METALS DESIGN HANDBOOK

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February 21, 1989

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U.S. Department of Energy
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Subject: Metals Design Handbook

Dear Andy:

Enclosed for your use/information is DOE-HTGR-88106, Rev. 0, "Metals Design Handbook". Copies have already been sent to C-E and ORNL.

Very truly yours,

G. C. Bramblett, Manager
MHTGR Project Operations

Enclosure

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LIST OF EFFECTIVE PAGES

<u>Page Number</u>	<u>Page Count</u>	<u>Revision</u>
i through viii	8	0
1-1 through 1-8	8	0
2-1 through 2-2	2	0
3-1 through 3-33	33	0
4-1 through 4-16	16	0
5-1 through 5-9	9	0
6-1 through 6-10	10	0
7-1 through 7-8	<u>8</u>	0
Total Pages	94	

CONTENTS

1. INTRODUCTION	1-1
1.1. Objective	1-1
1.2. Scope	1-2
1.3. Applicability	1-3
1.4. Definition of Symbols and Acronyms	1-3
1.5. References	1-4
2. RESPONSIBILITY AND AUTHORITY	2-1
2.1. Responsibility	2-1
2.2. Quality Assurance	2-1
2.3. Change Control	2-1
3. HIGH NICKEL ALLOY, ALLOY 800H	3-1
3.1. Product Forms and Applicable Specifications	3-1
3.2. Time-Independent Mechanical Properties	3-1
3.3. Time-Dependent Mechanical Properties	3-1
3.4. Fatigue Life	3-4
3.5. Thermal Properties	3-5
3.6. Additional Material Properties	3-5
3.7. Effects of Primary Coolant Chemistry and Temperature	3-5
3.7.1. Time-Independent Mechanical Properties	3-6
3.7.2. Time-Dependent Mechanical Properties	3-6
3.7.3. Fatigue Life	3-6
3.7.4. Thermal Properties	3-7
3.7.5. Additional Material Properties	3-7
3.8. Effects of Irradiation	3-7
3.8.1. Time-Independent Mechanical Properties	3-7
3.8.2. Time-Dependent Mechanical Properties	3-8
3.8.3. Fatigue Life	3-8
3.8.4. Thermal Properties	3-9
3.8.5. Additional Material Properties	3-9
3.9. References	3-9

4.	LOW ALLOY STEEL, 2-1/4 Cr - 1 Mo	4-1
4.1.	Product Forms and Applicable Specifications	4-1
4.2.	Time-Independent Mechanical Properties	4-1
4.3.	Time-Dependent Mechanical Properties	4-1
4.4.	Fatigue Life	4-1
4.5.	Thermal Properties	4-2
4.6.	Additional Material Properties	4-2
4.7.	Effect of Primary Coolant Chemistry and Temperatures . .	4-2
4.8.	Effects of Irradiation	4-2
4.9.	References	4-2
5.	THREADED FASTENER MATERIAL SA-638 GRADE 660 (26 Ni - 15 Cr - 2 Ti)	5-1
5.1.	Applicable Specifications	5-1
5.2.	Time-Independent Mechanical Properties	5-1
5.3.	Time-Dependent Mechanical Properties	5-1
5.4.	Fatigue Life	5-2
5.5.	Thermal Properties	5-2
5.6.	Effect of Primary Coolant Chemistry and Temperature . .	5-2
5.7.	Effect of Irradiation	5-2
5.8.	References	5-2
6.	BOLTING MATERIAL SA-193 GRADE B7 (1 Cr - 2 Mo)	6-1
6.1.	Applicable Specifications	6-1
6.2.	Time-Independent Mechanical Properties	6-1
6.3.	Time-Dependent Mechanical Properties	6-1
6.4.	Fatigue Life	6-1
6.5.	Thermal Properties	6-1
6.6.	Effect of Primary Coolant Chemistry and Temperature . .	6-2
6.7.	Effect of Irradiation	6-2
6.8.	References	6-2
7.	BOLTING MATERIAL SA-453 GRADE 660 (26 Ni - 15 Cr - 2 Ti) . . .	7-1
7.1.	Applicable Specifications	7-1
7.2.	Time-Independent Mechanical Properties	7-1
7.3.	Time-Dependent Mechanical Properties	7-1
7.4.	Fatigue Life	7-1
7.5.	Thermal Properties	7-1

7.6. Effect of Primary Coolant Chemistry and Temperature . .	7-2
7.7. Effect of Irradiation	7-2
7.8. References	7-2

FIGURES

3-1. Alloy 800H - Poisson's ratio (ν)	3-23
3-2. Alloy 800H - typical rupture strength	3-24
3-3. Alloy 800H - minimum stress-to-rupture strength	3-25
3-4. Alloy 800H - stress-to-rupture strength given in N-47 . . .	3-26
3-5. Alloy 800H - S_t	3-27
3-6. Alloy 800H - S_{mt}	3-28
3-7. Alloy 800H - design fatigue strain range, ϵ_T	3-29
3-8. Alloy 800H - design fatigue strain range, ϵ_T (elastic analysis)	3-30
3-9. Alloy 800H - thermal diffusivity	3-31
3-10. Alloy 800H - thermal conductivity	3-32
3-11. Alloy 800H - specific heat (C_p)	3-33
4-1. 2-1/4 Cr - 1Mo - design fatigue curves for metal temperatures not exceeding 700°F	4-13
4-2. 2-1/4 Cr - 1 Mo - thermal conductivity	4-14
4-3. 2-1/4 Cr - 1 Mo - thermal diffusivity	4-15
4-4. 2-1/4 Cr - 1 Mo - specific heat (C_p).	4-16
6-1. Bolting SA-193 Grade B7 - stress intensity (S_m)	6-7
6-2. Bolting SA-193 Grade B7 - thermal conductivity	6-8
6-3. Bolting SA-193 Grade B7 - thermal diffusivity	6-9
6-4. Bolting SA-193 Grade B7 - coefficient of thermal expansion, mean and instantaneous	6-10

TABLES

1-1. Metallic components of the reactor system and hot duct assembly and their materials	1-5
1-2. Summary of structural criteria for metallic components of the reactor system and hot duct assembly	1-6
1-3. ASME code limits and requirements	1-7
1-4. Nomenclature and acronyms	1-8

TABLES (Continued)

3-1.	Alloy 800H: Minimum specified room temperature tensile properties, product forms, and specifications	3-11
3-2.	Alloy 800H: Chemical composition	3-12
3-3.	Alloy 800H: Tensile ultimate strength (S_u), yield strength (S_y), and time-independent design stress intensity (S_m)	3-13
3-4.	Alloy 800H: Modulus of elasticity	3-14
3-5.	Alloy 800H: S_t allowable stress intensity values	3-15
3-6.	Alloy 800H: S_{mt} allowable stress intensity values	3-16
3-7.	Alloy 800H: Expected minimum stress-to-rupture values	3-17
3-8.	Alloy 800H: Design fatigue limits	3-18
3-9.	Alloy 800H: Design fatigue strain range, ϵ_f (elastic analysis)	3-19
3-10.	Alloy 800H: Design fatigue strain range, ϵ_f	3-20
3-11.	Alloy 800H: Nominal coefficients of thermal conductivity	3-21
3-12.	Alloy 800H: Coefficient of thermal expansion	3-22
4-1.	2-1/4 Cr - 1 Mo: minimum specified room temperature tensile properties, product forms, and ASME specifications	4-3
4-2.	2-1/4 Cr - 1 Mo: chemical composition	4-4
4-3.	2-1/4 Cr - 1 Mo Grade 22 Class 1: tensile ultimate strength (S_u), yield strength (S_y), and time-independent design stress intensity (S_m)	4-5
4-4.	2-1/4 Cr - 1 Mo: modulus of elasticity	4-6
4-5.	2-1/4 Cr - 1 Mo: S_t - allowable stress intensity values	4-7
4-6.	2-1/4 Cr - 1 Mo: S_{mt} - allowable stress intensity values	4-8
4-7.	2-1/4 Cr - 1 Mo: expected minimum stress-to-rupture values	4-9
4-8.	2-1/4 Cr - 1 Mo: design fatigue strain range, ϵ_f	4-10
4-9.	2-1/4 Cr - 1 Mo: nominal coefficients of thermal conductivity (k) and thermal diffusivity (a)	4-11
4-10.	2-1/4 Cr - 1 Mo: coefficient of thermal expansion	4-12
5-1.	SA-638 Grade 660: mechanical property requirements	5-3
5-2.	SA-638 Grade 660: Chemical composition	5-4

TABLES (Continued)

5-3.	SA-638 Grade 660: design stress intensity (S_m) for threaded structural fastener material	5-5
5-4.	SA-638 Grade 660: modulus of elasticity	5-6
5-5.	SA-638 Grade 660: design fatigue	5-7
5-6.	Nominal coefficients of thermal conductivity (k) and thermal diffusivity (a) for high alloy steel Grade 660 . .	5-8
5-7.	Coefficient of thermal expansion for high alloy steel Grade 660	5-9
6-1.	Bolting material SA-193 Grade B7: chemical composition . .	6-3
6-2.	Bolting material SA-193 Grade B7: minimum specified room temperature tensile properties and specifications	6-4
6-3.	Bolting material SA-193 Grade B7: design stress intensity (S_m) values	6-5
6-4.	Bolting material SA-193 Grade B7: various property values	6-6
7-1.	Bolting material SA-453 Grade 660: chemical composition	7-3
7-2.	SA-453 Grade 660: mechanical property requirements	7-4
7-3.	SA-453 Grade 660: stress-rupture requirements	7-5
7-4.	Bolting material SA-453 Grade 660: design stress intensity values (S_m)	7-6
7-5.	Nominal coefficients of thermal conductivity (k) and thermal diffusivity (a) for high alloy steel Grade 660 . .	7-7
7-6.	Coefficient of thermal expansion for high alloy steel Grade 660	7-8

1. INTRODUCTION

1.1. OBJECTIVE

The objectives of the Metals Design Handbook (MDH) are:

1. To provide and maintain a single source of metal properties and material models to be used for design of Modular High-Temperature Gas-Cooled Reactor (MHTGR) metallic internals components, namely control rods, upper plenum elements, metallic core support, core lateral restraint, upper plenum shroud, hot duct, and circulator outlet shroud.
2. To provide a single source of data and material models for use in component design, performance, and safety analyses.
3. To present properties and equations for material models in a form which can be used directly by the designer or analyst without the need for interpretation and are compatible with analytical methods and structural criteria used in the MHTGR project.
4. To control the properties and material models used in the MHTGR design and analysis to proper quality assurance (QA) standards and project requirements.

1.2. SCOPE

This report gives an approved set of material properties over a range of environmental conditions which are sufficient to design the metallic components in the reactor system and hot duct assembly. Table 1-1* list these metallic components together with the reference design material chosen for each component. Table 1-2 summarizes the structural criteria of each metallic component taken from the component specifications. In all cases, the criteria references the ASME B&PV Code (Refs. 1-1 through 1-5).

The ASME-Code includes the material properties of Coded material in Refs. 1-2, 1-4, and 1-5. The Code does not, however, include environmental effects (such as irradiation, corrosion, or thermal aging), and for some components the material maximum allowable temperature is below that of the design and/or postulated "safety-related" accident conditions.

Table 1-3 gives the Code limits for the portions of the Code given in Table 1-2.

This document includes the effects of the radiation environment, chemical impurity effects (in the primary coolant), and the effects of thermal aging and corrosion on the metallic properties.

The design information introduced in this document includes that available from the ASME B&PV Code High-Temperature Code Cases plus material information from General Atomics (GA) and Oak Ridge National Laboratories (ORNL) that is published.

*Tables and figures are located at the end of each section.

1.3. APPLICABILITY

The reference properties presented in this document are approved by the Component Engineering Department for use in MHTGR design, performance, and safety calculation.

1.4. DEFINITION OF SYMBOLS AND ACRONYMS

Table 1-4 lists the symbols and acronyms used in this report. It is intended that the symbols correspond to those used in the ASME B&PV Code when applicable. Below is a detailed definition of S_m and S_t .

Time-Independent Design Stress Intensity (S_m)

The value of S_m is based on tensile and yield strengths of the material. The criteria employed are defined as follows.

The allowable stress intensity value (S_m) for austenitic steels, nickel-chromium-iron and nickel-iron-chromium alloys is the lowest of the following four values:

1. One-third of the specified minimum tensile strength at room temperature.
2. One-third of the tensile strength at operating temperature.
3. Two-thirds of the specified minimum yield strength at room temperature.
4. Ninety percent (90%) of the yield strength at the operating temperature.

Time-Dependent Design Stress Intensity (S_t)

The symbol S_t is used for the basic time and temperature-dependent allowable stress intensity for load-controlled stresses. S_t values are the least of each of the three quantities:

1. Two-thirds of the minimum stress to cause rupture in time t .
2. Eighty percent (80%) of the minimum stress to cause the onset of tertiary creep in time t .
3. The minimum stress to produce 1% total strain in time t .

1.5. REFERENCES

- 1-1. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NG - Core Support Structures, 1986 Edition through the 1987 Addenda.
- 1-2. ASME Boiler and Pressure Vessel Code, Nuclear Components-Code Case N-201-1, Class CS Components in Elevated Temperature Service, Section III, Division 1, July 16, 1982.
- 1-3. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB - Class 1 Components, 1986 Edition through the 1987 Addenda.
- 1-4. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendix I, Design Stress Intensity Values, Allowable Stresses, Material Properties, and Design Fatigue Curves, 1986 Edition through the 1987 Addenda.
- 1-5. ASME Boiler and Pressure Vessel Code Case N-47-23, Class 1 Components on Elevated Temperature Service, Section III, Division 1, February 20, 1986.
- 1-6. "Reactor System Design Description HTGR," DOE-HTGR-86-035, Rev. 2, April 1988.

TABLE 1-1
METALLIC COMPONENTS OF THE REACTOR SYSTEM AND HOT
DUCT ASSEMBLY AND THEIR MATERIALS

Component	Material Alloy	ASME Specification
1. Hot duct assembly (HDA)	800H	SB-408, SB-409
2. Upper plenum shroud (UPS)	800H	SB-408, SB-409
3. Upper plenum elements	800H	SB-408, SB-409
4. Core lateral restraint (CLR)	800H	
• Core barrel/coolant channels	800H	SB-409
• Boss	800H	SB-564
• Seismic keyways	800H	SB-409
• Seismic keyway shear pins	A2286	SA-638, Grade 660
• Thermal barrier - coverplates, seal sheets, attachments, and studs	800H	SB-408, SB-409
5. Metallic core support structure (MCSS)	2-1/4 Cr - 1 Mo	SA-387, Grade 22, Class 1
6. Control rods	800H	SB-408, SB-409
7. Bolts(a)	1 Cr - 2 Mo or 25 Ni - 15 Cr - 2 Ti	SA-193, Grade B7, SA-453, Grade 660

(a) Used in CLR keyways, at the connection between UPS and core barrel (CLR) and in the HDA at the interface between the thermal barrier attachment and the hot duct pipe cylinder.

TABLE 1-2
SUMMARY OF STRUCTURAL CRITERIA FOR METALLIC COMPONENTS
OF THE REACTOR SYSTEM AND HOT DUCT ASSEMBLY

Component	ASME Code Subsection Section III, Division 1	
	(a)	(b)
1. Hot duct assembly	--	NB(c), N-47
2. Upper plenum shroud	NG	NB(c), N-47
3. Upper plenum elements	N-47	NB(c)
4. Core lateral restraint	NG, N-47	N-201(d)
5. Metallic core support structure	NG	N-201
6. Control rods	N-47	--

(a) Code requirements per Section 3.2.X.10 of appropriate design description document (Ref. 1-6).

(b) This column includes additional requirement which are necessary to handle temperature conditions of the component.

(c) During service levels A and B the design temperatures are sufficiently low that Subsection NB can be used. Portions of the hot duct assembly operate at temperature for which Subsection NB is applicable.

(d) Those portions of the core lateral restraint used to support the core must meet High Temperature Code Case N-201 (for Subsection NG).

TABLE 1-3
ASME CODE LIMITS AND REQUIREMENTS

Component	Subsection	Mechanical Property Criteria	Permissible Materials (MHTGR)	High Temperature Code Case	Permissible Materials (MHTGR)
Class 1	NB	$1/3 S_u - 2/3 S_y$	2-1/4 Cr - 1 Mo Grade 22 Class 1(a) $RT < T \leq 700^\circ F$ Alloy 800H $RT < T \leq 800^\circ F$ SA-193 Grade B7 $RT < T \leq 800^\circ F$ SA-453 Grade 660 $RT < T \leq 800^\circ F$	N-47	2-1/4 Cr -1 Mo Grade 22 Class 1 $< 1200^\circ F$ Alloy 800H $800^\circ F < T \leq 1400^\circ F$ -- -- --
Core support structures	NG	Same as Class 1	2-1/4 Cr - 1 Mo Grade 22 Class 1 $RT < T \leq 700^\circ F$ Alloy 800H $RT < T \leq 800^\circ F$	N-201	-- Alloy 800H $800 < T \leq 1200^\circ F$ (t $\leq$ 20 h) $T \leq 1100^\circ F$ (t $\leq$ 750 h)

(a)Note: Grade 22 Class 2 is also permissible in Subsections NB and NG, but not on Code Case N-47.

TABLE 1-4
NOMENCLATURE AND ACRONYMS

a	thermal diffusivity = $k/(\rho C_p)$
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
C_p	specific heat
E	modulus of elasticity
GAQAM	General Atomics Quality Assurance Manual
J_{IC}	fracture toughness
k	thermal conductivity
K_{IC}	critical stress intensity
MCSS	metallic core support structure
MDH	Metals Design Handbook
N_d	number of design allowable cycles at a given loading condition
PRPM	Program/Resource Procedures Manual
S_a	allowable amplitude of the alternating stress intensity (one-half alternating stress intensity range)
S_m	time-independent design stress intensity
S_t	time-dependent design stress intensity
S_{mt}	the lesser of S_m or S_t
S_R	stress-to-rupture strength
S_{Rm}	minimum stress-to-rupture strength
S_u	ultimate tensile strength
S_y	yield strength (0.2% offset)
T	temperature
t	time
t_R	time-to-rupture
t_3	average time to 0.2% tertiary
α	coefficient of thermal expansion (CTE)
ϵ_T	design fatigue strain range
ν	Poisson's ratio
ρ	mass density
σ	stress
<u>Subscript</u>	
AR	as received
R	rupture

2. RESPONSIBILITY AND AUTHORITY

2.1. RESPONSIBILITY

Responsibility for maintaining this document is vested in the Manager, Core Engineering Branch, General Atomics.

2.2. QUALITY ASSURANCE

This handbook is an GA Approval Level 5 document and shall be approved in accordance with procedure QP-3 given in the GA Quality Assurance Manual (GAQAM) and in the engineering procedures section of the GA Program/Resource Procedures Manual (PRPM).

Material properties must be either obtained from an approved referenceable document or generated from relevant data. Approved documents include the ASME B&PV Code and other nationally recognized standards. Relevant data must be obtained under conditions which comply with the Quality Assurance Criteria of Appendix B, 10CFR50.

Properties generated from data must be obtained from either of two methods. The first method relies on techniques previously used to determine design properties given in the ASME B&PV Code. The second method relies on a statistical treatment of the data to give a 95% confidence that exposure to a given environment does not degrade a selected property more than the specified amount.

2.3. CHANGE CONTROL

Requests for data not now included in this handbook or for new analyses of data presently incorporated will be made to the manager

of the Core Engineering Branch within the Component Engineering Department, General Atomics. Data compiled as a response to requests will be approved as required by GAQAM and will be issued as required by the GA PRPM.

3. HIGH NICKEL ALLOY, ALLOY 800H

3.1. PRODUCT FORMS AND APPLICABLE SPECIFICATIONS

This product is available in many forms and compositions as shown in Tables 3-1 and 3-2, respectively.

3.2. TIME-INDEPENDENT MECHANICAL PROPERTIES

This section includes the following properties of Alloy 800H: S_y (Table 3-3), minimum S_u (Table 3-3), S_m (Table 3-3), E (Table 3-4), and ν (Fig. 3-1).

3.3. TIME-DEPENDENT MECHANICAL PROPERTIES

This section includes S_t , S_{mt} , minimum S_R , and the associated constitutive creep equations for Alloy 800H.

The constant load creep strain-time behavior of Alloy 800H can be estimated by the following equation (Sterling's model):

$$t = \sigma^{U_1/T} \epsilon_c^{(U_2/T + U_3)} 10^{(U_4/T + U_5)} \quad , \quad (1)$$

$$\text{Log } t = U_1/T \text{ Log } \sigma + [U_2/T + U_3] \text{ log } \epsilon_c + U_4/T + U_5 \quad , \quad (2)$$

$$\text{Log } \epsilon_c = (\text{Log } t - U_1/T \text{ log } \sigma - U_4/T - U_5) / (U_2/T + U_3) \quad , \quad (3)$$

where $T = ^\circ\text{F} + 460$,

ϵ_c = creep strain (%),

σ = stress (ksi),

t = time (hours).

Per Ref. 3-4 for $800 \leq ^\circ\text{F} \leq 1600$

$$U_1 = -14,683.81$$

$$U_2 = 10,109.78$$

$$U_3 = -4.21621$$

$$U_4 = 63,683.08$$

$$U_5 = -24.4598$$

Per Ref. 3-5 for $1600 < ^\circ\text{F} \leq 2000$

$$U_1 = -12,162.6$$

$$U_2 = 1078.49$$

$$U_3 = 0.471666$$

$$U_4 = 51,416.6$$

$$U_5 = -19.0780$$

Limitations:

$0 \leq \sigma \leq$ minimum expected ultimate tensile strength at temperature
(minimum S_u per Table 3-3).

$0 \leq \text{time} \leq$ minimum time to 0.2% tertiary creep.

The 0 lower limits apply to the Eq. 1 form. (Log of 0 is undefined.)

The average time to rupture can be estimated from the following equation, per Ref. 3-4:

$$\text{Log}(t_R + 3) = -17.628 + 50160.84/T - (11781.7/T) \text{Log } S_R, \quad (4)$$

The average stress-to-rupture strength can be estimated by solving Eq. 4 for $\text{Log } S_R$.

$$\text{Log } S_R = [\log (t_R + 3) + 17.628 - 50160.84/T] \left(\frac{-T}{11781.7} \right) , \quad (5)$$

where t_R = time to rupture (hour), $t_R > 0$,

$T = ^\circ\text{F} + 460$, $800 \leq ^\circ\text{F} \leq 1500$,

S_R = average stress-to-rupture strength (ksi).

For temperatures between 1500° and 2000°F , S_R can be estimated by solving Eq. 6.

$$\begin{aligned} \text{Log } (t_R + 3) = & -17.0212 + \frac{48158.12}{T} \\ & + \left(0.78572 - \frac{12379.81}{T} \right) \log S_R , \end{aligned} \quad (6)$$

The average time to 0.2% tertiary (t_3) can be estimated by the use of the following correlation with time rupture:

$$t_3 = 0.385 t_R^{0.994} . \quad (7)$$

The minimum stress-to-rupture strength (S_{Rm}) can be estimated from the following equation:

For $800 \leq ^\circ\text{F} \leq 1500$ (per Ref. 3-4)

$$\begin{aligned} \text{Log } S_{Rm} = & [\text{Log } (t_R + 3) + 0.566 + 17.628 \\ & - 50160.84/T] \left(\frac{-T}{11781.7} \right) . \end{aligned} \quad (8)$$

For $1500 < ^\circ\text{F} \leq 2000$ (per Ref. 3-5)

$$S_{Rm} = 0.820 S_R \quad , \quad (9)$$

Where S_R is from Eq. 6.

The minimum stress to onset of 0.2% tertiary creep can be estimated for a given t_3 by solving Eq. 7 for $t_R = 2.612 t_3^{1.006}$ and substituting in Eq. 8 (average by substituting in Eq. 5).

The typical rupture strength of Alloy 800H (according to Eqs. 5 and 6) for the temperature range of 1200° to 2000°F are presented in Fig. 3-2.

Figure 3-3 give the minimum stress-to-rupture strength S_{Rm} based on Eq. 8. Figure 3-4 gives the values of S_{Rm} from Ref. 3-6 (N-47). Comparison between these shows that, typically, the values obtained from Eq. 8 (per Ref. 3-4) give somewhat lower S_{Rm} for a given time and temperature. It is recommended that the more conservative values of S_{Rm} from Ref. 3-4 be used.*

Additional design information from Ref. 3-6 (N-47) is presented in Figs. 3-5 and 3-6, and Tables 3-5 and 3-6.

3.4. FATIGUE LIFE

Tables 3-7, 3-8, and 3-9, and Figs. 3-7 and 3-8 give design fatigue limits Alloy 800H. Table 3-7 is from Ref. 8 (N-201) and gives allowable stress amplitude (S_a) based on elastic analysis. Table 3-8 and Fig. 3-9 are from Ref. 3-6 (N-47) and gives allowable strain range (ϵ_T) based on elastic analysis. By definition, $S_a = \epsilon_T / (2E)$. This relationship can

*Mr. D. Roberts indicates that he still expects the values from Ref. 3-6 to be incorporated into N-47.

be used to show that the ϵ_T values in Table 3-8 corresponded exactly to the S_a values in Table 3-7. Therefore, the properties in both tables are applicable to both N-201 and N-47 within the temperature limits of N-201.

The design fatigue strain range in Table 3-9 and Fig. 3-7 is from Ref. 3-6 (N-47) and applies to strains computed using inelastic analysis techniques.

3.5. THERMAL PROPERTIES

The following thermal properties shall be used for Alloy 800H: thermal diffusivity (α) (Fig. 3-9), thermal conductivity (k) (Table 3-10; Fig 3-10), and specific heat (C_p) (Fig. 3-11).

3.6. ADDITIONAL MATERIAL PROPERTIES

The coefficients of thermal expansion (α) in Table 3-11 shall be used in design.

3.7. EFFECTS OF PRIMARY COOLANT CHEMISTRY AND TEMPERATURE

This section documents the effects of primary coolant chemistry and temperature on the properties of Alloy 800H. The primary coolant helium contains impurities (Ref. 3-5), which can cause corrosion in the form of oxidation, decarburization, and carburization. At design temperatures above 538°C (1000°F), carbon transport in Alloy 800H via long-term interaction with the primary coolant helium has been shown to be the most potentially significant mode of corrosion with respect to influencing bulk mechanical properties such as tensile and creep properties. In addition, surface oxidation along with concurrent carbon transport may significantly affect surface sensitive properties such as fatigue, creep-fatigue, and crack growth. The bases for the values of these properties are given in Section 4.1.3 of Ref. 3-2.

There is no adverse effect on the as received material properties due to exposure at temperatures less than or equal to 1000°F. Long term (up to 300,000 h) exposure at temperatures between 1000° and 1400°F are affected as given in the following subsections.

The following sections shall be followed in design.

3.7.1. Time-Independent Mechanical Properties

$$S_y = 0.8 (S_y)_{AR}$$

$$S_u = 0.8 (S_u)_{AR}$$

$$S_m = 0.8 (S_m)_{AR}$$

$$E \text{ is within } \pm 20\% \text{ of } E_{AR}$$

$$\nu = \nu_{AR}$$

3.7.2. Time-Dependent Mechanical Properties

There is no adverse effect on S_t and S_{Rm} .

Therefore,

$$S_t = (S_t)_{AR}$$

$$S_{Rm} = (S_{Rm})_{AR}$$

3.7.3. Fatigue Life

$$\epsilon_T = 0.8 (\epsilon_T)_{AR}$$

$$S_a = 0.8 (S_a)_{AR}$$

3.7.4. Thermal Properties

There is no adverse effect on α , k , or C_p .

Therefore,

$$\alpha = \alpha_{AR}$$

$$k = k_{AR}$$

$$C_p = (C_p)_{AR}$$

3.7.5. Additional Material Properties

$$\alpha = \alpha_{AR}$$

$$J_{IC} \geq 160 \text{ kJ/m}^3 \text{ (900 in.-lb/in.}^2\text{)}$$

$$K_{IC} \geq 192 \text{ MPa}\sqrt{\text{m}} \text{ (175 ksi } \sqrt{\text{in.}}\text{)}$$

3.8. EFFECTS OF IRRADIATION

This section documents the effects of irradiation at the design level of Ref. 3-2 on the properties of Alloy 800H. The bases for the values of these properties are given in Section 4.1.3 of Ref. 3-2. The confidence in these values is adequate for preliminary design.

The following allowable stresses shall be used in design.

3.8.1. Time-Independent Mechanical Properties

$$S_y = 0.8 (S_y)_{AR}$$

$$S_u = 0.8 (S_u)_{AR}$$

$$S_m = 0.8 (S_m)_{AR}$$

$$E \text{ is within } \pm 20\% \text{ of } E_{AR}$$

$$\nu = \nu_{AR}$$

3.8.2. Time-Dependent Mechanical Properties

For rupture times (t_R) less than 1000 h

$$S_t = 0.8 (S_t)_{AR}$$

$$S_{Rm} = 0.8 (S_{Rm})_{AR}$$

For $t_R \geq 10,000$ h

$$S_t = (S_t)_{AR}$$

$$S_{Rm} = 0.8 (S_{Rm})_{AR}$$

interpolation on log scale for $1,000 \leq t < 10,000$ shall be used to compute S_t and S_{Rm} .

3.8.3. Fatigue Life

For $N \leq 1000$ cycles

$$\epsilon_T = 0.5 (\epsilon_T)_{AR}$$

$$S_a = 0.5 (S_a)_{AR}$$

For $N \geq 10^5$ cycles

$$\epsilon_T = 0.8 (\epsilon_T)_{AR}$$

$$S_a = 0.8 (S_a)_{AR}$$

interpolation on log scale for $10^3 < N < 10^5$ shall be used to compute ϵ_T and S_a .

3.8.4. Thermal Properties

There is no adverse effect on a , k , or C_p .

Therefore,

$$a = a_{AR}$$

$$k = k_{AR}$$

$$C_p = C_{PAR}$$

3.8.5. Additional Material Properties

$$\alpha = \alpha_{AR}$$

3.9. REFERENCES

- 3-1. "Preliminary Assessment of Structural Materials for Use at Temperatures in the Range 1200° to 2000°F," GA-D15431, Rev. 2, February 1980.
- 3-2. Betts, W. S. "Metals Technology Development Plan MHTGR," DOE-HTGR-86087, Rev. 1, March 1987.
- 3-3. "Status Report on Creep-Rupture Tests of 2-1/4 Cr - 1 Mo Steel, Alloy 800H and Hastelloy X in Simulated HTGR-SC/C Helium," DOE-HTGR-85131, Rev. 0, August 1985.
- 3-4. "HTGR Design Data Manual (Metals and Ceramics)," DOE-HTGR-85048, Rev. 0, June 1985.
- 3-5. "MHTGR-Primary Coolant chemistry-Requirements," DOE-HTGR-88086, Rev. 0, April 1988.
- 3-6. "ASME Boiler and Pressure Vessel Code Case N-47-23, Class 1 Components on Elevated Temperature Service, Section III, Division 1," February 20, 1986.
- 3-7. "ASME Boiler and Pressure Vessel Code, Section III, Division 1," Appendices, 1986 Edition through the 1987 Addenda.

- 3-8. "ASME Boiler and Pressure Vessel Code Case N-201-1," Class CS Components on Elevated Temperature," July 16, 1982.
- 3-9. INCO Alloys International, Inc., "Incoloy Alloys 800 and 800HT," Huntington, West Virginia, dated 1986.
- 3-10. "Criteria for Design of Elevated Temperature Class 1 Components in Section III, Division 1 of the ASME Boiler and Pressure Vessel Code," published by ASME in May 1976.

TABLE 3-1
ALLOY 800H: MINIMUM SPECIFIED ROOM
TEMPERATURE TENSILE PROPERTIES,
PRODUCT FORMS, AND SPECIFICATIONS

Minimum Specified Tensile Strengths

Ultimate	65 ksi	448 MPa
Yield	25 ksi	172 MPa

Typical Applicable Specifications^(a)

<u>Form</u>	<u>ASTM</u>	<u>ASME</u>
Seamless condenser tubing	B163	SB-163
Seamless pipe and tubing	B407	SB-407
Rod and bar	B408	SB-408
Plate, sheet, and strip	B409	SB-409
Forgings	B564	SB-564

^(a)UNS N08810 designation in specification is Incoloy 800H.

TABLE 3-2
 ALLOY 800H: CHEMICAL COMPOSITION,
 PERCENT BY WEIGHT

Ni		30 to 35
Cu	Maximum	0.75
Fe		Balance
Mn	Maximum	1.5
C		0.05 to 0.10
Si	Maximum	1.0
S	Maximum	0.015
Cr		19 to 23
Al		0.15 to 0.60
Ti		0.15 to 0.60

Note: For Code Case N-47 usage,
 the following additional
 restrictions apply:

Al + Ti $\geq$ 0.50%

Minimum solution heat treatment temperature 2050°F

TABLE 3-3
 ALLOY 800H: TENSILE ULTIMATE STRENGTH (S_u),
 YIELD STRENGTH (S_y), AND TIME-INDEPENDENT
 DESIGN STRESS INTENSITY (S_m)

Temperature (°F)	Strength, ksi		
	S_u (a)	S_y (b)	S_m (c)
RT	65.0	25.0	16.7
100	64.0	24.3	16.7
200	60.5	22.5	16.7
300	58.4	21.1	16.7
400	57.0	20.0	16.7
500	56.0	19.0	16.7
600	56.0	18.3	16.5
650	--	17.7	--
700	56.0	17.5	15.7
750	--	17.2	15.5
800	56.0	17.0	15.3
850	--	16.6	15.1
900	55.5	16.5	14.8
950	--	16.2	14.6
1000	54.6	16.0	14.4
1050	--	15.8	14.3
1100	51.0	15.6	14.1
1150	--	15.5	13.9
1200	46.5	15.3	13.8
1250	--	15.1	13.5
1300	39.6	14.7	13.2
1350	36.0	14.5	12.0
1400	33.0	14.0	11.0
1450	--	13.5	--
1500	23.0	13.0	--
1550	--	12.0	--
1600	16.0	11.2	--
1700	11.8	9.0	--
1800	9.0	7.0	--
2000	5.0	4.0	--

(a) For $T \leq 1200^\circ\text{F}$. Values of S_u are from Ref. 3-4. These values are lower than the ASME code values given in Table I-3.2 of Ref. 3-7 and Table I-3.2 of Ref. 3-8. At high temperatures, values based on $S_u = 3 S_m$ for $1300 \leq T \leq 1400^\circ\text{F}$ and Ref. 3-1 for $T > 1400^\circ\text{F}$.

(b) Per Table I-2.2, Ref. 3-7, $RT \leq T \leq 800^\circ\text{F}$, Table I-2.2, Ref. 3-8, $800 < T \leq 1200^\circ\text{F}$, Table I-14.5, Ref. 3-6, $1200 < T \leq 1600^\circ\text{F}$, and Ref. 3-1 for $T > 1600^\circ\text{F}$.

(c) Per Table I-1.2 of Ref. 3-7 for $T \leq 800^\circ\text{F}$, Table I-1.2 of Ref. 3-8 for $800 < T \leq 1200^\circ\text{F}$, Table I-14.3 of Ref. 3-6 for $1200^\circ < T \leq 1400^\circ\text{F}$.

TABLE 3-4
ALLOY 800H: MODULUS OF ELASTICITY

Temperature (°F)	(Static) Modulus of Elasticity (psi x 10 ⁻⁶)
70	28.5
100	28.4
200	27.8
300	27.4
400	27.1
500	26.6
600	26.4
700	25.9
750	25.7
800	25.4
850	25.1
900	24.8
950	24.5
1000	24.2
1050	24.1
1100	23.8
1150	23.5
1200	23.2
1250	22.9
1300	22.7
1350	22.2
1400	21.9
1450	21.7
1500	21.2

(a) Per Table I-14.7 of Ref. 3-6.

TABLE 3-5
ALLOY 800H: S_t ALLOWABLE STRESS INTENSITY VALUES
(ksi)

Temperature (°F)	1 h	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h	300,000 h
800	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2
850	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
900	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.7	19.6
950	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.5	19.3	19.2	19.1
1000	19.4	19.4	19.4	19.4	19.4	19.3	19.1	18.9	18.6	18.5	17.0
1050	19.3	19.3	19.3	19.3	19.3	18.9	18.7	18.4	17.4	15.3	13.4
1100	19.1	19.1	19.0	18.6	18.4	18.0	17.8	15.7	13.6	11.7	10.3
1150	18.6	18.5	18.4	18.1	17.7	16.3	14.0	12.0	10.5	9.1	8.0
1200	18.2	17.6	17.3	16.6	14.7	12.5	10.9	9.4	8.2	7.2	6.4
1250	17.7	16.6	15.8	13.3	11.5	9.8	8.6	7.5	6.6	5.8	5.1
1300	16.6	14.5	12.4	10.5	9.1	7.9	6.9	6.0	5.3	4.6	4.1
1350	14.9	11.4	9.9	8.4	7.4	6.4	5.6	4.9	4.3	3.7	3.3
1400	12.6	9.2	8.0	6.8	6.0	5.2	4.6	4.0	3.5	3.0	2.6

(a) The values in this table are from Table I-14.4C, Ref. 3-6.

TABLE 3-6
ALLOY 800H: S_{mt} ALLOWABLE STRESS INTENSITY VALUES
(ksi)

Temperature (°F)	1 h	10 h	30 h	100 h	300 h	1,000 h	3,000 h	10,000 h	30,000 h	100,000 h	300,000 h
800	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
850	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
900	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
950	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6
1000	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
1050	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
1100	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	13.6	11.7	10.3
1150	13.9	13.9	13.9	13.9	13.9	13.9	13.9	12.0	10.5	9.1	8.0
1200	13.8	13.8	13.8	13.8	13.8	12.5	10.9	9.4	8.2	7.2	6.4
1250	13.5	13.5	13.5	13.3	11.5	9.8	8.6	7.5	6.6	5.8	5.1
1300	13.2	13.2	12.4	10.5	9.1	7.9	6.9	6.0	5.3	4.6	4.1
1350	12.0	11.4	9.9	8.4	7.4	6.4	5.6	4.9	4.3	3.7	3.3
1400	11.0	9.2	8.0	6.8	6.0	5.2	4.6	4.0	3.5	3.0	2.6

(a) The values in this table are from Table I-14.3C of Ref. 3-6.

TABLE 3-7
ALLOY 800H: EXPECTED MINIMUM STRESS-TO-RUPTURE VALUES
(ksi)

Later - values can be obtained from Fig. 3-6.

TABLE 3-8
ALLOY 800H: DESIGN FATIGUE LIMITS
(Elastic Analysis)

N _d , No. of Cycles	≤800°F	S _a , Allowable Stress Amplitude (ksi)	
		1000°F	1200°F
10 ¹	708.0	58.9	59.5
2 × 10 ¹	521.0	50.4	44.3
4 × 10 ¹	--	41.3	32.9
5 × 10 ⁻¹	345.0	--	--
10 ²	261.0	32.9	22.5
2 × 10 ²	201.0	28.0	17.6
4 × 10 ²	--	23.8	14.2
5 × 10 ⁻²	148.0	--	--
10 ³	119.0	19.2	11.1
2 × 10 ³	97.0	16.8	9.5
4 × 10 ³	--	15.1	8.5
5 × 10 ⁴	76.0	--	--
10 ⁴	64.0	13.0	7.5
2 × 10 ⁴	55.5	11.8	6.9
4 × 10 ⁴	--	11.4	6.6
5 × 10 ⁴	46.3	--	--
10 ⁵	40.8	10.7	6.2
2 × 10 ⁵	35.9	10.1	6.0
4 × 10 ⁵	--	9.9	5.7
5 × 10 ⁵	31.0	--	--
10 ⁶	28.3	9.6	5.6

Notes:

1. E = 26 × 10⁶ psi.
2. The value for temperatures less than or equal to 800°F were obtained from Table I-9.1 of Ref. 3-7. The values at T > 800°F are from Table I-9.2(b), Ref. 3-8.
3. Interpolation between tabular values is permissible based upon data representation by straight lines on a log-log plot. Accordingly, for S₁ > S > S_j:

$$\left(\frac{N}{N_1} = \frac{N_j}{N_1} \right) [\log(S_1/S)] / \log(S_1/S_j)$$

Where S, S₁, and S_j are values of S_a; N, N₁, and N_j are corresponding numbers of cycles from design fatigue data. Example: from the data given in the table above, use the interpolation formula above to find the number of cycles N for S_a = 84 ksi at 800°F.

$$\frac{N}{2000} = \left(\frac{5000}{2000} \right) [\log(97/84)] / \log(97/76)$$

N = 3430 cycles.

TABLE 3-9
 ALLOY 800H: DESIGN FATIGUE STRAIN RANGE, ϵ_T
 (Elastic Analysis)

N _d , No. of Cycles	ϵ_T Strain Range (in./in.) at Temperature		
	1000°F	1200°F	1400°F
10 ¹	0.00453	0.00458	0.00462
2 x 10 ¹	0.00388	0.00341	0.00295
4 x 10 ¹	0.00318	0.00253	0.0019
10 ²	0.00253	0.00173	0.00114
2 x 10 ²	0.00215	0.00135	0.000791
4 x 10 ²	0.00183	0.00109	0.000581
10 ³	0.00148	0.00085	0.000411
2 x 10 ³	0.00129	0.00073	0.000341
4 x 10 ³	0.00116	0.00065	0.000291
10 ⁴	0.001	0.00058	0.000251
2 x 10 ⁴	0.00091	0.00053	0.000231
4 x 10 ⁴	0.00088	0.00051	0.000214
10 ⁵	0.00082	0.00048	0.000201
2 x 10 ⁵	0.00078	0.00046	0.000192
4 x 10 ⁵	0.000765	0.00044	0.000186
10 ⁶	0.00073	0.00043	0.000181

(a) The values in this table are from Table T-1430-1c of Ref. 3-6 (N-47).

TABLE 3-10
ALLOY 800H: DESIGN FATIGUE STRAIN RANGE, ϵ_T

Nd, No. of Cycles ^(a)	ϵ_T Strain Range (in./in.) at Temperature						
	800°F	900°F	1000°F	1100°F	1200°F	1300°F	1400°F
10^1	0.0513	0.0498	0.0468	0.0378	0.0308	0.0263	0.0231
2 x 10^1	0.0328	0.0313	0.0298	0.0243	0.0198	0.0168	0.0129
4 x 10^1	0.0218	0.0208	0.0190	0.0163	0.0130	0.0113	0.00866
10^2	0.0139	0.0219	0.0119	0.01	0.00823	0.00725	0.00566
2 x 10^2	0.0103	0.00939	0.00861	0.00722	0.00603	0.00535	0.00426
4 x 10^2	0.00777	0.00699	0.00641	0.00542	0.00463	0.00405	0.00331
10^3	0.00537	0.00489	0.00441	0.00392	0.00328	0.00285	0.00254
2 x 10^3	0.00427	0.00379	0.00351	0.00312	0.00261	0.0023	0.00209
4 x 10^3	0.00347	0.00314	0.00291	0.00259	0.00213	0.00195	0.00176
10^4	0.00277	0.00249	0.00233	0.0021	0.00174	0.00159	0.00143
2 x 10^4	0.00242	0.00219	0.00201	0.00182	0.00155	0.00142	0.00125
4 x 10^4	0.00215	0.00193	0.0018	0.00162	0.0014	0.00127	0.00109
10^5	0.00187	0.00164	0.00151	0.00139	0.00122	0.00115	0.000959
2 x 10^5	0.00169	0.00149	0.00141	0.00128	0.00113	0.00105	0.000919
4 x 10^5	0.00157	0.00139	0.00129	0.00121	0.00108	0.000987	0.000889
10^6	0.00139	0.00129	0.00119	0.00112	0.00103	0.000937	0.000869

(a) Cyclic strain rate: 1×10^{-3} in./in./s.

(b) The values in this table are from Table T-1420-IC, Ref. 3-6.

TABLE 3-11
ALLOY 800H: NOMINAL COEFFICIENTS
OF THERMAL CONDUCTIVITY

Temperature (°F)	k(a)
70	6.7
100	6.8
150	7.1
200	7.4
250	7.7
300	8.0
350	8.3
400	8.6
450	8.8
500	9.1
550	9.3
600	9.6
650	9.8
700	10.1
750	10.3
800	10.6
850	10.8
900	11.1
950	11.3
1000	11.6
1050	11.9
1100	12.1
1150	12.4
1200	12.7
1250	13.0
1300	13.2
1350	13.2
1400	13.8
1450	14.2
1500	14.5
1600	15.1
1800	17.3

(a) k is thermal conductivity, Btu/h ft° F. Values for $T \leq 1500^\circ\text{F}$ are per Table I-4 of Ref. 3-7 values for $T > 1500^\circ\text{F}$ are from Ref. 3-1. For $T \leq 1500^\circ\text{F}$, $k \approx 6.3 + 5.4 \times 10^{-3} T$.

TABLE 3-12
ALLOY 800H: COEFFICIENT OF THERMAL EXPANSION

Temperature (°F)	Coefficient of Thermal Expansion (in./in.-°F x 10 ⁻⁶)	
	Mean(a)(b)	Instantaneous(c)
70	7.75	7.75
100	7.79	8.05
200	7.90	8.50
300	8.30	8.80
400	8.80	9.00
500	8.90	9.12
600	9.00	9.20
700	9.10	9.32
750	9.15	9.40
800	9.20	9.50
850	9.25	9.65
900	9.30	9.80
950	9.35	9.97
1000	9.40	10.16
1050	9.45	10.37
1100	9.50	10.60
1150	9.55	10.80
1200	9.60	11.00
1250	9.65	11.20
1300	9.70	11.37
1350	9.77	11.54
1400	9.84	11.68
1450	9.91	11.80
1500	10.00	11.92
1550	10.10	12.00
1600	10.20	12.10

(a) The mean coefficient of thermal expansion at temperature (T) is given by:

$$\frac{\text{Length at } T - \text{length at } 70^{\circ}\text{F}}{(\text{Length at } 70^{\circ}\text{F}) (T - 70^{\circ}\text{F})}$$

(b) Per Table I-14.9 of Ref. 3-6.

(c) Per Table I-14.8 of Ref. 3-6.

Per Ref. 3-1

Fig. 3-1. Alloy 800H - Poisson's ratio (ν)

Based on Eqs. 5 and 6

Fig. 3-2. Alloy 800H - typical rupture strength

Curve from Fig. 3.1-8 of Ref. 3-4

Fig. 3-3. Alloy 800H - Minimum stress-to-rupture strength

From Fig. I-14.6, Ref. 3-6

Fig. 3-4. Alloy 800H - stress-to-rupture strength given in N-47

From Fig. I-14.4C, Ref. 3-6

Fig. 3-5. Alloy 800H - S_t

From Fig. I-14.3C, Ref. 6

Fig. 3-6. Alloy 800H - S_{mt}

From Fig. I-1420-1C, Ref. 3-6

Fig. 3-7. Alloy 800H - design fatigue strain range, ϵ_r

Fig. 3-8. Alloy 800H - design fatigue strain range, ϵ_f (elastic analysis)

From Fig. T-1430-1C, Ref. 3-6 (N-47)

From Ref. 3-4

Fig. 3-9. Alloy 800H - thermal diffusivity

From Ref. 3-1

Fig. 3-10. Alloy 800H - thermal conductivity

From Ref. 3-4

Fig. 3-11. Alloy 800H - specific heat (C_p)

4. LOW ALLOY STEEL, 2-1/4 Cr - 1 Mo

4.1. PRODUCT FORMS AND APPLICABLE SPECIFICATIONS

This product is available in many forms and compositions as shown in Tables 4-1 and 4-2, respectively.

4.2. TIME-INDEPENDENT MECHANICAL PROPERTIES

The following mechanical properties of 2-1/4 Cr - 1 Mo shall be used in design: ultimate strength (S_u) (Table 4-3), yield strength (S_y) (Table 4-3), design stress intensity (S_m) (Table 4-3), and modulus of elasticity (E) (Table 4-4). The material 2-1/4 Cr - 1 Mo Grade 22 Class 1 is not included in the high-temperature Code Case N-201-1, but it is included in Code Case N-47 (Ref. 4-3).

4.3. TIME-DEPENDENT MECHANICAL PROPERTIES

The only metallic component to use 2-1/4 Cr - 1 Mo is the metallic core support structure (per Table 1-1). This structure is to be designed to the ASME B&PV Subsection NG and Code Case N-201 (per Table 1-2).

Values of S_t , S_{mt} , and minimum S_R for 2-1/4 Cr - 1 Mo found in Tables 4-5, 4-6, and 4-7 shall be used in design.

4.4. FATIGUE LIFE

The fatigue life of 2-1/4 Cr - 1 Mo steel presented in Fig. 4-1 and Table 4-8 shall be used in design.

4.5. THERMAL PROPERTIES

The values of thermal diffusivity (α), thermal conductivity (k) (Table 4-9, Figs. 4-2, 4-3), and specific heat (C_p) (Fig. 4-4) for 2-1/4 Cr - 1 Mo shall be used in design.

4.6. ADDITIONAL MATERIAL PROPERTIES

This section contains the coefficient of thermal expansion (α) (Table 4-10) of 2-1/4 Cr - 1 Mo that shall be used in design.

4.7. EFFECT OF PRIMARY COOLANT CHEMISTRY AND TEMPERATURES

The effect of primary coolant chemistry and temperature is expected to be small on the mechanical properties of 2-1/4 Cr - 1 Mo at the design temperatures less than 850°F and can be neglected.

4.8. EFFECTS OF IRRADIATION

The irradiation effects on the mechanical properties of 2-1/4 Cr - 1 Mo can be neglected when irradiated at temperatures below 800°F at total fluences of less than 10^{19} n/cm².

4.9. REFERENCES

- 4-1. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices, 1986 Edition through the 1987 Addenda.
- 4-2. Wattier, J. B., "HTGR Data Manual (Metals and Ceramics)," DOE-HTGR-85048, Rev. 0, June 1985.
- 4-3. ASME Boiler and Pressure Vessel Code Case N-47-23, "Class 1 Components in Elevated Temperature Service, Section III, Division 1," February 20, 1986.
- 4-4. ASME Boiler and Pressure Vessel Code, Section II, Material Specifications, Part A, "Ferrous," 1986 Edition through the 1987 Addenda.

TABLE 4-1
2-1/4 Cr - 1 Mo: MINIMUM SPECIFIED ROOM TEMPERATURE TENSILE
PROPERTIES, PRODUCT FORMS, AND ASME SPECIFICATIONS

ASME Specification	Grade	Product Form	S_u [ksi (MPa)]	S_y [ksi (MPa)]
SA-182	F22a	Fittings and valves	60 (414)	30 (207)
SA-213	T-22	Seamless tubes	60 (414)	30 (207)
SA-335	P22	Seamless pipe	60 (414)	30 (207)
SA-336	F22a	Forgings	60 (414)	30 (207)
SA-369	FP22 pipe	Forged and bored	60 (414)	30 (207)
SA-387	22 Class 1	Plate	60 (414)	30 (207)
SA-387	22 Class 2	Plate	75 (518)	45 (311)

Note: Except for Grade 22 Class 2, all the above materials are permissible materials at elevated temperatures (above 700°F) per Code Case N-47 (Ref. 4-3).

TABLE 4-2
2-1/4 Cr - 1 Mo: CHEMICAL COMPOSITION
(Percent By Weight)

ASME Specification SA-387, Grade 22

C, maximum	0.15
Mn	0.25 - 0.66
P, maximum	0.035
S, maximum	0.035
Si, maximum	0.50
Cr	1.88 - 2.62
Mo	0.85 - 1.15
Fe	Balance

Values from Ref. 4-4.

TABLE 4-3
 2-1/4 Cr - 1 Mo GRADE 22 CLASS 1: TENSILE
 ULTIMATE STRENGTH (S_u), YIELD STRENGTH (S_y),
 AND TIME-INDEPENDENT DESIGN
 STRESS INTENSITY (S_m)

Temperature (°F)	Strength (ksi)		
	S_y (a)	S_u (b)	S_m (c)
100	30.0	60.0	20.0
200	27.8	60.0	18.5
300	27.1	58.2	18.1
400	26.9	58.2	17.9
500	26.9	58.2	17.9
600	26.9	58.2	17.9
700	26.9	58.2	17.9
750	26.9	58.2	17.9
800	26.7	58.2	17.8
850	26.2	58.2	17.4
900	25.7	58.2	17.1
950	24.8	58.2	16.5
1000	23.7	54.7	15.8

(a) Per Table I-2.1, Ref. 4-1 and
 Table I-14.5 of Ref. 4-3.

(b) Per Table I-3.1, Ref. 4-1.

(c) Per Table I-1.1 of Ref. 4-1 for
 $T \leq 700^\circ\text{F}$; otherwise, S_m based on two $S_y/3$.

TABLE 4-4
2-1/4 Cr - 1 Mo: MODULUS
OF ELASTICITY

Temperature (°F)	E x 10 ⁶ (a) (psi)
70	30.6
200	29.8
300	29.4
400	28.8
500	28.3
600	27.7
700	27.1
800	26.3

(a)Per Table I-6.0,
Ref. 4-1.

TABLE 4-5
2-1/4 Cr - 1 Mo: S_t - ALLOWABLE STRESS INTENSITY VALUES
(ksi)

Temperature (°F)	1 h	10 h	30 h	10 ² h	3 x 10 ² h	10 ³ h	3 x 10 ³ h	10 ⁴ h	3 x 10 ⁴ h	10 ⁵ h	3 x 10 ⁵ h
700	--	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5
750	35.3	35.2	34.6	33.5	32.5	31.3	29.7	28.4	26.6	25.0	23.3
800	35.0	33.2	31.8	30.4	28.8	26.8	25.0	23.0	20.5	18.0	16.1
850	32.3	29.4	28.0	26.4	25.0	23.2	21.0	18.3	16.3	14.0	12.3
900	29.0	25.5	23.7	22.0	20.2	18.5	16.5	14.4	12.5	10.9	9.6
950	25.0	21.0	19.3	17.5	16.3	14.8	13.2	11.3	9.7	8.4	7.3
1000	20.7	17.1	15.5	14.2	13.1	11.9	10.4	8.7	7.5	6.3	5.2
1050	16.8	13.8	12.5	11.2	10.2	9.3	7.9	6.7	5.7	4.7	4.0
1100	13.6	11.0	10.0	9.0	8.2	7.2	6.2	5.0	4.1	3.3	2.7
1150	10.8	8.8	8.0	7.2	6.3	5.4	--	--	--	--	--
1200	9.0	6.2	6.1	5.9	5.1	4.1	--	--	--	--	--

Per Table I-14.4D of Ref. 4-3 (N-47) for 2-1/4 Cr - 1 Mo Grade 22 Class 1.

TABLE 4-6
2-1/4 Cr - 1 Mo: S_{mt} - ALLOWABLE STRESS INTENSITY VALUES
(ksi)

Temperature (°F)	1 h	10 h	30 h	10 ² h	3 x 10 ² h	10 ³ h	3 x 10 ³ h	10 ⁴ h	3 x 10 ⁴ h	10 ⁵ h	3 x 10 ⁵ h
700	--	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
750	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
800	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	16.1
850	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	16.3	14.0	12.3
900	17.2	17.2	17.2	17.2	17.2	17.2	16.5	14.4	12.5	10.9	9.6
950	16.7	16.7	16.7	16.7	16.3	14.8	13.2	11.3	9.7	8.4	7.3
1000	15.9	15.9	15.5	14.2	13.1	11.9	10.4	8.7	7.5	6.3	5.2
1050	14.9	13.8	12.5	11.2	10.2	9.3	7.9	6.7	5.7	4.7	4.0
1100	13.6	11.0	10.0	9.0	8.2	7.2	6.2	5.0	4.1	3.3	2.7
1150	10.8	8.8	8.0	7.2	6.3	5.4	--	--	--	--	--
1200	9.0	6.2	6.1	5.9	5.1	4.1	--	--	--	--	--

Per Table I-14.3D of Ref. 4-3 (N-47) for 2-1/4 Cr - 1 Mo Grade 22 Class 1.

TABLE 4-7
2-1/4 Cr - 1 Mo: EXPECTED MINIMUM STRESS-TO-RUPTURE VALUES
(ksi)

Temperature (°F)	10 h	30 h	10 ² h	3 x 10 ² h	10 ³ h	3 x 10 ³ h	10 ⁴ h	3 x 10 ⁴ h	10 ⁵ h	3 x 10 ⁵ h
700	59.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0	54.0	49.0
750	58.0	57.0	56.0	54.6	53.0	51.2	48.0	43.3	37.5	34.1
800	56.0	55.5	54.0	48.5	43.0	37.5	34.5	30.5	27.0	24.0
850	52.0	50.5	46.0	40.5	35.0	31.0	27.5	24.0	21.0	18.5
900	46.0	41.0	36.0	32.0	28.0	25.0	21.6	19.0	16.4	14.1
950	40.0	35.0	30.0	26.0	22.2	19.5	17.0	14.6	12.6	11.0
1000	31.5	27.5	24.0	21.0	17.9	15.2	13.1	11.0	9.4	7.9
1050	26.0	22.5	19.0	16.5	14.0	12.0	10.0	8.3	7.0	5.8
1100	21.0	18.0	15.1	13.0	10.8	9.1	7.5	6.2	5.0	4.1
1150	17.0	14.1	11.8	9.8	8.0	--	--	--	--	--
1200	13.5	11.1	9.2	7.6	6.2	--	--	--	--	--

Values per Table I-14.6D of Ref. 4-3 (N-47) for 2-1/4 Cr - 1 Mo Grade 22 Class 1.

TABLE 4-8
2-1/4 Cr - 1 Mo: DESIGN FATIGUE STRAIN RANGE, ϵ_T

No. of Cycles ^(a)	ϵ_T Strain Range (in./in.) at Temperature		
	800°F	900° to 1100°F	≤700°F
10^1	0.056	0.040	0.039
4 x 10^1	0.023	0.0163	--
10^2	0.013	0.0097	0.014
2 x 10^2	0.0094	0.0070	--
4 x 10^2	0.0070	0.0056	--
10^3	0.0052	0.0042	0.055
2 x 10^3	0.0044	0.0039	--
4 x 10^3	0.0040	0.0035	--
10^4	0.0032	0.00265	0.00253
2 x 10^4	0.0026	0.00215	--
4 x 10^4	0.0023	0.00182	--
10^5	0.00195	0.00158	0.00133
2 x 10^5	0.00173	0.00142	--
4 x 10^5	0.00155	0.00130	--
10^6	0.00137	0.00118	0.000833

(a) Cycle strain rate: 4×10^{-3} in./in./s. The values at $T > 700^\circ\text{F}$ are from Table T-1420-1D of Ref. 4-3 (N-47). For $T \leq 700^\circ\text{F}$, values were computed from Table I-9.0 of Ref. 4-1 using $E = 30 \times 10^6$ psi ($\epsilon_T = 2 S_a/E$).

TABLE 4-9
2-1/4 Cr - 1 Mo: NOMINAL COEFFICIENTS OF THERMAL
CONDUCTIVITY (k) AND THERMAL DIFFUSIVITY (a)

Temperature (°F)	k(a)(b)	a(a)(b)
70	20.9	0.408
100	21.0	0.397
150	21.2	0.391
200	21.3	0.385
250	21.4	0.378
300	21.5	0.371
350	21.5	0.364
400	21.5	0.357
450	21.5	0.349
500	21.4	0.341
550	21.3	0.332
600	21.1	0.323
650	20.9	0.314
700	20.7	0.305
750	20.5	0.295
800	20.2	0.285
850	20.0	0.274
900	19.7	0.264
950	19.4	0.252
1000	19.1	0.241
1050	18.8	0.229
1100	18.5	0.217
1150	18.3	0.205
1200	18.0	0.192
1250	17.7	0.179
1300	17.2	0.163
1350	16.4	0.136
1400	15.6	0.075
1450	15.4	0.127
1500	15.3	0.197

(a) k is the thermal conductivity, Btu/h-ft-°F; and
a is the thermal diffusivity, ft²/h:

$$a = \frac{k \text{ (Btu/h-ft-°F)}}{\text{Density (lb/ft}^3\text{) x specific heat (Btu/lb-°F)}}$$

(b) From Table I-4.0, Ref. 4-1.

TABLE 4-10
2-1/4 Cr - 1 Mo: COEFFICIENT OF
THERMAL EXPANSION

Temperature (°F)	CTE(a) (in./in./°F x 10 ⁻⁶)
70	--
100	6.27
150	6.41
200	6.54
250	6.65
300	6.78
350	6.88
400	6.98
450	7.07
500	7.16
550	7.24
600	7.32
650	7.41
700	7.47
750	7.55
800	7.61

(a) Per Table I-5.0, Ref. 4-1.

From Fig. I-9.1.1, Ref. 4-1

Fig. 4-1. 2-1/4 Cr - 1 Mo - design fatigue curves for metal temperatures not exceeding 700°F

From Fig. 3.2-2, Ref. 4-2

Fig. 4-2. 2-1/4 Cr - 1 Mo - thermal conductivity

From Fig. 6.1-10, Ref. 4-2

Fig. 4-3. 2-1/4 Cr - 1 Mo - thermal diffusivity

From Fig. 6.1-9, Ref. 4-2

Fig. 4-4. 2-1/4 Cr - 1 Mo - specific heat (Cp)

5. THREADED FASTENER MATERIAL SA-638 GRADE 660 (26 Ni - 15 Cr - 2 Ti)

Devices which are used to assemble structural elements of core support structures are referred to as threaded structural fasteners in Subsection NG (where the core support structures are located within a pressure-retaining boundary). For connections joining parts of pressure-retaining boundaries, NB-3230 (Ref. 5-1) rules apply.

This material is listed in Table I-1.1 (Ref. 5-2) and shall be used for applicable threaded structural fasteners in the MHTGR.

The data base is limited because of the maximum temperature conditions allowed by the Code. Until such time that the data base is expanded to include mechanical properties up to 1200°F for some of the MHTGR internal metallic operating/accident conditions use the values in this handbook.

5.1. APPLICABLE SPECIFICATIONS

The applicable specifications are given in Tables 5-1 and 5-2 is from Ref. 5-3.

5.2. TIME-INDEPENDENT MECHANICAL PROPERTIES

The threaded-structural-fastener material SA-638 Grade 660 design stress values to be used are presented in Table 5-3. The modulus of elasticity to be used is given in Table 5-4.

5.3. TIME-DEPENDENT MECHANICAL PROPERTIES

[LATER]

5.4. FATIGUE LIFE

The fatigue life of SA-638 Grade 660 to be used is presented in Table 5-5.

5.5. THERMAL PROPERTIES

The following thermal properties shall be used : thermal conductivity (k) (Table 5-6), thermal diffusivity (Table 5-6), and coefficient of thermal expansion (Table 5-7).

5.6. EFFECT OF PRIMARY COOLANT CHEMISTRY AND TEMPERATURE

The effect on the mechanical properties of SA-638 Grade 660 can be neglected because there is not expected to be an effect in the MHTGR environment at design temperatures less than 700°F.

5.7. EFFECT OF IRRADIATION

[LATER]

5.8. REFERENCES

- 5-1. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB - Class 1 Components, 1986 Edition through the 1987 Addenda.
- 5-2. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices, 1986 Edition through the 1987 Addenda.
- 5-3. ASME Boiler and Pressure Vessel Code, Section III, Material Specifications Part A, "Ferrous," 1986 Edition through the 1987 Addenda.

TABLE 5-1
SA-638 GRADE 660: MECHANICAL PROPERTY REQUIREMENTS

Tensile strength, minimum	
psi	130,000
MPa	895
Yield strength (0.2% offset), minimum	
psi	85,000
MPa	585
Elongation in 4D minimum, %	15
Reduction of area, minimum, %	18
Brinell hardness	248 minimum
Stress-to-rupture at 1200°F (649°C) and 65,000 psi (460 MPa)	
Minimum hours	23
Elongation, %	3

Note: Values in this table are from Ref. 5-2.

TABLE 5-2
SA-638 GRADE 660: CHEMICAL COMPOSITION(a)
(Percent By Weight)

	Grade 660 (UNS K66286)(b)	
	Ladle Analysis Range (%)	Check Analysis Over or Under
Carbon	0.08 maximum	0.01 over
Manganese	2.00 maximum	0.04 over
Silicon	1.00 maximum	0.05 over
Phosphorus	0.040 maximum	0.005 over
Sulfur	0.030 maximum	0.005 over
Chromium	13.50 to 16.00	0.20
Nickel	24.00 to 27.00	0.20
Molybdenum	1.00 to 1.50	0.05
Titanium	1.90 to 2.35	0.05
Copper	--	--
Aluminum	0.35 maximum	0.05 over
Vanadium	0.10 to 0.50	0.03
Boron	0.0010 to 0.010	0.004 under 0.001 over

(a) Values from this table are from Ref. 5-2.

(b) New designation established in accordance with Recommended Practice E 527 and SAE J1086.

TABLE 5-3
SA-638 GRADE 660: DESIGN STRESS INTENSITY
(S_m) FOR THREADED STRUCTURAL
FASTENER MATERIAL^(a)

Temperature (°F)	Design Stress Intensity Values S_m ^(b) (ksi)
100	43.3
200	43.3
300	43.3
400	43.3
500	43.3
600	43.3
700	43.3

^(a)Minimum specified strength ratio
 $S_y/S_u = 85/130$.

^(b)Per Table I-1.1 (Ferritic Steels),
Ref. 4-1.

TABLE 5-4
SA-638 GRADE 660: MODULUS OF ELASTICITY

[LATER]

TABLE 5-5
SA-638 GRADE 660: DESIGN FATIGUE LIMITS

[LATER]

TABLE 5-6
NOMINAL COEFFICIENTS OF THERMAL CONDUCTIVITY
(k) AND THERMAL DIFFUSIVITY (a) FOR
HIGH ALLOY STEEL GRADE 660

Temperature (°F)	k (Btu/h-ft-°F)	a (ft ² /h)
70	7.5	0.134
100	7.7	0.135
150	8.0	0.137
200	8.2	0.138
250	8.5	0.140
300	8.8	0.142
350	9.0	0.144
400	9.3	0.146
450	9.5	0.148
500	9.8	0.150
550	10.0	0.152
600	10.2	0.154
650	10.4	0.155
700	10.7	0.157
750	10.9	0.159
800	11.1	0.160
850	11.3	0.162
900	11.6	0.164
950	11.8	0.165
1000	12.0	0.167
1050	12.2	0.168
1100	12.4	0.167
1150	12.6	0.164
1200	12.8	0.161
1250	13.1	0.161
1300	13.3	0.163
1350	13.5	0.165
1400	13.7	0.168
1450	13.9	0.171
1500	14.1	0.174

Note: The values in this table are from Table I-4.0, Ref. 4-1. Values are applicable to both SA-638 Grade 660 and SA-453 Grade 660.

TABLE 5-7
COEFFICIENT OF THERMAL EXPANSION FOR
HIGH ALLOY STEEL GRADE 660

Temperature (°F)	Instant ^(a) (10 ⁻⁶ /°F)	Mean
70	8.22	--
100	8.31	8.24
150	8.46	8.32
200	8.61	8.39
250	8.75	8.47
300	8.89	8.54
350	9.02	8.62
400	9.14	8.69
450	9.26	8.76
500	9.37	8.82
550	9.48	8.88
600	9.58	8.94
650	9.68	9.0
700	9.77	9.06
750	9.85	9.11
800	9.93	9.17

(a) Per Table I-5.0, Ref. 4-1.
This is applicable to both SA-638
Grade 660 and SA-453 Grade 660.

6. BOLTING MATERIAL SA-193 GRADE B7 (1 Cr - 2 Mo)

This bolting material is a low alloy steel listed in Table I-1.3 (Ref. 6-1).

6.1. APPLICABLE SPECIFICATIONS

The chemical compositions and mechanical properties are given in Tables 6-1 and 6-2 (Ref. 6-3).

6.2. TIME-INDEPENDENT MECHANICAL PROPERTIES

The bolting material SA-193 Grade B7 design stress values presented in Table 6-3 and Fig. 6-1 shall be used in design.

6.3. TIME-DEPENDENT MECHANICAL PROPERTIES

[LATER]

6.4. FATIGUE LIFE

[LATER]

6.5. THERMAL PROPERTIES

This section includes the following thermal properties to be used: thermal conductivity (k) (Fig. 6-2), thermal diffusivity (Fig. 6-3), and coefficient of thermal expansion (Table 6-4, Fig. 6-4).

6.6. EFFECT OF PRIMARY COOLANT CHEMISTRY AND TEMPERATURE

The effect of primary coolant impurities can be neglected because no effect on the mechanical properties of SA-193 Grade B7 is expected in the MHTGR environment at design temperatures of less than 700°F.

6.7. EFFECT OF IRRADIATION

[LATER]

6.8. REFERENCES

- 6-1. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices, 1986 Edition through the 1987 Addenda.
- 6-2. "HTGR Design Data Manual (Metals and Ceramics)," DOE-HTGR-85048, Rev. 0, June 1985.
- 6-3. ASME Boiler and Pressure Vessel Code, Section III, Material Specifications Part A, "Ferrous," 1986 Edition through the 1987 Addenda.

TABLE 6-1
 BOLTING MATERIAL SA-193 GRADE B7:
 CHEMICAL COMPOSITION
 (Percent By Weight)

Chromium-Molybdenum (AISI 4140, 4142, 4145,
 4140 H, 4142 H, and 4145 H)

	Range(a)	Product Variation, Over or Under
C	0.37 to 0.49(b)	0.02
Mn	0.65 to 1.10	0.04
P, max	0.04	0.005 over
S, max	0.04	0.005 over
Si	0.15 to 0.35	0.02
Cr	0.75 to 1.20	0.05
Mo	0.15 to 0.25	0.02

(a) Per Table 10.1-2 of Ref. 6-2 which is from Ref. 6-3.

(b) For bar sizes over 3.5 to 4 in. inclusive, the carbon content may be 0.05% maximum.

TABLE 6-2
 BOLTING MATERIAL SA-193 GRADE B7: MINIMUM SPECIFIED ROOM
 TEMPERATURE TENSILE PROPERTIES AND SPECIFICATIONS

Diameter (in.)	(S _u) Ultimate Strength	(S _y) Yield Strength	Elongation (%)	Reduction of Area (%)
	Minimum (ksi)	Minimum (ksi)		
≤2.5	125	105	16	50
>2.5 ≤ 4	115	95	16	50
>4 ≤ 7	100	75	18	50

Per Table 10.1-1 of Ref. 6-2. The values of S_u and S_y are given in Table I-1.3 of Ref. 6-1. All values are given in Ref. 6-3.

TABLE 6-3
BOLTING MATERIAL SA-193 GRADE B7:
DESIGN STRESS INTENSITY (S_m) VALUES

Minimum Specified Strengths S_y/S_u (ksi/ksi)

105/125

95/115

75/100

Bolt Diameter (In.)

≤ 2.5

> 2.5

> 4

≤ 4

≤ 7

Temperature (°F)	Allowable (S_m) Values (ksi)					
100	35.0		31.6		25.0	
200	32.6		29.5		23.3	
300	31.4		28.4		22.4	
400	30.5		27.4		21.8	
500	29.5		26.7		21.0	
600	28.4		25.7		20.3	
650	27.4		25.0		19.7	
700	26.8	25.0	24.3	23.0	19.2	18.7
750	25.8	25.0	23.4	23.0	18.5	18.7
800	24.6	25.0	22.3	23.0	17.5	18.7
850	--	25.0	--	23.0	--	18.7
900	--	23.7	--	21.8	--	18.7
950	--	21.7	--	20.0	--	17.4
1000	--	19.6	--	18.0	--	15.7
Ref.	(a)	(b)	(a)	(b)	(a)	(b)

(a) Section III, Division 1, Appendix I, Table I-1.3 (S_m Values).

(b) Code Case N-253-4, Table C-1.1(b) (NC and ND Class 2 and Class 3) for information only.

TABLE 6-4
 BOLTING MATERIAL SA-193 GRADE B7:
 VARIOUS PROPERTY VALUES

Temperature (°F)	α , Coefficients of Thermal Expansion		k, Thermal Conductivity (Btu/h-ft-°F)	a , Thermal Diffusivity (ft ² /h)
	Instant (10 ⁻⁶ /°F)	Mean (10 ⁻⁶ /°F)		
70	5.60		24.2	0.471
100	5.83	5.73	24.3	0.464
150	6.20	5.91	24.4	0.452
200	6.55	6.09	24.4	0.439
250	6.88	6.27	24.3	0.426
300	7.18	6.43	24.2	0.414
350	7.47	6.59	24.0	0.402
400	7.73	6.74	23.9	0.390
450	7.79	6.89	23.6	0.378
500	8.18	7.06	23.4	0.367
550	8.38	7.18	23.1	0.355
600	8.55	7.28	22.7	0.344
650	8.70	7.40	22.3	0.333
700	8.83	7.51	22.0	0.320
750	8.94	7.61	21.6	0.307
800	9.02	7.71	21.2	0.295
850			20.9	0.283
900			20.5	0.271
950			20.1	0.259
1000			19.8	0.248
1100			19.1	0.225
1200			18.2	0.199

Values are from Table 10.1-4 of Ref. 6-2. The values of α correspond to values for material group B in Table I-5.0 of Ref. 6-1. The values of k and a are from material group C in Table I-4.0 of Ref. 6-1.

Per Fig. 10.1-5, Ref. 6-2

Fig. 6-1. Bolting SA-193 Grade B7 - stress intensity (S_m)

Per Fig. 10.1-8, Ref. 6-2

Fig. 6-2. Bolting SA-193 Grade B7 - thermal conductivity

Per Fig. 10.1-7, Ref. 6-2

Fig. 6-3. Bolting SA-193 Grade B7 - thermal diffusivity

Per Fig. 10.1-9, Ref. 6-2

Fig. 6-4. Bolting SA-193 Grade B7 - coefficient of thermal expansion, mean and instantaneous

7. BOLTING MATERIAL SA-453 GRADE 660 (26 Ni - 15 Cr - 2 Ti)

This bolting material is a high alloy steel listed in Table I-1.3 (Ref. 7-1).

7.1. APPLICABLE SPECIFICATIONS

The chemical composition and mechanical properties shall be as given in Tables 7-1, 7-2, and 7-3 (Ref. 7-2).

7.2. TIME-INDEPENDENT MECHANICAL PROPERTIES

The bolting material SA-453 Grade 660 design stress values presented in Table 7-4 shall be used in design.

7.3. TIME-DEPENDENT MECHANICAL PROPERTIES

[LATER]

7.4. FATIGUE LIFE

[LATER]

7.5. THERMAL PROPERTIES

The following thermal properties shall be used in design: thermal conductivity (k) (Table 7-5), thermal diffusivity (Table 7-5), and coefficient of thermal expansion (Table 7-6).

7.6. EFFECT OF PRIMARY COOLANT CHEMISTRY AND TEMPERATURE

The effect of primary coolant chemistry can be neglected because no effect on the mechanical properties of SA-453 Grade 660 is expected in the MHTGR environment at the design temperatures less than 700°F.

7.7. EFFECT OF IRRADIATION

[LATER]

7.8. REFERENCES

- 7-1. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices, 1986 Edition through the 1987 Addenda.
- 7-2. ASME Boiler and Pressure Vessel Code, Section III, Material Specifications Part A, "Ferrous," 1986 Edition through the 1987 Addenda.

TABLE 7-1
 BOLTING MATERIAL SA-453 GRADE 660: CHEMICAL COMPOSITION
 (Percent By Weight and Heat Treatment)

	Content (%)	Product Analysis Variation Over or Under (%)
Carbon	0.08 maximum	0.01 over
Manganese	2.00 maximum	0.04 over
Silicon	1.00 maximum	0.05 over
Phosphorus	0.040 maximum	0.005 over
Sulfur	0.030 maximum	0.005 over
Chromium	13.50 to 16.00	0.20
Nickel	24.00 to 27.00	0.20
Molybdenum	1.00 to 1.50	0.05
Titanium	1.90 to 2.35	0.05
Columbium	--	--
Aluminum	0.35 maximum	0.05 over
Vanadium	0.10 to 0.50	0.03
Boron	0.0010 to 0.010	0.0004 under 0.001 over
Copper	--	--

Per Ref. 7-2.

TABLE 7-2
SA-453 GRADE 660: MECHANICAL PROPERTY REQUIREMENTS

Class	(S _u) Ultimate Tensile Strength Minimum		(S _y) Yield Strength Minimum		Elongation in 4 x Diameter Minimum (%)	Reduction of Area Minimum (%)	Brinell Hardness No.
	ksi	MPa	ksi	MPa			
A and B	130	895	85	585	15	18	248 to 341

Values of S_u and S_y are from Table I-1.3 of Ref. 7-1. All values given in Ref. 7-2.

TABLE 7-3
SA-453 GRADE 660: STRESS-RUPTURE REQUIREMENTS

Class	Test Temperature		Stress Minimum		Time to Rupture Minimum (h)	Elongation Minimum (%)
	(°C)	(°F)	ksi	MPa		
A and B	650	1200	56	385	100	5

Values from Ref. 7-2.

TABLE 7-4
 BOLTING MATERIAL SA-453 GRADE 660:
 DESIGN STRESS INTENSITY VALUES (S_m)

Temperature (°F)	Allowable S_m Values (ksi)	
100	28.3	--
200	27.6	--
300	27.3	--
400	27.2	--
500	27.1	--
600	28.0	--
700	26.8	--
800	26.6	27.0
850	--	27.0
900	--	28.0
950	--	26.8
1000	--	26.7
Ref.	(a)	(b)

(a) Per Table I-1.3 (Bolting),
 Ref. 7-1.

(b) Code Case N-253-4,
 Table D-2.1(b) - Allowable stress
 values for Class 2 bolting on ves-
 sels using -3200 rules. The high
 temperature code cases N-201-1
 (NG-Core Support Structure) and
 N-47-23 (NB-Class 1) do not include
 SA-453 Grade 660 in their bolting
 materials. (For information only.)

TABLE 7-5
 NOMINAL COEFFICIENTS OF THERMAL
 CONDUCTIVITY (k) AND THERMAL
 DIFFUSIVITY (a) FOR HIGH
 ALLOY STEEL GRADE 660

Temperature (°F)	k (Btu/h-ft-°F)	a (ft ² /h)
70	7.5	0.134
100	7.7	0.135
150	8.0	0.137
200	8.2	0.138
250	8.5	0.140
300	8.8	0.142
350	9.0	0.144
400	9.3	0.146
450	9.5	0.148
500	9.8	0.150
550	10.0	0.152
600	10.2	0.154
650	10.4	0.155
700	10.7	0.157
750	10.9	0.159
800	11.1	0.160
850	11.3	0.162
900	11.6	0.164
950	11.8	0.165
1000	12.0	0.167
1050	12.2	0.168
1100	12.4	0.167
1150	12.6	0.164
1200	12.8	0.161
1250	13.1	0.161
1300	13.3	0.163
1350	13.5	0.165
1400	13.7	0.168
1450	13.9	0.171
1500	14.1	0.174

Note: The values in this table are from Table I-4.0, Ref. 7-1. Values are applicable to both SA-638 Grade 660 and SA-453 Grade 660.

TABLE 7-6
COEFFICIENT OF THERMAL EXPANSION FOR
HIGH ALLOY STEEL GRADE 660

Temperature (°F)	Instant ^(a) (10 ⁻⁶ /°F)	Mean
70	8.22	--
100	8.31	8.24
150	8.46	8.32
200	8.61	8.39
250	8.75	8.47
300	8.89	8.54
350	9.02	8.62
400	9.14	8.69
450	9.26	8.76
500	9.37	8.82
550	9.48	8.88
600	9.58	8.94
650	9.68	9.0
700	9.77	9.06
750	9.85	9.11
800	9.93	9.17

(a) Per Table I-5.0, Ref. 7-1.
This is applicable to both SA-638
Grade 660 and SA-453 Grade 660.