AREVA NP Inc.,

an AREVA and Siemens company

Technical Data Record

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ASME/DOE Gen IV Task 7 Part 1
Review of Current Experience on Intermediate Heat Exchanger (IHX)

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AREVA NP Inc.,
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Safety Related? ☐ YES ☒ NO

Does this document contain assumptions requiring verification? ☐ YES ☒ NO

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Record of Revision

Revision No.	Date	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
000	12-04-2008	All	Original document
001	04-23-2009	Section 1.0	Added acronym for THCHE "Tubular Helical Coil Heat Exchanger". Reworded the last paragraph.
		Section heading 3.1	Title changed to "Tubular Helical Coil Heat Exchanger (THCHE)"
		Section 3.1	Reworded the 2nd paragraph.
		Section 3.1.1	Changed title of Section heading
		Table 3-1	Changed title to "Parameters of KVK Tubular IHX"
		Table 3-2	Changed title to "HTTR Tubular IHX Parameters". Changed the column heading from "Vertical helically coiled counter flow type" to "Vertical helical coil counter flow type"
		Section 3.2	Change "IHX" to "HX" in the 2nd and 3rd sentences. Added "Conventional" to the 2nd sentence. Changed "impure" to "pure or impure" in the 4th sentence.
		Section 3.2.1	Added "Plate Stamped Heat Exchanger" to the 1st sentence.
		Figure 3.2-1	Updated Figure
		Section 3.2.2	Changed "plate type IHX" to "Plate Machined Heat Exchanger" in the 1st sentence.
		Figure 3.2-2	Updated Figure
		Section 3.2.3	Added "Plate Fin Heat Exchanger" to the 1st sentence. Reworded last sentence.
		Figure 3.2-3	Updated Figure
		Section 3.2.4	Added Section 3.2.4
		Figure 3.2-4	Added Figure 3.2.4
		Section 4.0	Added sentence "In service inspection is discussed in Part II of Task 7." the first paragraph.
		Section heading 4.1	Title changed to "Tubular Helical Coil Heat Exchanger maturity"
		Section 4.1.1	Changed first sentence in this Section. Changed the 1st, 3rd, and 4th bulleted statements in this section.
		Section 4.1.1	In the 3rd bullet under the Thermo-Mechanical Issues section , "(about 350^o - 500 ^{o}C depending on concept) but, dependant upon design, may have to" was "(about 350^{o}C) but it has to"
		Section 4.1.1	The second sentence under Subsection Material Degradation changed to "… is very pure helium gas …" from "… is inert helium gas …" . The following sentence was added to the second paragraph "Additional discussion

Revision No.	Date	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
			of this topic is provided in Section 4.2.1 under Subsection Material Issues.”.
		Section 4.1.2	Subsection Forging of the hot header: Reworded the 5th sentence. Subsection Welding: Reworded the first sentence.
		Section 4.1.3	Revised the 1st sentence. Changed subheading from “HTTR/HENDEL” to “JAERI HTTR”.
		Section 4.1.4	In 1st sentence, changed “proof” to “confidence”
		Section 4.2.1	“…for a roughly 7.5 MWth IHX as anticipated by AREVA for the 60 MWth 850°-950°C NGNP side loop),” was “…the 60 MWth IHX),”; Added “A protective coating may also help reduce diffusion of tritium from the primary to secondary coolants” to the third paragraph below “Material Issues”. Added two paragraphs to the end of this Section.
		Section 4.2.2	Changed the last sentence to, “60 MWth modular IHX” from “60 MWth IHX”.
		Section 4.2.3	In the 1st sentence changed “PWR,” to “power,”
		Section 4.4.1	Added to the last sentence of the 2nd paragraph “per unit volume”. In the 1st sentence of the 3rd paragraph “coolant” was “impure helium” and added “and coating techniques” to the end of the sentence.
		Section 4.4.2	In the 2nd sentence of the 1st paragraph “bonding” was “welding”
		Section 6.1.1	In subsection AREVA, changed “950˚C” to “900˚C” in the 2nd sentence.
		Section 6.1.2	Added paragraph on alloy 617b. Added a sentence to the end of the third paragraph of this Section. Reworded the sixth paragraph. Added Figure 6.1-1
		Table 6-1	Deleted lower limit of Al for Alloy 230
		Section 6.2.1	Last sentence of 1st paragraph, “Section III,” was “Section II”. Last sentence of 2nd paragraph, … of a significantly reduced …” was “… of a reduced …”.
		Section 6.2.2	Last sentence of 1st paragraph, “… , at higher temperatures, or longer allowable component life.” was “or at higher temperatures.”
		Section 6.3	Last sentence of the 1st paragraph “Part II of this Task.” Was “a later document”
		Section 6.3.3	Added sentence 2 to the 2nd paragraph.
		Section 6.3.6	Reworded last sentence
		Section 7.0	“helical coil shell and tube IHX” changed to “THCHE”. In the next to last sentence of the 1st paragraph, “The challenges of the compact” was “The sections of compact

Revision No.	Date	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
			IHXs”
		Section 8.0	Added References 22 and 23
		Appendix B	Added Appendix B (acronyms)
		Appendix C	Added Appendix C
		ALL	Changed Figure numbering format. Minor grammatical corrections were made throughout the document.

Table of Contents

Page

Table of Contents
(continued)

Page

Table of Contents
(continued)

List of Tables

Page

List of Figures

Page

1.0 PURPOSE

The purpose of the ASME/DOE Gen IV Task 7 Part I is to review the current experience on various high temperature reactor intermediate heat exchanger (IHX) concepts. There are several different IHX concepts that could be envisioned for HTR/VHTR applications in a range of temperature from 850C to 950C. The concepts that will be primarily discussed herein are:

- Tubular Helical Coil Heat Exchanger (THCHE)
- Plate-Stamped Heat Exchanger (PSHE)
- Plate-Fin Heat Exchanger (PFHE)
- Plate-Machined Heat Exchanger (PMHE).

The primary coolant of the NGNP is potentially subject to radioactive contamination by the core as well as contamination from the secondary loop fluid. To isolate the radioactivity to minimize radiation doses to personnel, and protect the primary circuit from contamination, intermediate heat exchangers (IHXs) have been proposed as a means for separating the primary circuit of the NGNP or other process heat application from the remainder of the plant.

2.0 SCOPE

This task will first review the different concepts of IHX that could be envisioned for HTR/VHTR applications in a range of temperature from 850 to 950°C. This will cover shell-and-tube and compact designs (including the plate-fin concept). The review will then discuss the maturity of the concepts in terms of design, fabricability and component testing (or feedback from experience when applicable). Particular attention will be paid to the feasibility of developing the IHX concepts for the NGNP with operation expected in 2018-2021. This report will also discuss material candidates for IHX applications and will discuss specific issues that will have to be addressed in the context of the HTR design (thermal aging, corrosion, creep, creep-fatigue, etc). Particular attention will be paid to specific issues associated with operation at the upper end of the creep regime.

3.0 REVIEW OF DIFFERENT IHX CONCEPTS

3.1 Tubular Helical Coil Heat Exchanger (THCHE)

The basic characteristics of the THCHE are that the primary side thermal energy is transferred to the secondary side by means of convective heat transfer through the tubular wall. Typical flow of the IHX (see Fig. 3-1) is that hot He (850-950^{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 hot header and passes back through the outlet at the top. The tubes are coiled to maximize the heat transfer area as well as to minimize the stress caused by thermal expansion. One end of each tube is attached to the tube plate while the other end of the tube is attached to the hot header (i.e., hot gas collector). To keep the pitch distance between the tubes even, spacer grids are inserted 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, the IHX is outfitted with insulation for better thermal efficiency.

Tubular helical coil heat exchangers are already used in conventional industries and in HTR applications; they also benefit 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 (Ref. 1). 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 (Ref. 2). This IHX is coupled to the HTTR nuclear reactor reaching outlet gas temperatures of up to 950°C. The design of the HTTR IHX is shown in Figure 3.1-2.

3.1.1 KVK tubular helical coil IHX

To deliver the nuclear process heat to a coal gasification process or to split methane in a steam reformer, an IHX design was developed under the 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. The mock-up helical-tube IHX was fabricated by Steinmuller/Sulzer consortium and was 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. The table below shows the key parameters of the design.

Table 3-1: Parameters of KVK 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)

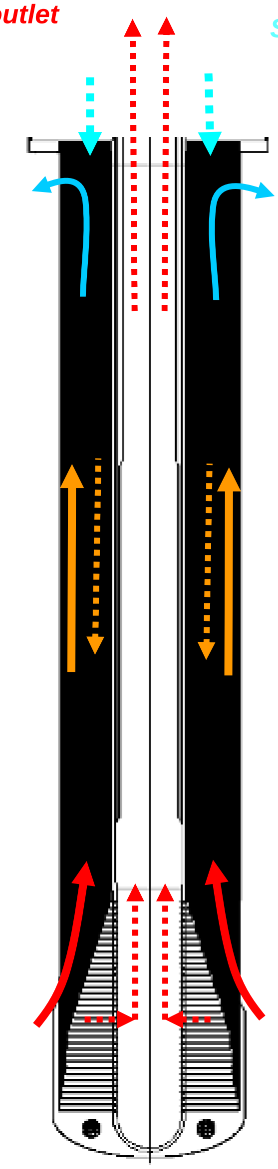


Figure 3.1-1: Typical flow of the Tubular IHX

3.1.2 HTTR tubular IHX

To develop the HTGR (High Temperature Gas-cooled Reactor) for hydrogen production with economic competitiveness by 2020, formerly Japan Atomic Energy Research Institute (JAERI) launched the HTTR (High Temperature Testing Reactor, Ref. 2) project with 30MW of thermal power and 950°C of reactor outlet coolant temperature. The core of the HTTR is made of prismatic fuel blocks with graphite as moderator. Its expected plant lifetime is 20 years. The HTTR reached first criticality in November 1998, full power at 850°C in December 2001 and high temperature at 950°C in April 2004 (Ref. 3). The IHX in the HTTR is a 10 MW vertical counter flow helical tube type heat exchanger much like the KVK 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 3.1-2.

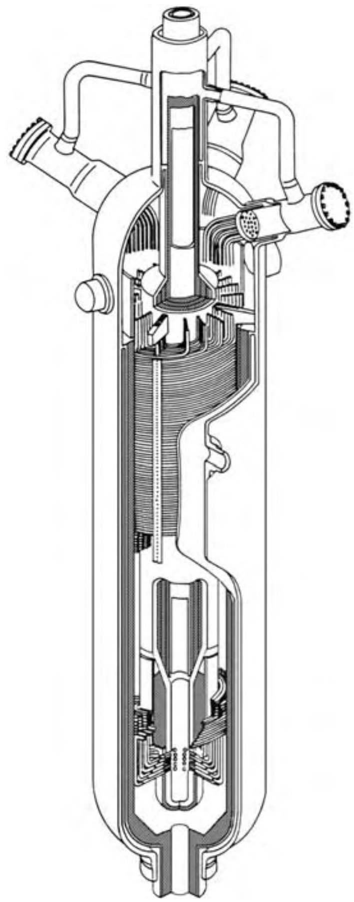


Figure 3.1-2: JAERI Tubular IHX Design

Other noteworthy parameters are tabulated in Table below.

Table 3-2: HTTR Tubular IHX Parameters

Type		Vertical helical coil 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

3.2 Compact IHX

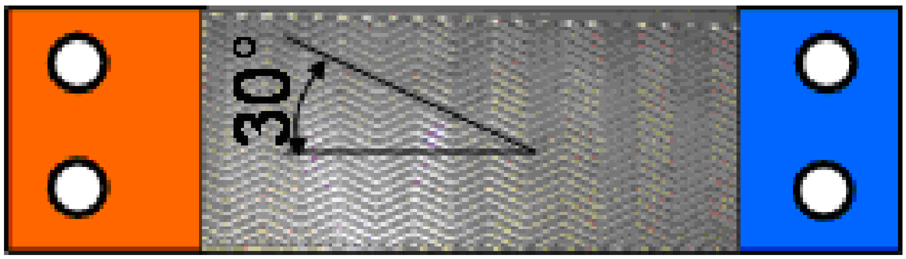
Plate type concepts are seen as the most promising compact IHXs concepts. Conventional metallic plate type HXs are used as “class 3” components in many nuclear applications, but they are innovative for applications at high temperatures. There is no commercial plate type HX for high temperatures (≥650°C which requires the use of high temperature nickel base alloys) in operation today, but numerous development projects have been carried out in the conventional industries. However, their manufacturability and their ability to withstand the pressure and thermal loads as well as the corrosion by pure or impure Helium during a significant lifetime at high temperatures have yet to be proven.

Each concept consists of elementary modules distributed 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 significantly smaller (the larger being 2.6 mm for the PSHE) than the tubular IHX which enables high heat transfer coefficients.

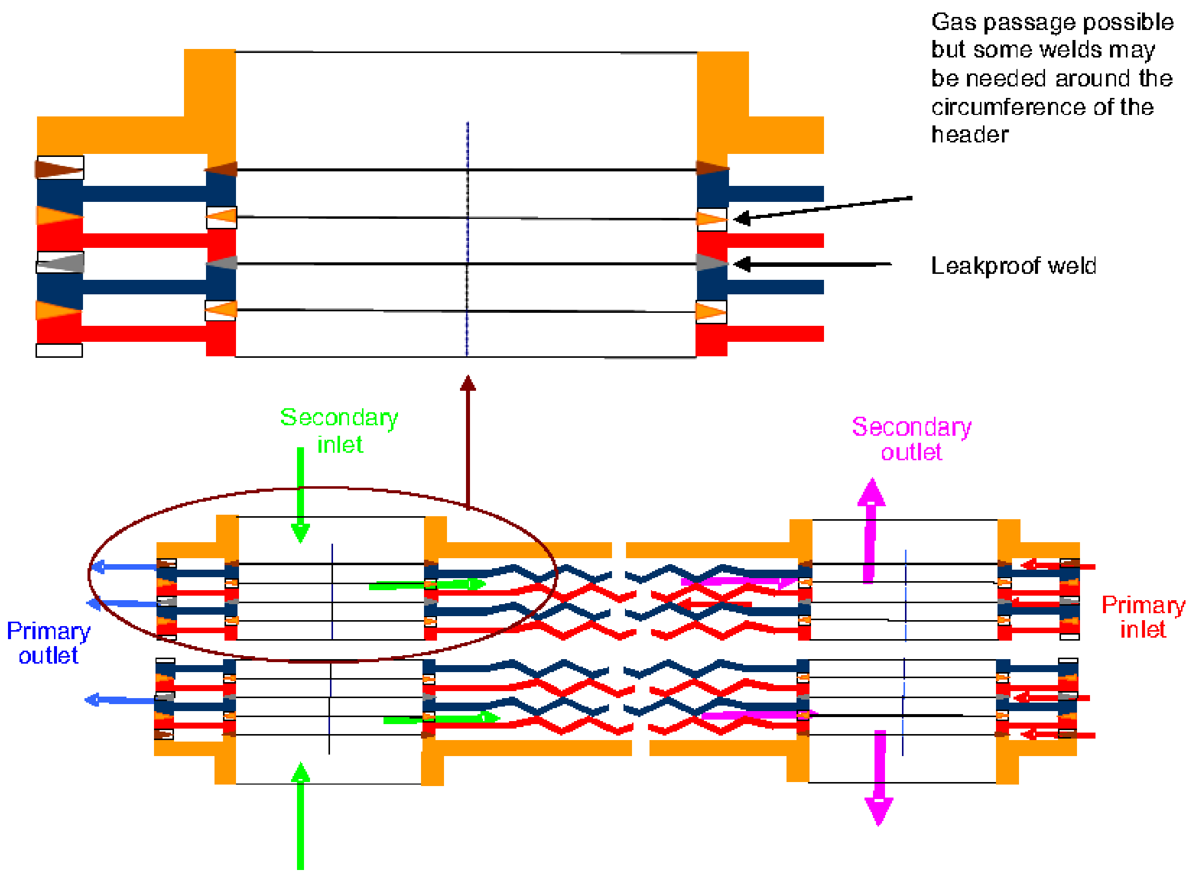
Details about each concept are given hereafter.

3.2.1 PSHE

The Plate Stamped Heat Exchanger (PSHE) concept consists of a set of modules, each being composed of a stack of plates stamped with corrugated channels. The plates are stacked in such a way to cross (see Figure 3.2-1) 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.



Typical PSHE header arrangement



Typical PSHE flow path

Figure 3.2-1: PSHE

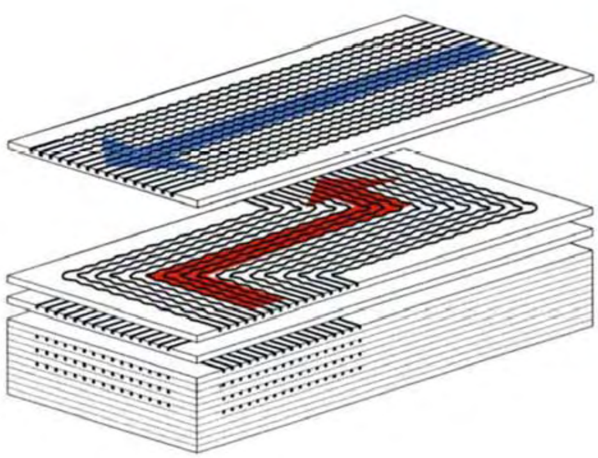
3.2.2 PMHE

The Plate Machined Heat Exchanger (PMHE) concept is based on the assembling of nickel alloy plates. The plates (thickness of about 1.4 mm) are provided with channels machined (see Figure 3.2-2) using high speed machining, electrochemical etching (also called a printed circuit heat exchanger, PCHE) or chemical machining. The plates are then assembled using diffusion bonding to make a module.

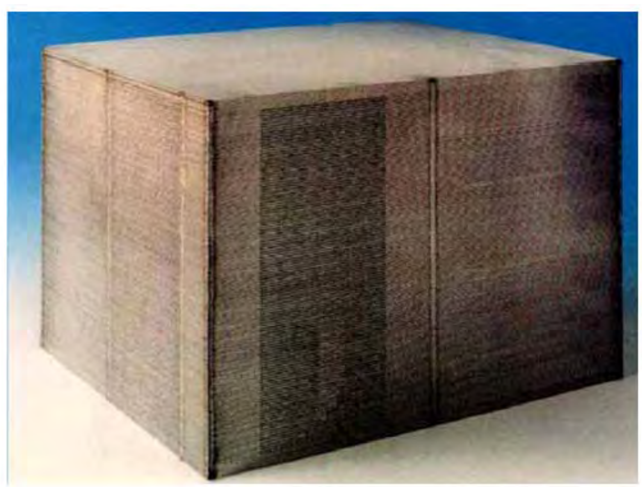
The geometry of a plate (left) and the assembly of three plates (right) are shown hereunder.

Typical machined flow channel

Diffusion bonded plates



Typical PMHE flow path

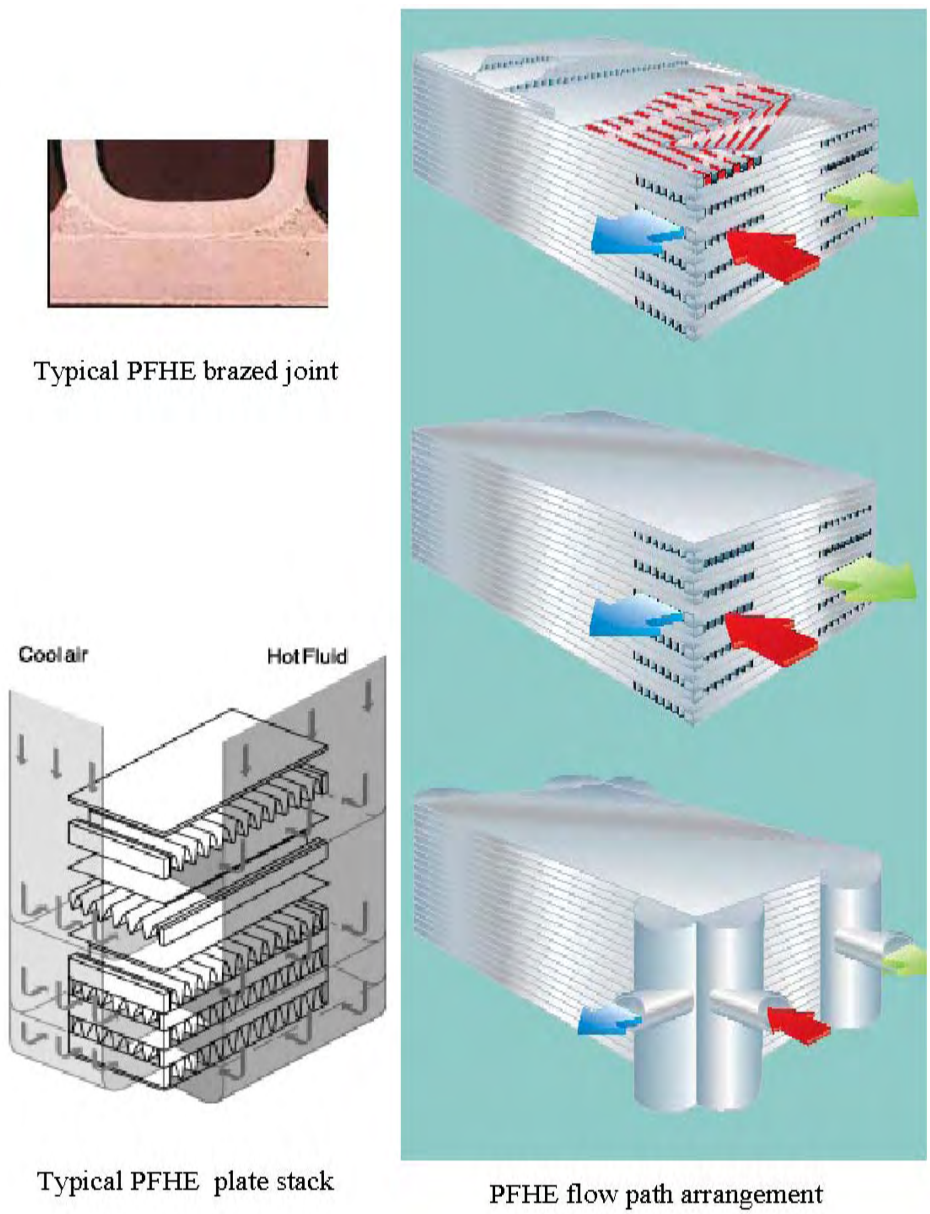


PMHE plate stack after diffusion bonding

Figure 3.2-2: PMHE

3.2.3 PFHE

The Plate Fin Heat Exchanger (PFHE) is a well known technology outside the nuclear field (cryogenic, aerospace, and automotive systems). They consist of a set of modules, each composed of a stack 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 normally brazed on the plates but some PFHE's have been developed that use diffusion bonding.



Typical PFHE brazed joint

Typical PFHE plate stack

PFHE flow path arrangement

Figure 3.2-3: PFHE

3.2.4 Two Stage IHX Concept

A significant technical tradeoff study of a two stage IHX versus one stage IHX has been performed in Section 3.7 of reference 5. The concept is that the first stage would reduce the coolant temperature to levels that can be confidently managed by a second IHX of current material technology. A multistage IHX would allow more frequent replacement of the smaller first stage IHX. The separate stages could be any combination of IHX designs and may or may not be in separate pressure vessels. The concept chosen for the AREVA design NGNP was that of a tubular IHX/compact IHX combination contained within a single vessel. This concept reduces the number of tubes and the size of the hot header of the first stage IHX which reduces the design and manufacturing complexity. It reduces the risks involved with developing a compact IHX to operate at the extreme temperatures demanded. The two stage concept does not reduce overall compactness of the NGNP. The pressure vessel is more complex as is ISI and potential component replacement for the single vessel concept. With separate vessels for each stage compactness is even further reduced. The cost benefit of a two stage IHX concept would require careful scrutiny as it isn't a clear technical advantage from one combination of IHX designs and vessel configuration to another.

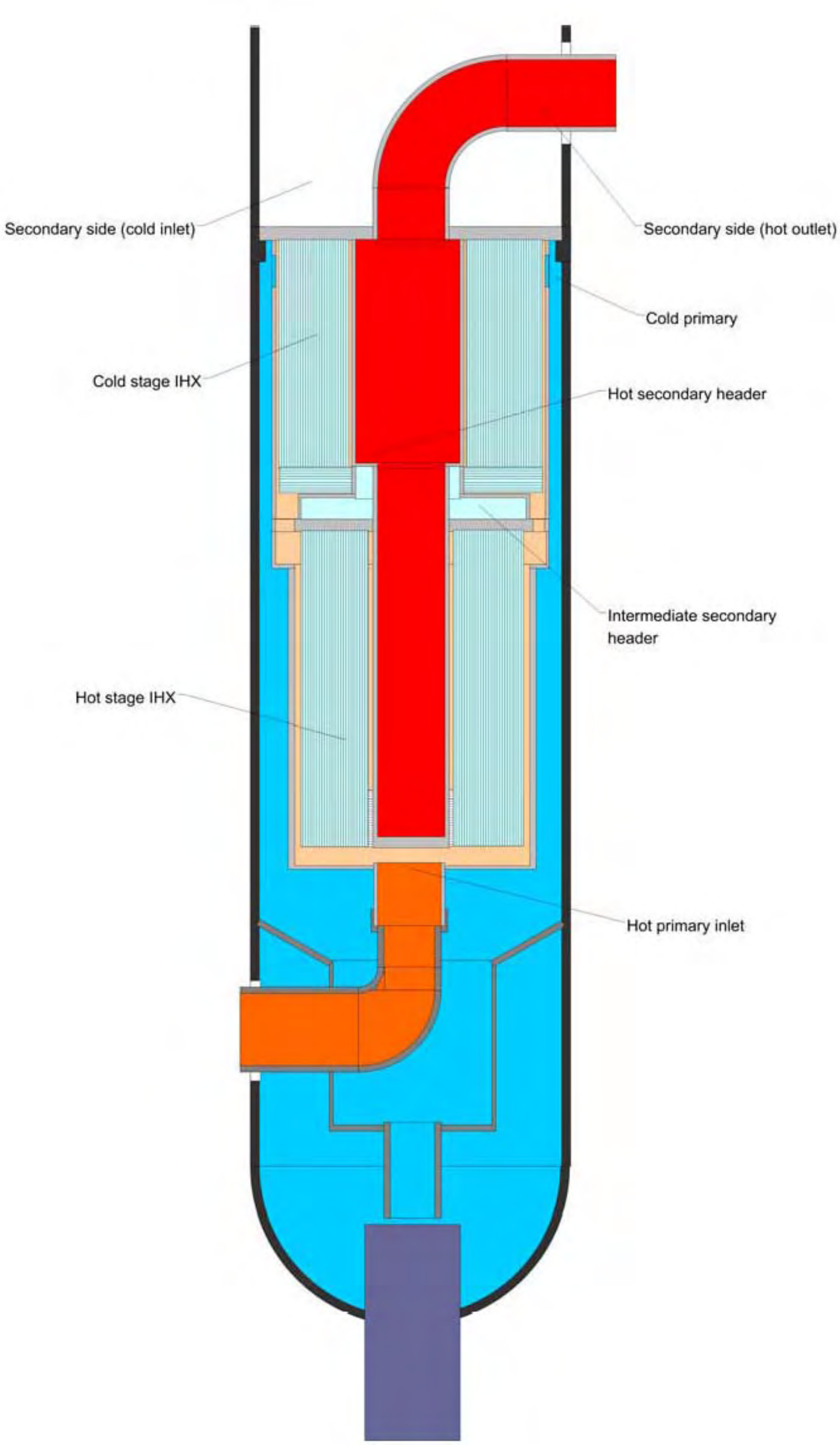


Figure 3.2-4 Duel Stage IHX

4.0 MATURITY OF THE CONCEPTS

In this section, the maturities of the concepts (tubular IHX and compact IHXs) are discussed in terms of design, fabricability and component testing. In service inspection is discussed in Part II of Task 7.

4.1 Tubular Helical Coil Heat Exchanger Maturity

The tubular IHX is most matured concept amongst IHXs. They have actually been built and tested at HTR conditions and one of them is still being tested.

However, there are some concerns or issues that the tubular IHX has to consider.

4.1.1 Design

Thermo-hydraulic Aspect

In spite of having advantages of reduced thermal strain due to thermal expansion than the compact IHX, there are some disadvantages related to the helical tube design concept. 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.

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

- The length of individual tubes may vary a small amount. The pressure drop on these differing length tubes will vary as well, though the resulting differing mass flow and temperature are expected to be of little 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 tube row and the shroud. This induces higher heat flux on the shroud, lower pressure drop, higher primary helium outlet temperature, and consequently lower overall heat exchanger effectiveness. See Figure 4.1-1.

- FIV - A flow-induced-vibration (FIV) can occur because of the fluid / structure interaction between the cross-flow and the tightly packed tube bundle. The FIV can be caused by any turbulent flow.

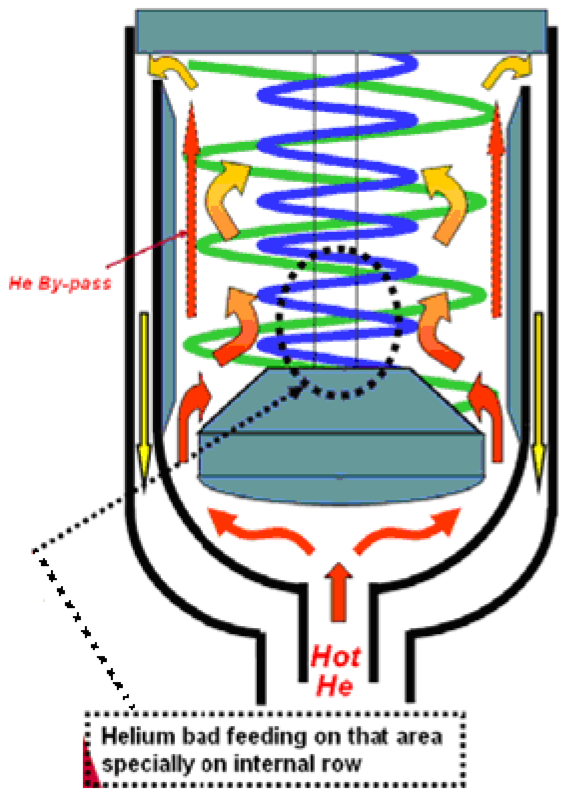


Figure 4.1-1: Misdistribution

Thermo-mechanical Aspect

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 their entire 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° - 500 °C depending on concept) but, dependant upon design, may have 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.

Seismic Aspect

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/tube connection failure by seismic condition

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 very pure helium gas but the material is still subject to corrosion. Even though the thickness of the tube is about 2.3mm, it is essential to assure that corrosion does not affect its expected life span. The study of this phenomenon will require numerous long term tests to understand the specific behavior of the chosen material under IHX atmosphere and is a serious concern.

One solution to the corrosion issue is to coat the exposed surfaces of the IHX. Various research efforts have been done regarding the coating technique on the tubes. Additional discussion of this topic is provided in Section 4.2.1 under Subsection Material Issues. However, coating of long, thin and curved tubes still needs to be developed. Furthermore, even if coating of the long tubes can be achieved, the coating of the welded sections must be performed in the assembly line.

- Corrosion on tubes
- Coating techniques on tubes
- Coating the welded sections

4.1.2 Fabricability

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 (Ref. 4), 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 a hot header made of nickel base alloy (e.g., alloy 617) is not going to be easily performed 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 economic risk involved in case the finished hot header does not qualify for the required material specifications.

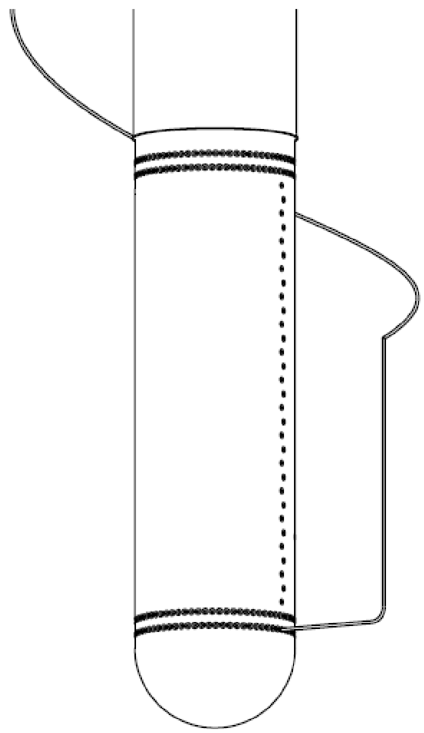


Figure 4.1-2: Hot Header

Assembling of the tube bundle

Each tube needs to be welded at each end to the tube plate and to the hot header; consequently, the assembling the tubes (possibly more than 2500 tubes) may be a difficult task. Whether the tube is a continuous length or welded with several pieces, the difficulty will be to bend the tubes 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 increasing manufacturing difficulty and time (See Figure 4.1-3 below). Also, putting a support between each tube might not be an 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 to establish the most suitable assembly process and to confirm the feasibility of the tubular IHX assembly. 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.

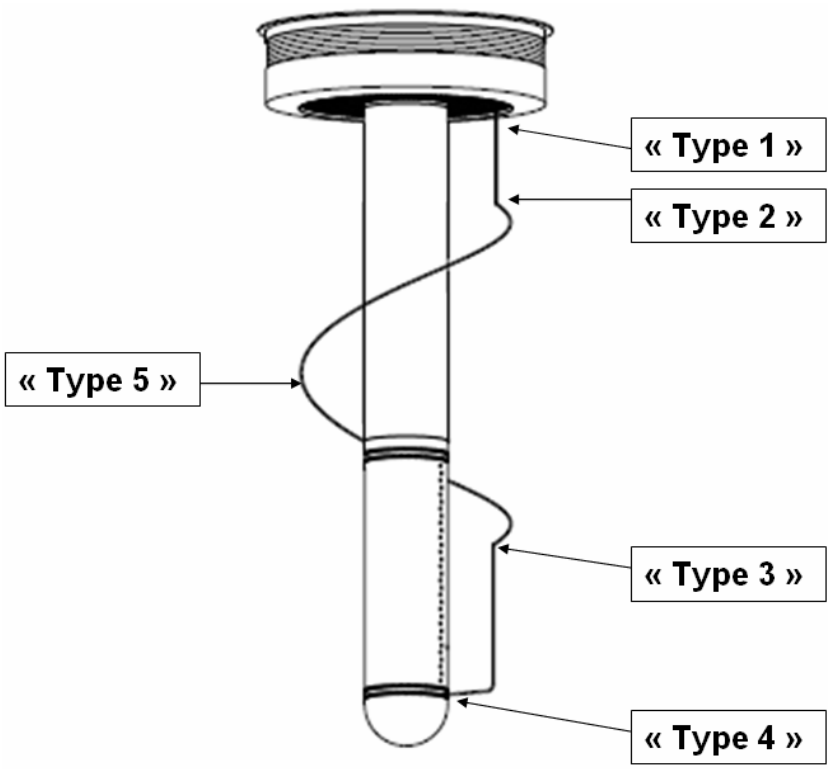


Figure 4.1-3: Possible Weld Type in a Tubular IHX

Bending of the tubes

The tubes will have to be preformed (bent) 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

According to the German experience, the tubesheet-to-tube welds can be performed with GTAW (Gas Tungsten Arc Welding) with a rotating torch inside the tube and the tube-to-tube welds from the OD. 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. If a full length seamless tube or pipe is not used, special tooling will need to be developed to perform the intermediate welds (Types 2, 3, & 5).

4.1.3 Component testing

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

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.

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. Cyclic and steady state conditions were tested over a range of power outputs. Accident conditions were tested at 100% power.

Figure 4.1-4: View of 10MWth Mock-up for KVK Facility

JAERI HTTR

The HTTR (High Temperature Test 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. 3). 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 3.2-1.

Several experimental and analytical studies (Ref. 2) 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.

Hot Header (KVK tests only)

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

4.1.4 Feasibility of AREVA Concept

The AREVA NGNP design is based on the German design which was tested in the mid-eighties and though some of the test results might not be available, it still offers confidence 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. The testing performed provides confidence that the concept will succeed but additional testing, possibly including large scale (30 MWth), is needed

4.2 PSHE Maturity

There are numerous developments in non-HTR industries. The PSHE concept has to be qualified in HTR conditions.

4.2.1 Design

Thermo-hydraulic design

Correlations for the thermo-hydraulic 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 (0.9) is reachable 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 for a roughly 7.5 MWth IHX module as anticipated by AREVA for the 60 MWth 850°-950°C NGNP side loop),
- 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 through 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.

Thermo-mechanical design

Similar to the tubular IHX, 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 the plates
- Creep behavior of the hot header
- Creep behavior of the piping connecting the hot header to the IHX modules

Material issues

Corrosion by the 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 still does not seem sufficient to ensure an acceptable impact of corrosion.

A protective coating could provide the required protection. A protective coating may also help reduce diffusion of tritium from the primary to secondary coolants. 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 thermo-mechanical cyclic loadings.

Some interesting work has been done with regard to SiC coating (see Reference 22). This process uses Ion beam mixing technology to a highly adherent coating of SiC to the base metal. The referenced document suggests that some testing has been done to confirm bonding above 900˚C and by examination with a scanning auger microprobe. Another coating material, zirconium oxide stabilized with yttrium (ZrO_2 13% Y_2O_3 NiCr AlY), was applied using atmospheric plasma thermal spray to a hot gas return duct tested at the KVK facility (see Reference 23). No matter the thermal barrier coating chosen, testing is needed to verify its acceptability for this application.

Additional material information will be included in Part II of this Task.

4.2.2 Fabricability

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 time of realization for a large size IHX. In the case of a 60 MWth modular IHX, this time should be reasonable.

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.

Figure 4.2-1: Stamped Plate

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.

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 detail.

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.

4.2.3 Component testing

As mentioned previously, this PSHE concept has been used or tested in several applications such as recuperators in the power, oil industries, etc.). However, those were at much lower temperature level. Various performance tests and welding tests are being conducted in high temperature environment.

4.2.4 Discussion on Feasibility

Even though the PSHE has been tested or used in various industries, it is for a lower temperature range. There are still a few hurdles to overcome such as welding of the plates, machining/stamping plates etc. To meet the NGNP operation by 2018, the PSHE IHX should be available by the end of 2016. This timeframe is considered to be short to qualify the PSHE IHX.

4.3 PMHE Maturity

The PMHE concept has been used in lower temperature conventional applications. There is no large scale testing or nuclear demonstration done to this date. This concept has to be qualified for the HTR conditions.

4.3.1 Design

On thermal-hydraulic aspect, since channels are stacked tightly, there is possibility of flow misdistribution especially on the primary side. A CFD study showed that the induced flow misdistribution within the plane (primary side) is about 5%. Thus, it is determined to be acceptable. Increase of heat exchange area will result in much lower flow misdistribution.
Thermal performance is very good with uncertainty assessed to be between 10% and 15%. The heat transfer area per unit volume is much larger compared to tubular type. However, it is subject to severe thermal gradient and likewise thermal stress.

On 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 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.

Despite a visco-plastic calculation, lifetime under nominal condition doesn’t seem to be acceptable.

Corrosion by the 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.

4.3.2 Fabricability

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). Mechanical machining works well for straight grooves and makes precise groove but machining speed and reliability of drills could be improved. Electro-chemical etching works well for more intricate grooves. But, plate surface is needed to be kept clean before every operation and electrolyte draining is difficult. Furthermore, there is a risk of corner rounding.

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, it is found that the shape of the channels undergo some additional deformations.

4.3.3 Component Testing

Tests have been limited to lab-scale tests or single module testing. Multiple-module tests need to be performed.

4.3.4 Discussion on Feasibility

It seems to be less feasible compared to other plate type heat exchangers (PSHE and PFHE) because there are thermo-mechanical issues and fabrication issues. PMHE is seen as a less promising concept for the deployment of NGNP by 2018.

4.4 PFHE Maturity

Like other plate type IHXs, this PFHE concept has been used in many industrial applications. However, this concept has to be qualified in the HTR condition.

4.4.1 Design

For both designs (serrated fin and straight crested fin), the fin thinness (≤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.

The risk of flow misdistribution on PFHE with the serrated fin is very low due to open channels unlike PMHE. However, there is risk of flow misdistribution on PFHE with straight crested fins due mainly to the tight layers. Much like other plate type heat exchangers, thermal performance is very good with uncertainty assessed to be between 10% and 15%. The heat transfer area per unit volume is much larger compared to tubular type.

Corrosion by the coolant remains a challenge for the plate-type IHX at temperatures above 800°C (especially, PFHE with thinnest fins), which could require developing specific measures like a protective coatings and coating techniques.

Lastly, similar to the PMHE concept, the stress levels calculated do not seem to be compatible with the desired lifetime and temperatures.

4.4.2 Fabricability

Convolutions manufacturing is demonstrated by industrial tools with Haynes 230 and Inconel 617. Brazing has been the usual bonding process to put fins to the plates. However, some difficulties have been encountered regarding brazing of the fins onto the plates.

One study (Ref. 6) shows that diffusion weld might be better option for PFHE. The literature concluded that reliability of brazing is insufficient when PFHE is used for long term duration as primary and secondary components. It also mentioned that the tensile and creep strength in the diffusion weld are superior to those in the brazing in high temperature condition.

4.4.3 Component Testing

There are lots of industrial experiences with PFHE but those are for much lower temperatures. Tests at high temperature have been limited to lab-scale testing or single module testing. Multiple module tests at high temperature need to be performed.

4.4.4 Discussion on feasibility

Even though PFHE is already available in heat exchange industry, there are issues regarding high temperature environment that need to be taken care of. For these reasons, the PFHE is not seen as a promising concept for the deployment of NGNP by 2018.

5.0 SURVEY

A survey questionnaire was sent to several organizations including reactor vendors and designers, heat exchanger suppliers and research organizers. The purpose of this survey is to collect inputs from vendors who specialized in heat exchanger type components and to summarize the inputs so that they can be utilized in improvement of codification. The survey consists of five categories:

- general information,
- design,
- material,
- fabrication
- non-destructive examination.

Also, included in the survey are the suggestions of improvement on the Codes and Standards.

The surveys received are included in Appendix A. Each lists using (or planning to use) the ASME Code as a guideline for all aspects of design and fabrication. Some reported shortcomings of the ASME Code were:

- material properties and design guidelines need to be extended to at least 950˚C
- diffusion bonding needs to be addressed for fabrication, NDE, and possibly material properties
- Alloy 617 needs to be included

See Appendix A for additional information.

6.0 MATERIAL CANDIDATES FOR IHX APPLICATIONS

The IHXs pose significant engineering challenges because (1) some components will be exposed to very high temperatures, (2) large amounts of heat must be transferred from the primary coolant, (3) the requirements for reliability and leak-tightness are stringent, and (4) the desired lifetime for the plant is very long.

This section reviews previous efforts on materials selection for the IHX and discusses the performance of the candidate materials. It also provides initial observations on how the ASME Boiler and Pressure Vessel Code would need to be extended to cover the NGNP.

6.1 Identification of Candidate Materials

6.1.1 Recommendations of Reactor Vendors

AREVA, General Atomics, and Westinghouse are the three reactor vendors working on the U.S. Department of Energy's NGNP project. Each company has prepared a preconceptual design for the NGNP that includes one or more IHXs and has made a materials selection for the hot section of the VHTR IHXs. In each case, gas-to-gas heat exchangers are being considered (Ref.7, p. 12; Ref. 8, p. 20; Ref. 9, p. 17; Ref. 10, pp. 21, 43). The selections are reviewed and additional candidate materials are suggested.

<u>AREVA</u>

AREVA (Ref. 7, p. 11) has proposed a multicolor reactor system, with one compact IHX dedicated to the hydrogen production system and two or three tubular (shell-and-tube) heat exchangers dedicated to the power conversion system. The reactor outlet temperature could be as high as 900 °C. AREVA has specified alloy 617 as the preferred material for the hot section of the IHXs, with alloy 230 as an alternative (Ref. 8, pp. 86, 285). Alloy XR (also called as Hastalloy XR) is a possible alternative material if corrosion in hot helium proves to be a problem (Ref. 8, p. 86). Ceramics are considered to be promising but impractical at this time (Ref. 8, p. 318).

General Atomics

General Atomics (Ref. 9, pp. 15, 17) 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 (Ref. 9, pp. 21-23). 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 (Ref. 9, p. 63).

Westinghouse

Westinghouse has selected a one-loop design with two heat exchangers in series (Ref. 10, p. 38). The first heat exchanger reduces the temperature of the primary gas from the reactor outlet temperature, approximately 950 °C (Ref. 10, p. 25), to some lower temperature and delivers it to the second heat exchanger. Both heat exchangers would use a compact design (Ref. 10, p. 26). The reference material for the high-temperature heat exchanger is alloy 617, with alloy 230 identified as an alternative (Ref. 10, p. 44), although it is recognized that the internals of the high-temperature heat exchanger will require periodic replacement if these alloys are used.

6.1.2 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. If the reactor outlet temperature is reduced, other alloys may be suitable for the hot sections of the IHX. A good example is alloy 800H, which might be usable at temperatures up to about 750 °C. The composition limits of alloy 617, 230, X, XR, and 800H are provided in Table 6-1.

Alloy XR is a refinement on alloy X, with generally tighter composition limits that were chosen to improve particular aspects of alloy performance (Ref. 11). 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. The strategy of refining alloy specifications may also yield improvements in the performance of other alloys, such as 617 and 230.

A new material has been developed by ThyssenKrupp VDM based upon alloy 617 specifically for use in power plant boilers. This new material, Nicrofer 5520CoB-alloy 617b is reported to increase permissible mechanical stresses by 20%. The manufacturer accomplished this by adding boron and controlling the content of strength enhancing elements such as aluminum, titanium, and cobalt. Pipe of this material is in use in the test facility COMTES (COMponent TESt Facility) at a power plant in Germany. It is planned for use in a power plant operating at 700˚C and 350 bar. According to ThyssenKrupp VDM, the next step is to validate the cost-effective production of standard components from this alloy. This material may prove useful in the future.

Additional materials have been considered in feasibility studies but found to be unsuitable for a variety of reasons. Some of these are cataloged briefly below.

Ceramic materials are promising because of their high thermal conductivity, corrosion resistance, and resistance to creep, but they are not considered to be technologically mature enough for the large parts to be used in the NGNP (Ref. 8, p. 318). There is research being conducted to develop this technology, both in manufacturing and analysis. Ceramatec, Inc. has been developing a Laminated Object Manufacturing (LOM) method that can be easily automated. The LOM method uses pre-ceramic polymers (carbo-silanes) that when pyrolyzed, decompose into a silicon carbide composition. By processing silicon carbide components with this pre-ceramic polymer and pyrolyzing the polymer, a fused silicon carbide monolith is formed. Proof of principle manufacturing tests of small ceramic plate stacks in a compact IHX configuration have been performed. Evaluation of the bonded joints under magnification reveals an excellent bond. Analysis of the design pictured in Figure 6.1-1 suggests that it should withstand 3 bar at 1000˚C and have other designs capable of 70 bar at that temperature. Engineering scale component testing and manufacturing process development are needed to make an IHX of this material a viable option. If these hurdles can be overcome, ceramics may be an excellent replacement for the metallic IHX.

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.

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. 12) 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. 13). Weld cracking of these alloys still poses a problem for fabrication, however.

Development continues on additional materials, such as alloy 740 (Ref. 14). This Ni-Cr-Co alloy has substantially greater creep strength than alloy 617, at least at temperatures up to 800 °C (Ref. 15). This material is probably not sufficiently mature for deployment in an NGNP reactor, but it may be useful for later designs.

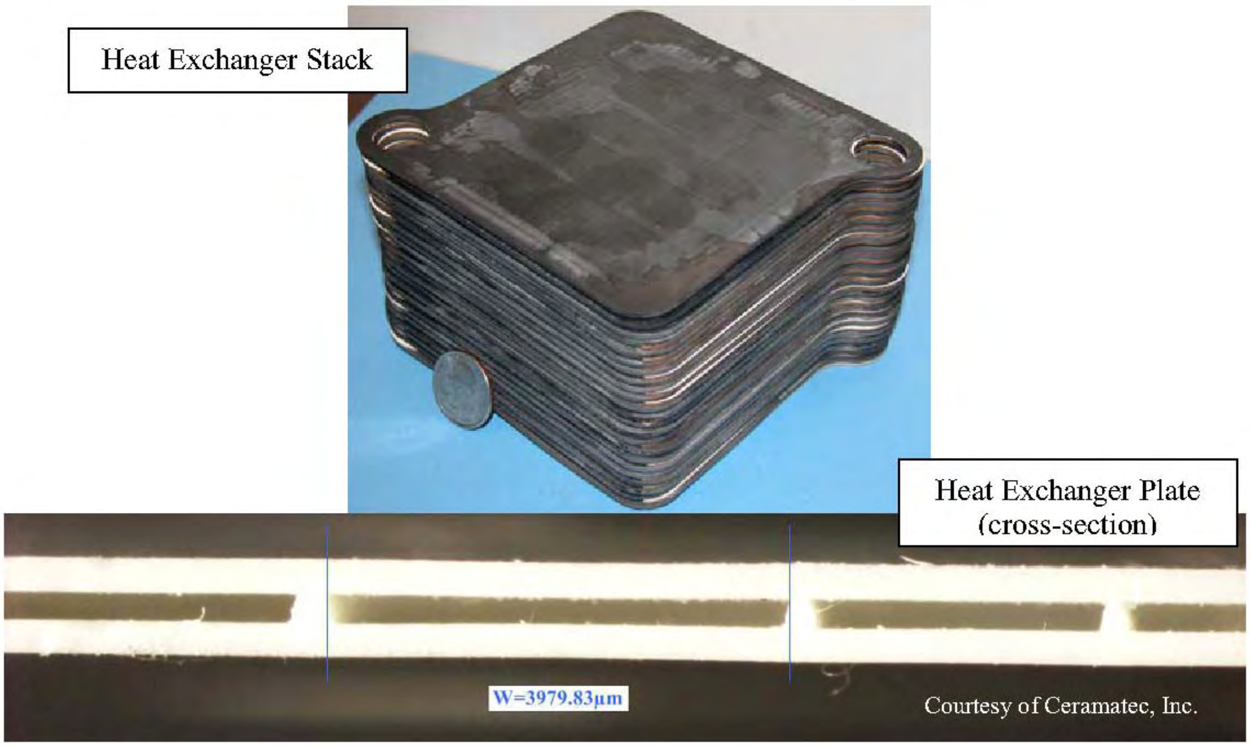


Figure 6.1-1 Ceramic compact heat exchanger using Ceramatec's LOM process

Table 6-1: Compositions of candidate materials for IHX

	617		230		X		XR		800H	
	min	max	min	max	min	max	min	max	min	max
Ni	44.5		remainder		remainder		remainder		30.0	35.0
Fe		3.0		3.0	17.0	20.0	17.0	20.0	39.5	
Cr	20.0	24.0	20.0	24.0	20.5	23.0	20.5	23.0	19.0	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	0.05	0.10
Cu		0.5						0.50		0.75
Si		1.0	0.25	0.75		1.00	0.25	0.50		1.0
Mn		1.0	0.30	1.00		1.00	0.75	1.00		1.5
P				0.030		0.04		0.04		
S		0.015		0.015		0.03		0.03		0.015
Ti		0.6						0.03	0.15	0.60
Al	0.8	1.5		0.50				0.05	0.15	0.60
La			0.005	0.050						
B		0.006		0.015				0.01		

6.2 Primary Issues in Materials Selection

6.2.1 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 III, Subsection NH for use up to 760 °C (Ref. 16, p. 52).

Outlet temperatures as high as 1000 °C have been discussed but are considered to be beyond the current capability of metallic materials (Ref. 17, p. 38). 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 significantly reduced lifetime for the affected components (Ref. 17, p. 38).

6.2.2 Creep Rupture

Data on creep rupture are available for alloys 617, 230, X, and XR. Figure below shows the data for alloys 617 and 230. For temperatures up to 850 °C, these alloys have comparable strengths (Ref. 16, p. 43), with some investigators noting a slightly better creep rupture strength for alloy 230 over the temperature range from 700 to 850 °C (Ref. 15). At 950 °C, however, alloy 617 has better strength at long lives (> 3000 hours) (Ref. 16, p. 43). 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 to that of alloy X at 900 °C. The creep rupture strength of alloy 800H is even lower. Again, in rough terms, the stress/time performance of alloy 800H at 760 °C falls between the values for alloy 617 at 850 °C and 950 °C. Alloy 617 therefore has an advantage over the other alloys in that it can be used either in thinner sections, at higher temperatures, or longer allowable component life.

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. 15, 16) may also provide some benefit.

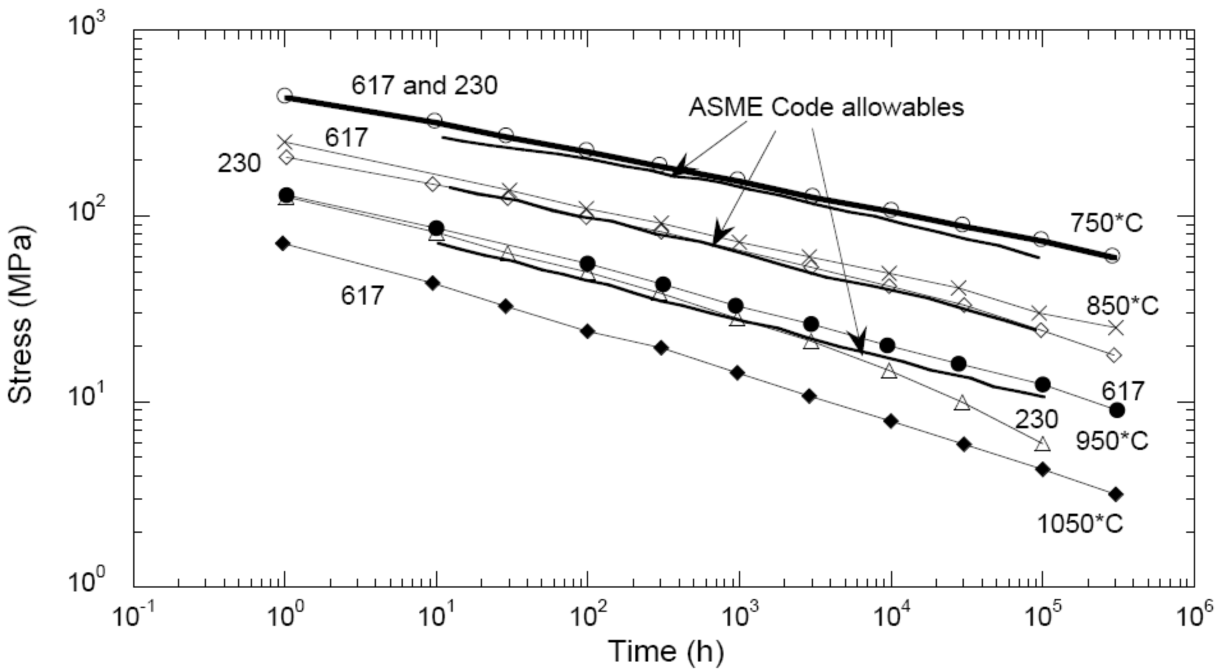


Figure 6.2-1: Creep-rupture strength of alloys 617 and 230 as a function of temperature and time to fail

6.2.3 Creep-Fatigue

Significant creep-fatigue effects have been seen in alloy 617 (Ref. 16, pp. 40-41), alloy 230 (Ref. 16, pp. 45-46), alloy X (Ref. 16, pp. 45, 60-61), and alloy 800H (Ref. 16, pp. 52-54). The magnitude of the effect on IHX life is currently unknown but will depend on the temperature of operation, strain cycling, and chemical environment. It may also depend on the thickness of the material used in the IHX (Ref. 16, p. 65). It would not be surprising to find that the effects of creep-fatigue are more severe for a compact IHX than for a shell-and-tube IHX because the blocky structure of a compact IHX makes it less compliant.

6.2.4 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. 18). Alloy 617 is considered to be easier to weld than alloy 230.

Weldability typically increases with iron content, so alloys X and XR should be similar to each other in weldability, and both should be more easily welded than alloys 617 and 230. Alloy 800H should be even more weldable than alloys X and XR.

6.2.5 Microstructural Stability

All of the candidate alloys are primarily solid-solution strengthened materials. Ref. 16 (p. 22) 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. 16, p. 41).

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. 16, p. 47). Aging did not produce sigma, mu, or Laves phases (Ref. 16, p. 47). However, additional data are still needed on long-term stability (Ref. 16, p. 48).

Alloy X (and therefore presumably alloy XR as well) does not appear to be as microstructurally stable as alloys 617 and 230. Ref. 16, p. 58 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."

Alloy 800H, like alloy 617, contains aluminum and titanium, so "After long times at a service temperature of ≈550°C, [γ'] precipitates tend to form. These precipitates can reduce the creep ductility of the alloy… To minimize the decrease in creep ductility, the volume fraction of [γ'] precipitates is controlled by specifying a concentration limit … for the Al + Ti content in the alloy" (Ref. 16, p. 52).

6.2.6 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.

Alloy 800H appears to be slightly more susceptible than the other alloys to oxidation in impure helium (Ref. 16, pp. 50, 67)

6.3 Issues to Be Addressed for Codification

It has been assumed that the NGNP will be constructed in accordance with the ASME Boiler and Pressure Vessel Code. Because of restrictions in the Code, however, that is currently impossible. This section discusses how the Code would need to be extended to cover the design of the NGNP. Additional discussion will be provided in Part II of this Task.

The portion of the Code that comes closest to covering the materials and operating conditions of the NGNP is Section III, Subsection NH. That subsection covers Class 1 nuclear components in high-temperature service and is itself an extension of Section III, Subsection NB. Subsection NH provides design rules that are intended to prevent failure by the following modes:

- ductile rupture from short-term loading
- creep rupture from long-term loading*

- creep-fatigue failure*
- gross distortion due to incremental collapse and ratcheting
- loss of function due to excessive deformation
- buckling due to short-term loading
- creep-buckling due to long-term loading*.

The failure modes marked with an asterisk are unique to Subsection NH; the others are used in both Subsection NB and Subsection NH. All of the failure modes are applicable to the NGNP, and it is possible that an additional mode will have to be added, as is discussed below.

For the purposes of this document, it is assumed that the changes would be implemented in Subsection NH, so the discussion is in terms of extensions to Subsection NH that may be needed. If the IHX is determined to be a Class 2 or Class 3 component, however, extensions might be made in other parts of the Code instead.

6.3.1 Acceptable Materials of Construction

Subsection NH currently allows only six materials. Of these six, five are structural materials (Types 304 and 316 stainless steel, 2¼ Cr - 1 Mo steel, 9Cr1Mo-V, and alloy 800H) and three are bolting materials (Types 304 and 316 stainless steel and nickel-base alloy 718). Of these materials, the only one that is under consideration for the sections of the IHX is alloy 800H, and even that material would be usable only if the outlet temperature were substantially reduced. It is therefore necessary to extend Subsection NH to cover alloys 617, 230, X, and XR. Such an extension will necessarily require a substantial effort to measure performance data on these alloys.

One feature of Subsection NH concerns the use of material specifications that are more restrictive than the standard ASME/ASTM standards. That topic is discussed in Appendix X of Subsection NH. Under Subsection NH, inelastic analyses can be used to predict the performance of a component. The analyses use the nominal properties of the material. Of course, there will be scatter in properties from one heat of material to another, and that must be taken into account, so margin is provided by imposing safety and design factors. It is possible to reduce the scatter, and thereby relax the safety and design factors, by using a specification that is more restrictive than the ASME/ASTM standard. Examples of such restrictions include a more closely defined composition, specification of a particular melting practice, and specification of a particular range of grain sizes.

The NGNP IHX will place heavy demands on its structural materials, so the feature of allowing more restrictive material specification should be retained when Subsection NH is extended.

6.3.2 Maximum Temperature

Subsection NH was developed for a sodium-cooled fast breeder reactor, and the operating temperatures of such a reactor are substantially lower than those of the NGNP. Accordingly, the temperature limits in Subsection NH seem quite restrictive: 2¼ Cr - 1 Mo steel has a maximum temperature of 593 °C, the austenitic stainless steels have a maximum temperature of 816 °C, and alloy 800H has a maximum temperature of 760 °C (Ref. 19, p. 18). Alloy 800H might be acceptable as an IHX material if the outlet temperature of the NGNP is significantly reduced, but an increase in the temperatures allowed under the Code is required if the NGNP is to operate at or near the current design temperature.

A draft code case has been prepared to allow the use of alloy 617 at temperatures up to 982 °C (Ref. 20). This code case could serve as a guide for revisions to Subsection NH. As will be seen below, the draft code case has features other than high temperature that would require additional changes to Subsection NH.

6.3.3 Maximum Design Life

Subsection NH currently imposes a maximum design life of 300000 hours, or about 34 years with a 100% duty cycle, or 38 years with a 90% duty cycle. That design life is apparently sufficient for the current NGNP schedule (Ref. 7, p. 29), but a commercial plant would probably require a longer design life, such as 60 years (Ref. 8, p. 35), or nearly 500000 hours with a 90% duty cycle. Obtaining data to support a 500000 hour design life would pose a challenge. It would not be practical to actually test the material for such a long time, so some means of extrapolating from shorter-term tests would be needed. The need for extrapolation could be reduced if the plant were designed to allow periodic replacement of the IHX.

It is noted in passing that the draft code case for alloy 617 was limited to a design life of 100000 hours (Ref. 19, p. 37). As described above, design data needs to be provided for a considerably greater design life than that contained in the draft code case; however, it remains to be seen if a design life of 60 years is practical for an IHX.

6.3.4 Nonclassical Creep

Many engineering materials follow a “classical” pattern of primary, secondary, and tertiary creep, as is shown schematically in Figure 6.3-1. In contrast, alloy 617 is said to show “nonclassical” creep behavior (Ref. 16, p. 31; Ref. 19, p. 55), as is shown schematically in Figure 6.3-2.

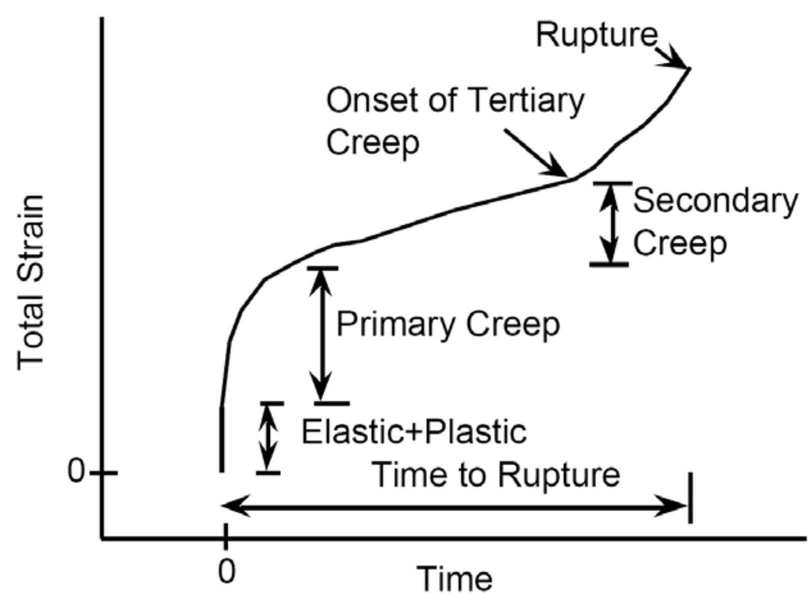


Figure 6.3-1: Schematic of classical creep strain as a function of time

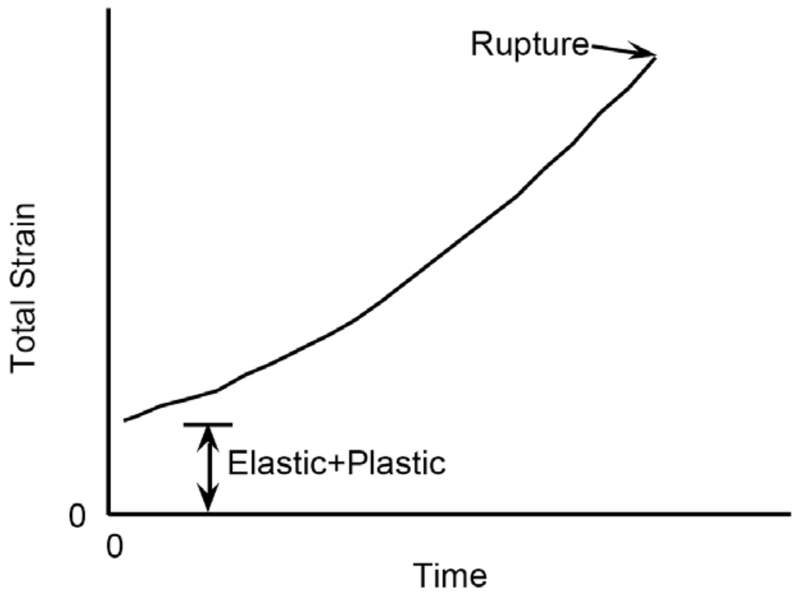


Figure 6.3-2: Schematic of nonclassical creep strain as a function of time

The differences in creep behavior must be taken into account if the Code design rules are to be applied to alloy 617. Subsection NH sets values of the allowable time-dependent primary stress S_t, and these are derived in terms of classical creep behavior (Ref. 19, p. 55). The draft code case for alloy 617 uses constitutive equations for creep that do not distinguish between time-independent plasticity and time-dependent creep (Ref. 21, p. 32). Adapting the Code to such behavior will therefore require careful reconsideration of the design rules.

6.3.5 Environmental Effects

At the high temperatures envisioned for the NGNP, the candidate alloys are subject to environmental effects, including carburization, decarburization, and oxidation. All of these affect the mechanical properties, so it would be appropriate if Subsection NH provided guidelines on how to evaluate these effects.

6.3.6 Possible New Failure Mode

It is possible that the long-term behavior of alloy 617 will require the addition of brittle fracture as a failure mode. There appears to be some disagreement on this point. On one hand, Ref. 16 (p. 22) 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." On the other hand, Ref. 21 (p. 32) states that the draft code case "recognizes that extended exposure at elevated temperature may cause a significant reduction in fracture toughness of Alloy 617, thus introducing an additional failure mode—brittle fracture—to be considered." Brittle fracture is undesirable in a nuclear component. How this will be addressed in the ASME Code has yet to be resolved.

7.0 CONCLUSIONS

A variety of IHX configurations are being evaluated for future VHTR applications. The THCHE the most mature concept. Such tubular IHXs have been built and tested in mockup test loops and are being tested currently in the HTTR. Compact IHX concepts are less mature, but they offer the potential to reduce IHX volume and cost with comparable or increased thermal performance. A variety of compact IHXs are being examined. While significant experience exists with these concepts in lower temperature non-nuclear applications, substantial development will be required for VHTR applications. The challenges of the compact IHX amplify concerns regarding material properties and corrosion resistance. ISI concerns will also have to be resolved.

The most promising candidate for IHX material is alloy 617. Other candidates are alloys 230, XR, and 800H. The properties of alloys 617 and 230, particularly for creep rupture, appear to be somewhat better than those for XR, which in turn is superior to 800H. Alloy 800H has a unique advantage in that it is approved under ASME Code Section II Subsection NH for use up to 760 °C. The remaining alloys would all require code approval. A draft code case has been prepared to allow the use of alloy 617 at temperatures up to 982 °C. This code case could serve as a guide either for new code cases or for revisions to Subsection NH.

8.0 REFERENCES

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APPENDIX A: RETURNED SURVEYS

Gen IV Task 7 - ASME Code Considerations for IHX			
1	Organization	Data removed	
2	Contact person and email address	Data removed	
	General information		
3	Heat Exchanger (HX) application (nuclear, petrochemical, etc.)	Gas-to-Liquids, Hydrogen	
4	Type of Heat Exchanger *If compact HX, what type of compact HX (e.g., Plate-Fin, Plate-Stamped, etc.)?* *If tubular HX, what type of tubular HX? (e.g., helical coil, U-tube, etc.)?*	Microchannel, integrated 5-stream recuperator, integrated into Steam Methane Reformer reactor block	
5	HX Thermal Power (MWt)	N/A (steam methane reformer, not just heat exchanger)	
6	Normal operating conditions	*Primary side*	*Secondary side*
	Inlet Temperature (°C)	~300C	~60C (fuel) & ~130C (air)
	Outlet Temperature (°C)	~400C	~400C
	Pressure (MPa)	~2 MPaG	~0.1 MPaG
	Maximum reaction temperature (added line)	~850C	~890C
7	Maximum temperatures expected in off-normal situations	~920C	~920C
8	Heat transfer medium	1. Reactants (steam, methane), 2. fuel & 3. air	1. Reformate product (CO, CO_2, H_2, H_2O), 2. Combustion Exhaust
9	Expected design life and, if operated, how many years of operation have been performed	10 year design life. Fulll scale block has not yet been built and operated. Smaller scale devices have been operated for ~1000 hrs	
10	Materials used or envisioned *If possible, specify materials for the main parts (vessel, tubes, tube-plate, etc.) and expected product forms and thicknesses*	Alloy 617 Possible alternatives: Haynes 230, HR-120	
11	Any surface treatment used or envisioned (coating, preoxidation, etc.)	Aluminization	
12	If stress relieving process is used or envisioned, specify which part	None	
	Design		
13	Which Codes or Standards are used or envisioned (ASME, RCC-MR, ISO or EN Standards, etc.)?	ASME	
14	How do you (or did you) define the primary pressure boundary?	Reactor: Exterior of the block (diffusion bonded stack)	
15	What part of the Code&Standards is used or envisioned for the pressure boundary?	Reactor block is designed per ASME Section VIII, Division 1. However, reactor block will be enclosed in an external Pressure Containment Shell (PCS) - a pressure vessel designed to ASME Section 8 Division 1	
16	What part of the Code&Standards is used or envisioned for internals including heat exchange part?	ASME Section VIII Divison 1.	
17	If there were any difficulties applying the Code&Standards, please specify what it was and how it was applied	Elements of Section VIII Division 3 and NH were applied because of considerations of thermal cycling and creep-fatigue damage	
18	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	Refinement of T-1433, Creep Damage Evaluation.	
19	If erosion is a concern, how is this taken into account in the design (e.g., graphite dust in the heat transfer medium)?	None	

20	How are the environmental effects taken into account in the design (e.g., extra thickness, reduction of material properties etc)?	None
21	What is the limiting factor on lifetime (creep-fatigue etc)?	Creep-Fatigue
	Clarify if practice is to rely upon elastic or inelastic analyses and were specific constitutive equations developed? If applicable, mention type of constitutive equations and for which material.	Both Elastic and Inelastic. No constitutive equations developed
	Material	
22	Which Codes or Standards are used or envisioned for procurement?	SB-168
23	What is the source of material properties used for design (Codes, internal documentation)?	Internal documentation and Section II, part D
24	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	Consistency of material (esp. creep properties) of SB-168 is highly variable. Refinement of SB-168 for diffusion bonding applications is recommended; and Table TM-4, Table Y-1, and Table TE-4: values for N06617 to 1800 deg.F.
	Fabrication	
25	Which Codes or Standards are used or envisioned for fabrication? *If need be, clarify between the different parts of the HX*	Section IX Welding and Brazing Qualifications
26	Which processes are used or envisioned for welding?	TIG
27	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	Inclusion of diffusion bonding (diffusion welding)
	Non Destructive Examination (NDE)	
28	Which NDE techniques are used or envisioned for the HX? *If possible, clarify between the different parts of the HX and mention the extent of control. A distinction can be made between NDE during and after fabrication and NDE in the context of In-Service Inspection*	Hydrostatic leak test. Fluorescent die penetrant test of welds
29	Which Codes or Standards are used or envisioned for fabrication?	N/A
30	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	None

Gen IV Task 7 - ASME Code Considerations for IHX			
1	Organization	Data removed	
2	Contact person and email address	Data removed	
	General information		
3	Heat Exchanger (HX) application (nuclear, petrochemical, etc.)	Nuclear, Petro-chemical, Chemical Reactor	
4	Type of Heat Exchanger ***If compact HX, what type of compact HX (e.g., Plate-Fin, Plate-Stamped, etc.)?*** ***If tubular HX, what type of tubular HX? (e.g., helical coil, U-tube, etc.)?***	Compact HX (PCHE, FPHE, H^2X)	
5	HX Thermal Power (MWt)	Modular construction to suit application (up to 3.6GWt so far)	
6	Normal operating conditions	***Primary side***	***Secondary side***
	Inlet Temperature (°C)	up to 950°C	minimum 2°C temperature approach
	Outlet Temperature (°C)	Up to 98% Effectiveness	
	Pressure (MPa)	Alloy, temperature and process dependant; For PCHE this is not normally a constraint	
7	Maximum temperatures expected in off-normal situations	Maximum temperature for metallic HX is up to 982°C	
8	Heat transfer medium	Gas - Liquid Metal - Water; All clean fluid	
9	Expected design life and, if operated, how many years of operation have been performed	See attached product reference list (IHX is first of a kind so design life is to suit customer requirements)	
10	Materials used or envisioned *If possible, specify materials for the main parts (vessel, tubes, tube-plate, etc.) and expected product forms and thicknesses*	Austenitic Stainless steels - Nickel based super alloy; Choice to suit process requirements	
11	Any surface treatment used or envisioned (coating, preoxidation, etc.)	Coating to include Aluminium oxide has been considered for other applications	
12	If stress relieving process is used or envisioned, specify which part	As required by the code	
	Design		
13	Which Codes or Standards are used or envisioned (ASME, RCC-MR, ISO or EN Standards, etc.)?	ASME, RCC	
14	How do you (or did you) define the primary pressure boundary?	As required by customer and code	
15	What part of the Code&Standards is used or envisioned for the pressure boundary?	ASME, RCC	
16	What part of the Code&Standards is used or envisioned for internals including heat exchange part?	ASME VIII, RCC	
17	If there were any difficulties applying the Code&Standards, please specify what it was and how it was applied	Inspection requirements, ASME III is not currently applicable to Gen IV applications	
18	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	ASME III should consider compact heat exchanger technology and high temperature applications	
19	If erosion is a concern, how is this taken into account in the design (e.g., graphite dust in the heat transfer medium)?	Velocity control and erosion allowance.	
20	How are the environmental effects taken into account in the design (e.g., extra thickness, reduction of material properties etc)?	Case by case as determined with testing and agreed with customer.	
21	What is the limiting factor on lifetime (creep-fatigue etc)?	Process specific, alloy dependant, creep fatigue, corrosion, erosion, ageing.	

	Clarify if practice is to rely upon elastic or inelastic analyses and were specific constitutive equations developed? If applicable, mention type of constitutive equations and for which material.	Generaly elastic (as per design code)
	Material	
22	Which Codes or Standards are used or envisioned for procurement?	ASME materials
23	What is the source of material properties used for design (Codes, internal documentation)?	Codes, ASME II D and RCC supplemented by client, approved test program
24	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	High temperature in ASME III
	Fabrication	
25	Which Codes or Standards are used or envisioned for fabrication? *If need be, clarify between the different parts of the HX*	ASME, RCC
26	Which processes are used or envisioned for welding?	TIG, MIG, Diffusion Bonding, Submerged arc.
27	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	Rules for qualification process and categorisation of final product form of diffusion bonded core
	Non Destructive Examination (NDE)	
28	Which NDE techniques are used or envisioned for the HX? *If possible, clarify between the different parts of the HX and mention the extent of control. A distinction can be made between NDE during and after fabrication and NDE in the context of In-Service Inspection*	Radiography, Phased array, Dye-pen, Eddy current, UT, Visual.
29	Which Codes or Standards are used or envisioned for (fabrication) NDE?	ASME, RCC
30	If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development	Investigation into Phased array and Eddy current.

Gen IV Task 7 - ASME Code Considerations for IHX			
1	**Organization**	Data removed	
2	**Contact person and email address**	Data removed	
	General information		
3	**Heat Exchanger (HX) application (nuclear, petrochemical, etc.)**	Nuclear, High-Temperature Gas-Cooled Reactor	
4	**Type of Heat Exchanger** ***If compact HX, what type of compact HX (e.g., Plate-Fin, Plate-Stamped, etc.)?*** ***If tubular HX, what type of tubular HX? (e.g., helical coil, U-tube, etc.)?***	Compact Plate-Fin or Plate (etched or machined microchannels in plates that are diffusion bonded, e.g., PCHE)	
5	**HX Thermal Power (MWt)**	508MWt total Two Section IHX: IHX A: ~158MWt/IHX B: ~350MWt	
6	**Normal operating conditions**	*Primary side*	*Secondary side*
	Inlet Temperature (°C)	IHX A: 950C IHX B: 760C [nominal]	IHX A: 710C [nominal] IHX B: 287C
	Outlet Temperature (°C)	IHX A: 760C [nominal] IHX B: 337C	IHX A: 900C IHX B: 710C [nominal]
	Pressure (MPa)	8.8	9.1
7	**Maximum temperatures expected in off-normal situations**	[TBD]	[TBD]
8	**Heat transfer medium**	Helium	Helium
9	**Expected design life and, if operated, how many years of operation have been performed**	IHX A: 10 years [min] design life IHX B: 60 years design life	
10	**Materials used or envisioned** *If possible, specify materials for the main parts (vessel, tubes, tube-plate, etc.) and expected product forms and thicknesses*	IHX A: Vessel - Low-Alloy Steel (SA508/533) (vessel to operate below 371C) HT Modules, Internal Piping & Manifolds - Alloy 617 IHX B: Vessel - Low-Alloy Steel (SA508/533) (vessel to operate below 371C) HT Modules, Internal Piping & Manifolds - Alloy 800H	
11	**Any surface treatment used or envisioned (coating, preoxidation, etc.)**	None presently identified, but may be considered	
12	**If stress relieving process is used or envisioned, specify which part**	None anticipated, except in the normal course of vessel manufacture	
	Design		
13	**Which Codes or Standards are used or envisioned (ASME, RCC-MR, ISO or EN Standards, etc.)?**	Vessels: ASME Section III Internal Structures: [TBD] (likely ASME Section III)	
14	**How do you (or did you) define the primary pressure boundary?**	This is being discussed. We are not convinced that the present Code framework provides an adequate basis for definition of the two-loop Primary/Secondary Heat Transport System (PHTS/SHTS) architecture. In particular, we do not believe that treatment of the heat transfer surface of a microchannel HX as a classical primary pressure boundary is necessary or appropriate for the NGNP design, in which leakage would be from one closed loop to another closed loop. It is suggested that ASME and/or other Code organizations provide a forum for further discussion of this application type and for the possible development of more appropriate rules for such interfaces.	
15	**What part of the Code&Standards is used or envisioned for the pressure boundary?**	Vessels: ASME Section III Internal pressure boundary between PHTS and SHTS: See below.	
16	**What part of the Code&Standards is used or envisioned for internals including heat exchange part?**	Not yet determined. ASME Section III a likely candidate. There are several C&Ss that could be fully or partially applied to individual internal components (notably the use of the draft code case on IN617 for material properties and design rules, i.e. creep-fatigue interaction). There is no Code framework at present that would adequately address the highest temperature components. Guidance from and partial applicability of Section III/NH, Section VIII and German KTA Codes (e.g., 3221) are options. The present approach for the highest temperature components is design by analysis, using German data for materials.	

17	**If there were any difficulties applying the Code&Standards, please specify what it was and how it was applied**	No present Code basis exists for: 1. Highest temperatures in the IHX (design or materials) 2. The design architecture of compact HX modules at any temperature
18	**If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development**	See above comments.
19	**If erosion is a concern, how is this taken into account in the design (e.g., graphite dust in the heat transfer medium)?**	Not believed to be a concern. If it becomes a concern, would consider a thickness allowance, similar to corrosion allowance, based on testing.
20	**How are the environmental effects taken into account in the design (e.g., extra thickness, reduction of material properties etc)?**	Characterization of environmental effects on thin sections identified as a key technology development issue/ prerequisite for metals in IHX A. Beyond a limited degree, added thickness is not a practical option in compact HXs.
21	**What is the limiting factor on lifetime (creep-fatigue etc)?**	Corrosion of thin sections appears to be potentially limiting in the highest temperature areas of the compact HX surface. Creep and creep-fatigue do not appear to be limiting at the level investigated to date; however, only scoping preconceptual analysis has been done to date.
	Clarify if practice is to rely upon elastic or inelastic analyses and were specific constitutive equations developed? If applicable, mention type of constitutive equations and for which material.	To date, only scoping elastic and inelastic analyses done. No specific constitutive equations have been developed to date.
	Material	
22	**Which Codes or Standards are used or envisioned for procurement?**	Vessels: ASME Section II/III Heat Transfer Surface and Internal Piping: [TBD]
23	**What is the source of material properties used for design (Codes, internal documentation)?**	ASME Section III & VIII; German KTA 3221 , Draft Code case on IN617
24	**If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development**	Extend materials coverage to high temperature alloys and to at least 950C. Extend ASME III, NH rules to HT alloys and design temp's up to 950C. Qualify applicable product forms.
	Fabrication	
25	**Which Codes or Standards are used or envisioned for fabrication?** *If need be, clarify between the different parts of the HX*	Vessels: ASME Section III Internals: Design by Analysis, KTA 3221
26	**Which processes are used or envisioned for welding?**	Vessels and internal piping: Standard welding practices HT Modules: brazing or diffusion bonding
27	**If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development**	Coverage for brazing/diffusion bonding. Resistance Welding
	Non Destructive Examination (NDE)	
28	**Which NDE techniques are used or envisioned for the HX?** *If possible, clarify between the different parts of the HX and mention the extent of control. A distinction can be made between NDE during and after fabrication and NDE in the context of In-Service Inspection*	Vessels: Standard fabrication NDE & ISI practices Internal Piping: Standard fabrication NDE; ISI TBD HT modules: Pressure/leak testing during fabrication; ISI TBD (possibly pressure testing/leak detection during maintenance outages for ISI)
29	**Which Codes or Standards are used or envisioned for fabrication?**	Vessels: ASME III & V(NDE) Internal piping and HX modules: TBD
30	**If applicable, provide suggestions of improvement of the Codes&Standards or identify needs for development**	Coverage for compact HXs. The code need to provide rules for treating the diffusion-bonded material, whose properties could appreciably have been changed in the bonding process. i.e. what material designation is ascribed to this material, and what allowable design stress values should be applied.

APPENDIX B ACRONYMS USED WITHIN THIS DOCUMENT

IHX	Intermediate Heat Exchanger
HX	Heat Exchanger
PMHE	Plate Machined Heat Exchanger
PSHE	Plate Stamped Heat Exchanger
PFHE	Plate Fin Heat Exchanger
PCHE	Printed Circuit Heat Exchanger
HTR	High Temperature Reactor
VHTR	Very High Temperature Reactor
HTTR	High Temperature Test Reactor
KVK	A former HTR component testing facility in Germany
JAERI	Japan Atomic Energy Research Institute
FIV	Flow-Induced-Vibration
GTAW	Gas Tungsten Arc Welding
CFD	Computational Fluid Dynamics
PWR	Pressurized Water Reactor
THCHE	Tubular Helical Coil Heat Exchanger
LOM	Laminated Object Manufacturing

APPENDIX C PERTINENT DOCUMENT LIST

Below is a list of documents that offer noteworthy information not directly referenced within this document. It is meant to provide the reader additional, readily available resources for information about IHX design and manufacturing.

1. International Working Group on Gas-Cooled Reactors, IWGGCR-9, Specialist meeting on Heat Exchanging Components of Gas-Cooled Reactors, 16-19 April 1984

This meeting was divided into eight subject sessions:
I. Heat exchanging components for process heat application - design requirements and r/d programs
11. Status of the design and construction of intermediate He/He heat exchangers
111. Design, construction and performance of steam generators
IV. Design, development and fabrication of steam reformers.
V. Metallic materials and design codes
VI. Design and construction of valves and hot gas ducts
VII. Description of component test facilities and test results
VIII. Manufacturing of heat exchanging components

A total of 38 papers were presented by the participants on behalf of their organizations during the meeting.

2. Nuclear Energy for Hydrogen Production, Karl Verfondern (Editor), Energy Technology Volume 58, ISBN 978-3-89336-468-8

This document provides the major items of a roadmap for implementation of an industrial production of hydrogen using nuclear energy. Chapter three focuses on the nuclear production technologies for hydrogen including a technical discussion of the coupling schemes. Section 3.2 provides a discussion on intermediate heat exchangers for high temperature gas cooled reactors.

3. International Working Group on Gas-Cooled Reactors, IWGGCR-18, Specialist meeting on Heat Exchanging Components of Gas-Cooled Reactors, 20-23 June 1988

This document has a great deal of information pertaining to HTGR material issues. Most of the information centers around alloy 617 and 800; however, other materials such as Hastelloy X and XR are discussed. There are a number of papers directly applicable to IHX design considerations.

4. 2008 Proceedings of the ASME 4th International Topical Meeting on high Temperature Reactor Technology http://catalog.asme.org/ConferencePublications/CDROM/Proceedings_4th_International.cfm

The proceedings are available for sale at the ASME web site indicated. Several documents are the IHX. Below is a list of some that are:
HTR2008-58071, Development of a Coupling Process Heat Exchanger Between a
VHTR and a Sulfur-Iodine Hydrogen Production System
HTR2008-58097, Investigation of Printed Circuit Heat Exchanger for VHTRs
HTR2008-58130, IHX Design and Development for the Next Generation Nuclear Plant
HTR2008-58143, Integrated Systems CFD Modelling applied to Diffusion-Bonded Compact Heat Exchangers
HTR2008-58146, State of the Art of Helium Heat Exchanger Development for Future HTR-Projects

HTR2008-58175, Design Option of Heat Exchanger for the Next Generation Nuclear Plant

5. La conversion d'énergie en technologie gaz, tronc commun aux nouveaux RNR et auxR(T)HT
   English translation: Conversion of energy by gas technology, a common point between Fast Neutron Reactor and HTR.

www.cea.fr/content/download/4870/29071/file/clefs55_p091_097_Berjon.pdf

This document contains information on compact high temperature heat exchanger (IHX) designs. The document is only available in French.

AREVA NP Inc.,

an AREVA and Siemens company

Technical Data Record

Document No: 12 - 9100008 - 001

ASME Task 7, Part 2 - Recommended Code Approach for Intermediate Heat Exchanger

ASME Task 7 – Recommended Code Approach for Intermediate Heat Exchanger

Safety Related? ☐ YES ☒ NO

Does this document contain assumptions requiring verification? ☐ YES ☒ NO

Does this document contain Customer Required Format? ☐ YES ☒ NO

Signature Block Rev 001

Name and Title/Discipline	Signature	P/LP, R/LR, A/A-CRF	Date	Pages/Sections Prepared/Reviewed/ Approved or Comments
Duane Spencer Principle Engineer / Mechanical Engineering	[signature]	P	1-26-10	All
Lew Lommers HTR Project Engineering Manager	[signature]	R	2-2-10	All

Note: P/LP designates Preparer (P), Lead Preparer (LP)
R/LR designates Reviewer (R), Lead Reviewer (LR)
A/A-CRF designates Approver (A), Approver of Customer Requested Format A-CRF
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Record of Revisions

Revision No.	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
000	ALL	Initial issue
001	All	Editorial and grammatical corrections made throughout the document.
	All	"In 617" changed to "Alloy 617" wherever used
	3.2, page 11, 2nd hollow bullet	Changed "1200˚C" to "1200˚F" in 2 places
	3.2, page 11, last hollow bullet	"Reference 4" was "Reference 3"
	3.2, page 12, 1st paragraph	"Reference 2" was "Reference 4"
	3.2, page 12, 2nd paragraph	"Case design fatigue curves" was "Case design curves"
	3.4, last bullet	Sentence rewritten
	3.5, last sentence	"relevant" was "efficient"
	3.7, 1st paragraph	ACRS was defined
	3.8.1, 2nd paragraph	Added reference to reference 24 and brief discussion of that article.
	3.8.2.1 last paragraph	"100,000 h" was "100,000"
	3.8.2.1 last sentence	Deleted sentence
	3.8.2.2 the 4 bullets	Added "UNS"
	3.8.2.7 1st paragraph	Sentence added to end of paragraph
	3.8.2.7 2nd paragraph	Reference callout to reference 25.
	3.8.2.7 last sentence	"Section 3.8.2.6" was "Section 3.2.4"
	3.8.2.8, 1st paragraph	"Section 4.2" was "Section 3.3"
	3.8.2.8, last paragraph	2 sentences added to end of paragraph
	3.8.3, 1st paragraph	Reworded first paragraph
	6.1.4, 1st sentence	Reworded sentence
	6.2, last paragraph	Sentence added to end of paragraph
	6.2.3, 1st paragraph	Sentence added to end of paragraph
	8.0, 4th paragraph	Added sentence to end of paragraph
	9.0	Added references 24 and 25

Table of Contents

Page

List of Tables

Page

List of Figures

Page

1.0 INTRODUCTION

This report has been prepared in the context of Task 7 of the ASME/DOE Gen IV / NGNP material project. It is aimed at providing recommendations in terms of Code approach for the Intermediate Heat Exchangers envisioned for High Temperature gas-cooled Reactors. This report follows the work performed in Part 1 of this Task (Ref. 23) which listed the current experience on high temperature Intermediate Heat Exchangers (IHX) technology, including service experience, qualification and materials.

The present task will address the following:

1. Recommend key features of a construction code needed to address the unique issues associated with the VHTR IHX and associated equipment

2. Identify the tests which should be required to establish cyclic life or to calibrate design methods

3. Identify required in-service inspection and associated NDE

4. Review the adequacy of existing ASTM specifications for materials, testing, examination, etc. to determine if any new standards will need to be developed to support IHX design, fabrication, operation or inspection.

5. Provide recommendations in terms of Code infrastructure

In HTR/VHTR design, intermediate heat exchangers (IHX) are envisioned for application in a range of temperature from 850 to 900°C. There are several designs for the heat exchanging part of the IHX which will be mentioned in Section 2 of this document. A common point of the designs is that the heat exchanging parts exposed to hot primary helium are located inside a pressure vessel. As long as hot transient can be withstood by this pressure vessel, the material selected for it can be the same as that of main reactor vessel.

For the exchanging part of IHX, the selected materials are currently high nickel alloys following the choices made in Germany and in Japan for service in high temperature helium. In Section 3.8.2 of this document, an evaluation of the different high nickel alloys will be made according to their chemical analyses and their mechanical properties as available in ASME code or other similar documents. The goal of this evaluation is to identify the tests necessary to assess design methods and to establish cyclic life. Testing to determine the effects of representative helium environment to be performed will be discussed in Section 4. Section 3.8.3 will address manufacturing features including welding.

2.0 CONSIDERED DESIGNS FOR HTR IHX

2.1 Helical tubes design

The helical tube design needs plates for internal shell, and tubes around 2mm thick. Welding techniques must be developed for these types of products. As particular part, the helical tube design involves at least one tube sheet, the geometry of which needs to be clarified. Except high or very high temperatures and environmental effects, assessment of the design of helical tubes IHX does not require particular methods to be developed and codified.

2.2 Compact Stacked Plate IHX designs

Three types of plate heat exchangers have been considered:

- Plate Machined Heat Exchanger (PMHE)
- Plate Stamped Heat Exchanger (PSHE)
- Plate Fins Heat Exchanger (PFHE)

Concerning the needs for materials and products, PMHE and PSHE do not require materials with properties different from those of the helical tube IHX as the properties of plates and tubes are expected to be similar if their thicknesses are similar. In the case of PFHE, much thinner sheets (0.1 and 0.38 mm) are needed. Past experiences on materials for micro-turbine (Ref.13) have shown that mechanical properties of such sheets at elevated temperatures can be very different from properties of the bulk material. In this case, particular characterization of thin sheets is required.

In the technology of plate heat exchangers, particular developments are devoted to fabrication of the plate assembly. Processes such as brazing, diffusion bonding, and laser welding have been considered. The feasibility and qualification of these techniques will need to be evaluated. It should be noted that brazing as well as diffusion bonding implies a relatively long heat treatment at a temperature which can affect the base material properties. Compatibility of the material with this treatment must be checked and will result in rules for the selection of brazing or bonding conditions.

The IHX can be designed such that the separation between primary and secondary fluid is made using base material plates without joints other than at the periphery. Welds in the plate periphery as well as welds in the fluid inlet and outlets system, will introduce weld factors in the design. However, ordinary and standard welding methods can be used.

For plate heat exchangers used at current upper limit temperatures, the maximum allowable pressure is related to failure pressure measured experimentally with representative mock-ups tested under increasing pressure. For plate IHX for HTR, this kind of approach should be mentioned in the section of the code devoted to Level D service limits.

3.0 KEY FEATURES OF A CONSTRUCTION CODE

3.1 Introduction

This section will first summarize the code developments carried out in the US , Germany and Japan for HTR applications, then the code development on heat exchanger performed for other low and high temperature applications. Issues raised by the Nuclear Regulatory Commission (NRC) in the context of high temperature design (Clinch River Breeder Reactor) will be also listed. The remainder of the section will discuss, based on current technology and expected licensing path, what should be the key features to be introduced in the Code.

3.2 High temperature Code development in the US

A draft Alloy 617 Code Case was issued in the late eighties by the ASME Task Force on Very High Temperature Design (Reference 2). The specific component considered by the Task Force was a steam methane reformer which would be part of the primary pressure boundary and the Code Case was therefore based on Code Case N-47 (for class 1 components) and consisted in the following differences compared to high temperature design rules of that Code Case:

- Code Case limited to components made of UNS N06617 (Alloy 617) for operation up to 1800°F (982°C)
- Limitation of the design life to 100,000 hours or less,
- Mention that Alloy 617 has several unique characteristics which should be addressed:
  - No clear distinction between time-independent elastic plastic behavior and time-dependent creep behavior at the temperatures of interest
  - Flow stresses very dependent on strain rate
  - Material can soften with time, temperature and strain.
- Recommendations to use above 1200°F (649°C) unified constitutive equations covering the following features:
  - Effect of plastic strain hardening and softening (including cyclic loading effects and the hardening or softening which can occur with high temperature exposure)
  - Primary, secondary and tertiary creep and the effects of creep strain hardening as well as softening (due to reverse loading)
  - Effects of prior creep on subsequent plasticity and vice-versa.
- Design (Primary stress) limits based on S_o or S_{mt} for the corresponding design life, whichever is greater.
- Level D service limits defined as 70% of the lesser of the collapse load and the plastic instability load.
- Bolts not permitted (due to risks of low fracture thoughness)
- Warning that exposure at elevated temperatures may cause significant reductions in the fracture toughness of materials
- Material properties specific to Alloy 617 up to 1800°F (982°C):
  - S_0 maximum allowable stress

- S_m time independent allowable stress. S_m is defined as the lesser of 1/3 tensile strength at room temperature, 11/30 of minimum tensile strength at temperature, 2/3 of specified minimum yield strength at room temperature, 90% of minimum yield strength at temperatures up to 1200°F (649°C) or 2/3 of minimum yield strength for temperatures above 1200°F (649°C).
- S_{mt} time dependent allowable stress
- S_t time dependent allowable stress defined as the minimum of 2/3 minimum creep stress to rupture in time t and minimum stress to produce 1% strain in time t (S_t does not therefore depend on tertiary creep)
- S_y yield strength
- S_r minimum creep stress to rupture, based on Larson-Miller and defined as 1.65 standard deviations below the mean
- Modulus of elasticity
- Instantaneous and mean coefficients of thermal expansion
- Design fatigue curve
- Isochronous stress-strain curves starting from 1200°F (649°C), based on the ORNL unified equations (improved Robinson's model) for a representative single heat, then moved to pass through average 0.2% and 1% strain based on Huntington Alloy data package (Reference 4)

- Limitation of strain limits (ratcheting) using elastic analysis and simplified inelastic analysis to 1200°F (649°C)
- Cross over between time independent (S_m) and time dependent allowable stress (S_t) at 1050°F (about 565°C)
- Factor for determining creep damage K'=0.67
- Bi-linear creep-fatigue damage envelope with intersection at (0.1;0.1)
- Thermal expansion elastic follow-up to be accounted for in the design of piping systems even though no practical rules are provided.
- Buckling analyses to be based on unified constitutive equations for temperatures exceeding 1200°F (649°C)
- Consideration of buckling due to short term loadings and non ductile rupture as additional failure modes

The following points were mentioned but not provided in the Code Case:

- Permissible weld materials

- Weld factors (stress rupture factors),
  even though information in support of the Code Case (Reference 2) indicates that creep stress to rupture results were available on welded joints obtained with Inconel welding electrode 117 and Inconel filler material 617, weldment stress rupture factors were not provided.

It is also to be mentioned that even though mention is made several times that strain rate effects should be taken into account, no practical rules are provided to take this effect into account and fatigue curves provided are not strain rate dependent. The background to the Code Case design fatigue curves is provided in Reference 5. This document also indicates that only in air tests were considered and it is mentioned that the bulk of continuous fatigue test results indicate little or no effect of the impure helium environment (except in severe carburizing atmosphere). Longer term tests under creep-fatigue conditions may show a larger environmental effect.

Reference 6 outlined gaps and shortcomings identified at that time:

- Alloy 617 must be added to the low-temperature rules of section III

- Weldment stress rupture factors must be added

- Additional isochronous curves must be added (covering in particular the lower temperatures domain)

- Complete database with weldment fatigue results and creep-fatigue results

- Improve understanding of effects of environment on material properties

- Characterize the effect of aging on toughness

- Extend constitutive equations to multiaxial case for design analyses purposes

- Perform tests on structural models

- Simplified ratcheting evaluation methods must be extended for application above 1200°F (649°C)

- Identify and validate other more appropriate creep-fatigue damage models to replace the linear damage fraction.

The draft Code Case listed the following high temperature failure modes. The last two are specific to Alloy 617.

- Ductile rupture from short term loading

- Creep rupture from long term loading

- Creep-fatigue failure

- Gross distortion due to incremental collapse and ratcheting
- Creep buckling due to long term loadings
- Loss of function due to excessive deformation
- Buckling due to short term loadings
- Non-ductile rupture

3.3 High temperature Code development in Germany

An extensive program has been carried out in Germany in the 80's and 90's in the context of HTRs. For metallic high temperature materials, the program focused mainly on Alloy 617 and Alloy 800 (different grades studied) and led to the preparation of a draft KTA section providing design material properties (ref. 7) and series of specifications for the base and weld metal. The complete set of KTA rules prepared in the context of the German HTR program is the following:

- KTA 3221.1 Metallic HTR-Components, Manufacturing of Materials and Product Forms, Draft Version 1992
- KTA 3221.2 Metallic HTR-Components, Design, Construction and Analysis, Draft Version 1992
- KTA 3221.3 Metallic HTR-Components, Manufacturing of Components, Draft Version 1992
- KTA 3231 Prestressed Concrete Reactor Pressure Vessel, Draft Version 1992
- KTA 3232 Ceramic Internals in HTR-Pressure Vessels, Draft Version 1992
- KTA 3221.5 Metallic HTR-Components, Additional Requirements for Reactor Pressure Vessel, Draft Version 1992

Appendix A6 of Ref. 7 provides material properties for Alloy 617 up to 1000°C:

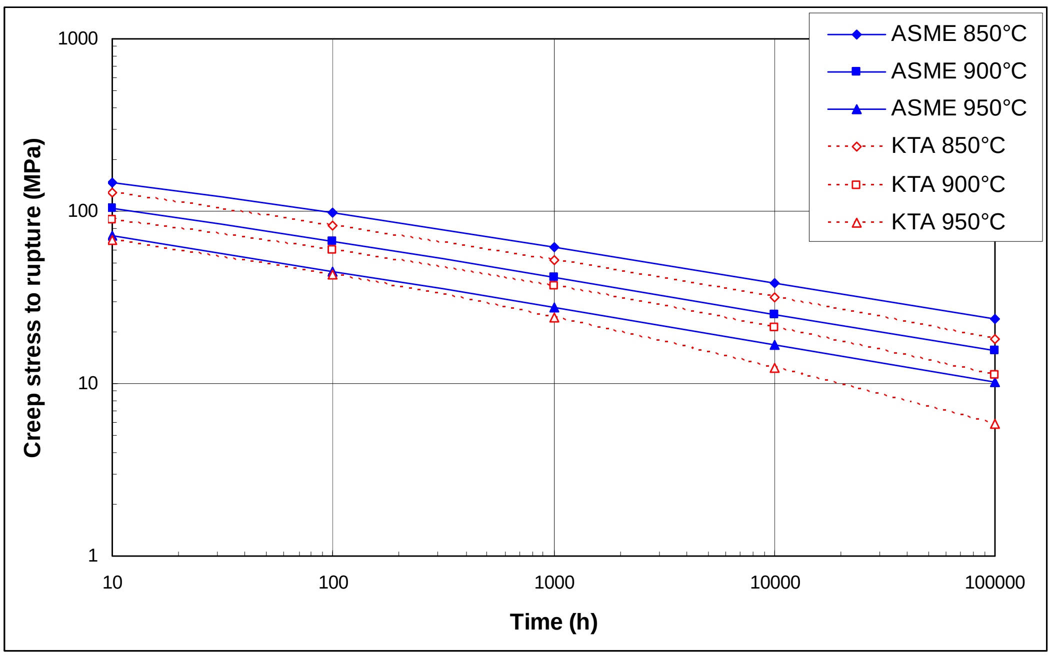
- Modulus of elasticity
- Shear modulus
- Specific heat
- Instantaneous and mean coefficients of thermal expansion
- Thermal conductivity
- Density
- Mean and minimum 0.2% and 1% yield strength ($R_{p0,2}$ and $R_{p1\%}$)
- Mean and minimum ultimate tensile strength R_m
- Mean and minimum elongations
- Mean and minimum 1% deformation stress
- Mean and minimum creep stress to rupture $R_{m,t}$

- Time dependent allowable stress S_t defined as the minimum of : $R_{m,t}$ / 1.35 ; $R_{p1\%,t}$; $R_{m,3.t}$; $R_{m,t}$(T+15K) (T temperature)
- Isochronous stress-strain curves starting from 750°C to 1000°C
- Best estimate and design fatigue curves in air and HTR helium
- Norton Law Constants
- Paris law constants (C, n) for fatigue crack growth
- Constants for creep crack growth law ($da/dt = BC^{*m}$)
- Weld factors up to 950°C.

Reference 7 provides also qualitative information on the effect of Helium environment.

It is to be noted that the data basis used in Germany and in the US are different. Figure 3.3-1 compares creep stress to rupture from KTA (ref. 7) to that from the ASME Code Case (interpolated to the same temperatures as those used by KTA). It can be noted that the German curves are more conservative than US curves and a thorough evaluation should be performed to understand the differences between the German and US Code design data.

Figure 3.3-1: Comparison creep stress to rupture



3.4 High temperature Code development in Japan

The High Temperature Test Reactor (HTTR) operates with an IHX at 900°C and specific developments have been carried out to enable the design of such a component whose exchange tubes and hot header are made of Hastelloy XR (Reference 8).

The High Temperature Structural Design Guideline for the HTTR was based on the FBR Code (Elevated Temperature Structural Design Guide for class 1 Components of Prototype Fast Breeder Reactor “Monju”) authorized by the Japanese government. The latter was originated from the ASME Boiler and Pressure Vessel Code Case N-47. Table 3-1 summarizes the tests performed to support the code development.

The emphasis of the structural mechanics work was placed on the verification of the applicability of the FBR code to the HTR design and the following was demonstrated

- Applicability of strain hardening rule and Von Mises’ multiaxiality criterion for creep damage assessment (under primary+secondary stresses)
- Creep strain curve data better correlated by the time function law proposed by Garofalo et al. (1963)
- Adequacy of the design rules for the integrity of the heat exchange tubes against creep buckling (based on tests performed at HENDEL test loop)
- Applicability of the linear summation rule of cycle and time fractions to Hastelloy XR with a great deal of safety margin even at very high temperatures
- There are no detrimental effects of a He environment for Hastelloy XR, provided that the primary coolant of the reactor operates in a controlled benign environment

It was also pointed out that special attention had to be paid to dynamic recrystallization of Hastelloy XR at high temperature and a new tensile test procedure with a change in strain rate to 100%/min at temperatures over 800°C was proposed to obtain the time-independent elastic–plastic properties.

Finally, it should be noted that fatigue curves used in the Structural Design Guideline for Hastelloy XR are strain rate dependent and the design of the heat transfer tubes and central hot gas duct for HTTR had to be performed based on inelastic analyses.

TABLE 3-1: Mechanical tests on Hastelloy XR

Test item	Test conditions
Tensile tests	Temperatures: room temperature to 1000 °C, every 25 °C Strain rates: 0.3–100 %/min
Creep tests	Temperatures: 500–1050 °C, every 50 °C Maximum test time: about 38,000 h Total number of tests: about 300
Fatigue and creep–fatigue interaction tests	Temperatures: room temperature to 1000 °C, every 50 °C at high temperatures Strain rates: 2×10^{-5} to 1×10^{-3} s^{-1} Hold times: 0–1 h Materials: as received and thermally aged
Fracture toughness tests	Thermal aging conditions Temperatures: 800–1000 °C Maximum aging time: 2000 h Test items: V-notch charpy, fracture toughness and fatigue crack propagation rate
Corrosion tests	Environment: HTTR coolant gas-simulated helium Temperatures: 900–1000 °C Maximum test time: 30,000 h
Others	Poisson's ratio, thermal expansion and so on

3.5 Other heat exchanger code development

European Standard EN 13445-3 (Reference 9) section 13 provides rules for the design of the following types of heat exchangers:

- U-tube tubesheet heat exchangers
- Fixed tubesheet heat exchangers
- Floating tubesheet heat exchangers.

The approach used is similar to that used in ASME VIII division 1.

Annex J of EN 13445-3 provides an alternative method for the calculation of tubesheets. This method, which is based on limit analysis theory, leads to very different, much more relevant results (Reference 10).

3.6 Considerations on safety classification of the IHX

In simplistic terms, a loss of forced cooling accident without a reactor trip for a gas-cooled VHTR can be described as follows: If the primary coolant flow is lost and the reactor fails to trip, the core temperature will rise causing the reactivity of the core to reduce. This negative reactivity temperature coefficient effect causes fewer neutrons to be produced which will result in an increase in available xenon. The increased amount of xenon will absorb more of the neutrons that are produced thereby further reducing the reactivity of the core. The temperature of the core will rise at first due to the loss of coolant flow but slowly reduce as heat generation of the core subsides. The graphite moderator and the vessel are designed to absorb and withstand the increased temperature of a loss of coolant flow accident. The core is passively cooled via heat loss through the reactor vessel. The reactor vessel is cooled via a passive cooling system in the reactor cavity. Eventually a reactor trip will be needed to shut the reactor down and continue core cooling otherwise the reactor will become re-critical but at a lower power level and the cycle continues until the reactor is tripped and cooled. The gas cooled VHTR does not require forced cooling either in a pressurized or depressurized reactor loss flow accident conditions to achieve the safe shutdown and cooldown of the reactor. The reference design described in Part 1 of Task 7 uses helium as the secondary side coolant. The reactor core will be designed to remain subcritical in the event of secondary side coolant or air ingress. It is assumed that future analysis and testing will show that air ingress due to a loss of coolant accident will not cause significant damage or sustained oxidation of the reactor internals nor the fuel. That said, the reactor forced cooling systems (shutdown cooling system, primary circulator or the IHX) are not required for the safe shutdown and cooldown of the reactor. Therefore, the IHX should be classified as a non-safety related component.

ASME Boiler and Pressure Vessel Code design and fabrication rules are broken into several classes with Class 1 being most rigorous. As stated in the Code: “The Code classes allow a choice of rules that provide assurance of the structural integrity and quality commensurate with the relative importance assigned to the individual items of the nuclear power plant.” While total loss of reactor coolant does not compromise the safe shut down of the reactor, it is no small matter and could potentially cause considerable damage and in the least cause extensive loss of revenue due to an unplanned outage. Transfer of coolant from the primary to the secondary side or vise versa will reduce the efficiency of the power plant. Protection of such an important capital investment is of utmost importance. Likewise, the rules for design and construction should be of the highest degree reasonable. ASME Section III, Division 1, Subsection NH applies to Class 1 nuclear components designed and fabricated for use at elevated temperatures and should be the applicable Code for the VHTR IHX.

3.7 Issues raised by the NRC in the context of high temperature design

A project was carried out in the context of the ASME Gen IV material project to identify issues relevant to ASME Section III, Subsection NH, and related Code Cases that must be resolved for licensing purposes for HTRs (Reference 11). The work was mainly based on issues raised by NRC and the Advisory Committee on Reactor Safeguards (ACRS) in the context of the licensing process of the Clinch River Breeder Reactor (CRBR) in the late 1970’s and early 1980’s.

Issues listed can be categorized in 9 areas:

1. Weldment cracking
2. Notch weakening
3. Material property representation for inelastic analysis

4. Steam generator tubesheet evaluation
5. Elevated-temperature seismic effects
6. Elastic follow-up in piping
7. Creep-fatigue evaluation
8. Plastic strain concentration factors
9. Intermediate piping transition weld

Reference 11 provides a detailed account of NRC concerns under each area. Actions were defined at that time to resolve those issues but were stopped at the end of the Sodium Fast Reactor program in the US.

3.8 Discussion on the key features to be introduced

This section is divided into design, material, fabrication, and NDE in order to cover all aspects of a construction code.

3.8.1 Design

ASME design rules should be modified to cover the following points:

- Provide designers with ratcheting rules applicable in the whole range of applicable temperatures

- Provide weldment factors, both for fatigue, creep-fatigue and creep stress to rupture.

- Provide rules to account for the effect of ageing. This effect should be taken into account to correct tensile properties, short term time dependent allowable stresses, and creep stress to rupture.

- If needed, provide rules to account for the effect of HTR environment in normal and abnormal situations. This could cover rules to account for required extra thickness or strength reduction factors to account for a degradation of material properties for instance in He environment (if tests show detrimental effects compared to tests in air which should remain the reference).

- Provide recommendations for inelastic analyses, including selection of appropriate constitutive equations, identification of the associated material parameters and sequence of loading. Proposed constitutive equations should be able to deal with multiaxial loading and should be appropriate not only to deal with creep-fatigue damage but also with ratcheting. Particular attention is drawn to the difficulty of having a set of parameters conservative for all failure modes (ratcheting, fatigue, creep, buckling) and recommendations should be provided to the designer on how to select these parameters.

- The current NH creep-fatigue damage evaluation procedure has been mainly developed for use with austenitic stainless steel and the applicability to Ni base superalloys at high temperature is not necessarily straightforward. It is to be noted that IHX at 900°C or more with a design life greater than 20 years will require a design in a domain of low stresses where the notion of plastic strains as defined in Subsection NH is likely not to be appropriate. In addition, the current approach does not account for the effect of strain rates which could be proved to be significant for the temperatures of interest. If the current NH approach is used to perform creep-fatigue assessment, isochronous stress-strain curves should be provided in the whole range of applicable temperatures (covering in particular the lower temperatures domain).

- If required, identify and validate other more appropriate creep-fatigue damage models to replace the linear damage fraction.

- For tubular IHX concept, provide reliable calculation methods for the design of the tubeplate and hot header. A specific concern is to ensure that the conventional approach based on the solid plate concept and accounting for stress concentration through stress multiplier is still adequate in the range of temperature of interest.

In addition, ageing could result in a reduction of ductility which could require performing fracture mechanics analysis in the context of the defense in depth approaches. Fracture mechanics tools and fatigue and creep crack growth laws will need to be developed. Reference 24 discusses a method for developing crack growth material properties in very thin materials that may prove useful. This paper presents a new method to develop the J-integral for very thin materials, specifically the Zircaloy tubes used in LWR fuel bundles.

The design of an IHX will also require an adequate treatment of interfaces. This could require developing rules for high temperature bellows (Ref. 17) and improving rules for high temperature piping. A specific concern for the latter is the development of a method for quantifying elastic follow-up effects and the definition of a criterion for determining the portion of thermal expansion stress to be treated as primary. High temperature piping design rules have been significantly developed in the RCC-MR code (Ref. 12) (including effect of elastic follow-up) and ASME could benefit from such developments.

3.8.2 Material

3.8.2.1 Introduction

Most of the Ni base superalloys envisioned for IHX application are currently only permitted according to ASME VIII division 1. Actions are needed to authorize these materials for Section III applicable to both the low and high temperature sections.

A complete characterization of the material envisioned will be needed to obtain reliable design data. This should cover the following:

- Tensile properties with considerations on how to take into account the strain rate effect

- Creep properties

- Fatigue including the effect of strain rate

- Creep-fatigue properties

- Fracture toughness properties

- Fatigue and creep crack growth properties (for defense in depth assessment)

- Effect of ageing (including on toughness properties)
- Effect of cold work
- Effect of product form (e.g. effect of thin foils on creep properties in the case of the Plate Fin Heat Exchanger)
- Effect of HTR environment
- Effect of welded joints with the objective of defining fatigue and creep strength reduction factors.

In the specific case of Alloy 617, a significant data base already exists (in particular with regard to creep properties) but a significant effort is still needed with regard to the creep-fatigue behavior and the effect of welded joints. The development of specific constitutive equations should also be required and specific tests should be needed for the identification of the corresponding parameters.

A difficulty may be linked to the definition of reliable allowable stresses corresponding to the design life of the component. The Draft Code Case discussed in Section 3.2, limited the design life of Alloy 617 to 100,000 h (about 11 years) to avoid hazardous extrapolations to long times and low stresses. There is an obvious economical interest of designing IHXs for a longer design life than 100,000 h and long term creep test results will be required together with appropriate extrapolation methods (covering both the base and weld metal).

3.8.2.2 Chemical analysis and code status

Table 3-2 gives the ASME-ASTM specified chemical analysis of four high nickel alloys:

- Alloy 800H (UNS NO8810)
- Alloy X (UNS NO6002)
- Alloy 617 (UNS NO6617)
- Alloy 230 (UNS NO6230)

For the first three alloys, there is a service experience in helium, in USA for Alloy 800H, in Germany for Alloy 617, in Japan for Alloy X. The ASME code status of the alloys is given in Table 3-3.

Alloy 230 was added to this list as a cobalt free alloy with a high temperature strength approaching that of Alloy 617. As a matter of fact, screening tests have demonstrated that a heat of cobalt free Alloy 230 can have the same high temperature strength as standard alloy grade.

Table 3-3 compares the allowable stress limit of the four different alloys at a temperature of 899 °C (1650°F) which is the maximum service temperature of some of the alloys following section VIII-1 of ASME code. The screening criterion used to choose material for a successful design in normal service condition at elevated temperature is: S ≥ 10 MPa. Following this criterion only Alloy 617 and Alloy 230 can be considered for IHX with service temperature up to 900°C. Note that a similar practical criterion is argued in Reference 2 to limit the time dependent properties to 100,000 h: when the allowable stresses are less than 7 MPa (1 ksi), there is a lack of experience in designing reliably with such a low allowable.

Alloy 800H was considered to have a service temperature limited to 800°C due to loss of strength beyond that temperature.

In the case of Alloy X, the Japanese experience has shown that modifications of specified chemical analysis were necessary to improve corrosion resistance of the alloy in HTR representative helium (Ref.15). These modifications do not improve high temperature strength of the alloy and following the criterion proposed above, Alloy X is not considered viable for service temperature as high as 900°C.

The two candidate alloys which should be covered by ASME code and standards for HTR – IHX application are therefore Alloy 617 and Alloy 230. The status of properties of these two alloys will be summarized in order to identify the tests which should be required to improve design methods and improve cyclic life.

TABLE 3-2: SPECIFIED CHEMICAL ANALYSIS OF HTR IHX ALLOYS

Alloy	Cr	Ni	Fe	Mo	Co	W	C	Al	Ti	P	S	Si	Mn
800H	19,0 – 23,0	30,0 – 35,0					0,05 – 0,10	0,15 – 0,60	0,15 – 0,60		≤ 0,015	≤ 1,0	≤ 1,5
X	20,5 – 23,0		27,0 – 23,0	8,0 – 10,0	0,5 – 2,5	0,2 – 1,0	0,05 – 0,15			≤ 0,040	≤ 0,030	≤ 1,0	≤ 1,0
617	20,0 – 24,0	≤ 3,0		8,0 – 10,0	10,0 – 15,0	-	0,05 – 0,15	0,8 – 1,5	≤ 0,6		≤ 0,015	≤ 1,0	≤ 1,0
230	10.0 – 24.0	≤ 3,0		1.0 – 3.0	≤ 5.0	13.0 – 15.0	0.05 – 0.15			≤ 0,030	≤ 0,015	0.25 - 0.75	0.3 – 1.0

TABLE 3-3: CODE STATUS OF THE DIFFERENT IHX ALLOYS

Grade	Section III (NB)	Section III (NC, ND)	Section III (NH)	Section VIII-1	Section VIII-2	S at 899°C (1650°F)
Alloy 800H (NO8810)	427°C (800°F)	427°C (800°F)	760°C (1400°F)	899°C (1650°F)	899°C (1650°F)	5.9 MPa (0.86 ksi)
Alloy X (NO6002)	427°C (800°F)	427°C (800°F)	NP	899°C (1650°F)	482°C (900°F)	8.3 MPa (1.2 ksi)
Alloy 617 (NO6617)	NP	NP	NP	982 °C (1800°F)	NP	12.4 MPa (1.8 ksi)
Alloy 230 (NO6230)	NP	NP	NP	982 °C (1800°F)	NP	10.3 MPa (1.5 ksi)
NP = not permitted						

3.8.2.3 Tensile properties

Minimum values of the yield strength Sy and of the tensile strength Su of Alloy 617 were proposed up to 982°C (1800°F) in 1988 by the Task Force – Very High-Temperature Design (Ref.2). These minimum values of the yield strength were introduced in Section II Part D of ASME code in 2004 up to 538°C (1000°F). It is important to note that the minimum values of tensile strength introduced in Section II Part D of the ASME code in 2004 up to 538°C (1000°F), exceed the values proposed by the Task Force.

Comparison with the results of some tests in air available today, gives the following conclusions:

- The proposed minimum values of the yield strength appear to be over pessimistic up to 750°C and optimistic at temperatures exceeding 750°C. These trends are confirmed when the ASME and Task Force data are compared to the data up to 1 000°C of German KTA in Reference 1 and to the data up to 750°C of European standard in Reference 16.
- The proposed minimum values of the tensile strength appear to be realistic up to 700°C and optimistic at temperatures exceeding 700°C. These trends are confirmed when Task Force data are compared to KTA data (Ref.1) up to 900°C.

In the case of Alloy 230, the minimum values of the yield strength and of the tensile strength are given up to 538°C (1000°F) in Section II Part D of ASME code. In this temperature domain, the yield and the tensile strengths of Alloy 230 are greater than those of Alloy 617. Above 750°C the advantage of Alloy 230 over Alloy 617 in term of yield and tensile strength tends to disappear.

At high or very high temperatures, the yield and tensile strengths are very significantly strain rate dependent. It will be important to indicate the reference strain rate associated with minimum values and further more to quantify the strain rate dependences of these properties in order to take them into account in some future design rules.

3.8.2.4 Allowable stress limit Sm

Allowable stress limits Sm were derived by the Task Force, as usual, from the minimum values of the yield and of the tensile strength. However at temperatures exceeding 650°C (1200°F), a factor of 0.67 was applied to the minimum values of the yield strength instead of 0.9 at lower temperatures. The factor of .67 may be overly conservative. It must be decided whether or not to incorporate it in the future ASME code or cases for very high temperatures.

3.8.2.5 Creep stress to rupture

In the case of Alloy 617, minimum values of creep stress to rupture are proposed in Reference 2 up to 100 000 h at temperatures up to 982°C (1800°F). Preliminary test results at 850°C and 950°C, under vacuum, in pure helium or in HTR representative helium give time to failure greater than the minimum stress to rupture curves of the Task Force except for a 2 mm thick plate at 850°C, and for test durations shorter than 500 h. The minimum stress to rupture data proposed by the Task Force are however significantly larger than the KTA minimum data particularly at 950°C and for time longer than 1000 h. At 850˚C, the time to rupture reported by the Task Force was 2.5 times greater than that reported by KTA while the Task Force stress value was 30% greater. A larger creep data base on products representative of materials used in fabrication of HTR components with longer time durations would improve assessment of minimum stress to rupture.

From presently available test results, it is not discernable which alloy is best from a stress to rupture standpoint because data for Alloy 230 is limited to 850°C and less than 3000 h.

3.8.2.6 Unified constitutive model for stress- strain prediction

For the prediction of stress strain-relationship, Subsection NH considers the addition of separately evaluated plastic and creep strains: this method was used for example to generate the isochronous stress-strain curves. Several features of the behavior of nickel alloys at high or very high temperatures (> 650°C) show that such an addition is not applicable:

- The tensile behavior of the material is significantly time dependent through the strain rate dependence of flow stress.
- The tensile curves at very high temperature (950°C) show strain softening which results in small values of strain to maximum load without indication of contraction of cross section.
- The creep tests at 950°C do not show clearly secondary creep stage at minimum stationary creep strain rate. The strain rate is increasing during all the test progression.

Appropriate constitutive equations describing stress-strain relationship must predict quantitatively these three features. The ability to predict relaxation behavior can also be evaluated by comparison with experimental data. But at high or very high temperatures, it is expected that relaxation behavior will be correctly predicted through creep strain law.

3.8.2.7 Fatigue properties

Three fatigue curves have been proposed for Alloy 617 in Reference 2: for maximum temperatures of 704°C (1300°F), 871°C (1600°F), and 982°C (1800°F). When compared to some recent test results, these curves seems applicable to design works but in continuous fatigue conditions. For IHX of HTR, predictions of creep fatigue or of time dependent fatigue endurances are required to establish cyclic life. In high nickel alloys, environment is known to affect fatigue endurance at elevated temperature. Environmental effects are likely enhanced at high or very high temperature. It is our opinion that assessment of creep fatigue for HTR IHX cannot be made without considering the representative environment. This will be treated in part 3.8.2.12 and 3.8.2.13 of this document. We think also that the wording “time dependent fatigue” is better than “creep fatigue” in the case that it would be necessary to propose another damage assessment rather than bilinear creep-fatigue damage. In addition to the environment, issues such as material hardening or softening and dynamic strain aging must also be considered.

Preliminary testing seems to indicate better fatigue endurance in Alloy 230 than in Alloy 617 (Reference 25). It is not clear whether this is a material trend or a particular product feature related to respective grain sizes.

There is no information about the cyclic stress-strain behavior which could be used to extend the constitutive equations of Section 3.8.2.6 to cyclic loadings.

3.8.2.8 Toughness of alloys for IHX

In as received condition, the impact values and the toughness of Alloy 617 are generally high (KV > 150 J at room temperature). Some lower values have been found in hot rolled plate (88 J). Nevertheless the toughness level in as received condition is larger in Alloy 617 than in Alloy 230. But considering the service temperature of HTR IHX and the large expected deterioration due to aging, the toughness in as received condition is not useful in design work. The effect of thermal aging is treated in Section 4.2. Determination of material toughness can be very difficult and beyond the boundaries of currently accepted test methods. Reference 24 presents a method for determining material toughness in very thin materials which may prove useful for this task.

3.8.2.9 End of life properties

For HTR IHX design, the evaluation of end of life properties requires extrapolation. With service temperatures of 850-950˚C, the properties to be evaluated are:

- the tensile strength for design for level D service load
- the toughness level for fracture analysis as mentioned in Reference 14.

In the case of yield and tensile strength of Alloys 617 and 230, preliminary tests indicate that Sy is affected more than Su and both affected more at 950˚C than 850˚C. The Sy and Su reduction seems to be monotonous and extrapolation appears possible; however, data longer than 5000h is still needed.

In the case of toughness, the trends as detected by impact tests are much more intricate.

- At a given temperature the toughness deterioration seems to be concentrated in the first 1000 h.
- The aging effect does not seem to be clearly accelerated by the temperature from 750°C to 950°C.

As this can be the result of several combined aging mechanisms, extrapolation to long term seems problematic and prediction of toughness level at end of life will be difficult.

3.8.2.10 Effect of heat treatment associated to brazing or diffusion bonding

The heat treatment effect should be considered in the selection of brazing filler and for specifying the brazing or bonding operating parameters. More tests in base material should be associated to the qualification of brazing or bonding modes in order to check the effect of the heat treatment, short term tests may be sufficient to guarantee the level of longer term properties but cannot be assured.

3.8.2.11 Limit to level D service load

In Reference 2, it is proposed to relate Level D service limits to 70% of the lesser of the collapse load and the plastic instability load. In the case of plate heat exchangers, referring to low temperature experience, the collapse load seems difficult to calculate and experimental determinations are preferred. In the case of HTR plate heat exchangers the collapse load is likely even more difficult to calculate. Some experimental determination using mock-ups, should be mentioned in the design code or documents.

3.8.2.12 Corrosion in impure helium

Concerning the impurity content in HTR helium (H2, CO and CO2, CH4, N2), a "benign atmosphere" domain has been delineated in which passive oxidation occurs. Nevertheless 800 h of exposure of industrial nickel alloys to this environment at 950°C produce internal oxidation limited or not to grain boundaries (Ref.17). This behavior is thought to be related to the aluminum and perhaps titanium contents of the alloys and the limits of these elements should be established in the future specifications. Both 617 and 230 alloys are suitable candidates for HTR application at 800°C. For service at 900°C tighter control of helium chemistry (critical minimum value for CO) and/or development of suitable coating will be necessary.

3.8.2.13 Helium environment and time dependent fatigue

Considering the corrosive effect of impure helium, time dependent fatigue tests should be performed in priority in impure helium environment. Such tests include test with hold times (tensile and compressive hold times) as well as fatigue tests at low frequency or fatigue with dissymmetric triangular cycles[(1)]. When results will be available, analyses of the data including bilinear creep-fatigue damage and frequency dependent fatigue with separation of tensile and compressive phases could be performed. Their ability for extrapolation to service conditions will be evaluated.

Tests in air should be considered as comparative reference tests using the same material batches. In case of similar results as the test in HTR environment, they could be used to perform more easily long term tests to allow more accurate extrapolations.

3.8.3 Fabrication

The rules of ASME Section III, Subsection NH – Class 1 are the most likely choice for fabrication. ASME fabrication rules may need to be revised to include heat treatment requirements after forming, welding, brazing, or joining of any kind. Material grain size may need to be specified as is currently for 800H. Other fabrication concerns are as follows in the subparagraphs.

3.8.3.1 Forming

Alloys 617 and 230 appear to have similar ability to be formed, at least for common forming operations (bending of tubes, rolling of plate). For thin plate forming included in the fabrication of PFHE and PSHE, Alloy 617 seems easier to use. However, Reference 2 has mentioned that Alloy 617 should not be used in cold worked condition for very high temperature considering the risk of recrystallization. This risk is probably to be considered also for Alloy 230. It is to be taken into account for stamping in fabrication of PSHE or for forming of fins in fabrication of PFHE. During qualification of forming processes, the possibility of subsequent recrystallization at service temperature should be discarded by particular tests including exposure to service temperatures.

3.8.3.2 Welding

For common welding processes such as GTAW (TIG), the selected filler metals need to be confirmed. Alloy 617 seems easier to weld than Alloy 230, butt-welding of tubes 2 mm thick seems easier than butt-welding of plates with thickness exceeding 10 mm. GTAW seems easier than SMAW which is not recommended for Alloy 230.

After filler metal and welding processes are confirmed, weld factors to be used in design should be established. Weld factors will be likely needed for:

- Tensile strength at high temperature
- Creep strength
- Fatigue and time dependent fatigue endurances

(1) Dissymmetric triangular cycles are time-strain triangular cycles with different strain rates in the tensile and compressive parts of the cycle.

These factors should be established by comparative tests with base metal tests in condition as close as possible to service conditions.

As fracture mechanics assessment will concern likely welded joints, evaluation of end of life toughness should take into account the aging behavior of weld metals.

3.8.3.3 Joining of plate heat exchangers

The design of each type of plate heat exchangers mentioned in paragraph 2.2 comprises particular arrangements to join the exchanging plates. These arrangements must be considered by the design and fabrication code:

- Plate Fins Heat Exchanger (PFHE) needs brazing
- Plate Machined Heat Exchanger (PMHE) needs diffusion bonding
- Plate Stamped Heat Exchanger (PSHE) needs particular laser or TIG welding

3.8.3.4 Brazing of IHX plates

There are several limitations for using brazing in components following ASME Code Section III. One of these limitations requires that brazing temperature should be 280°C (500°F) above maximum service temperature. The corresponding minimum brazing temperatures are 1080°C and 1180°C for services at 800°C and 900°C respectively:

- Acceptable brazing fillers are limited.
- Harmlessness of the brazing heat treatment on base material properties used in the design must be proven during qualification of the process.

These conflicting restrictions on brazing temperature are difficult to conciliate.

In addition, when a brazed joint is to be cyclically loaded, a similar joint should be tested in representative simulated conditions.

Finally the type of examination and control of brazed joints should be defined and codified as much as possible to verify the correct development of brazing operations.

3.8.3.5 Diffusion bonding of IHX plates

As in brazing, diffusion bonding comprises a heat treatment at elevated temperature and a similar difficult compromise should be found and justified in the selection of bonding temperature:

- Temperature high enough to permit diffusion
- Harmlessness of the treatment for base material.

Also as in the case of brazed joints a maximum service temperature of diffusion bonding should be defined as disbonding can likely occur at temperature approaching that used for diffusion bonding.

Post operation examinations and controls are to be defined as in the case of brazing.

Diffusion bonding needs stress which can be applied by uniaxial load or by Hot Isostatic Pressure (HIP). Uniaxial loads produce more deformation of channels during assembly. Capacities of HIP equipments are limited in size. HIP as well as diffusion bonding under uniaxial load produce grain growth, the acceptability of which must be checked.

3.8.4 Examination of joints (NDE)

3.8.4.1 Welds of helical tubes IHX

The usual provisions for non destructive volumetric examination of vessel welds have to be applied to IHX vessel. Suitable examination methods need to be developed for

- Tube to tube sheet welds taking into account the geometry of these welded joints
- Tube to tube butt welds as the length of helical tube of the IHX is likely exceeding the length of tubes as fabricated.

In both cases, volumetric examination methods have been developed for steam generators of fast neutron reactors.

3.8.4.2 Joints of plate IHX

Provisions for non destructive volumetric examination of welds of headers need to be made in the design of the headers. In the case of plate assembly by different processes such as brazing, diffusion bonding, laser welding, there are yet no available volumetric examination practice, plus, the geometry frequently precludes examination of each individual joint. At a minimum, a pressure/leak test should be performed. Dye penetrant and visual examination should be performed where practical. It would be beneficial to develop non destructive methods to check the effective joined area of IHX plates.

4.0 TESTS REQUIRED FOR THE QUALIFICATION OF DESIGN METHODS

4.1 Standard tests and extension of corresponding data base

These actions will concern three types of standard tests: tensile, creep, and continuous fatigue. They will include:

- More numerous representative materials for statistical improvement of data as minimum values.
- Extension to higher temperatures
- Extension to longer times

In the case of tensile tests, the introduction in the data base of strain rate dependence of yield and tensile strengths would be valuable.

From the three types of tests, strain results to improve the constitutive equations and extend them to cyclic loading are required.

4.2 Tests after thermal aging

The aim of these tests is to allow, using as pertinent as possible extrapolations, an evaluation of end of life expected values for:

- Yield and tensile strengths
- Fracture toughness

4.3 Tests in HTR helium environment

Creep-fatigue and time dependent fatigue tests (Section 3.8.2.13) should be performed in a representative helium environment before the testing described in Paragraphs 4.1 and 4.2 are performed. Corrosion evaluation of the material surface can be the result of post fatigue examinations.

4.4 Tests on weldments

Comparative tests with base metal tests defined in 4.1 to 4.3, in conditions as close as possible to service conditions should be performed to establish weld factors when necessary.

4.5 Mock-ups to be tested

Fabrication and testing of mock-ups are for confirmation of the following:

- Feasibility particularly necessary in the cases of the different plate heat exchangers
- Thermal-hydraulic performance
- Collapse limit by bursting or loss of leak tightness
- Ability to be exposed to high or very high temperature
- Ability to withstand cyclic conditions

The two last points could be covered only by accelerated testing. The prediction of service cyclic life will need extrapolation. If accelerated tests are successfully carried on to failures their results can be used to assess prediction method based on tests on specimens (Section 4.3).

5.0 REQUIRED IN-SERVICE INSPECTION AND ASSOCIATED NDE

5.1 Introduction

There is currently no inspection guideline set forth in the ASME Code directly applicable to the NGNP IHX. Guidelines like those provided in ASME Section XI for light water reactors will need to be established. The IHX of the NGNP is not a safety related component in that it isn't required for the safe shutdown of the plant. With regard to the tubes of the tube and shell IHX and the stacked plate compact IHX, the leak path is from one contained system to another. The HTR design concept allows for very low contamination levels in the primary coolant loop such that a small leak should not transfer significant amounts of contaminants. Depending on the secondary side coolant chosen, there may be little concern over small transfers of fluid between the two loops. Leakage could be detected by the coolant "make-up" system as it attempts to maintain proper pressure differential between the primary and secondary loops or by detecting trace elements in the helium purification train. Nonetheless, catastrophic failure of a large number of tubes or passages could cause unwanted thermal transients and any leakage will affect plant efficiency. Consequently, from an investment safeguard point of view, it is envisioned that in-service inspections would be desired to the extent practical.

The two IHX designs discussed in Reference 23 (Part 1 of this Task) are the tubular and compact heat exchangers. The issues affecting the compact (stacked plate) heat exchanger apply equally to each of the designs considered feasible in Reference 23. The compact IHX will be modular units arranged inside of a pressure vessel in a manner like that shown in Figure 5.1-1. The tubular IHX concept, similar to that shown in Figure 5.1-2, is not contained inside a separate pressure vessel but rather a stand-alone unit. What we are concerned with in this discussion is primarily the heat transfer surfaces.

Figure 5.1-1 TYPICAL COMPACT IHX MODULE ARRANGEMENT

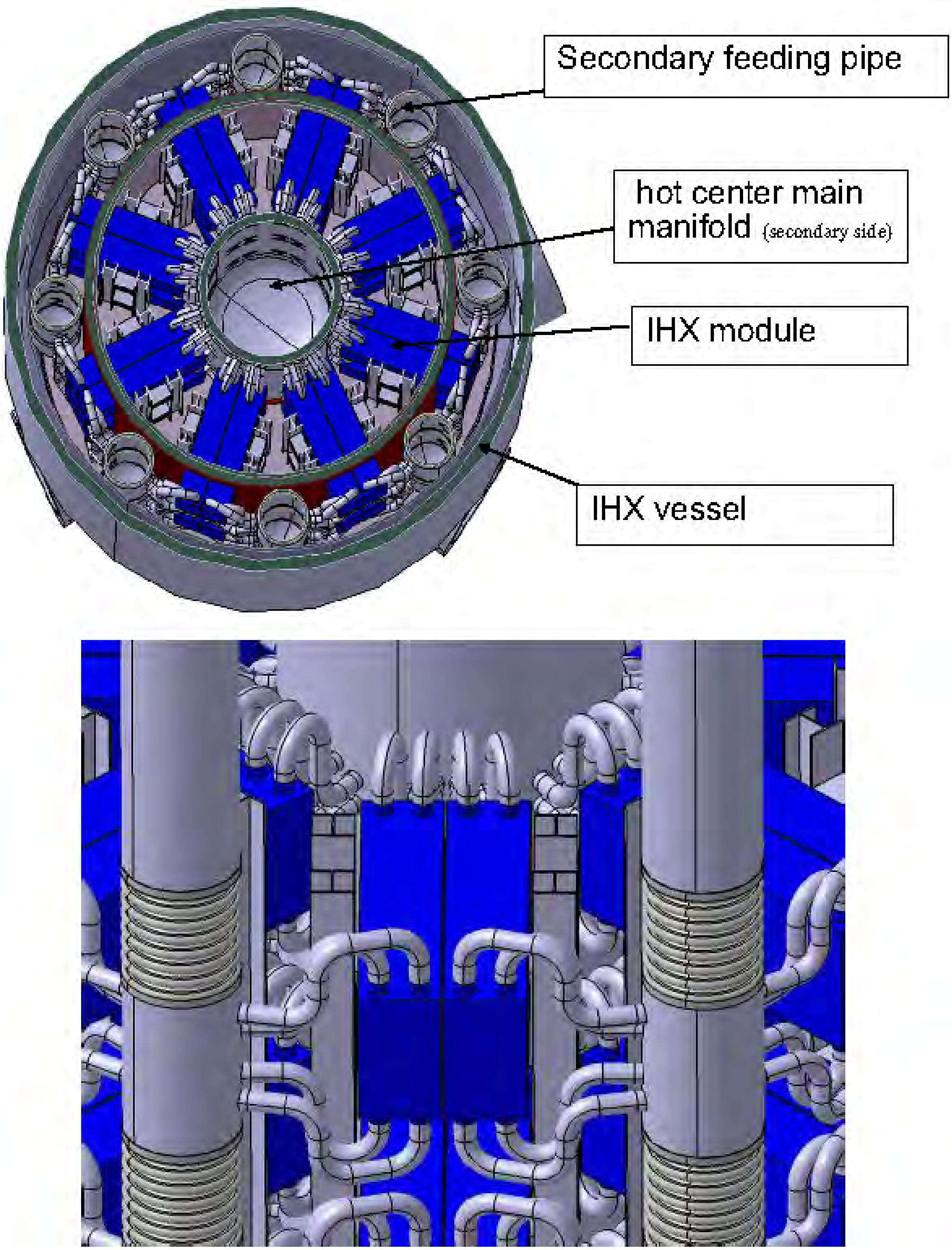
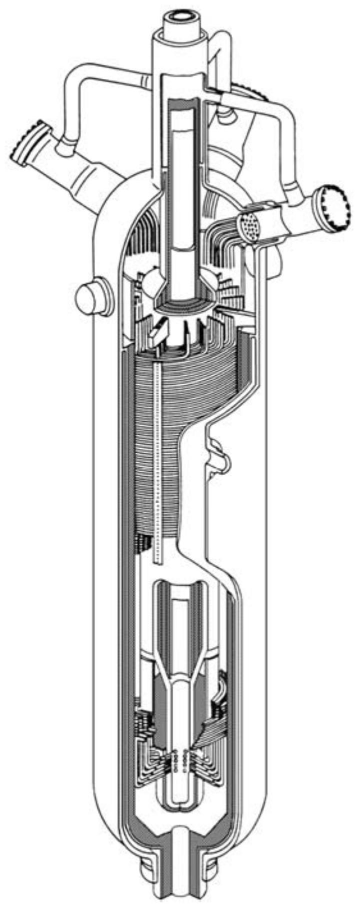


Figure 5.1-2 TYPICAL TUBULAR IHX



5.2 Current PWR ISI Requirements

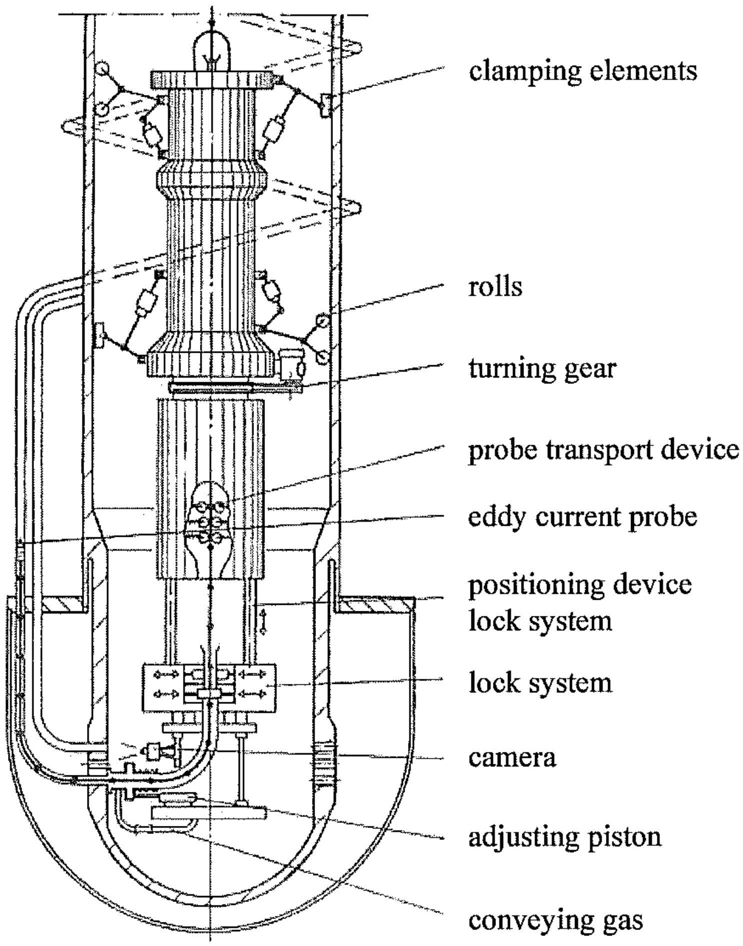
This information is provided as a point of reference only. For steam generators, ASME Section XI provides an inspection schedule and NDE requirements for performing inspection of all welds and important parts or features of the steam generator with the exception of the heat transfer tubes. The inspection intervals for the heat transfer tubes are governed by the plant technical specification. The guidelines within this specification are based upon operating experience and a thorough degradation assessment. A similar arrangement could be made for the IHX.

The same basic requirements apply for heat exchangers except that the flow channels (heat transfer tubes) are not volumetrically examined, only a leak test is performed.

5.3 KVK (German) HTR Heat Exchanger ISI Experience

In the nineteen eighties a German R&D program tested two different He/He HTR heat exchangers at their KVK facility. Both were shell and tube heat exchangers, one u-bend, the other a helical coil design. The tube diameters were practically the same as those envisioned for the NGNP IHX. Both heat exchanger designs were successfully examined using eddy current. The Figure below provides a representation of the Eddy Current delivery tool used at KVK for the helical IHX design. Tube plugging was tested successfully as well.

Figure 5.3-1 Schematic of KVK Eddy Current Delivery in the Helical IHX



5.4 Feasibility of NDE for the Shell and Tube IHX

It is envisioned that all welds of the pressure vessel (shell) could be conventional “ultrasonic” means. The heat transfer tubes can be examined by eddy current. Eddy current inspection of the KVK IHX tubes was successfully performed. There is a lot of eddy current inspection experience for light water reactor (LWR) steam generators. There is no reason to believe that the same inspection could not be done on a shell and tube IHX as long as eddy current inspection is considered in the design. Inspection frequency and survey size should be developed by performing a degradation assessment. If a tube is found to be defective it can be plugged. Tube plugging techniques are well established from LWR steam generator experience. It was also tested and proven successful at KVK. Like that of LWR steam generators, the inspection program and criteria for the heat transfer surfaces can be provided in a plant technical specification.

5.5 Compact Heat IHX

The main concern with regards to ISI of a plate type IHX is that the individual coolant passages cannot easily be inspected. The most reasonable way to inspect a compact heat exchanger is to perform a leak test. Inspection of individual primary/secondary boundary joints is virtually impossible. If leaks are found, repair is normally done in a "shop" environment after removal which is not practical in this situation. For this reason it is recommended that the compact IHX's be replaced at a predetermined "end of life" for the product. A gross system over-check as described above can be performed. If a leak is found to be beyond predetermined limits, efforts would be made to isolate the location of the leak. Once found, the IHX module could be isolated from the system. Like the tubular IHX, the inspection program and criteria can be provided in a plant technical specification.

5.6 Conclusion of ISI Requirements

The tube and shell IHX provides the best opportunity to perform ISI and repairs. It uses proven technology in both regards. It is recommended that the tubes and vessel be inspected at prescribed intervals.

ISI of the compact IHX is more problematic. Inspection and repair of individual channels while installed is practically impossible. The failure of a compact IHX module would not result in fluid release to the atmosphere. The design of the HTR provides for minimal amounts of contamination of the cooling fluid; thus, prevention of primary / secondary fluid mix is not as critical as is a light water reactor, provided that the two fluids are compatible. It is recommended that leak testing of individual modules be performed only when the system is found to be leaking beyond acceptable limits as monitored by plant operation indicators. Acoustic sensors placed along the outer surface of the containment vessel might be possible. Preliminary discussions with an acoustic monitoring system vendor suggest that monitoring of the IHX modules and headers within would provide the general location of the leak. The main issue with this approach is the noise generated by the circulators. The repair for an individual compact IHX would be to cap off the header pipes entering and exiting the IHX thereby removing the module from service.

Rules governing ISI of the VHTR IHX should be added to Section XI, Division 2. The surveillance/replacement plan could be established through a plant technical specification (like current PWR's) to allow for timely adjustments as deemed necessary by the most current operating experience. Criteria for inspection could be included the plant technical specification as well.

6.0 ADEQUACY OF EXISTING ASTM SPECIFICATIONS

ASTM standards interface with the ASME Code in two important ways. First, approval for use of a material under the Code is typically preceded by development and approval of an ASTM specification. The ASTM specification can then be incorporated into the Code with few or even no changes. For example, ASTM B 564 was used as the basis for the corresponding ASME specification, SB-564. As the ASME specifications are based on ASTM specifications, rather than the other way around, changes are made first in the ASTM version, and the version adopted by the ASME may not be considered current by the ASTM. The second interface between ASTM standards and the ASME Code arises because approval of a material under the Code requires submission of a substantial body of data on the properties of the material. To ensure that the data are collected and interpreted in a way that is comparable for all materials, and that represents an industry consensus, ASTM standards are needed for testing as well.

This section reviews existing ASTM standards for both materials and testing and, as appropriate, suggests changes that may be needed to support HTR development.

6.1 Standards for Materials

This section introduces the ASTM specifications that apply to Alloys 617 and 230. It then reviews the specific requirements on chemical composition, mechanical properties, dimensions, and heat treatment. Other aspects of the specifications (such as sampling, testing, certification, and marking) are not reviewed because they are considered to be unlikely to determine what products can be ordered. The section ends with a discussion of how the materials specifications might affect HTR development.

Table 6-1 lists selected ASTM specifications for products made from Alloys 617 (UNS N06617) and 230 (UNS N06230), which are the primary candidates for the hot portions of the IHX. The specifications cover bar, rod, seamless pipe and tube, plate, sheet, strip, reforging stock, and forgings. At least four additional specifications (B 366, B 546, B 619, and B 626) exist for pipe fittings and welded pipe and tube. These forms were considered to be of less interest and are not reviewed here.

TABLE 6-1 Selected ASTM specifications for Alloys 617 and 230

ASTM Designation	Included in ASME Code	Alloys Covered		Forms
		617	230	
B 166 – 08	yes	yes	no	bar, rod, wire (not 617 wire)
B 167 – 08	yes	yes	no	pipe, tube
B 168 – 08	yes	yes	no	plate, sheet, strip
B 435 – 06	yes	no	yes	plate, sheet, strip
B 472 – 04a	no	yes	yes	reforging stock (billets, bars)
B 564 – 06a	yes	yes	yes	forgings
B 572 – 06	yes	no	yes	rod
B 622 – 06	yes	no	yes	pipe, tube
B 829 – 04a	yes	yes*	yes*	(pipe, tube)

*B 829-04a does not mention either alloy, but it is cited by the pipe and tube specifications for both.

The current revisions of ASTM specifications are considered here; the specifications in the ASME code may be based on earlier revisions.

In these specifications, rod refers to round products, and bar refers to solid products with rectangular, square, or hexagonal cross sections. The pipe and tube specifications are for seamless products, and B 167 clarifies that these must be “produced with a continuous periphery in all stages of the operations.” Welded pipe and tube are therefore excluded even if they are worked after welding.

It will be noted from Table 6-1 that, with the exception of reforging stock and forgings, there are different specifications for product forms made from Alloy 617 and Alloy 230. Of course, the requirements for composition and mechanical properties differ between the two alloys, but different specifications for the same form (for example, B 167 and B 435) may also differ in more subtle ways, such as the available sizes. A change from B 167 to B 435 may therefore change the availability of certain sizes.

ASTM B 166 covers wire as well as bar and rod, but wire is not considered to be of interest for HTR construction, so it is not discussed further here.

ASTM B 472 is for reforging stock rather than for a finished form, so it is not surprising that there is not a corresponding ASME specification. It may not be necessary to procure material to B 472, however, because B 564 does not specify that the raw material for forgings be procured to B 472.

ASTM B 829 provides general requirements for pipe and tube. Products are not ordered to this specification. Instead, other specifications invoke it to provide additional requirements.

6.1.1 Chemical Composition

All of the specifications listed in Table 6-1 impose composition requirements. The five specifications for Alloy 617 are all strictly consistent. Surprisingly, two inconsistencies were noted in the five specifications for Alloy 230. The first inconsistency is subtle: B 564 and B 622 give the composition limits for molybdenum as 1.0 – 3.0 weight percent, whereas the others give the limits as 1.0 – 3.00 weight percent. Because of the different levels of rounding, some molybdenum contents may be acceptable under one specification but not under another. A more significant difference is noted in the composition limits for aluminum. Specification B 472 gives the limits as 0.20 – 0.50 weight percent, whereas the others give the limit as 0.50 weight percent maximum. Reasons for these differences have not been determined.

The allowable composition ranges for both alloys are fairly broad, and it is expected that alloy producers will optimize properties by imposing more restrictive proprietary limits. An example of such a practice is the difference between Alloys X and XR. The composition of Alloy XR is based on that for Alloy X, but limits were added for four new elements, and the limits for three other elements were modified (Ref. 15)

6.1.2 Mechanical Properties

Mechanical property requirements may vary from one specification to another. Because B 472 is not for a finished form, it does not impose mechanical property requirements. The four specifications (B 435, B 564, B 572, and B 622) for finished Alloy 230 forms give the minimum tensile strength as 110000 psi, minimum yield strength at 0.2% offset as 45000 psi, and the minimum elongation as 40%. All four require that the material be in the solution annealed condition.

Similarly, the four specifications (B 166, B 167, B 168, and B 564) for finished Alloy 617 forms give the minimum tensile strength as 95000 psi and the minimum yield strength at 0.2% offset as 35000 psi. All but B 168 require a minimum elongation of 35%; B 168 has requirements that vary from 25% for cold-rolled sheet to 35% to hot-rolled plate. All four require that the material be in the annealed condition.

6.1.3 Dimensions

Limits on the dimensions of products come in two types. One is an explicit limit, such as a requirement that plate have a minimum thickness. The other is an implicit limit. With implicit limits, the specification provides requirements for some sizes of product but not for others. For example, B 829 gives permissible variations in outside diameter for pipes with nominal outside diameters from 1 to 9¼ inches, inclusive. Limits on variations in diameter would nevertheless be needed for larger pipes, so if such pipes were to be used for reactor construction, it would be desirable to extend the specification to cover the additional sizes.

Limitations on dimensions are provided in various ways within the specifications, so it can be difficult to ascertain what the actual limitations are. It is also difficult to present the limitations in a consistent way, so the following paragraphs list the limitations as found in the specifications. It will be noted that some of the specifications, especially B 168 – 08, provide a complex set of requirements. There has generally been no attempt to harmonize the requirements or eliminate redundancy.

NOTE: The references to tables and sections in the following ASTM specifications pertain to the sections and tables provided within the ASTM specification being discussed.

B 166 – 08: Bar is explicitly limited (Section 3.1.1) to a maximum width of 10 inches and a minimum thickness of ⅛ inch. Cold-worked rods (round) are implicitly limited (Table 4) to a minimum diameter of 1/16 inch and a maximum diameter of 2½ inches. Cold-worked bars are implicitly limited (Table 4) to a maximum of 2 inches in thickness (rectangles) or between parallel flats (hexagons and squares). There is no implicit limitation (Table 5) on the thickness of hot-worked rods or bars.

B 167 – 08: Pipe is explicitly limited (Section 3.1.2) to commercial pipe sizes. ASTM B 829 is cited (Section 7.1) for permissible variations in diameter and wall thickness.

B 168 – 08: Sheet and strip are explicitly limited (Table 1) to a maximum thickness of 0.250 inch. Plate is explicitly limited (Table 1) to a minimum thickness of 3/16 inch. Cold-rolled, deep-drawing, and spinning-quality sheet and strip are implicitly limited (Table 4) to a maximum width of 56 inches. Rectangular plate with a nominal thickness of 2 inches or less is implicitly limited (Table 5) a maximum width of 160 inches. Rectangular plate is implicitly limited (Table 6) to a maximum thickness of 4 inches. Sheet and cold-rolled strip are implicitly limited (Table 7) to a minimum thickness of 0.018 inch and a maximum width of 60 inches. Sheared plate is explicitly limited (Table 8, Note D) to a minimum width of 10 inches for material ¾ inch and under in thickness and 20 inches for material over ¾ inch in thickness. Abrasive-cut rectangular plate is explicitly limited (Table 8, Note E) to a minimum width that varies from 2 to 4 inches, depending on the thickness of the plate. (No specification for the dependence on thickness was found.) Rectangular plate is implicitly limited (Table 8) to a maximum width of 160 inches. Sheared circular plates are implicitly limited (Table 9) to a maximum thickness of ⅜ inch, a minimum diameter of 20 inches, and a maximum diameter of 140 inches. Plasma-torch-cut circular plates are implicitly limited to a minimum diameter of 19 inches and a maximum diameter of 140 inches; they are also subject (Table 9) to an implicit maximum thickness that is diameter-dependent and ranges from 1¼ inches to 3 inches. Strip is implicitly limited (Table 10) to a maximum width of 48 inches. Sheared, abrasive-cut, and plasma-torch-cut rectangular plates are implicitly limited (Table 11) to maximum thicknesses of 1¼, 2¾, and 3 inches, respectively. Rectangular, circular, and sketch plates are implicitly limited (Table 12) to a maximum thickness of 4 inches. B 168 also implicitly requires (Table 1) that Alloy 617 be supplied as hot-rolled plate or sheet or as cold-rolled sheet or strip.

B 435 – 06: Plate is explicitly limited (Section 3.1.1) to a minimum thickness of 3/16 inch. Sheet and strip are explicitly limited (Section 3.1.2) to a maximum thickness of less than 3/16 inch.

B 472 – 04a: Hot-rolled round bars for reforging are implicitly limited (Table 2) to a minimum diameter of greater than 7/16 inch and a maximum diameter of 8 inches. No size limitations were found for billets for reforging.

B 564 – 06a: No limitations were found on the size of forgings.

B 572 – 06: Hot or cold finished, solution annealed, and pickled or mechanically descaled rods are explicitly limited (Section 1.2.1) to a minimum diameter of 5/16 inch and a maximum diameter of less than ¾ inch. Hot- or cold-finished, solution annealed, and ground or turned rods are explicitly limited (Section 1.2.2) to a minimum diameter of ¾ inch and a maximum diameter of 3½ inches. Hot-finished, annealed, and descaled rods are implicitly limited (Table 4) to a minimum diameter of 5/16 inch and a maximum diameter of less than ¾ inch. Hot-finished, annealed, and ground or turned rods are implicitly limited (Table 4) to a minimum diameter of ¾ inch and a maximum diameter of 3½ inches.

B 622 – 06: No size limitations were found for pipe and tube other than that pipe is explicitly limited (Section 3.1.2) to commercial pipe sizes. However, B 829 is cited (Section 4.1) for applicable requirements.

B 829 – 04a: Seamless cold-worked pipe and tube are implicitly limited (Table 2) to a minimum outside diameter of greater than 0.400 inch and a maximum outside diameter of 24 inches. Hot-finished tube is implicitly limited (Table 3) to a minimum outside diameter of ¾ inch and a maximum outside diameter of 9¼ inches. Seamless hot-worked pipe is implicitly limited (Table 4) to a minimum outside diameter of 1 inch and a maximum outside diameter of 9¼ inches. A table of NPS pipe sizes is provided (Table 1); it covers pipe sizes from ⅛ NPS (0.405 inch outside diameter) to 30 NPS (30.000 inches outside diameter).

6.1.4 Heat Treatment

The specifications are consistent in their requirements that both Alloy 617 and Alloy 230 be solution annealed. The only exceptions are for “forging quality” rod and bar produced to B 166, and billets and bars for reforging produced to B 472. As those are not finished forms, their heat treatment will not affect HTR design.

A description of the annealing process for Alloy 617 was not found in the specifications, but a producer provides the following discussion (Ref. 2, p. 9): “Alloy 617 is normally used in the solution-annealed condition. Solution annealing is performed at a temperature of 2150 °F (1175 °C) for a time commensurate with section size. Cooling should be by water quenching or rapid air cooling.”

In contrast, the specifications do provide descriptions of the solution annealing processes for Alloy 230. There is some variation in the required temperature, from 2150 °F (B 564 – 06a, Table 2, Note C) to 2200 – 2275 °F (B 435 – 06, Table 2, Note B, and B 572 – 06, Table 3, Note B). In each case, the solution anneal is to be followed by water quenching or rapid cooling by other means. The requirements of the specification are consistent with the guidance provided by a manufacturer (Ref. 20 p. 3): “The alloy is solution heat-treated in the range of 2150 to 2275 °F (1177 to 1246 °C) and rapidly cooled or water-quenched for optimum properties.”

Adding a description of the annealing process should be included in the Alloy 617 specifications as it is in the Alloy 230 specifications.

6.1.5 Conclusions for Material Specifications

The specifications for Alloy 617 and 230 are surprisingly divorced from each other. Only forgings and reforging stock share a common specification; rod, tube, pipe, plate, sheet, and strip are all treated by specifications that are alloy-specific. (No specification was found for (non-round) bar of Alloy 230.) Because different specifications have different requirements, a change in material is apt to require a thorough review of how the resulting change in requirements will affect design and procurement. It would be desirable to revise the specifications so that the materials are treated more consistently. That goal could be achieved either by adding one alloy to specifications that currently treat only the other, or by revising the requirements of one or both specifications so that their requirements converge.

The specifications generally provide consistent, straightforward guidance on chemical composition. Because the composition ranges are fairly broad, it is expected that suppliers will produce material to more restrictive, proprietary requirements to optimize properties. But if the Code reflects data for optimized materials, it is not clear how it will account for other materials that are not optimized but still fall within the specification.

The specifications also generally provide consistent, straightforward guidance on mechanical properties. Because the two alloys have different mechanical properties, if a change in materials is expected, the part geometry would need to change as well. A slight additional complication is that the ductility requirements for Alloy 617 depend on the form (plate, sheet, or strip) and rolling temperature.

Some of the specifications (notably B 168) have complex requirements on permissible variations in dimensions. Different requirements apply to different forms or to material that is processed in different ways (e.g., sheared vs. abrasive cut). It would be very desirable to have the requirements simplified so that it would be more evident whether a given piece of material does or does not conform to the specification.

Some specifications also provide implicit limitations on the sizes that may be produced. It would be very desirable to have each specification provide explicit statements of the sizes of materials to which it applies, and also to have each specification provide requirements that correspond exactly to the allowable sizes. An inconsistency was found in the imposition of dimensional requirements: The pipe and tube specifications provide pipe dimensions in appendixes, where they are nonmandatory information (B 167 – 08, Table X2.1; B 622 – 06, Table X2.1), but the general requirements for pipe and tube put pipe dimensions in the standard itself (B 829 – 04a, Table 1), where they are mandatory information. Oddly enough, B 167 and B 622 both cite B 829, so it would appear that the pipe sizes are mandatory for B 167 and B 622, despite assertions to the contrary in these specifications.

There is some variation in the heat treatment temperatures specified for Alloy 230, but these are not judged to be significant.

Different producers specialize in different alloys, so it seems likely that a change from one alloy to the other would require a change in suppliers as well.

The forms of interest for HTR construction are primarily plates and tubes. B 435 does not impose a maximum size or thickness for plates. The sizes of plates that are discussed in B 168 range up to 160 inches in width and up to 4 inches in thickness. These dimensions are at least as large as what can currently be produced for Alloys 617 and 230. Therefore, it is not expected that the specifications will significantly constrain the procurement of plate. In contrast, the maximum tube diameter covered by B 829 is probably 24 inches, and certainly not greater than 30 inches. That size would significantly constrain the design of the hot header for a helical-tube heat exchanger.

Billets or ingots for extrusion of pipe for the hot header would be substantially larger than the sizes discussed in B 472. However, the billets or ingots are not finished forms, so it is probably not necessary to procure them to ASTM specifications.

6.2 Standards for Testing

As was mentioned previously, the use of standards in testing is desirable to ensure that the data are collected and interpreted in a way that represents an industry consensus and is comparable for all materials. To that end, ASTM also publishes three types of standards that are related to testing: (1) test method, “a definitive procedure that produces a test result”, (2) practice, “a definitive set of instructions for performing one or more specific operations that does not produce a test result”, and (3) guide, “information or series of options that does not recommend a specific course of action”. In general, test methods are more specific than practices, which in turn are more specific than guides. ASTM standards for testing are not incorporated into the ASME Code.

The ASTM/ASME materials specifications often cite a particular ASTM test method, such as E 8, “Standard Test Methods for Tension Testing of Metallic Materials”. Use of the cited test method is obviously mandatory in those cases. When a test method is not cited, the Code requires the use of ASTM test methods or practices to collect data.

Approval of a new material under the ASME Code requires submission of a substantial body of data. ASME data requirements include (1) time-independent data, (2) time-dependent data, (3) toughness data, (4) external pressure data (if applicable), (5) cyclic service data (if applicable), and (6) other data. The following paragraphs consider the ASTM standards that are available for obtaining these data. Though the section is specifically related to ASTM standards, this is not meant to infer that only ASTM testing methods are acceptable.

6.2.1 Time-Independent Data

Time-independent data required by the Code include tensile strength, yield strength, reduction of area at failure, and elongation at failure. These data are considered to be time-independent because the time scales for standard mechanical testing are much shorter than the typical service life of components designed to the Code. The data are to be provided at room temperature and at intervals throughout (and slightly beyond) the range of service temperatures. Table 6-2 lists the applicable test methods.

The standards listed in Table 6-2 allow for measuring all of the required time-independent data and are considered to be applicable to and acceptable for testing the IHX materials.

TABLE 6-2 ASTM standards for measuring time-independent properties of materials

ASTM Designation	Temperature	Title
E 8	room	Standard Test Methods for Tension Testing of Metallic Materials
E 21	elevated	Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials

6.2.2 Time-Dependent Data

Time-dependent data required by the Code include stress-rupture and creep rate data. These data are considered to be time-dependent because creep produces dimensional changes over time scales that are comparable to or greater than the service life of components designed to the Code. Data are to be provided for a range of temperatures that is slightly broader than the range of service temperatures for which creep may govern. The lower end of the creep range is typically above room temperature.

Per E 139, a stress-rupture test is “a test in which time for rupture is measured, no deformation measurements being made during the test”. Such a test is much less demanding in terms of data collection than a creep-rupture test, that is, “a test in which progressive specimen deformation and the time for rupture are measured”.

Table 6-3 lists ASTM standards for measuring time-dependent properties. E 139 allows for measuring all of the required time-dependent data and is considered to be applicable to and acceptable for testing the IHX materials.

E 1457 can be used to take additional data beyond what is required by the Code. The current version, E 1457 – $07^{\varepsilon1}$, is poorly edited. This test method may nevertheless be useful in collecting data to support rules for design beyond those currently in the Code.

Although it is included in Table 6-3, WK21984 is a “work item”, not an ASTM standard. It is expected to lead to a new standard that, like E 1457, may be useful in measuring data to support rules for design beyond those currently in the Code.

TABLE 6-3 ASTM standards for measuring time-dependent properties of materials

ASTM Designation	Temperature	Title
E 139	elevated	Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials
E 1457	elevated	Standard Test Method for Measurement of Creep Crack Growth Times in Metals
WK21984	elevated	New Test Method for Creep-Fatigue Crack Growth Rate Testing

6.2.3 Toughness Data

The Code also requires notch toughness data if Code toughness rules are expected to apply. Table 6-4 lists ASTM standards that can be used to measure these data. Of these, E 399 and E 1820 are considered to be applicable to and acceptable for testing the IHX materials. E 292 may be found to be useful in measuring additional data to support rules for design beyond those currently in the Code. Reference 24 proposes a method of developing a fracture toughness J-integral from very thin material.

Because the IHX is expected to include welded joints, toughness data must be supplied for weld metal and the heat-affected zone as well as the base metal.

TABLE 6-4 ASTM standards for measuring toughness properties of materials

ASTM Designation	Temperature	Title
E 292	room and elevated	Standard Test Methods for Conducting Time-for-Rupture Notch Tension Tests of Materials
E 399	variable	Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials
E 1820	variable	Standard Test Method for Measurement of Fracture Toughness

6.2.4 External Pressure Data

For material that is loaded under external pressure, the Code requires stress-strain curves measured in tension or compression. The data are to be provided at temperature intervals throughout the range of service temperatures. This requirement goes beyond the time-independent data of Section 6.2.1 in that the entire curve, rather than just a few characteristic values, must be supplied.

The standards listed in Table 6-5 focus on the time-independent data of Section 6.2.1 but also cover the recording of full stress-strain curves. They are considered to be applicable to and acceptable for testing the IHX materials.

TABLE 6-5 ASTM standards for measuring stress-strain curves of materials

ASTM Designation	Temperature	Title
E 8	room	Standard Test Methods for Tension Testing of Metallic Materials
E 9	room	Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature
E 21	elevated	Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E 209	elevated	Standard Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates

6.2.5 Cyclic Service Data

The IHX will be in cyclic service, so the Code requires fatigue data over the range of design temperatures. Table 6-6 lists ASTM standards for measuring cyclic service (fatigue) data. Standards E 466, E606, and E 647 are considered to be applicable to and acceptable for testing the IHX materials.

Standard E 2368 appears to go beyond the requirements of the Code in that it describes a test in which temperature and strain are simultaneously varied and independently controlled. Results obtained by such testing may nevertheless be useful if new design rules consider thermomechanical fatigue.

As was noted previously, WK21984 is a “work item”, not an ASTM standard, though it is expected to lead to a new standard. Both E 2368 and the standard resulting from WK21984 may be useful in measuring data to support rules for design beyond those currently in the Code.

Table 6-6 includes both standard test methods and standard practices. Both are acceptable under the Code.

TABLE 6-6 ASTM standards for measuring cyclic service properties of materials

ASTM Designation	Temperature	Title
E 466	room	Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
E 606	variable	Standard Practice for Strain-Controlled Fatigue Testing
E 647	variable	Standard Test Method for Measurement of Fatigue Crack Growth Rates
E 2368	variable	Standard Practice for Strain Controlled Thermomechanical Fatigue Testing
WK21984	elevated	New Test Method for Creep-Fatigue Crack Growth Rate Testing

6.2.6 Other Data

Other data required by the Code include those required to determine the coefficient of thermal expansion, thermal conductivity and diffusivity, Young’s modulus, shear modulus, and Poisson’s ratio. The properties are to be provided over the range of service temperatures.

It appears that Code policy does not require the determination of these properties in accordance with ASTM standards, but standards were reviewed under the assumption that they would be acceptable and would be good practice. This section divides the data into thermal properties and elastic properties. Thermal properties are treated first.

The coefficient of thermal expansion, thermal conductivity, and thermal diffusivity for Alloy 230 are already included in the Code for temperatures up to 1500 °F. Additional data would be required if Alloy 230 is to be used at temperatures above 1500 °F, or for Alloy 617.

It should be noted that the thermal conductivity is equal to the product of the thermal diffusivity, density, and specific heat capacity. The Code only requires that data be provided to establish values for all four of these quantities, not that all four be measured, so it is sufficient to measure three of these four properties. Densities of Alloys 617 and 230, presumably at room temperature, are already included in the Code.

Table 6-7 lists ASTM standards for measuring thermal properties of materials. Standards E 229, E 289, E 831, E 1225, E 1269, and E 1461 have been reviewed and appear to be applicable to Alloys 617 and 230. In some cases (especially for E 1269), the temperature range stated may not quite cover the temperatures expected in the IHX, but the standards indicate that the temperature range can be extended by proper choice of instrumentation, specimen holders, and/or calibration materials. With the possible exception of E 1269, these standards are considered to be applicable to and acceptable for testing the IHX materials.

E 1952 is listed, but it is applicable to materials with thermal conductivities in the range from 0.1 to 1.0 W/(m·K). Those values are smaller than what is expected for Alloys 617 and 230, so this standard is not applicable.

E 2584 is listed, but it is applicable to materials with thermal conductivities in the range from 0.02 to 2 W/(m·K). Those values are smaller than what is expected for Alloys 617 and 230, so this standard is not applicable.

Although they are included in Table 6-7, WK12876 and WK14560 are “work items”, not ASTM standards. They are expected to lead to new standards that may be useful in measuring data to support Code qualification. Preliminary descriptions indicate that the standards will be applicable to Alloys 617 and 230.

TABLE 6-7 ASTM standards for measuring thermal properties of materials

ASTM Designation	Temperature	Title
E 228	variable	Standard Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer
E 289	variable	Standard Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry
E 831	variable	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
E 1225	variable	Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique
E 1269	variable	Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry
E 1461	variable	Standard Test Method for Thermal Diffusivity by the Flash Method
E 1952	near room	Standard Test Method for Thermal Conductivity and Thermal Diffusivity by Modulated Temperature Differential Scanning Calorimetry
E 2584	room and elevated	Standard Practice for Thermal Conductivity of Materials Using a Thermal Capacitance (Slug) Calorimeter
WK12876	room and elevated	New Test Method for Determination of Specific Heat Capacity by Modulated Temperature Differential Scanning Calorimetry
WK14560	variable	New Practice for Thermal Diffusivity by the Flash Method

The moduli of elasticity (Young's moduli) for Alloys 617 and 230 are already tabulated in the Code for temperatures up to 1500 °F. The tables in the Code also give Poisson's ratio and density for Alloys 617 and 230 at a single temperature, presumably room temperature. Under the assumptions that Poisson's ratio is temperature-independent and the material is isotropic, the shear modulus G may then be calculated as

$$G = \frac{E}{2(1-\nu)}$$

where E is the elastic modulus and v is Poisson's ratio.

If either alloy is to be used above 1500 °F, additional data on the elastic modulus will be required. Table 6-8 lists ASTM standards for measuring elastic properties. These standards are considered to be applicable to and acceptable for testing the IHX materials. Two of the standards (E 1875 and E 1876) produce dynamic values of the elastic constants; results produced under these standards would require suitable correction for the differences between static and dynamic testing.

TABLE 6-8 ASTM standards for measuring elastic properties of materials

ASTM Designation	Temperature	Title
E 111	variable	Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E 132	room	Standard Test Method for Poisson's Ratio at Room Temperature
E 143	room	Standard Test Method for Shear Modulus at Room Temperature
E 1875	variable	Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Sonic Resonance
E 1876	variable	Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration

6.2.7 Conclusions for ASTM testing specifications

The preceding review of ASTM standards for testing has largely followed the current guidance in the ASME Code, that is, that certain properties are to be measured over the expected range of service conditions, and that those properties are to be used in accordance with established design rules. For that approach to codifying Alloys 617 and 230, the existing ASTM standards are satisfactory. That finding is not surprising, because the Code already includes numerous alloys, which were presumably codified by using ASTM standards for testing.

It is more difficult to determine what testing standards will be needed in the future if new design rules are to be used with Alloys 617 and 230. One indication of how the design rules will need to be changed is the concern with creep-fatigue in these alloys (Ref. 21). Another indication is the behavior of the materials at high temperature: “(1) lack of a clear distinction between time-independent (elastic-plastic) behavior and time-dependent (creep) behavior, (2) high dependence of flow stresses on strain rate, and (3) softening with time, temperature, and strain” (Ref. 14). It is also recognized that the helium environment may have a significant effect on these alloys and their performance (Refs. 21, 22).

These aspects of alloy performance indicate the need for an additional ASTM standard on creep-fatigue crack growth rate testing, such as the standard that is expected to result from WK21984. The unusual softening behavior indicates that a great deal of creep-rupture data, rather than just stress-rupture data, will be needed. It appears that such results could be obtained under E 139 with little or no modification. Testing under E 1457 may also be in order; if so, the standard will need general improvement in clarity and quality. Fatigue crack growth rates may also need to be measured, per E 647. Like E 139, that standard appears to be acceptable.

Because of the importance of the testing environment, it would be beneficial to have one or more standards on establishing and controlling a high temperature gaseous environment, reporting the characteristics of the environment, and testing in the environment. A starting point might be G 111, “Standard Guide for Corrosion Tests in High Temperature or High Pressure Environment, or Both”. It would be preferable to have a standard practice rather than a standard guide.

It appears that new design rules will be needed to take advantage of the specific characteristics of Alloys 617 or 230. The development of such rules would require a great deal of involvement by the ASME, so it does not appear to fit into the scope of the ASTM, and a new ASTM standard to guide development of design rules is probably not justified.

7.0 RECOMMENDATIONS IN TERMS OF CODE INFRASTRUCTURE

Changes to the ASME Section III, Division 1, Subsection NH or a Code Case for this application will be required to support IHX design and fabrication. If either of the materials proposed, Alloy 230 or Alloy 617, is chosen, it will have to be allowed by Subsection NB as well as NH. Additional material testing is required for either material for a sufficiently developed material database as well as to develop analytical design tools. Welding, brazing, and diffusion bonding parameters will need to be developed. This work will have to be well coordinated in order to provide design tools needed to meet proposed HTR deadlines.

It is proposed to adopt an approach similar to that initiated in the US in 1983 with the creation of a Task Force mandated to draft specific design rules. This task force should draft a roadmap of activities and should be able to rely on experts sponsored by DOE to prepare specific tasks in accordance with the roadmap. Proper interface with reactor vendors is needed to ensure that proposed design rules would fully respond to designer needs and it is recommended that reactor vendors be represented in this task force. It is also imperative that design rules be tested on representative structures and under realistic operating conditions in order to ensure adequate safety margins. Benchmark exercises supported by structural tests are needed to avoid implementing excessive conservatism. It is also recommended to involve NRC as early as possible in the process of drafting design rules in order to ensure that issues identified by the NRC are properly addressed.

It is expected that draft design rules could be prepared in a 2 to 3 years period, subject that the work be supported by proper funding by DOE, managed like a project and not like ASME subgroup activities, and that contributors actively work between ASME quarterly meeting and not only in preparation of quarterly meeting.

8.0 CONCLUSIONS

There are two basic types of heat exchanger envisioned for the VHTR IHX, shell & tube design and a stacked plate design. The stacked plate design is compact and efficient and has a proven track record at lower temperatures. The shell and tube IHX design is much larger and more expensive to manufacture. However, there is real experience using this type of heat exchanger in the range of temperatures required for the VHTR thanks to Germany’s KVK program and Japan’s JAERI program.

The shell and tube IHX has another advantage in that ISI and repair are much more easily accomplished and is a proven technology.

The materials discussed in this document are those used to separate the primary and secondary coolants. Either design is contained within a pressure vessel that could operate at a lower temperature thus allowing the use of reactor vessel material. Of the materials looked at, Alloys 617 and 230 are the most promising. They are the strongest of the set evaluated at the temperatures envisioned. Of these two alloys 617 appears to be the strongest at the higher temperatures and is more easily welded. There is considerably more material data available for Alloy 617. For these reasons Alloy 617 would be the first choice for development. Neither of these materials is currently allowed by ASME Section III, Division 1, Subsection NH or NB and would need to be added to both for Class 1 construction with properties provided at the temperatures of concern for the IHX. Additional material testing and review of existing data would be required for either material.

The design rules provided in Subsection NH will need to be reviewed closely to ensure adequacy of use for these alloys and special considerations may be needed. Guidance should be provided to account for the effect of operation in a VHTR/HTR environment if testing shows that they are needed. The same is true for the effects of aging. A complete material model including unified constitutive equations to handle inelastic analysis is needed. Considerable work is required for complete development of design rules.

Not many changes to Code fabrication rules are needed for the shell and tube design IHX. Some development of cold working parameters and tube and tubesheet/header welding parameters may be required for the shell and tube design. For the stacked plate IHX, a lot depends upon which manufacturing methods are chosen. The stacked plate design may require rules for brazing, diffusion bonding, as well as welding. The geometry of the stacked plate IHX does not lend itself to volumetric examination of the joints separating primary and secondary coolant and examination/test requirements should be provided in the Code of construction. Heat treatment parameters may need to be developed or reviewed for post forming and joining activities.

Not surprisingly, a review of ASTM specifications for material and material testing revealed few issues to be resolved prior to use for VHTR IHX applications. One potential issue is that B 829, which governs pipe and tube dimensions, is limited to 30 inch pipe and 24 inch tube. This would significantly constrain the design of the hot header for the tube and shell design and possibly for the stacked plate design as well. If creep crack growth parameters are needed, E 1457 will need general improvement in clarity and quality. Lastly, the specifications for Alloy 617 do not include annealing parameters while the specifications for 230 do. It is suggested that they be included in each of the specifications for Alloy 617.

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