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Very High Temperature Reactor (VHTR)

Survey of Materials Research and Development Needs to Support Early Deployment

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Executive Summary

The VHTR reference concept is a helium-cooled, graphite moderated, thermal neutron spectrum reactor with an outlet temperature of 1000°C or higher. It is expected that the VHTR will be purchased in the future as either an electricity producing plant with a direct cycle gas turbine or a hydrogen producing (or other process heat application) plant. The process heat version of the VHTR will require that an intermediate heat exchanger (IHX) and primary gas circulator be located in an adjoining power conversion vessel. A third VHTR mission – actinide burning – can be accomplished with either the hydrogen-production or gas turbine designs. The first "*demonstration*" VHTR will produce both electricity and hydrogen using the IHX to transfer the heat to either a hydrogen production plant or the gas turbine.

The plant size, reactor thermal power, and core configuration will be designed to assure passive decay heat removal without fuel damage during accidents. The fuel cycle will be a once-through very high burnup low-enriched uranium fuel cycle.

The purpose of this report is to identify the materials research and development needs for the VHTR. To do this, we focused on the plant design described in Section 2, which is similar to the GT-MHR plant design (850°C core outlet temperature). For system or component designs that present significant material challenges (or far greater expense) there may be some viable design alternatives or options that can reduce development needs or allow use of available (cheaper) materials. Nevertheless, we were not able to assess those alternatives in the time allotted for this report and, to move forward with this material research and development assessment, the authors of this report felt that it was necessary to use a GT-MHR type design as the baseline design.

The following major components are discussed in this report:

- The reactor pressure vessel;
- The reactor core graphite;
- The reactor internals materials including the metallic, carbon-carbon composite, and insulation materials;
- The intermediate heat exchanger; and
- The power conversion system including the turbine inlet shroud, turbine, and recuperator.

Materials development and qualification needs for components of the portion of the hydrogen-production subsystem downstream from the intermediate heat exchanger were explicitly not considered in this report.

After assessing the available high temperature materials information and prior research and development results, we concluded that, although there are significant materials developments and qualification needs for the VHTR, existing materials are available that should meet the requirements of all VHTR components and subsystems.

The needed materials development tasks, schedules, and costs are presented in Section 4 of the report. The costs for the needed work for the GT-MHR and the VHTR are summarized below:

Component	**GT-MHR Costs**	**VHTR Costs**
Reactor pressure vessel	39	55
Graphite	30	42
Metallic internals materials	10	12
Carbon-carbon composite and insulation internals materials	17	31
Intermediate heat exchanger materials	0	22
Power conversion system	5	15
Total	101	177

The total cost estimate for development of the needed materials for the VHTR is $177 million dollars. The VHTR costs include and/or replace the corresponding materials developmental needs for the GT-MHR, now estimated to be a total of $101M. It is worth noting that much of the materials development required for the Gen IV VHTR will also be required by and will support the other Generation IV reactor concepts.

Contents

Introduction

The VHTR reference concept is a helium-cooled, graphite moderated, thermal neutron spectrum reactor with an outlet temperature of 1000°C or higher. It is expected that the VHTR will be purchased in the future as either an electricity producing plant with a direct cycle gas turbine or a hydrogen producing (or other process heat application) plant. The process heat version of the VHTR will require that an intermediate heat exchanger (IHX) and primary gas circulator be located in an adjoining power conversion vessel. A third VHTR mission – actinide burning – can be accomplished with either the hydrogen-production or gas turbine designs. The first "*demonstration*" VHTR will produce both electricity and hydrogen using the IHX to transfer the heat to either a hydrogen production plant or the gas turbine.

The plant size, reactor thermal power, and core configuration will be designed to assure passive decay heat removal without fuel damage during accidents. The fuel cycle will be a once-through very high burnup low-enriched uranium fuel cycle.

The basic technology for the VHTR has been established in former high temperature gas-cooled reactor plants (DRAGON, Peach Bottom, AVR, THTR, Fort St. Vrain). In addition, the technologies for the VHTR are being advanced in the Gas Turbine-Modular Helium Reactor (GT-MHR) Project and the pebble bed and prismatic reactor (PBR and PMR) International Near-Term Deployment projects. Furthermore, the Japanese HTTR and Chinese HTR-10 projects are demonstrating the feasibility of some of the planned VHTR components and materials. (The HTTR is expected to reach a maximum coolant outlet temperature of 950°C in 2003.) Therefore, the VHTR project is focused on building a demonstration plant, rather than simply confirming the basic feasibility of the concept.

One or more of three basic processes will use the heat from the high temperature helium coolant to produce hydrogen. The first process is the thermo-chemical splitting of water into hydrogen and oxygen. The primary candidate thermo-chemical process is the iodine-sulfur (IS) process. The second process is steam reformation of methane. This is the primary means, today, for hydrogen generation used in fossil fueled process plants. The third process is thermally assisted electrolysis. The high efficiency Brayton cycle enabled by the VHTR may be used to generate the hydrogen from water by electrolysis. The efficiency of this process can be substantially improved by heating the water to high temperature steam before applying electrolysis. The waste heat from the pre-cooler and inter-cooler of the Brayton cycle, therefore, can be used to further improve the efficiency of hydrogen production.

The VHTR is the nearest term of the six reference Generation IV reactor concepts. It is envisioned that a deliberate and focused program of R&D in support of a disciplined design and construction project could make a demonstration VHTR, with a flexible hydrogen production system, operational by 2017. The significant advantages of high fuel burnup, passive safety, low O&M cost, and potential modular construction were evident in the Generation IV submitted concepts. The final design of the demonstration VHTR will be constrained to maintain these advantages.

The purpose of this report is to identify the materials research and development needs for the VHTR. To do this, we have chosen to focus on the plant design described in Section 2, which is similar to the GT-MHR plant design. The single most significant factor in changing the materials needs in going from the reference GT-MHR design to the VHTR is the associated increase in operating temperature from 850°C to 1000°C. However, it must be noted that the VHTR design alternative studies and point design have not been completed and there are many open issues including:

- The choice of prismatic versus pebble bed fuel
- The choice of the hydrogen production process
- The use of silicon-carbide versus zirconium-carbide pressure boundary material in the TRISO coatings
- The core geometry including both the details of the neutronics and the coolant flow distribution
- The reactor power, inlet temperature, and temperature drop across the core
- Temperature variations and fluctuations in the core and lower plenum
- The expected peak temperatures during hypothetical accident conditions
- The IHX and primary coolant system coolant circulator designs
- Use of metallic versus carbon-carbon composite materials in the core and cross duct region

For system or component designs that present significant material challenges (or far greater expense) there may be some viable design alternatives or options that can reduce development needs or allow use of available (cheaper) materials. Nevertheless, we were not able to assess those alternatives in the time allotted for this report and, to move forward with this material research and development assessment, the authors of this report felt that it was necessary to identify a plausible design. All of the authors of this report feel comfortable that the design described in Section 2 is a promising design, but none of us believe that it is the final design.

Also, it should be noted that this survey covers the materials involved with the reactor and power conversion systems. Materials related directly to the fuel or hydrogen production processing are not included in the survey.

Section 3 is organized by major component and within each major component subsection we discuss for both the GT-MHR and VHTR:

- The status of the existing information
- The materials selection and development and qualification requirements
- The regulatory and codification requirements
- The materials testing and data base requirements
- The needed manufacturing infrastructure

Section 3.1 addresses the reactor pressure vessel, Section 3.2 covers the reactor core graphite, Section 3.3 address the reactor internals materials including the metallic, carbon-carbon composite, and insulation materials, Section 3.4 discusses the intermediate heat exchanger, and Section 3.5 covers the power conversion system including the turbine inlet shroud, turbine, and recuperator. The needed materials development programs and costs are summarized in Section 4 and compared with historical benchmarks. We conclude in Section 5 that there are significant materials development and qualification needs for the VHTR, but existing materials been identified that should meet the requirements of all VHTR components and subsystems.

2. Reactor Description

2.1. Introduction

As mentioned above, the VHTR will be an extension of previous high temperature gas-cooled reactor plant designs, taking advantage of the prior engineering design and technology development work already completed. The most mature design in the high temperature gas reactor family is the Gas-Turbine-Modular Helium Reactor (GT-MHR) design being developed in the joint NNSA-MINATOM (Russia) program for disposition of excess weapons-grade Plutonium, and that is the design we have chosen to base this materials survey on. It was initially developed as the U.S. DOE/General Atomics (GA) concept, and subsequently refined by the Russians through the preliminary design stage. Current activities include work on the final design and extensive R&D testing. The major design objectives for the VHTR are an outlet temperature of 1000°C and a fully passively safe plant. The increase from 850 to 1000°C in core coolant outlet temperature for the VHTR is a major increment for in-vessel metallic components; but is not expected to be a problem for the graphite and ceramics.

The VHTR will eventually be either an electricity producing plant with a direct cycle gas turbine or a hydrogen producing (or other process heat application) plant with an intermediate heat exchanger (IHX) between the reactor primary coolant system and the process heat application. Most likely the IHX will be a helium gas-to-gas heat exchanger with another heat exchanger downstream to avoid mixing process fluids with the reactor primary coolant in the event of heat exchanger leaks. The process heat version of the VHTR will most likely require that the IHX and primary gas circulator be located in an adjoining power conversion vessel. The gas-turbine version of the VHTR will be very similar to the GT-MHR, the differences between the VHTR and the current GT-MHR design will be mainly in the materials needed in the reactor and power conversion systems. As mentioned in the Introduction, the *demonstration* VHTR will be designed and built to produce both electricity and hydrogen. Therefore, the demonstration VHTR will probably have two power conversion vessels, one containing the IHX for the hydrogen production (and also the primary coolant system gas circulator) and the other (downstream) one containing an electric power conversion system similar to the current GT-MHR design. Table 1 lays out the operating conditions and other important features of the *demonstration* VHTR and provides direct comparisons with the GT-MHR and the Fort St. Vrain reactor designs.

The important operating parameter establishing the core inlet temperature is the core coolant temperature rise. Experience tells us that this should not exceed about 400°C, otherwise the variations in hot streak temperatures exiting the core, due to local power variations, will be too high. GA's initial optimization studies showed that for the VHTR, the core delta-T should not exceed ~360 to 400°C. To define the operating conditions for the materials survey, a core inlet temperature of 600°C is being used initially, allowing judgments as to how components are affected (noted in Table 1). The lifetime neutron fluence for VHTR components is expected to be about the same as for the GT-MHR. Additional detailed conditions are listed in appropriate places of Section 3.

Table 1. Comparison of VHTR operating conditions and features with GT-MHR and Fort St. Vrain.

Condition or Feature	Fort St. Vrain HTGR	GT-MHR	VHTR
Power Output [MW(t)]	841	600	600 (Needs to be optimized)
Average power density (w/cm^3)	6.3	6.5	6.5
Coolant @ Pressure (MPa / psia)	Helium @ 4.83 / 700	Helium @ 7.12 / 1032	Helium @ 7.12 / 1032
Moderator	Graphite	Graphite	Graphite
Core Geometry	Cylindrical	Annular	Annular
Safety Design Philosophy	Active Safety Sys	Passive	Passive
Plant Design Life (Years)	30	60	60
Core outlet temperature (°C)	785	850	1000
Core inlet temperature (°C)	406	488	600 estimated (Needs to be optimized)
Fuel – Coated Particle	HEU-PyC/SiC Th/ ^{235}U (93% enriched)	LEU-PyC/SiC	a) LEU-PyC/SiC b) LEU-PyC/ZrC
Fuel Max Temp – Normal Operation (°C)	1260	1250	a) ~1250 b) ~ 1400
Fuel Max Temp – Emergency Conditions (°C)	NA Active Safety System cools fuel.	1600	a) 1600 b) TBD
Fuel Element Design	Particles disbursed in carbon rods 0.5 in. dia x 1.95 in. long placed inside large graphite blocks.	Particles disbursed in carbon rods 0.5 in. dia x 1.95 in. long placed inside Fort St. Varin type large graphite blocks.	Modified GT-MHR design to reduce fuel rod linear heat rate.
Control Rods	Inconel structure containing B_4C compacts.	carbon-carbon/ Graphite Structure containing B_4C Compacts.	carbon-carbon/ Graphite Structure containing B_4C Compacts.
Backup Reactivity Control System	B_4C pellets dropped in core	SiC coated B_4C balls dropped in core	SiC coated B_4C balls dropped in core.
Core Inlet Gas Plenum	-Metallic upper core support. -Metallic control rod guide tubes. -Ceramic fiber/metallic plate insulation. -Boronated graphite shielding.	-Carbon-carbon composite upper core support. -High-temp metallic control rod guide tubes. -Ceramic fiber/high-temp metallic plate insulation. -Boronated graphite shielding.	Modified GT-MHR design: -Carbon-carbon composite upper core support. -Carbon-carbon composite control rod guide tubes. -Ceramic fiber/hi-temp metallic plate insulation. -Boronated graphite shielding.
Core Outlet Gas Collector Plenum	Graphite structures with metal covered ceramic fiber and ceramic block insulation. Water-cooled pressure vessel liner.	Graphite structures with graphite and C/C composite insulation.	Requires some modification of the GT-MHR system with possibly more insulation.

Condition or Feature	**Fort St. Vrain HTGR**	**GT-MHR**	**VHTR**
Hot Gas Duct	Inconel plates over ceramic fiber insulation mats.	High-temp steel structure with nickel-base alloy sheets containing ceramic fiber mats.	Requires some modification of the GT-MHR system. Specifically, the cover plates may need to be a C/C composite material.
Reactor Internals structures	Medium-temp steel plate rolled into cylinder	High-temp steel sheets & plates fabricated into cylinders and plate.	The upper plenum and some of the other internals insulation material may need to be changed.
SCS heat exchanger entrance structures and tubes	Inconel plates over ceramic fiber insulation mats.	Nickel base alloy sheets containing ceramic fiber mats. High-temp steel tubes.	Requires high temperature insulation.
Primary Coolant Gas Circulator	Axial flow-Steam turbine drive: -9550 RPM -Press Rise = 0.097 Mpa/ 14 psi -Inlet temp = 395°C/ 742°F	Single shaft Axial flow Gas Turbine with 2 stage axial flow inter-cooled compressor: -Press Rise = 4.69 MPa/ 680 psi -Inlet temp = 26°C/ 79°F -Outlet temp = 110°C/ 230°F	Extend GT-MHR turbo-machine to 1000°C turbine inlet temperature or, for hydrogen production, a motor driven axial flow circulator at core inlet conditions (in the vessel with the IHX)
Reactor Vessel	Pre-stressed Concrete Reactor Vessel Designed to ASME Code Div 2 for gas reactors.	2 ¼ CrMo, ASME Code Section III, Div 1, (alternate material: 9CrMoVNb) -Normal op Temp: 440°C -Accident max temp: 500°C for 400 hr, 540°C for 50 hr	9Cr MoVNb, ASME Code Section III, Div 1, -Normal op Temp: 600°C -Accident max temp: 620°C for 400 hr, 660°C for 50 hr (Initial approximations)
Cross Vessel	NA	2 ¼ CrMo, ASME Code Section III, Div 1, (alternate material: 9CrMoVNb), -Normal op temp: 440°C -Accident max temp: 440°C	9CrMoVNb, ASME Code Section III, Div 1 -Normal op temp: 600°C -Accident max temp: 600°C (Initial approximations)
Power Conversion System Vessel	NA	2 ¼ CrMo, ASME Code Section III, Div 1, (alternate material: 9CrMoVNb), -Normal op temp: 150°C -Accident max temp: 250°C	9CrMoVNb, ASME Code Section III, Div 1, (alternate material: 2 ¼ CrMo), -Normal op Temp: 150°C -Accident max temp: 300°C
IHX	NA	NA	Compact heat exchanger, material is TBD, but may need to be a high temperature nickel alloy.

2.2. GT-MHR Plant Description

Figure 1 shows the GT-MHR reactor system and power conversion system within the reactor building. The plant is designed for a 60-year life with a capacity factor of at least 80%. Passive safety is achieved by designing for a core cool-down during a postulated long-term depressurized loss-of-forced convection (D-LOFC) accident that limits the peak fuel temperatures to 1600°C. This is accomplished by conducting the decay heat radially through the core and pressure vessel, and then radiating it to passively cooled panels in the reactor cavity building. High temperature concrete is not needed for the reactor building because of the cooling panels. There is also a nonsafety shutdown cooling system (SCS) used only to remove decay heat during normal shutdowns, such as during refueling operations.

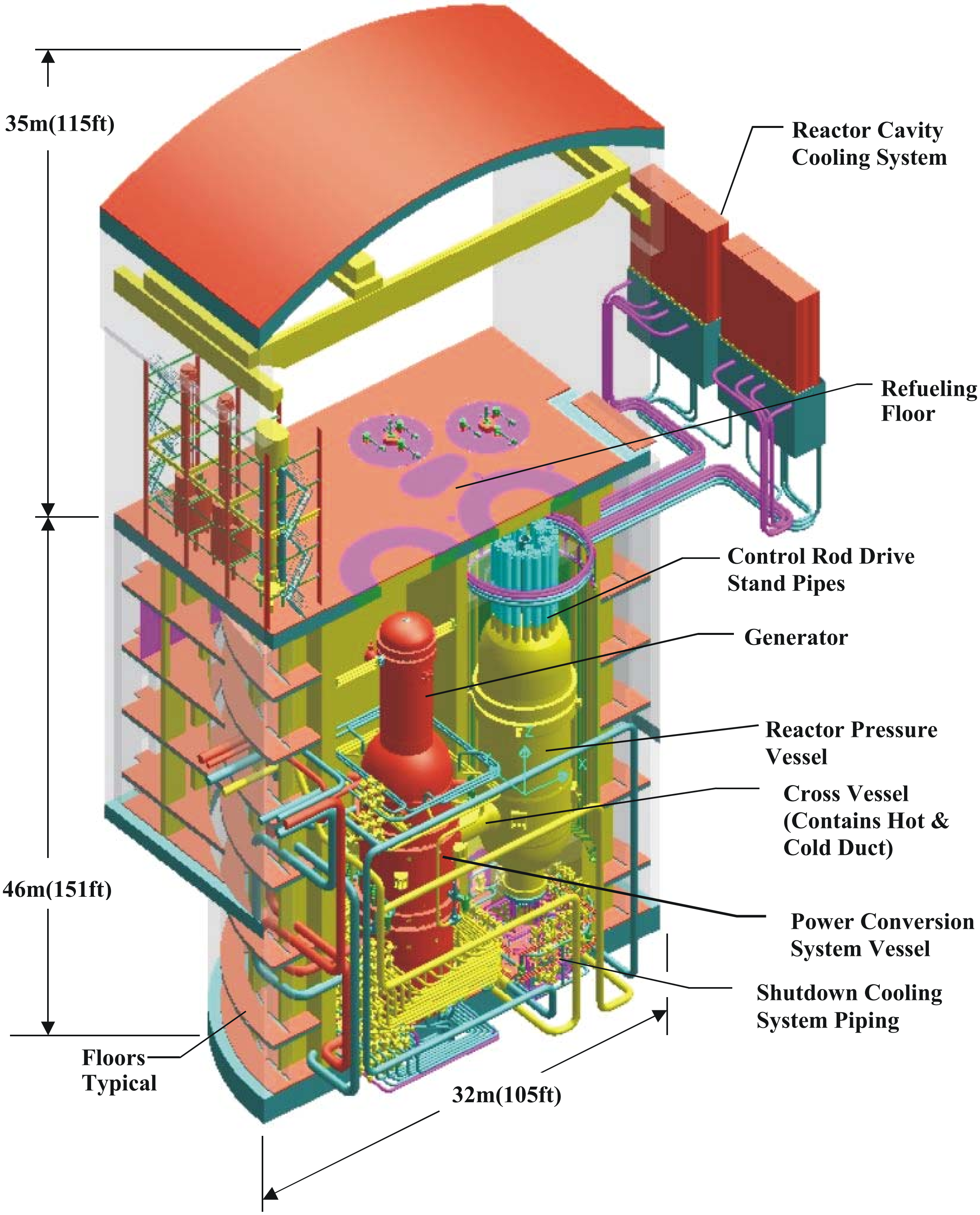

Figure 1. GT-MHR Reactor building cutaway showing the arrangement of the reactor and power conversion systems.

The entire reactor confinement structure is under ground. The reactor vessel and power conversion vessel are side-by-side and connected by a cross-vessel that is deliberately made as short as possible to minimize thermal expansion differences between the two large vessels. Within the cross-vessel the reactor inlet gas flows in an annular duct along the inside surface of the cross vessel to the reactor inlet. The core exit hot gas flows in a central duct along the centerline of the cross-vessel to the turbine inlet.

Figure 2 is a cutaway view of the reactor vessel showing more details of the inside of the core. The core consists of graphite blocks with an annular-fueled region surrounded by reflector elements. The fuel is TRISO coated fuel particles embedded in graphite compacts and placed in graphite prismatic blocks. The center of the core is a non-fueled graphite reflector. Normal operating maximum fuel temperatures do not exceed 1250°C. The reflectors mitigate the high-energy fluxes, and boron pins placed in the outer reaches of the reflectors reduce thermal neutron fluxes on the metallic internals structures and reactor vessel.

From the cross-vessel, the reactor helium coolant inlet (~500°C and ~7 MPa) then flows upward in the annulus between the vessel and the metallic core barrel surrounding the side reflector. Hence it is a major determinant of the vessel operating temperature. For alternative flow paths, further removed from the vessel, lower operating temperatures for the vessel could be attained. The coolant then enters the upper plenum region volume, which contains the lower parts of the control rod housings. The reactor pressure vessel upper head is protected by fibrous “Kaowool” insulation blankets supported by high-temperature metallic plates. The insulation protects the head from hot plumes that could occur during a pressurized loss-of-forced-convection (P-LOFC) accident.

The inlet flow then passes down through the core’s upper support plates, which are made of carbon-carbon composite material that must also withstand the hot gases in a long-term P-LOFC. The coolant then flows primarily into the coolant channel holes in the fuel elements. Some of the flow bypasses these channels, passing through the gaps between the fuel elements and reflector blocks. Thus the temperature rise of the coolant in the various flow paths through the core varies over a wide range. The coolant in the fuel element channels with the highest local power peaking is quite hot whereas the coolant in the relatively unheated gaps adjacent to the cooler reflectors remains near the inlet temperature. Since the average temperature rise through the core is ~350°C, good mixing of the outlet coolant is needed to avoid material stresses downstream resulting from large temperature gradients and fluctuations and to assure that the gas entering the turbine has a uniform mixed mean temperature of 850 C. Various design options are available to mitigate the affects of these perturbations.

The reactor vessel operates at a maximum temperature of 440°C during normal operation and reaches about 550°C during a conduction cool down event. The core’s fuel elements and graphite reflectors, plus the control rods and housings and the shutdown ball channels are all non-metal, capable of withstanding the prescribed maximum core temperatures (~1600°C) or higher in the design-limiting D-LOFC accident.

The “Hot Duct” assembly is composed of a structural duct separating the core entrance gas from the core exit gas, and an insulation assembly on the inside surface of the structural duct to protect it from direct contact with the 850°C core exit gas. The structural duct is subjected to the core pressure drop as an external pressure load on a cylinder. The insulation assemblies are designed to be remotely removed and replaced if needed during the 60-year plant life.

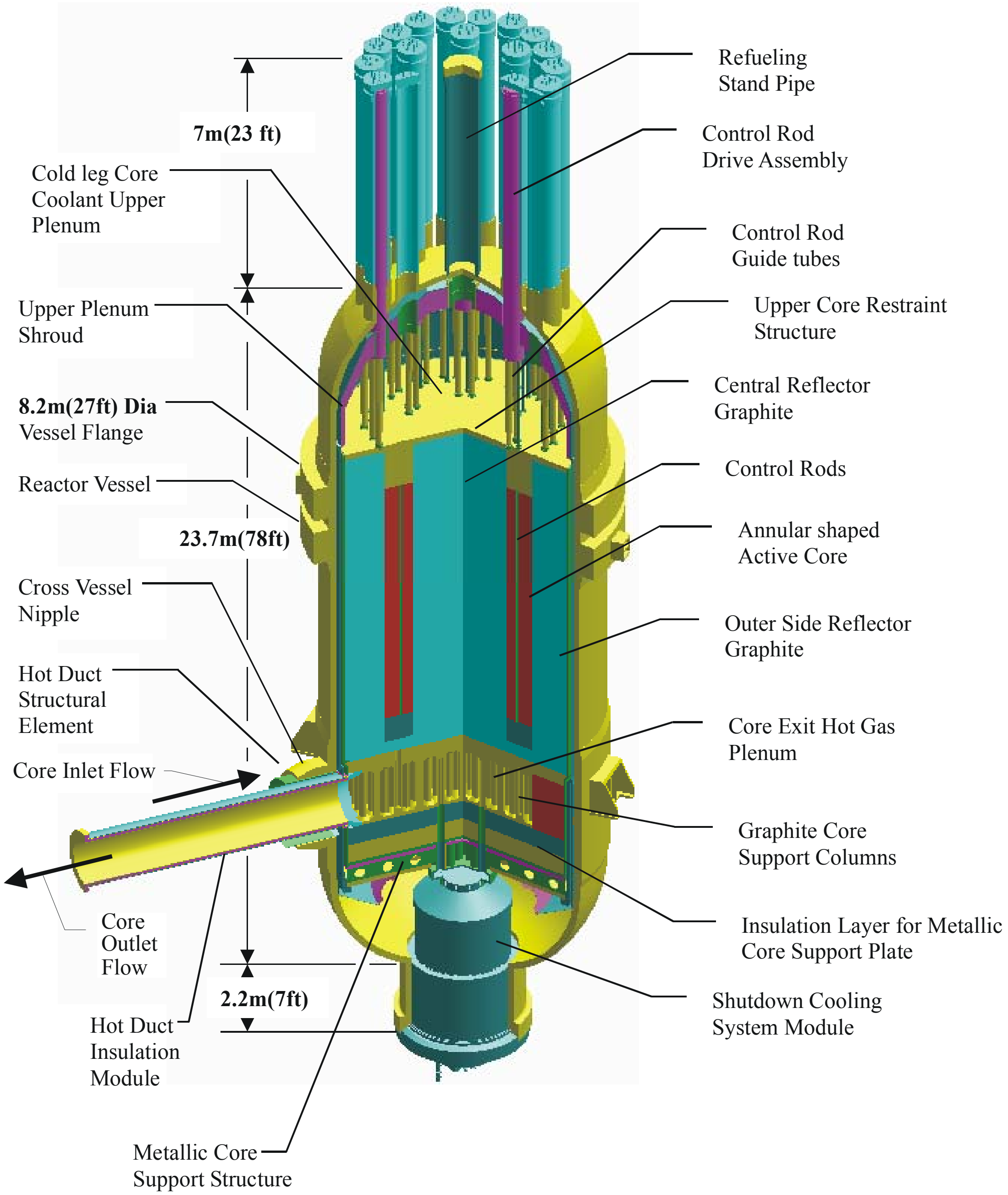

Figure 2. Reactor system cutaway showing the metallic internals structures, core, control rod guide tubes, and shutdown cooling system.

Between the core exit plenum and the bottom metallic core support plate is an insulation layer ~1.2 meters thick. It is composed of a meter of nuclear graphite and 200 mm of carbon-carbon composite blocks. This combination of materials and thickness drops the temperature from 850°C (core outlet temp) to ~510°C on the top of the core support plate and ~490°C on the bottom.

Below the bottom metallic core support is the SCS module shown in Figure 3, used to remove decay heat from the core during normal shutdowns. It is not a safety system. It contains a water-cooled heat exchanger and a motor driven circulator. It can be removed and replaced for maintenance. The high temperature thermal insulation in the upper gas collector plenum will need to be upgraded to withstand the 1000 C core outlet temperature of the VHTR.

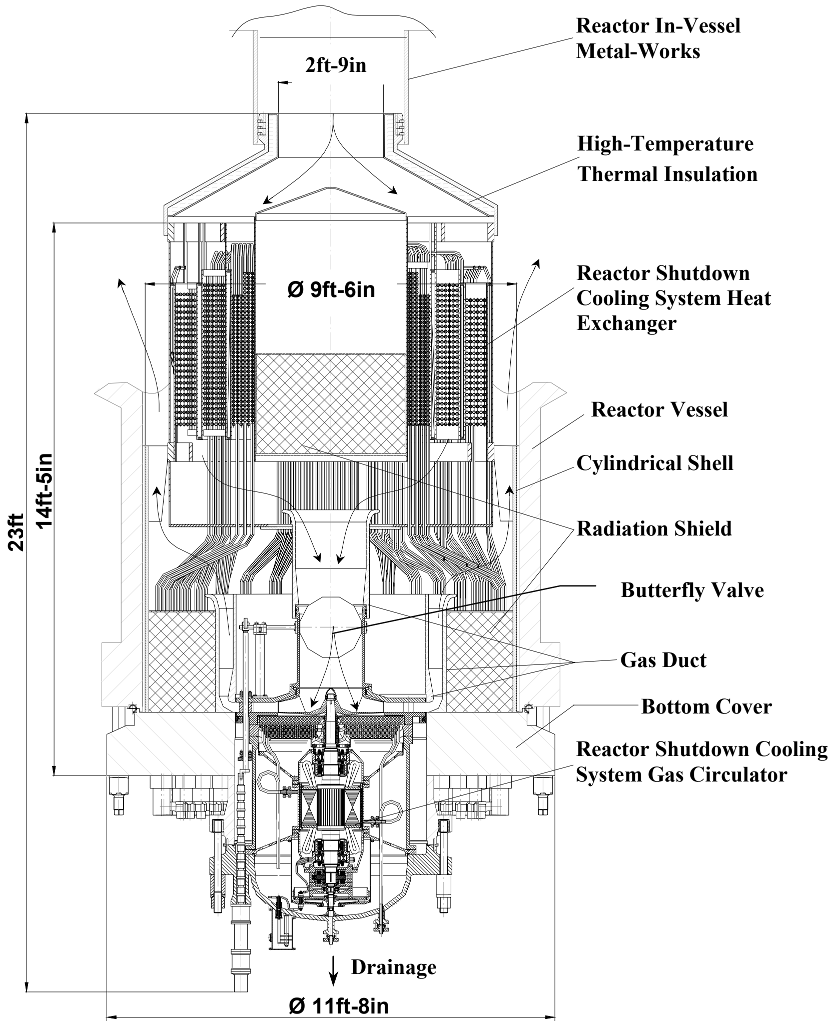

Figure 3. Cross-section of the GT-MHR shutdown cooling system.

The power conversion unit (PCU) is shown in Figure 4. It is a direct (Brayton) cycle vertical single shaft axial flow gas turbine. The compressor is a two-stage compressor with a pre-cooler and an intercooler. Hot gas from the reactor enters the turbine from the hot duct. The turbine inlet volute is designed as an insulated structure like the hot duct. High temperatures are experienced by the turbine's first few stages, the turbine inlet structure, and the recuperator. All the other PCU structures operate at relatively low temperatures. Gas exiting the turbine is passed through the recuperator to raise the core inlet coolant temperature to ~500°C. The generator is contained within the primary helium coolant.

In the PCU, the turbine blades and disks operate at temperatures considerably lower than those of modern air turbines because the PCU turbine lifetime requirements (~6 years) are much more stringent. Some components (e.g., recuperator) must also withstand very rapid and severe temperature transients when bypass valves operate to prevent generator runaway in a sudden loss of electrical load event.

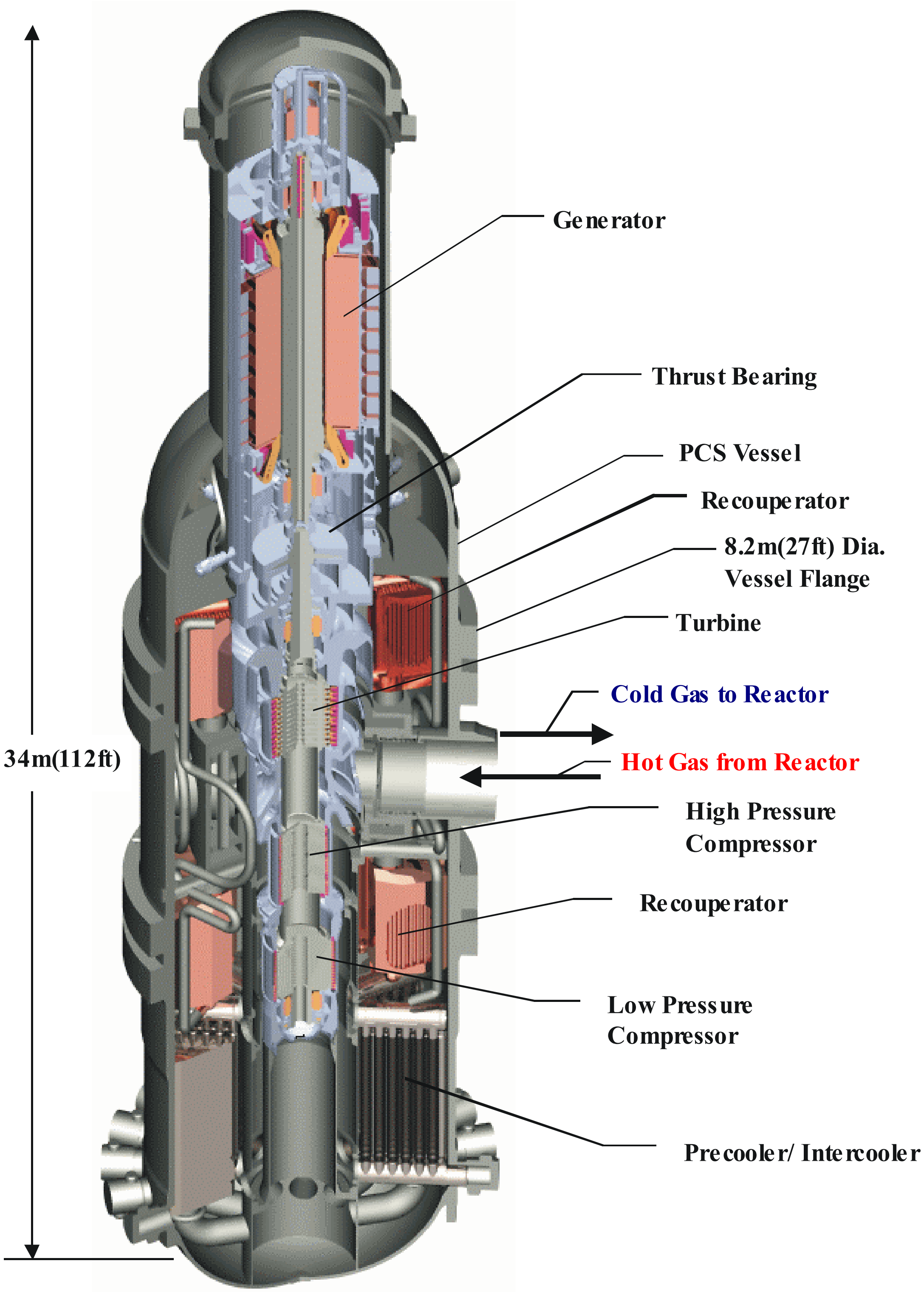

Figure 4. Power conversion unit (PCU) cutaway showing the turbomachine, recouperator, intercooler, precooler, and generator.

2.3. VHTR Incremental Design Changes

The major driver for the VHTR design is high temperature process heat for hydrogen production. Studies have shown that obtaining attractive hydrogen production efficiencies requires reactor outlet temperatures near 1000°C, as shown in Figure 5.

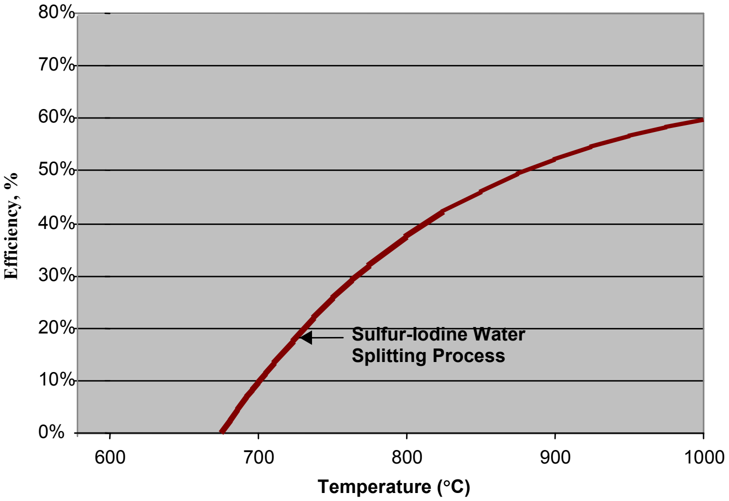

Figure 5. Hydrogen production process energy efficiency as a function of process heat input maximum temperature.

The demonstration VHTR plant configuration will be a reactor system similar to that shown in Figure 2 plus a vessel with an IHX and primary reactor coolant system gas circulator, with the secondary of the IHX acting as a heat source for: a) a hydrogen production plant (that will use either a sulfur iodine thermochemical water-splitting or steam reforming of methane process); and b) a high temperature gas-turbine similar to that shown in Figure 4 to produce electricity.

The fuel will be low-enriched TRISO coated UCO particles embedded in graphite compacts inside graphite prismatic blocks with cooling holes. However, it may be necessary to consider the use of zirconium carbide (ZrC) rather than silicon carbide (SiC) as the primary fission product retention material in the TRISO coating system. Also, the use of pebbles, rather than prismatic blocks will be evaluated.

A second important design requirement of the VHTR is that it be passively safe. Therefore the total power is expected to be similar to the 600MW(t) of the GT-MHR design, however additional analysis is needed to set the final power value. To accommodate the reference core inlet temperature of 600°C, medium temperature alloys are used for the metallic components and vessel. For those components bathed in the core exit gas, the design temperature increase from 850 to 1000°C is very significant. All metallic materials at this temperature will have to be replaced with higher temperature alloys or non-metallic materials, such as carbon-carbon composites. Because of the 150°C higher core outlet temperature, the outlet plenum temperatures would also need to have stricter requirements on temperature gradients and fluctuations due to the higher absolute temperatures. The upper plenum shroud inner surface materials will need to be changed, and possibly the control rod guide tubes will need to be changed as well if the P-LOFC accident plume temperatures go above 1000°C.

The reactor core has only graphite or carbon-carbon composite materials and will not be appreciably effected by the increased core out let temperature. However these materials will need to be tested at slightly higher temperatures than those for the GT-MHR.

The IHX for the VHTR will have to be developed to handle 1000°C temperatures. Some initial design studies have been performed for an IHX with 850°C inlet temperature. Compact heat exchangers were found to be feasible. However, much engineering work remains for both an 850 and 1000°C IHX. Depending on the function and design of the IHX secondary, large pressure differentials may occur with depressurization events. The IHX will probably not need to withstand rapid temperature transients such as those seen by the recuperator in the PCU during sudden loss of generator load events.

Also, the gas turbine will need to be modified, and the inlet ducting and recuperator materials will need to be evaluated to find acceptable materials that can operate at the higher temperatures resulting from the increased core outlet temperature of 1000°C. . It is also likely that the turbine may require blade cooling and /or more disk cooling.

3. VHTR Reactor System Materials Data Needs

3.1. Reactor Pressure Vessel

3.1.1. Status

The reactor pressure vessel system envisioned for both the GT-MHR and the VHTR is illustrated in Figure 6. It will comprise a large reactor pressure vessel (RPV) containing the core and internals, a second large vessel for power conversion (PCV) containing either the turbine-generator or the intermediate heat exchanger (IHX) and primary coolant system circulator, and a pressure-containing cross vessel joining the RPV and the PCV.

The anticipated operating conditions for the pressure vessel system are detailed in Table 2. The vessels will be exposed to air on the outside and helium on the inside. The most promising materials types, approved for nuclear service, which may meet the needs of those operating conditions are also included in Table 2. The additional materials development and qualification that will be required to resolve questions about the suitability of these materials are addressed in the remainder of Section 3.1.

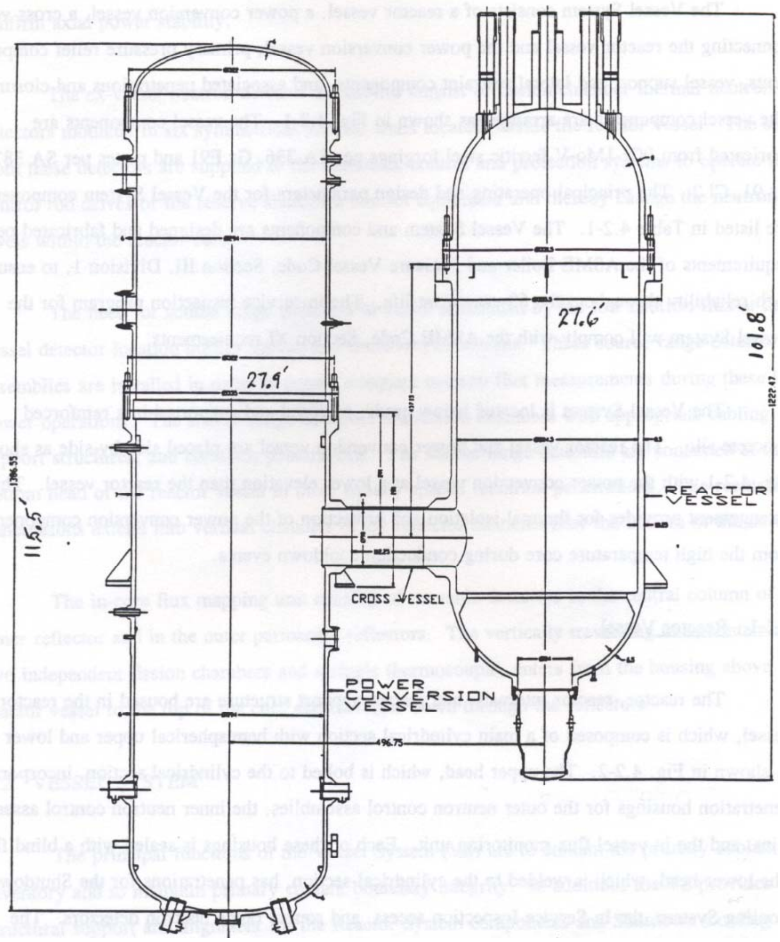

Figure 6. Schematic of reactor pressure vessel system for GT-MHR or VHTR.

The materials tentatively selected for gas-cooled RPV service are both low-alloy ferritic/martensitic steels, alloyed primarily with chromium and molybdenum. The most significant difference in demands placed on the RPV system between the GT-MHR and the VHTR are the temperatures at which they will be required to operate. It is anticipated that 2 1/4 Cr-1Mo could likely meet the requirements associated with the lower relative temperatures of the GT-MHR, whereas modified 9Cr-1Mo will be needed for the VHTR. Both of these materials have been widely used for pressure boundary applications for fossil-fueled power generation and are approved for nuclear service[1] by inclusion in Subsection NH of Section III of the ASME Boiler and Pressure Vessel Code. Consequently, the code allowables for high-temperature operation have been established for both time-dependent and time-independent loading conditions. However, there are a number of issues that still need to be addressed regarding both materials.

Table 2. Reactor pressure vessel system operating conditions and candidate materials for the GT-MHR and VHTR.

Component	Normal VHTR System Operating Conditions		Abnormal Conditions	Materials for the 850°C GT-MHR	Candidate Materials for the 1000°C VTHR
	Temp. [°C]	Neutron Fluence, E>0.1 MeV			
Reactor Pressure Vessel	600	3x10^{18} n/cm^{-2} per 60 years	≈650°C for 50 h	2 1/4Cr-1Mo -Plate: SA-387, Grade 22, Cl. 1. -Forgings: SA-182 Grade F22 Cl. 1.	Modified 9Cr-1Mo -Plate: SA-387, Grade 91. -Forgings: SA-182 Grade F91.
Cross Vessel	600	3x10^{18} n/cm^{-2} per 60 years	≈600°C		
Power Conversion Vessel	150	3x10^{14} n/cm^{-2} per 60 years	>250°C		
Closure Bolting	600	3x10^{18} n/cm^{-2} per 60 years	≈650°C for 50 h	Inconel 718	Inconel 718 or 304 or 316 stainless steel

The issues that will need to be addressed for the RPV-system materials for the GT-MHR and/or the VHTR include: (1) scale-up of fabrication practices for very large vessels, (2) very long-term materials aging and structural integrity associated with a 60-year reactor life, (3) effects of irradiation, (4) environmental effects on fatigue crack growth and life at very high temperatures, (5) long-term emissivity control on the vessel exterior, and (6) high-temperature bolting.

Additionally, it is necessary to develop the high-temperature design methodology that applies to these and other Generation IV reactor components to provide an adequate basis for design, use, and codification of the materials under combined time-independent and time-dependent loadings. It will be necessary to update and validate existing high-temperature design methods for new data on the materials that have already been codified and extend them to the new higher-performance, high-temperature materials. It will be further necessary to develop improved methods for high-temperature design that incorporate improved creep-fatigue criteria, methods to adequately account for effects of weldments and notch weakening, extensions of lifetime prediction methods to operational lifetimes of 60 years, and high-temperature flaw-assessment methods.

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[1] Final editing and units conversion for incorporation of 9Cr-1Mo into Subsection NH is underway currently, but its approval is effectively completed.

3.1.2. Materials Selection and Development and Qualification Requirements

The materials development and qualification requirements are fairly similar for the use of 2 1/4Cr-1Mo for GT-MHR vessels and 9Cr-1Mo for VHTR vessels. Both materials have code-approved stress allowables for high-temperature operation, though both are just about at the useful end of their upper temperature capabilities under the operating conditions specified in Table 2 for both reactor concepts. Both materials will require development in the other areas listed above, although, in general, there is more data and experience in using 2 1/4Cr-1Mo steel and hence it will require less additional development work than will be required for the 9Cr-1Mo. Details of the technical issues that need to be addressed for both materials are described below. It should be noted that resolving these issues for 9Cr-1Mo steel would enable its use for either reactor concept.

Scale-up of fabrication practices. The size and thickness of the vessels required for the gas-cooled reactors being considered are very large compared with current industrial experience. Scale-up of vessel fabrication must include the use of very large forgings (up to 450 tons), section thickness (up to 10 inches for vessel walls and 20 inches for flanges), and heavy-section welding technology. The vessels themselves will be very large compared with pressure vessels made for light-water cooled reactors (LWRs) and will require detailed analysis of transportation options with the potential need for on-site production of major fabrication welds and the associated more challenging requirements for on-site post-weld-heat-treatment (PWHT) and non-destructive examination (NDE). A graphical comparison of the sizes of both the RPV and the PCV versus LWR vessels is provided in Figure 7. Even if on-site welding of the RPV and PCV is not required, their assembly with the cross vessel will entail significant on-site welding, PWHT, and NDE. The selection of 9Cr-1Mo steel will entail somewhat more development since the industrial experience for fabrication and joining of very heavy sections of 9Cr-1Mo steel is lower than that for 2 1/4Cr-1Mo. The higher PWHT temperatures required for the 9Cr-1Mo will also increase the difficulty and requirements for on-site welding technology development.

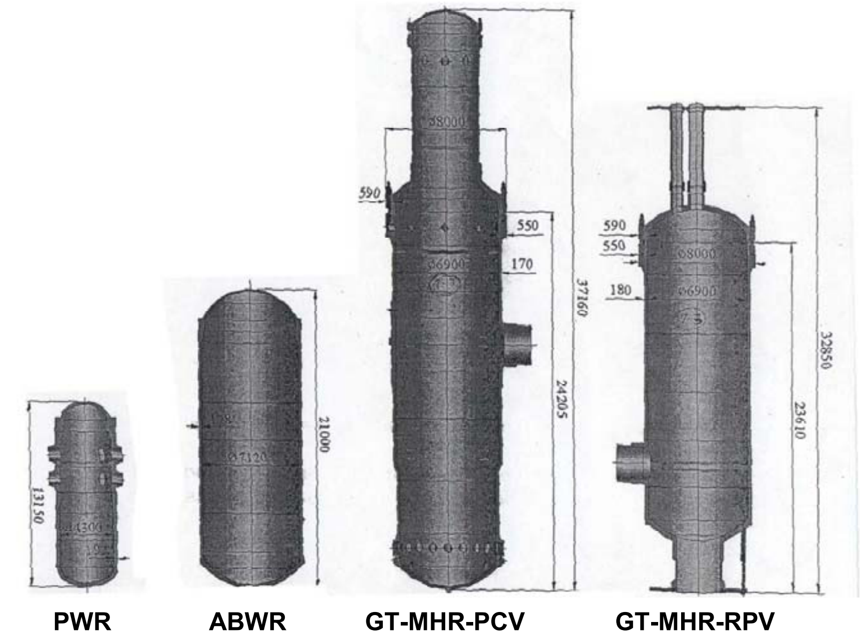

Figure 7. Graphical comparison of reactor pressure vessel sizes.

Sixty-year lifetime considerations. Currently, both 2 1/4Cr-1Mo and 9Cr-1mo steels have databases that support operating lifetimes of up to 300,000 hours. While these materials are expected to support the extremely long lifetimes anticipated for the Generation IV reactors, additional data will need to be developed for very long-term creep and creep-rupture properties, as well as general materials degradation due to thermally induced aging of the microstructures.

Irradiation Effects. A great deal of work has been done to illuminate the effects of irradiation on both 2 1/4Cr-1Mo and 9Cr-1Mo. Based on a wide body of existing evidence, it is not anticipated that any significant degradation (embrittlement, swelling, accelerated aging, etc.) due to irradiation in either material will occur at the proposed operating temperatures and doses. However, confirmation of the general expected trends at the explicit conditions of interest will be required for either class of material and an extensive analysis, supported by a surveillance program for the specific heats of materials to be used in the vessels, will be required to ensure that no unexpected degradation occurs during service.

Environmental effects. Both 2 1/4Cr-1Mo and 9Cr-1mo steels have been used extensively within the fossil fuel power generation industry. Additionally, the effects of helium with appropriate impurities have been extensively examined for 2 1/4Cr-1Mo steel at temperatures up to those envisioned for the GT-MHR. However, there remain concerns regarding the fatigue and crack-growth behavior of 9Cr-1Mo steel at the higher VHTR temperatures in both helium and air that will need to be addressed.

Long-term emissivity control of the vessel exterior. To ensure that passive heat removal systems will function adequately for both the GT-MHR and the VHTR, it is desirable to ensure that the exterior surface of the RPV develops and maintains a very high coefficient of thermal emissivity (>0.85). Ferritic steels normally have a fairly low emissivity (<0.4) but this increases sufficiently when covered with an appropriate oxide layer. Both 2 1/4Cr-1Mo and 9Cr-1mo steels form iron oxide (both Fe_2O_3 and Fe_3O_4) layers during high temperature exposure in air, but can also include both chromia and spinel as well. It will be necessary to evaluate the formation and composition of surface layer formations of the RPV steels, their resulting emissivities, and their stability during very long life operation (including thermal transients) to see if additional surface treatments are required.

High-temperature service of main closure bolting. The use of Inconel 718 bolting material will need to be examined for the higher service temperatures of the VHTR. It is currently approved only up to 566°C in ASME III, Subsection NH. It will be necessary to examine the data base upon which that use is based and possibly issue a code case for use up to 600°C. Alternately, Types 304 and 316 stainless steel, which have stress allowables for bolting use up to 704°C, may be substituted. Irradiation effects will also need to be examined for the material selected.

3.1.3. Regulatory and Codification Requirements

It will be necessary to develop: (1) very long-term ASME Code creep and creep rupture allowables for 2 1/4Cr-1Mo or 9Cr-1mo steels at the temperatures of interest; (2) initial predictions and the associated surveillance program to monitor the minimal anticipated irradiation-induced degradation of the vessel material during service; and (3) an updated high-temperature materials design methodology adequate to provide a sound basis for design, use, and codification of materials under combined time-independent and time-dependent loadings.

3.1.4. Materials Testing And Data Base Requirements

We need to generate the accelerated creep, creep-rupture, creep-fatigue, and materials-aging data required for the 60-year operating lifetimes for vessel and bolting materials, perform confirmatory irradiation testing to validate the expected irradiation degradation, perform fatigue and fatigue-crack growth testing in helium and air up to 600°C to assess environmental effects, perform exposure studies to examine the formation and stability of high-emissivity oxide layers at operating temperatures, and develop improved lifetime prediction methods for operational lifetimes of 60 years and develop high-temperature flaw-assessment methods.

3.1.5. Industrial Base and Infrastructure Requirements

The important development activities associated with fabrication of the reactor and power conversion pressure vessels includes work to scale up the current large pressure vessel fabrication practices so that thicker ring forgings can be produced and on-site fabrication of the vessel, or parts of the vessel, is possible. There is currently no domestic manufacturer that can supply the very large ring forgings that are needed for the RPV and PCV. Only Japan Steel Works currently has the capacity to produce forgings of this size and they do not have the needed experience to fabricate them from either 2 1/4Cr-1Mo or 9Cr-1Mo steel. Even the individual vessels for a demonstration plant will require an extension of current forging, fabrication, and heat treating technology to produce vessel rings with adequate through-thickness properties. If needed, it would be possible to fabricate the vessel rings from welded plate, however experience from the LWR community has shown this to be less desirable, if it can be avoided.

There are also currently no domestic production facilities that routinely perform welding and machining of reactor pressure vessels, though there are multiple foreign suppliers that maintain such facilities. There should be no significant problem in obtaining a vessel fabricator, though heavy-section welding and PWHT of the chromium-moly steels will need to be developed further, particularly for the high-alloy 9Cr-1Mo steels.

If the Generation IV reactor program eventually results in the deployment of many VHTRs within the U.S., there would be a significant value and justification to rebuild the domestic industrial base for vessel manufacture.

3.2. Reactor Core Graphite, Pile, and Supports

The reactor core structural elements are made from graphite to provide neutron moderation and high temperature structural support to the fuel and cooling passage arrangement. The graphite components are the fuel elements, replaceable reflector elements, permanent side reflector elements, and core supports. The control rod materials are carbon-carbon composite materials supporting boron carbide compacts and will be covered in Section 3.3.2 along with other components made of carbon-carbon-composite materials. Table 3 lists the core components, their operating conditions and materials for the GT-MHR as a point-of departure for the VHTR. A photograph of a typical graphite fuel element block is shown in Figure 8.

Table 3. Reactor system graphite components & control rods and VHTR operating conditions with GT-MHR materials and candidates for the VHTR.

Component	Sub-components	Normal VHTR Operating Conditions			Abnormal Operating Conditions	GT-MHR Materials	Candidate VHTR Materials
		Nominal Temp (°C)	Neutron fluence with E≥0.1 MeV	Medium			
Core	Fuel Element	600–1250	$5.0 \cdot 10^{21}$ cm^{-2} over 3 years. Max Elem. Bow 1mm.	Helium	Up to 1600°C during CCD	H-451 by SGL or equivalent	NBG-10 by SGL H-451 by SGL PCEA by GrafTek IG-110 by Toyo Tanso
	RR Element	600-1150	Max Elem. Bow 1mm. Set by Irradiation effects limits		Up to 1600°C during CCD	H-451 by SGL or equivalent	NBG-10 by SGL H-451 by SGL PCEA by GrafTek IG-110 by Toyo Tanso
	Control Rod Structure	600-1100	Set by Irradiation effects limits		Up to 1600°C during CCD	Carbon-carbon-composite materials	Carbon-carbon-composite materials
	Control Rod n-Absorber inserts	600-1100	Set by Irradiation effects limits		Up to 1600°C during CCD	B_4C in C/Graphite Matrix	B_4C in C/Graphite Matrix
	Reserve Shutdown Pellets	< 600	NA		Up to 1600°C during CCD	SiC coated B_4C compacts	SiC coated B_4C compacts

Component	Sub-components	Normal VHTR Operating Conditions			Abnormal Operating Conditions	GT-MHR Materials	Candidate VHTR Materials
		Nominal Temp (°C)	Neutron fluence with E≥0.1 MeV	Medium			
Permanent Side Reflector & Core Support	Permanent Side Reflector	600-1000	$2.0\cdot10^{19}\ \mathrm{cm}^{-2}$ over 60 years.	Helium	Up to 1100°C during CCD	HLM By SGL or PGX by GrafTek	HLM By SGL or PGX by GrafTek
	Graphite Core Support	1000-1200	$5.0\cdot10^{19}\ \mathrm{cm}^{-2}$ over 60 years		Up to 1000°C during CCD	H-451 by SGL or equivalent	H-451 by SGL, or Carbone USA 2020
	Bottom Graphite Insulator Blocks	700-1050	$2.0\cdot10^{19}\ \mathrm{cm}^{-2}$ over 60 years		Up to 1000°C at top & 600 C at bottom during CCD		
	Bottom Insulator Blocks	600-700	$2.0\cdot10^{17}\ \mathrm{cm}^{-2}$ over 60 years		600-700°C	Carbon-carbon-composite material or, Al_2O_3 and SiO_2 ceramic blocks	Carbon-carbon-composite material or, Al_2O_3 and SiO_2 ceramic blocks
	Thermal Neutron Shielding pins	600-1200	$<5.0\cdot10^{19}\ \mathrm{cm}^{-2}$ over 60 years		Up to 1100°C during CCD	B_4C in C/Graphite Matrix	B_4C in C/Graphite Matrix

3.2.1. Status

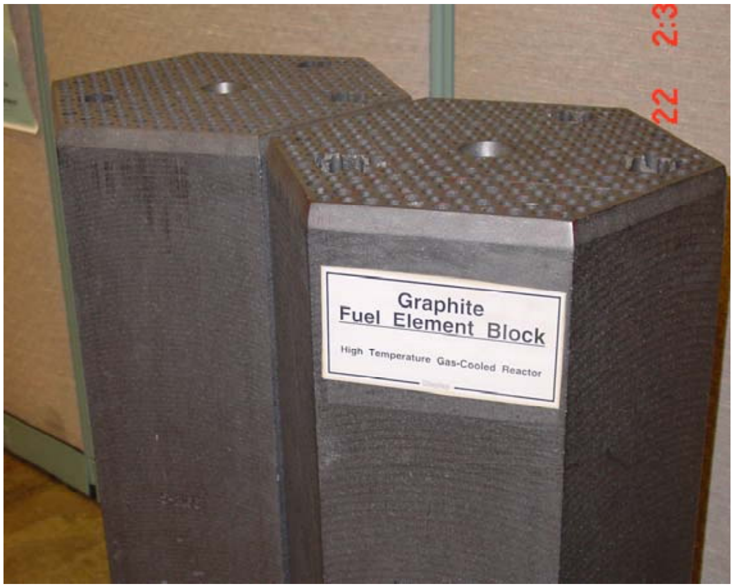

Figure 8. Graphite fuel element blocks showing the array of fuel and coolant holes

Near-isotropic, extruded, nuclear graphites (e.g., grade H-451 manufactured by SGL Carbon) were developed in 1970's for large helium cooled reactors such as the Fort St. Vrain reactor. However, grade H-451 graphite has not been manufactured in the USA for more than 25 years.

There is a substantial database for Grade H-451, including data for the effect of neutron irradiation on the properties, statistical variation of properties, oxidation behavior, etc. This body of data was considered sufficient to license the Fort St. Varin reactor. Moreover, graphite behavior models were developed for Grade H-451 graphite. Fine grained isotropic, molded or isostaticaly pressed, high strength graphites suitable for core support structure (e.g., Carbone USA grade 2020 or Toyo Tanso grade IG-110) are available today. Toyo Tanso grade IG-110 was used in the Japanese HTTR for fuel blocks and in the Chinese HTR-10 pebble bed reactor. These fine-grained materials are suitable for the fuel elements and replaceable reactor components, but they cost about 3 or 4 times more than extruded graphite such as H-451.

New near isotropic, extruded, nuclear graphites have been developed in the USA and Europe for the South African Pebble Bed Modular reactor. The new, currently available graphites are GrafTek (UCAR) grade PCEA (a petroleum coke graphite) and SGL Grade NBG-10 (a pitch coke graphite based on UK AGR fuel sleeve graphite). These graphites may be candidates for the fuel elements and replaceable reactor components. Graphites suitable for the large permanent reflector components are currently in production, e.g., SGL grade HLM or GrafTek (UCAR) grade PGX. Some data are available for these graphite grades. Grade PGX was used for the permanent reflector of the Japanese HTTR, also PGX and HLM were used in Fort St. Varin for the core support and permanent reflectors respectively. Fine-grain, high strength, graphites are available from POCO Graphite, Inc. However, the available billet sizes are small and very expensive, thus not suited for GT-MHR or VHTR core applications

3.2.2. Materials Selection and Development and Qualification Requirements

Properties data must be obtained for the currently available graphites to support design activities for both the GT-MHR and the VHTR. The available near-isotropic, extruded graphites are somewhat similar to the prior grade H-451. Therefore, design models for H-451 can be incrementally adjusted for the currently available graphites as new data becomes available. A radiation effects database must be developed for the currently available, graphite materials and this requires a substantial graphite irradiation program. There is the potential to leverage data from European Union activities in the area of irradiation experiments on PBMR graphites (Petten Reactor irradiation experiments are currently being initiated). Presumably, such data sharing would require an international agreement.

VHTR graphite temperatures are as much as 200°C greater than that in the GT-MHR, and thus additional data are required for all properties at these higher temperatures, including radiation damage effects. Existing material behavior models will be modified based on sound materials physics and validated/verified against new data for currently available graphites.

3.2.3. Regulatory and Codification Requirements

ASME code proposed Section III, Division 2, Subsection CE, "design requirements for graphite core supports" was issued for review and comment in 1990, but needs to be completed and approved.

ASTM Committee DO2-F is preparing a nuclear graphite material specification at the request of the US-NRC. This activity is being led by ORNL. ASTM nuclear graphite materials standard test methods currently exist for the majority of graphite property tests. However, new test methods must be developed in certain areas and added to the ASTM standards.

3.2.4. Materials Testing And Data Base Requirements

A properties database must be developed to support the design of graphite core components. Data are required for the physical, mechanical and oxidation properties of graphites. Moreover, the data must be statistically sound and take account of in-billet, between billets, and lot-to-lot variations of properties. Properties data must support the service conditions, including effects of temperature, helium gas (plus air and water), and neutron irradiation effects. Details of the service conditions and irradiation doses are given in Table 3. Irradiation creep data for the candidate graphites must be obtained. These experiments are particularly complex and expensive because they involve insertion of test samples in an instrumented irradiation capsule and subsequent post irradiation examination in a hot cell.

3.2.5. Manufacturing Infrastructure Required

Manufacturing infrastructure, including processing and machining, is in place in the USA and Europe for the manufacture of all required grades of graphite to support both the GT-MHR and the VHTR.

3.3. Reactor Internals

3.3.1. Metallic Reactor Internals

The reactor internals components support the graphite core assembly and maintain it in the required geometry for nuclear physics control and cooling. They include the core barrel, metallic core support plate, upper plenum shroud, and hot duct as shown in Figures 9 and 10 below. Also included as reactor internals are various sub-components of the CPS and RSS drive systems. The GT-MHR metallic structures will be exposed to inlet gas temperatures from ~500°C to about 600-650°C during normal operation. (See the table below for the temperatures of the VHTR components.) The same holds for the hot gas structural duct which separates the inlet gas flow from the core outlet gas flow and is bathed in core inlet gas (Figure 10). The pressure shell of the hot duct is loaded on its outer surface by the pressure drop across the core (~ 8psi). Note that a leak in the structural duct results in leakage flow from the core inlet side (cold gas) to the core outlet side (hot gas).

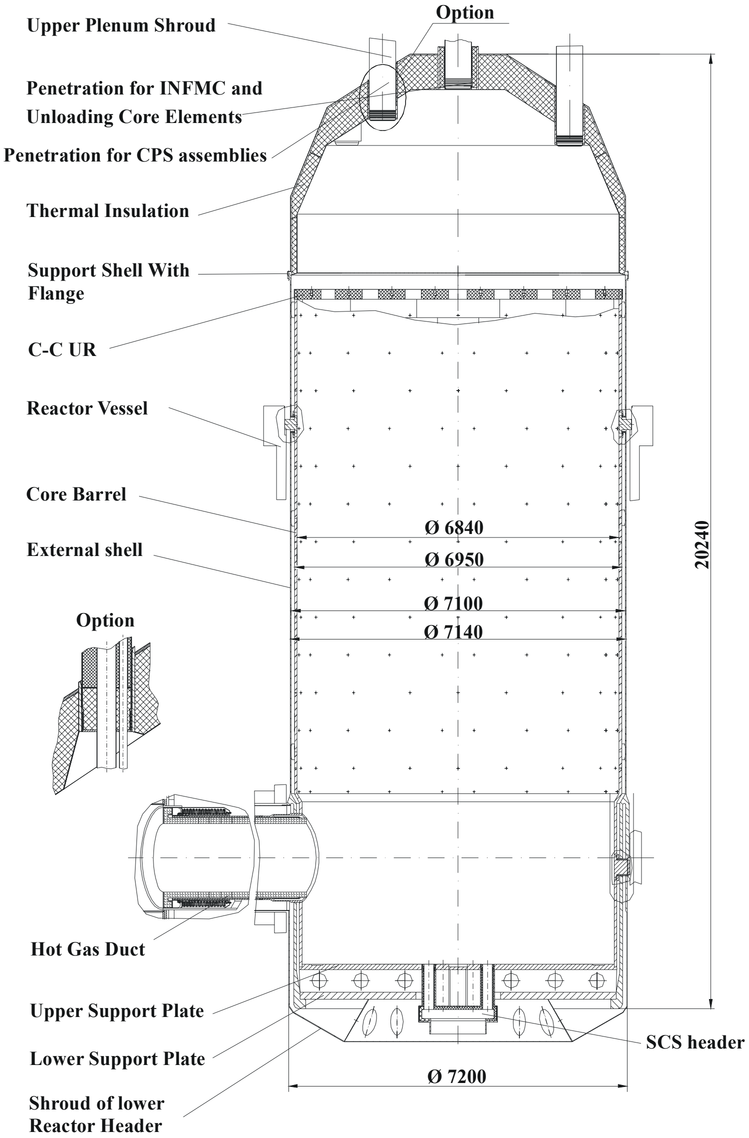

Figure 9. Metallic internals.

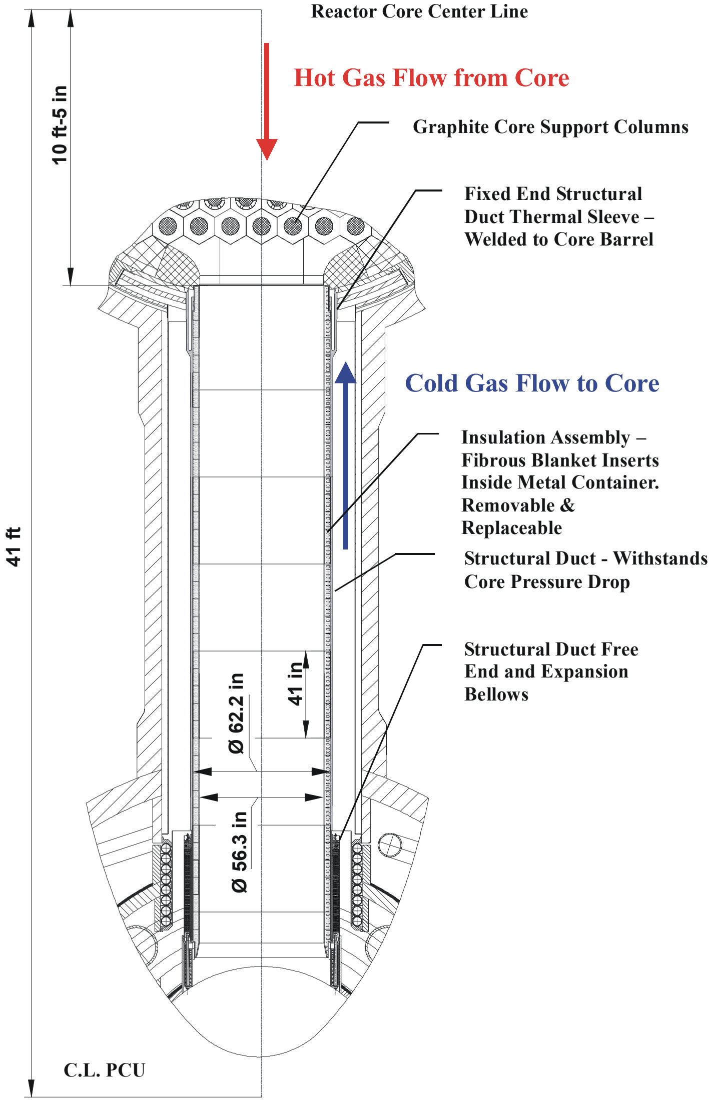

Figure 10. Hot gas duct cross-section.

Figure 10 also shows the details of the hot duct insulation subassemblies. These subassemblies are made up of cylindrical metallic containers that contain fibrous insulation. The structural duct is insulated from the hot core outlet gas by these cylinders. The inner diameter surface is bathed in core exit gas (~850°C for the GT-MHR and 1000°C for the VHTR) and must sustain the highest temperature of the primary coolant. The inside surface will be slightly above core inlet gas temperature. The cylinders are remotely removable and replaceable should the need arise during plant operations. The hot duct only rises in temperature about 30°C during a loss of forced circulation (LOFC) event followed by a conduction cooldown because it does not come in contact with the natural circulation flows in the core.

A listing of the VHTR in-reactor metallic components and their operating conditions is given in Table 4 below. The normal operating temperatures range from 600°C to 1000°C (the core outlet temperature); under abnormal conditions the temperatures of some of the sub-components can reach 1200°C for relatively short periods of time. All of the components are exposed to helium. End-of-life fluences for the components are also given in the table as well as the reference materials for these same components in the GT-MHR. The operating temperatures of equivalent components in the GT-MHR can be taken as 500°C where 600°C is noted in the table and 850°C where 1000°C is listed. The abnormal condition temperatures are similar for many of the VHTR and GT-MHR components.

Control and Protection System (CPS) and Reactivity Shutdown System (RSS) Pipes. The guide pipes in the CPS Drive and the RSS Drive pipes operate normally at about 500°C in the GT-MHR and 600°C in the VHTR. This is well within the capabilities of the Alloy 800H material specified in earlier GT-MHR designs. However, these pipes could reach 1200°C in both systems under abnormal conditions. The behavior of the Fe/Ni-base Alloy 800H would be very suspect at this temperature; very low strengths would be expected and melting is incipient at ~1360°C. Because of this, carbon-carbon composites should be considered as high priority candidates to substitute for the Alloy 800H.

It is also noteworthy that use of Alloy 800H above 816°C is not "approved" in ASME BPVC Article NH-3000. Therefore, assuming that the CPS and RSS applications require a material approved for nuclear service, a revision to the Code would be needed to permit use of Alloy 800H at the temperatures representative of abnormal events. The development, regulatory, and testing efforts associated with the use of carbon-carbon composite materials are described in Section 3.3.2.

Shutdown Cooling System (SCS) Components. The SCS heat exchanger shell sees essentially the full core outlet temperature (850°C and 1000°C, respectively, for the GT-MHR and VHTR). Although Alloy 800H should operate satisfactorily at 850°C, a material with higher temperature capability is needed for 1000°C operation. Examples of such materials are Hastelloy X and Alloy 617 (see Sections 3.4 and 3.5 for further information on these materials including development and testing requirements). However, even the behavior of these materials is problematic under abnormal (1200°C) conditions. Perhaps the best solution is to design with carbon-carbon composite materials as discussed in Section 3.3.2.

Hot Gas Duct. The pressure bearing shell of the hot duct operates at the core return gas temperature (i.e., 500°C for the GT-MHR and 600°C for the VHTR). Temperatures rise to about 660°C under abnormal conditions. Therefore, Alloy 800H might be suitable for both the GT-MHR and VHTR applications.

The inner diameter surface of the insulation canisters internal to the hot duct pressure shell will see full core exit temperature during normal operation, but temperatures under abnormal conditions will be little, if any, higher. Alloy 800H should be suitable for use in this application in the GT-MHR at 850°C with no additional development, regulatory, testing, or manufacturing infrastructure efforts. However, carbon-carbon composite material is also under consideration for this use and will almost certainly be required for long-term 1000°C service in the VHTR. (See Section 3.3.2 for a discussion of carbon-carbon composites.)

Table 4. Operating conditions and candidate materials for the system metallic components in the GT-MHR and VHTR.

Component	Sub-component	Normal VHTR System Operating Conditions		Abnormal Conditions	Materials Selected for the 850°C GT-MHR	Candidate Materials for the 1000°C VHTR
		Temp. [^oC]	Neutron Fluence, E>0.1 MeV [n/cm^2]			
Control and Protection System (CPS) Drive	Guide Pipe	600	$3x10^{16}$ per year	1200°C	Alloy 800H or carbon-carbon-composites	Alloy 800H or carbon-carbon-composites
Reserve Shutdown System (RSS) Drive	Pipe	600	As above	1200°C	Alloy 800H or carbon-carbon-composites	Alloy 800H or carbon-carbon-composites
Shutdown Cooling System [SCS]	SCS Heat Exchanger Shell	1000	$3x10^{16}$ in 60 years	1200°C	Alloy 800H	Hastelloy X, Alloy 617 or carbon-carbon-composites
	SCS Unit Bottom	600	$1x10^{16}$ in 60 years	1200°C	Alloy 800H	Hastelloy X, Alloy 617 or carbon-carbon-composites
Hot Gas Duct	Pressure Bearing Shell	600	$2x10^{17}$ in 60 years	660°C	Alloy 800H	Alloy 800H
	Outer Shell of Insulation Element	1000	As above	1000°C	Alloy 800H	Alloy 800H or carbon-carbon-composites
Core Barrel	Barrel Shell	600	$1x10^{19}$ in 60 years	700°C	Alloy 800H	Alloy 800H
In-vessel Metal-Works	SCS Entrance Tubes, Shell, and Insulation	600	$1x10^{19}$ in 60 years	1200°C	Alloy 800H or carbon-carbon-composites	Alloy 800H or carbon-carbon-composites
	Bottom Plate and Supports	600	As above	700°C	Alloy 800H	Alloy 800H
	Upper Plenum Shroud	600	As above	1100°C	Alloy 800H or carbon-carbon-composites	Alloy 800H or carbon-carbon-composites

Core Barrel. The core barrel shell surrounding the reactor core and reflector structure operates at the core inlet temperature, 500°C for the GT-MHR and 600°C for the VHTR. These temperatures increase to only 600°C and 700°C, respectively under abnormal conditions. Alloy 800H is suitable for this application for both the GT-MHR and the VHTR. Additional consideration should, however, be given to radiation effects at 500°C to 600°C as the end-of-life fluence reaches 10^{19} n/cm^2. This will likely not be a problem, but should be confirmed by reference to all the Alloy 800H radiation effects data. No other regulatory, testing, etc. efforts are necessary for this application.

In-vessel Metal-Works. All of the sub-components described earlier in the table (SCS entrance tubes, bottom plate and supports, and the upper plenum shroud) operate at the core inlet temperature (488°C for the GT-MHR and 600°C for the VHTR). However, temperatures for the entrance tubes (~1200°C) and the upper plenum shroud (~1100°C) are very high for the VHTR under abnormal conditions; those for the GT-MHR are likely almost as high. On the other hand, the abnormal condition temperature for the bottom plate and supports is 700°C or less for both systems and Alloy 800H should suffice for both without additional work. Carbon-carbon composite materials should be seriously considered for the other sub-components of both the GT-MHR and VHTR.

3.3.2. Carbon-Carbon-Composite Materials

A carbon-carbon-composite material comprises a carbon or graphite matrix that has been reinforced with carbon or graphite fibers. Multi-directional reinforced carbon-carbon-composite materials are substantially stronger, stiffer, and tougher than conventionally manufactured graphites, and are thus preferred over graphites for certain applications where high tensile strength is needed. Carbon-carbon-composite manufacture involves two major processing stages, namely, preform weaving and billet densification. The preform is woven from carbon fibers derived from a variety of precursors and arranged in multi filament bundles or tows. The woven fiber preform is converted to a densified composite material by repetitive impregnation, using resins or pitch, followed by carbonization and graphitization. Alternatively, densification can be achieved by using carbon vapor infiltration or a combination of pitch or resin impregnation and carbon vapor infiltration. Typically, the desired final density is achieved by several re-impregnations, carbonizations, and graphitizations. Final densities of 1.9-2.0 g/cm^3 can be attained. A flow diagram for a typical carbon-carbon-composite material manufacturing process is shown in Figure 11.

The carbon-carbon composite material components of the GT-MHR and VHTR are listed below and in Table 5.

- Control rod structural elements
- Control rod guide tubes
- Hot duct insulation cover sheets
- Lower core support insulation blocks
- Upper core restraint structure blocks
- Upper shroud insulation cover sheets
- Shut Cooling System entrance insulation

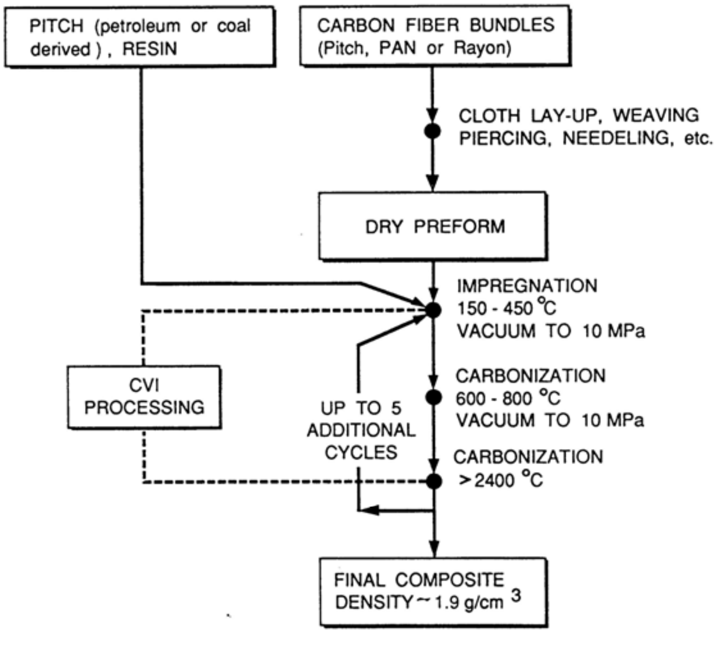

Figure 11. The processing steps in the production of carbon-carbon composite materials.

Table 5. Reactor internals list of VHTR operating conditions with GT-MHR materials and candidates for the VHTR.

Component	Sub-components	Normal VHTR operating conditions			Abnormal operating conditions	GT-MHR Materials	Candidate VHTR Materials
		Nominal Temp (C)	Neutron fluence with E≥0.1 MeV	Medium			
CPS drive	Control rod guide tube	600 at CRD to UPS Interface.	$3\cdot10^{16}$ cm^{-2} per year	Helium	Working fluid temperature in cooldown mode through RCCS can increase to 1200°C within 100 h	800H Tube	800H Tube (Could use carbon-carbon-composite material)
RSS drive	RSS balls guide tube					800H Tube	800H Tube (Could use carbon-carbon-composite material)
SCS unit metalwork	Conical shell at SCS HX	1000	$3\cdot10^{16}$ cm^{-2} per 60 years	Helium	~1200°C at start of cool down. Then ~1000°C	800H	800H
Hot gas duct	Pressure bearing shell	600	$2\cdot10^{17}$ cm^{-2} per 60 years	Helium	600°C at start of cooldown	800H	800H
	Outer shell of thermal insulation element unit	1000			1000°C at start of cooldown		800H [Alternative carbon-carbon-composite material]
	Inner shell of thermal insulation element unit	650			1000°C at start of cooldown		800H [Alternative carbon-carbon-composite material]
	Large diameter bellows	600			600°C		800H
	Thermal insulation	600-1000			1000°C at start of cooldown	Special Kaowool assy. (Mix of Al_2O_3 & SiO_2 fibers held with 800H screen and wires stays.)	Special Kaowool assy. (Mix of Al_2O_3 & SiO_2 fibers. With carbon-carbon-composite screen and stays)

Component	**Sub-components**	**Normal VHTR operating conditions**			**Abnormal operating conditions**	**GT-MHR Materials**	**Candidate VHTR Materials**
		Nominal Temp (C)	**Neutron fluence with E≥0.1 MeV**	**Medium**			
In-vessel metalworks	Metal support including outer shell, core shell, bottom Plate	600	$2.0 \cdot 10^{17}$ cm^{-2} per year	Helium	~700°C	Alloy 800H Plate	800H Plate
	SCS entrance structural tubes & chamber shell				~1200°C at start of cool down. Then ~1000 C	Alloy 800H tube & plate	800H tube & plate
	SCS entrance tubes & chamber insulation assembly				~1200°C at start of cool down. Then ~1000°C	Alloy 800H) Sheet & Plate. [Could be carbon-carbon-composite tubes] Special Kaowool assy. (Mix of Al_2O_3 & SiO_2 fibers.)	800H Sheet & Plate. [Could be carbon-carbon-composite tubes] Special Kaowool assy. (Mix of Al_2O_3 & SiO_2 fibers.)
	Upper core restraint				~1200°C	Carbon-carbon-composite blocks	Carbon-carbon-composite blocks [Was 800H plate]
	Upper collection header casing				~1100°C	Alloy 800H	800H

Of these components only the control rod structural elements, upper core restraint, and bottom core support insulation blocks are common to both the GT-MHR and the VHTR. Figure 12 shows a prototype carbon-carbon-composite control rod that was developed for the NP-GTMHR and reveals the structure of a three-directionally reinforced carbon-carbon-composite material such as that used for the connecting components of the control rods.

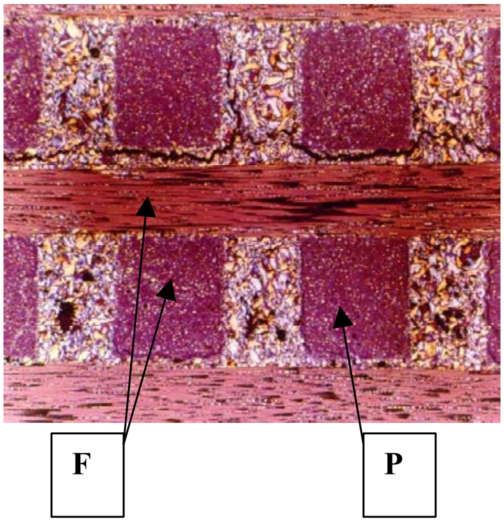

Figure 12. Prototype CCCM control rod canisters showing the articulating joint design (left) and the microstructure of a three directionally reinforced CCCM (above) showing the fiber bundles (F) and the carbonized pitch impregnant (P).

Carbon-carbon-composite materials are typically developed for specific applications and are not available off the shelf. The composite architecture (i.e., fiber type, fraction, orientation, lay-up) and processing conditions are selected to tailor the carbon-carbon-composite material for a specific application. Thus, prototype components must be produced from which material test specimens are cut and subjected to the appropriate thermal and irradiation conditions in the materials test program.

3.3.2.1. Status

The effects of neutron irradiation damage in carbon-carbon-composite materials have been studied because of their application in Tokamak fusion energy devices. Sufficient information is available about the behavior of carbon-carbon-composite material's to guide selection of precursor carbon materials (fiber type, impregnant type, processing conditions, etc.). However, insufficient neutron irradiation data exists to qualify these materials for reactor use. Composite architectures must be developed to meet design requirements for specific components, such as the prototype C/C control rods manufactured under the NP-GTMHR program in the 1990's (Figure 12).

3.3.2.2. Materials Selection and Development and Qualification Requirements

Prototype carbon-carbon-composite material components should be manufactured and tested for in-service conditions, i.e., service temperatures and environment. Properties data must be obtained for carbon-carbon-composite material components. Moreover, design models for C/C composites must be developed and verified as data becomes available. A radiation effects database must be developed for the selected carbon-carbon-composite material for control rod components. VHTR core temperatures are as much as 200°C greater, and thus additional data are required for all properties at these higher temperatures, including radiation damage effects.

3.3.2.3. Regulatory and Codification Requirements

There are no ASME codes or other industrial standards pertaining to the design of carbon-carbon-composite materials. Consequently, a full materials and component qualification test program will be required.

3.3.2.4. Materials Testing And Data Base Requirements

A properties database must be developed to support the design of carbon-carbon-composite material components. Data are required for the physical, mechanical & oxidation properties of carbon-carbon-composite materials. Properties data must support the service conditions, including effects of temperature, helium gas (plus air and water), and neutron irradiation effects (where applicable).

3.3.2.5. Manufacturing Infrastructure Required

The infrastructure is in place for manufacturing carbon-carbon-composite materials. Such materials are widely used in the aerospace industry for aircraft brakes, the semiconductor manufacturing industry for production of chips, and in the defense industry for reentry vehicle nose cones and rocket motor throats and nozzles.

3.3.3. Thermal Insulation Materials

High temperature fibrous insulation must be used throughout the reactor system and the power conversion unit notably in the hot duct, upper plenum shroud, SCS helium inlet plenum, and turbocompressor. Figures 9 and 10 show where insulation is required in the reactor metallic internals and hot gas duct. The insulation is required to retain its resiliency and physical characteristics during normal operating and conduction cooldown accident conditions. Mechanical loads on the thermal insulation result from differential thermal expansion, acoustic vibration, seismic vibration, fluid flow friction, and system pressure changes.

There are many ways to achieve insulation. A meter of graphite thickness plus 0.2 meter of carbon-carbon composite blocks is sufficient to insulate the lower metallic core support structure from the core outlet gas. However, where room is limited to a few inches of insulation thickness to do the same job, a more efficient form of insulation is needed. Insulation design studies have determined that the best insulation system for the GT-MHR application is the use of Al_2O_3 and SiO_2 mixed ceramic fiber mats contained between metallic cover plates attached to the primary structure that requires insulation. Figure 13 illustrates the basic principle of this type of insulation. Figure 10 shows this type of insulation applied to the hot gas duct. If the Al_2O_3 and SiO_2 mixed ceramic fiber mat insulation is found to inadequate, the alternative thermal insulation designs are a metal foil sandwich, or solid ceramic blocks encased in high temperature canisters. These design s can be used at very high temperatures if there is a problem with the fibrous insulation system.

The fibrous insulation material is heat treated to remove impurities and formed into a mat that will conform to the shape of the insulation canister. For the hot duct, the canisters are concentric cylinders with end plates, then joined together between sections. For other structures, these canisters will be segments that conform to the shape of and be attached to the larger primary structure. The canisters must be vented to adjust to system pressure changes. They are designed to accommodate the differential thermal expansion between the hot and cold sides of the insulation canisters. They must also withstand the mechanical forces from fluid flow, acoustic and seismic vibration.

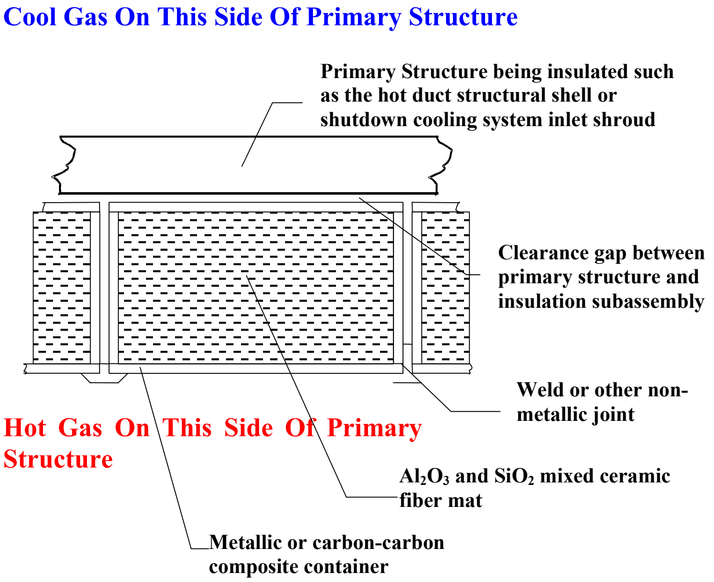

Figure 13. Thermal insulation system for the GT-MHR.

The canisters are in direct contact with the hottest gas conditions in the reactor. Thus, the materials chosen for these canisters will need to withstand 1000°C for 60 years, or up to 1200°C for up to 50 hours and then 1100°C for 100 hours during an LOFC followed by a conduction cooldown transient. For this reason non-metallic materials such as carbon-carbon composites may be required for some of these canisters. The insulation materials and their operating conditions are listed in Table 6.

3.3.3.1. Status

Insulation of this type was used in The Fort Saint Vrain HTGR built by Public Service Company of Colorado in the 1970's. It has also been used in other gas reactors in Germany and Japan. Test programs to support the acquisition of design and performance data were conducted on Kaowool and Quartz-et-Silice fibrous mats to determine their ability to sustain compression as a function of temperature to determine the effect on resiliency. Limited irradiation effects tests data is available. Tests to determine fatigue properties as a function of acoustic noise were planned but not conducted.

3.3.3.2. Materials Selection and Development and Qualification Requirements

The development of thermal insulation systems for the 850°C GT-MHR is being done in Russia. The VHTR will require nearly a complete revision of these insulation components for the higher temperature operating conditions. Most likely the fibrous mats will withstand the higher temperatures, but this will need to be verified by sub-component tests. In addition new materials are needed for the insulation canisters to withstand the higher normal operating and accident conditions. Thus much of the work being done on the Russian program will be repeated with new materials and configurations, especially if carbon-carbon composite materials are used for the canisters.

Table 6. Reactor internals thermal insulation operating conditions and candidate GT-MHR and VHTR materials.

Component	Sub-components	Normal VHTR operating conditions			Abnormal operating conditions	GT-MHR Materials	Candidate VHTR Materials
		Nominal Temp (°C)	Neutron fluence with $E \geq 0.1$ MeV	Medium			
SCS unit metalworks Insulation	Conical shell at SCS HX	1000	$3\cdot10^{16}$ cm^{-2} per 60 years	Helium	~1200°C At start of cool down. Then ~1000°C	800H Canisters with Al_2O_3-SiO_2 ceramic fiber mats	Hasteloy X or carbon-carbon composite canisters with Al_2O_3-SiO_2 ceramic fiber mats
Hot gas duct	Outer shell of thermal insulation element unit	1000	$2\cdot10^{17}$ cm^{-2} per 60 years	Helium	1000°C At start of cooldown	800H canisters with Al_2O_3-SiO_2 ceramic fiber mats	Hasteloy X or carbon-carbon composite canisters with Al_2O_3-SiO_2 ceramic fiber mat]
	Inner shell of thermal insulation element unit	650			1000°C At start of cooldown		Hasteloy X or carbon-carbon composite canisters with Al_2O_3-SiO_2 ceramic fiber mat]
	Thermal Insulation	600-1000			1000°C At start of cooldown	Special Kaowool assy. (Mix of Al_2O_3 & SiO_2 fibers held with high temperature screen and wires stays	Special Kaowool assy. (Mix of Al_2O_3 & SiO_2 fibers held with high temperature screen and wires stays.))
In-vessel metalworks Insulation	Metal support bottom Plate insulation	600	$2.0\cdot10^{17}$ cm^{-2} per year	Helium	~700°C	Carbon-carbon composite blocks	Carbon-carbon composite blocks
	SCS entrance structural tubes Insulation				~1200°C At start of cool down. Then ~1000 C	800H tubular canisters with Al_2O_3-SiO_2 ceramic fiber mats	Hasteloy X or carbon-carbon composite canisters with Al_2O_3-SiO_2 ceramic fiber mats
	Upper Plenum Shroud Insulation				~1200°C At start of cool down. Then ~1000°C	800H Canisters with Al_2O_3-SiO_2 ceramic fiber mats	Hasteloy X or carbon-carbon composite canisters with Al_2O_3-SiO_2 ceramic fiber mats

3.3.3.3. Regulatory and Codification Requirements

The insulation systems for this application are not designed to any particular industry code. However, materials property test data will be needed to license the plant that is statistically similar to ASME code type quality standards. In addition, component performance tests will need to be performed in some cases to show that components with safety functions are not compromised during plant operation or realistic accident scenarios.

3.3.3.4. Materials Testing And Data Base Requirements

Data on the manufacture and performance of fibrous insulation are needed to ensure that the selected materials are capable of lasting for the life of the plant. The data include: physical properties (heat resistance, heat conductivity and heat capacity), long term thermal and compositional stability, mechanical strength at temperature, resistance to pressure drop, vibrations and acoustic loads, radiation resistance, corrosion resistance to moisture- and air-helium mixtures, stability to dust release and gas release, and manufacturing tolerances and mounting characteristics. The acquisition of these data requires testing of insulation specimens or small assemblies of thermal insulation panels. Specific test rigs and facility requirements include helium flow, vibration, and acoustic test equipment as well as an irradiation facility and hot cell.

3.3.3.5. Manufacturing Infrastructure Required

Ceramic fiber insulation materials and metallic or carbon-carbon plates can be readily obtained from existing infrastructure in the U.S.A. Western Europe, and Russia.

3.4. Intermediate Heat Exchanger (IHX)

The VHTR IHX is the component in which the heat from the primary circuit helium (1000°C at 1000psi) is transferred to the secondary circuit helium (about 950°C at 1000psi), thus keeping the secondary circuit free of radioactive contamination. The IHX will be located within a pressure vessel within the reactor containment that will be attached to the reactor pressure vessel by the cross-vessel. Therefore, the only pressure differential that the IHX will see during normal service is a relatively low circulation pressure, not the large pressure drop to ambient. This significantly reduces long-term loading on the materials within the IHX. However, in the event of loss of pressure in the secondary circuit, the IHX will need to provide short-term containment of the primary system pressure during reactor cooldown.

The secondary fluid will exit the IHX and the reactor containment through a vessel similar to the hot duct vessel. The secondary fluid, which is free of radioactive contamination, will be used for the production of hydrogen or other process heat applications.

3.4.1. Status

The VHTR IHX design will probably be a compact, counter-flow heat exchanger design consisting of metallic plate construction with small channels etched into each plate (Figure 14) and assembled into a module such as shown in Figure 15. This heat exchanger design is refereed to as a “printed circuit heat exchanger”. This heat exchanger is significantly smaller in size than a standard shell and tube heat exchanger due to the effective use of the heat transfer area, and, with appropriate materials of construction, it can withstand relatively high temperatures and pressures. In the event that a printed circuit type heat exchanger will not work, the backup IHX will be a conventional tube and shell heat exchanger that will be considerably larger than the printed circuit type heat exchanger.

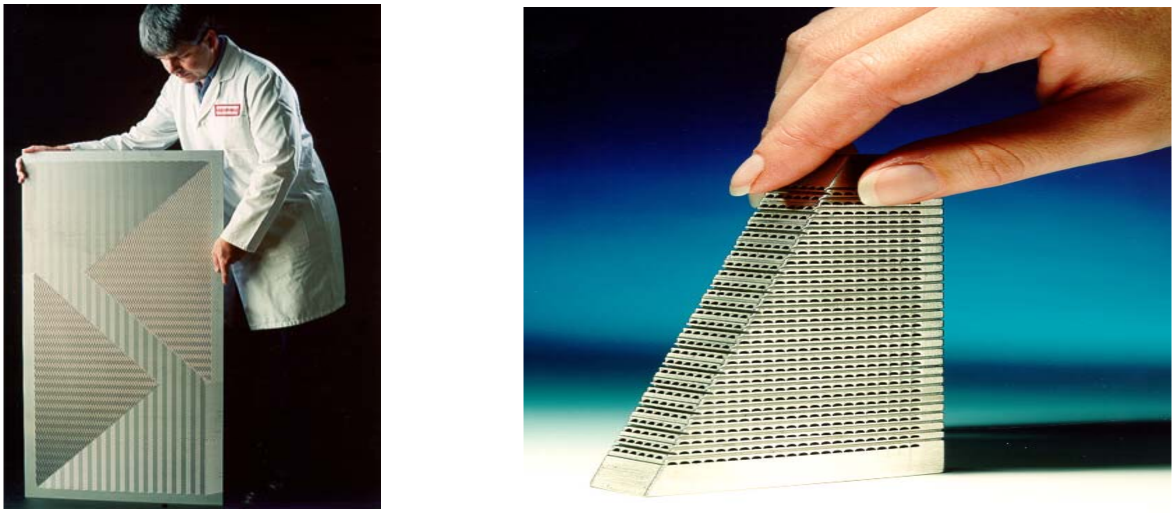

Figure 14. View of etched plate and close-up view of a portion of the heat exchanger module.

Figure 15. Printed circuit heat exchanger module.

Printed circuit type heat exchanger are constructed from flat metal plates into which fluid flow channels are chemically milled. The milled plates are stacked and diffusion bonded together. Diffusion bonding converts the stack of plates into a solid block containing precisely engineered flow passages. Figure 16 shows a photo-micrograph of a bonded printed circuit heat exchanger cross-section.

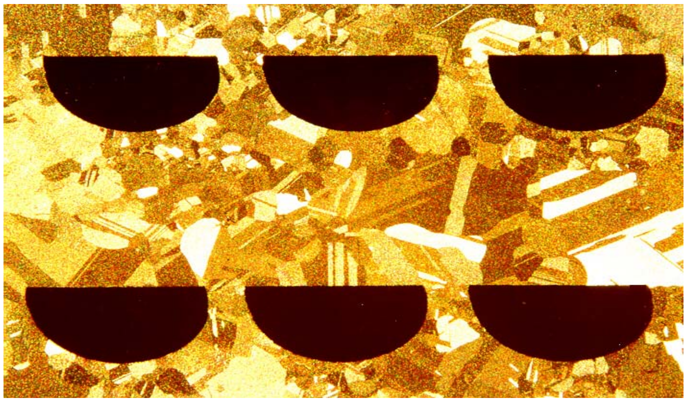

Figure 16. Photo-micrograph of a bonded printed circuit type heat exchanger cross-section.

HEATRIC, a division of Meggitt of Dorset, England, has been identified as a potential supplier. Heatric operates a quality system accreted to ISO 9001 and is an approved manufacture to ASME Section VIII, Div 1. Examples of assembled modules are depicted in Figure 17.

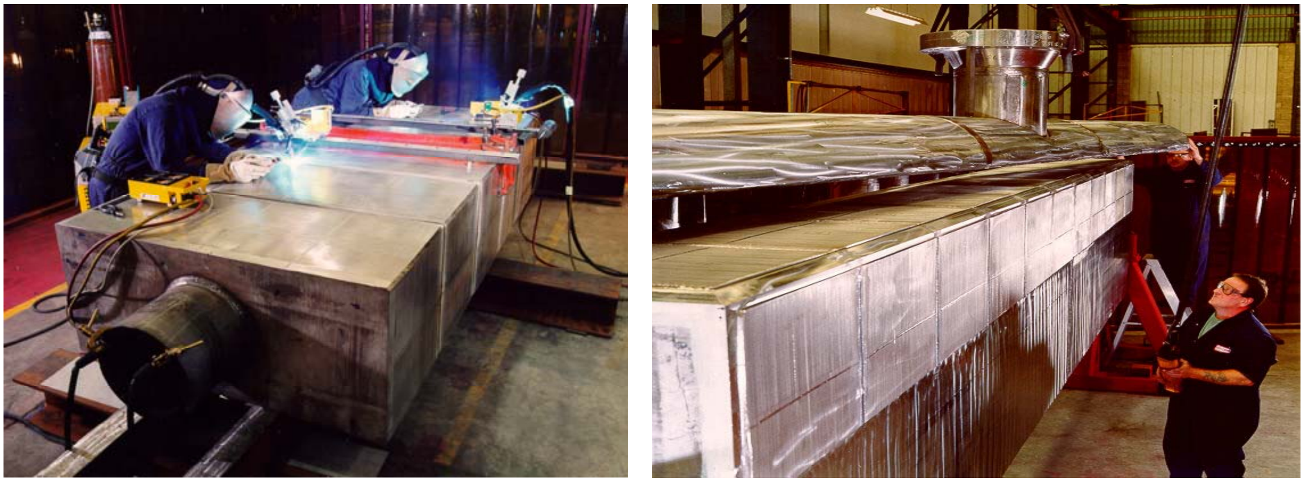

Figure 17. Examples of assembled PCHE modules.

However, the Heatric capabilities are not sufficient for the VHTR. The VHTR requires the use of higher temperature alloys, such as Incoloy 800HT (1650 F or 900°C) or Alloy 617 (1800°F or 980°C) and a formal materials selection process will be required. Although the ASME code does not presently support the use of these material for stand alone pressure containment, there does appear to be adequate data to support design of printed circuit heat exchanger modules as internals of an IHX pressure vessel. The external IHX pressure vessel will be designed and fabricated from existing ASME code materials.

3.4.2. Materials Selection and Development and Qualification Requirements

An ASME code case was prepared by ORNL for Alloy 617 in the early 1980s, but was withdrawn due to a lack of interest and funding. This work would have to be retrieved and reviewed to determine if sufficient data exist to support the alloy as a candidate material for the internals of the IHX. Additional data may be required to assure sufficient margin exists in the IHX module design at 1000°C.

The diffusion bonding technology for the IHX sheets, and methods for ensuring their resulting mechanical integrity and leak tightness, will need to be developed and demonstrated. ASME code modifications for Alloy 617 are not required to support the design of the IHX internals.

3.4.3. Regulatory and Codification Requirements

Since the VHTR design is a passively safe design, the IHX is not required for a safe shut-down of the reactor. Therefore, no regulatory actions are required for the IHX.

3.4.4. Materials Testing And Data Base Requirements

An extensive testing program would be required for the following:

- Physical, mechanical, and oxidation properties (1000 plus C).
- Verification that there would not be slumping problems.
- Development and demonstration of the candidate alloy diffusion bonding technology.
- Fouling and plugging studies.
- Flow distribution studies tests.
- Development and demonstration of NDE or pressure testing methods to ensure primary circuit integrity

3.4.5. Manufacturing Infrastructure Required

The unit would have to be specifically designed. It is not envisioned that there would be any unique manufacturing or assembly problems. Field assembly may be necessary.

3.5. Power Conversion System

The three most critical components in terms of elevated temperature service in the Power Conversion System (PCS) for the 1000°C VHTR are the inlet turbine shroud, the turbine disks and blades, and the recuperator. The system operating conditions for these components are shown in Table 7 below; these conditions include temperature (both normal and abnormal), end-of-life neutron fluence, and operating environment. Also included in Table 7 are the materials currently anticipated as appropriate for these components in the 850°C GT-MHR.

Table 7. VHTR Power conversion system operating conditions and candidate materials selections for the 850°C GT-MHR and 1000°C VHTR.

Component	**Normal VHTR System Operating Conditions**			**Abnormal Conditions**	**Materials for the GT-MHR**	**Candidate Materials for the VHTR**
	Temperature [°C]	**Neutron Fluence, E>0.1MeV [n/cm^2]**	**Environment**			
Turbine Inlet Shroud	1000	5×10^{13} in 7 years	Helium	~1050°C, <350 h in 7 years	Hastelloy X	Alloy 617 or carbon-carbon composites
Turbine Disks and Blades	1000	As above	Helium	As above	Wrought Ni-base alloy for disks, cast Ni-base alloy for blades	Wrought Ni-base alloy for disks, cast Ni-base alloy for blades
Recuperator	600	2×10^{15} in 60 years	Helium	<600°C	300 Series SS	300 Series SS

3.5.1. Turbine Inlet Shroud

Figure 18 shows a cutaway sketch of the GT-MHR turbine assembly. The turbine inlet shroud accepts the helium coolant exiting from the hot duct and directs it to the turbine inlet. It is insulated both to minimize the thermal gradient across the shroud wall and to limit heat losses. However, there is a stiffening element or collar between the shroud and turbine that is non-insulated and sees the maximum system operating temperature [i.e., ~850°C for GT-MHR and ~1000°C for VHTR]. The maximum metal temperature in the bulk of the GT-MHR turbine inlet shroud is ~750°C.

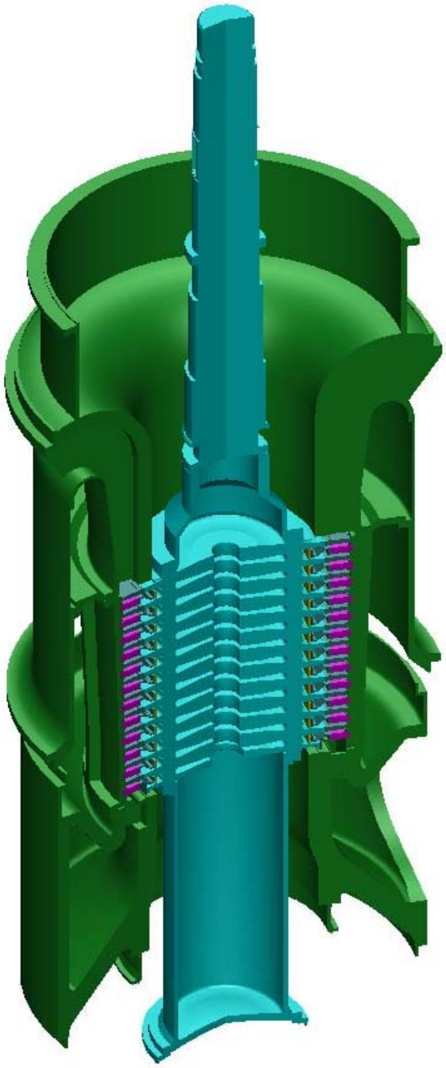

Figure 18. Cutaway sketch of the GT-MHR turbine assembly. The first stage turbine blades are at bottom of the figure. The inlet volute with high temperature insulation is just below turbine.

3.5.1.1. Status

The shroud material for the GT-MHR is, as shown in Table 7 above, likely to be a wrought Ni-base alloy such as Hastelloy X. There is an excellent database, including gas-metal compatibility in gas-cooled reactor environments, in the US, Europe, and Japan. It is expected that strength and compatibility issues will be minimal for use of this alloy at 850°C.

A change to a material or materials of greater strength will likely be required for the VHTR. Use of Alloy 617 is one possibility for the inlet turbine shroud, including that portion operating at 1000°C. Alternatively, an insert of a high-strength cast Ni-base alloy might be employed in this area. It will also be necessary to change the boundary/container material for the insulation package. Alloy 617 might be acceptable or it may be more desirable to go to a package based on carbon-carbon composites [see Section 3.3.2].

3.5.1.2. Materials Selection and Development and Qualification Requirements

No developmental efforts beyond data assembly and analysis should be required for the GT-MHR.

For the VHTR, it will be necessary to evaluate the applicability of Alloy 617 and/or cast Ni-base alloys for use at 1000°C in the turbine inlet shroud. It will also be necessary to evaluate changes in insulation package container material.

3.5.1.3. Regulatory and Codification Requirements

No regulatory efforts should be required for the materials selected for either system.

3.5.1.4. Materials Testing And Data Base Requirements

No testing efforts related to Hastelloy X are anticipated for its use in the GT-MHR. Attention should be directed to questions of 1000°C long-term strength and compatibility of any Ni-base alloys selected for the turbine inlet shroud. Additional data may be required in the temperature range 950°C to 1050°C. For questions of carbon-carbon composites see Section 3.2.

3.5.1.5. Manufacturing Infrastructure Required

For both concepts (i.e., GT-MHR and VHTR) it is desirable to demonstrate manufacturing processes [forming and welding] for the shroud. However, there is no question of feasibility.

3.5.2. Turbine

As shown in Figure 18, a twelve-stage turbine is employed for the 850°C GT-MHR and the same type of turbine will probably be used for the 1000°C VHTR system. The disks of the first three stages of the 850°C machine are cooled to maintain the temperature of the disk alloy to below 650°C; the blades are not cooled and the maximum temperature is in the range 800-850°C. For the VHTR, with a maximum temperature approaching 1000°C, the disk temperature can be limited to 750°C by cooling of the first six stages and the blades could be cooled to nominally 900°C.

3.5.2.1. Status

The current disk material selection for the GT-MHR is a wrought Ni-base alloy with additions of Cr, Mo, Ti, and Al. An example of such an alloy is Nimonic 80A developed for service in the temperature range up to 750°C. The selected blade material is a cast Ni-base alloy. For example, this could be a material such as cast Alloy 713LC. It is worthy of note here that the exact materials selected will be a function of the turbine manufacturer; each has his own favorite materials based on experience and turbine conditions.

A disk material acceptable for the GT-MHR (650°C maximum temperature) should also be acceptable for the VHTR at 750°C; the blade material may also be acceptable for both machines but should be evaluated in each case.

3.5.2.2. Materials Selection and Development and Qualification Requirements

There should be no developmental efforts required for the GT-MHR application other than evaluation of the alloys selected.

For the VHTR, the materials selected for the GT-MHR should be evaluated for acceptability for use at the higher temperatures required (i.e., 750°C for the disks and 900 to 1000°C for the blades. Blade cooling should be considered if it is desirable to limit temperature to the 900°C range. The potential beneficial effects [e.g., lower blade temperatures] of applied coatings should also be examined.

3.5.2.3. Regulatory and Codification Requirements

No regulatory efforts should be required for either system.

3.5.2.4. Materials Testing And Data Base Requirements

For both systems, this will need to be revisited after the selection of turbine disk and blade alloys. For example, the existence of test data on these alloys in gas-cooled reactor environments will needed to be confirmed, especially for the blade materials at temperatures >800°. If data or relevant experience does not exist, a change to materials with existing data or a test program to obtain relevant data must be considered. If blade coating were to be selected as an option, a test program of coating durability and compatibility would be required.

3.5.2.5. Manufacturing Infrastructure Required

No efforts should be required for either system.

3.5.3. Recuperator

The recuperator shown in Figure 19 is a modular counter-flow helium-to-helium heat exchanger with corrugated-plate heat exchange surfaces. The helium inlet temperature is ~500°C for GT-MHR and ~600°C for VHTR; exit temperatures in both cases are nominally 120°C.

3.5.3.1. Status

An austenitic 300 series stainless steel will probably be selected for all portions of the recuperator. Options include such steels as 316L and stabilized steels such as 321 and 347. Sufficient data should be available for design and confirmation of acceptable compatibility in all cases at both 500°C and 600°C.

3.5.3.2. Development, Regulatory, and Testing Efforts Required

None should be required for materials.

3.5.3.3. Manufacturing Infrastructure Required

Manufacture of the corrugated heat exchange surfaces of the recuperator requires very high quality 0.35-mm sheet material of size 2.8-m x 2.2-m. The capability to provide such materials should be demonstrated on a commercial scale.

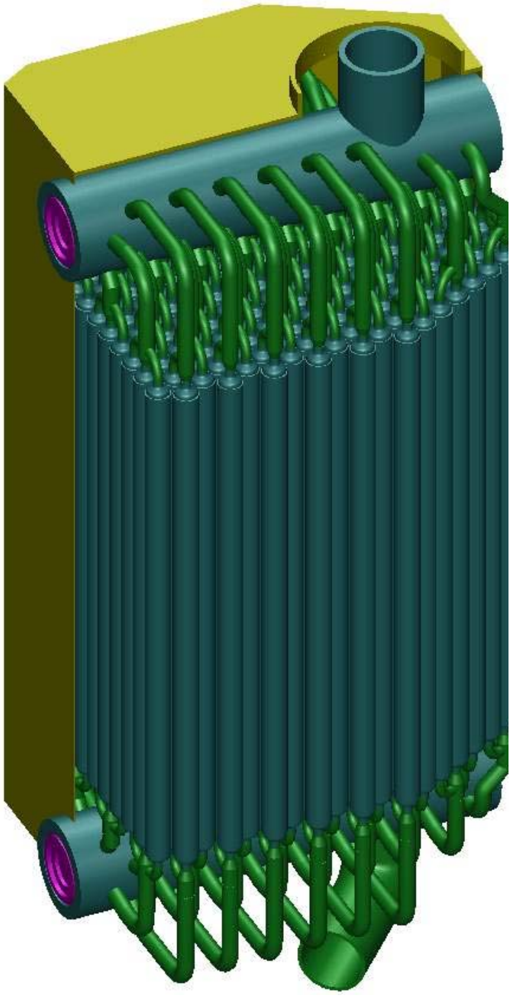

Figure 19. GT-MHR recuperator (one unit is shown out of total of ten units).

4. Materials Development Programs And Order-of-Magnitude Costs

4.1. Development Tasks, Costs, and Schedules for the Reactor Pressure Vessel Materials

With the exception of the environmental effects work specific to the 9Cr-1Mo steel in support of the higher temperatures of the VHTR, a fairly comparable set of tasks would be needed to use 2 1/4Cr-1Mo for the GT-MHR vessels or 9Cr-1mo steel for the VHTR vessels. Therefore, with the exception of the environmental-effects task and the increment indicated for the more challenging problem of scale-up for the 9Cr-1Mo steel, the funding and schedules noted below would be needed for either material/reactor combination. However, the development and qualification of 9Cr-1Mo steel for the VHTR vessel system would also be sufficient for the GT-MHR.

Table 8. Tasks, schedules, and costs associated with developing a suitable database for the reactor pressure vessel materials.

Test Description	**Applicability**	**Test Duration** (months)	**Cost** ($k)
Develop very large ring forging and heavy-section welding and NDE (including on-site assembly) technology for 2 1/4Cr 1Mo steel	GT-MHR	48	1,800
Develop very large ring forging and heavy-section welding and NDE (including on-site assembly) technology for 9Cr 1Mo steel	VHTR	72	6,000
Creep, creep-rupture/fatigue and aging data for 60-year lifetimes	GT-MHR and VTHR	120	5,200
Confirmatory radiation-effects testing and model development	GT-MHR and VTHR	60	7,000
High-temperature environmental fatigue and crack-growth testing	VTHR	36	2,400
High-emissivity scale studies	GT-MHR and VTHR	36	2.000
High-temperature bolting	VTHR	36	2,400
High-temperature design methodology development	GT-MHR and VTHR	96	30,000
Total Test Duration And Costs		**120**	**55,000[1]**

[1] Cost total reflects sum of higher VHTR costs that incorporate or replace GT-MHR costs

The total funding required for the GH-MHR reactor pressure vessel materials work is about $39 million and the total funding required for the GT-MHR and VHTR reactor pressure vessel materials work is about $55. It should be noted that while the development of the materials technology described here is needed for the GT-MHR or VHTR, much of it will also be required for, and applicable to, other Generation IV reactor concepts and their components. In particular, the relatively costly high-temperature design methodology development task will be required for and applicable to virtually all the Generation IV materials and components that operate at high enough temperatures to be governed by time-dependent behavior. To avoid double counting, costs for this task are included in this section only.

4.2. Development Tasks, Costs, and Schedules for the Reactor Core Graphite Materials

Tasks associated with developing a suitable design database for the GT-MHR and VHTR graphites are noted in Table 9 below. Estimates of the "period of performance" and costs for each task are also given in the table. These estimates are only first order and are subject to revision upon detailed planning. The development task will be completed with 5 years and the estimated total cost is $42 million. Of this, $30 million is applicable to both the GT-MHR and the VHTR and $12 million is specific to the VHTR.

Table 9. Tasks, schedules, and costs associated with developing a suitable database for the core graphite materials.

Task	Applicability	Period of Performance (Months)	Cost (K$)
Fuel Element & Replaceable Reflector			
Phys. & mech. Properties data acquisition as a function of temperature & property statistics	GT-MHR & VHTR	48	2,000
Oxidation behavior & effects on properties	GT-MHR & VHTR	18	1,000
Neutron irradiation effects on properties[1]	GT-MHR & VHTR	24	4,000
High temperature irradiation effects[1]	VHTR	12	2,000
Irradiation creep effects[1]	GT-MHR & VHTR	36	3,000
High temperature irradiation creep[1]	VHTR	12	2,000
Core Support Structure Graphite			
Phys. & mech. Properties data acquisition as a function of temperature & property statistics	GT-MHR & VHTR	24	2,000
Oxidation behavior & effects on properties	GT-MHR & VHTR	18	1,000
Neutron irradiation effects on properties[1]	GT-MHR & VHTR	24	4,000
High temperature irradiation effects[1]	VHTR	12	3,000
Irradiation creep effects[1]	GT-MHR & VHTR	36	3,000
High temperature irradiation creep[1]	VHTR	12	2,000
Permanent Reflector Graphite			
Phys. & mech. Properties data acquisition as a function of temperature & property statistics	GT-MHR & VHTR	24	2,000
Oxidation behavior & effects on properties	GT-MHR & VHTR	18	1,000
Neutron irradiation effects on properties	GT-MHR & VHTR	24	4,000
High temperature irradiation effects[1]	VHTR	12	2,000
Irradiation creep effects[1]	GT-MHR & VHTR	36	3,000
High temperature irradiation creep[1]	VHTR	12	1,000
Total Costs			**42,000**[1]

[1] Cost total reflects sum of higher VHTR costs that incorporate or replace GT-MHR costs.

4.3. Development Tasks, Costs, and Schedules for the Metallic Components in the Reactor Core Region

Tasks associated with demonstrating the suitability of metallic materials for major high-temperature Reactor Internals components for both the GT-MHR and the VHTR are listed in Table 10 below. (They have been numbered to facilitate further discussion.) Essentially the only metallic material being considered for these applications is Alloy 800H Fe/Ni-base alloy. However, it is extremely unlikely that this alloy will perform satisfactorily for long (full life) periods at 1000°C (e.g., for the VHTR SCS heat exchanger shell) or for shorter periods at 1200°C under abnormal conditions. Even so, testing tasks (Tasks 2 and 7) have been shown assuming that a decision might be made to employ Alloy 800H under these stringent conditions. There is also a significant testing task (Task 4) if Ni-base alloys are selected for use. If all of the tasks shown in the table are pursued the total cost would be \$12 million with all but \$2 million of the total applicable to both the GT-MHR and the VHTR.

Table 10. GT-MHR and VHTR materials tasks, schedules, and costs for metallic reactor internals.

Task	Applicability	Period of Performance (months)	Cost (K\$)
Control and Protection System and Reactivity Shutdown System Pipes			
1. Assess viability of using Alloy 800H at the high temperatures associated with abnormal events.	GT-MHR & VHTR	4	400
2. Assuming a decision to use Alloy 800H, pursue extension of ASME Code Case for short times at temperatures between 816°C and 1200°C.	GT-MHR & VHTR	96	3,000
Shutdown Cooling System Components			
3. Evaluate metallic materials for full service life at 1000°C and short term service to 1200°C	GT-MHR & VHTR	6	300
4. Conduct compatibility and strength tests on materials selected in task above.	GT-MHR & VHTR	96	5,400
Hot Gas Duct and Insulation Package			
5. Assess viability of using Alloy 800H as pressure bearing shell for short periods at temperatures to 1000°C[1]	GT-MHR & VHTR	4	100
6. Assess viability of using Alloy 800H for full lifetime as insulation package shell at 1000°C.	VHTR	4	300
7. Conduct limited high temperature compatibility and strength tests of Alloy 800H for 1000°C service[2].	GT-MHR & VHTR	72	2,000
Core Barrel			
8. Evaluate existing radiation effects data for Alloy 800H to confirm suitability for use.	GT-MHR & VHTR	8	400
In-vessel Metalworks			
9. Assess viability of using Alloy 800H at the high temperatures associated with abnormal events[1]	GT-MHR & VHTR	4	100
Total Test Duration and Costs		96	12,000[3]

[1] Cost and effort covered in 1st task in this table.

[2] Also applies to the core barrel application.

[3] Cost total reflects sum of higher VHTR costs that incorporate or replace GT-MHR costs

Viable candidates for all of the very high temperature applications are carbon-carbon composites (see Section 3.3.2 for details). However, there are several applications in which the Alloy 800H should perform satisfactorily for both the GT-MHR and the VHTR (core barrel, the hot gas duct pressure shell, and in-vessel bottom plate and supports). Implementation of this choice would require completion of Task 7. Going this route (Option 2) would eliminate Tasks 2, 3, and 4. Option 2 should not be considered as providing an overall cost savings since carbon-carbon composite materials developments will have considerable associated costs. However, this combination of Alloy 800H and carbon-carbon composite components appears optimum for Reactor Internals.

4.4. Development Tasks, Costs, and Schedules for CCCM Components in the Reactor Core Region

Tasks associated with developing a suitable design database for the GT-MHR and VHTR CCCM's are noted in Table 11 below. Estimates of the "period of performance" and costs for each task are also given in the table. These estimates are only first order and are subject to revision upon detailed planning as design details become available. The development task will be completed with 4 years and the estimated total cost is \$21 million. Of this, \$11.5 million is applicable to both the GT-MHR and the VHTR and \$9.5 million is specific to the VHTR.

Table 11. Tasks, schedules, and costs associated with developing a suitable database for the core CCCM materials.

Task	Applicability	Period of Performance (Months)	Cost (K$)
Control Rod Structural Elements			
Develop prototype control rod clad/structures	GT-MHR & VHTR	24	1,000
Conduct component testing	GT-MHR & VHTR	18	1,000
Determine materials properties	GT-MHR & VHTR	18	1,000
Neutron irradiation effects	GT-MHR & VHTR	36	5,500
Oxidation behavior and effect on properties	GT-MHR & VHTR	36	1,000
Upper Core Restraints and Bottom Core Support Insulation Block			
Develop prototype control rod clad/structures	GT-MHR & VHTR	24	1,500
Conduct component testing	GT-MHR & VHTR	18	3,000
Determine materials properties	GT-MHR & VHTR	18	1,000
Oxidation behavior and effect on properties	GT-MHR & VHTR	36	1,000
Other CCCM Components			
Develop prototype control rod clad/structures	VHTR	24	1,000
Conduct component testing	VHTR	18	2,000
Determine materials properties	VHTR	18	1,000
Oxidation behavior and effect on properties	VHTR	36	1,000
Total Costs			**21,000**[1]

[1] Cost total reflects sum of higher VHTR costs that incorporate or replace GT-MHR costs.

4.5. Development Tasks, Costs, and Schedules for the Insulation Materials in the Reactor Core Region

The testing to obtain thermal insulation data can be completed in about three to four years. The total cost of these tests is estimated at about $10 million not including the costs for irradiation and hot cell facilities. Detail elements of the test program are shown in Table 12.

Table 12. Thermal insulation development tasks, schedules, and costs.

Test Description	**Applicability**	**Test Duration** (months)	**Cost** ($k)
Insulation Material Screening Tests	VHTR	6	1,000
Acoustic Vibration Endurance Tests	GT-MHR & VHTR	9	500
Pressurization-Depressurization Endurance Tests	GT-MHR & VHTR	9	500
Mechanical & Physical Properties Tests	VHTR	9	500
Thermal Insulation Element Conductivity Tests	VHTR	9	500
Neutron Radiation effect tests on Thermal/Physical/Mechanical Properties	VHTR	48	5,600
Tests to determine effect of steam/helium & air/helium mixtures on insulation material endurance	VHTR	9	400
Dust & Gas Release tests	VHTR	9	400
Dimensional stability Tests on Insulation materials and assemblies.	VHTR	6	200
Manufacturing and Installation development tests	VHTR	6	200
Performance tests of selected Thermal insulation materials	VHTR	6	200
Total Test Duration And Costs		**36**	**10,000**[1]

[1] Cost total reflects sum of higher VHTR costs that incorporate or replace GT-MHR costs.

4.6. Development Tasks, Costs, and Schedules for the Intermediate Heat Exchangers (IHX)

The IHX development test program will involve qualifying the use of higher temperature materials to replace the current materials. Inconel 617 has been identified as a potential candidate. The techniques of constructing compact heat exchangers are well understood and backed by successful performance in non-nuclear applications. Thus, the development program would emphasize qualifying a new material, such as Inconel 617, to nuclear quality standards and verifying performance of a prototype IHX.

The rough estimate of the IHX development program is shown in Table 13. These estimates are subject to modification as more detailed test plans are developed.

Table 13. VHTR materials tasks, schedules, and costs for the intermediate heat exchanger.

Test Description	**Applicability**	**Test Duration** (months)	**Cost** ($k)
Candidate Materials Diffusion Bonding Development	VHTR	36	4,800
Material Behavior and Welding Tests (Phys/ Mech/ Creep/ Corrosion/ Oxidation/ Carborization/ Fatigue)	VHTR	48	4,000
High Temperature Performance Test of Prototype sub-modules	VHTR	12	2,000
Flow passage fowling and plugging tests to validate flow passage size	VHTR	6	600
Flow Distribution test of prototype manifolds for representative IHX blocks.	VHTR	12	2,000
NDE/pressure testing methods development	VHTR	24	4,600
Performance Confirmation test of Prototype IHX	VHTR	18	4,000
Total		**48**	**22,000**[1]

[1] Cost total reflects VHTR costs only

4.7. Development Tasks, Costs, and Schedules for Power Conversion System (PCS) Materials

Tasks associated with demonstrating the suitability of metallic materials for major high-temperature components of the PCS for both the GT-MHR and the VHTR are noted in Table 14 below. Also shown in the table are estimates of the "period of performance" of the tasks and the cost for each.

Note from inspection of the footnotes to the table that some tasks could grow, shrink, or disappear entirely based on the exact materials selected and their existing databases. We have taken a middle of the road approach in assigning costs for these tasks. Further, the cost of any tasks associated with advanced alloys (e.g., Alloy 617) might be shared with materials development efforts for other components (e.g., the IHX). The total of costs for the tasks described in the table is $15 million. Of this, about $5 million is specific to the GT-MHR and $10 million is specific to the VHTR.

Table 14. GT-MHR and VHTR materials tasks, schedules, and costs for the power conversion system.

Task	Applicability	Period of Performance (months)	Cost (K$)
Turbine Inlet Shroud			
Hastelloy X data assembly and analysis	GT-MHR	6	100
Demonstrate manufacturing processes with Hastelloy X and Alloy 617	GT-MHR and VHTR	12	1600
Evaluate suitability of Alloy 617 and/or other Ni-base alloys for use at 1000°C and select reference materials	VHTR	6	300
Evaluate changes in the insulation package shell materials and select reference materials[1]	VHTR	6	200
Conduct compatibility tests on reference metallic materials in the range 950°C to 1050°C[2]	VHTR	48	1,800
Conduct strength tests on reference metallic materials in the range 950°C to 1050°C[2]	VHTR	60	4,000
Demonstrate manufacturing processes with reference metallic materials	VHTR	12	1,200
Turbine Disks and Blades			
Evaluate selection and confirm suitability of Ni-base alloys for turbine disks and blades	GT-MHR & VHTR	18	1,200
Assess the need/desirability of blade cooling and/or coatings	VHTR	6	300
Conduct coating durability/compatibility tests if the coating option is selected[3]	VHTR	36	2,100
Conduct compatibility tests on blade materials for operation at >800°C[2]	VHTR	36	1,800
Recuperator			
Demonstrate capability to provide very high quality stainless steel sheets of size 0.35-mm x 2.8-m x 2.2-m.	GT-MHR & VHTR	18	1,000
Demonstrate capability for large-scale joining technology	GT-MHR & VHTR	12	1,100
Total Test Duration and Costs		72	15,000[4]

[1] See Section 3.3.2 if carbon-carbon composites are chosen. [2] Testing efforts could be greater or less depending on the existing databases for the materials selected. [3] Applicable only if coatings are used.

[4] Cost total reflects sum of higher VHTR costs that incorporate or replace GT-MHR costs.

4.8. Summary of Development Tasks and Costs

The costs for the needed work for the GT-MHR and the VHTR are summarized in Table 15 below.

Table 15. GT-MHR and VHTR costs.

Component	**GT-MHR Costs**	**VHTR Costs**
Reactor pressure vessel	39	55
Graphite	30	42
Metallic internals materials	10	12
Carbon-carbon composite and insulation internals materials	17	31
Intermediate heat exchanger materials	0	22
Power conversion system	5	15
Total	101	177

The total cost estimate for development of the needed materials for the VHTR of $177 million dollars includes and/or replaces the corresponding materials developmental costs for the GT-MHR, now estimated to be $101M. It is worth noting that much of the materials development required for the Gen IV VHTR will also be required by and will support the other Gen IV reactor concepts.

As a benchmark for the cost estimates based on expert opinion that are contained in this report, it is very useful to consider the detailed estimates (Refs. 1 and 2) of the materials development costs for a GT-MHR concept made in 1994 in a joint effort among industry, DOE, and the national laboratories[2,3]. The costs estimated at that time (in 1994 dollars) for the required GT-MHR materials development totaled $56M. Doing nothing more than adjusting the 1994 estimated costs for inflation and adding the increases associated with a 20-year longer operating lifetime and the inclusion of needed improvements in high-temperature design methodology would increase that earlier estimate (in 2003 dollars) to $106M.

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[2] "Graphite Topical Development Plan", DOE-GT-MHR-100207, July 1994 (Draft).

[3] "Reactor Metals Topical Development Plan", DOE-GT-MHR-100208, July 1994 (Draft).

5. Summary

Based on the expert opinion of those providing input for this report, there are significant materials development and qualification needs for the VHTR, but there are no-show stoppers. Existing materials were identified that should meet the requirements of all VHTR components and subsystems. Fairly extensive materials characterization, modeling, and industrial scale-up, as well as limited codification, of available materials will be required. If needed, there are both design alternatives available that could reduce materials requirements, as well as more advanced, non-commercial materials with improved properties that could be used. At present, neither are envisioned as necessary.

No high-risk technical issues were identified, though there are moderate risks in meeting in the required schedule of materials technology development and demonstration necessary for the timely deployment of the VHTR. Given the status of and plans for the VHTR materials development and qualification needs, it appears feasible to meet the current proposed schedule to build a demonstration plant in 2017 with an aggressive and adequately funded materials program.