IHX	Compact IHX	Compact IHX	Compact IHX	Compact IHX
IHX material	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H	In 625 or Alloy 800H
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1175 C Max. operational fuel temp.	1138 C Max. operational fuel temp.	1101 C Max. operational fuel temp.	1065 C Max. operational fuel temp.	1029 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.	700 C Inlet Temp. May impact SG sizing and reheat capability.
Reactor Outlet Temperature 800 C					
Total Pri. Circ. Pwr. - MWe	6	8	10	12	15
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	3.0	4.0	5.0	6.0	7.5
Total Sec Circ. Pwr - MWe	17	20	25	32	41
Nb of Sec. Circ. per Loop	1	1	1	1	2
Sec. Circ. Pwr. MWe	8.5	10.0	12.5	16.0	10.3
Circ. Pwr. Fraction	9%	10%	13%	16%	21%
IHX concept	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start	Tubular IHX - Compact may be possible but could impact 2018 start
IHX material	In 617	In 617	In 617	In 617	In 617
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1259 C Max. operational fuel temp.	1222 C Max. operational fuel temp.	1185 C Max. operational fuel temp.	1149 C Max. operational fuel temp.	1113 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

		Reactor Power 300 MWTh					Reactor Power 400 MWTh					Reactor Power 500 MWTh					Reactor Power 600 MWTh				
		Primary System Pressure 9 Mpa					Primary System Pressure 9 Mpa					Primary System Pressure 9 Mpa					Primary System Pressure 9 Mpa				
Reactor Outlet Temperature 850 C	Total Pri. Circ. Pwr. - MWe	3	3	4	5	6	4	5	6	7	9	5	6	7	9	11	6	7	8	10	13
	Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pri. Circ. Pwr. MWe	3.0	3.0	4.0	5.0	6.0	2.0	2.5	3.0	3.5	4.5	2.5	3.0	3.5	4.5	5.5	3.0	3.5	4.0	5.0	6.5
	Total Sec Circ. Pwr - MWe	8	9	11	14	17	10	12	15	18	23	13	15	18	23	28	15	18	22	27	34
	Nb of Sec. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Sec. Circ. Pwr. MWe	8.0	9.0	11.0	14.0	17.0	5.0	6.0	7.5	9.0	11.5	6.5	7.5	9.0	11.5	14.0	7.5	9.0	11.0	13.5	17.0
	Circ. Pwr. Fraction	8%	9%	11%	14%	17%	8%	9%	12%	14%	18%	8%	9%	11%	14%	17%	8%	9%	11%	14%	17%
	IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
	IHX material	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1265 C Max. operational fuel temp.	1229 C Max. operational fuel temp.	1193 C Max. operational fuel temp.	1157 C Max. operational fuel temp.	1123 C Max. operational fuel temp.	1292 C Max. operational fuel temp.	1255 C Max. operational fuel temp.	1219 C Max. operational fuel temp.	1183 C Max. operational fuel temp.	1148 C Max. operational fuel temp.	1318 C Max. operational fuel temp.	1281 C Max. operational fuel temp.	1244 C Max. operational fuel temp.	1208 C Max. operational fuel temp.	1172 C Max. operational fuel temp.	1343 C Max. operational fuel temp.	1305 C Max. operational fuel temp.	1268 C Max. operational fuel temp.	1232 C Max. operational fuel temp.	1196 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	SG	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp	800 C Inlet Temp
Reactor Outlet Temperature 900 C	Total Pri. Circ. Pwr. - MWe	3	3	4	4	5	4	4	5	6	7	4	5	6	7	9	5	6	7	9	11
	Nb of Pri. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pri. Circ. Pwr. MWe	3.0	3.0	4.0	4.0	5.0	2.0	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5	4.5	2.5	3.0	3.5	4.5	5.5
	Total Sec Circ. Pwr - MWe	7	8	10	12	15	9	11	13	16	19	11	14	16	20	24	14	16	20	24	29
	Nb of Sec. Circ. per Loop	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Sec. Circ. Pwr. MWe	7.0	8.0	10.0	12.0	15.0	4.5	5.5	6.5	8.0	9.5	5.5	7.0	8.0	10.0	12.0	7.0	8.0	10.0	12.0	14.5
	Circ. Pwr. Fraction	7%	8%	10%	12%	15%	7%	8%	10%	12%	14%	7%	8%	10%	12%	15%	7%	8%	10%	12%	15%
	IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
	IHX material	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617	In 617
	RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
	Fuel	1349 C Max. operational fuel temp.	1312 C Max. operational fuel temp.	1276 C Max. operational fuel temp.	1240 C Max. operational fuel temp.	1206 C Max. operational fuel temp.	1376 C Max. operational fuel temp.	1339 C Max. operational fuel temp.	1303 C Max. operational fuel temp.	1267 C Max. operational fuel temp.	1231 C Max. operational fuel temp.	1402 C Max. operational fuel temp.	1365 C Max. operational fuel temp.	1327 C Max. operational fuel temp.	1291 C Max. operational fuel temp.	1255 C Max. operational fuel temp.	1427 C Max. operational fuel temp.	1390 C Max. operational fuel temp.	1352 C Max. operational fuel temp.	1315 C Max. operational fuel temp.	1279 C Max. operational fuel temp.
	Nb of loop	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	SG	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp	850 C Inlet Temp

Reactor Outlet Temperature 950 C

	Reactor Power 300 MWTh				
	Primary System Pressure 9 Mpa				
Total Pri. Circ. Pwr. - MWe	2	3	3	4	5
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.0	3.0	3.0	4.0	5.0
Total Sec Circ. Pwr - MWe	6	7	9	11	13
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	6.0	7.0	9.0	11.0	13.0
Circ. Pwr. Fraction	6%	7%	9%	11%	13%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1432 C Max. operational fuel temp.	1395 C Max. operational fuel temp.	1359 C Max. operational fuel temp.	1323 C Max. operational fuel temp.	1289 C Max. operational fuel temp.
Nb of loop	1	1	1	1	1
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

	Reactor Power 400 MWTh				
	Primary System Pressure 9 Mpa				
Total Pri. Circ. Pwr. - MWe	3	4	4	5	6
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	1.5	2.0	2.0	2.5	3.0
Total Sec Circ. Pwr - MWe	8	10	12	14	17
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	4.0	5.0	6.0	7.0	8.5
Circ. Pwr. Fraction	6%	8%	9%	11%	13%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1460 C Max. operational fuel temp.	1423 C Max. operational fuel temp.	1386 C Max. operational fuel temp.	1350 C Max. operational fuel temp.	1314 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

	Reactor Power 500 MWTh				
	Primary System Pressure 9 Mpa				
Total Pri. Circ. Pwr. - MWe	4	5	6	7	8
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.0	2.5	3.0	3.5	4.0
Total Sec Circ. Pwr - MWe	10	12	15	18	21
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	5.0	6.0	7.5	9.0	10.5
Circ. Pwr. Fraction	6%	8%	9%	11%	13%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1487 C Max. operational fuel temp.	1449 C Max. operational fuel temp.	1412 C Max. operational fuel temp.	1374 C Max. operational fuel temp.	1339 C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

	Reactor Power 600 MWTh				
	Primary System Pressure 9 Mpa				
Total Pri. Circ. Pwr. - MWe	5	6	7	8	10
Nb of Pri. Circ. per Loop	1	1	1	1	1
Pri. Circ. Pwr. MWe	2.5	3.0	3.5	4.0	5.0
Total Sec Circ. Pwr - MWe	13	15	18	21	26
Nb of Sec. Circ. per Loop	1	1	1	1	1
Sec. Circ. Pwr. MWe	6.5	7.5	9.0	10.5	13.0
Circ. Pwr. Fraction	7%	8%	9%	11%	13%
IHX concept	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX	Tubular IHX
IHX material	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic	In 671, ODS or Ceramic
RPV material	SA 508	SA 508	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection	mod 9 Cr or SA 508 with cooling system or thermal protection
Fuel	1512 C Max. operational fuel temp.	1474 C Max. operational fuel temp.	1436 C Max. operational fuel temp.	1399 C Max. operational fuel temp.	1363C Max. operational fuel temp.
Nb of loop	2	2	2	2	2
SG	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp	900 C Inlet Temp

APPENDIX B: HTS OPERATING CONDITION MATRIX FOR THE DIRECT STEAM CYCLE CONCEPT

Reactor Power 300 MWTh (Reactor Outlet Temperature 750 C)

Primary Sys.Press.	5 MPA	7 MPa	9MPA
Reactor Inlet Temp	350 C	350 C	350 C
Total Pri. Circ. Pwr. - MWe	6	5	4
Nb of Pri. Circ. per Loop	1	1	1
Pri. Circ. Pwr. MWe	6.0	5.0	4.0
Total Sec Circ. Pwr - MWe			
Nb of Sec. Circ. per Loop			
Sec. Circ. Pwr. MWe			
Circ. Pwr. Fraction	4%	4%	3%
IHX concept			
IHX material			
RPV material	SA 508	SA 508	SA 508
Fuel	1098 C Max. operational fuel temp.	1098 C Max. operational fuel temp.	1098 C Max. operational fuel temp.
Nb of loop	1	1	1
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

Reactor Power 400 MWTh (Reactor Outlet Temperature 750 C)

Primary Sys.Press.	5 MPA	7 MPa	9MPA
Reactor Inlet Temp	350 C	350 C	350 C
Total Pri. Circ. Pwr. - MWe	9	6	5
Nb of Pri. Circ. per Loop	1	1	1
Pri. Circ. Pwr. MWe	9.0	6.0	5.0
Total Sec Circ. Pwr - MWe			
Nb of Sec. Circ. per Loop			
Sec. Circ. Pwr. MWe			
Circ. Pwr. Fraction	5%	3%	3%
IHX concept			
IHX material			
RPV material	SA 508	SA 508	SA 508
Fuel	1125 C Max. operational fuel temp.	1125 C Max. operational fuel temp.	1125 C Max. operational fuel temp.
Nb of loop	1	1	1
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

Reactor Power 500 MWTh (Reactor Outlet Temperature 750 C)

Primary Sys.Press.	5 MPA	7 MPa	9MPA
Reactor Inlet Temp	350 C	350 C	350 C
Total Pri. Circ. Pwr. - MWe	11	8	6
Nb of Pri. Circ. per Loop	1	1	1
Pri. Circ. Pwr. MWe	5.5	4.0	3.0
Total Sec Circ. Pwr - MWe			
Nb of Sec. Circ. per Loop			
Sec. Circ. Pwr. MWe			
Circ. Pwr. Fraction	5%	4%	3%
IHX concept			
IHX material			
RPV material	SA 508	SA 508	SA 508
Fuel	1150 C Max. operational fuel temp.	1150 C Max. operational fuel temp.	1150 C Max. operational fuel temp.
Nb of loop	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp

Reactor Power 600 MWTh (Reactor Outlet Temperature 750 C)

Primary Sys.Press.	5 MPA	7 MPa	9MPA
Reactor Inlet Temp	350 C	350 C	350 C
Total Pri. Circ. Pwr. - MWe	13	9	7
Nb of Pri. Circ. per Loop	1	1	1
Pri. Circ. Pwr. MWe	6.5	4.5	3.5
Total Sec Circ. Pwr - MWe			
Nb of Sec. Circ. per Loop			
Sec. Circ. Pwr. MWe			
Circ. Pwr. Fraction	5%	3%	3%
IHX concept			
IHX material			
RPV material	SA 508	SA 508	SA 508
Fuel	1175 C Max. operational fuel temp.	1175 C Max. operational fuel temp.	1175 C Max. operational fuel temp.
Nb of loop	2	2	2
SG	750 C Inlet Temp	750 C Inlet Temp	750 C Inlet Temp