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911175
Revision 0

ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Effect of Reactor Outlet Helium Temperature on the Need for Composites in the NGNP

Prepared by General Atomics
For the Battelle Energy Alliance, LLC

Subcontract No. 00075309
Uniform Filing Code UFC: 8201.3.1.2

GA Project 30302

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GA 1485 (REV. 08/06E)

ISSUE/RELEASE SUMMARY

	APPVL LEVEL	DISC	QA LEVEL	SYS	DOC. TYPE	PROJECT	DOCUMENT NO.	REV
☐ R & D ☐ DV&S ☒ DESIGN ☐ T&E ☐ NA	5	N	I	11	RGN	30302	911175	0

TITLE:

Effect of Reactor Outlet Helium Temperature on the Need for Composites in the NGNP

			APPROVAL(S)			
CM APPROVAL/ DATE	REV	PREPARED BY	ENGINEERING	QA	PROJECT	REVISION DESCRIPTION/ W.O. NO.
7 ISSUED JUN 11 2009	0	R. Vollman R. Vollman	A. Shenoy	K. Partain K. Part	J. Saurwein	Initial Issue W.O # A30302-0324

CONTINUE ON GA FORM 1485-1

NEXT INDENTURED DOCUMENT(S)	911125
COMPUTER PROGRAM PIN(S)	N/A

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PAGE ii OF *

EXECUTIVE SUMMARY

This report presents the results of a study that was performed to assess the effect of lower reactor outlet helium temperature on the materials needed for the reactor internals components of a 600-MWt prismatic Modular Helium Reactor (MHR), which is a candidate reactor concept for the Next Generation Nuclear Plant (NGNP). This study is a follow-on to a previous study (Ref. 1) conducted in 2008 to select candidate ceramic composite materials and to identify the R&D efforts needed to incorporate them into the hardware. In the previous study, ceramic composite materials were chosen for a 600-MWt reactor with reactor inlet helium temperatures ranging from 490°C to 590°C, and an outlet helium temperature of 950°C. In this study, the reactor inlet helium temperature was 350°C, and the reactor outlet temperature was varied from 700°C to 950°C in 50°C increments. The temperature of the relevant reactor internals components were estimated for 100% power normal operation and for pressurized conduction cool down (PCCD) and de-pressurized conduction cool down (DCCD) conditions. The conduction cool down (CCD) temperatures were estimated from previously performed analyses.

Historically, the nominal reactor outlet helium temperature in the MHR has increased from 700°C - 750°C for steam-cycle plant designs to 850°C for direct cycle gas-turbine designs (Refs. 1 and 2). The Department of Energy (DOE) has identified a very-high temperature gas-cooled reactor (VHTR) having a nominal reactor outlet helium temperature of 950°C as one of the GEN IV reactor concepts. In the MHR, with its passively safe features, some reactor system components are subject to helium temperatures substantially higher than 950°C during CCD events.

In the 2008 study with a 950°C reactor outlet helium temperature, ceramic composite materials were identified that meet the design requirements; and the R&D program needed to verify their use was described. The 2008 study also included a cursory evaluation of the need for composites as a function of reactor outlet helium temperature. The results of the evaluation showed that high-temperature metals can be used rather than ceramic composites for several components if the reactor outlet helium temperature is reduced. If readily available metallic materials are used, then the R&D program needed to qualify the materials of construction can be reduced in scope, size, and cost.

In this follow-on study, the reactor outlet helium temperature was varied from 700°C to 950°C, in 50°C increments, with emphasis given to the range from 750°C to 800°C, the conditions for a steam cycle plant. In all cases, the reactor inlet helium temperature was maintained at 350°C. The reactor inlet helium temperature of 350°C was chosen to remove the need for direct cooling of a reactor pressure vessel fabricated from the light water reactor vessel material SA 508/533

(i.e., thereby eliminating the need for a vessel cooling system). The operating conditions (e.g., temperatures and neutron fluence) and material requirements were established for the reactor internals components, and the materials best suited to these operating conditions and requirements were selected based on a review of the properties of candidate materials, including high-temperature metallic alloys, ceramics, and ceramic composites. Component temperatures were estimated for normal operation at 100% power and for PCCD and DCCD conditions. The CCD cases were for a 600-MWt reactor with 6.6 w/cc average power density.

In the 2008 study (Ref. 1), it was shown that for the components located in the upper plenum, the critical conditions for material selections are the PCCD conditions. For components located in the lower plenum, the critical conditions for material selections are normal operating conditions. Thus, to conduct the evaluation efficiently, the material capabilities were obtained from the previous study (Ref. 1), and a new set of component design temperatures were derived for the new reactor operating conditions. The results are presented in a format that shows how the material selections change as a function of reactor outlet helium temperature.

The Reactor System components that were the subject of this study include:

- Control rod assemblies, specifically the structural part that contain the B_4C compacts
- Control rod and reserve shutdown material guide tubes
- Upper core restraint elements
- Upper plenum shroud thermal barrier assembly
- Lower plenum sidewall thermal barrier assembly
- Hot duct thermal barrier assembly
- Metallic core support thermal barrier load bearing thermal insulators
- Shutdown cooling system inlet tube assembly
- Shutdown cooling system heat exchanger thermal barrier assembly

The primary conditions that drive the choice of materials for the reactor core and internals components are as follows:

- Neutron fluence received by the component
- Long term operational temperature, including primary coolant hot streaks
- The cumulative effect of short term operational hot streaks
- The cumulative effect of transient increases in temperature during CCD events
- The effect of impurities in the primary coolant on material properties over the life of the component

The material selections from this study are summarized in the Table E-1. The table is color coded to facilitate understanding of how temperature affects the choices. The colors change from blue (cool), to yellow (warm), to red (hot). The reds require ceramic composites to meet the requirements. Some red temperatures are just over the temperature limit for high-temperature metals such as Hastelloy X. Options for using metals in the red temperature range are discussed in the conclusions below.

Conclusions

1. The metallic core support load bearing insulator pads are unaffected by the reactor outlet helium temperature since they are very nearly at the temperature of the reactor inlet helium (350°C). Thus, they can be made from Macor glass ceramic, the original choice of material in the 2008 study (Ref. 1), for its low conductivity and strength, produced by both Morgan Technical Ceramics and Corning, Inc.

2. The shutdown cooling system thermal barrier can be made of Alloy 800H for all reactor outlet helium temperatures evaluated.

3. The shutdown cooling system flow entrance tubes and the lower plenum side wall thermal barrier should be made from Alloy 800H for reactor outlet helium temperatures from 700°C - 800°C and Hastelloy X for reactor outlet helium temperatures from 850°C - 950°C.

4. Hot duct thermal barrier cover plates are affected by reactor outlet helium temperature during normal operation as follows:

    - Alloy 800H is needed for a reactor outlet helium temperature of 700°C.
    - Hastelloy X is needed for reactor outlet helium temperatures from 750°C - 850°C
    - Ceramic composites are needed for reactor outlet helium temperatures at or above 900°C

Table E-1. Material Selections for 600-MWt NGNP High-temperature Reactor Internals Components

Comp	Temperature Condition	Reactor Outlet Helium Temperature and Material Selection[1]											
		700C	Mat'l Sel	750C	Mat'l Sel	800C	Mat'l Sel	850C	Mat'l Sel	900C	Mat'l Sel	950C	Mat'l Sel
Inner CR[2]	Normal Op PCCD Max DCCD Max	788 1,159 1,413	C-C or SiC-SiC	808 1,164 1,418	C-C or SiC-SiC	832 1,169 1,463	C-C or SiC-SiC	850 1,174 1,428	C-C or SiC-SiC	871 1,179 1,433	C-C or SiC-SiC	894 1,184 1,438	C-C or SiC-SiC
Outer CR[2]	Normal Op PCCD Max DCCD Max	420 924 975	C-C or SiC-SiC	440 929 980	C-C or SiC-SiC	464 934 980	C-C or SiC-SiC	482 939 990	C-C or SiC-SiC	503 944 995	C-C or SiC-SiC	526 1,129 1,000	C-C or SiC-SiC
CR & RSM Guide Tubes	Normal Op PCCD Max DCCD Max	346 928 438	Hast X	346 933 418	Hast X	346 638 423	Hast X	346 943 428	C-C or SiC-SiC	346 948 433	C-C or SiC-SiC	346 953 438	C-C or SiC-SiC
UCR[3]	Normal Op PCCD Max DCCD Max	346 1,023 599	C-C or SiC-SiC	346 1,028 604	C-C or SiC-SiC	346 1,033 609	C-C or SiC-SiC	346 1,038 614	C-C or SiC-SiC	346 1,043 619	C-C or SiC-SiC	346 1,048 624	C-C or SiC-SiC
UPS T/B	Normal Op PCCD Max DCCD Max	318 872 450	Hast X	318 877 455	Hast X	318 882 460	Hast X	318 887 465	Hast X	318 892 470	Hast X	318 897 475	Hast X
MCS Load Pads	Normal Op PCCD Max DCCD Max	615 615 615	Macor Glass Ceramic	653 653 653	Macor Glass Ceramic	692 692 692	Macor Glass Ceramic	730 730 730	Macor Glass Ceramic	769 769 769	Macor Glass Ceramic	807 807 807	Macor Glass Ceramic
Hot Duct T/B	Normal Op Long Term Peak Short Term Peak PCCD Max DCCD Max	699 734 766 699 699	800H	749 486 820 749 749	Hast X	798 837 874 798 798	Hast X	848 837 923 848 848	Hast X	898 937 972 898 898	C-C or SiC-SiC	948 986 1,022 948 948	C-C or SiC-SiC
LPS T/B	Normal Op Long Term Peak Short Term Peak PCCD Max DCCD Max	630 664 697 630 630	800H	670 707 742 670 670	800H	711 750 786 711 711	800H	752 791 826 752 752	Hast X	792 831 867 792 792	Hast X	833 871 907 833 833	Hast X
SCS Entrance Tubes	Normal Op Long Term Peak Short Term Peak PCCD Max DCCD Max	615 664 697 615 615	800H	653 690 724 653 653	800H	691 730 766 691 691	800H	729 768 804 729 729	Hast X	768 806 842 768 768	Hast X	806 844 880 806 806	Hast X
SCS T/B	Normal Op PCCD Max DCCD Max	350 350 350	800H	350 350 350	800H	350 350 350	800H	350 350 350	800H	350 350 350	800H	350 350 350	800H

1. Reactor inlet helium temperature is 350°C for all cases
2. The control rods can be made of Hastelloy XR until ceramic composite materials are qualified. The metallic CRs will then be replaced with CRs manufactured from composite materials. See conclusions 6, 7, & 8 and recommendations 2 & 3.
3. The UCR elements can be made of Hastelloy XR until ceramic composite materials are qualified. The UCR elements will then be replaced with UCR elements manufactured from composite materials. See conclusion 5 and recommendations 2 & 3.

5. The Upper Core Restraint (UCR) elements should be made from ceramic composites because the temperatures that result from the decay heat for a 600-MWt reactor are too high for use of metallic materials during a PCCD event for all reactor outlet helium temperatures evaluated. However, it is considered unlikely that ceramic composite UCR elements can be developed and qualified on a schedule that would make them available for an NGNP startup in 2021. Thus, an alternate strategy would be to make the initial UCR elements for the NGNP from Hastelloy XR, while ceramic composite UCR elements are being qualified as replacements for the metal components. If these elements are made from Hastelloy XR, it is anticipated that excessive creep deformation could occur that will make it difficult to remove and replace these elements after a PCCD so that normal operations can be continued. Thus, this strategy involves a risk of prolonged reactor downtime due to replacement difficulties caused by excessive creep deformation of the UCR. However, GA considers this is an investment risk, not a safety issue.

6. The control rod and reserve shutdown material guide tubes can be made from Hastelloy X for reactor outlet helium temperatures ranging from 700°C - 800°C and ceramic composite for reactor outlet helium temperatures at or above 850°C. The maximum temperature for the PCCD is 953°C, which is still within the range of possibilities for Hastelloy X use, but above the current allowable temperature range. If it can be shown from test data that Hastelloy X can withstand this temperature and meet requirements, then the CR & RSM guide tubes can be made from Hastelloy X for reactor outlet helium temperatures up to 950°C. Hastelloy XR, with its low cobalt content, is not needed for the guide tubes because the neutron fluence is low.

7. The outer control rods are needed to control and shut down the reactor. These rods experience a very-high neutron fluence and need to be made from ceramic composite materials because the maximum temperatures during a DCCD event are just above the current short-term allowable temperature limits for high-temperature metals. Outer control rod temperatures during a PCCD event are low enough to use Hastelloy XR for reactor outlet helium temperatures up to 850°C. Hastelloy XR is preferred over Hastelloy X for these high fluence components because of its low cobalt content. Low cobalt results in less neutron activation for easier waste management. Ceramic composites are needed above this reactor outlet helium temperature. During normal operation, the rods are at a maximum of 526°C, well within the capability of Hastelloy XR. Hastelloy XR could be used for reactor outlet helium temperatures up to 850°C, where the CR temperature reaches 939°C, if data show that recovery to normal operation is possible after the PCCD event. This is predicated on allowing excessive creep deformation of the rods for the slightly higher-temperature-DCCD event because removal and replacement of the rods is not required. Slumping of the control rods is not a safety problem because the neutron

absorber materials remain in the core at the proper location. It is only an investment risk concern if the rods are required to be removed and replaced quickly to minimize reactor downtime.

8. The inner control rods are used only to shut down the reactor to cold conditions. Power level and shaping are done with the outer rods. Long term, the inner control rod structural elements should be made from ceramic composite material because the CCD temperatures are too high for use of metals for all reactor outlet helium temperatures considered in this study. Thus, they should be fabricated from a 3-dimensional C-C composite because the maximum temperature during all CCD events ranges from 924°C to 1438°C. They could also be made of SiC-SiC composites for longer life in a nuclear radiation environment. The current strategy is to insert all control rods for any required scram causing the inner rods to experience the high temperatures of the CCD event in the core rather than hanging above the core. The inner rods could be made from Hastelloy XR if they are not inserted into the core at the beginning of a scram, but held out until core temperatures are low enough to insert the Hastelloy XR rods. Normal operation temperatures would allow the use of a metallic structure made of Hastelloy XR. Again, Hastelloy XR is preferred over Hastelloy X because it has lower cobalt content.

9. Currently, the C-C composite FMI-222 is the only candidate that has enough radiation data to be selected for the control rods. The maximum life appears to be eight years. This life is adequate because the control rods can be replaced easily. The corrosion resistance of this material in the expected NGNP reactor helium environment must be evaluated on an expedited basis to ensure there are no life-limiting corrosion effects.

   A longer-term material choice for the control rods is a SiC-SiC composite, possibly Hi-Nicolan^{TM}, due to its apparent much-greater radiation and corrosion tolerance. However, at this time, it is limited to a temperature of 1400°C. If this limit can be increased to 1600°C, a SiC-SiC composite would be a better choice because the control rod lifetime could be 60 years if this material is used. However, more tests need to be conducted on this material, including corrosion tests, to verify that it is a viable choice. Also, the final choice of architecture and SiC-SiC material needs to be completed.

   For reactor outlet helium temperatures from 700°C to 850°C, Hastelloy XR could be used as an interim material until such time as composites can be fully qualified. While considerable creep of the rods would occur, there would be no safety problem with metallic rods because the neutron poison stays in place during a CCD event. However, there is a risk of extended reactor down time if all the rods have to be removed and replaced.

Recommendations

1. Include in the NGNP Technology Program the development of both C-C and SiC-SiC composite materials to provide qualified ceramic composite materials for use in fabrication of high-temperature reactor internals components.

2. For reactors with a reactor inlet helium temperature of 350°C and reactor outlet helium temperature range of from 700°C - 800°C use the following materials:

    - In the short term, while ceramic composites are being qualified, use Hastelloy XR for the control rod and UCR structures. Long term, qualify a ceramic composite material for fabrication of replacement control rods and UCR elements.

    - Use Hastelloy X for the CR & RSM Guide tubes, Upper Plenum Shroud thermal barrier.

    - For the Hot Duct thermal barrier cover plates, use Alloy 800H for a reactor outlet helium temperature of 700°C and Hastelloy X for reactor outlet helium temperatures ranging from 750°C to 800°C.

    - Use Alloy 800H for the Lower Plenum Side Wall thermal barrier, SCS Entrance Tubes thermal barrier, and SCS heat exchanger shroud.

3. Allow the interim use of Hastelloy XR for control rod and upper core restraint devices, with appropriate changes in the strategy for removal and replacement of these components after a CCD event. Adopt a strategy of holding out the inner control rods for a scram until such time as the core is cool enough to insert them. Replace the metal components with ceramic composite units when sufficient development has been completed and the composite units are available.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
CAMTEC	Composites and Advanced Materials Technology Centre
C-C	Continuous carbon fiber-reinforced carbon-matrix composite
CFC	Carbon fiber composite
CCD	Conduction cool down
CR	Control rod
CTE	Coefficient of thermal expansion
CVD	Chemical vapor deposition
CVI	Chemical vapor infiltration
DCCD	De-pressurized conduction cool down
DDN	Design data need
DPA or dpa	Displacements per atom
GA	General Atomics
GT-MHR	Gas-Turbine Modular Helium Reactor
HFIR	High Flux Isotope Reactor
HTGR	High Temperature Gas-cooled Reactor
HTTR	High Temperature Test Reactor (JAERI)
HX	Heat exchanger
INL	Idaho National Laboratory
JMTR	Japan Material Test Reactor (Japan)
KAERI	Korea Atomic Energy Research Institute (Republic of Korea)
MCS	Metallic core support
NGNP	Next Generation Nuclear Plant
NRC	United States Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PCCD	Pressurized conduction cool down
PSR	Permanent side reflector
QA	Quality Assurance
R&D	Research and development

RS	Reactor System
RSM	Reserve shutdown material
SCS	Shutdown Cooling System
S/S	Steady state
SiC	Silicon carbide
SiC-SiC	Continuous silicon carbide fiber-reinforced silicon carbide-matrix composite
T/B	Thermal barrier
UCR	Upper core restraint
UPS	Upper plenum shroud
VHTR	Very High Temperature Reactor (900°C to 1000°C reactor outlet helium temperature)

1 INTRODUCTION

This report presents the results of a study that was performed to assess the effect of lower reactor outlet helium temperature on the materials needed for the reactor internals components of a 600-MWt prismatic Modular Helium Reactor (MHR), which is a candidate reactor concept for the Next Generation Nuclear Plant (NGNP). This study is a follow-on to a previous study (Ref. 1) conducted in 2008 to select candidate ceramic composite materials and to identify the R&D efforts needed to incorporate them into the hardware. In the previous study, ceramic composite materials were chosen for a 600-MWt reactor with reactor inlet helium temperatures ranging from 490°C to 590°C, and a reactor outlet helium temperature of 950°C. In this study, the reactor inlet helium temperature was 350°C, and the reactor outlet helium temperature was varied from 700°C to 950°C in 50°C increments. The temperature of the relevant reactor internals components were estimated for 100% power normal operation and for pressurized conduction cool down (PCCD) and de-pressurized conduction cool down (DCCD) conditions. The conduction cool down (CCD) temperatures were estimated from previously performed analyses.

Historically, the nominal reactor outlet helium temperature in the MHR has increased from 700°C - 750°C for steam-cycle plant designs to 850°C for direct cycle gas-turbine designs (Refs. 1 and 2). The Department of Energy (DOE) has identified a very-high temperature gas-cooled reactor (VHTR) having a nominal reactor outlet helium temperature of 950°C as one of the GEN IV reactor concepts. In the MHR, with its passively safe features, some reactor system components are subject to gas temperatures substantially higher than 950°C during CCD events.

In the 2008 study with a 950°C reactor outlet helium temperature, ceramic composite materials[1] were identified that met the design requirements, and the R&D program needed to verify their use was described. The 2008 study also included a cursory evaluation of the need for composites as a function of reactor outlet helium temperature. The results of the evaluation showed that high-temperature metals can be used rather than ceramic composites for several components if the reactor outlet helium temperature is reduced. If readily-available metallic materials are used, then the R&D program needed to qualify the materials of construction can be reduced in scope, size, and cost.

In this follow-on study, the reactor outlet helium temperature was varied from 700°C to 950°C, in 50°C increments, with emphasis given to the range from 750°C to 800°C, the conditions for a steam cycle plant. In all cases, the reactor inlet helium temperature was maintained at 350°C.

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[1] Ceramic composites as discussed herein (and sometimes referred to simply as "composites") include both carbon-carbon (C-C) composites (i.e., carbon fibers in a carbonaceous matrix) and SiC-SiC composites (i.e., SiC fibers in a SiC matrix).

The inlet temperature of 350°C was chosen to remove the need for direct cooling of a reactor pressure vessel fabricated from the light water reactor vessel material SA 508/533 (i.e., thereby eliminating the need for a vessel cooling system). The operating conditions (e.g., temperatures and neutron fluence) and material requirements were established for the reactor internals components, and the materials best suited to these operating conditions and requirements were selected based on a review of the properties of candidate materials, including high-temperature metallic alloys, ceramics, and ceramic composites. Component temperatures were estimated for normal operation at 100% power and for PCCD and DCCD conditions. The CCD cases were for a 600-MWt reactor with 6.6 w/cc average power density.

In the 2008 study (Ref. 1), it was shown that for the components located in the upper plenum, the critical conditions for material selections are the PCCD conditions. For components located in the lower plenum, the critical conditions for material selections are normal operating conditions. Thus, to conduct the evaluation efficiently, the material capabilities were obtained from Ref. 1, and a new set of component design temperatures were derived for the new reactor operating conditions. The results are presented in a format that shows how the material selections change as a function of reactor outlet helium temperature.

2 IDENTIFICATION OF COMPONENTS

2.1 Reactor System Components

The purpose of this section is to describe the Reactor System in general and to show the location and hierarchy of the Reactor System components that require the use of high-temperature materials. This section was adopted from Ref 1.

The Reactor System consists of the reactor core and the reactor internals. The reactor core components are those directly involved in the production of neutrons such as the fuel element assemblies, the various graphite reflectors, the boron shielding, and the neutron control materials including the control rods and reserve shutdown material. There are other components in the core, but they are not relevant to this study. The reactor internals components are those that support the reactor core assembly and insulate the various metallic structural elements from the high-temperature gas of the primary coolant system. The Reactor System diagram is shown in Figure 2-1. A cross section of the Reactor System illustrating the various physical components is shown in Figure 2-2.

2.2 Components to be evaluated in this study

The reactor system components reviewed in this study that are considered to be candidates for fabrication from high-temperature materials are as follows:

- Control rod assemblies, specifically the structural part that contain the B_4C compacts
- Control rod & reserve shutdown material guide tubes; hollow tubes that span from the control rod drives to the top of the core.
- Upper core restraint elements; devices on top of the core that maintain fuel column alignment and coolant flow gaps between them.
- Upper plenum shroud thermal barrier assembly; thermal insulation system that protects the reactor pressure vessel from high-temperature helium during a CCD event.
- Lower plenum sidewall thermal barrier assembly; thermal insulation that controls heat flow from the core outlet helium to the core barrel.
- Hot duct thermal barrier assembly; thermal insulation that controls heat flow from the reactor exit helium in the hot duct to the duct primary structural elements and parasitic heat loss to the reactor inlet helium.
- Metallic core support thermal barrier assembly; thermal insulation pads that control heat flow from the graphite core support assembly to the metallic core support structure. These insulators also transfer the core weight, pressure drop, and seismic loads to the metallic core support.

- Shutdown cooling system inlet tube assembly; tubes that provide a flow path from the lower plenum to the entrance to the shutdown cooling system heat exchanger.

Two components that were in the original study (Ref. 1) are excluded. These are:

- Permanent side reflector seal sleeves; these were found to be adequate if made of graphite. No need was found to make them from ceramic composites.
- Shutdown cooling system heat exchanger thermal barrier assembly; this is not needed since there is no reactor vessel cooling system. The entire reactor pressure vessel is bathed in reactor inlet helium at 350°C. Thus, there is no insulated flow shroud separating the reactor inlet helium from the vessel coolant helium. In fact, the reactor inlet helium bathes the reactor vessel and the entire SCS shroud by design.

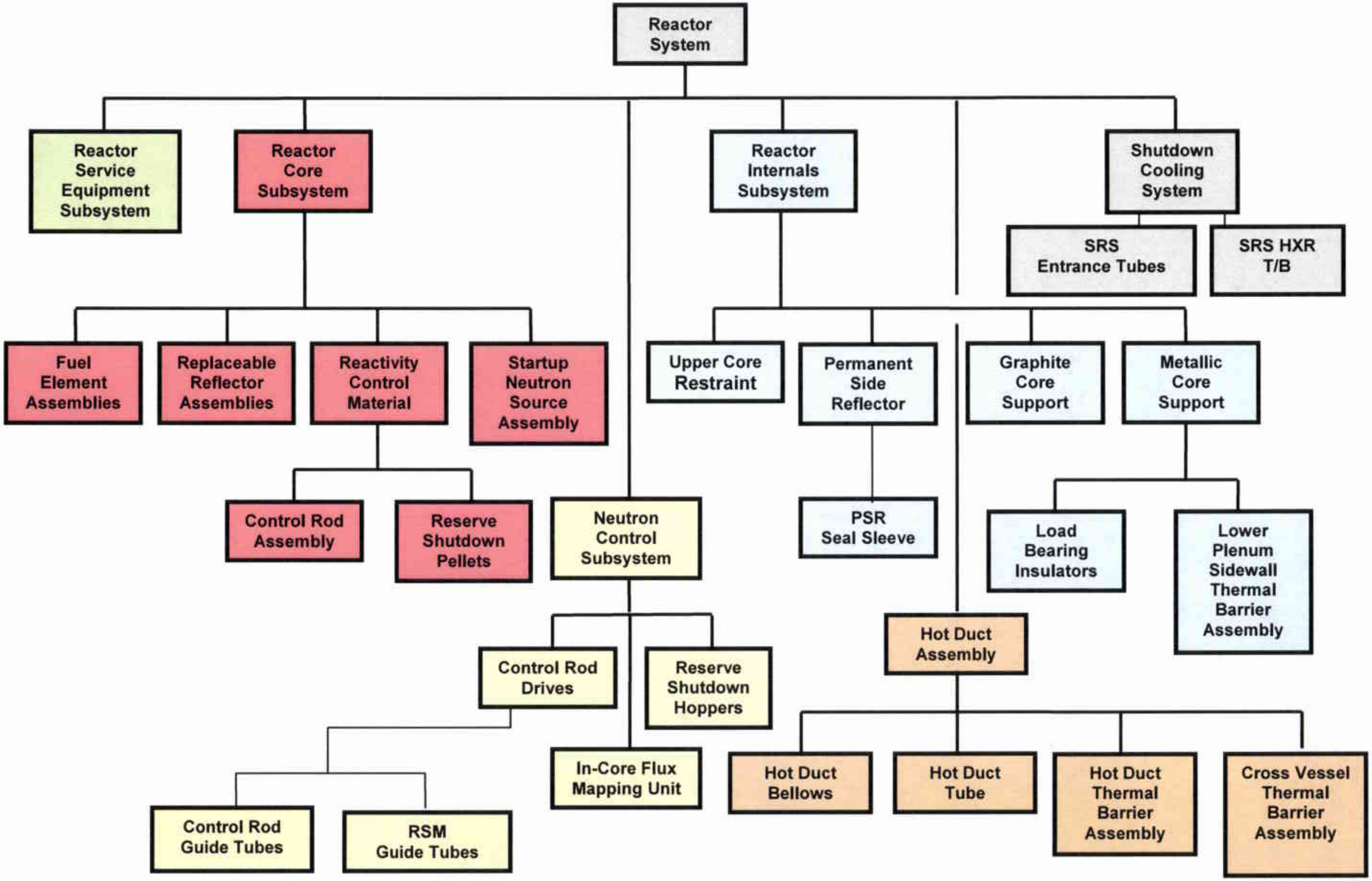


Figure 2-1. Reactor System Hierarchy

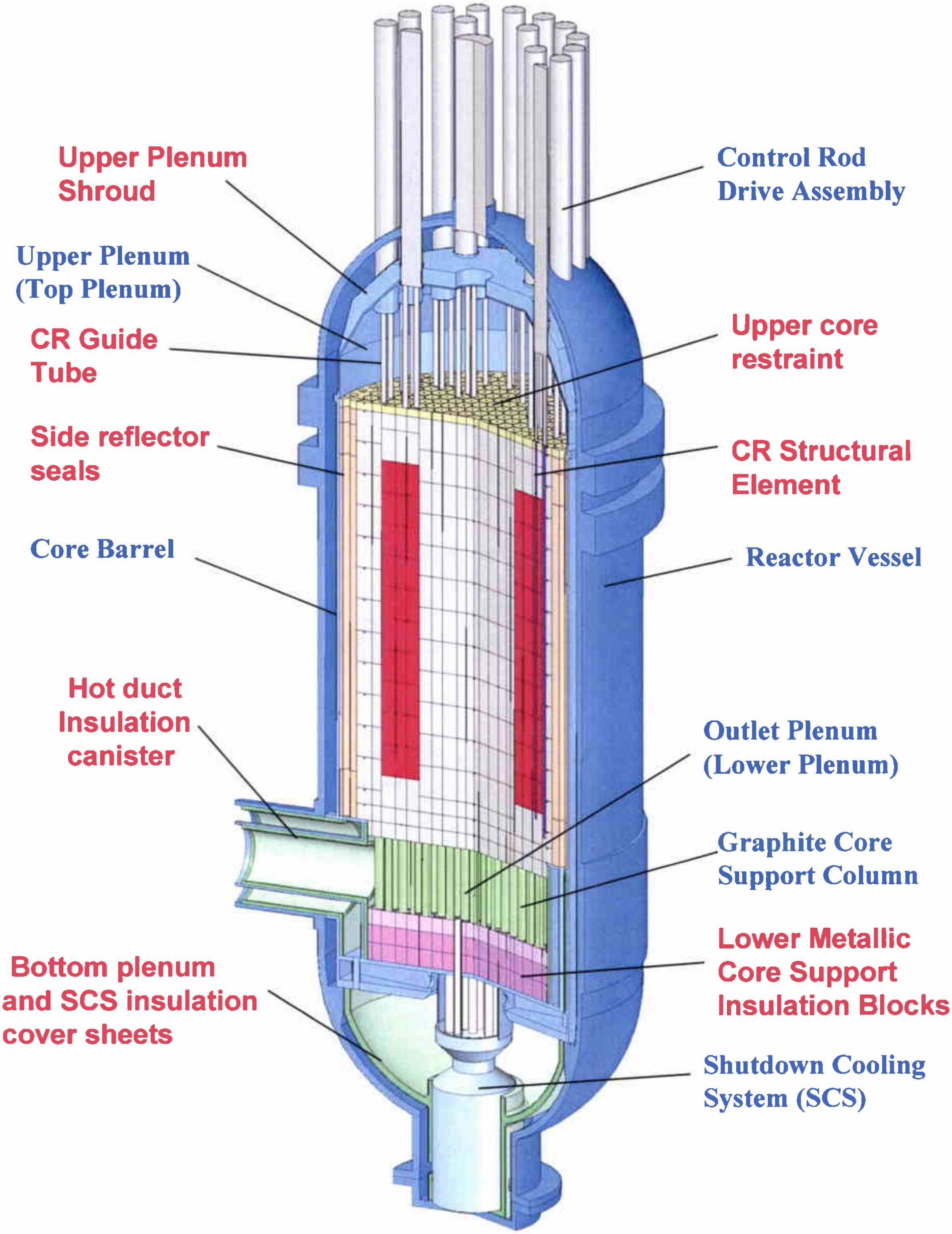


Figure 2-2. Physical location of Reactor System high temperature hardware

3 DESIGN CONDITIONS & REQUIREMENTS

3.1 Normal Operation and Off-Normal Conditions

The purpose of this section is to define the operating conditions and design requirements for the high-temperature reactor internals components. It is not intended to be an exhaustive set of conditions and design requirements, as would be found in the design specification, but just those needed to select materials of construction. These requirements will be compared with the material capabilities in Section 4 as the basis for materials selection. Table 3-1 summarizes the key reactor design parameters for which the evaluation is being performed.

Table 3-1. Key Reactor Design Parameters

Parameter	600-MWt NGNP	
	Value	Units
Reactor thermal power (100% power)	600.0	MWt
Core average power density	6.6	MW/m^3
System pressure (100% power)	7.07	MPa abs
Reactor inlet helium temperature	350	°C
Reactor outlet helium temperature	700 to 950	°C
Reactor Life	60	years

As discussed in Section 2, a ground rule for this study is that the materials selected for the reactor system components must provide the capability for the NGNP to operate with a nominal reactor outlet helium temperature ranging from 700°C to 950°C. The reactor inlet helium temperature is assumed to be 350°C for all reactor outlet helium temperatures. The inlet temperature of 350°C was chosen to allow the use of the light water reactor vessel material, SA 508/533, without a vessel cooling system. For material evaluation, the reactor outlet temperature is varied in 50°C increments. Thus, the reactor inlet helium temperatures considered are 700°C, 750°C, 800°C, 850°C, 900°C, and 950°C. In all cases, it is assumed that a fuel shuffling refueling scheme will be used to 1) minimize peak fuel temperatures at local hot spots (resulting in minimal fission product release to the primary coolant), and 2) minimize hot streaks emanating from the core into the lower plenum, all during normal operation.

The primary conditions that drive the choice of materials for the reactor core and internals components are as follows:

- Neutron fluence received by the component
- Long term operational temperature, including primary coolant hot streaks

- The cumulative effect of short term operational hot streaks
- The cumulative effect of transient increases in temperature during CCD events
- The effect of impurities in the primary coolant on material properties over the life of the component

3.2 Component Temperature Requirements

The thermal conditions for the reactor inlet/outlet helium temperatures of 350°C/700°C - 950°C were estimated from previous analyses conducted by KAERI (Ref. 4), and parametric fuel temperature analyses for NGNP conducted by GA (Ref. 5). To make a design distinction between the inner and outer control rods, an additional analysis was conducted by KAERI (Ref. 2) to predict the outer control rod temperatures for the reactor inlet/outlet helium temperatures of 490°C-590°C/950°C. Also, a more thorough evaluation of the attenuation of hot gas streaks in the lower plenum during full power operation was performed.

In the previous study (Ref. 1), hot streaks were conservatively estimated by adding 250°C to the reactor outlet helium temperatures. To help remove some of this conservatism, two additional reports were consulted: 1) the results of a 3-D analysis, using the computer code FLUENT (Ref. 7), and 2) the results of analysis using empirically derived coefficients of thermal mixing in the lower plenum (Ref. 6).

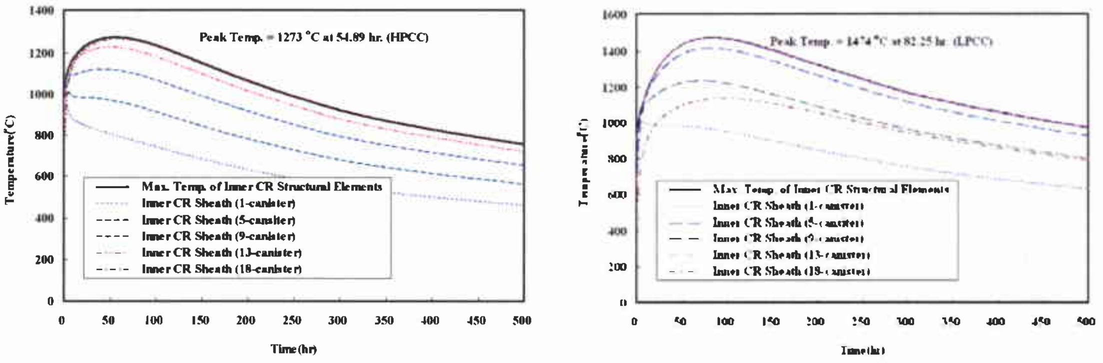
The helium coolant exiting the reactor core is not at uniform temperature due to the presence of new and older fuel. The refueling scheme used is called shuffling. This scheme mixes new and used fuel blocks in a fuel column to minimize peak fuel temperatures, thus reducing fission product release from locally hot fuel.

These hot streaks enter specially designed passages in the bottom reflector elements that help mix the different temperature gases within and with the adjacent fuel columns. Jets at different temperature emanate into the lower plenum where they turn and flow towards the hot duct entrance. Small flow streams entering this main transverse flow are mixed. In this way, the temperature of the hot streaks is considerably reduced. From lower plenum mixing data and 3-D fluid flow analysis attenuation factors have been derived. These factors are a function of where the hot streak is injected relative to the hot duct entrance and the position down stream at which the hot streak temperature is to be calculated. Attenuation factors were developed for the lower plenum sidewall thermal barrier, the Shutdown Cooling System entrance tubes at the bottom of the lower plenum, and the entrance plane of the hot duct. Some hot streaks are long lasting while others last less than a short time of only a few full power days in a fuel cycle. The short term cumulative time is less than 3000 hours. Thus, the short term allowable temperatures are higher than the long term hot streak allowable temperature because they take into account this lesser time at temperature. Table 3-2 summarizes steady state design temperatures.

For CCD conditions, the previous and recent KAERI analyses are used (Refs. 4 & 6). These analyses are for a reactor of 600-MWt and reactor inlet and outlet helium temperatures of 490°C - 590°C and 950°C, respectively. The decay heat curve is assumed to be the same for all 600-MWt reactors. However, it is observed that the effect of initial reactor inlet helium temperature on the upper plenum component temperatures is significant. This effect of lowering the reactor inlet helium temperature to 350°C from 490°C/590°C was estimated from the change in temperature of the components from the results of the KAERI analysis cases between the 490°C and 590°C inlet temperatures.

CCD analyses have also been conducted to obtain the outer control rod temperature histories. KAERI performed analyses for reactor inlet/outlet helium temperatures of 490°C - 590°C/950°C. For this study, KAERI provided the additional information on outer control rod temperatures so that the differences could be accounted for in the selection of materials. The maximum temperatures calculated for selected key reactor core components during steady-state 100% power operation and CCD events are summarized in Table 3-2. The temperatures in these tables were estimated from the KAERI analysis results. Typical CCD temperature time histories are shown in Figure 3-1. The control rod temperature history for CCD transients with reactor inlet helium temperatures of 490°C and 590°C were used in Figure 3-1 to illustrate time at temperature.

The CCD temperature histories are very slow, taking hundreds of hours to complete as seen in the plots of temperature versus time. The peak temperature is reached in 40 to 70 hours with the peak temperature lasting about 50 to 70 hours.



Pressurized Conduction Cool Down
Peak Temp = 1236°C

De-pressurized Conduction Cool Down
Peak Temp = 1474°C

Figure 3-1. Typical CCD temperature histories shapes

Table 3-2. Reactor Internals Component Maximum Temperature Requirements

Component	Reactor Outlet Temperature / Op. Condition	Component Temperature					
		700°C	750°C	800°C	850°C	900°C	950°C
Inner Control Rods	Normal Op.	788	808	832	850	871	894
	PCCD Max	1,159	1,164	1,169	1,174	1,179	1,184
	DCCD Max	1,413	1,418	1,463	1,428	1,433	1,438
Outer Control Rods	Normal Op.	420	440	464	482	503	526
	PCCD Max	924	929	934	939	944	1,129
	DCCD Max	975	980	980	990	995	1,000
Control Rod & Reserve Shutdown Sys Guide Tubes	Normal Op.	346	346	346	346	346	346
	PCCD Max	928	933	638	943	948	953
	DCCD Max	438	418	423	428	433	438
Upper Core Restraint	Normal Op.	346	346	346	346	346	346
	PCCD Max	1,023	1,028	1,033	1,038	1,043	1,048
	DCCD Max	599	604	609	614	619	624
Upper Plenum Shroud Thermal Barrier	Normal Op.	318	318	318	318	318	318
	PCCD Max	872	877	882	887	892	897
	DCCD Max	450	455	460	465	470	475
Metallic Core Support Load Bearing Insulator Pads	Normal Op.	615	653	692	730	769	807
	PCCD Max	615	653	692	730	769	807
	DCCD Max	615	653	692	730	769	807
Hot Duct Thermal Barrier	Normal Op.	699	749	798	848	898	948
	Long Term Peak	734	486	837	837	937	986
	Short Term Peak	766	820	874	923	972	1,022
	PCCD Max	699	749	798	848	898	948
	DCCD Max	699	749	798	848	898	948
Lower Plenum Sidewall Thermal Barrier	Normal Op.	630	670	711	752	792	833
	Long Term Peak	664	707	750	791	831	871
	Short Term Peak	697	742	786	826	867	907
	PCCD Max	630	670	711	752	792	833
	DCCD Max	630	670	711	752	792	833
Shutdown Cooling Sys Entrance Tubes	Normal Op.	615	653	691	729	768	806
	Long Term Peak	664	690	730	768	806	844
	Short Term Peak	697	724	766	804	842	880
	PCCD Max	615	653	691	729	768	806
	DCCD Max	615	653	691	729	768	806
Shutdown Cooling Sys Thermal Barrier	Normal Op.	350	350	350	350	350	350
	PCCD Max	350	350	350	350	350	350
	DCCD Max	350	350	350	350	350	350
Note: Reactor inlet helium temperature is 350°C in all cases							

3.3 Neutron Fluence Requirements at the Reactor System Components

Sections 3.3 and 3.4 are a repeat of sections in Ref. 1. Neutron fluxes and fluence were estimated from prior program information and gleaned from Design Data Needs (Ref. 8). In addition, a detailed nuclear analysis including components outside the permanent side reflector was used (Ref. 12). The neutron fluence for each component is listed in Table 3-3.

Table 3-3. Reactor Internals Lifetime Neutron Fluence

Component	Design Life	Lifetime Fluence	
		n/m^2	dpa (estimate)
Outer Control Rods (Used to control power level)	8 y	3.22×10^{26}	4.0
Inner Control Rods (used to shutdown the reactor to cold conditions.)	60 y	1.03×10^{23}	0.00128
Control Rod & RSM Guide Tubes	60 y	1.03×10^{23}	0.00128
Upper Core Restraint	60 y	3.49×10^{24}	0.0434
Upper Plenum Shroud Thermal Barrier	60 y	1.20×10^{22}	0.00098
Permanent Side Reflector Seal Sleeves	60 y	3.22×10^{24}	0.0400
Metallic Core Support Load Bearing Insulators	60 y	8.50×10^{21}	0.00011
Hot Duct & Cross Vessel Thermal Barrier	60 y	8.50×10^{21}	0.00011
Lower Plenum Sidewall Thermal Barrier	60 y	8.50×10^{21}	0.00011
Shutdown Cooling System Entrance Tubes	60 y	8.50×10^{21}	0.00011
Shutdown Cooling System HX Thermal Barrier	60 y	8.50×10^{21}	0.00011

3.4 Primary Coolant Chemistry Requirements

The coolant chemistry levels required for design are shown in Table 3-4. This data was taken from DDN 11.07.01 (Ref. 2). This chemistry is not in equilibrium with the temperatures in the primary coolant loop, but represents probabilistic maximum values. The expected values of oxidants in the coolant are shown in Table 3-5. These values are for lower reactor inlet/outlet helium temperatures, but are shown here to provide an indication of what might be expected during normal operation. The primary coolant impurity levels for which the components must sustain operation are considerably higher than the expected values for equilibrium conditions due to uncertainty in predicting the levels of oxidants in the primary coolant.

Table 3-4. Design Levels of Primary Coolant Impurities for Reactor Internals Components

Parameter	Value	Units	Ref	Comment
Design Primary He Coolant Impurities at S/S 100% power			2	This is an equilibrium coolant chemistry at 100% power for a reactor inlet helium temperature of 490°C and a reactor helium outlet temperature of 850°C
H_2O	2.0	ppmV		140 microatm
CO_2	2.0	ppmV		140 microatm
CO	5.0	ppmV		350 microatm
H_2	10.0	ppmV		700 microatm
CH_4	2.0	ppmV		140 microatm
N_2	10.0	ppmV		700 microatm
Particulates	10.0	lb/yr		

Table 3-5. Expected Levels of Primary Coolant Impurities for Reactor Internals Components

Parameter	Value	Units	Ref	Comment
Expected Primary He Coolant Impurities at S/S 100% power (For reference only)			2	This is an equilibrium coolant chemistry at 100% power for a reactor inlet helium temperature of 490°C and a reactor helium outlet temperature of 850°C
H_2O	0.5	ppmV		35 microatm
CO_2	1.0	ppmV		69.7 microatm
CO	2.0	ppmV		140 microatm
H_2	3.0	ppmV		210 microatm
CH_4	0.1	ppmV		7 microatm
N_2	2.0	ppmV		140 microatm
Particulates	1.0	lb/yr		

4 MATERIAL PROPERTIES AND CAPABILITIES

The purpose of this section is to identify potential materials that will meet the design requirements identified in Section 3 and to list the relevant properties of these materials. In addition, the properties will be evaluated to establish design limits for evaluation against the design requirements. Limits on useful temperature, neutron fluence, and corrosion properties are identified for the materials. The ability of the materials to meet life requirements is noted. Selection of materials for fabrication of parts is based on the material properties, material limits, manufacturing feasibility, and availability. Of course, the materials must have the capability to meet the design requirements to be acceptable for use in the hardware.[2]

4.1 Material Properties

This subsection catalogues the material properties of the candidate materials with the objective of developing the service limits for the selected candidates. Three types of materials are being considered for use in the high temperature areas of the reactor core and internals structures. They are high-temperature metallic alloys, monolithic ceramics, and ceramic composites. Properties of these types of materials have been obtained from a myriad of sources and organized into these three groups. The capability of these materials for short term peak temperature excursions that accumulate to less than 3000 hours is of interest to use for CCD transients and core exit helium transient hot streaks. These allowable temperatures can be used to allow higher temperatures for some components for short duration temperature excursions. The properties are displayed in tables in the following subsections.

4.1.1 Metallic material properties

Table 4-1 lists the material properties for candidate high-temperature metallic alloys.

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[2] This section is a shortened version of Section 4 in Ref. 1.

Table 4-1. High-Temperature Alloy Properties at Maximum Allowable Temperatures

Mat'l	ASME Code Info			Mechanical Properties at Code Temp Limit						Physical Properties at Code Temp Limit			Environmental Effects			Comment
	Applicable Codes & Stds	Code Temp Limit		Elastic Mod	Min UTS	Min YS	S_m	S_o	Temp	CTE (Mean)	Conductivity	Cobalt Content	Corrosion & Fluence Limits			
		F	C	10^3 KSI	KSI	KSI	KSI	KSI	F	in/in/°F	W/m.K	%	Codes & Stds	n/m^2	DPA	
718 AMS5596C	ASME Sect III, Div 1	1,200	649	23.6	146.3	122.1	41.2	6.7	1,200	8.3	22.3	1.2 Max	Owner's Responsibility Maintain at least 10% ductility	3.0E+22	0.00246	
800H SB-409	ASME Sect III, Div 1	1,400	760	21.9	30.6	14.0	11.0	3.6	1,400	10.2	23.8	2.0	Owner's Responsibility Maintain at least 10% ductility	3.0E+22	0.00246	Fluence of 1.2E23 is all thermal fluence. High energy neutrons don't affect ductility
617	ASME Sect VIII, Div 1 Code Case 1956-7	1,650	899	21.9	126.5 *	58.3*	39.1	?	1,650	8.7	26.7	10 to 15	Owner's Responsibility Maintain at least 10% ductility	3.0E+22	0.00246	Gamma & Gamma-Prime formation causes increase in strength and reduction in ductility with increasing temp
617	ASME Sect VIII, Div 1 Code Case 1982-1	1,800	982	19.0	**	**	**	**	1,800	9.0	28.4	10 to 15	Owner's Responsibility Maintain at least 10% ductility.	3.0E+22	0.00246	** Could not find 1800F data before completion of report
Hast X AMS5536G	ASME Sect VIII, Div 1	1,600	871	19.8	30.3	17.0	11.1	1.3	1,600	9.0	25.6	0.5-2.5	Owner's Responsibility Maintain at least 10% ductility	3.0E+22	0.00246	Can have a higher use temperature if use time is dependant on stress values
Mitsubishi Hast XR	Not in Code Yet. Code Case 2315 Sect Viii, Div. 1	1700?	927	**	**	**	**	**	1,700	**	**	0 to 1.0	Owner's Responsibility Maintain at least 10% ductility	3.0E+22	0.00246	** Could not find 1700F data before completion of report. Observe low Co content
Haynes 230	ASME Sect VIII, Div 1 Code Case 2384	1,800	982	30.9 RT	35.0	21.0	11.6	< 0.8	1,800	7.0	8.9 RT	5.0 Max	Owner's Responsibility Maintain at least 10% ductility	3.0E+22	0.00246	

4.1.2 Monolithic Ceramic Material Properties

Table 4-2 lists candidate monolithic ceramic material properties.

Table 4-2. Monolithic Ceramic Material Properties

Manufacturer	Product Name	Density (Fired) g/cm^3	Porosity (apparent) (%)	Thermal Expansion Coefficient (10E-6/°C)	Thermal Conductivity (W/m.K)	Specific Heat (J/kg.K)	Thermal shock (Delta °C)	Poisson's Ratio
Morgan Advanced Ceramics	Alumina (typical of fully dense grades)	3.75 - 3.95	0	6.9 - 8.9 (RT) 8.5 - 9.0 (800°C)	25.6 - 30.0 (RT) 12.5 (400°C)	880	160 - 210	
Kyocera	Alumina (A479SS) 99.5%	3.9		7.2 (400°C) 8.0 (800°C)	32 (20°C)	780	250	0.23
Morgan Advanced Ceramics	Zirconia Toughened Alumina (ZTA)	4.32	0	8.3 (RT)	20 (RT)			0.24
Morgan Advanced Ceramics	MgO Stabilized Zirconia (Z500)	5.6 - 5.7	0	10 (RT) 10 (800°C)	2.5 (RT)	460	300	
Kyocera	Zirconia (Z-220)	5.6		10 (400°C 10.5 (800°C)		460	450	0.31
Saint Gobain Ceramics	Hexaloy SA SiC	3.1		4.02 (700°C)	125 (RT) 103 (200°C)	670		0.14
Saint Gobain Ceramics	Hexaloy SP SiC	3.04		4.2 (700°C)	110 (RT)	590		0.14
Kyocera	Silicon carbide (SC-211)	3.2		3.7 (400°C) 4.4 (800°C)	60	670	400	0.16
Morgan Advanced Ceramics	Silicon Carbide	2.7 - 3.1	0.1 - 5.0	4.5 - 5.0 (1000°C)	35 - 124 (200°C)			
Morgan Advanced Ceramics	Cordierite	2.4	0	3.0 (RT)	2.0 (RT) 3.0 (400°C)	950	300	
Morgan Advanced Ceramics	Aluminum Silicates	2.3 - 3.0	0 - 11	2.9 (RT) 5.7 - 6.3 (1000°C)	1.4 - 6.0 (200°C)	800 - 900		55 - 150
Morgan Advanced Ceramics	Fused Silica	1.35 - 2.0	0	0.5 (RT)	0.9 (RT)			
Morgan Advanced Ceramics	RBSN	2.5	20	3.1 (1000°C)	12 (RT)	1100	> 600	
Morgan Advanced Ceramics	SSN	3.2	0	3.3 (RT)	15 (RT)	900	> 600	
Kyocera	Silicon Nitride (SN - 240)	3.3		2.8 (400°C) 3.3 (800°C)	27	650	> 800	0.28
Corning / Morgan	MACOR	2.52	0	11.4 (25-600°C)	1.46	790		0.29
Morgan Advanced Ceramics	Cordierite	2.4	0	3.0 (RT)	2.0 (RT) 3.0 (400°C)	950	300	
	Aluminosilicate glass-ceramics							
Morgan Advanced Ceramics	Mullite Alumina (typical of fully dense grades)	1500 - 1725	14.3 - 18.5	310 - 500	2000 - 2500		4 - 5.9	

Manufacturer	Product Name	Density (Fired) g/cm^3	Porosity (apparent) (%)	Thermal Expansion Coefficient (10E-6/°C)	Thermal Conductivity (W/m.K)	Specific Heat (J/kg.K)	Thermal shock (Delta °C)	Poisson's Ratio
Kyocera	Alumina (A479SS) 99.5%	1600	16	360	2350		4	
Morgan Advanced Ceramics	Zirconia Toughened Alumina (ZTA)			430				
Morgan Advanced Ceramics	MgO Stabilized Zirconia (Z500)	1000	11	500-550	2000		8.4	
Kyocera	Zirconia (Z-220)		10.7	750			7.0 - 8.0	
Saint Gobain Ceramics	Hexaloy SA SiC	1900	2800 Knoop 0.1Kg	380 (4 Point)	3900		4.6	
Saint Gobain Ceramics	Hexaloy SP SiC	1900	2800 Knoop 0.1Kg	240 (4 Point)			4.3	
Kyocera	Silicon carbide (SC-211)	1200	22	540			4.0 - 5.0	
Morgan Advanced Ceramics	Silicon Carbide	1300 - 1650		80 - 400				
Morgan Advanced Ceramics	Cordierite	1000		88.1	500			
Morgan Advanced Ceramics	Aluminum Silicates	1150 - 1350		64	275			
Morgan Advanced Ceramics	Fused Silica	1000 - 1100		125	850 - 900			
Morgan Advanced Ceramics	RBSN	1300		200	650			
Morgan Advanced Ceramics	SSN	1000	16	650	> 3000			
Kyocera	Silicon Nitride (SN - 240)	1200	14	1020			7	
Corning / Morgan	MACOR	1000		345			1.53	
Morgan Advanced Ceramics	Cordierite	1000		88	500			
	Aluminosilicate glass-ceramics					Tensile at 950°C, 15MPa: 1.7E-08/s (ref 5) Compressive at 1300°C, 15MPa: 10E-04/s (ref 6)		
	Mullite					Tensile at 1300°C, 15MPa: <10E-08/s. At 45MPa: 3E-08/s (ref 1) Compressive at 1300°C, 15MPa: 4.8E-08/s (ref 2)		

4.1.3 Ceramic Composite Material Properties

Table 4-3 lists ceramic composite material properties.

Table 4-3. Ceramic Composite Material Properties

Mat'l	Density	Conductivity			CTE	Tensile Strength	Fract Toughness	Use Temp	Fluence Limit		Codes & Stds	Comment
	g/cc	W/m.° K	Temp C	Direction	10^{-6}/°C	MPa	MPa-m$^{1/2}$	C	n/m^2	DPA		
C-C* FMI-222 3-D	1.48	160	21	In Pl		~175		>2000 Long duration 2400 Short duration	3.2E+26	4.00	ASTM, ASM. Industry Practice. Designer Responsibility.	Control Rod Life 8 years. Guide Tube Life 60 years. Cov Pl Life 60 Years
		100	800	In Pl		~175						
		93	1200	In Pl		~175						
		90	1600	In Pl		~175						
SiC-SiC Hi-Nicalon 2-D**	2.60	30	21	In Pl	4.5	150-300	20-30	1400 Long duration 1600 Short duration	2.4E+27	> 30	ASTM, ASM. Industry Practice. Designer Responsibility.	Control Rod Life 60 Years.
		15	1000	In Pl		150-300	20-30					
		15	21	Trans Thickness	**4.5**	20-30						
		8	1000	Trans Thickness		20-30						
A/N720 (Ox/Ox)	2.61	4.21	21	In Pl	3.5	218	na	1150		na	industry Practice Owners Responsibility	COIC
		2.39	1200	"	6.0	"	"					
SiC-SiC (Ideal Matl)	2.6	9-35	21	In Pl	4.7	na	na	1200		na	"	"
		8-20	1000	"	na							

4.2 Material Limits

The purpose of this subsection is to list the selected candidate materials and their limits for comparison with design requirements.

4.2.1 Metallic Material Limits

Typical metallic materials for high temperature nuclear applications are Alloy 800H, Hastelloy X, Hastelloy XR, Inconel 617, and Haynes Alloy 230.

Table 4-4 shows the limits for temperature and fluence for the various metallic materials. Cobalt content is also a discriminator due to activation and subsequent transport of radioactive cobalt throughout the coolant loop.

4.2.2 Monolithic Ceramic Material Capabilities and Limits

Table 4-5 shows the limits for temperature and fluence for the various monolithic ceramic materials considered in this study.

Table 4-4. Metallic Material Capabilities and Limits

Material	Temperature Capability			Cobalt Content		Neutron Fluence Limit			Comment
	°C	S_o KSI	Codes & Standards	%	Use In n-Irradiation Environment?	n/m^2 (HTGR Spectrum)	dpa	Codes & Standards	
Alloy 800H	760 Long Duration	3.6	ASME Sect III, Div 1	2.0	Yes	3.0×10^{22}	0.00246	Owners Responsibility. At least 10% Ductility.	Fluence of 3×10^{22} is all thermal energy. High energy neutrons don't have significant effect.
	866 Short duration < 3000 h and stress < 1000 psi	1.0	Use Time dependant allowable stress						Might be useful at 1590°F (866°C) for thermal barrier cover plates and fasteners.
Inconel 617	982	12.8	ASME Sect VIII, Div 1	10 to 15	No. Cobalt too high	3.0×10^{22}	0.00246	Owners Responsibility. At least 10% Ductility.	Eliminated because cobalt is too high.
Hastelloy X	899 for long duration. 938 for short duration < 3000 h and stress , 1000 psi	1.3 Long duration 1.0 short duration	ASME Sect VIII, Div 1 Use Time dependant allowable stress	0.5 to 2.5	Possibly. Co a little high.	"	"	"	Can use up to 1600°F (871°C) For short duration can use at 938 C if < 3000 h and stress < 1000 psi.
Mitsubishi Hastelloy XR	927 long duration for stress < 1000 psi 940 short duration < 3000 h and stress < 1000 psi	1.3 Long duration 1.0 short duration	Not In Code yet. Push for inclusion. Complete code work. Use Time dependant allowable stress	0 – 1.0	Yes	3.0×10^{22}	0.00246*	Owners Responsibility. At least 10% Ductility for pressure boundary. *Could be < 10% for non press boundary use.	Long duration: 1700°F (927°C) if stress < 1300 psi. Short duration 940 for < 3000 h if stress < 1000 psi. Has low Co content compared to Hastelloy X
Haynes 230	982	~ 0.8	ASME Sect VIII, Div 1	5.0	No. Cobalt too high	3.0×10^{22}	0.00246	Owners Responsibility. At least 10% Ductility.	Eliminated because Cobalt too high.

Table 4-5. Monolithic Ceramic Material Capabilities and Limits

Material	Density	Conductivity		CTE	Bend Strength	Use Temperature		Codes & Stds	Neutron Fluence Limit			R e f	Comment
	g/cc	k W/m.°K	Temp C	10^{-6}/°C	MPa	C	F		n/m^2 (HTGR Spectrum)	dpa	Codes & Stds	No.	
Kaowool In helium (For Ref Only)	na	0.11	21	na	na	1000	1832	Industry practice. Owner's responsibility.	Unavail	Unavail	Owners Responsibility	7	Data from CEA experiments in 1970s.
	na	0.65	982	na	na	1000	1832	"	"	"	"	7	"
Fused Silica GA	2.01	0.72	400	0.8	14.0	1000	1832	ASTM, ACMAASTM, ACMA Industry Ceramic Design Practice for Brittle Mat'ls Owners Responsibility.	"	"	"	8	Data from Large HTGR program tests
	2.01	1.13	850	0.8	16.0	"	"	"	"	"	"	8	
Fused Silica GA	1.68	0.09	21	0.5	125	1000	1832	"	"	"	"	"	
Alumina-fully dense	3.75-3.95	25.6-30	21	7.9	310	1500	2732	"	"	"	"	20	Morgan Adv Ceramics
	"	12.5	400	8.75								"	"
Alumina (A479SS) 99.5%	3.9	32	21	7.2	360	1600	2912	"	"	"	"	21	Kyocera
Zirconia Toughened Alumina (ZTA)	4.32	20	21	8.3	430	NAa	NA	"	"	"	"	20	Morgan Adv Ceramics

Material	Density	Conductivity		CTE	Bend Strength	Use Temperature		Codes & Stds	Neutron Fluence Limit			Ref No.	Comment
	g/cc	k W/m.°K	Temp C	10^{-6}/°C	MPa	C	F		n/m^2 (HTGR Spectrum)	dpa	Codes & Stds		
MgO Stabilized Zirconia (Z2500)	5.6	2.5	21	10	500	1000	1832	"	"	"	"	20	Morgan Adv Ceramics
Zirconia (Z-220)	5.6	na	na	10	750	na	na	Owners Responsibility	na	na	Owners Responsibility	21	Kyocera
Hexaloy SA SiC	3.1	103	200	4.02	380	1900	3452	"	"	"	"		St.Gobain Ceramics
Hexaloy SP SiC	3.04	110	21	4.2	240	1900	3452	"	"	"	"		St.Gobain Ceramics
Silicon Carbide (SC 211)	3.2	60	21	4.4	540	1200	2192	"	"	"	"	21	Kyocera
Silicon Carbide	2.9	35-124	200	4.8	80-400	1300	2372	"	"	"	"	20	Morgan Adv Ceramics
Cordierite	2.4	2	21	3.0	88	1000	1832	"	"	"	"	20	Morgan Adv Ceramics
		3	400										
Aluminum Silicates	2.7	4.5	200	3.0	64	1150	2102	"	"	"	"	20	Morgan Adv Ceramics
Fused Silica	1.7	0.9	21	0.5	125	1000	1832	"	"	"	"	20	Morgan Adv Ceramics
RBSN	2.5	12	21	3.1	200	1300	2732	"	"	"	"	20	Morgan Adv Ceramics
SSN	3.2	15	21	3.3	650	1000	1832	"	"	"	"	20	Morgan Adv Ceramics
Silicon Nitride (SN-240)	3.3	27	21	3.3	1020	1200	2129	"	"	"	"	20	Morgan Adv Ceramics
Macor	2.52	1.46	21	11.4	345	1000	1832	"	"	"	"	20	Coming & Morgan Adv Ceramics

4.2.3 Ceramic Composite Material Limits

Table 4-6 shows the limits for temperature and fluence for the acceptable ceramic composite materials. Materials without irradiation data were omitted from consideration.

Table 4-6. Ceramic Composite Material Capabilities and Limits

Mat'l	Density	Conductivity			CTE	Tensile Strength	Fract Tough	Use Temp	Fluence Limit		Codes & Stds	Comment
	g/cc	W/m. °K	Temp C	Direction	10^{-6}/°C	MPa	MPa-$m^{1/2}$	C	n/m^2	dpa		
C-C* FMI-222 3-D	1.48	160	21	In Pl		~175		>2000 Long duration 2400 Short duration	3.2E+26	4.00	ASTM, ASM, Industry practice, Designer responsibility.	Control rod life 8 years. Guide tube life 60 years. Cover plate life 60 Years
		100	800	In Pl		~175						
		93	1200	In Pl		~175						
		90	1600	In Pl		~175						
SiC-SiC Hi-Nicalon 2-D**	2.60	30	21	In Pl	4.5	150-300	20-30	1400 Long duration 1600 Short duration	2.4E+27	> 30	ASTM, ASM, Industry practice, Designer responsibility.	Control rod life 60 Years
		15	1000	In Pl		150-300	20-30					
		15	21	Trans Thickness	4.5	20-30						
		8	1000	Trans Thickness		20-30						

5 MATERIAL SELECTION EVALUATION

The basis for the selection of materials for the various reactor core and internals components is explained in this section. A component-by-component evaluation is presented based on materials that meet the design requirements in Section 3. A summary of the materials selected for each component is shown in Table 5-1. The selections are explained in the following sections.

Table 5-1. Summary of Material Selections

Component	Material Selected - Applicable Reactor Outlet Temperature
Control Rod Structural Elements	C-C Composite – 700C $\leq T_{out} \leq$ 950C SiC-SiC long term Hastelloy XR - Interim until composites qualified
Control Rod & RSM Guide Tubes	Hastelloy X - $T_{out} \leq$ 800C C-C or SiC-SiC Composite – 850C $\leq T_{out} \leq$ 950C
Upper Core Restraint	C-C Composite - 700C $\leq T_{out} \leq$ 950C SiC-SiC Composite Long term Hastelloy X – Interim until composites qualified
Upper Plenum Shroud Thermal Barrier	Hastelloy X – $T_{out} \leq$ 950C
PSR Seal Sleeves	Graphite (No change from original study)
Metallic Core Support Load Bearing Insulators	Monolithic Ceramic (No change from original study)
Hot Duct Thermal Barrier	Alloy 800H – at or below T_{out} = 700C Hastelloy X – 750C $\leq T_{out}$ <850C C-C or SiC-SiC Composite – Tout$\geq$ 900C
Lower Plenum Sidewall Thermal Barrier	Alloy 800H – $T_{out} \leq$ 800C Hastelloy X – 850C $\leq T_{out} \leq$ 950C
SCS Gas Entrance Tubes	Alloy 800H – $T_{out} \leq$ 800C Hastelloy X – 850C $\leq T_{out} \leq$ 950C
SCS Heat Exchanger Thermal Barrier	Metal - Alloy 800H Cooled by reactor inlet helium during operation No heat up during CCD

5.1 Material Allowable Temperatures

The basis for the selection of materials for the various reactor core and internals components is explained in this section. The estimated maximum service temperatures for these components are shown in Table 3-2 in Section 3. The materials are selected based on all requirements, but heavily influenced by operating temperature and neutron fluence.

The process for selecting materials is to assign an allowable temperature in Table 5-2 for each material candidate and compare it to the maximum service temperatures for the various reactor conditions (e.g., normal operation, PCCD, DCCD, etc.) in Table 3-2. A set of allowable temperatures has been developed based on continuous operation at a particular temperature and cumulative operation for a total of 3000 hours for transient peak temperatures. The allowable temperature is obtained from metallic material design curves for time-dependant allowable stresses (S_t) for a time duration of 3000 hours and at an operating stress of 1000 psi. The composite allowable temperatures are estimates based on the behavior of C-C and SiC-SiC composites. Table 5-2 shows the allowable temperature for each material being considered. The allowable temperatures are color coded to aid in identification of material choices in subsequent tables.

Table 5-2. Material Allowable Temperatures

Material	Long Term Temperature Limit (C)	Short Term 3000 Hour Temperature Limit (C)
800H	760	
800H		871
Hastelloy X	899	
Hastelloy X		938
Hastelloy XR	927	
Hastelloy XR		940
SiC-SiC	1400	~1600
C-C	2000	2400

Table 5-3 is the working table where materials are assigned to each component for each reactor condition based on the maximum service temperature for that condition. The materials are allocated to each condition to see what material is needed as though the condition existed alone. The color code facilitates visualization of the conditions that are driving the material decision.

For temperatures above the allowable temperature of Hastelloy XR, ceramic composites are needed. However, to mitigate schedule delays associated with qualification tests for ceramic composites, Hastelloy X and Hastelloy XR could be used for the Guide Tubes, UCR, and control rods until replaced with components made of ceramic composite material when qualification is complete. This carries the additional investment risk that creep deformation occurring in the components during a CCD event could make the temporary metallic components difficult to remove and replace after the event. There is no safety risk since the components made of metallic materials will still perform their safety function during the CCD event. In addition, the inner control rods would have to be held out of the core during a scram of the reactor until such time as the reactor core is cool enough to insert them. Again, this is not a safety risk since the outer control rods are all that is needed to shutdown the reactor. The inner rods are only needed to bring the reactor to cold conditions.

Table 5-3. Reactor Internals Component Material Selections for Different Reactor Conditions

Component	Temperature	Reactor Outlet Helium Temperature												Comment
	Condition	700C	Selected Mat'l	750C	Selected Mat'l	800C	Selected Mat'l	850C	Selected Mat'l	900C	Selected Mat'l	950C	Selected Mat'l	
Fuel	Long Term Peak	974	NA	1041	NA	1107	NA	1155	NA	1203	NA	1251	NA	Fuel temperature for reference only
Inner Control Rods (See comment)	Normal Op	788	HastXR	808	HastXR	832	HastXR	850	HastXR	871	HastXR	894	HastXR	HastXR good to 927C long term. Need low Co in high-radiation environment
	Max Pressurized CCD	1,159	C-C or SiC-SiC	1,164	C-C or SiC-SiC	1,169	C-C or SiC-SiC	1,174	C-C or SiC-SiC	1,179	C-C or SiC-SiC	1,184	C-C or SiC-SiC	C-C good to 2000C; 2400C short term. If Hast XR used, then must adopt a hold-out strategy for scram until core cools low enough to insert inner rods
	Max Depressurized CCD	1,413	C-C or SiC-SiC	1,418	C-C or SiC-SiC	1,423	C-C or SiC-SiC	1,428	C-C or SiC-SiC	1,433	C-C or SiC-SiC	1,438	C-C or SiC-SiC	SiC-SiC good to 1400; 1600C short term If Hast XR used, then must adopt a hold-out strategy for scram until core cools low enough to insert inner rods.
Outer Control Rods (See comment)	Normal Op	420	HastXR	440	HastXR	464	HastXR	482	HastXR	503	HastXR	526	HastXR	HastXR good to 927C long term. Need low Co in high-radiation environment
	Max Pressurized CCD	924	HastXR*	929	HastXR*	934	HastXR*	939	HastXR*	944	C-C or SiC-SiC	1,129	C-C or SiC-SiC	HastXR good to 940C up to 3000 hr. Could use Hast XR above 940C until ceramic composites qualified, but carries investment risk that creep during PCCD would make removal and replacement difficult after event
	Max Depressurized CCD	975	C-C or SiC-SiC	980	C-C or SiC-SiC	985	C-C or SiC-SiC	990	C-C or SiC-SiC	995	C-C or SiC-SiC	1,000	C-C or SiC-SiC	C-C good to 2000C; 2400C short term. SiC-SiC good to 1400; 1600C short term. Could use Hast XR above 940C until ceramic composites qualified, but carries investment risk that creep during PCCD would make removal and replacement difficult after event
Control Rod & Reserve Shutdown Material Guide Tubes	Normal Op	346	800H	346	800H	346	800H	346	800H	346	800H	346	800H	
	Max Pressurized CCD	928	HastX*	933	HastX*	938	HastX*	943	C-C or SiC-SiC	948	C-C or SiC-SiC	953	C-C or SiC-SiC	HastX good to 938C up to 3000 hr.
	Max Depressurized CCD	438	800H	418	800H	423	800H	428	800H	433	800H	438	800H	
Upper Core Restraint (See comment)	Normal Op	346	800H	346	800H	346	800H	346	800H	346	800H	346	800H	
	Max Pressurized CCD	1,023	C-C or SiC-SiC	1,028	C-C or SiC-SiC	1,033	C-C or SiC-SiC	1,038	C-C or SiC-SiC	1,043	C-C or SiC-SiC	1,048	C-C or SiC-SiC	Hast XR could be used until composites are qualified, but this involves an investment risk that creep deformation during a PCCD could make the UCR difficult to remove and replace after the event. Once ceramic composite installed, the risk is mitigated.
	Max Depressurized CCD	599	800H	604	800H	609	800H	614	800H	619	800H	624	800H	
Upper Plenum Shroud T/B Covered Sheets	Normal Op	318	800H	318	800H	318	800H	318	800H	318	800H	318	800H	
	Max Pressurized CCD	872	HastX	877	HastX	882	HastX	887	HastX	892	HastX	897	HastX	HastX good to 899C long term.
	Max Depressurized CCD	450	800H	455	800H	460	800H	465	800H	470	800H	475	800H	HastX good to 938C for up to 3000 hr.
Metallic Core Support Load Bearing Insulators	Normal Op	615	Macor Glass Ceramic	653	Macor Glass Ceramic	692	Macor Glass Ceramic	730	Macor Glass Ceramic	769	Macor Glass Ceramic	807	Macor Glass Ceramic	Macor Glass Ceramic chosen for low thermal conductivity & hi-temp capability
	Max Pressurized CCD	615	"	653	"	692	"	730	"	769	"	807	"	
	Max Depressurized CCD	615	"	653	"	692	"	730	"	769	"	807	"	
Hot Duct Thermal Barrier Assy	Normal Op	699	800H	749	800H	798	HastX	848	HastX	898	HastX	948	C-C or SiC-SiC	800H good to 760C long term.
	Long Term Peak	734	800H	786	HastX	837	HastX	887	HastX	937	C-C or SiC-SiC	986	C-C or SiC-SiC	HastX good to 899C long term. HastXR good to 927C long term.
	Short Term Peak	766	800H	820	800H*	874	HastX	923	HastX*	972	C-C or SiC-SiC	1,022	C-C or SiC-SiC	HastX good to 938C for up to 3000 hr.
	Max Pressurized CCD	699	800H	749	800H	798	800H*	848	800H*	898	HastX	948	C-C or SiC-SiC	800H good to 871C for up to 3000 hr.

Component	Temperature	Reactor Outlet Helium Temperature												Comment
	Condition	700C	Selected Mat'l	750C	Selected Mat'l	800C	Selected Mat'l	850C	Selected Mat'l	900C	Selected Mat'l	950C	Selected Mat'l	
	Max Depressurized CCD	699	800H	749	800H	798	800H*	848	800H*	898	HastX	948	C-C or SiC-SiC	
Lower Plenum Sidewall Thermal Barrier Assy	Normal Op	630	800H	670	800H	711	800H	752	800H	792	800H	833	HastX	
	Long Term Peak	664	800H	707	800H	750	800H	791	HastX	831	HastX	871	HastX	
	Short Term Peak	697	800H	742	800H	786	800H*	826	800H*	867	800H*	907	HastX*	**HastX good to 938C for up to 3000 hr.**
	Max Pressurized CCD	630	800H	670	800H	711	800H	752	800H	792	800H	833	800H*	**800H good to 871C for up to 3000 hr.**
	Max Depressurized CCD	630	800H	670	800H	711	800H	752	800H	792	800H	833	800H*	
Shutdown Cooling Circulator Entrance Tubes	Normal Op	615	800H	653	800H	691	800H	729	800H	768	HastX	806	HastX	
	Long Term Peak	664	800H	690	800H	730	800H	768	HastX	806	HastX	844	HastX	
	Short Term Peak	697	800H	724	800H	766	800H*	804	800H*	842	800H*	880	HastX	**800H good to 871C for up to 3000 hr.**
	Max Pressurized CCD	615	800H	653	800H	691	800H	729	800H	768	800H*	806	800H*	
	Max Depressurized CCD	615	800H	653	800H	691	800H	729	800H	768	800H*	806	800H*	
Shutdown Cooling Circulator Heat Exchanger Thermal Barrier Assy	Normal Op	350	800H	350	800H	350	800H	350	800H	350	800H	350	800H	Could choose lower-temperature material for this component
	Max Pressurized CCD	350	800H	350	800H	350	800H	350	800H	350	800H	350	800H	
	Max Depressurized CCD	350	800H	350	800H	350	800H	350	800H	350	800H	350	800H	

5.2 Material Selections

5.2.1 Control Rods

The first two components in Table 5-3 are the inner and outer control rods. During normal operation, if the control rods are partially inserted for reactor control purposes, the inner control rods will operate at a maximum temperature from 788°C, when the reactor outlet helium temperature is 700°C, up to 894°C when the reactor outlet helium temperature is 950°C. Likewise, the outer control rods will operate from 420°C to 526°C, respectively. These are temperatures at which Alloy 800H could be used. However, the radiation environment is severe for the control rods since parts of them reside in the reactor core for significant times. Due to the high cobalt content of Alloy 800H and Hastelloy X, it is desirable to use Hastelloy XR, which has 0 to 1.0% Co, for this application. Thus, Hastelloy XR is considered the best choice for normal reactor operation even though it has a higher temperature limit than needed.

Looking at the CCD events, it is seen that the maximum temperature of the outer control rods is reasonable for the PCCD, but the DCCD temperatures are very high. The inner control rods have very high maximum temperatures during both PCCD and DCCD events. Thus, both the inner and outer control rods should be fabricated from either C-C or SiC-SiC composites for all reactor outlet helium temperatures considered. This selection assumes that both the inner and outer control rods will be inserted at the beginning of a CCD event.

Another strategy could be implemented that would allow the outer control rods to be fabricated from Hastelloy XR for reactor outlet helium temperatures from 700°C to 850°C. This strategy involves using the outer control rods only for shutting the reactor down, and holding out the inner rods until the core has cooled enough, several hundred hours later, to insert the inner rods at an acceptable temperature. For reactor outlet helium temperatures from 700°C to 850°C, this strategy will work for PCCD events, but not for a DCCD event. For a DCCD event, composite materials are needed to minimize problems retracting the control rods after the event. However, there is no safety problem with inserting the outer or the inner control rods. The neutron absorber material is boronated graphite, which has adequate high-temperature capability to withstand the CCD temperatures. However, the metallic structural parts of the control rod will be in the creep regime resulting in creep elongation of the metallic spine of the rod assembly. The rods will bottom out in the control rod channels. However, the boron absorber material will maintain its shape and remain in the CR channel in the proper position for shutting down the chain reaction. Subsequent removal of a highly deformed control rod may be difficult, but it is not a safety concern because the neutron absorber material is maintained in the proper location to shut down the chain reaction.

The conclusion from this scenario is that a strategy can be developed to use Hastelloy XR material for the structural parts of the control rods with minimal R&D. During that interim period of time, C-C or SiC-SiC composite material control rods can be retro-fitted in the reactor after all necessary irradiation effects data are collected, analyzed, and incorporated into the hardware design. Once the composite control rods are installed in a reactor, all rods can be inserted into the core for any condition, removing the need to hold out the inner rods. It is recommended that this strategy be adopted for the NGNP with reactor outlet helium temperatures up to 850°C. For higher reactor outlet helium temperatures, 900°C to 950°C, only composite materials should be used because even the outer rods need to be made of composites.

5.2.2 Upper Plenum Components

The control rod and reserve shutdown guide tubes, UCR, and upper plenum shroud could be made from Alloy 800H if they were exposed only to normal operation and DCCD conditions. However, higher-temperature materials must be used for these components because a PCCD event subjects them to much higher temperatures.

The upper plenum shroud thermal barrier should be made from Hastelloy X for all reactor outlet helium temperatures from 700°C to 950°C. Hastelloy X can be used because of the low neutron fluence. If activation of Co is a concern, Hastelloy XR can be substituted for Hastelloy X.

The guide tubes should be made of Hastelloy X for reactor outlet helium temperatures up to 850°C, but composites should be used when the reactor outlet helium temperatures is 850°C and above.

Unless the maximum service temperature for the UCR during a PCCD event is found to be lower in subsequent systems analyses than the estimate herein, it is not advisable to make the UCR elements from metals. This is because it is doubtful that excessive creep deformation would be allowed during a PCCD event given that the plant will be expected to be operational after such an event and the UCR elements may be difficult to remove and replace if excessive creep deformation has occurred. Although this is not a safety issue, the reactor down time required to remove and replace these elements is unknown. Thus, the UCR elements should be made of SiC-SiC or C-C composites because the composite UCR elements would not have to be replaced after the PCCD event.

However, it is considered unlikely that ceramic composite UCR elements can be developed and qualified on a schedule that would make them available for an NGNP startup in 2021. Thus, an alternate strategy would be to make the initial UCR elements for the NGNP from Hastelloy XR, while ceramic composite UCR elements are being qualified as replacements for the metal components. However, as noted above, this strategy involves a risk of prolonged reactor downtime due to replacement difficulties caused by excessive creep deformation of the metallic UCR elements. However, this is an investment risk, not a safety issue.

In summary, the following is recommended:

1. The upper plenum shroud thermal barrier cover plate assemblies should be made of Hastelloy X.

2. The control rod and reserve shutdown guide tubes should be made of Hastelloy X for reactor outlet helium temperatures ranging from 700°C to 800°C, but be made of ceramic composites for reactor outlet helium temperatures above 800°C.

3. The UCR elements should be made from ceramic composites for all reactor outlet helium temperatures considered because of the high temperatures to which these elements are subjected during a PCCD. However, it may be necessary to make the UCR elements for the initial NGNP core from a high-temperature metal because it is unlikely that the ceramic composites can be developed and qualified on a schedule that would make them available for an NGNP startup in 2021. The recommended metallic material for the initial UCR elements is Hastelloy XR because of its good high-temperature properties and low cobalt content. Longer term, the metallic UCR elements would be replaced with composite UCR elements after development and qualification of the UCR elements has been completed.

5.2.3 Lower Plenum Components

The lower plenum components that are directly affected by high temperatures are the metallic core support load-bearing insulator pads, hot duct thermal barrier cover plate assemblies, lower plenum sidewall thermal barrier assembly, and the shutdown cooling circulator entrance tubes. The shutdown circulator shroud is bathed in the reactor inlet helium at 350°C and does not experience the high temperatures associated with higher inlet-helium-temperature designs.

The load bearing insulator pads shall be made from Macor glass ceramic (produced by both Morgan Technical Ceramics and Corning, Inc.) since the temperatures are not critical and the insulation qualities are good. Thus, no change in material is found necessary, from the selection made in the original study (Ref 1).

The choice of materials in the lower plenum is greatly affected by the magnitude of helium hot streaks that occur during normal operation and contact the materials of the components. Helium hot streaks are an inherent part of this reactor design because no local flow control devices are used to control flow in the fuel columns resulting in different fuel column outlet temperatures. These hot streaks need to mix together in the lower plenum and hot duct to minimize variation in temperature of the gas entering the gas turbine or steam generator. The design of the passages in the bottom reflector aids in mixing local hot streaks before they enter the lower plenum. Also the mixing of many small gas streams in the lower plenum is found to be quite good.

The CCD temperatures are not critical for these components. They decline steadily from the normal operation temperatures during a CCD event.

Thus, normal operation hot streaks determine the materials for lower plenum components. For this reactor design, the hot streaks have been found to be sufficiently mixed to allow use of readily available metallic materials for reactor outlet helium temperatures up to 950°C, except for the hot duct. As can be seen in Table 5-3, the hot duct requires composite thermal barrier cover plates for reactor outlet helium temperatures above 900°C.

The following summarizes the choice of materials for the lower plenum:

1. The hot duct thermal barrier assembly parts should be made of Alloy 800H for a 700°C reactor outlet helium temperature, Hastelloy X for reactor outlet helium temperatures from 750°C to 850°C, and composites for reactor outlet helium temperatures above 900°C.

2. The lower plenum side wall thermal barrier and the shutdown circulator entrance tubes should be made of Alloy 800H for reactor outlet helium temperatures from 700°C to 800°C, and Hastelloy X for reactor outlet helium temperatures of 850°C to 950°C. If activation of the cobalt in Hastelloy X is a concern, then Hastelloy XR can be used.

The material choices are summarized in Table 5-4, color-coded to show the changes in materials as the reactor outlet helium temperature increases. The reactor inlet helium temperature is 350°C for all cases.

Table 5-4. Material Selections for 600-MWt NGNP Reactor Internals Components

Comp	Temperature Condition	Reactor Outlet Helium Temperature and Material Selection[1]											
		700C	Mat'l Sel	750C	Mat'l Sel	800C	Mat'l Sel	850C	Mat'l Sel	900C	Mat'l Sel	950C	Mat'l Sel
Inner CR[2]	Normal Op	788	C-C or SiC-SiC	808	C-C or SiC-SiC	832	C-C or SiC-SiC	850	C-C or SiC-SiC	871	C-C or SiC-SiC	894	C-C or SiC-SiC
	PCCD Max	1,159		1,164		1,169		1,174		1,179		1,184	
	DCCD Max	1,413		1,418		1,463		1,428		1,433		1,438	
Outer CR[2]	Normal Op	420	C-C or SiC-SiC	440	C-C or SiC-SiC	464	C-C or SiC-SiC	482	C-C or SiC-SiC	503	C-C or SiC-SiC	526	C-C or SiC-SiC
	PCCD Max	924		929		934		939		944		1,129	
	DCCD Max	975		980		980		990		995		1,000	
CR & RSM Guide Tubes	Normal Op	346	Hast X	346	Hast X	346	Hast X	346	C-C or SiC-SiC	346	C-C or SiC-SiC	346	C-C or SiC-SiC
	PCCD Max	928		933		638		943		948		953	
	DCCD Max	438		418		423		428		433		438	
UCR[3]	Normal Op	346	C-C or SiC-SiC	346	C-C or SiC-SiC	346	C-C or SiC-SiC	346	C-C or SiC-SiC	346	C-C or SiC-SiC	346	C-C or SiC-SiC
	PCCD Max	1,023		1,028		1,033		1,038		1,043		1,048	
	DCCD Max	599		604		609		614		619		624	
UPS T/B	Normal Op	318	Hast X	318	Hast X	318	Hast X	318	Hast X	318	Hast X	318	Hast X
	PCCD Max	872		877		882		887		892		897	
	DCCD Max	450		455		460		465		470		475	
MCS Load Pads	Normal Op	615	Macor Glass Ceramic	653	Macor Glass Ceramic	692	Macor Glass Ceramic	730	Macor Glass Ceramic	769	Macor Glass Ceramic	807	Macor Glass Ceramic
	PCCD Max	615		653		692		730		769		807	
	DCCD Max	615		653		692		730		769		807	
Hot Duct T/B	Normal Op	699	800H	749	Hast X	798	Hast X	848	Hast X	898	C-C or SiC-SiC	948	C-C or SiC-SiC
	Long Term Peak	734		486		837		837		937		986	
	Short Term Peak	766		820		874		923		972		1,022	
	PCCD Max	699		749		798		848		898		948	
	DCCD Max	699		749		798		848		898		948	
LPS T/B	Normal Op	630	800H	670	800H	711	800H	752	Hast X	792	Hast X	833	Hast X
	Long Term Peak	664		707		750		791		831		871	
	Short Term Peak	697		742		786		826		867		907	
	PCCD Max	630		670		711		752		792		833	
	DCCD Max	630		670		711		752		792		833	
SCS Entrance Tubes	Normal Op	615	800H	653	800H	691	800H	729	Hast X	768	Hast X	806	Hast X
	Long Term Peak	664		690		730		768		806		844	
	Short Term Peak	697		724		766		804		842		880	
	PCCD Max	615		653		691		729		768		806	
	DCCD Max	615		653		691		729		768		806	
SCS T/B	Normal Op	350	800H	350	800H	350	800H	350	800H	350	800H	350	800H
	PCCD Max	350		350		350		350		350		350	
	DCCD Max	350		350		350		350		350		350	

1. Reactor inlet helium temperature is 350°C for all cases
2. The control rods can be made of Hastelloy XR until ceramic composite materials are qualified. The metallic CRs will then be replaced with CRs manufactured from composite materials. See conclusions 6, 7, & 8 and recommendations 2 & 3.
3. The UCR elements can be made of Hastelloy XR until ceramic composite materials are qualified. The UCR elements will then be replaced with UCR elements manufactured from composite materials. See conclusion 5 and recommendations 2 & 3.

6 TECHNOLOGY DEVELOPMENT REQUIREMENTS

Development issues and the technology needed to support a reactor design and build program have been identified for ceramic composites in the previous report (Ref. 1). Therefore, no additional discussion of data needs for composites will be addressed in this report.

The metallic materials Alloy 800H, Hastelloy X and Hastelloy XR are well known materials. Alloy 800H and Hastelloy X are part of the ASME Code. Hastelloy XR is a refinement of Hastelloy X with low cobalt content and slightly higher temperature limits. It has not been completely endorsed by the ASME code For reactor internals components that are primary load bearing structures which transmit the core mechanical loads to the reactor vessel, use of the ASME code is an important factor in the design and licensing the nuclear plant. However, for those components that perform important functions necessary for control, or cooling/insulation, of the reactor, but do not carry primary loads, the ASME Code is an important source of well established rules for design and construction of equipment, but not absolutely necessary. The control rods, thermal barrier, and non-load bearing internals fit into this category.

The increased reactor inlet and outlet helium temperatures associated with the desire to design ever higher efficiency reactor plants, has pushed the limit on the high temperature metallic materials being recommended for the NGNP. Thus, to use them at even higher temperatures for which they are currently qualified requires some additional technology development effort. Material behavior information must be obtained to validate the engineering processes for design and qualification of these materials.

The technology steps that are needed are:

1. Search the existing literature for all the information on Alloy 800H, Hastelloy X, and Hastelloy XR, and incorporate it into a design handbook specifically for the NGNP. Write a DDN to obtain the existing Data.

2. Identify the data that is missing from this handbook, any statistical analysis of the data that is needed, and material behavior and strength modeling needed to support the design and qualification process for NGNP application. Write as many DDNs as needed to define the missing data.

3. Obtain the necessary data by purchasing it from others, or performing appropriate tests. Identify any neutron irradiation data that is needed. Identify any helium effects tests needed for the required NGNP environment.

4. Incorporate the newly obtained data into the design handbook and design methods.

5. Prepare material specifications for purchase of these materials so that the required behavior is assured.
6. Prepare joining specifications for fabrication of components from these materials.
7. Use this information in the design validation process, procurement and fabrication of components, along with any component performance tests deemed necessary to validate the required component performance.

Design data needs need to be developed and will be shown in Section 6.2, but the technology development schedule is first discussed below.

6.1 Technology Development Schedule

This schedule shown in Figure 6-1 was taken from the previous report issued in late 2008 (Ref. 1). It is inaccurate on the specific times that milestones must be met, but has the correct sequence of events. It serves well as a framework upon which to discuss the technology needs.

For the most part the material behavior and strength models must be available for the preliminary and final design phases. This should not be a problem since these models already exist. Any new data must be available during the final design to validate the design. Material and joining specifications must be completed by the time procurement of the metallic reactor internals is initiated.

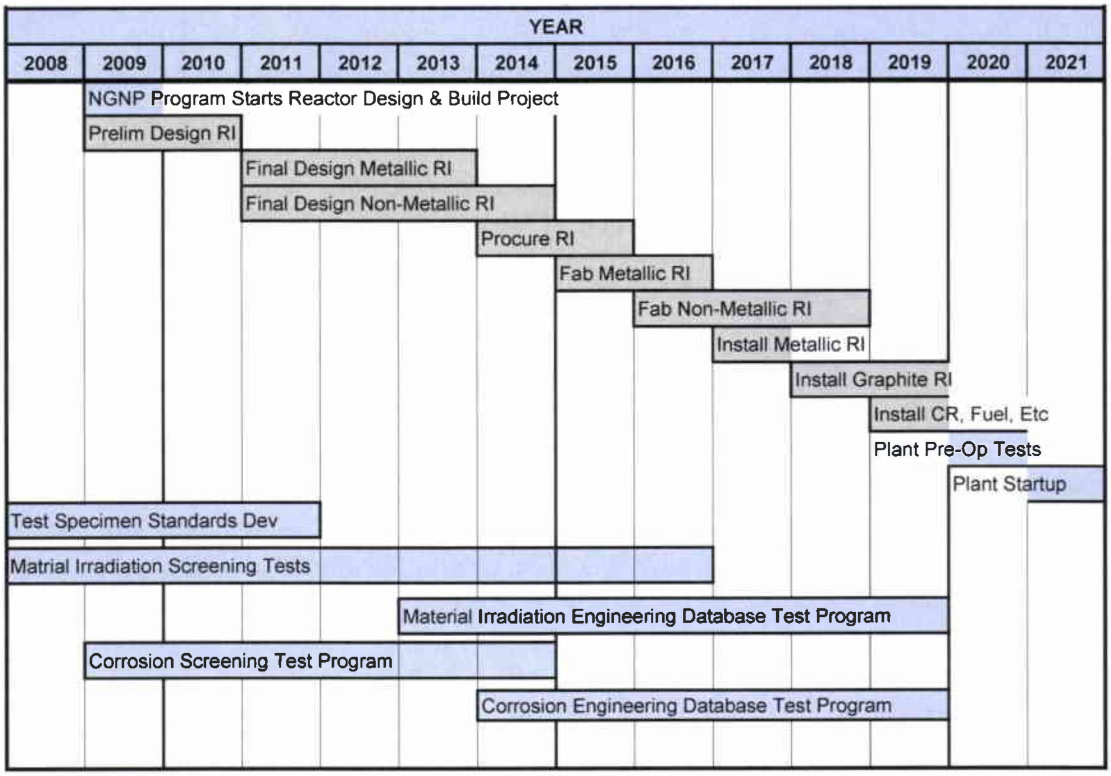

Figure 6-1. Summary-level technology development notional schedule

6.2 Design Data Needs

The technology program has already been established, for the most part, for these metallic materials. Design data needs (DDNs) have been identified to obtain data. Table 6-1 lists the relevant DDNs that pertain to high-temperature materials for the NGNP. These DDNs were extracted from the NGNP DDN list contained in Ref. 16. Only the additional data needed to support higher temperature use of Alloy 800H, Hastelloy X, and Hastelloy XR in the NGNP are discussed below. The existing DDNs can be modified to include the data needed for higher temperature use as described in this report.

Table 6-1. DDNs for Reactor Internals Design and Procurement

DDN NO.	DDN TITLE	SOURCE
C.11.00	REACTOR System (RS)	
C.11.01	Neutron Control System	Commercial GT-MHR
N.11.01.12	CR & RSM Guide Tubes - Effect of Low Level Irradiation on Composite Materials	Reference 1
N.11.01.13	CR & RSM Guide Tubes - Composite Material Properties	"
N.11.01.14	CR & RSM Guide Tubes - Effects on Composites of Primary He and Temperature	"
N.11.01.15	CR & RSM Guide Tubes - Composite Component Manufacturing Process Development	"
C.11.02	Reactor Internals (RI) and Hot Duct	Commercial GT-MHR
N.11.02.10	Effects of Primary He and Temperature on Metallic Reactor Internals Materials	New
N.11.02.11	Irradiation Effects on Metallic Reactor Internals Materials	Significant Changes
N.11.02.12	Irradiation Effects on Hot Duct Metals	"
N.11.02.13	Effects of Primary He and Temperature on Hot Duct Materials	"
N.11.02.14	Fibrous Insulation Material Properties	"
C.11.02.15	Hard Ceramic Insulation Properties Data	Commercial GT-MHR
N.11.02.16	Emissivity of Metallic Materials Reactor Internals	Significant Changes
N.11.02.17	Hot Duct-Effect of Low Level Irradiation on Composite Materials	Reference 1
N.11.02.18	Hot Duct-Composite Material Properties	"
N.11.02.19	Hot Duct- Effects on Composites of Primary He and Temperature	"
N.11.02.20	Hot Duct-Composite Component Manufacturing Process Development	"
N.11.02.21	UPS-Effect of Low Level Irradiation on Composite Materials	"
N.11.02.22	UPS-Composite Material Properties	"
N.11.02.23	UPS- Effects on Composites of Primary He and Temperature	"
N.11.02.24	UPS-Composite Component Manufacturing Process Development	"
N.11.02.25	UCR-Effect of Low Level Irradiation on Composite	"

DDN NO.	DDN TITLE	SOURCE
	Materials	
N.11.02.26	UCR-Composite Material Properties	"
N.11.02.27	UCR- Effects on Composites of Primary He and Temperature	"
N.11.02.28	UCR-Composite Component Manufacturing Process Development	"
C.11.03	Reactor Core	Commercial GT-MHR
C.11.03.05	Control Rod Shock Absorber Data	"
C.11.03.06	Control Rod Structural Integrity Data	"
C.11.03.24	Properties of High Temperature Control Rod Materials	"
N.11.03.53	Control Rod - Effect of High Level Irradiation on Composite Materials	[Vollman 2008]
N.11.03.54	Control Rod - Composite Material Properties	"
N.11.03.55	Control Rod - Composite Component Manufacturing Process Development	"
		"
C.14.00	SHUTDOWN COOLING SYSTEM (SCS)	
C.14.01	Shutdown Circulator	Commercial GT-MHR
N.14.01.05	Irradiation Effects on SCS Circulator Materials	New
N.14.01.06	Effects of Primary Coolant Helium and Temperature on SCS Circulator Materials	New

The metallic materials being recommended are not new. Alloy 800H and Hastelloy X are well characterized and included in the ASME code for temperatures up to a non time dependant limit and further where creep effects are important. What is needed is to extend the use of these materials to the maximum capability of each material. These maximums are in the neighborhood of 900°C for Alloy 800H and 950°C for Hastelloy X. The Mitsubishi alloy, Hastelloy XR, also need to be extended.

Hastelloy XR is an alloy developed by Japanese technologists at Mitsubishi for use in gas-cooled reactors. It has a lower cobalt content (0 - 1.0%) than Hastelloy X (0.5% - 2.5%) to minimize activation by neutron irradiation. It also has additional data to support its use at higher temperatures than Hastelloy X. It has been tentatively qualified for use up to 927°C.

In general these alloys are very well characterized materials. Data are needed beyond the current temperature limit of 871°C for Alloy 800H, 899°C for Hastelloy X, and 927°C for Hastelloy XR. Corrosion effects data are needed for the helium impurities shown in Tables 3-4 and 3-5, specifically the effects on material behavior, and strength. Data are needed to 950°C and 1000°C on conductivity, specific heat, emissivity, thermal expansion, static strength, time dependant strength, fracture toughness, crack propagation rates, creep, elastic modulus, Poison's ratio, and fatigue. The effects on welds needs to be determined for the base metal, weld metal, and weld affected zone. It is very important to obtain creep curves for the material to establish the rate of deformation with time. Only with this information can the temperature limits be established and the necessary materials identified as a prerequisite to performing time-dependant stress analysis of these components.

These DDNs, listed in Table 6-1, need to be modified to incorporate the higher-temperature data needs. Most of these data are available from the database that has been obtained to set the high-temperature allowable stress levels in the ASME Code. Thus, a thorough literature search and discussions with material experts may be all that is needed. Once this has been completed, any additional testing found necessary to complete the database can be planned and performed using already existing test standards.

The effects of neutron radiation need to be understood. Any data not found in the literature shall be identified, tests planned and executed. The same holds for corrosion in helium with the required impurities. Oak Ridge National Laboratory, among others, has the capability to obtain this data. Irradiation of specimens can be done in the HFIR at ORNL.

Material and strength models must be extended to enable time dependant design analysis and validation of the efficacy of the final design. Material and weld specifications need to be modified, as needed, to procure and fabricate these materials.

It is anticipated that the literature search will provide most data needed, including irradiation and helium effects data. It is also expected that only a small amount of high temperature creep data will be needed. Table 6-2 identifies the additional tests needed for these high-temperature metallic materials.

Table 6-2. Additional Data Needed for Alloy 800H, Hastelloy X, and Hastelloy XR

Item – Type of Data	Alloy 800H	Hastelloy X	Hastelloy XR
Currently Allowed Maximum Temperature	760°C	899°C	927°C
Max. Temperature Data Needed	950C	1000C	1000C
Max. Neutron Fluence – Control Rods	NA	NA	3.2×10^{26} n/m^2
Max. Neutron Fluence - Upper Core Restraint	NA	NA	3.5×10^{24} n/m^2
Max. Neutron Fluence – Reactor Internals	1×10^{23} n/m^2	1×10^{23} n/m^2	1×10^{23} n/m^2
Conductivity	X	X	X
Specific Heat	X	X	X
Emissivity	X	X	X
Thermal expansion	X	X	X
Static strength	X	X	X
Ductility	X	X	X
Elastic modulus/ tangent Modulus	X	X	X
Time dependant strength & ductility	X	X	X
Creep rates vs. temperature and stress	X	X	X
Poison's ratio	X	X	X
Fatigue vs. number of cycles	X	X	X
Creep fatigue interaction	X	X	X
Fracture toughness (K_{Ic})	X	X	X
Crack propagation rate vs. Stress intensity factor range (da/dn vs. delta K_I)	X	X	X
Base Metal	X	X	X
Weld affected zone	X	X	X
Weld	X	X	X

7 CONCLUSIONS AND RECOMMENDATIONS

This section lists the essential conclusions of this study regarding the effect on the choice of materials for the high-temperature components of the 600-MWt Reactor System for a constant reactor inlet helium temperature of 350°C and a range of reactor outlet helium temperatures from 700°C to 950°C. The technology issues associated with use of several high-temperature materials are also discussed. It also presents recommendations that, if adopted, should enhance the potential for successful deployment of high-temperature metals, and ceramic composite materials in the NGNP Reactor System.

7.1 Conclusions

1. The metallic core support load bearing insulator pads are unaffected by the reactor outlet helium temperature since they are very nearly at the temperature of the reactor inlet helium (350°C). Thus, they can be made from Macor glass ceramic, the original choice of material in the 2008 study (Ref. 1), for its low conductivity and strength, produced by both Morgan Technical Ceramics and Corning, Inc.

2. The shutdown cooling system thermal barrier can be made of Alloy 800H for all reactor outlet temperatures evaluated.

3. The shutdown cooling system flow entrance tubes and the lower plenum side wall thermal barrier should be made from alloy 800H for reactor outlet temperatures from 700°C - 800°C and Hastelloy X for reactor outlet temperatures from 850°C - 950°C.

4. Hot duct thermal barrier cover plates are affected by reactor outlet helium temperature during normal operation as follows:

    - Alloy 800H is needed for a reactor outlet helium temperature of 700°C
    - Hastelloy X is needed for reactor outlet helium temperatures from 750°C - 850°C
    - Ceramic composites are needed for reactor outlet helium temperatures at or above 900°C

5. The Upper Core Restraint (UCR) elements should be made from ceramic composites, because the temperatures that result from the decay heat for a 600-MWt reactor are too high for use of metallic materials during a PCCD event for all reactor outlet helium temperatures evaluated. However, it is considered unlikely that ceramic composite UCR elements can be developed and qualified on a schedule that would make them available for an NGNP startup in 2021. Thus, an alternate strategy would be to make the initial UCR elements for the NGNP from Hastelloy XR, while ceramic composite UCR elements are

being qualified as replacements for the metal components. If these elements are made from Hastelloy XR, it is anticipated that excessive creep deformation could occur that will make it difficult to remove and replace these elements after a PCCD so that normal operations can be continued. Thus, this strategy involves a risk of prolonged reactor downtime due to replacement difficulties caused by excessive creep deformation of the UCR. However, GA considers this is an investment risk, not a safety issue.

6. The control rod and reserve shutdown material guide tubes can be made from Hastelloy X for reactor outlet temperatures ranging from 700°C - 800°C and ceramic composite for outlet temperatures at or above 850°C. The maximum temperature for the PCCD is 953°C, which is still within the range of possibilities for Hastelloy X use, but above the current allowable temperature range. If it can be shown from test data that Hastelloy X can withstand this temperature and meet requirements, then the CR & RSM guide tubes can be made from Hastelloy X for reactor outlet helium temperatures up to 950°C. Hastelloy XR, with its low cobalt content, is not needed for the guide tubes because the neutron fluence is low.

7. The outer control rods are needed to control and shut down the reactor. These rods experience a very-high neutron fluence and need to be made from ceramic composite materials because the maximum temperatures during a DCCD event are just above the current short-term allowable temperature limits for high-temperature metals. Outer control rod temperatures during a PCCD event are low enough to use Hastelloy XR for reactor outlet helium temperatures up to 850°C. Hastelloy XR is preferred over Hastelloy X because of its low cobalt content for these high fluence components. Low cobalt results in less neutron activation for easier waste management. Ceramic composites are needed above this reactor outlet temperature. During normal operation the rods are at a maximum of 526°C, well within the capability of Hastelloy XR. Hastelloy XR could be used for reactor outlet temperatures up to 850°C, where the CR temperature reaches 939°C, if data show that recovery to normal operation is possible after the PCCD event. This is predicated on allowing excessive creep deformation of the rods for the slightly higher temperature DCCD event because removal and replacement of the rods is not required. Slumping of the control rods is not a safety problem because the neutron absorber materials remain in the core at the proper location. It is only an investment risk concern, if the rods are required to be removed and replaced quickly to minimize reactor downtime.

8. The inner control rods are used only to shut down the reactor to cold conditions. Power level and shaping are done with the outer rods. Long term, the inner control rod structural elements need to be made from ceramic composite material because the CCD temperatures are too high for all reactor outlet temperatures considered in this study. Thus, they should be fabricated from a 3-dimensional C-C composite because the maximum temperature during all CCD events ranges from 924°C to 1438°C. They could also be made of SiC-SiC

composites for longer life in a nuclear radiation environment. The current strategy is to insert all control rods for any required scram causing the inner rods to experience the high temperatures of the CCD event in the core rather than hanging above the core. The inner rods could be made from Hastelloy XR if they are not inserted into the core at the beginning of a scram, but held out until core temperatures are low enough to insert the Hastelloy XR rods. Normal operation temperatures would allow the use of a metallic structure made of Hastelloy XR. Again, Hastelloy XR is preferred over Hastelloy X because it has a much lower cobalt content.

9. Currently, the C-C composite FMI-222 is the only candidate that has enough radiation data to be selected for the control rods. The maximum life appears to be eight years. This life is adequate because the control rods can be replaced easily. The corrosion resistance of this material in the expected NGNP reactor helium environment must be evaluated on an expedited basis to ensure there are no life-limiting corrosion effects.

   A longer-term material choice for the control rods is a SiC-SiC composite, possibly Hi-Nicolan^{TM}, due to its apparent much-greater radiation and corrosion tolerance. However, at this time it is limited to a temperature of 1400°C. If this limit can be increased to 1600°C, a SiC-SiC composite would be a better choice because the control rod lifetime could be 60 years if this material is used. However, more tests need to be conducted on this material, including corrosion tests, to verify that it is a viable choice. Also, the final choice of architecture and SiC-SiC material needs to be completed.

   For reactor outlet helium temperatures from 700°C to 850°C, Hastelloy XR could be used as an interim material until such time as composites can be fully qualified. While considerable creep of the rods would occur, there would be no safety problem with metallic rods because the neutron poison stays in place during a CCD event. However, there is a risk of extended reactor down time if all the rods have to be removed and replaced.

7.2 Recommendations

1. Include in the NGNP Technology Program the development of both C-C and SiC-SiC composite materials to provide qualified ceramic composite materials for use in fabrication of high-temperature reactor internals components.

2. For reactors with a reactor inlet helium temperature of 350°C and reactor outlet helium temperature range of from 700°C - 800°C use the following materials:

   - In the short term, while ceramic composites are being qualified, use Hastelloy XR for the control rod and UCR structures. Long term, qualify a ceramic composite material for fabrication of replacement control rods and UCR elements.

- Use Hastelloy X for the CR & RSM Guide tubes, Upper Plenum Shroud thermal barrier.

- For the Hot Duct thermal barrier cover plates use Alloy 800H for reactor outlet temperature of 700°C and Hastelloy X for reactor outlet temperatures ranging from 750°C to 800°C.

- Use Alloy 800H for the Lower Plenum Side Wall thermal barrier, SCS Entrance Tubes thermal barrier, and SCS heat exchanger shroud.

3. Allow the interim use of Hastelloy XR for control rods and UCR elements, with appropriate changes in the strategy for removal and replacement of these components after a CCD event. Adopt a strategy of holding out the inner control rods for a scram until such time as the core is cool enough to insert them. Replace these components with ceramic composite units when sufficient development has been completed and the composite units are available.

8 REFERENCES

1. "NGNP Composite R&D Technical Issues Study," GA Report 911125, Rev. 0, October 13, 2008

2. C-Min-Hwan Kim, Jisu-Jun, Won Jae Lee, "A Thermal-Fluid Analysis for the Selection of Operating Conditions of Reactor Internals," KAERI Report No. NHDD-RD-08-005, Rev. 2, April 21, 2009

3. "600MWt Gas Turbine-Modular Helium Reactor System Design Description," GA DRAFT Report No. DOE-MHR-100011 (RDI#2320-0007) Rev. 0, September 22, 1994

4. Min-Hwan Kim, Jisu-Jun, Won Jae Lee, "A thermal-Fluid Analysis for the Selection of Operating Conditions of Reactor Internals," KAERI Report No. NHDD-RD-08-005, Rev. 1, September 12, 2008

5. "Final Report – NGNP Core Performance Analysis, Phase 1," GA Report 91160, Rev. 0, March 16, 2009

6. "Heat Transport System Design Report," GA Report No. DOE-HTGR-86122, Rev. 2, September 28, 1990

7. Presentation by David G. Schowalter, PhD, of Fluent, Inc., on FLUENT analysis of the lower plenum by Richard R. Schultz & Walt L. Weaver, PhD, INEEL, Proceedings of ICONE11, April 20-23, 2003

8. "600MWt Gas Turbine-Modular Helium Reactor Design Data Needs," GA Report No. DOE-MHR-100217, Rev 0, August 29, 1996

9. ASME Code for Metals, Section III, Div. 1

10. ASME Code for Graphite, Section III, Div. 2, Subsection CE

11. ASTM Standards Committee C28 on Advanced Ceramics, "C" series ASTM standards on Ceramics and Ceramic Composites, Status Report Dated January, 2007

12. T.E. Blue, Miller, D.E., "Nuclear Power Monitoring Using Silicon Carbide Semiconductor Radiation Detectors," NERI Quarterly Report for the Period April-June 2003, Project No. DE-FG03-02SF22620, Ohio State University

13. Osborne, Hubbard, Snead and Steiner, "Neutron irradiation effect on the density, tensile properties and microstructural changes in Hi-Nicalon™ and Sylramic™ SiC fibers"

14. Newsome et al, "Evaluation of neutron irradiated silicon carbide and silicon carbide composites," Journal of Nuclear Materials 371, pp. 76-89, 2007

15. Morgan Technical Ceramics, Materials Data (Advanced Ceramics), data handbook, September 2005

16. "Reconciliation of NGNP DDNs with NRC PIRTs", GA Report PC-000570, Rev. 0, September 2008, Table 3-1, pp 18-28.

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