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**ADVANCED GAS COOLED NUCLEAR REACTOR MATERIALS EVALUATION
AND DEVELOPMENT PROGRAM**

Selection of Candidate Alloys. Vol. 1: Advanced Gas Cooled Reactor Systems
Definition, Topical Report

By
Mason D. Marvin

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October 31, 1978

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Energy Systems Programs Department
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Schenectady, New York

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ADVANCED GAS COOLED NUCLEAR REACTOR MATERIALS EVALUATION AND DEVELOPMENT PROGRAM

TOPICAL REPORT

SELECTION OF CANDIDATE ALLOYS VOL. 1: ADVANCED GAS COOLED REACTOR SYSTEMS DEFINITION

**BY
MASON D. MARVIN**

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**ENERGY SYSTEMS PROGRAMS DEPARTMENT
SCHENECTADY, NEW YORK 12345**

OCTOBER 31, 1978

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FOREWARD

The Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program is being conducted for the Nuclear Power Development Division, U.S. Department of Energy, by the Energy Systems Programs Department, General Electric Company, Schenectady, New York 12345 under Contract EY-76-C-02-2975. This is the first in a series of topical reports to be issued under this program and is being published in three volumes:

- Volume 1 - Advanced Gas Cooled Reactor Systems Definition
- Volume 2 - Selection of Alloys for Screening Creep and Structural Stability Studies
- Volume 3 - Selection of Surface Coating/Substrate Systems for Screening Creep and Structural Stability Studies

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1.0 INTRODUCTION

1.1 BACKGROUND

The Very High Temperature Reactor (VHTR) Nuclear Process Heat (NPH) and the Direct Cycle Helium Turbine (DCHT) Systems are being developed to provide an expanded nuclear power capability. In both cases the use of high temperature helium-cooled reactors will require a knowledge of the long term properties of reactor primary coolant containment materials and of the materials used in constructing related hardware. Because of the very high temperatures required for Nuclear Process Heat (NPH) and DCHT applications, the need is evident for materials testing in the proper helium environment in the temperature range from 750°C - 1050°C (1382°F - 1922°F) on those alloys which might serve as materials of construction for heat exchangers, ducting, turbine buckets and vanes and other high temperature structural components.

The objectives of the Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program are to:

1. Evaluate candidate alloys for Very High Temperature Reactor (VHTR) Nuclear Process Heat (NPH) and Direct Cycle Helium Turbine (DCHT) applications, in terms of the effect of the primary coolant exposure and thermal exposure on:
 - Surface stability ("corrosion" resistance) in 10,000 hours.
 - Structural stability in 10,000 hours - changes in microstructure and tensile, impact and fatigue properties.
 - Creep properties in 15,000 hours.
 - Stress rupture properties in 10,000 hours.

- Fatigue Properties

Low Cycle 10^3 to 10^5 cycles

High Cycle 10^5 to 10^7 cycles

2. Select and recommend materials for future test facilities and more extensive qualification programs.

It is important to point out that advanced alloy and/or process development is not a major function of the existing program. Therefore, alloy selections for the primary test program had to be made from choices among commercially or reasonably available sources. Also, it is appropriate to comment on the evaluation testing plan with respect to its effect on the alloy selections. The testing and evaluation program approach is to conduct structural stability (surface and bulk) and screening creep tests on as many of the selected alloys as can be accommodated within the test equipment capability. However, since creep testing capacity is limited, some of the alloys will be subjected to unstressed exposure only - specifically those alloys that were selected primarily for the comparison of surface stability. The later stages of the test program will concentrate on intensive testing of a more limited number of alloys based on the screening creep and structural stability test results.

Finally, it is worth noting that the current materials test program actually encompasses the initial phases of a much more comprehensive long-range research and development needs to qualify materials and components for advanced gas cooled reactor systems as identified in a previous General Electric study.*⁽¹³⁾ However, the data base to be obtained in this program will permit the selection of materials of construction and should provide a reliable level of design data for the construction of various items of development hardware leading to the successful development of NPH and DCHT systems. The present lack of an accurate measure of materials capabilities under these high temperature helium environments is a factor which is currently limiting the development of the NPH/DCHT systems. This program is intended to provide such initial information.

*References are indicated by a number enclosed in parenthesis. References are listed by number in Section 5.7.

1.2 OBJECTIVE OF THIS REPORT

The objective of this report is to provide a concise consolidation of reference design data to assist in the selection of the initial candidate alloys to be evaluated (for baseline data) for the Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program. The data provided relates primarily to the definition of the alloy in-service requirements but other related or pertinent information is included. This involves examining the NPH/DCHT systems to (1) establish the material needs for the various components and (2) define the temperature, pressure, composition, and velocity requirements for the simulated reactor helium coolant.

Ideally, this information will also assist the facility designers and test operations engineers in establishing test conditions representative of the expected system environment.

As an introductory note, it should be pointed out that definition of specific material property requirements in critical system components is difficult for two reasons. First, most of the designs are only conceptual and lack the precise details needed to define the stress levels. Second, all material property curves are a function of temperature and it is usually possible to design around their limitations. For example, it usually is possible to reduce the stress levels by using larger sections or thicker walls or by reducing the metal temperatures through supplementary cooling and/or insulating layers. This latter technique is illustrated by the hot gas duct design where a hot liner is used at zero stress and by utilizing insulation between the liner and the pressure shell a cool stress containment shell results. By designing around the problem in this manner, the high pressure, high temperature helium can be contained without simultaneously imposing both the temperature and stress conditions as required material properties.

1.3 DATA SOURCE

The data presented herein which relates to nuclear heat source plants is extracted from published reports resulting from DOE sponsored programs to define the DCHT and VIATR-NPH systems. Portions of

the ASME Boiler and Pressure Vessel Code are extensively used to establish material design requirements. Other technical papers and reports are utilized where applicable. Appendix Section 5.7 contains a listing of the references used for preparation of this report.

1.4 REPORT ORGANIZATION

Section 2.0 defines the scope of the candidate material application and limits the material consideration to metallic alloys in the reactor primary coolant loop.

Section 3.0 presents general data which influences the material candidates selection independent of the process application. A typical plant specification is presented. A listing of desirable materials properties is summarized. The stress considerations required for a licensable mechanical design are briefly discussed.

Section 4.0 contains individual subsections categorized by systems application which include helium turbine power generation and process heat applications such as hydrocarbon reforming and coal gasification. VHTR-NPH systems with and without an IHX loop are shown. Each system is concisely defined with schematic cycle diagrams illustrating pertinent system parameters. Conceptual designs for the major system components are shown and comments provided relative to the desired material properties and stress conditions at critical locations.

Section 5.0 is an appendix section and presents miscellaneous support data considered to be applicable.

2.0 SCOPE

2.1 SYSTEMS

Evaluation and development of materials for both DCHT and VHTR/NPH systems with simulated primary circuit helium coolant temperatures in the range from 750°C – 1050°C (1382°F – 1922°F) is a conceptual requirement for this program. The 1050°C upper temperature is considerably above the operating temperatures proposed for the current conceptual designs. Specifically the DCHT reference design proposes a reactor outlet temperature of 1500°F (816°C). The VHTR/NPH systems generally assume 1742°F (950°C) for this temperature. The systems described in Section 4.0 reflect these values.

DOE has indicated (in Reference 10) that a DCHT demonstration power plant with an operating temperature range to 1600°F (871°C) should provide the basis for choosing construction materials. Likewise a VHTR/NPH demonstration plant with the primary system operating temperature to 1800°F (982°C) should be considered. These higher temperature objectives should be included in the rationale leading to the selection/recommendation of the candidate alloys for evaluation.

2.2 MATERIALS

Only metallic alloys located in the primary helium coolant loop are included in the scope of this program. As such bearings, seals, lubricants, insulation and nuclear fuels or nuclear core related items are not directly involved.

The simulation of nuclear irradiation damage is beyond the scope of this evaluation phase as is the definition of the nuclear irradiation intensity.

Specialized mechanical design problems associated with a specific reactor style are also considered beyond the scope of this subtask. An example in this later category is the fuel ball insertion and removal mechanism associated with a pebble bed reactor.

3.0 GENERAL DATA INFLUENCING MATERIAL SELECTION

3.1 TYPICAL PLANT SPECIFICATION

As part of the Advanced Energy Conversion Study⁽¹⁾ conducted by CRDC* in 1975 for Electric Power Research Institute (EPRI), a set of power plant evaluation criteria was formulated. Good, Fair and Poor plant characteristics were defined. From this data the following minimal specification for a desired plant can be extracted.

Design Life	40 years
Severe Thermal Transients	1000 cycles
Start Up Time	4 hours

A 100,000 to 300,000 hours creep-rupture capability is consistent with this design life for inaccessible items not readily subjected to maintenance or overhaul. The following tabulations is for convenient reference.

1 yr. = 8,760 hrs.	3,000 hrs. = 0.3 yrs.
10 yrs. = 87,600 hrs.	10,000 hrs. = 1.1 yrs.
20 yrs. = 175,200 hrs.	30,000 hrs. = 3.4 yrs.
30 yrs. = 263,000 hrs.	100,000 hrs. = 11.4 yrs.
40 yrs. = 350,000 hrs.	300,000 hrs. = 34.2 yrs.

Table 3.1-1 shows a plant specification prepared by General Atomic (GA) for a load following DCHT power plant. This table shows the number of transient operations anticipated over the 40 year plant life. Notice that there are several tens of thousands of cyclic conditions as part of normal operations. The more severe transients associated with Upset, Emergency and Faulted Conditions are expected to occur less than 500 times during design life.

* General Electric Co., Corporate Research and Development Center, Schenectady New York.

TABLE 3.1-1

REPRESENTATIVE PLANT TRANSIENTS WITH NUMBER OF OCCURRENCES⁽²⁾

(3000 MWt DCHT - 40 Year Plant Life)

<u>Type of Transient</u>	<u>Number of Occurrences</u>
<u>Normal</u>	
1. Startup from refueling status	145
2. Startup with controlled helium inventory	270
3. Shutdown to refueling status	81
4. Shutdown with controlled helium inventory	44
5. Rapid load increase (5%/min)	2,000
6. Normal load increase (3%/min)	18,000
7. Rapid load decrease (5%/min)	2,000
8. Normal load decrease (3%/min)	18,000
9. Step load increase (+10%)	2,000
10. Step load decrease (-10%)	2,000
<u>Upset (From Full Load)</u>	
11. Loop shutdown	90
12. Reactor trip	115
13. Load rejections	120
14. Sudden reduction of precoolers flow with plant above minimum load level (25% power)	30
15. Water leak to PCR.V. with correct protective action	30
16. Loop shutdown with first overspeed trip	*
<u>Emergency and Faulted</u>	
17. Slow primary system depressurization	3
18. Rod withdrawal with core power to flow trip	3
19. Loop shutdown with helium valve failure	3
20. Shaft break with loop shutdown	1
21. Shutdown with two auxiliary cooling loops - up to 10	10
22. Shutdown with one auxiliary cooling loop - up to 10	
23. Sudden depressurization and shutdown with one auxiliary cooling loop failed	1

* Later.

Equivalent detailed plant specifications (such as Table 3.1-1) for VHTR Process Heat Systems have not been uncovered by the author if such exist. Intuitively, one would expect a process heat system to experience considerably fewer transients than those associated with a load following electrical power generating plant. However, the assumption that a process heat plant will run essentially transient free seems far from the true situation when the current performance records of existing chemical process plants in this country are reviewed^(3,4). These records show that ammonia plants are averaging 8-1/2 shutdowns per year with 45-1/2 days total down time. Methane reformers although designed for 10 years life actually last approximately 4 years.

In light of such experience it is suggested that for detailed design considerations approximately 1/2 the transients shown under the "Normal" condition in Table 3.1-1 be assumed applicable for a process heat plant. The number of Upset, Emergency and Faulted transients should be considered the same for both systems.

3.2 DESIRABLE MATERIAL PROPERTIES

The following summary of desirable material properties for VHTR/NPH and DCHT systems is presented herein for reference.

3.2.1 VHTR/NPH Systems

Prime Considerations

- Creep-Rupture Resistance

Properties better than Inconel 617 at 100,000 (or 300,000) hrs. with temperatures to 2000°F are desired. See Figure 3.2-1.

- Structural Stability

Loss of ductility and toughness is perhaps the most severe result of instability. (Essential to conduct tests for largest possible time.)

Figure 3.2-1. 100,000 Hour Rupture Strength of Various Classes of Metals/Alloys.

- Environmental Resistance

Helium impurity levels are very critical. Table 3.2-1 suggests typical impurity levels.

Additional Requirements

- Good Mechanical/Physical Properties

- Rupture ductility (10% min.)	- High K_{IC}
- Yield strength (high)	- Good Impact (10 ft-lb min)
- Minimize ductility degradation	- Good Thermal Conductivity (for HX tubes)
- High Cycle Fatigue (10^7 runout)	- Expansion Coefficient (compatible with adjacent materials)
- LCF resistance	

- Fabrication Capability

Tube fabrication techniques required, specifically: hot and cold working, welding, bending and heat treating.

- Low H_2 Permeability (see discussion in Appendix Section 5.3)

Hydrogen permeability approximately indicates relative tritium permeability. Coating or oxide layers have major impact on reducing tritium permeability.

- Galling and Wear Resistance

Differential thermal expansion with small resultant motions (such as HX tubes in baffle support) should be accommodated.

3.2.2 DCHT Systems

Ducts, Casing, Etc.

- Same requirements for these components as identified under VHTR Systems.

Turbine Blades and Vane (and other rotating equipment)

- Fabricability

Casting, forming, machining and joining manufacturing processes are highly desirable requirements for these components.

TABLE 3.2-1

SUGGESTED HELIUM IMPURITY LEVELS AND CHEMICAL RATIOS IN
PRIMARY CIRCUITS OF POWER REACTORS *

		Steam Generating Reactor			Process Heat Reactor	
		Normal	H ₂ O Leak	HTGR/GT Direct Cycle	No Intermediate Circuit	With Intermediate Circuit
H ₂	μatm	200	500	200	200-1000	100
H ₂ O	μatm	1.5	15	0.5	1-5	0.5
CO	μatm	40	300	20	20-100	20
CO ₂	μatm	1-2	1-5	1	1-2	1
CH ₄	μatm	20	25	20	20-30	15
N ₂	μatm	5-10	5-10	5-10	5-10	5-10
$\frac{P_{H_2}}{P_{H_2O}}$		130	33	400	200	200
Oxidation Ratios						
$\frac{P_{CO}}{P_{CO_2}}$		20-40	60-300	20	20-50	20
$\frac{P_{CO}^2}{P_{CO_2}}$ atm		0.8-1.6 x 10 ⁻³	9 x 10 ⁻² 1.8 x 10 ⁻²	4 x 10 ⁻⁴	4 x 10 ⁻⁴ 5 x 10 ⁻³	4 x 10 ⁻⁴
Carburizing Ratios						
$\frac{P_{CH_4}}{P_{H_2}^2}$ atm ⁻¹		5 x 10 ²	10 ²	5 x 10 ²	5 x 10 ² -30	1.5 x 10 ³

* This data has been extracted from Table II of technical paper IAEA-SM-200/82 entitled "Environmental Conditions in HTRS and the Selection and Development of Primary Circuit Materials", by L.W. Graham, M.R. Everett, et al of the Dragon Project, October 1975. (Reference 5)

- Mechanical Properties

Creep-rupture, fatigue and yield strength are the prime requirements. The rotating components of the DCHT system will experience considerably more cyclic stresses than VHTR/NPH components tending to increase the importance of fatigue resistance.

- Environmental Resistance

Oxidation, corrosion, surface stability require consideration. Data in helium environment with impurities is minimal and contradictory. New thinking relative to composition of metals may "open the door" for new alloys. Tantalum and cobalt to be avoided. High chromium may not be required. Refractory elements need not be minimized.

3.3 GENERAL DESIGN CRITERIA (STRESS RELATED)

DCHT and VHTR/NPH systems, if built in this country, will undoubtedly require design compliance with the applicable portions of the ASME Boiler and Pressure Vessel Code⁽⁶⁾. Section III Division 1 of this code deals with Nuclear Power Plant Components and will generally be the applicable section for the alloys involved in this materials development program. Section VIII applies to Non-nuclear, Unfired Pressure Vessels and would be the applicable document for plant components which were isolated from the primary coolant loop by an intermediate loop heat exchanger for example. Since the scope of this program limits consideration to alloys in the reactor primary coolant loop, Section III Division 1 becomes of primary importance.

Section III Division 1 is subdivided into component classes with reduced design margins required for less critical components. Safety Class 1 is the most severe and concerns primarily the pressure boundary that contains the primary coolant and in the case of the VHTR includes the PCR structure and supports. The steam generator pressure parts are included in this safety class and in the case of an intermediate loop heat exchanger for the process heat plant it would include parts inside the PCR that are exposed to the primary coolant including all piping*.

* Appendix Section 5.5 summarizes proposed Safety Requirements and Criteria for gas cooled reactor plants and presents current interpretations of the safety class definitions.

ASME Code Case 1592⁽⁷⁾ was written to establish rules of materials, design, and stamping for Section III Class 1 components when metal temperatures exceeded the previous 800°F limit. This code case is a monumental document and establishes the design criteria which will be applicable to many potential VHTR/NPH and DCHT components.

The Code Case addresses the high temperature creep situation by defining allowable design stress intensity levels for both time-dependent and time-independent conditions. Figure 3.3-1 taken from Code Case 1592 attempts to show the analyses procedure. The design stress requirements are categorized in a matrix arrangement with various plant conditions such as "Design", "Upset", "Emergency" and "Faulted" cross-plotted under "Load-controlled Stress Limits" and "Strain and Deformation Limits". In order to meet the load controlled stress limits a certain minimum cross-sectional area is required and it is usually possible to meet all the load-controlled stress limits simply by using a thicker wall or heavier section.

The stress symbols S_m and S_t are established to define the time-independent and the time-dependent allowable stress levels respectively. The time-independent stress intensity limitation S_m is a carryover from Section III Division 1 Class 1 and is essentially the same as the S_o and S limitation previously defined in Section VIII. The S_t allowable stress intensity is a function of time as well as temperature. The S_{mt} limitation which applies to "Normal plus Upset" plant conditions is the lower of the S_t or S_m value.

The strain and deformation limits require that (1) deformation (or strain) be maintained within certain limits, (2) that a combined creep-fatigue evaluation indicates a satisfactory life and (3) that buckling and instability criteria indicates a satisfactory design. Generally speaking for any very high temperature design, the combined creep-fatigue evaluation will be the limiting stress consideration.

For VHTR/DCHT systems and components a long life with relatively few fatigue cycles is required as indicated by the minimal plant specification in Section 3.1 (life = 300,000 hrs., transient cycles = 1000). Such conditions probably mean that the most desirable mechanical charac-

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

Figure 3.3-1. Flow diagram for elevated temperature analyses

teristic for HTR metallic materials is superior high temperature creep-rupture properties. If the components are subjected to numerous cyclic stresses beyond the 1000 plant start up transients, then the fatigue characteristics at temperature become more important. This is highly likely for many systems and/or components.

The design procedure for meeting the combined creep-fatigue requirements is defined in the Code Case 1592 and consists of summing the accumulated creep and fatigue damage per the following relation.

$$\sum_{j=1}^P \left(\frac{n}{N_d} \right)_j + \sum_{k=1}^Q \left(\frac{t}{T_d} \right)_k < D$$

where: D = total creep-fatigue damage (D allowable is 1.0 or less)
 n = number of cycles at loading j
 N_d = number of design allowable cycles at loading j (evaluated from an appropriate S-N curve for the material and temperature)
 t = time duration of load condition k
 T_d = allowable time at stress intensity condition k (evaluated from an appropriate stress-rupture curve for the material and temperature)

The design of components in accordance with Section III Division 1 Class 1 (including Code Case 1592) requires that an equivalent uniaxial stress be determined from the 3 dimensional load conditions and that this so-called stress intensity be less than the appropriate tabulated value. The equivalent uniaxial stress is determined from the load conditions by utilizing the maximum shear stress failure criteria which means that the stress intensity is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. (tensile = positive, compressive = negative).

The allowable stress intensities tabulated in the ASME code include factors of safety and are derived from uniaxial test data. Appendix Section 5.2 contains the ASME sections and other documents which define in detail the procedure for converting test data to code approved design

allowables. The following items summarize this procedure for austenitic stainless steel, NiCrFe, and NiFeCr alloys:

1. S_m (time-independent) is the lowest of
 - 1/3 specified minimum room temperature tensile strength
 - 1/3 tensile strength at temperature^{*}
 - 2/3 specified minimum room temperature yield stress
 - 0.9 yield stress at temperature^{*}

^{*}Strength at temperature determined by multiplying minimum specified R.T. strength by the hot strength/cold strength ratio.

2. S_t (time-dependent) is the lowest of
 - 2/3 minimum creep-rupture stress $f(t,T)$
 - 0.8 stress to initiate tertiary creep $f(t,T)$
 - 1.0 stress that produces 1% total strain $f(t,T)$

4.0 SPECIFIC SYSTEMS AND COMPONENT MATERIAL REQUIREMENTS

This section presents summary discussions of 6 conceptual power plants each of which employs a helium cooled nuclear reactor as the heat source. Each system is briefly defined with schematic cycle diagrams and other data illustrating pertinent system parameters. Conceptual designs for the major system components are shown and where possible tabulated summaries of the limiting design stress conditions and desired material properties are included.

Two DCHT plants and four VHTR/NPH plants are discussed. The VHTR plants can be further classified as to whether they contain an Intermediate Heat Exchanger(IHX). Table 4.0-1 shows the overall subdivision of this section by specific plant styles and identifies the appropriate section numbers.

The DCHT plants have been extensively studied by General Atomic(GA) and complete designs of most components are available. This facilitates identifying the key component material requirements since specific stress levels and time-temperature histograms are available. Table 4.0-2⁽⁸⁾ has been prepared by G.A. and summarizes the preliminary material requirements for key components of a DCHT system.

The VHTR-NPH plants are conceptual designs with varying degrees of design detail being available. Table 4.0-3 has been prepared by G.A.⁽⁹⁾ and summarizes the material requirements for structural components resulting from a design study conducted in 1976 under ERDA contract. Additional tabular data resulting from parallel G.E. studies is included in appropriate plant discussion sections. While not in exact agreement no significantly different material requirements are indicated by the two studies.*

* Appendix Section 5.6 presents the entire "Materials" chapter from the G.A. VHTR Study Final Report⁽⁹⁾ for review and comparison.

TABLE 4.0-1

SPECIFIC PLANTS DISCUSSED IN SECTION 4.0

DCHT Plants	VHTR-NPH Plants	
	Without IHX	With IHX
<u>Section 4.1</u> Reference DCHT Plant	<u>Section 4.3</u> Hydrocarbon Reforming	<u>Section 4.4</u> Hydrocarbon Reforming
<u>Section 4.2</u> Ammonia Bottoming Cycle DCHT Plant	—	<u>Section 4.5</u> Steam-Coal Gasification
	<u>Section 4.6 Variation 1</u> Coal Hydro- gasification	<u>Section 4.6 Variation 2</u> Coal Hydro- gasification

TABLE 4.0-2

PRELIMINARY MATERIAL REQUIREMENTS FOR KEY DCHT COMPONENTS

Component	Probable Material Type and (Example)	Nominal Full Power Operating Conditions	Primary Material Property Requirements (a)	Additional Requirements
Turbine Blade	Shell Cast Ni Base Alloy (IN100)	832°C (1530°F) Centrifugal Loading (3600 RPM)	Allowable Stress for <1% creep in 280,000 hrs ≥103 MPa (15.0 ksi)	High Cycle Fatigue Strength Low Cycle Fatigue Resistance Fretting and Adhesion Resistance
Turbine Vane	Shell Cast Ni Base Alloy (IN100)	850°C (1562°F) Gas Bending Loads	Allowable Stress for Rupture in 280,000 hrs ≥68.9 MPa (10.0 ksi)	Low Cycle Fatigue Resistance Castability and Fabricability
Turbine Hot Duct	Wrought Ni Base Solid Solution Alloy (Inconel 617) or ODS Alloy (T.D. Nickel)	850°C (1562°F) ΔP ≈ 0.34 MPa (0.05 ksi)	Allowable Stress for Rupture in 280,000 hrs ≥6.89 MPa (1.0 ksi)	Low Cycle Fatigue Resistance Joinability
Turbine Disc	Low-Alloy Ultra High Strength Steel (D6AC)	260°C (500°F) Rim Tangential and Radial Loading (3600 rpm)	Allowable Short Time Tensile Stress ≥ 505 MPa (73.3 ksi)	Good Fracture Toughness Crack Propagation Resistance
Thermal Barrier Cover Plates and Seal Sheets	Wrought Solid Solution Ni Base Alloy (Inconel 617)	899°C (1650°F) ΔP ≈ 0 Bending Loads	Allowable Stress for <1% creep in 280,000 hrs ≥10.4 MPa (1.5 ksi)	Low Cycle Fatigue Resistance Formability
Recuperator Lower Lead Tubes	Wrought Austenitic Stainless Steel (316)	523°C (973°F) ΔP = (4.7 MPa) 0.68 ksi Plus Bending Loads	Allowable Short Time Tensile Stress ≥ 103 MPa (15.0 ksi)	Weldable Low Cost
Recuperator Module Tubes	Low Alloy Steel (2-1/4 Cr, 1 Mo)	523°C (973°F) ΔP = (4.7 MPa) 0.68 ksi	Allowable Stress for Rupture in 280,000 hrs ≥44.8 MPa (6.5 ksi)	Weldable Low Cost
Precooler Module Tubes	Medium Carbon Steel (SA178)	246°C (475°F) ΔP = (1.03 MPa) 0.150 ksi	Allowable Short Time Tensile stress ≥ 138 MPa (20 ksi)	Weldable Low Cost

(a) Allowable stresses are for normal full power operating temperatures.

TABLE 4.0-3

**PRELIMINARY OPERATING CONDITIONS AND MATERIALS REQUIREMENTS FOR
STRUCTURAL COMPONENTS FOR VHTR PROCESS HEAT SYSTEM DESIGNS**

Component	Candidate Material	Nominal Operating Conditions		Primary Design Properties (σ values = operating stress at T and P)	Additional Requirements
		With IHX	Without IHX		
Primary duct					L/C fatigue resistance
Seal sheet	Inconel 617		1172 K (1650°F) $\Delta P \sim 0$		Formability
Cover plate	IN 713C			Creep strength: $< 1\% \epsilon_c$ at $\sigma \sim 10.3$ MPa (1,500 psi) (bending)	Galling resistance
Washers	IN 713C				
Fasteners	IN 713C				
Insulator liner	Carbon-carbon composite	1256 K (1800°F)		Tensile strength	Notch toughness
Outer liner	2-1/4 Cr - 1 Mo steel	$\Delta P \sim 0$ 811 K (1000°F)		Creep strength	No stress concentrations
Connecting brackets	IN 713C	1256 K (1800°F)		Creep strength	Carburization-resistant coating
IHX					
Module tubes	Inconel 617	727 to 1227 K (850° to 1750°F)	NA	Creep strength: $\sigma \sim 6.90$ MPa (1000 psi) High-temperature tensile strength: $\sigma \sim 27.6$ -55.2 MPa (4000-8000 psi) for 10 hr	Weldability Formability Ductility
Lower lead tubes	Inconel 617	1172 K (1650°F)		Low-cycle fatigue Creep-fatigue	
Headers (upper) (lower)	Inconel 617	727 K (850°F) 1227 K (1750°F)		Tensile strength Rupture strength High-temperature tensile strength: $\sigma \sim 55.2$ MPa (8000 psi) for 10 hr	Weldability (to 2-1/4 Cr - 1 Mo steel)
Upper lead tubes	2-1/4 Cr - 1 Mo steel	727 K (850°F)		Tensile strength: τ (shear) = 69 MPa (10,000 psi) $\tau_{max} = 124$ MPa (18,000 psi) for 10 hr	Weldability (to 617) Formability Ductility
Tube supports	Inconel 617	1227 K (1750°F)		Rupture strength: $\sigma \sim 6.90$ MPa (1000 psi)	Formability Weldability
Deflector	Carbon-carbon composite	1256 K (1800°F)		Tensile strength	No stress concentrations
Central return duct	Inconel 617	727 to 1227 K (850° to 1750°F)	NA	Creep strength: $\sigma \sim 8.28$ MPa (1200 psi) High-temperature tensile strength: $\sigma \sim 55.2$ MPa (8000 psi) for 10 hr	Weldability
Tubesheet	2-1/4 Cr - 1 Mo steel	721 K (840°F)		Tensile strength: $\sigma \sim 138$ MPa (20,000 psi)	Forgability or castability Weldability

TABLE 4.0-3 (Continued)

Component	Candidate Material	Nominal Operating Conditions		Primary Design Properties (σ values = operating stress at T and P)	Additional Requirements
		With IHX	Without IHX		
Reformer					
Catalyst (reformer) tubes	HK-40	1130 K (1575°F) $\Delta P \sim 2.50$ MPa (365 psi)	1130 K (1575°F) $\Delta P \sim 2.50$ MPa (365 psi)	Creep strength: $\sigma \approx -8.5$ MPa (-1243 psi) Buckling (collapse) High-temperature tensile strength: $\sigma = -17.6$ MPa (-2550 psi) for 10 hr Creep-fatigue (low-cycle)	Weldability Low tube ovality Oxidation resistance (i.d.)
Pigtails	Inconel 617	1130 K (1575°F) $\Delta P \sim 2.76$ MPa (400 psi)	1130 K (1575°F) $\Delta P \sim 2.76$ MPa (400 psi)	Creep strength: $\sigma \approx -12.1$ MPa (-1750 psi) High-temperature tensile strength: $\sigma = -24.1$ MPa (-3500 psi) for 10 hr Creep-fatigue (low-cycle)	Weldability Formability Oxidation resistance (i.d.) Ductility
Common return tube	Inconel 617	1089 K (1500°F) $\Delta P \sim 2.50$ MPa (365 psi)	1089 K (1500°F) $\Delta P \sim 2.50$ MPa (365 psi)	Creep strength: $\sigma \approx -20.7$ MPa (-3000 psi) High-temperature tensile strength: $\sigma = -40.3$ MPa (-5850 psi) for 10 hr	Oxidation resistance (i.d.) Weldability
Shroud	Inconel 617	1172 K (1650°F)	1172 K (1650°F)	Rupture strength	Weldability
Bellows	316 stainless steel	977 K (1300°F)	977 K (1300°F)	Rupture strength High-temperature tensile strength Creep-fatigue (low-cycle)	Weldability Oxidation resistance
Tubesheet	316 stainless steel	840 K (1050°F)	840 K (1050°F)	High-temperature tensile strength: $\sigma \approx -104$ MPa (-15,100 psi) for 10 hr Creep strength: $\sigma \approx -73.8$ MPa (-10,700 psi)	Capacity for fabrication Weldability Oxidation resistance
Circulators					
Blades	422 stainless steel	775 K (935°F)	672 K (750°F)	Creep strength Fatigue strength (use of current HTGR technology and design)	
Discs					
Shafts					
Steam generator					
Upper tubes	Incoloy 800			Creep strength Rupture strength Creep-fatigue High-temperature tensile strength (use of current HTGR technology and design)	Corrosion resistance Formability Weldability
Lower tubes	2-1/4 Cr - 1 Mo steel				
Common return tube					
External piping	Mild steel A516, Grade 70			Tensile strength	Weldability

4.1 DIRECT CYCLE HELIUM TURBINE (WITH DRY COOLING TOWER)*

4.1.1 System Description

Figure 4.1-1 shows a simplified diagram of the DCHT system design showing the reactor core, turbomachinery, heat exchangers and helium ducting within the PCRV. Figure 4.1-2 shows a flow and heat cycle diagram for a DCHT system with the reactor helium exit temperature at 1500°F. The system shown rejects heat to the air using a dry cooling tower and has an overall system efficiency of approximately 36%.

Unlike present day Rankine-cycle reactor plants where the steam turbines and associated equipment are located outside the nuclear island, the DCHT plant incorporates three sets of helium turbomachinery and heat exchangers in the primary helium loop within the PCRV.

Each of the three sets of helium turbomachinery is housed in a horizontal cavity below the reactor. The turbine and compressor of each set operate off the same shaft, with the high pressure sections back-to-back. Flow design is axial.

Each of the three electric generators is of conventional design and horizontally mounted. They are located outside the PCRV and operate off the same shaft as the turbine and compressor.

There are six recuperator-precooler units, two for each power conversion loop. They are housed in 6 vertical cavities within the PCRV.

The recuperator recovers heat from the low pressure helium leaving the turbine and transfers it to the high pressure helium before it enters the reactor. The construction is modular in the sense that there are 90 identical modules in each recuperator.

The precooler is a helium-to-water heat exchanger whose function is to reject heat to the environment via a pressurized water loop, which

* The descriptive information presented herein has been extracted from ERDA Report No. ERDA-109, "Technical and Economic Assessment of the Direct-Cycle Gas-Cooled Reactor Plant", Sept. 1975. The evaluation was performed primarily by ERDA, ORNL, NASA-Lewis, and United Engineering and Constructors. (Reference 2)

Figure 4.1-1. Integrated DCMT Power Plant with single-shaft turbomachinery and horizontal generator.

Figure 4.1-2. Flow and Heat Cycle of the DCHT (Ambient Temperature 75°F)

circulates through a dry cooling tower. The precooler reference design is annular, with the modules wrapped around the recuperator.

Figure 4.1-3 is a sectional view of the turbomachinery in its horizontal PCRV cavity. Figure 4.1-4 is a sectional view of the recuperator-precooler in its vertical PCRV cavity. Table 4.1-1 lists the principal design parameters of the DCHT plant equipment.

4.1.2 Components Discussion

The following component discussion and material assessment was prepared by the ERDA evaluation team in their review of GA's reference design DCHT system. The descriptions have been extracted from ERDA Report #109, dated Sept. 1975.⁽²⁾

Turbine - The major problem is the selection of materials for disks and blades to permit the turbine to function trouble-free in the high temperature and radioactive helium environment over an extended period of time.

Some of the many nickel-base superalloys which have been used for high-temperature service in rotating machinery are shown in Table 4.1-2.

All the materials shown have been, or are still being, considered as candidates for the hot-stage parts of the DCHT. Each material is commercially available and all have been used to some extent in aircraft and industrial turbines. None of these alloys are ASME Code qualified for nuclear service.

Important considerations for the high-temperature rotating parts of the DCHT will include creep and creep-rupture strengths, high-cycle fatigue resistance, thermal stability, the effects of environment (including gas-metal reactions and fission-product interactions) on properties, and fretting and galling. At the design turbine inlet temperature of 1500°F, the 200,000-hour creep-rupture strengths of the nickel-base alloys being considered range from approximately 16,000 to 24,000 psi (all except INCO-713LC exceed 20,000 psi). However, strength decreases rapidly with temperature increases and, for these materials, is a maximum

Figure 4.1-3. Section through turbomachinery cavity

Figure 4.1-4 Section through recuperator and pre-cooler cavity

TABLE 4.1-1

DCHT POWER CONVERSION LOOP REFERENCE DESIGN DATA

	<u>First Stage</u>	<u>Last Stage</u>
A. <u>Helium Turbine</u>		
Outer diameter (in.)	76.6	86.4
Inner Diameter (in.)	67.0	63.6
Axial stator chord (in.)	3.3	5
Axial rotor chord (in.)	2.2	4
Overall bladed length (in.)	72.0	
B. <u>Helium Compressor</u>		
Diameter (in.)	63.6 Hub	63.6 Hub
	73.6 Tip	70.12 Tip
Axial velocity (ft/sec)	650	650
Blade speed (ft/sec)	1000 Hub	1000 Hub
	1157 Tip	1103 Tip
Rotor blade chord (in.)	3.85 Hub	3.17 Hub
	3.09 Tip	2.74 Tip
Stator blade chord (in.)	3.10 Hub & Tip	2.49 Hub & Tip
Blade height (in.)	5.0	3.26
Bending stress (lb/in ²)	10,000	
Centrifugal stress (lb/in ²)	9,860	
Inlet mass flow rate (lb/sec)	1,369	
Temperature rise (°F)	253	
C. <u>Recuperator</u>		
Flow configuration	Axial counterflow	
Fluid orientation	HP inside tube	
LMTD (°F)	80.6	
No. of tubes per unit	26,550	
No. of tubes per module	295	
Tube OD/wall/height (in;in;ft.)	7/16; .0375; 44	
Tube material	Austenitic stainless & low alloy steel (Ferritic)	
Unit weight (tons)	240	
D. <u>Precooler</u>		
Flow configuration	Axial counterflow	
Fluid orientation	Water in tube	
LMTD (°F)	39.5	
No. of tubes per module	726	
No. of tubes per unit	34,848	
Tube material	Ferritic	
Tube OD/wall/height (in;in;ft.)	3/8; .049; 43	
Unit weight (tons)	306	

TABLE 4.1-2

NICKEL-BASE SUPERALLOYS FOR HIGH-TEMPERATURE SERVICE

Alloying Additions (wt. %)

<u>Alloy</u>	<u>Cr</u>	<u>Al</u>	<u>Co</u>	<u>Mo</u>	<u>Ti</u>	<u>W</u>	<u>Cb</u>	<u>Ta</u>	<u>C</u>	<u>Other</u>
M-21LC	5.7	6.0	-	2.0	-	11.0	1.5	-	0.03	-
Rene' 100	9.5	5.5	15.0	3.0	4.2	-	-	-	0.18	1.0 V
INCO-713LC	12.0	5.9	-	4.5	0.6	-	2.0	-	0.05	-
MM-004	12.0	5.9	-	4.5	0.6	-	2.0	-	0.05	1.3 Hf
MM-246	9.0	5.5	10.0	2.5	1.5	10.0	-	1.5	0.15	-
IN-731	9.5	5.5	10.0	2.5	4.6	-	-	-	0.18	1.0 V
IN-738	16.0	3.	8.5	1.8	3.4	2.6	0.9	1.8	0.12	-

TABLE 4.1-3

CANDIDATE ALLOYS FOR TURBINE WHEEL SERVICE

Alloying Additions (wt. %)

<u>Alloy</u>	<u>Cr</u>	<u>Ni</u>	<u>Fe</u>	<u>Ti</u>	<u>Al</u>	<u>Mo</u>	<u>Mn</u>	<u>Cb</u>	<u>Other</u>
A-286	15.0	26.0	Balance	2.15	0.2	1.25	1.40	-	0.03 V
Inconel 706	16.0	41.5	Balance	1.75	0.4 max	-	0.35 max	2.9	0.3 Cu max

of about 12,000 psi at 1600°F (loop average temperature for 1% of life). High-cycle fatigue experience with these materials has been acceptable in oxidizing environments but essentially nothing is known with respect to their behavior in the expected DCHT environment. Similarly, little information is available on thermal stability or the effects of the gas turbine environment on strength (creep-rupture) properties and fretting tendencies.

What little experience is available on environmental effects indicates that alloying additions such as aluminum, chromium, and titanium greatly influence surface stability in this application. Further, high cobalt (Co) and tantalum (Ta) contents promote component activity and complicate maintenance. It is likely that the factors above will heavily influence the selection of alloys for "screening". Any estimate of the magnitude of environmental effects on these materials would be premature and speculative at this time.

The two most frequently mentioned candidate alloys for turbine wheel service (at approximately 1000°F) are listed in Table 4.1-3. Both have been used extensively for gas turbine parts but both would require qualification for elevated temperature nuclear service. As in the higher temperature components, creep and fatigue resistance are important factors. In addition, fracture toughness is an important criterion. Environmental effects, however, should be less of a problem than at the higher temperature.

Compressor - The compressor will operate at temperatures which should not exceed 400°F and, therefore, gas-metal reaction effects on properties should be minimal, if not totally absent. Fretting, perhaps aggravated by the non-oxidizing environment, must be considered as well as fatigue resistance. Fatigue properties can be strongly influenced by surface condition and, therefore, possibly by the DCHT atmosphere.

The material which is, perhaps, being most seriously considered for compressor blading is AISI 403 stainless steel. Type 403 stainless steel is a martensitic grade containing 11.5-13 wt. % Cr and maximums of 1% manganese (Mn), 0.15% carbon (C), 0.5% silicon (Si), 0.040% phosphorus (P), and 0.030% sulfur (S). Type 403 stainless steel also is sometimes

identified as being of "turbine quality" grade since it generally is used for steam turbine blading and other highly stressed parts.

High-Temperature Ducting - The material or materials used for high-temperature ducts and casings, in addition to possessing good creep resistance which is relatively immune to the effects of gas-metal reactions which may occur, must be readily fabricable because of the size and configuration of these components. Only two materials, Hastelloy X and Inconel 617, have been mentioned as candidates for this application and, of the two, only Hastelloy X can be considered as really "commercial". Its excellent balance of oxidation resistance, high temperature strength (e.g., typical 1000-hour rupture strength of 10,000 psi at 1500°F), and fabricability have made it attractive to the industry where it is widely used for gas turbine burner cans and transition ducts. Inconel 617 is a relatively new material which was developed for use in high-temperature oxidizing and corrosive environments. On the basis of limited data, it is somewhat stronger than Hastelloy X. These materials age (i.e., strengthen at the expense of ductility) on thermal exposure at 1200° to 1600°F.

Heat Exchangers - The status of technology with regard to the materials available for construction of the heat exchangers is superior to that of materials for the components discussed earlier. Type 316 stainless steel and 2-1/4Cr-1Mo ferritic steel are candidate alloys for the gas-gas heat exchangers (recuperators). Both of these materials are qualified for nuclear service (ASME B&PV Code Section III, Code Case 1592) to temperatures well above the 950° to 1000°F maximum required in service. The principle uncertainty related to their use in this application is the possible effect of environment on creep behavior and flaw growth.

The gas/water heat exchangers (precoolers) will probably be constructed of an ASME Section III-qualified, low-alloy steel such as 1/2Cr-1/2Mo (SA-369, FP2). Low metal temperatures (approximately 400°F) should preclude gas-metal reaction effects; corrosion on the waterside can be minimized by proper water chemistry control.

Control Valves - The bypass control valves are critical components in this system. Fortunately, the response requirement (approx. 1 second) does not appear to be extreme for this size valve and also, minor leakage past the seal when closed would not be a problem; however, the reliability must be extremely high and the valves must be capable of fine control as well as large step changes. The problems of friction and wear in these valves may be quite significant in view of the helium environment.

Location of the valves at the high-pressure recuperator discharge increases valve problems since the helium gas temperature at this point is approximately 935°F. At this temperature, the potential for galling and fretting between metal surfaces of the valve is high and many coatings that might be utilized to reduce galling and fretting at lower temperatures will not be applicable.

Conclusions - Considerable screening and testing will be required before materials can be rationally selected for many of the DCHT system components. The major uncertainty relative to the use of the candidate materials is the extent of their interaction with the DCHT environment (contaminated helium coolant) and the effect of such interactions on mechanical properties and behavior.

Other questions remain on their stability at high temperatures, fission-product interactions and effects, and fretting and galling behavior.

Appendix, Section 5.4 presents additional discussions by the ERDA DCHT evaluation team concerning the prospects for Improved Materials Technology.

4.1.3 Material Requirements Summary

Table 4.1-4 summarizes the key component material requirements based upon data published in ERDA Report 109.⁽²⁾ Higher temperature growth objectives are taken from the ERDA RFP dated Oct. 9, 1975.⁽¹⁰⁾

TABLE 4.1-4

DCHT KEY COMPONENT MATERIALS REQUIREMENTS

Component	Temperature	Design Life	Design Stress	Important Properties	Comments
<u>TURBINE</u>					
Blades	1500°F Normal Operating Temp. (1600°F Hot Streaks)	200,000 hrs	16-24 KSI req'd	Creep Rupture HCF Thermal Stab. Environ. Resist.	ASME (Case 1592) allowable stress intensity is minimum of:
	RFP indicates 1800°F as a mat'l req't/objective	300,000 hrs	20 KSI		$2/3 \sigma_r f(t,T)$
Blade (Root)	1000°F Normal Operating Stress	200,000 hrs	55-60 KSI	Creep Rupture HCF Fretting and Adhesion	or $0.8 \sigma_{tert. creep} f(t,T)$
	RFP indicates 1300°F-1500°F as a mat'l req't/objective	300,000 hrs	60 KSI		or $\sigma_{strain=1\%} f(t,T)$
Discs	1000°F Normal Operating Stress	200,000 hrs	20 KSI	Creep HCF Fabricability	
<u>DUCT LINERS</u>	1500°F Normal Operating Stress	300,000 hrs	956 psi	Environ. Resist. Fabricability Weldability	
	1800°F RFP Design Objective				
<u>COMPRESSOR BLADES</u>	400°F	300,000 hrs	10 KSI Bonding 9.8 KSI Centrif.	Fretting Environ. Resist. Fatigue	AISI 403 is a common candidate
<u>RECUPERATOR TUBING</u> (7/16 O.D. x .0375 Wall)	1019°F (max.)	200,000 hrs	3.5 KSI	Corrosion Resistance Fretting Weldability Heat Transfer	Primary Helium on ID & OD OD Pressure = 446 psia ID Pressure = 990 psia Design Basis ASME Section VIII
<u>PRECOOLER TUBING</u> (3/8 O.D. x .049 Wall)	441°F	200,000 hrs	0.9 KSI	Same as Recuperator Tubing	H ₂ O @ I.D. (300 psia) He @ O.D. (433 psia) Design Basis ASME Section III (Case 1592)

4.2 THE BOTTOMING-CYCLE DCHT SYSTEM

4.2.1 System Description

If sufficient cooling water is available the DCHT system described in the preceding Section 4.1 can be modified to include an ammonia bottoming cycle which improves the overall system efficiency by about 9% points (from 35% to 44%). Figure 4.2-1 shows a schematic flow diagram for the DCHT bottoming-cycle plant. All primary helium circuit components and environmental conditions are essentially identical to the dry-cooling system except for the precooler which instead of rejecting heat to pressurized water instead becomes an ammonia boiler.

For the purposes of this study, the high temperature components are unaffected by the presence or absence of the bottoming cycle. Although work may be needed to develop the bottoming cycle materials in terms of corrosion and compatibility, the maximum temperature is around 500°F, where many conventional alloys are very well characterized.

4.2.2 Supplementary System Description (Source G.A. Report GA-A13215)⁽¹¹⁾

The secondary power cycle uses ammonia as the working fluid. The cycle hardware is designed for add-on to the basic DCHT, with minimum impact on the design of the primary power system components. The design employs a primary helium-to-ammonia heat exchanger that directly replaces the precooler used for the dry cooled plant. It is of the same geometry as the precooler, but is longer to take maximum advantage of the available PCRV cavity height.

Table 4.2-1 summarizes primary cycle design point conditions for the binary cycle plant compared with the dry cooled gas turbine plant. Helium compressor inlet temperature is increased from 95°F to 170°F, while maintaining the temperature rise across the compressor at 254°F. This results in a pressure ratio of 2.14 as compared with 2.35 for the dry cooled DCHT plant. This requires modified blading for the compressor but retains the same number of stages, disk designs, basic dimensions, and other design details of the reference design. In addition, the helium flow rate increases from 15.1×10^6 lb/hr to 15.9×10^6 lb/hr.

Figure 4.2-1. Schematic Flow Diagram for the DCHT Bottoming-Cycle Plant

TABLE 4.2-1
COMPARISON OF PRIMARY CYCLE CONDITIONS

	Binary Plant	Dry Cooled Plant (Design Point Conditions)
Total compressor pressure ratio	2.14	2.35
Turbine inlet temperature, °F	1500	1500
Compressor inlet temperature, °F	170	95
Compressor discharge pressure, °F	1000	1000
Core inlet temperature, °F	985	934
Precooler (ammonia heater) helium inlet temperature, °F	512	441
Recuperator effectiveness	0.89	0.89
Turbine disk cooling flow ^(a) , %	3.4	3.4
Compressor leakage flow ^(a) , %	0.2	0.2
Compressor bypass valve leakage ^(a)	0	0
Primary system heat loss, MW(t)	14.4	14.4
Helium flow rate, lb/hr	15.9×10^6	15.1×10^6
Primary cycle efficiency, %	--	35.6

(a) Expressed as a percentage of compressor discharge.

4.3 VHTR HYDROCARBON REFORMING WITHOUT IHX

4.3.1 System Description

Figure 4.3-1 shows a cross-sectional view of the secondary containment for a VHTR hydrocarbon reforming plant which does not incorporate an intermediate heat exchanger loop. Figure 4.3-2 shows a flow schematic for the system. The reformer product gas may be applied in a number of systems such as a chemical heat pipe, hydrogasification of coal, direct reduction of iron ore, ammonia synthesis, methanol synthesis, hydrocracking, hydrogenation of coal, Fischer-Tropsch synthesis and oxosynthesis. Each of these systems requires different process conditions; the reference conditions shown for this system are typical of those for a chemical heat pipe application.

As shown in Figure 4.3-2, the primary helium flows through the reactor core where it is heated, passes through the reformer where heat is transferred to the reformer reactants, and finally flows through a steam generator where heat is transferred to vaporizing water. In this arrangement (without an IHX), the reformer and steam generator are within the secondary containment boundary. Also, the primary helium is in direct contact with the reformer and the steam generator tubes. A variation of this configuration provides a double tube barrier between the primary helium and the process gas by means of a duplex tube described in Reference 12. As discussed in Reference 13, between 80% and 95% of the hydrogen production at 2000°F peak process temperature can be produced at temperatures from 1400°F to 1600°F respectively. Consequently, a reference peak process temperature of 1517°F (825°C) is selected for this system which is consistent with the work reported in Reference 12. The corresponding reactor outlet mixed mean temperature is 1742°F (950°C) with hot streaks of 1795°F (980°C).

* All flows on a per loop basis.

Figure 4.3-2. Pressure, Temperature and Flow Rates Within the Containment Building

4.3.2 Hot Gas Ducting

Hot helium is transported from the reactor core to the process heat exchanger by means of large diameter hot gas ducts. A number of possible duct designs are described and compared in Reference 14. The design selected here for reference is a coaxial duct with an insulated hot gas duct. Hot helium from the reactor core flows in the inner duct which is insulated on its inside diameter. After flowing through the heat exchangers, the cooled helium is returned to the reactor core through an annulus formed by the coaxial ducts. Because its inner surface is insulated and its outer surface is exposed to low temperature helium, the hot gas containment duct runs at relatively low temperature. Also, the pressure difference across the hot gas containment duct is equal to the gas pressure drop across the reactor core which is relatively low.

Liner and Insulation - The insulation system consists of an inner liner with either metal foil or fibrous insulation between the liner and the hot gas containment duct. Liner materials requirements are determined by the following data:

1. Typical liner I.D. $\sim$ 33.5 in. (850 mm)
2. Liner temperature $\simeq$ helium temperature = 1742°F (950°C)
3. Life requirements = 30 yrs. (300,000 hrs.)
4. Steady state stresses approx. 0
5. Helium Conditions
 - Temperature = 1742°F (950°C)
 - Pressure = 600 psi (41.4 bar)
 - Velocity = $\sim$ 164 ft/s
 - Environment - High pressure helium with low levels of H_2 , H_2O , CO , CO_2 and CH_4

Nuclear contaminates - fission products

6. Loose particles from the liner and insulation must not affect the reactivity at the core, nor should they lead to contamination of the coolant circuits.
7. Removal of oxide films may lead to adhesion in places where dry friction takes place due to thermal expansion.

Hot Gas Containment Duct - Materials requirements are determined by the following data:

1. Typical I.D. $\approx$ 37.4 in. (950 mm)
2. Metal Temp. $\approx$ helium return temp. = 572°F (300°C)
3. Life requirement approx. 300,000 hrs.
4. Steady-state stress < 1000 psi
5. Helium Conditions on duct OD
 - Temperature = 572°F (300°C)
 - Pressure $\approx$ 606 psia
 - Velocity $\approx$ 119 ft/s °C
 - Environment - High pressure helium with low levels of H_2 , H_2O , CO, CO_2 and CH_4
6. Loose particles from the duct should not lead to contamination of the coolant circuits.
7. Material must be fabricable into large ducts and must be weldable.

Cold Gas Containment Duct - Materials requirements are determined by the following data:

1. Typical duct ID $\approx$ 67 in.
2. Metal Temp. < helium return temp. = 572°F (300°C)
3. Life requirement = 100,000 hrs.
4. Typical steady state stress approx. 20,000 psi.
5. Through 7 same as for hot gas containment duct.

4.3.3 Helium-Heated Steam/Methane Reformer

Figure 4.3-3 illustrates the principle of the helium-heated steam/methane reformer. A mixture of steam and methane enters the tube at the top and flows downward through a bed of catalyst pellets where the reforming reactions take place. After passing through the catalyst bed, the reaction products reverse direction, flow upward through a coiled "pigtail" tube and leave the reformer at the top. Hot helium from the reactor flows upward on the shell-side of the reformer. Heat is transferred from the helium to supply the energy requirements of the endothermic reforming reaction. The following data determine the materials requirements of the reformer tubes:

1. Typical tube I.D. = 3.54 in. (90 mm)
2. Typical wall thickness = 0.53 in. (13.5 mm) for a single-wall tube.
3. For a duplex tube, each tube wall has a thickness of 0.354 in. (9 mm).
4. Metal operating temp.

	<u>Hot End</u>	<u>Cold End</u>
4. Metal operating temp.	1672°F	1150°F
5. Steady-state membrane stress due to pressure difference from the process gas to the helium	100 psi	400 psi
6. Membrane stress due to upset depressurization of helium-side	~2000 psi	2000 psi
7. Secondary stress due to radial temperature gradient. This stress combined with start-up and shutdown cycles determines low cycle fatigue life	~10,000 psi with 200-400 cycles	
5. Steady-state membrane stress due to pressure difference from the process gas to the helium
6. Membrane stress due to upset depressurization of helium-side
7. Secondary stress due to radial temperature gradient. This stress combined with start-up and shutdown cycles determines low cycle fatigue life
8. Helium-side conditions (at tube outside diameter)
 - Temperature = 1742°F (950°C) Hot end
 - = 1292°F (700°C) Cold end
 - Pressure = 600 psi
 - Velocity = 98 ft/sec
 - Environment - High pressure helium with low levels of H_2 , H_2O , CO , CO_2 and CH_4

Data of Reformer Tubes

Helium side

Temperatures : $600 \dots 800 + 950^{\circ}\text{C}$
 Pressure : $\sim 40 \text{ b}$
 Pressure loss: $\sim 0.2 \text{ b}$
 Mass flow : $0.15 \dots 0.25 \text{ kg/sec}$

Process side

Temperatures : $450 \dots 300^{\circ}\text{C} + 800 \dots 850^{\circ}\text{C}$
 End pressure : 41 b
 Pressure loss: $3 \dots 5 \text{ b}$
 Mass flow : $100 \dots 150 \text{ Nm}^3 \text{ CH}_4/\text{h} + 200 \dots 400 \text{ kgH}_2\text{O}/\text{h}$

Dimensions

Tube length : $10 \dots 12 \text{ m}$
 Inner diameter: $\sim 100 \text{ mm}$
 Wall thickness: $\sim 15 \text{ mm}$

Figure 4.3-3. Principle of a Reformer Tube for Nuclear Applications (Ref. 3)

Nuclear contaminates - fission products

9. Process-side conditions (at tube inside diameter)

Temperature = 1517°F (825°C) Hot end

= 842°F (450°C) Cold end

= 1112°F (600°C) Pigtail outlet

Pressure = 638 psi product gas exit

Velocity = 10 ft/sec

<u>Gas Constituents</u>	<u>Mole Fractions</u>	
	<u>Inlet</u>	<u>Outlet</u>
H ₂	0	.447
CO	0	.078
CO ₂	0	.053
CH ₄	.333	.117
H ₂ O	.667	.305

10. Thermal conductivity should be high to reduce thermal resistance, to minimize thermal stress due to radial temperature gradient, and improve thermal shock resistance.
11. The reformer tubes must be capable of retaining a stable oxide film on the inside surface in order to minimize permeation of hydrogen from the process stream into the helium stream and tritium permeation from the helium stream into the process stream.

4.3.4 Steam Generator⁽¹²⁾

A conceptual design of a steam generator for this system is shown in Figure 4.3-4. Materials requirements are as follows:

1. OD = 1 inch, ID = 0.75 inch, Wall = 0.125 inch
2. Metal operating temperature ~ 1090°F
3. Steady-state primary membrane stress due to internal pressure ~ 14,000 psi.
4. Secondary stress due to radial temperature gradient ~ 8900 psi.

Figure 4.3-4

Reference Design for the Duplex Tube Steam Reformer/Steam Generator Assembly.

5. Steam-side conditions

Temperature = 1000°F

Pressure = 3450 psia

Table 4.3-1 presents additional design details for the combined steam reformer/steam generator assembly.

4.3.5 Key Component Material Requirements Summary

Table 4.3-2 summarizes and compares material requirements for two design concepts for the primary helium coolant ducts. The coaxial concept is consistent with the reference plant described in this Section 4.3. The single fluid concept is compatible with the G.A. reference design presented in Reference 9, where the reformers and steam generators are integrated in the PCR. Table 4.3-3 summarizes the critical material requirements for the steam reformer and steam generator components described in this section.

TABLE 4.3-1

STEAM REFORMER/STEAM GENERATOR ASSEMBLY DESIGN

<u>CHARACTERISTIC</u>	<u>VALUE</u>
<u>STEAM REFORMER</u>	
SR Helium Inlet Temperature	950°C
Reforming Temperature	825°C
SR Helium Outlet Temperature	718.6°C
Reactant Inlet Temperature	450°C
Product Outlet Temperature	600°C
Helium Flow Rate	73.6 Kg/sec
No. of Tubes	270
Outer Tube O.D.	126 mm
Outer Tube I.D.	108 mm
Inner Tube I.D.	90 mm
Tube Spacing Ratio (SR Proper)	1.11
(Tube Sheet)	1.25
SR Tube Bundle O.D.	2.39 m
Tube Sheet Thickness	42.2 cm
SR Pressure Drop	.47 b
Pressure Vessel O.D.	3.83 m
<u>STEAM GENERATOR</u>	
SG Helium Inlet Temperature	718.6°C
Steam Outlet Temperature	538°C
Steam Pressure	238 b
SG Helium Outlet Temperature	300°C
Feed Water Temperature	204°C
Steam Flow Rate	66.6 Kg/sec
Tube O.D.	2.54 cm
Tube I.D.	1.90 cm
No. of Tubes in Parallel	56
Tube Distribution	7 Tubes Across
	8 Threads in
	Parallel
SG Pressure Drop	.27 b
Overall SR/SG Assembly Weight	373,000 Kg

TABLE 4.3-2

COMPARISON OF DUCTING CONCEPTS FOR VHTR REFORMING PLANTS WITHOUT IHX LOOP

Coaxial Duct Concept (GE)

Single Fluid Concept (GA)

	Temp. °F	Design Life hrs.	Stress ksi	He Vel. ft/sec
Inner Liner	1742	3×10^5	0	164
Hot Gas Con- tainment Duct	572	3×10^5	1	119
Cold Gas Con- tainment Duct	572	3×10^5	20	NA

	Temp. °F	Design Life hrs.	Stress ksi
Cover Plate	1650	3×10^5	1.5 (bend.)
Liner	250	3×10^5	-0.7

TABLE 4.3-3

VHTR REFORMER PLANT KEY COMPONENT MATERIAL REQUIREMENTS

Component	Temperature °F	Design Life	Design Stress	Important Properties	Comments
REFORMER					
Catalyst Tubes (Duplex Tube)	1672	100,000 hrs.	100 psi P_m operating	Creep	Helium gas velocity = 98 ft/sec
	1672	10 hrs.	2000 psi P_m Upset	Tensile	
	1672	400 cycles	10,000 psi (Q+F) Upset	LCF	High thermal con- ductivity desired Stable oxide film desired to retard tritium permeation
Pigtail Tube	1575	100,000 hrs.	-1750 psi P_m operating	Creep	Formability
	1575	10 hrs.	-3500 psi (P_m +Q+F) Upset	Tensile LCF	
STEAM GENERATOR	1090	100,000 hrs.	14,000 psi P_m operating	Creep	2-1/4Cr-1Mo or Incoloy 800
	1090	500 cycles	8900 psi (Q+F)	LCF	

Q = Secondary Stress

F = Peak Stress

 P_m = Primary Stress

4.4 VHTR HYDROCARBON REFORMING WITH IHX (Reference 12)

4.4.1 System Description

Figure 4.4-1 illustrates a partial plant layout for a steam methane reforming system which employs an intermediate heat exchanger loop. Figure 4.4-2 shows the flow schematic for the system and indicates the approximate temperature and pressure levels of the primary and secondary loops. The primary helium circulates in sequence through the reactor, the IHX, a steam generator and the helium circulator. (In some plant conceptual arrangements, there is no steam generator in the primary loop.) The relative temperature and pressure levels as indicated on Figure 4.4-2 are such that (1) rupture of the IHX primary-secondary barrier wall permits inward leakage to the reactor and (2) a 50°C thermal potential is typically employed to drive heat from the primary loop to the secondary loop. Helium is used as the heat transfer fluid in the secondary loop which contains a steam reformer, a steam generator and a circulator.

4.4.2 Intermediate Heat Exchanger

This component poses the most critical material problem of any component in the system in that it must operate at the highest temperature location in the system. The concept of avoiding simultaneous stress and temperature loading is accomplished during normal operation by maintaining a small pressure differential across the primary-secondary barrier walls. However, the faulted condition which assumes a rupture of the secondary loop, imposes a large pressure differential across the tubes and tube sheets at high temperature for the time duration required to shut down the reactor. This time duration has been assumed in the 10 to 100 hours region for most plant concepts with 30 hours being a typical average.

Figures 4.4-3, 4.4-4 and 4.4-5 show a U-tube style IHX which General Electric (ESTD/AEP) studies⁽¹²⁾ have identified as an optimum design based on an overall assessment of safety, cost and other engineering considerations. Table 4.4-1 provides overall summary data relative to the plant, the IHX assembly and the IHX modules.

Figure 4.4-1. Partial Plant Layout Showing Steam - Hydrocarbon Reformer with IHX Loop

Figure 4.4-2. Steam Reforming Plant with Intermediate Heat Transfer Loop. (Schematic)

Figure 4.4-3. Engineering Drawing of Reference Design IXH Featuring 36 U-tube Style Modules. (Drawing No. 707E871)

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Section B-B (Rotated)

Figure 4.4-4. U-Tube Style Intermediate Heat Exchanger Assembly (Reference Design).

Figure 4.4-5. Exploded Parts View of U-tube IHX Module (Reference Design)

TABLE 4.4-1

SUMMARY DATA FOR REFERENCE DESIGN IHX

PLANT DATA

Chemical Process	Steam Methane Reforming
Thermal Power	3000 MW
No. of Process Loops	12
Reactor Primary Coolant	Helium
Core Outlet/Inlet Temperature	950/350°C
Reformer Inlet Temperature	900°C
Reformer Peak Process Temperature	825°C
Reformer Power Ratio	35.6%
S.G. Inlet/Exit Temperature	600/300°C

IHX ASSEMBLY DATA

IHX Power Rating	250 MW
No. of Modules	36
Primary Inlet/Exit Temperature	950/350°C
Secondary Exit/Inlet Temperature	900/300°C
Pressure Vessel O.D.	16' - 10-7/8"
Overall Height	62' - 6-1/2"
Approximate Weight	500K lbs
Primary/Secondary Flow	.63 x 10 ⁶ lb/hr
Primary ΔP (Shell Side)	15.9 psi
Secondary ΔP (Tube Side)	15.5 psi
No. of U-tubes	9036
Tube O.D. x Wall	0.500 x .050 inch

MODULE DATA

Module Power Rating	6.94 MW
Primary/Secondary Flow	4.861 lbs/sec
Primary ΔP (Shell Side)	15.9 psid
Secondary ΔP (Tube Side)	15.5 psid
Inlet Pressure Primary/Secondary	600/638 psi
IHX Cavity Pressure	585 psi
No. of U-tubes	251
No. of Cross Flow Passes	24
Tube O.D. x Wall	0.500 x .050 inch
Module Header O.D./Thick	15.62/3.5 inch
Module Skin O.D./Thick	15.62/.0625 inch
Tube Spacing-to-O.D. Tran/Long.	2.0/0.9
Overall Length	32' - 4-1/2"
Approximate Weight	4000 lbs

The most critically stressed item in the plant is the IHX tubes. Two severe stress conditions exists.

- Condition #1

At startup differential expansion of the U-tube legs will produce a thermal stress which will be in the order of 10,000 psi. This thermal stress will be self relieving as creep occurs and will occur in the U-tube turnaround section where the metal temperature is in the order of 1157°F (625°C). Combined creep-fatigue damage will be a function of the plant design specification, however preliminary analysis based on 40 years and 1000 cycles indicates that material properties equivalent to INCO 617 can provide a workable design although higher temperature, longer lasting materials are desirable.

- Condition #2

At the faulted condition (secondary loop ruptured) the maximum temperature and pressure conditions exist simultaneously for an assumed 10 to 30 hours. In accomplishing the VHTR design study reported in Reference 12, GE-ESTD/AEP made the assumption that a material would be developed that would have a stress intensity capability at 1742°F (950°C) approximately 50% stronger than the Incoloy 800H data shown in Table 4.4-2. The data shown in this table came from ASME Code Case 1592 up to 1400°F. Above this temperature, the allowable stress intensity was extrapolated from published INCO data. The specific design point utilized in the GE VHTR study (for this assumed material) was as follows:

<u>Temperature</u>	<u>Allowable Stress Intensity</u>	<u>Time Duration</u>
1742°F (950°C)	4460 psi	10 hrs.

There are indications that the newer INCO alloys are approaching this capability.

4.4.3 Key Component Material Requirements Summary

Table 4.4-3 summarizes the material requirements for the key components of the VHTR-reformer plant with an IHX loop. The mechanical design requirement for the reformer, steam generator and ducting are essentially identical with those tabulated in Section 4.3 for a reformer plant without the IHX loop.

TABLE 4.4-2

INCOLOY 800H ELEVATED TEMPERATURE PROPERTIES

Incoloy 800H Extended (Code Case 1592)

<u>Temp. °F</u>	<u>S_t (ksi)</u>	
	<u>T = 10 Hrs.</u>	<u>T = 30 Hrs.</u>
≤ 100	21.4	21.4
800	20.2	20.2
900	19.8	19.8
1000	19.4	19.4
1100	19.1	19.0
1200	17.6	17.3
1300	14.5	12.4
1400	9.2	8.0
1500	6.5	5.6
1600	4.2	3.6
1700	3.1	2.7
(950°C)	(2.8)	
1800	2.5	1.9

ASME Allowable $P_m = 1.2 S_t$ (Faulted Conditions)

TABLE 4.4-3

KEY COMPONENT MATERIAL REQUIREMENTS FOR
VHTR NON-INTEGRATED REFORMER PLANT WITH IHX LOOP

Component	Temperature °F	Design Life	Design Stress	Mech. Property	Comments
<u>GAS DUCTING (Coaxial Primary)</u>					
Inner Liner	1742	300,000 hrs.	~ 0	Fabricability Stability	164 ft/sec
Hot Gas Contain- ment Duct	572	300,000 hrs.	1000 psi		119 ft/sec
Cold Gas Contain- ment Duct	572	300,000 hrs.	20,000 psi		
<u>IHX</u>					
Module Tubes	1742	100,000 hrs.	$\sigma = 549 \text{ psi } P_m$	Creep	Normal
	1157	500 cycles	$\sigma = 10 \text{ ksi } (P_m + Q + F)$	LCF	Start-up Transient
	1742	10 hrs.	$\sigma = 5 \text{ ksi } P_m$	Tensile	Faulted Condition
	1750	100,000 hrs.	$\sigma = 1000 P_m$	Creep	Comparative data
	1750	10 hrs.	$\sigma = 8 \text{ ksi}$	Tensile	from Reference 9
<u>REFORMER</u>					
Catalyst Tube	1672	100,000 hrs.	$\sigma = 100 \text{ psi } P_m$ (Norm)	Creep	
	1672	10 hrs.	$\sigma = 2 \text{ ksi } P_m$ (Upset)	Tensile	
	1672	400 cycles	10 ksi (Q+F) Upset	LCF	
Pigtail Tube	1575	100,000 hrs.	$-1750 \text{ psi } P_m$ (Norm)	Creep	
		10 hrs.	-35 psi ($P_m + Q + F$)	Tensile	
<u>STEAM GENERATOR TUBES</u>					
	1090	100,000 hrs.	14,000 psi P_m		
		500 cycles	8,000 psi (Q+F)		

4.5 VHTR COAL GASIFICATION (STEAM)

4.5.1 System Description (Data Source Reference 15)

Figure 4.5-1 shows a plant schematic for accomplishing steam gasification of coal. The fundamental chemical reaction is $C + H_2O \rightarrow CO + H_2$ but further shift reactions continue as detailed in Table 4.5-1 so that the output gas is a mixture of H_2 , CO , CO_2 and CH_4 . This mixture becomes predominately H_2 and CO as the temperature is increased while increasing pressure raises the amount of CH_4 .

A helium-to-helium IHX is always required for this plant. The following items substantiate this conclusion.

- Primary helium must always be retained inside the secondary containment structure.
- It is inconceivable to consider vast quantities of coal being conveyed into the containment structure.
- Since the distribution system for the synthetic product gas (the plant output) can readily propagate tritium (or other harmful products) to the general public, a double barrier wall is probably required for safety and licensing.

The system is generally operated with approximately the same pressure levels (40 bars) in the primary, secondary and gasifier process side flow loops. Therefore, the stress levels are normally low and should be a nominal 1000 psi for long term creep strength.

Figure 4.5-2 shows that the coal conversion rate for this process is highly dependent upon the temperature in the coal gasifier for various types of coal. Lignite, which is commonly available in Europe, can be economically gasified at temperatures approximately 150°C (270°F) below that required for Pittsburgh #8 coal. The IHX and the gasifier both require temperature differentials to transfer the heat from the reactor coolant to the intermediate helium and then to the coal-steam mixture. In view of these temperature losses, 900°C (1652°F) reactor coolant outlet temperature is generally considered as the minimum practical level for lignite conversion. A 1950°F to 2000°F (1065°C - 1093°C) temperature

Figure 4.5-1. Steam Gasification Using an Intermediate He Circuit.

TABLE 4.5-1
COAL GASIFICATION REACTIONS AND GAS HEAT VALUES

The basic equations which are important in the gasification of coal are:

In general, the primary reaction of steam gasification of coal is reaction (1) forming predominately hydrogen and carbon monoxide. The carbon monoxide may react with more steam to form carbon dioxide [equation (2)], the so-called shift reaction. Equation (3) then summarizes equations (1) and (2) to show the maximum yield of hydrogen. The carbon dioxide then can further react with carbon to form more carbon monoxide [equation (4)]. The hydrogen then reacts with carbon to form methane and carbon monoxide and carbon dioxide to form methane plus water [equations (5-7)]. The methane then can react with water to form carbon monoxide plus hydrogen [equation (8), the steam reformer equation] or, if conditions are suitable, carbon dioxide and hydrogen [equation (9)]. Thus, gas from the steam gasification of coal is a mixture of H_2 , CO , CO_2 , and CH_4 which becomes predominately H_2 and CO as the temperature is increased while increasing pressure raises the amount of CH_4 .

RATE OF C-CONVERSION

$\left(\frac{\%C}{\text{min}}\right)$

Figure 4.5-2. Rate of Gasification as a Function of Isothermal Process Temperature.

would be needed for the type coal commonly available in this country, thus substantiating the desirability of primary loop materials with this capability.

4.5.2 Intermediate Heat Exchanger (IHX)

The IHX is the most critical component from a materials requirements viewpoint since it must operate at the highest temperature point in the system and it must be designed for the faulted condition where the secondary loop has ruptured producing considerably higher than normal stress conditions for the time period required to shut down the reactor. Additionally the thermal stress associated with transient stress must be accommodated.

4.5.3 Gasifier

The process heat exchanger or coal gasifier as illustrated in Figure 4.4-3 generally consists of a horizontal cylindrical pressure vessel. In its interior is a trough whose walls serve as the inlet distributor for the steam entering the fluidized bed from below. The heat exchanger tubes, through which helium from the intermediate circuit flows, project from above into the fluidized bed which is bounded by the trough. According to present ideas, the coal is introduced at one end of the gasifier. It moves in the longitudinal direction through the fluidized bed and is increasingly gasified. The ash accumulates at the other end and can be removed through an opening at the left end of the fluidized bed.

4.5.4 Summary

In summary, the design requirements for the primary loop components (the primary concern of this material development program) are essentially identical with those of the "Reformer Plant with IHX" discussed in Section 4.4 except that temperature capability to 1950° - 2000°F is now desired. The ducting and the IHX tubes present the most difficult material requirements. Specific material property objectives are:

- | <u>Temperature</u> | <u>Allowable
Stress Intensity</u> | <u>Time Duration</u> |
|--------------------|---------------------------------------|----------------------|
| 1950°F | 4460 psi | 10 hrs. |
- Creep-fatigue properties roughly equivalent to Inconel 617.

Figure 4.5-3. Gas Generator - Heating Area 4000 m².

4.6 VHTR COAL GASIFICATION (HYDROGASIFICATION)

4.6.1 System Description (Data Source Reference 16)

Hydrogasification is the conversion of coal with hydrogen to methane. The basic equation is $C + 2H_2 = CH_4$. The hydrogen required has to be produced by the process. Coal and water are supplied as feedstock. This is contrasted to the steam gasification of coal (see previous Section 4.5) which is the conversion of coal with steam to (primarily) hydrogen and carbon monoxide.

There are two variations of conceptual VHTR plants for hydrogasification of coal depending upon the method by which the hydrogen is produced. These are:

1. Hydrogen formation by steam-methane reforming
2. Hydrogen formation by steam gasification of coal.

The plants will be separately described.

Variation 1: Reformer System for H_2 Generation - Table 4.6-1(a) shows the basic equations for this plant. Some of the output methane is used internally with a steam-methane reformer to produce hydrogen which then reacts with the coal in the gasifier. Figure 4.6-1 shows a schematic flow diagram for this plant. As indicated an IHX is not utilized. The primary helium circulates in a loop containing a steam reformer, a steam generator, the circulator, and the reactor. The loop components are identical with those of the VHTR Hydrocarbon Reforming plant as described in Section 4.3. The steam reformer process side operates at essentially the same pressure as the primary loop so that under normal conditions a near zero pressure stress exists.

The coal gasifier and other components associated with the process have some rather severe materials problems associated with high pressure, temperature, corrosion, etc., but for the purposes of this study these components are beyond the scope of the program. Briefly the problem stems from the fact that the reaction rates require high temperature (850°C) and high pressure (80 bars) to be economically feasible. The environments are highly corrosive. The mechanical problem of intro-

TABLE 4.6-1

CHEMICAL REACTIONS FOR HYDROGASIFICATION OF COAL

(a) Variation 1 H₂ Generation by Methane Reforming

In the gasifier

In the reformer

Total Process

(b) Variation 2 H₂ Generation by Steam-Coal Gasification

In the gasifier

Total Process

Figure 4.6-1 Hydrogasification of Coal (H₂ Generation by Methane Reforming)

ducing a high-surface-area solid into a pressurized system is not easily accomplished.

Variation 2: Steam Gasification for H₂ Generation - Table 4.6-1(b) shows the basic equations for this plant. Steam and coal are supplied to the gasifier where two parallel processes occur. The steam-carbon reacts to form hydrogen and carbon monoxide (or carbon dioxide). The hydrogen thus generated reacts with the carbon to form methane. Figure 4.6-2 shows a schematic flow diagram of this plant which is much simpler than variation 1 since steam reforming of methane and shift conversions are not necessary. However, a severe pressure-stress problem is imposed at the process heat exchanger which transfers the heat from the primary loop to the process loop. The problem occurs because the gasifier must operate at approximately 80 bars, the primary helium side must operate at approximately 40 bars and the maximum temperature (950°C) is normally present.

It is difficult to comment on the stress levels at this component since no conceptual designs for this process heat exchanger are known by the author. Likewise it is not immediately obvious that the design is impossible. Thicker tubes and tube sheets may solve the pressure problem. However, thicker walls increase the radial thermal gradient which worsens the thermal stress-cyclic fatigue problem. Certainly the additional volume of metal will hurt economically. If a sound design for this component can not be found, then the system must be altered or abandoned as an academic nicety.

The remainder of the components in the primary loop are similar to previous VHTR systems.

Figure 4.6-2. Hydrogasification of Lignite Coupling of Nuclear Heat by Preheating of the Gasifying Agent

5.0 APPENDIX SECTION

This section contains miscellaneous support data and other information considered pertinent to the Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program being performed under DOE Contract No. EY-76-6-02-2975.A008. The information is categorized in the following subsections.

- 5.1 Material Property Curves for Inconel 617
- 5.2 Extracts from the ASME B&PV Code (et al) defining the methods for establishing the design allowable Stress Intensity from test data.
- 5.3 Summary discussion of Hydrogen and Tritium Permeation through metallic alloys.
- 5.4 Prospects for Improved Materials Technology as related to the DCHT Reactor Plant. (Evaluation by NASA-Lewis, ORNL, UE&C and DOE).
- 5.5 Design Bases and Safety Class definitions for high temperature gas cooled reactor plants and components.
- 5.6 VHTR/NPH "Materials" chapter from GA-VHTR Study, dated 1976.
- 5.7 List of References

5.1 INCONEL 617 MATERIAL PROPERTY CURVES

Inconel 617 has high temperature material properties which cause it to be a leading candidate material for many DCHT and VHTR/NPH components. The following curves are included for reference and possible assistance in planning creep-rupture test conditions since the candidate alloys to be evaluated should have approximately similar characteristics.

Figure 5.1-1. Creep Rupture Properties

Figure 5.1-2. Tensile Properties of Inconel 617

Figure 5.1-3. Larson-Miller Parameter (0.5% Plastic Creep)

Figure 5.1-4. Fatigue Behavior

RUPTURE PROPERTIES OF BAR
INCONEL alloy 617
Solution Annealed 2150F/1 hr., A.C. (INCO Data)

Figure 5.1-1

High-temperature tensile properties of solution-treated, hot-rolled rod.

High-temperature tensile properties of solution-treated, cold-rolled sheet.

Figure 5.1-2. Tensile Properties of Inco 617 (INCO Data).

Figure 5.1-3

Low-cycle fatigue strength of INCONEL alloy 617 at room temperature.

Fatigue Strength of INCONEL alloy 617 at 1600°F.

Figure 5.1-4. Fatigue Behavior of Inconel 617 (INCO Data).

5.2 ASME DESIGN STRESS CRITERIA

Article III-2000 which follows, is reprinted from Section III of the ASME B&PV Code. It defines the factors of safety involved in converting test data to the tabulated design allowable stress intensities published in the code for Nuclear Power Plant systems and components (Safety Class 1). The procedure is explained in more detail in the follow-on technical article entitled "Procedures Employed to Establish the Basic Time and Temperature Stress Intensities and Isochronous Stress-Strain Curves" (Reference 17).

The final article in this subsection is a reprint of Appendix P from Section VIII of the ASME B&PV Code. (Section VIII pertains to the design of Unfired [Non-nuclear] Pressure Vessels). By way of comparison it should be noted that Section VIII allows stress intensities to "67 percent of the average stress for rupture at 100,000 hours" while Section III allows stress intensities to "2/3 of the minimum stress to cause rupture in time t."

ARTICLE III-2000

DESIGN STRESS INTENSITY VALUES FOR CLASS 1 COMPONENTS

HI-2100 MECHANICAL PROPERTY CRITERIA

III-2110 FOR MATERIALS OTHER THAN BOLTING

(a) The mechanical properties considered and factors applied for Tables I-1.1 and I-1.2 are given in (1) through (4) below. At any temperature listed, the design stress intensity value for ferritic steels and nonferrous metals and alloys, except those covered in (b) below, is the lowest of the following:

- (1) $\frac{1}{3}$ of the specified minimum tensile strength at room temperatures;
- (2) $\frac{1}{3}$ of the tensile strength at temperature;
- (3) $\frac{2}{3}$ of the specified minimum yield strength at room temperatures;
- (4) $\frac{2}{3}$ of the yield strength at temperature.

(b) The design stress intensity value for austenitic steels, nickel-chromium-iron and nickel-iron-chromium alloys is the lowest of the following:

- (1) $\frac{1}{3}$ of the specified minimum tensile strength at room temperature;
- (2) $\frac{1}{3}$ of the tensile strength at temperature;
- (3) $\frac{2}{3}$ of the specified minimum yield strength at room temperature;
- (4) 90% of the yield strength at temperature but not to exceed $\frac{2}{3}$ of the specified minimum yield strength at room temperature.

(c) The upper temperature limit for the tabulated design stress intensity values in Tables I-1.1 and I-1.2 are the temperatures to the next lowest 50 F increment

at which the creep rate or the stress rupture effects would produce design stresses lower than those from tensile and yield strength data.

III-2120 FOR BOLTING MATERIALS

For bolting materials, the stress values in Table I-1.3 are based on $\frac{1}{3}$ of the minimum specified yield strength at room temperature or $\frac{1}{3}$ of the yield strength at temperature up to a temperature of 800 F.

III-2200 FATIGUE STRENGTH CRITERIA FOR ALL MATERIALS

The fatigue curves of Figs. I-9.0 are obtained from uniaxial strain cycling data in which the imposed strain amplitude (half range) is multiplied by the elastic modulus to put the values in stress units. A best fit to the experimental data is obtained by applying the method of least squares to the logarithms of the stress values. The curves are adjusted where necessary to include the maximum effect of mean stress. The design stress intensity values are obtained from the best fit curve by applying a factor of two on stress or a factor of twenty on cycles, whichever is the more conservative at each point. Fig. I-9.1 is applicable to the carbon and low alloy steels; Figs. I-9.2 and I-9.3 are applicable to the high alloy steels and nonferrous alloys listed in Tables I-1.1 and I-1.2; and Fig. I-9.4 applies to bolting materials listed in Table I-1.3.

APPENDIX A

PROCEDURES EMPLOYED TO ESTABLISH THE BASIC TIME AND TEMPERATURE STRESS INTENSITIES AND ISOCHRONOUS STRESS-STRAIN CURVES (Reference 17)

A.1 MAXIMUM ALLOWABLE VALUE OF GENERAL PRIMARY-MEMBRANE STRESS INTENSITY

The symbol S_o is used for this value. The S_o values are identical to the values for S given in Section VIII, Division 1 of the Code.

A.2 TIME-INDEPENDENT DESIGN STRESS INTENSITY

The symbol S_m is used for this value. These values are based on tensile and yield strengths of the material. The criteria employed are defined as follows:

- (a) The allowable stress intensity value, S_m , for ferritic steels and nonferrous metals and alloys, except those covered in paragraph (b) below, is the lowest of the following four values:
 - (1) 1/3 of the specified minimum tensile strength at room temperature.
 - (2) 1/3 of the short term tensile strength at temperature [defined as the ratio of ultimate tensile strength at temperature divided by the ultimate tensile strength at room temperature, multiplied by the minimum specified room temperature ultimate tensile strength; the total quantity increased by 10% (not to exceed however the minimum specified room temperature tensile strength). The ratio of UTS_T/UTS_{RT} , for austenitic stainless steel, is found in ASTM DS5-S2.]
 - (3) 2/3 of the specified minimum yield strength at room temperature.
 - (4) 2/3 of the short term 0.2% offset yield strength at temperature [defined as the ratio of yield strength at temperature divided by the yield strength at room temperature, multiplied by the minimum specified room temperature yield strength. The ratio of YS_T/YS_{RT} , for austenitic stainless steel, is found in ASTM DS5-S2.]

(b) 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) 1/3 of the specified minimum tensile strength at room temperature.
- (2) 1/3 of the tensile strength at the operating temperature.
- (3) 2/3 of the specified minimum yield strength at room temperature.
- (4) 90 percent of the yield strength at the operating temperature.

A.2.1 Yield and Tensile Strength

The procedures for establishing yield and ultimate strengths that were employed are:

The yield and tensile strength data available for a particular material grade are normalized by ratioing the elevated temperature strength of individual lots to the room temperature strength of the same lots, and then all sets of such ratios representing a particular grade are evaluated by the method of least squares to establish the curve of best fit for the data. The resulting "strength-ratio trend curve" is considered to represent the typical or characteristic variation of yield or tensile strength with temperature. Using such a ratio trend curve, it becomes possible to compute strength trend curves for any particular room temperature strength level of interest within the limits encompassed by the original data.

Since the design stress intensity criteria include fractions of the specified yield and tensile strengths, it is necessary to factor the ratio trend curves against the specified minimum yield and tensile strengths to define what may be termed minimum position yield and tensile strength curves. At temperatures above room temperature, the property "yield strength at temperature" is taken, for purposes of the criteria, to be this minimum position value. However, the property "tensile strength at temperature" is taken as the smaller of:

- (a) specified minimum tensile strength at room temperature, or
- (b) a value 10 percent greater than the minimum position value cited above.

A.3 TIME-DEPENDENT DESIGN STRESS INTENSITY

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 lesser of each of the three quantities:

- (a) 2/3 of the minimum stress to cause rupture in time t ,
- (b) 80 percent of the minimum stress to cause the onset of tertiary creep in time t , and
- (c) the minimum stress to produce one percent total strain in time t .

A.3.1 Minimum Stress-to-Cause-Rupture in Time t

The basic data and a description of the rupture strength evaluation procedures employed for several of the materials included in Code Case 1592, (i.e. types 304 and 316 stainless steel) may be found in Metal Property Council data evaluations.

Two principal procedures are employed in evaluating the dependence of the stress-to-cause-rupture upon time and temperature. A choice between the results, based on engineering judgment, is then made.

In the first procedure, the isothermal relation between stress and time for rupture of individual lots is interpolated or extrapolated, as required, to identify the stress to cause rupture in 100, 1000, 10,000, etc. hours. Plotting on log-log coordinates tends to linearize the variation, and thereby facilitate extrapolation, particularly at lower temperatures. At higher temperatures, the variation tends to curvilinearity at longer times, and extrapolation involves risk. The results of such interpolations or extrapolations for individual lots, as they vary with temperature, are then evaluated by the method of least squares to define an average rupture strength - temperature trend curve. A trend curve for minimum rupture strength is derived from the mean trend curve by subtracting 1.65 multiples of the standard deviation of the sample. If certain implicit assumptions hold, e. g., that the data are

normally distributed, that the average is without error, this minimum trend curve defines a lower boundary for 95% of the data. Inspection of the data plots has always shown that this is approximately true.

The second evaluation procedure that has been employed is an indirect one, involving one or another time-temperature parameter. One of the simplest of these, widely used, is Larson and Miller's:

$$P = T(C + \log t) = F(S)$$

where T is the temperature in degrees Rankin, t is the time for rupture in hours, C is a material constant, and $F(S)$ denotes that the parameter depends upon stress. Ordinarily, the available data are not adequate to permit evaluation of individual lots by the parameter procedure, as would be desirable; instead, the total data population must be treated as a common population on a universalized basis, assuming the constant C to remain invariant from lot to lot within the data population. Accordingly, the scatter band for the stress - parameter variation is evaluated by the method of least squares to determine an average curve of best fit, from which average values of rupture strength as dependent upon temperature can be derived. A minimum curve is developed, as in the previously described procedure, by subtracting 1.65 multiples of the standard deviation of the sample from the average curve.

A.3.2 Minimum Stress-to-Initiate-Tertiary-Creep in Time t

For the ferrous alloys included in Case 1592, Leyda and Rowe (Reference 19) had reported that the time to initiate tertiary creep is a fixed fraction of the time for rupture for a given material at a specific temperature. Thus, for 2 1/4 Cr-1 Mo, and Types 304 and 316 the minimum stress to initiate tertiary creep was computed from the minimum stress to rupture data. For the high-nickel alloys, tertiary creep information was developed by examination of available creep curves. In all instances, the initiation of tertiary creep was assessed visually. Extrapolations to lower temperatures were made by time-temperature parameter methods exactly analogous to those described for rupture strength, except that the time for tertiary creep to begin is now the measured quantity.

A.3.3 Minimum Stress to Cause 1 Percent Total Strain in Time t

In common with the criterion for stress to initiate tertiary creep, the criterion on minimum stress for 1 percent total strain is new to the ASME Code. For purposes of Section I and Section VIII, Division 1, creep strength has for many years been evaluated in terms of the stress causing a secondary creep rate of 0.01 percent per 1000 hours. In the new criterion, stress to cause 1 percent total strain can be evaluated in an exactly analogous manner as the stress to cause rupture or to initiate tertiary creep--the dependence upon stress tends to parallel that of rupture time--or it can be derived directly from the isochronous stress-strain curves. Both approaches have been employed in developing the material for Case 1592.

A.4 ISOCHRONOUS STRESS-STRAIN CURVES

For relatively short times, isochronous stress strain curves may be derived by taking constant time sections through a family of creep curves, such as those of Figure 2. However, this approach to their derivation is not generally practicable (unless forming only a part of a multi-approach procedure) since the time scale of interest extends beyond the feasible limit of experimental testing. Extrapolative procedures are required for the longer test turns and for strains below 1 percent. For generating the isochronous stress-strain curves in Case 1592, two procedures have been employed. In one of these, the curves are developed by performing evaluations exactly analogous to those described for developing information on the stress to produce 1 percent strain, except that other specific strains encompassing the range of interest, are also evaluated, and the various parts assembled in plots of stress versus strain for different fixed times.

In a second procedure, the strain has been expressed as an analytical function of time according to the general form:

$$\epsilon = \epsilon_{\text{loading}} + \epsilon_{\text{transient}} + \epsilon_{\text{steady state}}$$

where each of the parts is a function of stress and temperature. The individual parameters of the equation are then evaluated from the experimental results generated in conventional creep tests.

More complete descriptions of these procedures may be found in "The Generation of Isochronous Stress Strain Curves," Winter Annual ASME meeting, November 1972.

APPENDIX P

BASIS FOR ESTABLISHING STRESS VALUES

BASIS FOR ESTABLISHING STRESS VALUES

UA-500

In the determination of allowable stress values for pressure parts the Committee is guided by successful experience in service, insofar as evidence of satisfactory performance is available. Such evidence is considered equivalent to test data where operating conditions are known with reasonable certainty. In the evaluation of new materials, it is sometimes necessary to be guided to a certain extent by the comparison of test information with available data on successful applications of similar materials.

The mechanical properties considered, and the factors applied to establish the maximum allowable stresses are as given below:

At temperatures below the creep range, the maximum allowable stress value for ferrous materials (Table UCS-23, UCS-27, UHA-23, and UHT-23) and for nonferrous materials (Table UNF-23), is the lowest of these:

(1) $\frac{1}{4}$ of the specified minimum tensile strength at room temperature,

(2) $\frac{1}{4}$ of the tensile strength at temperature,

(3)(a) For ferrous materials:

$\frac{5}{8}$ of specified minimum yield strength at room temperature,

(b) For nonferrous materials:

$\frac{2}{3}$ of specified minimum yield strength at room temperature,

(4)(a) For ferrous materials:

$\frac{3}{4}$ of yield strength at temperature,

(b) For nonferrous materials:

$\frac{3}{4}$ of yield strength at temperature.

In Table UNF-23 for specific nonferrous alloys and in Table UHA-23 for austenitic materials, two sets of

allowable stress values are provided. The higher values should be used only where slightly greater deformation is not in itself objectionable. The higher alternative allowable stresses are identified by a footnote. These stresses exceed two-thirds for nonferrous alloys and $62\frac{1}{2}$ percent for austenitic materials but do not exceed 90 percent of the minimum yield at temperature. These higher stresses are not recommended for the design of flanges and other strain sensitive applications.

At temperatures in the creep range the maximum allowable stress value for all materials shall not exceed the lowest of the following:

(1) 100 percent of the average stress for a creep rate of 0.01 percent per 1000 hours,

(2) 67 percent of the average stress for rupture at the end of 100,000 hours,

(3) 80 percent of the minimum stress for rupture at the end of 100,000 hours.

For *ferrous bolting* materials, the basis for setting stresses is the same as for all other materials with the added requirement that the stresses for heat treated materials at temperature below the creep range will not exceed the lower of 20 percent of the room temperature specified minimum tensile strength, or 25 percent of the room temperature specified minimum yield strength.

For *nonferrous bolting* materials, at temperatures below the creep range, the maximum allowable stress values are the lowest of:

(1) $\frac{1}{5}$ of the specified minimum tensile strength at room temperature,

(2) $\frac{1}{5}$ of the tensile strength at temperature,

(3) $\frac{1}{4}$ of the specified minimum yield strength at room temperature,

(4) $\frac{1}{4}$ of the yield strength at temperature.

5.3. HYDROGEN AND TRITIUM PERMEATION (Data Extracted from Reference 12)

Tritium, the heavy isotope of hydrogen (^3H) is formed in all nuclear reactor systems through the fission process and through neutron interactions with various materials. To minimize the transfer of tritium, which is a radiological hazard, from the primary coolant loop to the secondary loop, consideration must be given to the permeability characteristic of candidate alloys during the selection process.

Permeation rates are slightly lower for tritium than for hydrogen through nickel and Incoloy 800 according to the data of Figure 5.3-1. Although several recent papers have addressed the subject of tritium permeation, only a few alloys have been involved. Hydrogen permeabilities may be used to compare materials with respect to tritium permeability on a relative basis for screening purposes. The relative permeabilities of several metals and alloys to hydrogen are shown in Figure 5.3-2. Also shown in the figure are two curves for Incoloy 800 which demonstrate the results of experiments on diffusion at high temperatures of pure hydrogen and a steam-hydrogen mixture. Hydrogen permeation was reduced by one to two orders of magnitude in the presence of steam, indicating that a diffusion barrier is formed by oxides of chromium and iron. Strehlow and Savage also showed that an oxide film can produce a large reduction in hydrogen permeation rate, but that the effectiveness of such films was dependent on the presence or absence of defects in the film and also on hydrogen pressure.

One method of taking advantage of this reduction in hydrogen permeation rates by oxide films is to oxidize the surface of the tubes prior to assembly of the IHX and to "dope" or to intentionally add oxygen impurity to the helium in the secondary loop to assist in maintaining the oxide film and to "heal" any defects in it.

Some of the hydrogen on the process side of the process heat exchanger will permeate through the walls of that heat exchanger and into the secondary coolant loop from which it then will permeate through the walls of the IHX and into the primary loop. Minimizing transfer of hydrogen into the primary loop helps protect the graphite fuel elements and reflectors from corrosion by the reaction: $\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4$. It is clear, therefore, that development effort aimed toward measuring and minimizing hydrogen and tritium

Figure 5.3-1. Hydrogen Permeation Data

Figure 5.3-2. Comparative Permeabilities of Hydrogen Through Various Metals

(a) Incoloy 800 data converted to these permeability units assuming a square root of pressure relationship

permeation through alloys suited to HTR service is needed. In addition, the effectiveness of oxide films in reducing permeation rates requires additional study.

5.4 PROSPECTS FOR IMPROVED MATERIAL TECHNOLOGY AS RELATED TO THE DCHT SYSTEMS

Extracted from ERDA Report No. 109, entitled "Technical and Economic Assessment of Direct-Cycle Gas-Cooled Reactor Plant, Sept. 1975."⁽²⁾

MATERIALS

One way to improve plant performance is to increase turbine inlet temperatures. GA estimates indicate that a 100°F increase in turbine inlet temperature improves plant efficiency about 2%. However, it is questionable whether any of the existing super alloys are suitable for temperatures much higher than 1500°F. Therefore, to take full advantage of increasing turbine inlet temperatures, without the complexities and performance penalties associated with additional cooling, would require the development of materials for use in the turbine, ducting, and thermal barriers. Such a development program would include alloy development, fabrication, welding, and mechanical testing and confirmation testing of a number of materials to the ASME Code or other qualification testing, where required. The long lead time to bring new materials from conception to Code-approved usage (nominally 10 years) much be recognized in planning for any such advanced system.

Any new alloy must be designed for the environment and not vice-versa. Ideally, the alloy should be in thermodynamic equilibrium with the environment and with itself. A non-reactive alloy without precipitated phases that overage would be ideal. Precipitated phases, if present, must be stable in the environment.

A required restriction on the development of advanced Ni-base super alloys for this application may be the elimination (or minimization) of alloying elements which could cause activation and radioactive contamination problems (e.g., Co and Ta). Additionally, low Al and Ti contents may be necessary to minimize internal oxidation and degradation of properties. This, of course, will compromise one of the major strengthening products, $[\text{Ni}_3(\text{Al}, \text{Ti})]$. It seems likely, then, that the strengthening potential of alloying additions such as Mo, W, and Nb must be more fully exploited in advanced super alloy development. The possibility of improving the properties of cast components by control of grain size and microporosity (using improved casting techniques and subsequent processing treatments such as hot isostatic pressing) also exists.

A new class of solid-solution Ni alloys that could be promising are the long-range-ordered (LRO) alloys based on the A_3B structure. Characteristically, activation energies for creep, diffusion, and transport in these alloys are significantly higher than for disordered alloys and the stress exponent for the creep rate varies as σ^3 rather than as σ^{5-7} for conventional alloys. Since these alloys contain precipitated phases, do not segregate, and cannot overage or decarburize, many problems are eliminated. Dispersion strengthened TD-Ni might also serve as a candidate material.

Molybdenum-base alloys are a logical choice for very high operating temperatures (1800°F and up). However, considerable development will be required for these materials. The only current commercial alloy, TZM, is a carbide strengthened material which could suffer some degeneration through selective oxidation of Ti and Zr -- the major strengthening

metallic additions. Development of solid solution strengthened alloys may be necessary. Also, the properties and behavior of Mo are very structure sensitive and a detailed study of the effects of processing history will be required.

Another possibility is for the environmental protection of high temperature components by the application of coatings. To be effective, these must not only be impervious, but must not degrade the substrate alloy under service conditions. Potential problems with coatings are lack of long-term reliability and proven methods of assuring high quality. For turbine components, coatings appear more applicable to situations that require non-bonding or non-galling interfaces rather than protection from the hot gases.

It is probable that improved Ni-base super alloys can be developed to allow operation of the gas turbine with inlet temperatures to 1700°F, without additional cooling. Alloys based on Mo have the potential for operation at temperatures up to 2200°F with 2000°F being an almost guaranteed minimum.

5.5 SAFETY CLASS DEFINITIONS FOR HTR PLANT COMPONENTS (Extracted from VHTR Report GEAP-14018(13))

INDUSTRY SAFETY CRITERIA

Industry criteria are formulated to supplement the federal requirements of 10 CFR 50. For gas cooled reactors, industry has prepared draft safety criteria ANSI-N213, January, 1975 for use in licensing and design. The design criteria, as tentatively defined in ANSI N213 apply strictly to gas-cooled, high temperature reactor (HTR) power-generating plants and do not cover all aspects of process heat applications.

The use of a VHTR as a source of process heat for endothermic chemical reactions occurring at high (<1700°F) helium temperatures (e.g., for coal gasification, hydrogen production, steelmaking, etc.) requires that the design criteria applicable to a gas-cooled power reactor, as tentatively defined in ANSI N213, be reevaluated

Specific Regulatory Guides

In addition to the long list of regulatory guides that apply to all reactor types, there is a Regulatory Guide 1.87 "Construction Criteria for Class 1 Components in Elevated Temperature Reactors (Supplement to ASME Section III Code Cases 1592, 1593, 1594, 1595 and 1596)". These code cases are an interim step to cover time dependent creep and relaxation phenomena that are important for HTR systems where high temperatures are involved. ASME III was designed to cover materials in use at LWR temperatures where these phenomena are insignificant. There are many areas relating to safety that are not covered by the code cases and Regulatory Guide 1.87 cautions against this. In addition, the process heat application for HTGR imposes new areas of concern regarding application of ASME Section III for Class 1, 2, 3 and MC.

DEFINITION OF DESIGN BASES

The bases for the design of all components that relate to the safety of the plant and to the control and spread of radioactivity are assigned by Safety Classes. Safety Class assignments to the systems or components of the plant will determine what codes or standards must be applied. ANSI-N213 interprets the intent of Regulatory Guide 1.26 in this respect as follows:

Safety Class 1 (SC-1)

This is primarily the pressure boundary that contains the primary coolant and in the case of the VHTR it is the PCR structure and supports. The steam generator pressure parts are included and in the case of the intermediate loop heat exchanger for the process heat plant it would be any parts inside the PCR that are exposed

to the primary coolant. Piping and heat exchanger parts must comply with ASME-III Class 1 and Seismic I applies. (Regulatory Guide 1.29).

Safety Class 2 (SC-2)

These are items that have a safety function to cool the reactor core, contain the primary coolant (this would include the liner inside the PCRV), insert negative reactivity, mitigate the consequences of failures of SC-1 equipment, or whose failure would prevent the accomplishment of the foregoing items. For the process heat plant, SC-2 items would include the PCRV liner, the reactor containment vessel, containment isolation valves outside containment, RACS circulator and piping out to and including the isolation valve outside containment, any shaft seals for shafts penetrating the primary coolant boundary, intermediate helium loop piping from where it penetrates the primary coolant pressure boundary out to and including the isolation valve outside containment, the reactor core assembly and small penetrations of primary containment. If any penetration of the PCRV primary containment (such as the intermediate helium piping) is larger in cross sectional area than that used in accident analyses, then it must be safety class 1. No credit is allowed for flow limiting devices.

Safety Class 3 (SC-3)

These are items that contain radioactivity that would exceed 10 CFR 20 upon release, provide or could prevent cooling to SC-1 or SC-2 systems, or comprise balance of systems that provide reactor core or spent fuel cooling. To process heat plants, this would include cooling for spent fuel storage, PCRV cooling, emergency electrical fuel supply, fuel handling equipment, and onsite emergency electrical power. Piping and components must comply with ASME-III Class 3 and seismic I applies.

Safety Class 1, 2 and 3 must comply with 10 CFR 50, Appendix B and Regulatory Guide 1.64 for Quality Assurance Provisions.

Non-Nuclear Class

These are all components or systems that do not have a direct safety function, but are influenced by any of the Safety classes. These would include the turbine generator set, main condenser, feedwater and main steam lines beyond isolation valves, condensate, fire protection, process heat exchanger and intermediate helium piping beyond isolation valves. Piping and components must comply with ANSI B31.1.0 and vessels to ASME-VIII. Quality Assurance must satisfy the safety class assignment at the interface.

5.6 "MATERIALS" SECTION from GA-VHTR STUDY (Extracted from Reference 9)*

8. MATERIALS

The objective of the approach used in the selection of structural and insulating materials for the two prime nuclear-heated reformer designs being compared was to establish minimal technical risk when possible. Selection of materials for the component designs having some uncertainty peculiar to material properties was made with an estimated equivalent risk position for each system. The qualitative risk assessments were applied to factors such as current development or application status of a material, specifically in the areas of strength, creep and thermal properties, capacity for fabrication and joining, cost, and anticipated availability.

The following subsections discuss requirements, alloy selection and description, and development objectives for the materials selected for the key components for the system configurations described in Section 5.

8.1. MATERIAL REQUIREMENTS

The goals of the two prime systems are parallel: to heat a reforming gas mixture to 1089 K (1500°F) at 2.41 MPa (350 psia). Since the presence of an IHX involves one additional heat exchange step, a higher core outlet coolant temperature is required for the intermediate loop plant. As expected, this condition influenced the design and material selection for each reactor system. Table 8-1 provides a summary comparison of the component structural materials for each system and the material requirements for the preliminary established operating conditions. The rationale for selection of each material is presented in Section 8.2. For critically stressed components (e.g., pressure boundary/heat transfer walls) which rely heavily on good high-temperature creep properties, the pertinent calculated stress and/or strain values are listed. The component names used in Table 8-1 relate to those used in the circuit configurations of Figs. 3-1 and 3-2 and the component designs described in Section 5.

* The references noted in this Section 5.6 are listed on page 5-64.

TABLE 8-1
PRELIMINARY OPERATING CONDITIONS AND MATERIALS REQUIREMENTS FOR STRUCTURAL COMPONENTS
FOR BOTH PROCESS HEAT SYSTEM DESIGNS

Component	Candidate Material	Nominal Operating Conditions		Primary Design Properties (σ values = operating stress at T and P)	Additional Requirements
		With IHX	Without IHX		
Primary duct					L/C fatigue resistance
Seal sheet	Inconel 617		1172 K (1650°F) $\Delta P \sim 0$		Formability
Cover plate	IN 713C			Creep strength: $<1\% \epsilon_c$ at $\sigma \sim 10.3$ MPa (1,500 psi) (bending)	Galling resistance
Washers	IN 713C				
Fasteners	IN 713C				Notch toughness
Insulator liner	Carbon-carbon composite	1256 K (1800°F)		Tensile strength	No stress concentrations
Outer liner	2-1/4 Cr - 1 Mo steel	$\Delta P \sim 0$ 811 K (1000°F)		Creep strength	
Connecting brackets	IN 713C	1256 K (1800°F)		Creep strength	Carburization-resistant coating
IHX					
Module tubes	Inconel 617	727 to 1227 K (850° to 1750°F)	NA	Creep strength: $\sigma \sim 6.90$ MPa (1000 psi) High-temperature tensile strength: $\sigma \sim 27.6$ -55.2 MPa (4000-8000 psi) for 10 hr	Weldability Formability Ductility
Lower lead tubes	Inconel 617	1172 K (1650°F)		Low-cycle fatigue Creep-fatigue	
Headers (upper) (lower)	Inconel 617	727 K (850°F) 1227 K (1750°F)		Tensile strength Rupture strength High-temperature tensile strength: $\sigma \sim 55.2$ MPa (8000 psi) for 10 hr	Weldability (to 2-1/4 Cr - 1 Mo steel)
Upper lead tubes	2-1/4 Cr - 1 Mo steel	727 K (850°F)		Tensile strength: τ (shear) = 69 MPa (10,000 psi) $\tau_{max} = 124$ MPa (18,000 psi) for 10 hr	Weldability (to 617) Formability Ductility
Tube supports	Inconel 617	1227 K (1750°F)		Rupture strength: $\sigma \sim 6.90$ MPa (1000 psi)	Formability Weldability
Deflector	Carbon-carbon composite	1256 K (1800°F)		Tensile strength	No stress concentrations
Central return duct	Inconel 617	727 to 1227 K (850° to 1750°F)	NA	Creep strength: $\sigma \sim 8.28$ MPa (1200 psi) High-temperature tensile strength: $\sigma \sim 55.2$ MPa (8000 psi) for 10 hr	Weldability
Tubesheet	2-1/4 Cr - 1 Mo steel	721 K (840°F)		Tensile strength: $\sigma \sim 138$ MPa (20,000 psi)	Forgability or castability Weldability

TABLE 8-1 (Continued)

Component	Candidate Material	Nominal Operating Conditions		Primary Design Properties (σ values = operating stress at T and P)	Additional Requirements
		With IHX	Without IHX		
Reformer					
Catalyst (reformer) tubes	HK-40	1130 K (1575°F) $\Delta P \sim 2.50$ MPa (365 psi)	1130 K (1575°F) $\Delta P \sim 2.50$ MPa (365 psi)	Creep strength: $\sigma \sim -8.53$ MPa (-1243 psi) Buckling (collapse) High-temperature tensile strength: $\sigma = -17.6$ MPa (-2550 psi) for 10 hr Creep-fatigue (low-cycle)	Weldability Low tube ovality Oxidation resistance (i.d.)
Pigtails	Inconel 617	1130 K (1575°F) $\Delta P \sim 2.76$ MPa (400 psi)	1130 K (1575°F) $\Delta P \sim 2.76$ MPa (400 psi)	Creep strength: $\sigma \sim -12.1$ MPa (-1750 psi) High-temperature tensile strength: $\sigma = -24.1$ MPa (-3500 psi) for 10 hr Creep-fatigue (low-cycle)	Weldability Formability Oxidation resistance (i.d.) Ductility
Common return tube	Inconel 617	1089 K (1500°F) $\Delta P \sim 2.50$ MPa (365 psi)	1089 K (1500°F) $\Delta P \sim 2.50$ MPa (365 psi)	Creep strength: $\sigma \sim -20.7$ MPa (-3000 psi) High-temperature tensile strength: $\sigma = -40.3$ MPa (-5850 psi) for 10 hr	Oxidation resistance (i.d.) Weldability
Shroud	Inconel 617	1172 K (1650°F)	1172 K (1650°F)	Rupture strength	Weldability
Bellows	316 stainless steel	977 K (1300°F)	977 K (1300°F)	Rupture strength High-temperature tensile strength Creep-fatigue (low-cycle)	Weldability Oxidation resistance
Tubesheet	316 stainless steel	840 K (1050°F)	840 K (1050°F)	High-temperature tensile strength: $\sigma \sim -104$ MPa (-15,100 psi) for 10 hr Creep strength: $\sigma \sim -73.8$ MPa (-10,700 psi)	Capacity for fabrication Weldability Oxidation resistance
Circulators					
Blades	} 422 stainless steel	} 775 K (935°F)	} 672 K (750°F)	} Creep strength Fatigue strength (use of current HTGR technology and design)	
Discs					
Shafts					
Steam generator					
Upper tubes	Incoloy 800			} Creep strength Rupture strength Creep-fatigue High-temperature tensile strength (use of current HTGR technology and design)	} Corrosion resistance Formability Weldability
Lower tubes	2-1/4 Cr - 1 Mo steel				
Common return tube					
External piping	Mild steel A516, Grade 70			Tensile strength	Weldability

The long-time thermal stability of the candidate alloys, which includes corrosion-independent changes in microstructure or precipitation of embrittling TCP phases under long-time thermal exposure, is an equally important concern for the design of extended lifetime components. The thermal stability of some of the candidate alloys considered in these system designs has not been sufficiently characterized for extended times at the temperatures required for application in the high-temperature components. In requiring long-time thermal stability of the alloys, particular emphasis is put on retention of high-temperature strength and adequate ductility at room temperature. Start-up and shutdown sequences must be feasible without having to fear fracture of long and flexible components which undergo substantial movement owing to thermal expansion.

A key requirement for all materials will be acceptable corrosion resistance to the impurity environment in the primary coolant. The type and extent of corrosion reactions between alloy constituents and impurities in the reactor helium and the effect of these reactions on pertinent mechanical properties are important data that must be developed in the future advanced gas-cooled nuclear reactor materials program. Past and current test programs have indicated that oxidation, carburization, or both may occur at the surface and/or in depth depending on the type and ratio of impurities and the alloy composition. The long-time static and/or cyclic load-carrying capability of a component could be significantly affected by possible corrosion mechanisms, which must be quantified and taken into account for component design.

An important feature of the system containing an IHX is that components in the intermediate loop are not required to be corrosion resistant to impurities in the primary coolant, since only the secondary helium is present. This outcome affects materials design strategy in that the secondary helium supply can be chemically adjusted to provide a desired oxidizing or carburizing potential for minimizing corrosion of the exposed alloys.

A number of off-normal operating conditions affect material requirements. In addition, some design concepts introduce stresses in a different manner than the usual pressure-induced stresses. A number of these are briefly discussed in the following paragraphs. Components pressurized on both sides require design consideration for sudden depressurization on one side at temperature, so short-time tensile and compressive strength properties are an important design parameter.

A number of pressurized components are under compressive stress during normal operating conditions. The reformer tubes, the common return tube, and the pigtails in the PHX are in this category. This may be an attractive condition for material creep behavior, since secondary (minimum) creep rate is of interest in design. Conditions for stress-rupture and accelerated tertiary creep do not prevail. Although Code Case 1592 does not specifically address this condition, it is possible that a longer lifetime at a given stress (in the creep regime) may be appreciated and realized in designs under compression loading.

Low-cycle fatigue resistance is needed in tubular components because all reactor system concepts encounter at least 500 start-up and shutdown cycles during a lifetime. Thermal expansion differentials and thermal stress gradients induce the low-cycle fatigue strain profile, which can be predicted to occur above and below the creep temperature range for most candidate alloys.

Isolation valve parts may experience high temperatures under tensile or compressive stress, but valve design will be likely to employ features for insulating key parts during normal loop operation. Material requirements will be peculiar to specific valve designs. Incoloy 800 is currently being considered, provided a temperature below 867 K (1100°F) can be maintained in the insulated metal parts.

The ducting for the integrated system follows established HTGR technology and utilizes a duct design which is integral with a thermal barrier for the PCRV containment. The primary stresses arise from the need

to compress fibrous insulation on the outside of the metal duct components. Thus, due to bending stresses, permissible creep of the duct cover plates is limited.

In the system utilizing an IHX, the primary ducts, the IHX pigtails, the IHX subheaders, and the tubing may also require creep resistance under localized hot streaking of the helium exiting from the core. If the gas temperature streaks to 56 K (100°F) above nominal, then the tube supports and the deflector may experience a 56 K (100°F) increase, while components exchanging heat would experience a rise of approximately 28 K (50°F). In the integrated system, the streaking condition would increase the primary duct and shroud temperature by 56 K (100°F), and the PHX reformer tubes, pigtails, and outlet manifold would experience an increase of about 28 K (50°F) above nominal operating temperature.

Thermal barrier systems were identified and categorized by functional requirements in Section 5. The approach follows the philosophy set by HTGR technology, along with a few additions. The use of Safil alumina fiber blankets for temperatures nominally at 1172 K (1650°F) with allowance for 56 K (100°F) excursions (integrated system) is demanding with respect to retention of adequate resiliency. The extensive use of carbon-carbon composites and carbon felt for insulation in the nonintegrated system sets a precedent for the HTGR, but such application is not new to industry for high-temperature insulation in inert or vacuum atmospheres and furnaces. The features of this type of insulation include excellent stability, no outgassing, and conventional fabrication techniques.

The use of carbon-carbon composite materials for structural components (ducting) in the nonintegrated system follows the concept of a similar technology used during the past decade in many aerospace applications such as skins and stiffeners for missiles (reentry vehicles), advanced framework for aircraft, and nuclear fuel capsules. Two kinds of carbonaceous fiber-reinforced composites are being utilized in the ducting/thermal barrier design, and there is an established industry manufacturing these materials

in the U.S. The first type, which has a higher strength (in two dimensions) than the second type, is manifested by a low-density carbon or graphite fiber-reinforced carbonized organic resin composite which is fabricated by conventional fiber glass laminate techniques and then densified by CVD infiltration of pyrolytic carbon. The second type emphasizes low thermal conductivity [~ 0.72 to 2.2 W/m-K (~ 5 to 15 Btu-in./hr-ft²-°F)], low cost, and more modest strength properties. This composite type is a carbonaceous fibrous-molded product which can be manufactured in several forms, each differing by degree of impregnation, infiltration, coating, etc. Another application for this low-conductivity material is as a replacement for Masroc (core floor insulation).

As with the graphite HTGR components, fabrication and application of carbon structural composites require brittle material design concepts and precautionary measures during assembly of parts. These materials have a linear stress-strain relationship, and their strength levels are definable on the basis of fiber type, orientation, density, and processing procedure. In contrast to high-temperature structural ceramics, carbon composites are readily machinable to precise final dimensions.

Two requirements for structural carbon composites are creep resistance (particularly in high neutron flux regions) and surface stability in reactor helium. Until now, high-temperature applications for these materials have been predominantly for relatively short time periods. However, reactor environment experience with graphite is an indication that carbon composites will be suitable for VHTR application.

Piping materials for the small sections of hot gas pipe between the reactor and the containment isolation valves conform to reactor standards for materials and thermal barrier. On the process plant side of the isolation valves, a conventional process plant construction is used which consists of a carbon-steel shell conforming to ASTM A516 grade 70, lined internally with a monolithic refractory lining (e.g., silicate, alumina, mullite, or zirconia type). The same construction is specified for some of the vessels in the external loop.

It is expected that the practices and standards of conventional process plant construction will be adequate, and the costing is based on this assumption.

8.2. MATERIAL SELECTION AND PROPERTY DATA

8.2.1. Selection and Description of Alloys

Alloys chosen for component parts which will operate at temperatures below 1089 K (1500°F) were selected from those covered in the applicable ASME Code sections or cases. When appropriate, precedents of materials selection covered by earlier HTGR technology (e.g., steam generators, circulators) were followed. For higher-temperature component applications, selection rationale included consideration of existing data on creep properties; alloy history in similar applications; cost; equivalent risk for the two prime systems under comparison; high-temperature short-time strength; coefficient of thermal expansion; weldability (and history of performance); fabrication difficulties (for component parts requiring a large quantity of materials); known corrosion resistance; and thermal stability. Current thinking and data from recent materials studies and surveys (Refs. 8-1 through 8-4) were used to assess the relative merit of candidate materials for the different high-temperature components. Table 8-2 identifies by component the alloys selected and the attractive alternates which may become preferred candidates following future high-temperature materials studies. Also included are the development and R&D materials which may offer substantially higher strength, stability, and corrosion resistance as compared with those currently commercially available.

A major factor contributing to the selection of alloys Inconel 617, HK-40, and Incoloy 800 H for most of the high-temperature >1033 K (>1400°F) components was the availability of data on creep rate (secondary range) and creep rupture. Sufficient data existed to accomplish reasonable long-term extrapolations and to develop rate equations for use in stress analysis and

TABLE 8-2
SELECTED ALLOYS AND ALTERNATES FOR SYSTEM COMPONENTS TO OPERATE
AT VERY HIGH TEMPERATURES [$>1033\text{ K}$ ($>1400^\circ\text{F}$)]

Component	System Design		Candidate Alloys (In Order of Consideration)	Attractive New or Development Alloys
	With IHX	Without IHX		
Primary Duct				
Seal sheet		X	Inconel 617 HD 556 Hastelloy X Hastelloy S	
Cover plate, fasteners, and washers		X	IN 713C IN 100 Inconel 617	MA 754 MA 956 HD 8077
Insulator liner	X		Carbon-carbon composite Mo-TZM	MA 754 MA 956 HD 8077
Connecting brackets	X		IN 713C IN 100 Inconel 617 HD 556	WAZ 16
IHX				
Module tubes and lower lead tubes	X		Inconel 617 Hastelloy S HD 556	
Headers (lower)	X		Inconel 617 Hastelloy S HD 556	
Tube supports	X		Inconel 617 HD 556	

TABLE 8-2 (Continued)

Component	System Design		Candidate Alloys (In Order of Consideration)	Attractive New or Development Alloys
	With IHX	Without IHX		
IHX (Continued)				
Deflector	X		Carbon-carbon composite Mo-TZM IN 100	MA 754 MA 956
Common return tube	X		Inconel 617 HK-40 Manaurite 900 HD 556	
PHX (reformer)				
Catalyst (reformer) tubes	X	X	HK-40 Inconel 617 Incoloy 800H Manaurite 36X IN 519 Mo - Re 1 Supertherm Incoloy 802	
Pigtails	X	X	Inconel 617 Hastelloy S HD 556	
Common return tube	X	X	Inconel 617 HK-40 Manaurite 900 Incoloy 800H Incoloy 802 IN 519 HD 556	

TABLE 8-2 (Continued)

Component	System Design		Candidate Alloys (In Order of Consideration)	Attractive New or Development Alloys
	With IHX	Without IHX		
PHX (Continued) Shroud	X	X	Inconel 617 HD 556 Incoloy 800H Incoloy 802	

sizing of pressurized components. Many high-temperature alloys are characterized only by creep rupture data and a limited amount of creep strength data. This is insufficient for even the preliminary stress analysis or good material trade-off studies.

Table 8-3 presents a status survey of selected and considered alloys. Table 8-4 lists the nominal chemical composition for these alloys. Final selection of specific alloys for reactor components will of course depend on results from the forthcoming ERDA Advanced Gas Cooled Nuclear Reactor Materials Program along with other factors such as materials cost, fabricability, and alloy availability.

For thick-wall ($>3/8$ in.) components such as the reformer tubes and larger-diameter return ducts, alloys in both wrought (hot extruded) and centrifugally cast product forms are contenders. For reformer tubes, cost will always be a factor influencing selection because of the large quantity of tubing required. However, since component integrity is indeed an essential requirement, product soundness and property uniformity and retention are key factors. Selection of a centrifugally cast tube product form and HK-40 as the baseline reformer tube alloy was based on the fulfillment of design operating requirements for the reformer component; specifically high temperature creep strength retention, the inherent soundness of centrifugally cast tubes of this size, a good performance record in properly operated conventional reformers, a microstructure having large and stable grains, good fabricability and weldability, good concentricity and low ovality, and a relatively low cost per pound. In comparison with the wrought alloys Incoloy 800 or Inconel 617, the retention of adequate room temperature ductility and toughness after thermal aging remains as an important question: each of the alloys is known to experience a decrease in these properties with thermal aging, but the absolute values for centrifugally cast alloys may be borderline or insufficient. Only further design definition and testing will answer this issue.

A brief overview by alloy category is presented of the characteristics which made the alloys attractive candidates for the reactor components listed in Table 8-3. Included is discussion of pertinent differences or similarities of the alloys.

TABLE 8-3
STATUS OF THE SELECTED AND ALTERNATE CANDIDATE ALLOYS PERTINENT
TO HIGH-TEMPERATURE [$>1033\text{ K}$ ($>1400^\circ\text{F}$)] COMPONENTS

Alloy	Alloy Category	System Design		Pertinent Product Forms	Current Status of Alloy Development
		With IHX	Without IHX		
Hastelloy S	Wrought, solid-solution-strengthened, Ni-base alloys ↓	X	X	Tubing, sheet, plate; extrusions, forgings	Commercial
Hastelloy X		X	X		Commercial
HD 556		X	X		Developmental
Inconel 617		X	X		Commercial
Incoloy 800H		X	--		
Incoloy 802		X	--		
RA 333	Wrought, solid-solution-strengthened, Ni-base alloys ↓	X	X	Tubing, sheet, plate; extrusions, forgings	
Molybdenum TZM		X	X	Sheet, plate; forgings, extrusions	Commercial
HD 8077	Oxide-dispersion-strengthened alloys	X	X		Developmental
MA 754	Oxide-dispersion-strengthened alloys	X	X		Not available, R&D
MA 956	Oxide-dispersion-strengthened alloys	X	X	Sheet, plate; extrusions, forgings	Not available, R&D
IN 100	Shell, vacuum cast, solid-solution-strengthened, Ni-base alloys ↓	X	X	Shell castings	Commercial
IN 713C		X	X	Shell castings	
WAZ 16		X	X	Shell castings	
HK 40		X	--	Thick-wall tubes	
IN 519	Centrifugally (or static) air cast alloys ↓	X	--	Thick-wall tubes; static castings	
Manaurite 900		X	--	Thick-wall tubes; static castings	
Manaurite 36X		X	--	Thick-wall tubes	
Mo - Re 1		X	--	Thick-wall tubes	
Supertherm	Centrifugally (or static) air cast alloys	X	--	Thick-wall tubes	
Ni-RESIST	Sand cast alloy	X	--	Static castings	Commercial

TABLE 8-4
NOMINAL COMPOSITION OF ALLOYS

Alloy	Element (wt%)															Other Intentional Additions	Applicable Specifications or Alloy Developer
	C	Ni	Fe	Cr	Mn	Si	Mo	Co	W	Nb	Ta	Al	Ti	S	Zr		
Hastelloy S	0.02	67	1.0	15	0.5	0.4	15	--	--	--	--	0.2	--	0.009	--	0.02 La	Cabot Corp.
Hastelloy X	0.08	45	19	21	0.3	0.3	9.0	2.0	0.6	--	--	--	--	0.004	--	0.02 La	AMS 5754
HD 556	0.10	20	47	22	1.5	0.4	3.0	20.0	2.5	0.1	0.9	0.3	--	--	0.02	0.02 La; 0.2 N	Cabot Corp.
HD 8077	0.05	80	1.0	16	--	--	--	--	--	--	--	4.0	--	--	--	1.3 Y ₂ O ₃	NASA (Cabot Corp.)
Inconel 617	0.07	54	0.1	22	0.02	0.08	9.0	12	--	--	--	1.0	--	--	--	--	Huntington Alloys
Incoloy 800H	0.08	32	46	20	1.0	0.3	--	--	--	--	--	0.4	0.4	--	--	--	ASME SB408
Incoloy 802	0.35	32	46	21	1.0	0.5	--	--	--	--	--	0.6	0.6	--	--	--	Huntington Alloys
MA 754	0.06	77	1.5	20	--	--	--	--	--	--	--	0.4	0.4	--	--	0.7 Y ₂ O ₃	Huntington Alloys
MA 956	--	--	74	20	--	--	--	--	--	--	--	5.0	--	--	--	1.0 Y ₂ O ₃	Huntington Alloys
Molybdenum TZM	0.02	--	--	--	--	--	99.3	--	--	--	--	--	0.5	--	0.09	--	AMS 7817, ASTM-B384
RA 333	0.05	45	18	25	1.5	1.3	3.0	3.0	3.0	--	--	--	--	--	--	0.3 N	AMS 5593 and 5717
HK 40	0.35	20	50	26	1.5	1.5	0.3	--	--	--	--	--	--	--	--	--	ASTM - A297
IN 100	0.18	60	0.1	10	--	--	3.0	15	--	--	--	5.5	4.7	0.013	0.08	1.0 Va	AMS 5397
IN 519	0.30	24	48	24	0.75	1.0	--	--	--	1.5	--	--	--	--	--	--	PWA 658N International Nickel Corp.
IN 713C	0.12	74	--	12.5	--	--	4.2	--	--	2.0	--	6.1	0.8	0.013	0.10	--	PWA 655F
Manaurite 36X	0.40	34	36	25	1.5	1.5	--	--	--	1.5	--	--	--	--	--	--	Acieries du Manoir Pompey Corp.
Manaurite 900	0.15	32	43	21	1.5	1.0	0.3	--	--	1.5	--	--	--	--	--	--	Acieries du Manoir Pompey Corp.
Mo - Re 1	0.45	35	34	25	1.5	1.5	--	--	2.0	--	--	--	--	--	--	--	Blaw-Knox Corp.
Supertherm	0.50	35	17	26	0.5	1.6	--	15	5	--	--	--	--	--	--	--	Abex Corp.
WAZ 16	0.18	72	--	--	--	--	2.0	--	16	2.0	--	7.0	--	--	0.5	--	NASA patent

8.2.1.1. Wrought, Solid-Solution-Strengthened Alloys. This group of alloys will play an important role in the development of VHTRs. Sheet and tubing product forms capable of being formed and welded represent an important feature of this alloy group. The alloys generally have adequate strength and creep resistance for use at 1033 to 1366 K (1400° to 2000°F), the temperature range of interest. Although microstructural changes with time (i.e., instability) do occur, acceptable ductility is usually retained, which is important in component applications experiencing rapid changes in temperature and pressure.

High-temperature strength and creep resistance in these austenitic alloys are principally established through additions of Cr, Co, Mo, and W to the matrix. Incoloy 800H, Hastelloy X, and RA333 have experienced many years of high-temperature application as components in jet engines and petrochemical processing plants and as pressure vessels and heat exchangers. Considerable data exist for defining strength, creep, ductility, and fatigue behavior. Incoloy 800H and Hastelloy X are component materials in the GA helium-cooled demonstration reactors (Ref. 8-5). However, Hastelloy X has carburized and experienced accelerated creep rate in recent GT-HTGR helium tests at 1172 K (1650°F), and thus its use in a VHTR environment (Ref. 8-6) is in question. This behavior is apparently unique to the temperature and carburizing environment of the GT-HTGR and VHTR. Hastelloy S, Inconel 617, and Haynes development alloy 556 (HD556) are relatively new and demonstrate improvements in high-temperature strength, creep resistance, creep rupture strength, and thermal fatigue resistance over the formerly mentioned alloys. An improvement in the retention of strength and ductility after extended aging under stress is also anticipated in the newer alloys.

8.2.1.2. Oxide-Dispersion-Strengthened Alloys. Oxide dispersion strengthening of Ni-base or iron-base alloys has become a viable approach for manufacturing alloys which have a substantial increase in creep strength with good oxidation resistance at temperatures in the range of 1227 K (1750°F) and above for long-time exposure. Characteristic of oxide-

dispersion-strengthened (ODS) alloys is the stability of the strengthening response at high temperatures, even at temperatures approaching the melting point of the matrix.

The creep strength of the ODS alloys is derived from the presence of a uniform dispersion of fine (typical diameter = 100 to 300 Å) oxide particles. The four selected ODS alloys use yttria (Y_2O_3), which is very stable at the temperatures of interest, as the strengthening dispersoids. The dispersoid functions in two ways: first, it acts as a barrier to the deformation of individual grains; second, it makes the material amenable to the use of controlled thermomechanical processing so that the size, shape, and crystallographic orientation of the grains can be optimized.

The alloys are made by carefully controlled thermomechanical working of a pressed-powder billet. Although most R&D studies are directed toward extruded forms, and early commercial products were extruded forms, there have been efforts to produce sheet. In fact, Haynes development alloy 8077 has been made into sheet 1067 x 1067 x 1.27 mm (42 x 42 x 0.05 in.) thick.

The ODS materials are considered to be commercially available, but use of these alloys in quantity in VHTRs will require a substantial increase in production capability. With such an increase, the current high cost of these alloys would be anticipated to decrease. Also, the capability for fabrication and welding of ODS alloys is a problem area that would have to be solved. Braze and diffusion-bonded joints with some of these alloys have been made. It has been reported that spot-welded and diffusion-bonded joints can have strengths comparable to the strength of the base material.

MA754, MA755E, and HD8077 are Ni-base alloys, but MA956 is iron-base alloy, a factor which will hopefully facilitate a good assessment of the comparative potential for corrosion resistance in simulated reactor helium at the high test temperatures 1255 and 1366 K (1800° and 2000°F). The Ni-base ODS alloys must be canned and hot rolled while MA956 can be cold rolled, an attribute which should greatly reduce the cost of iron-base ODS alloys.

8.2.1.3. Centrifugally Cast Alloys. These alloys play an important role as tubing for catalyst reformers and pyrolysis crackers in the petrochemical industry and as reformers in the direct iron ore reduction process. Inherent to the practicality of the centrifugal casting process is the development of thick-walled tubular products that are intrinsically sound, i.e., free from solidification shrinkage, frequent porosity defects, and entrapment of foreign particles or cracks often assumed to be typical in static air castings. These alloys are weldable and very competitive costwise with wrought product forms; thus, they definitely constitute an interesting family of alloys in the future materials study.

Centrifugally cast alloys achieve good creep strength for long-time exposure at high temperatures by virtue of their relatively high carbon content (typically 0.3 to 0.5 wt %) and large as-cast grain size. Because of their high carbon content, appreciable carbide agglomeration and precipitation occur with time, so a substantial decrease in ductility and toughness will be anticipated. The fact that current industrial reformer designs can operate satisfactorily with low toughness and ductility is of practical significance. This fact offers an incentive to continue considering the cast alloys in material and component designs for VHTR process heat concepts.

The alloys listed in Table 8-3 represent a spread of the three methods currently used to strengthen centrifugally cast austenitic alloys for applications in which creep is the controlling mode of deformation. First, all the alloys are cast to obtain large grain size. Second, appreciable carbon is added to obtain a scattered phase of eutectic chromium carbides and secondary carbides of chromium, iron, and manganese. The strengths of alloys HK-40, Manaurite 36X, IN519, and Manaurite 900 rely substantially on this mechanism. Third, alloys such as Supertherm and Mo-Re 1 attain higher temperature applicability and creep strength through the additional use of solid-solution-strengthening elements. All the alloys are iron based, and chromium and nickel are common matrix strengtheners. However, tungsten is added to the latter two alloys. Supertherm also contains cobalt.

By adding niobium to IN519, Manaurite 900, and Manaurite 36X, an increase in creep resistance is obtained through the precipitation of finely scattered primary niobium carbides. The alloys IN519 and Manaurite 900 have relatively low carbon, which gives them excellent thermal shock resistance and improved ductility retention following long-time exposure. Some strength and creep resistance are sacrificed by the carbon reduction. The latter two alloys have been successfully used in nontubular forms made by static casting and are thus competitive with forgings for components like subheaders.

All the alloys can be centrifugally cast to diameters approaching 1.52 m (5 ft), which qualifies them as candidates for large outlet manifolds in the PHX or the IHX. All the alloys can be lathe turned and bored to desired configurations.

8.2.1.4. Vacuum-Cast Ni-Base Superalloys. The Ni-base superalloys of interest are generally vacuum cast in shell molds. These alloys are contenders for components like the ducting cover plates and fasteners and are currently used in gas turbine aircraft engines and land-based turbines. As candidates for the proposed program, these alloys demonstrate a broad range of alloy chemistry, strength, and creep resistance. The candidates were chosen from a file of at least 30 alloys. IN713C has moderate strength properties at high temperature compared with IN100, but it has a history of good casting capability, low contraction of volume during solidification, and good product reliability. IN100 is exhibiting the least amount of weight change of all the Ni-base alloys under test at 1172 K (1650°F) in helium in the current direct cycle materials program. In addition, no effect on creep behavior has been observed.

A relatively new alloy, WAZ-16, is a candidate for connecting brackets; it offers good strength and stability at temperatures above 1366 K (2000°F) and does not rely heavily on gamma prime strengthening as do most of the cast superalloys.

These alloys achieve high-temperature strength and creep resistance through precipitation and/or solid solution strengthening. The additions of chromium, aluminum, and titanium are principally for high-temperature corrosion resistance. Cast superalloys are very difficult to machine and do not offer good weldability. Applications will therefore be limited to shapes that can be cast to size and mechanically attached.

8.2.1.5. Refractory Alloys. As reported in Ref. 8-4, molybdenum alloy TZM is the sole candidate refractory alloy. The anticipated high temperatures and long exposure times contemplated for VHTR and DCHT (Direct Cycle High Temperature) applications should enable this alloy to be used in sheet, tube, or forged product forms that have been warm worked and stress relieved, which is the condition for which TZM offers optimum ductility and toughness. In contrast to pure molybdenum, recrystallization of cold-worked and stress-relieved TZM should be suppressible at temperatures up to 1900°F for long-term application of 300,000 hr. The ductile-brittle transition temperature would also be well below room temperature, a factor which is important during component fabrication and installation. The foremost attraction of TZM, however, is its high creep strength properties, even at 1366 K (2000°F). While rapid surface oxidation should not be a problem for molybdenum alloys in the VHTR or DCHT environments, an ongoing GA program (Ref. 8-6), indicates that there is a definite concern over the possible inward diffusion of interstitial impurities such as carbon and a resulting reduction of the alloy's ductility and toughness at room temperature. Low notch-toughness was reported in post-creep test, tensile-pull tests on TZM at Brown-Boveri (Ref. 8-7).

When successfully welded, Mo-TZM offers a weld joint that has a ductile-brittle transition temperature close to room temperature. Mechanical joints are therefore generally recommended for structural applications of Mo-TZM. The refractory metal niobium and its alloys were not seriously considered because they become severely embrittled by even low concentrations of hydrogen, oxygen, or carbon.

8.2.2. Review of High-Temperature Behavior of Candidate Alloys

8.2.2.1. Alloy Classification and Rating. Table 8-5 assists in classifying the reviewed and selected alloys for system components and reviews mechanical properties. This table represents a preliminary classification of the alloys (based on air data and extrapolations) in relation to three important parameters which are useful in establishing the suitability of alloys for component design requirements. The first is short-time tensile strength, which is often a key design property during a transient encounter such as depressurization on one side of a component. The second is creep rupture strength. For long time periods, these estimates could require eventual adjustment because they are mainly based on shorter-time air data. Microstructural thermal stability (the third factor) estimates were included to suggest that nearly all the alloys will experience changes in microstructure at operating temperatures. New phases will form, and these new phases and the primary second phases are anticipated to undergo changes in total volume, distribution, and particle morphology. Of key importance, however, will be the effect of these changes on material properties, in particular, strength and ductility.

A number of observations can be made by looking at the strength columns in Table 8-5. First, there is a tendency for the alloys within an alloy category to exhibit a similar trend of change with temperature. This is true even though the strength values of the alloys may be substantially different. No attempt is currently being made to quantitatively compare each alloy within an alloy category. Second, for all alloys except Mo-TZM and the ODS alloys, extrapolations to long times suggest that the creep rupture strength values at 1144 K (1600°F) or higher will be below 20.7 MPa (3 ksi); above 1256 K (1800°F), values will be below 9 MPa (1.3 ksi), with many reaching only a few hundred psi. The ODS alloys may show higher rupture strengths, but test data to date have been for relatively short test periods.

8.2.2.2. Key Data From Past and Current Tests on Alloys in High-Temperature [≥ 1033 K ($\geq 1400^\circ\text{F}$)] Helium. For the candidate alloys under consideration for the two system designs, Table 8-6 presents a summary of results from past and current materials tests in high-temperature helium.

TABLE 8-5
ALLOY RATINGS FOR ASSESSMENT OF ALLOY APPLICABILITY TO HIGH-TEMPERATURE, LONG-DURATION DESIGNS
(BASED ON AIR DATA EXTRAPOLATIONS)

Alloy	Key Material Properties						
	Short-Time Tensile Strength ⁽ⁱ⁾ (Average)			Creep-Rupture Strength ⁽ⁱⁱ⁾ (Average)			Microstructural (Thermal) Stability ⁽ⁱⁱⁱ⁾
	1033 to 1144K (1400° to 1600°F)	1144 to 1256K (1600° to 1800°F)	1256 to 1367K (1800° to 2000°F)	1033 to 1144K (1400° to 1600°F)	1144 to 1256K (1600° to 1800°F)	1256 to 1367K (1800° to 2000°F)	1033 to 1367K (1400° to 2000°F)
Hastelloy S	2	2	3	C	D	D	c
Hastelloy X	2	3	3	C	D	D	c
HD 556	3	3	3	C	D	D	c
Inconel 617	2	3	3	B	C	D	b
Incoloy 800H	3	3	3	C	D	D	b
Incoloy 802	3	3	3	C	D	D	b
RA 333	2	3	3	C	D	D	c
Molybdenum TZM ^(iv)	1	1	1				
	2	2	2	A	A	A	a
IN 100	1	1	2	B	C	D	c
IN 713C	1	1	2	B	C	D	c
M 21LC	1	1	2	B	C	D	c
WAZ 16	1	1	2	B	C	D	c
HK 40	3	3	3	C	D	D	c
IN 519	3	3	4	B	C	D	c
Manaurite 900	3	3	4	C	C	C	c
Manaurite 36X	2	3	3	B	C	D	c
Mo-Re 1	2	3	3	B	C	D	c
Ni-RESIST	3	--	--	D	--	--	c
Supertherm	2	3	3	B	C+	D+	c
HD 8077	2	3	3	A	B	B	c
MA 754	2	3	3	A	B	B	b
MA 956	2	3	3	A	B	B	c

- (i) Estimated corridor: (1) 1035 to 414 MPa (150 to 60 ksi); (2) 414 to 241 MPa (60 to 35 ksi); (3) 241 to 55.1 MPa (35 to 8 ksi);
 (4) 55.1 to 20.7 MPa (8 to 3 ksi).
 (ii) Estimated corridor for time period within 10^5 to 3.5×10^5 hr: (A) 241 to 82.8 MPa (35 to 12 ksi); (B) 82.8 to 20.7 MPa (12 to 3 ksi);
 (C) 20.7 to 9.0 MPa (3 to 1.3 ksi); (D) 9.0 to 1.38 kPa (1.3 to 0.2 ksi).
 (iii) Estimated: (a) no phase precipitation after high-temperature exposure; (b) only one minor phase precipitates after high-temperature exposure (i.e., carbides); (c) two or more phases precipitate.
 (iv) (1) for worked and stress-relieved material and (2) for recrystallized material.

TABLE 8-6
SUMMARY OF RESULTS OF HIGH-TEMPERATURE HELIUM TESTS
ON CANDIDATE ALLOYS TO DATE(a)

Alloy (b) and Data Source	Thermal Aging Conditions				Environmental Effects			Location of Test Facility	Average Impurity Levels in Helium (u atm)			
	Temp [K (°F)]	Time (hr)	Applied Stress [MPa (psi)]	Measured Creep Strain (%)	Depth (c) [mm (in.)]	Oxidation	Carburization (d)		H ₂	H ₂ O	CO	CH ₄
Hastelloy S												
Ref. 8-1	1033 (1400)	10,000	0	0	0.015 (0.0006)	Yes	No	GA	200	0.5	10	20
Ref. 8-1	1144 (1600)	10,000	0	0	0.0305 (0.0012)	Yes	No	GA	200	0.5	10	20
Ref. 8-8	1073 (1472)	3,000	62.8 (9,100)	16	NE(e)	--	--	CIIR, Oslo, Norway	500	1.0	50	50
Ref. 8-8	1123 (1562)	1,560	51.8 (7,500)	39 (rupture)	NE	--	--		500	1.0	50	50
Ref. 8-8	1173 (1652)	945	26.2 (3,800)	17	NE	--	--		500	1.0	50	50
Hastelloy X												
Ref. 8-3	1023 (1382)	5,000	33.0 (4,785)	0.18	0.013 (0.005)	Yes	No		75	1.8	38	5
	1023 (1382)	10,000	33.0 (4,785)	0.23	NE	--	--					
	1023 (1382)	15,000	55.0 (7,976)	0.46	NE	--	--					
	1023 (1382)	15,000	55.0 (7,976)	2.27	NE	--	--					
Ref. 8-3	1073 (1472)	3,000	0	0	0.020 (0.0008)	Yes	No		75	1.8	38	5
Ref. 8-6	1073 (1472)	3,000	0	0	0.022 (0.0009)	Yes	Yes		500	1.0	50	50
	1073 (1472)	3,000	31.0 (4,495)	0.00	NE	--	--					
	1073 (1472)	3,000	31.0 (4,495)	0.14	NE	--	--					
	1173 (1652)	2,760	13.0 (1,885)	5.02 (rupture)	0.038 (0.0015)	Yes	Yes					
	1173 (1652)	3,300	13.0 (1,885)	~5 (rupture)	NE	--	--					
Ref. 8-6	1173 (1652)	3,000	0	0	0.041 (0.0016)	Yes	Yes	CIIR, Oslo, Norway	500	1.0	50	50
Ref. 8-1	1033 (1400)	5,000	0	0	0.0025 (0.0001)	Yes	No	GA	200	0.5	10	20
	1033 (1400)	10,000	0	0	0.015 (0.0006)	Yes	No	GA				
	1144 (1600)	5,000	0	0	0.046 (0.0018)	Yes	No	GA				
Ref. 8-1	1144 (1600)	10,000	0	0	0.046 (0.0018)	Yes	No	GA	200	0.5	10	20
IN 100												
Ref. 8-9	1073 (1472)	1,000	0	0	ND (f)	ND	Yes	GA	500	0.5	50	50
Ref. 8-6	1073 (1472)	3,000	0	0	0.010 (0.0004)	No	ND	CIIR, Oslo, Norway	500	1.0	50	50
	1073 (1472)		125 (18,127)	0.06	NE	--	--					
	1073 (1472)		125 (18,127)	0.21	NE	--	--					
	1173 (1652)		69 (10,006)	0.00	NE	--	--					
	1173 (1652)		69 (10,006)	0.16	NE	--	--					
Ref. 8-6	1173 (1652)	3,000	0	0	0.025 (0.0010)	No	ND	CIIR, Oslo, Norway	500	1.0	50	50

TABLE 8-6 (Continued)

Alloy (b) and Data Source	Thermal Aging Conditions				Environmental Effects			Location of Test Facility	Average Impurity Levels in Helium (u atm)			
	Temp [K (°F)]	Time (hr)	Applied Stress [MPa (psi)]	Measured Creep Strain (%)	Depth (c) [mm (in.)]	Oxidation	Carburization (d)		H ₂	H ₂ O	CO	CH ₄
Incoloy 800												
Ref. 8-1	1033 (1400)	5,000	0	0	0.025 (0.0010)	Yes	No	GA	200	0.5	10	20
	1033 (1400)	10,000	0	0	0.031 (0.0012)	Yes	No					
	1144 (1600)	5,000	0	0	0.046 (0.0018)	Yes	No					
Ref. 8-1	1144 (1600)	10,000	0	0	0.048 (0.0019)	Yes	No	GA	200	0.5	10	20
Ref. 8-3	1023 (1382)	460	34.6 (5,017)	1.0	NE	--	--	CIIR, Oslo, Norway	75	1.8	38	5
	1023 (1382)	5,000	34.6 (5,017)	1.25	0.031 (0.0012)	Yes	Yes-2.54 mm (0.1 in.) depth					
	1073 (1472)	130	31.0 (4,500)	1.0	NE	--	--					
Ref. 8-3	1073 (1472)	5,000	31.0 (4,500)	2.29	0.051 (0.0020)	Yes	Yes-1.27 mm (0.05 in.) depth					
Ref. 8-10	1023 (1382)	5,000	40.0 (5,800)	0.13	0.038 (0.0015)	Yes	No					
	1073 (1472)	6,000	26.0 (3,770)	0.89	NE	--	--					
	1073 (1472)	2,000	0	0	0.020 (0.0008)	Yes	No					
	1023 (1382)	7,000	33.0 (4,785)	0.40	0.071 (0.0028)	Yes	No					
Ref. 8-10	1073 (1472)	6,000	26.0 (3,770)	3.3	0.066 (0.0026)	Yes	No		75	1.8	38	5
Ref. 8-11	1123 (1562)	2,800	0	0	0.035 (0.0014)	Yes	No		400	90	400	0
Ref. 8-11	1023 (1382)	5,000	0	0	0.013 (0.0005)	Yes	No		100	20	100	0
Ref. 8-11	1123 (1562)	5,000	0	0	0.035 (0.0014)	Yes	No		100	20	100	0
Incoloy 802												
Ref. 8-8	1123 (1562)	1,310	52.0 (7,541)	8.4 (rupture)	NE	--	--		500	1.0	50	50
Ref. 8-8	1123 (1562)	1,560	52.0 (7,541)	7.5 (rupture)	NE	--	--	CIIR, Oslo, Norway	500	1.0	50	50

TABLE 8-6 (Continued)

Alloy (b) and Data Source	Thermal Aging Conditions				Environmental Effects			Location of Test Facility	Average Impurity Levels in Helium (μ atm)			
	Temp [K (°F)]	Time (hr)	Applied Stress [MPa (psi)]	Measured Creep Strain (%)	Depth (c) [mm (in.)]	Oxidation	Carburization (d)		H ₂	H ₂ O	CO	CH ₄
IN 519												
Ref. 8-6	1073 (1472)	3,000	0	0	0.010 (0.0004)	Yes	No	CIIR, Oslo, Norway	500	1.0	50	50
	1073 (1472)		32.0 (4,640)	0.12	NE	--	--					
	1073 (1472)		32.0 (4,640)	0.14	NE	--	--					
	1173 (1652)		13.0 (1,885)	1.20	NE	--	--					
	1173 (1652)		13.0 (1,885)	1.36	NE	--	--					
Ref. 8-6	1173 (1652)		0	0	0.025 (0.0010)	Yes	Yes					
IN 713C												
Ref. 8-6	1073 (1472)		0	0	0.022 (0.0009)	Yes	ND					
	1073 (1472)		124 (17,982)	0.00	NE	--	--					
	1073 (1472)		124 (17,982)	0.0	NE	--	--					
	1173 (1652)		69 (10,006)	0.11	NE	--	--					
	1173 (1652)		69 (10,006)	0.32	NE	--	--					
Ref. 8-6	1173 (1652)	3,000	0	0	0.028 (0.0011)	Yes	ND					
Ref. 8-8	1073 (1472)	6,000	199 (28,860)	0.35	NE	--	--					
Ref. 8-8	1073 (1472)	6,000	176 (25,520)	0.31	NE	--	--	CIIR, Oslo, Norway	500	1.0	50	50

TABLE 8-6 (Continued)

Alloy (b) and Data Source	Thermal Aging Conditions				Environmental Effects			Location of Test Facility	Average Impurity Levels in Helium (μ atm)			
	Temp [K (°F)]	Time (hr)	Applied Stress [MPa (psi)]	Measured Creep Strain (%)	Depth (c) [mm (in.)]	Oxidation	Carburization (d)		H ₂	H ₂ O	CO	CH ₄
Inconel 617												
Ref. 8-1	1033 (1400)	10,000	0	0	0.071 (0.0028)	Yes	No	GA	200	<1	10	20
Ref. 8-1	1144 (1600)	10,000	0	0	0.076 (0.0030)	Yes	No	GA	200	<1	10	20
Ref. 8-6	1073 (1472)	3,000	0	0	0.020 (0.0008)	Yes	Yes	CIIR, Oslo, Norway	500	1.0	50	50
	1073 (1472)		31.0 (4,495)	0.00	NE	--	--					
	1073 (1472)		31.0 (4,495)	0.14	NE	--	--					
	1173 (1652)		13.0 (1,885)	0.07	NE	--	--					
	1173 (1652)		13.0 (1,885)	0.19	NE	--	--					
Ref. 8-6	1173 (1652)	3,000	0	0	0.033 (0.0013)	Yes	Yes					
Ref. 8-8	1123 (1562)	6,000	37.0 (5,365)	0.52	NE	--	--					
Ref. 8-8	1123 (1562)	6,000	37.0 (5,365)	0.66	NE	--	--	CIIR, Oslo, Norway	500	1.0	50	50
Molybdenum-TZM												
Ref. 8-7	1173 (1652)	8,000	297 (43,000)	0.2	NE	Light grayish surface	ND	Brown Boveri & Cie; Mannheim, Germany	Static bottled He; <25 ppm impurities including <1 ppm O ₂ ; no controlled impurity additions			
	1173 (1652)	70,000	297 (43,000)	0.8								
	1173 (1652)	80	393 (57,000)	1.0								
	1173 (1652)	10,000	393 (57,000)	34 (rupture)								
	1273 (1832)	6,500	345 (50,000)	36 (rupture)								
	1273 (1832)	10,000	276 (40,000)	1.0					Static bottled He; <25 ppm impurities including <1 ppm O ₂ ; no controlled impurity additions			
Ref. 8-7	1273 (1832)	65,000	276 (40,000)	No failure	NE	Light grayish surface	ND	Brown Boveri & Cie; Mannheim, Germany				
Ref. 8-12	1200 (1700)	1,700	13.8 (2,000)	ND	0.038 (0.0015)	No	Yes Bulk C content changed from 0.01 to 0.15 wt % in 500 hr	GA	Flowing He (99.995% pure); specimen in contact with graphite at 2000 psi contact pressure; outgassing of H ₂ , CO, and CO ₂ impurities detected			

(a) Candidate alloys from Table 8-2.

(b) For Table 8-2 alloys not listed in this table, data do not exist or are not available.

(c) Depth values can include surface scale, subscale oxidation, and zone of depleted second phases. Values are typical and were obtained from reported data or measurements taken on reported photomicrographs.

(d) Internal carburization not limited to zone indicated by "Depth" column.

(e) NE = not examined.

(f) ND = not determined.

Table 8-6 also summarizes the status of available creep data in helium. In general, the environmental effects were determined by review of the microstructure (actual specimens or reported photomicrographs) of a cross-sectioned specimen. It is not the intention of Table 8-6 to delineate precisely the different phenomena observed, but rather to indicate the apparent depth to which scale formation, subscale oxidation, or second-phase depletion had occurred. A preliminary interpretation of the material within the reported depth should be that it is of lower strength than the bulk material. Another objective of the table was to indicate whether surface or subsurface activity appeared to be due to oxidation or carburization or both. Recent data obtained in the Direct Cycle Materials Program (Ref. 8-6) on alloys indicate that carburization is occurring in addition to some oxidation in DCHT* helium [50 Pa H₂, 5 Pa CO, 5 Pa CH₄, 0.1 Pa H₂ (500 μ atm H₂, 50 μ atm CO, 50 μ atm CH₄, $\sim$ 1 μ atm H₂)] at 1173 to 1273 K (1473° to 1650°F); thus, it is a matter of concern in VHTR and DCHT environments. A case in point is the creep rupture of two Hastelloy X specimens, stressed at 12.4 MPa (1.8 ksi) after approximately 3000 hr at 1172 K (1650°F). Based on predictions using air data for a Hastelloy X bar, material at this stress level should have resisted failure for between 100,000 and 200,000 hr. Post-test metallurgical analyses revealed that substantial carburization had occurred and was predominantly manifested in the form of large molybdenum-rich carbide particles. Figure 8-1 presents a comparison of microstructure near and at the surface of Hastelloy X before and subsequent to aging in the simulated DCHT environment. Evidence of carburization was observed even at the center of the 6.35-mm (0.25-in.) diameter creep specimens. Further evidence depicting carburization in Hastelloy X and in Inconel 617 is shown in Figs. 8-2 and 8-3. The forementioned figures and other associated data was reported in Refs. 8-6 and 8-9, and further analysis is currently in progress at General Atomic in the Direct Cycle Materials Program. As seen from Table 8-6, a review of the alloys which were tested in different helium environments but at similar temperatures and their results definitely demonstrates the important role that the impurity environment will play in assessing and predicting material behavior.

*Direct-Cycle Helium Turbine

MT1855

Oxalic Etch

1000 X

Unaged specimen showing as machined surface and primary carbides

MT1895

Oxalic Etch

1000 X

Specimen aged 3000 hr in 1473°F impure helium showing ~ 0.0003 in. duplex oxide layer, ~ 0.0013 chromium depletion depth, and carburization

Fig. 8-1. Photomicrographs of etched Hastelloy X wrought alloy corrosion specimens used for measurement of surface and subsurface corrosion

MT1901

Oxalic Etch

1000 X

Fig. 8-2. Photomicrograph of center of Inconel 617 corrosion specimen aged 3000 hr in 1650°F DCHT helium showing in-depth grain boundary and intragranular carburization

MT1897

Oxalic Etch

250 X

Fig. 8-3. Photomicrograph near fracture surface of failed Hastelloy X creep-screening specimen showing intergranular failure, carburization, and creep void coalescence. Specimen failed after 2760 hr in 1650°F DCHT helium at 1.8 KSI

8.2.3. Design Values for Materials Not Covered in ASME Codes

Stress analysis of alloy components above 1089 K (1500°F) using Code Case 1592 principles is difficult because the necessary creep data for only a few alloys are available. Four alloys which are reasonably well characterized are HK-40, Inconel 617, Incoloy 800, and Hastelloy X. The data for these alloys were frequently used in the preliminary stress analyses on high-temperature components.

For cast alloy HK-40, the high-temperature creep behavior and properties for three different heats of material with a range of alloy chemistry were reviewed. The mechanical property data provided a good representation of the creep behavior of HK-40. Specimens were obtained from static castings and centrifugally cast reformer tubes.

A series of creep curves were constructed for alloy HK-40 and used to select design stresses for components subjected to deformation by creep. Figures 8-4 and 8-5 indicate stress levels as a function of time for prevention of stress rupture (under tensile loading) and straining to 0.5% strain (assumed at this time to be for either tensile or compressive loading).

The philosophy used in constructing design curves exercises some conservatism. For the curves used in tensile loading application, 60% of the average stress rupture values were used for ASME Code, Section 3, Class I components. This was done for two reasons: (1) the limited amount of data and (2) the long-time values represent extrapolations from shorter times. For the curves used in compression loading applications, the values represent the average stress for 0.5% ϵ , rather than 1.0% ϵ (allowable code value). In this case, one-half of the permissible strain was reserved for deformation by other loading modes and to account for the extrapolations required for long-time values. Figure 8-6 presents the curves from which creep rate equations were written for 1144 K (1600°F) and 1227 K (1750°F) secondary creep behavior for use in a preliminary tube

Fig. 8-4. Preliminary design tensile stresses for alloy HK-40 (Design curves based on 60% average stress-rupture property)

Fig. 8-5. Preliminary design compressive stresses for alloy HK-40 (based on average stress for tensile creep to 0.5% strain)

Fig. 8-6. Tensile creep rate for alloy HK-40

collapse analysis. Long-time, low-stress (of interest for reformer tube designs) creep tests are presently in progress at Battelle Memorial Institute.

Using the high-temperature creep data generated on Inconel 617 by Huntington Alloys Company over the last few years, a good representation of creep behavior for the alloy was obtained. A series of design stress curves (Fig. 8-7) was prepared for use in the system design studies. These curves indicate design stress levels as a function of time for prevention of stress rupture under tensile loading. As with HK-40, the philosophy used in constructing the design curves exercises some conservatism. For the curves used in tensile loading application, 60% of the average stress rupture values were used for ASME Code, Section 3, Class I components. This was done for two reasons: (1) the limited amount of multiple heat data and (2) long-time values represent extrapolations from shorter times. A review of the data available on the creep behavior for Inconel 617 along with extrapolations to longer times showed that the design curves based on 0.6 times the average rupture strength are more conservative than a design stress philosophy based on 0.5% creep strain or onset of tertiary creep in 3.5×10^5 hr.

Creep behavior predictions were established for IN713C by using extrapolated values as listed in Table 8-7. The amount of creep resistance appears adequate for cover plate material in the ducting (core outlet) of the integrated system.

Table 8-8 lists the key material properties of the alloys used for high-temperature components. Because the property values are typical, a reduction factor was used to incorporate conservatism at this time. For the carbon-carbon composite materials, mechanical property values are very specific to processing parameters and part configuration, but they are controllable. Generally, the density and fiber amounts and orientation are varied to achieve a desired set of physical and/or mechanical properties. Table 8-9 illustrates some typical values for the two types of composites which are presently of interest. These values were used as guidelines for

Fig. 8-7. Preliminary design stress for Inconel 617 [design curves based on 60% of the average rupture strength (extrapolated values)]

TABLE 8-7
PREDICTED CREEP BEHAVIOR FOR CAST SUPERALLOY IN713C

<u>Temperature [K (°F)]</u>	<u>Stress for 0.5% Creep Strain in 2×10^5 hr [MPa (psi)] (a)</u>
1089 (1,500)	75.9 (11,000)
1144 (1,600)	55.2 (8,000)
1200 (1,700)	20.7 (3,000)

(a) Based on extrapolation of higher stress, shorter-time creep data.

TABLE 8-8
KEY MATERIAL PROPERTIES USED FOR DESIGNING HIGH-TEMPERATURE COMPONENTS

Alloy	Temperature [K (°F)]	Properties			
		Yield Strength (0.2% Offset) [MPa (Kpsi)]	Tensile Strength [MPa (Kpsi)]	Modulus of Elasticity [GPa (psi × 10 ⁶)]	Coefficient of Thermal Expansion × 10 ⁻⁶ /K (°F) 294 K (70°F) → 1144 K (1600°F)
Inconel 617	1130 (1575)	193 (28)	248 (36)	143 (20.7)	15.7 (8.7)
	1172 (1650)	186 (27)	221 (32)	134 (19.5)	
	1213 (1725)	152 (22)	172 (25)	129 (18.7)	
	1256 (1800)	96.5 (14)	131 (19)	124 (18.0)	
HK-40	1130 (1575)	141 (20.5)	186 (27.0)	88.3 (12.8)	18.0 (10.0)
	1172 (1650)	110 (16.0)	138 (20.0)	82.7 (12.0)	
IN713	1172 (1650)	448 (65)	655 (95.0)	154 (22.3)	15.5 (8.63)
	1227 (1750)	352 (51)	531 (77.0)	150 (21.7)	

TABLE 8-9
TYPICAL MATERIAL PROPERTIES FOR CARBONACEOUS FIBER-REINFORCED COMPOSITES

Material Type	Temperature (a) [K (°F)]	Density [g/cc (lb/ft ³)]	Tensile Strength(b) [MPa (psi)]	Tensile Modulus of Elasticity(b) [GPa (psi x 10 ⁶)]	Flexure Strength [MPa (psi)]	Thermal Expansion(b) [x 10 ⁻⁶ /K (°F)]	Thermal Conductivity(b) [W/m-K (Btu-ft/ft ² -hr-°F)]
Laminate, fiber-reinforced composites (matrix carbonized and CVD densified)(c)	294 (70)	1.45 (90.5)	77.6 (11,250)WP 4.27 (620)AP	15.2 (2.2)WP	103 (15,000)	2.25 (1.25)WP 4.32 (2.40)AP	0.012 (1.0)WP 0.031 (2.5)AP
Fibrous, molded composites(d)							
Carbonized	294 (70)	0.9 (56.2)	5.17 (750)	-- --	-- --	1.51 (0.84)	-- --
Carbonized and CVD densified	294 (70) 1367 (2000)	1.3 (81.2)	8.62 (1,250) 5.86 (850)	6.55 (0.95)	17.5 (2,540)	1.51 (0.84)	0.012 at 478 K (1.C at 400°F)

(a) 70°F strength data assumed to be an estimate of values at 2000°F.

(b) WP = with plies; AP = across plies.

(c) Data source: HITCO (400 series composites).

(d) Data source: HITCO (300 and 400 series Pyrolarex product).

the thermal barrier/ducting components for the system utilizing an IHX. A temperature of 1366 K (2000°F) does not cause a reduction in strength properties, but rather a slight increase. Thus, room temperature values are adequate to predict and conduct conceptual design studies for HTGR applications.

8.3. DEVELOPMENT OBJECTIVES

Long-term data are needed for further assessment of materials applicability for high-temperature components; data for material tested under applied stress but at low stresses, simulating the regime of design values, would be preferred. In parallel with material data generation should be a systematic study of corrosion and thermal stability phenomena in controlled helium impurity environments. Differentiation between primary and secondary helium coolant behavior with alloys will be required not only in the area of mechanical properties, but also for hydrogen or tritium permeation.

Table 8-10 summarizes the properties and temperatures important for candidate alloys in the current system design. Of particular need in preliminary design studies of pressurized components is a mathematical representation of the creep strain relationship to applied stress and holding time. It is with such a "law" that the stress analyst can quantitatively scrutinize component dimensions and operating conditions and thus determine conditions for optimum resistance to collapse, excessive creep strain, rupture, etc. Having a Larson-Miller equation for creep-rupture behavior is not adequate for developing even a good conceptual design. Also of interest, but more specific to detailed design configuration, are properties such as low-cycle fatigue behavior, creep-fatigue interaction, and aging effects on toughness properties, such as impact strength.

Once alloy selection for high-temperature components is firm (presumably after a detailed materials screening program), an effort should commence to develop firm design stress values and to meet ASME Code

TABLE 8-10

MECHANICAL PROPERTIES AND TEMPERATURE RANGES OF INTEREST FOR FUTURE DESIGN STUDIES
ON HIGH-TEMPERATURE COMPONENTS

Candidate Alloy	Components	Temperature Ranges of Interest [K (°F)]			
		Key Mechanical Properties			
		Creep Strength (to 1% ϵ)		Rupture Strength	Short-Time Tensile Properties Before and After Aging
		Tensile	Compressive		
Inconel 617	IHX: tubes, headers, tube supports, central return duct	811 - 1283 (1000 - 1850)		922 - 1283 (1200 - 1850)	922 - 1283 (1200 - 1850)
	PHX: pigtailed, tube supports	1033 - 1256 (1400 - 1800)		1033 - 1256 (1400 - 1800)	1033 - 1256 (1400 - 1800)
	Primary duct: seal sheet	1033 - 1283 (1400 - 1850)		--	--
IN713	Primary duct: cover plate, washers, fasteners, brackets	1033 - 1283 (1400 - 1850)		1033 - 1283 (1400 - 1850)	1033 - 1283 (1400 - 1850)
HK-40	PHX: reformer tubes, central return duct	867 - 1256 (1100 - 1800)		867 - 1256 (1100 - 1800)	867 - 1256 (1100 - 1800)

requirements. The latter requires appreciable time because multiple heat testing is necessary and a number of material suppliers must enter the program. A 5 to 6-yr period should be anticipated. Determination of properties will be required for long-term creep, low-cycle fatigue, creep-fatigue, and short-time physical strength and ductility properties.

Insulation requirements indicate the need for long-term data in areas such as resiliency retention (i.e., creep behavior) and material stability in the presence of the high-temperature coolant impurity environment. The need for lower thermal conductivity values is not the controlling parameter in the current designs.

The thermal barrier/ducting concept using carbon-carbon composite materials will require materials studies in three areas. Creep resistance must be assessed in simulated reactor helium, and an associated study on the effect of high fluence on creep behavior must also be performed. Confirmation of the stability of the carbon composite surface layer would be required in these studies. The fact that carbon composites are brittle does not in itself require a material study, but rather a design study for using brittle materials. Unique to these materials would be a program to understand, characterize, and minimize defects inherent to the material.

There are two additional areas of concern for material structural integrity which have not received adequate investigation nor design consideration. First is fission product (within the primary coolant) compatibility with materials. The second is the concern for possible corrosion effects from high-velocity [>45.7 m/sec (>150 ft/sec)], high-pressure helium. During further preliminary design studies, consideration should be given to these subjects.

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