Fuel Requirements for the Advanced High-Temperature Reactor: Graphite Coated-Particle Fuel and Molten Fluoride Salt Coolant

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The technological base for high-temperature reactors is the graphite-matrix coated-particle fuel that can operate at temperatures approaching 1250EC with allowable accident temperatures approaching 1600EC. Historically, the reactor coolant has been helium. However, another reactor coolant is also compatible with graphite-based fuels: molten fluoride salts. Oak Ridge National Laboratory, Sandia National Laboratories, and the University of California at Berkeley are developing a new reactor concept, the Advanced High-Temperature Reactor (AHTR), which uses graphite-matrix coated-particle fuel with a clean high-temperature, low-pressure molten-fluoride-salt reactor coolant. The molten salt has a boiling point near 1400EC. Recent studies have developed a preconceptual design for 2400-MW(t) AHTR. Two outlet coolant temperatures were evaluated: 800 and 1000EC. The low pressure and high-temperature output matches the need for heat to produce hydrogen using thermochemical production techniques or electricity at high efficiency.

While the AHTR uses the same coated-particle fuels as those used in helium-cooled reactors, the difference in coolant characteristics and reactor design will likely change some of the fuel requirements. The superior heat transfer characteristics of liquid molten salts compared with those of gaseous helium reduces peak fuel operating temperatures. The decay-heat-cooling system reduces peak accident temperatures by several hundred degrees Celsius. The ability of the molten salt to absorb fission products reduces those fuel quality requirements necessary to minimize off-site radiation exposures under accident conditions. Because more fuel blocks must be moved during a refueling outage, the larger power output of the AHTR implies longer refueling times if the fuel has the same geometry and power densities as modular gas-cooled reactor fuel. Consequently, there are strong economic incentives to increase the power density, increase fuel burnup, and modify the fuel geometry to reduce refueling times. Neutronic requirements may require other modifications as well.

I. INTRODUCTION

A new type of high-temperature reactor is being developed (Forsberg December 1973, May 2004, June 2004): the Advanced High-Temperature Reactor (AHTR). The goal is to develop a reactor with a combination of three technical characteristics in a single reactor: high temperature, passive safety, and large power output.

Only one type of nuclear fuel has been fully demonstrated for use in high-temperature reactors for commercial applications: the graphite-matrix coated-particle fuel. Although helium has historically been the coolant used in high-temperature reactors, graphite-based fuel is also compatible with one other type of coolant: molten fluoride salts. For example, for over a century the aluminum industry has produced aluminum by electrolytic methods in graphite baths filled with molten fluoride salts at ~1000°C. The AHTR uses a low-pressure molten fluoride salt with a boiling point of ~1400ºC.

The AHTR is different from the traditional molten salt reactor (MSR). In an MSR, the uranium and resultant fission products are dissolved in a molten fluoride salt. In the 1950s and 1960s, the United States began development of MSRs for military aircraft propulsion and then as breeder reactors that produced electricity (Nucl. Appl. Tech, February 1970). Two experimental reactors were built and successfully operated. In the Molten Salt Reactor Experiment [an 8-MW(t) reactor], the reactor core was composed of pieces of bare graphite that served as the neutron moderator with the molten fuel salt rapidly flowing by the graphite. In contrast, the AHTR uses a solid fuel and a clean molten salt coolant. The AHTR is thus different from the MSR but builds upon that earlier technology.

Because the AHTR uses a liquid coolant, rather than a gas coolant, some differences in requirements for the fuel will exist. This paper describes the reactor concept and the potential differences in fuel requirements.

II. AHTR DESCRIPTION

The AHTR is a high-temperature reactor (Fig. 1, Table 1) that uses the same general type of fuel used in modular high-temperature gas-cooled reactors (MHTGRs). The optically transparent molten salt coolant is a mixture of fluoride salts with freezing points near 400EC and atmospheric boiling points of ~1400EC. The reactor operates near atmospheric pressure. At operating conditions, the molten-salt heat-transfer properties are similar to those of water at room temperature. Heat is transferred from the reactor core by the primary molten salt coolant to an intermediate heat-transfer loop. The intermediate heat-transfer loop uses a secondary molten salt coolant to move the heat to the turbine hall. In the turbine hall, the heat is transferred to a multi-reheat nitrogen or helium Brayton cycle power conversion system for the production of electricity. If hydrogen is to be produced, the intermediate heat-transfer loop transports heat to a thermochemical plant that converts water and high-temperature heat to hydrogen (H_2) and oxygen.

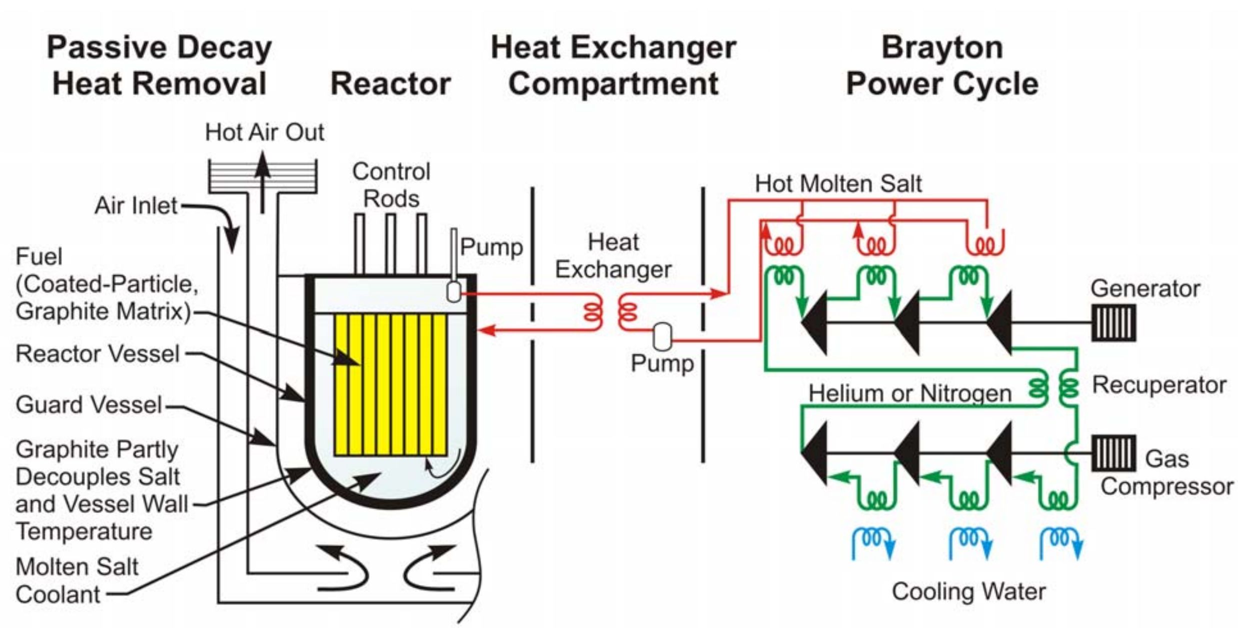

Fig. 1. Schematic of the AHTR for electricity production.

Table 1. AHTR Preconceptual Design Parameters

Power level	2400 MW(t)	Electricity (800ºC Option)	1300 MW(e) [1145 MW(e)]
Core inlet/outlet temp. (800ºC Option)	900EC/1000EC (700EC/800EC)	Power cycle	3-stage multi-reheat Brayton
Coolant (alternate)	$2^7LiF\text{-}BeF_2$ ($NaF\text{-}ZrF_4$)	Power cycle working fluid	Nitrogen (helium longer-term option)
Efficiency (800ºC Option)	54% (48%)	Vessel Diameter	9.2 m
Fuel Kernel	Uranium carbide/oxide	Height	19.5 m
Enrichment	10.36 wt % ^{235}U	Reactor core Shape	Annular
Form	Prismatic	Diameter	7.8 m
Block diam.	0.36 m (across flats)	Height	7.9 m
Block height	0.79 m	Fuel annulus	2.3 m
Columns	324	Power density	8.3 W/cm^3
Mean temperature	1050ºC	Reflector (outer)	138 fuel columns
Peak Temperature	1168ºC	Reflector (inner)	55 fuel columns
Mass flow rate	12,070 kg/s	Pressure drop	0.129 MPa

Parameters for 1000ºC reactor exit temperature unless otherwise noted. The 800ºC AHTR intermediate temperature option has the same power level and core size.

The AHTR facility layout (Fig. 2) is similar to that for the S-PRISM sodium-cooled fast reactor designed by General Electric. Both reactors operate at low pressure and high temperature; thus, they have similar design constraints. The 9.2-m diameter vessel of the AHTR is the same size as that used by the S-PRISM. Earlier engineering studies indicated that this was the largest practical size of low-pressure reactor vessel. The vessel size determines the power output. For our initial studies, we assumed fuel and power densities (8.3 W/cm^3) to be similar to those of MHTGRs.

The reactor core outlet coolant temperature is a design variable. Two peak coolant temperatures have been evaluated: 800 and 1000EC. Exiting materials may allow design of plants with exit molten salt coolant temperatures of ~800EC. Major materials development work will be required for a 1000EC coolant exit temperature. The AHTR includes a graphite blanket system that separates the reactor vessel from the reactor core so that the fuel and coolant can operate at higher temperatures than the vessel. This insulating blanket minimizes heat loss during normal operations and long-term high-temperature creep in the reactor vessel. In the current design, the AHTR has an annular core through which coolant flows downward. The molten salt coolant flows upward through the nonfuel graphite section in the middle of the reactor. The molten salt pumps and their intakes are located above the reactor core; thus, the reactor cannot lose its coolant except by vessel failure.

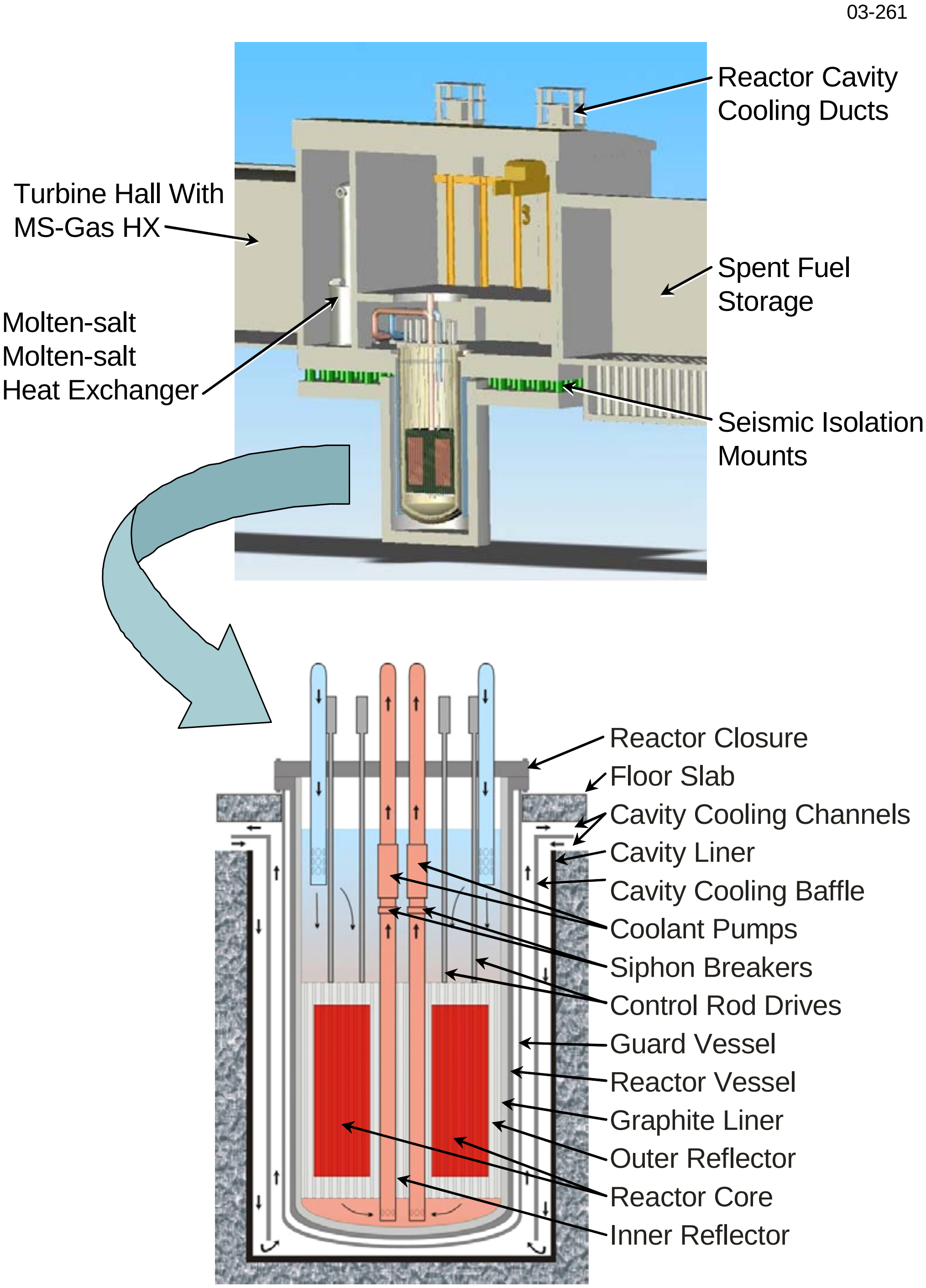

Fig. 2. Schematic of the AHTR nuclear island and vessel.

The reactor core physics is generally similar to that for the MHTGR because the molten salt coolant has a low neutron-absorption cross section. Reactor power is limited by a negative temperature coefficient, control rods, and other emergency shutdown systems.

When a reactor shuts down, radioactive decay heat continues to be generated in the reactor core at a rate that decreases over time. If this heat is not removed, the reactor will overheat and the core will be damaged, such as occurred during the Three Mile Island accident. The AHTR uses passive reactor vessel auxiliary cooling (RVAC) systems similar to that developed for decay heat removal in the General Electric sodium-cooled S-PRISM. The reactor and decay-heat-cooling system are located in a below-grade silo. In this low-pressure pool reactor, RVAC system decay heat is (1) transferred from the reactor core to the reactor vessel graphite reflector by natural circulation of the molten salts, (2) conducted through the graphite reflector and reactor vessel wall, (3) transferred across an argon gap by radiation to a guard vessel, (4) conducted through the guard vessel, and then (5) removed from outside of the guard vessel by natural circulation of ambient air. The rate of heat removal is controlled primarily by the radiative heat transfer through the argon gas from the reactor vessel. Radiative heat transfer increases by the temperature to the fourth power (T^4); thus, a small rise in the reactor vessel temperature (as would occur upon the loss of normal decay-heat-removal systems) greatly increases heat transfer out of the system. The design allows transfer of the heat by efficient liquid natural convection from the center of the reactor core (hot-spot location) to near the vessel wall.

Under accident conditions such as a loss-of-forced-cooling accident, natural circulation flow of molten salt up the hot fuel channels in the core and down by the edge of the core rapidly results in a nearly isothermal core with about a 50EC difference between the top and bottom plenums. For the reactor with a nominal coolant exit temperature of 1000EC, the calculated peak fuel temperature in such an accident is ~1160EC, which will occur at ~30 hours with a peak vessel temperature of ~750EC at ~45 hours. The average core temperature rises to approximately the same temperature as the hottest fuel during normal operations.

For electricity production, a recuperated gas (nitrogen or helium) Brayton cycle (Fig. 1) is used with three stages of reheating and three stages of intercooling. The gas pressure is reduced through three turbines in series, with reheating of the gas to its maximum temperature with hot molten salt before it reaches each turbine. The major advantage of the nitrogen Brayton cycle is that the turbomachinery is commercially available—it is similar to those used by electric utilities in combined-cycle natural-gas plants. For H_2 production, the intermediate loop delivers the high-temperature heat to the thermochemical H_2 production plant. In a thermochemical plant, high-temperature heat plus water yields H_2 and oxygen. All other chemicals are fully recycled in the facility.

As discussed earlier, the AHTR reactor vessel is the same size as the S-PRISM vessel and the facility sizes are almost identical. However, the S-PRISM sodium-cooled fast reactor has a thermal power output of 1000 MW(t) with an electrical output of 380 MW(e). A reactor vessel of the same size with the same type of passive decay-heat-cooling system, a similar-size nuclear island, and similar system configuration potentially can contain a 2400-MW(t) AHTR. The electrical output is between 1145 and 1300 MW(e), depending upon the molten salt exit temperatures from the reactor core. The larger power output in a similar-size system is primarily a consequence of two factors: (1) the higher operating temperature of the AHTR—with resultant higher plant efficiency and increased decay-heat-removal system performance and (2) a volumetric heat capacity of molten salts that is about four times that of sodium—which reduces the size of pumps, valves, and heat exchangers. The molten salt also provides a very large heat capacity under accident conditions. The sodium system cannot operate at higher temperatures, because of temperature limits on the fuel and because of the requirement the preclude boiling of sodium anywhere in the system. *It is the higher temperature capabilities of the coated-particle fuel and the low-pressure molten-salt coolant that may enable major improvements in nuclear plant economics by making possible passive safety in large high-temperature reactors.*

III. INTERACTIONS OF MOLTEN SALTS WITH GRAPHITE FUELS

There is a large experience base that shows the compatibility of molten fluoride salts and graphite in radioactive and non-radioactive systems. In particular, the molten salt breeder reactor program investigated the compatibility of molten salts with graphite in chemical tests, loop tests, and reactors. In a molten salt reactor, the reactor core made of bare graphite (the moderator) with the molten fuel salt flowing through channels in the graphite. Post irradiation examination from the MSRE showed no interactions (erosion or corrosion) between the salt and the graphite (McCoy December 1972). The original machining marks were still clearly visible. Out-of-reactor tests were conducted to 1400ºC with no interactions between the salt and graphite (Rosenthal 1969).

Experiments show the non wetting behavior (Fig. 3) of the fluoride salts of interest, that molten salts will not penetrate small cracks in the graphite and that the molten salt will not contact the fuel matrix (Briggs 1963; ORNL 1964; Fontana 1970). In a classical molten salt reactor where the uranium and fission products are dissolved in the fuel salt, the fuel salt is dumped to storage tanks during shutdown. For safety and maintenance purposes, it is essential to know exactly where all the salt, fission products, and uranium are. As a consequence, the interactions of salt and graphite were carefully investigated.

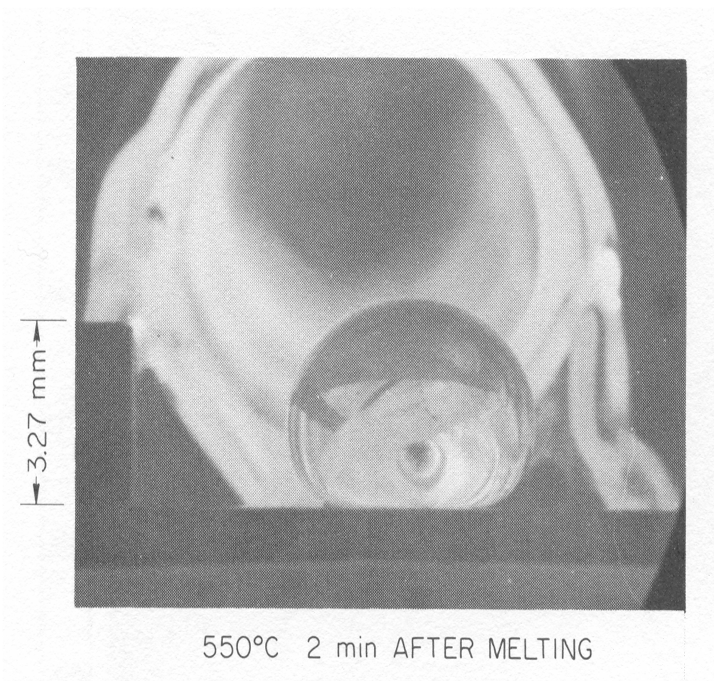

Fig. 3. Non Wetting Characteristics of Molten Fluoride Salts and Graphite.

IV. FUEL REQUIREMENTS

While the AHTR uses the same graphite-matrix coated-particle fuel as helium-cooled reactors, there will ultimately be differences in fuel requirements. Five potential differences have been identified but not yet been quantified.

IV.A. Peak Accident Temperatures

The accident analysis indicates a peak AHTR fuel temperature of ~1200EC under loss of forced circulation accident conditions. The coolant boils at ~1400EC. These peak temperatures are significantly less than those predicted for traditional gas-cooled reactors. As a consequence, the high-temperature accident performance requirements for AHTR fuel are likely to be less rigorous than those for helium-cooled reactors.

IV.B. Normal Operating Temperatures

As a consequence of the better heat transfer and heat transport properties of liquids compared with gases, the normal peak operating fuel temperature in an AHTR is expected to be lower than in helium-cooled reactors for heat delivered at the same temperatures to the power cycle or thermochemical hydrogen production plant. There are four effects.

Heat Transfer from Fuel to Coolant

The heat transfer coefficients for liquids are considerably better than those for gases. Figure 4 shows the temperature profile from the coolant at 1000°C to the center of the fuel compact for molten salt coolant at two different fuel power densities as well as a profile for helium. The temperature increase at the surface of the coolant channel is less for the liquid coolant; consequently, the fuel in the AHTR operates at lower temperatures for the same coolant exit temperatures as in a comparable gas-cooled reactor. Also shown is the temperature jump from the graphite matrix to the fuel compact.

Power Peaking

The power density in a reactor core will vary with position. As a consequence, there will be differences in the coolant temperatures exiting different coolant channels. The exit coolant temperatures from the hottest coolant channels will be significantly above the average core exit temperature with corresponding higher fuel temperatures near these coolant channels. Reducing the differences between peak and average coolant temperatures exiting the reactor core reduces the peak fuel temperature for any given average reactor-exit coolant temperature. There are many methods to reduce this temperature difference. The physical properties of liquids compared to gases helps reduce the differences between peak and average coolant temperatures exiting the core under normal and accident conditions.

The viscosity of helium increases with temperature as $T^{1/2}$. Consequently, as the temperature of the helium increases, the gas viscosity increases, the resistance to fluid flow increases, and the flow in the coolant channel decreases. The fuel channels with the highest power densities have lower gas flows and higher helium coolant-channel exit temperatures. In contrast, the viscosity (DeWitt 1974) of molten salts decreases with temperature [$A \times \exp(B/T)$]. Consequently, as the temperature of the molten salt increases, the liquid viscosity decreases and the flow in the coolant channel increases. The fuel channels with the highest power levels have the highest molten salt flows. This behavior reduces the temperature differences between the coolant exiting the hottest fuel channels and the average fuel channels.

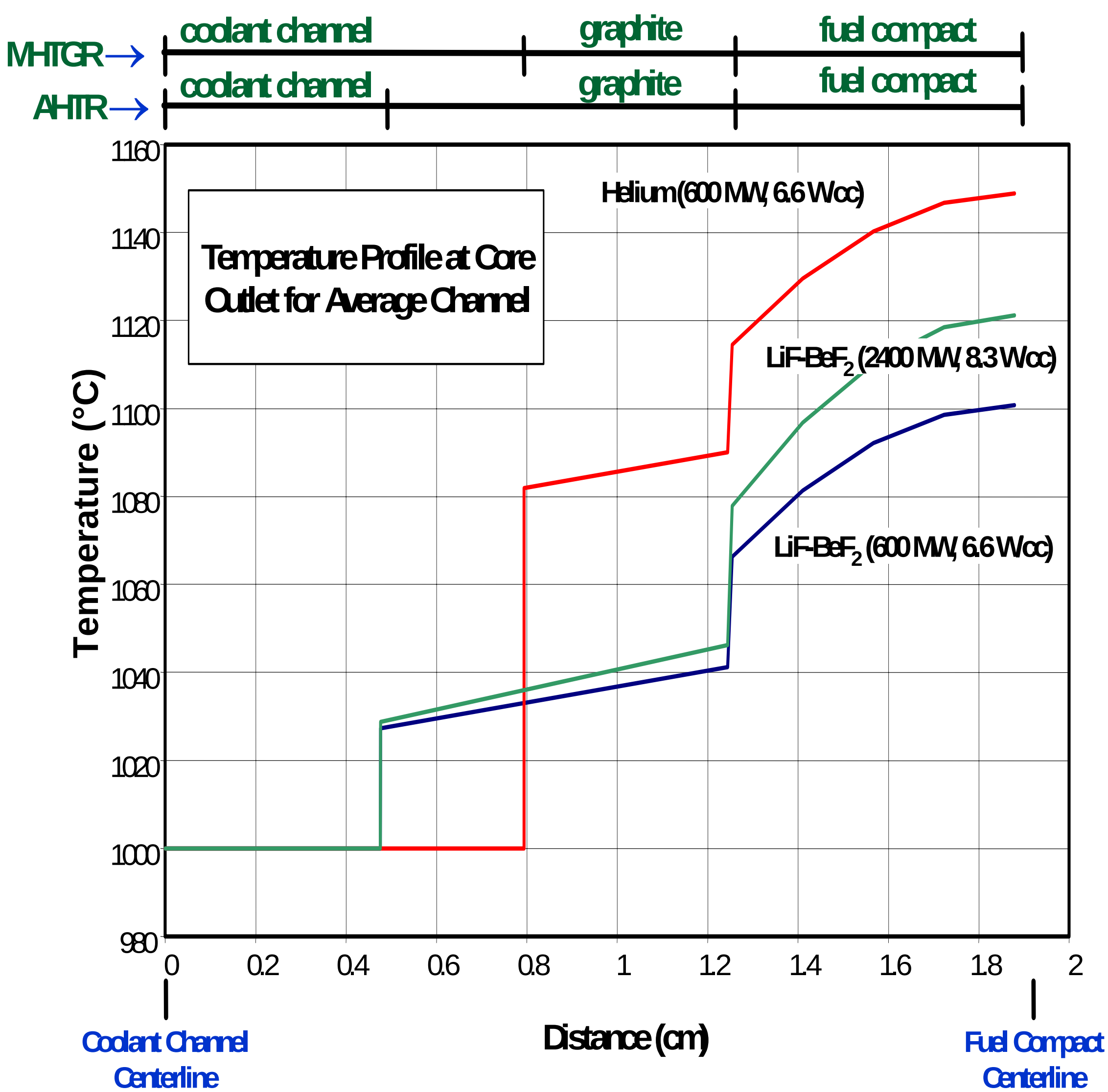

Fig. 4. Temperature Profile from the Coolant to Fuel Compact Centerline.

Temperature of Delivered Heat

Liquid-cooled reactors deliver most of their heat at temperatures close to the reactor coolant exit temperature while gas-cooled reactors deliver their heat over a large temperature range (Fig. 5). Gas-cooled systems have higher pumping costs relative to liquid-cooled systems. As a consequence, practical designs of gas-cooled reactors—such as the General Atomics helium-cooled Gas Turbine-Modular Helium Reactor (GT-MHR) and the British carbon dioxide-cooled Advanced Gas Reactor (AGR)—have large temperature changes across the reactor core and deliver their heat to the power cycle over a large temperature range. In contrast, liquid-cooled reactors such as the French sodium-cooled Super Phoenix liquid-metal fast-breeder reactor (LMFBR) and pressurized-water reactors (PWRs) have low pumping costs and are designed to deliver their heat from the reactor core to the power cycle over a small temperature range.

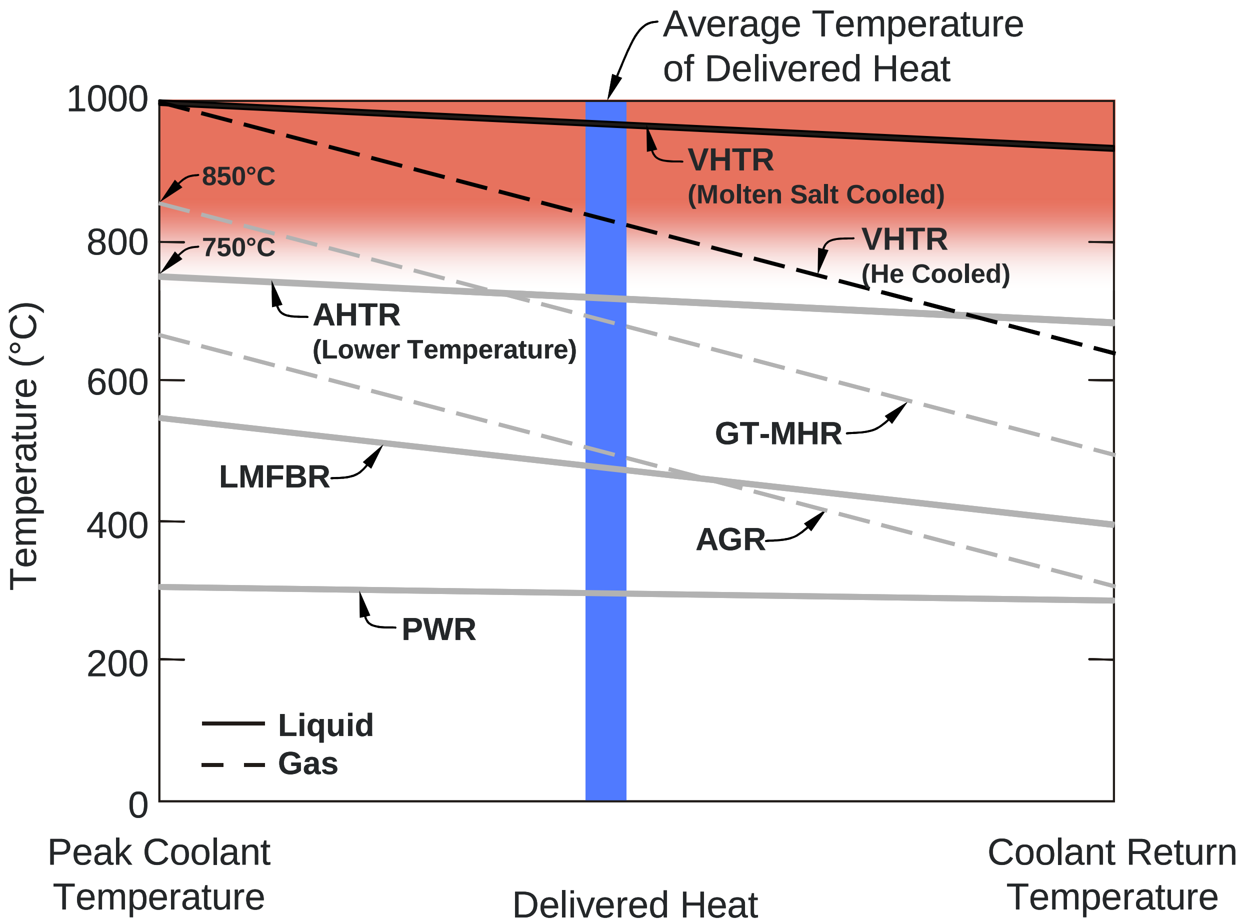

Fig. 5. Temperatures of Delivered Heat for Different Reactors.

For some applications, such as thermochemical production of hydrogen, much of the heat must be delivered above a specific temperature to drive chemical reactions. For any required temperature of delivered heat, molten salt cooling allows for lower reactor-core exit cooling temperatures than in a gas-cooled reactor.

If one compares a helium-cooled and a molten-salt-cooled high-temperature reactor, a helium cooled reactor (the GT-MHR) with a peak temperature of 850EC delivers its average heat at the same temperature as a molten-salt-cooled AHTR with a peak coolant temperature of 750EC. This implies that for any given peak temperature, the AHTR will have substantially higher efficiency that the gas-cooled reactor with the same peak temperatures. Alternatively, for the same efficiency the AHTR can operate at lower peak temperatures.

Heat Exchanger Losses

For hydrogen production, an intermediate heat transport loop will be used to isolate the reactor from the hydrogen production facility. As shown earlier, molten salts (liquids) have superior heat transfer characteristics compared with those for helium (gases). As a consequence, the temperature drops across intermediate heat exchangers will be less and thus the peak reactor temperature will be lower for heat delivered at any given temperature to a thermochemical hydrogen production plant or power cycle.

III.C. Fuel Quality

Fuel quality requirements are determined by operational and accident requirements. In an AHTR, the molten salt provides a major barrier to the release of radionuclides. Extensive studies (Nucl. Appl. Tech. 1970) during the operation of the Molten Salt Reactor Experiment showed that only the noble gases (Xe, Kr) and tritium are released to the cover gas. Most fission products are dissolved in the molten salt (CsF, SrF_2, BeI_2) although some exist as metals and tend to deposit on metallic surfaces (Ag and others). This barrier to the release of radionuclides reduces the fuel quality requirements.

For helium-cooled reactors, the fuel quality requirements depend upon the safety strategy. If the fuel is to be the primary barrier to prevent release of radionuclides to the environment under accident conditions, there are stringent fuel reliability requirements. Under such circumstances, a low-failure-fraction fuel, only about 1 particle in ~100,000, is required to meet normal operation or accident conditions and still meet the regulatory requirements. The most mobile radioactive species are Ag-110*m*, Cs, I, and Sr. The controlling isotopes for site-boundary release are Cs and I while Ag-110*m* tends to controls the maintenance dose (Moormann 2001; International Atomic Energy Agency 1997).

III. D. Power Density

The preconceptual AHTR designs have assumed fuel power densities (8.3 watts/cm^3) similar to those of traditional helium-cooled reactors. However, the heat transfer capabilities of the molten salt coolant are superior to those of helium. As a consequence, the peak fuel temperatures during normal operation are 100 to 200EC lower than for a comparable gas-cooled reactor. Economic incentives to reduce the reactor core size and thus lower plant capital cost and refueling times are substantial. As such, there are strong economic incentives to increase fuel power densities, which will, in turn, increase the thermal gradient between the centerline fuel temperature and the coolant channel.

III. E. Fuel Geometry

Both refueling times and neutronics potentially constrain reactor fuel geometry. Reducing these constraints may impose added requirements on the fuel. Reactor refueling times depend upon the time to shut down the reactor (including temperature cooldown), move the fuel elements, and restart the reactor. While the first and last steps are somewhat independent of the reactor size, the middle step depends upon the number of fuel assemblies. If the AHTR uses the traditional prismatic fuel assemblies, the number of fuel elements in the core could be up to four times the number of fuel assemblies in an MHTGR because the power output is four times larger. Strong economic incentives exist to reduce the number of fuel assemblies and modify the geometry to minimize refueling times. Methods to reduce the refueling times include doubling the length of the fuel block, and thus reducing by a factor of two the number of fuel assemblies that must be handled; increasing fuel burnup; and changing the geometry, such as fuel assemblies with the height of the reactor core (similar to the Peach Bottom gas-cooled reactor).

Neutronic studies are underway to optimize reactor core performance. Alternative distributions of fuel and coolant holes in the graphite block are being considered to improve core performance. These may or may not place additional geometric constraints on the fuel.

V. CONCLUSIONS

The AHTR is a second category of high-temperature reactor that uses graphite-matrix coated-particle fuel. The distinguishing technical characteristic is the use of a low-pressure molten-salt coolant rather than helium. Using a low-pressure liquid coolant enables the construction of large passively safe high-temperature reactors. The AHTR is a new reactor concept that is early in its development. Preliminary studies indicate that the minimum requirements for fuel performance (peak accident temperatures, peak operating temperatures, and fuel failure fraction) will be significantly less than for helium-cooled reactors. These factors may reduce fuel development requirements for first-generation AHTRs. However, strong economic incentives exist to operate the fuel at higher power densities than in helium-cooled reactors and more demanding requirements may be placed on the fuel assembly geometry.

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