Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity

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ABSTRACT

The molten-salt-cooled Advanced High-Temperature Reactor (AHTR) is a new reactor concept designed to provide very high temperature (750 to 1000EC) heat to enable efficient low-cost (1) thermochemical production of hydrogen (H_2) or (2) production of electricity. This paper provides an initial description and technical analysis of its key features. The proposed AHTR uses coated-particle graphite-matrix fuel similar to that used in high-temperature gas-cooled reactors (HTGRs), such as the General Atomics gas turbine–modular helium reactor. However, unlike the HTGRs, the AHTR uses a molten-salt coolant and a pool configuration, similar to that of the General Electric Super Power Reactor Inherently Safe Module (S-PRISM) liquid-metal reactor. Because the boiling points for molten fluoride salts are near ~1400EC, the reactor can operate at very high temperatures and atmospheric pressure. For thermochemical H_2 production, the heat is delivered at the required near-constant high temperature and low pressure. For electricity production, a multi-reheat helium Brayton (gas-turbine) cycle, with efficiencies >50%, is used. The low-pressure molten-salt coolant, with its high heat capacity and natural circulation heat transfer capability, creates the potential for (1) robust safety (including fully passive decay-heat removal) and (2) improved economics with passive safety systems that allow higher power densities and scaling to large reactor sizes [>1000 MW(e)].

I. INTRODUCTION

The Advanced High-Temperature Reactor (AHTR) is a new reactor concept developed by the authors to produce high-temperature heat (750 to 1000+EC) for efficient production of electricity and thermochemical H_2. The AHTR is based on four technological developments:

- High-temperature, low-pressure molten-fluoride-salt reactor coolants from the aircraft nuclear propulsion program [1] of the 1950s and the molten-salt breeder reactor program of the 1960s and 1970s [2]. Today, development continues on using these salts and associated advanced high-temperature materials for cooling fusion reactors.
- Coated-particle graphite-matrix fuel developed for high-temperature gas-cooled reactors [3] in the United States and Germany, starting in the 1960s.
- Passive safety systems for gas-cooled and liquid-metal reactors introduced in the 1980s.
- Advanced gas turbines—including commercialization in the last 5 years of magnetic bearing systems that can permit these turbines to be used in closed helium cycles.

As a class of reactors, the AHTR is defined by two characteristics: (1) high-temperature fuel and (2) low-pressure liquid coolant. A series of studies and evaluations were undertaken to understand the potential for and the characteristics of a molten-salt-cooled AHTR. This work provides (1) the basis for determination of whether further investigation is warranted and (2) a basis for development of a more detailed pre-conceptual design of an AHTR.

The AHTR core consists of coated-particle graphite-matrix fuel cooled with a molten salt (Fig. 1). The reactor core physics, general core design, and fuel cycle are similar to those of a gas turbine–modular helium reactor (GT-MHR) and pebble-bed modular reactor (PBMR). This is because the neutron absorption and scattering cross sections in these salts are low (mb)—significantly below that of water. The low-power-density graphite-moderated core has long neutron lifetimes, slow kinetics, and thermal neutron spectrum characteristics similar to a GT-MHR. The molten salt flows from the reactor core to an external heat exchanger (to provide the interface for the electricity or hydrogen production system), dumps the heat load, and returns to the reactor core.

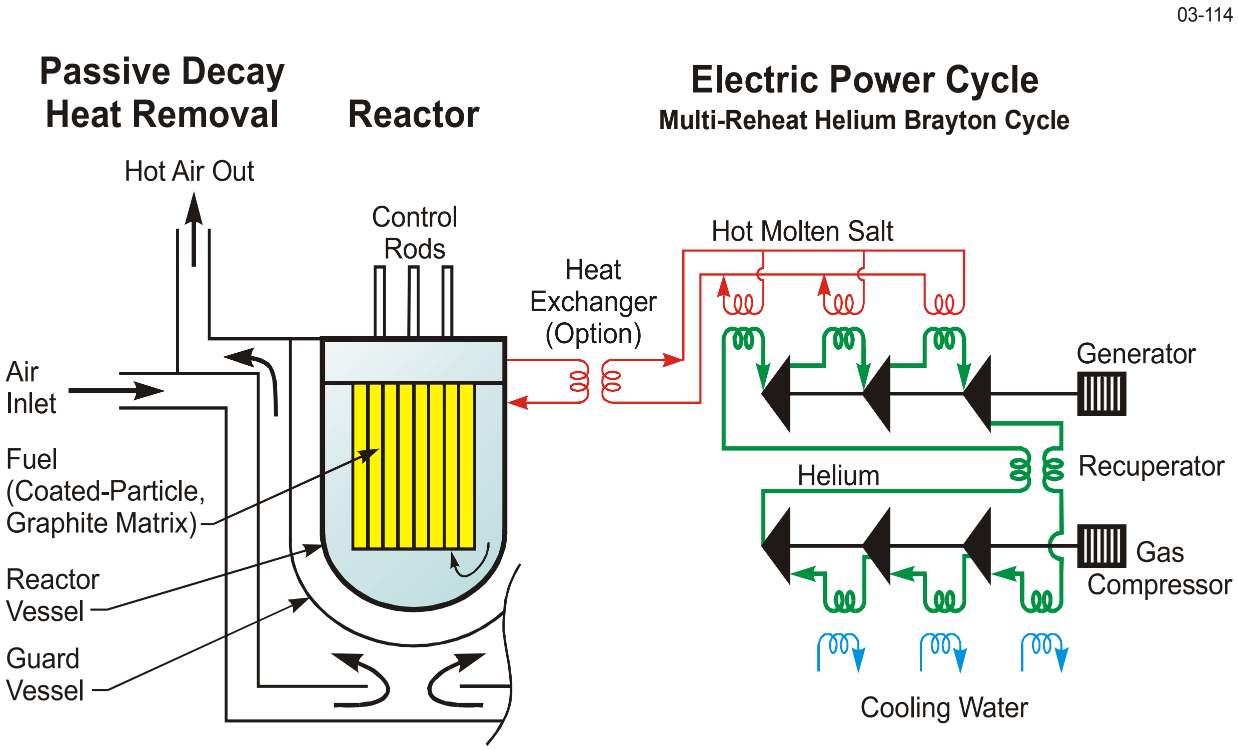

Fig. 1. Schematic of the AHTR for electricity production.

II. MOLTEN-SALT COOLANTS

II.A. Molten Salt Compositions

There are several potential molten-fluoride-salt coolants that have been in reactor or other applications that are potentially applicable to the AHTR. The Aircraft Reactor Experiment, a 2.5-MW(th) reactor, operated in the 1950s with a NaF/ZrF_4 molten salt, while the Molten Salt Reactor Experiment [2], an 8-MW(th) reactor, operated in the 1960s with a $^7Li_2BeF_4$ molten salt. In these reactors, the fuel was dissolved in the salt whereas the AHTR uses solid fuel. The term *molten salt reactors*, as discussed in the literature, refers to reactors in which the fuel and fission products are dissolved in the coolant. For the analysis herein, it is assumed that the AHTR uses a $^7Li_2BeF_4$ molten salt.

The use in the AHTR of a solid fuel and molten-salt coolant, rather than fissile materials and fission products dissolved in the salt, has major advantages in terms of operations and materials of construction. The radioactivity in the coolant is minimized. At operating temperatures up to ~750EC, various Hastelloy alloys are suitable as materials of construction. The allowable operating temperatures of these alloys are higher; however, the materials must be able to withstand expected reactor transients with the associated higher temperatures. The chemistry of the salt can be maintained in a chemically reducing condition to minimize system corrosion [4]. The metal is chemically noble with respect to the salt, in contrast to a water-cooled reactor where a passive layer protects the metal from corrosion. Avoiding high concentrations of various fission products in the salt (such as required in the molten salt reactor) eliminates several long-term corrosion mechanisms [5]. For long-term operation above 800EC, new materials of construction would be required, potentially derived from materials advances in the fusion materials research program.

The molten-salt breeder reactor program in the 1960s chose a $^7Li_2BeF_4$ salt because the primary goal was to maximize the breeding ratio in that reactor. Significant reactor experience and engineering test data exist for this salt. The lithium-6 version of this salt is being developed as a coolant and tritium breeder for fusion reactors. The physical properties and characteristics of many other candidate molten salts have been investigated. The ultimate choice of molten-salt coolant for the AHTR will depend upon goals and trade-offs involving coolant costs, salt melting points, activation products, reactor design goals (electricity, hydrogen production, etc.), occupational hazards, and other factors.

All primary-system salt components must have low neutron-absorption cross sections, reasonable melting points, and appropriate chemistry. Candidate fluoride salts include ^7Li, Na, Be, Zr, Rb, and other fluorides. Chloride molten salts are not realistic candidates because of their corrosive characteristics, high thermal-neutron-absorption cross sections, and generation of ^{36}Cl—a long-lived radionuclide [6]. The toxicity of the molten fluoride coolant depends upon the specific salt and varies from the fluoride salts used in toothpaste for prevention of tooth decay to toxic materials. All of the fluoride salts have high boiling points. The reference salt,

$^7Li_2BeF_4$, has a boiling point of ~1400EC. In all cases, binary or more complex fluoride salt mixtures are preferred because the melting points of fluoride salt mixtures are much lower than those for single-component salts. For example, the molten salt Li_2BeF_4 has a melting point of 457EC whereas pure LiF has a melting point of 847EC and pure BeF_2 has a melting point of 544EC. Other candidate salts include NaF-ZrF_4 (50 mol % NaF, 50 mol % ZrF_4), with a melting point of 510EC, and NaF-RbF-ZrF_4 (8 mol % NaF, 50 mol % RbF, and 42 mol % ZrF_4), with a melting point of 400EC. With some three-component mixtures such as ^{7}LiF-BeF_2-NaF and potentially four component mixtures, it is possible to reduce melting points to ~350EC. At operating conditions, molten fluoride salt thermophysical properties are similar to those of water except for the very low vapor pressure. Table 1 compares key thermophysical properties of representative molten salts with other reactor coolants and construction materials

TABLE I. Thermophysical properties* of S-PRISM, GT-MHR, and AHTR reactor coolants and materials

Material	T_{melt} (EC)	T_{boil} (EC)	ρ (kg/m^3)	C_p (kJ/kgEC)	ρC_p (kJ/m^{3}EC)	k (W/mEC)	$\nu \cdot 10^6$ (m^2/s)
$^7Li_2BeF_4$ (Flibe)	459	1,430	1,940	2.34	4,540	1.0	2.9
0.58NaF-0.42ZrF_4	500	1,290	3,140	1.17	3,670	~1	0.53
Sodium	97.8	883	790	1.27	1,000	62	0.25
Lead	328	1,750	10,540	0.16	1,700	16	0.13
Helium (7.5 MPa)			3.8	5.2	20	0.29	11.0
Water (7.5 MPa)	0	100	732	5.5	4,040	0.56	0.13
Hastalloy C-276	~1350		8,890	0.43	3,820	9.8	
Graphite			1,700	1.90	3,230	200	

*Approximate physical properties 700EC except the pressurized water data shown at 290EC for comparison, ρ is density, C_p is specific heat, k is thermal conductivity, and ν is viscosity.

II.B. Molten Salt Materials Compatibility

These molten fluoride salts do not react with air or carbon dioxide but will slowly react with water. Fluoride salts are compatible with graphite fuels [7]. In the Molten Salt Reactor Experiment, where the salt contained dissolved fuel and fission products, the reactor core contained bare graphite that was in direct contact with the salt. (The graphite was in the reactor core as a neutron moderator.) This reactor experience (and many test-reactor irradiations) showed that the molten fluoride salt does not react with the graphite under operating reactor conditions or decompose in radiation fields. There is a century of industrial experience with graphite and fluoride salt compatibility; almost all aluminum metal is electrolytically produced using molten cryolite ($3NaF-AlF_3$) in very large graphite baths at ~1000EC. Molten salts are candidates for cooling the first wall of fusion reactors [8] and are currently under active experimental study by the U.S. Department of Energy Office of Fusion Energy Science.

II.C. Molten Salt Heat Transfer Characteristics

The excellent heat transfer properties of molten salts (liquids), compared with those of helium gas (see Table 1), reduce the temperature drops between (1) the solid fuel and molten salt and (2) the molten salt and any secondary system. Comparable calculations were made of the temperature drop between (1) the centerline of a prismatic fuel element similar to that in a high-temperature gas-cooled reactor (HTGR) and (2) coolant for helium and molten-salt coolants. The temperature drops for helium and molten-salt coolants were, respectively, 415 and 280EC. The better heat transfer capabilities of molten salts (liquids) compared with those of helium (a gas) provide for several potential benefits:

- *Design margins*. The thermal design margins can be increased compared with those for gas-cooled reactors.

- *Higher temperatures*. The maximum exit coolant temperature for a molten-salt-cooled reactor can be significantly higher than that for a gas-cooled reactor—assuming the same maximum fuel temperature.

- *Higher core power densities*. The power densities can be increased to decrease the reactor core size or increase power output. Gas-cooled reactors traditionally have very low power densities because of poor heat transfer. With a liquid molten-salt coolant the power density can be increased significantly.

- *Improved decay heat removal*. Improved heat transfer by natural circulation of the molten salt allows the design of larger reactors with passive safety (see section IV).

The heat transfer analysis was undertaken using conventional correlations. This type of approach produces conservative results at higher temperatures. Molten salts, like molten glasses, are optically transparent in the visible light band and have significant transparency in the infrared band. The heat capacities are also large. These characteristics imply that above ~700EC, radiation transfer begins to become an important mechanism to enhance heat transfer. Radiation heat transfer increases as the fourth power of the temperature (T^4). The optical properties vary between salts and can be altered by addition of certain cations. Optical properties and thus high-temperature heat-transfer properties are partly controlled by the designer. Although this factor is a consideration in the design of industrial facilities that produce molten glass, it has not historically been a consideration for reactor coolants. The traditional reactor coolants operate at lower temperatures (water), have low volumetric heat capacities (helium), or are optically opaque (sodium).

II.D. Salt Freezing

The relatively high melting point (350–500EC) of the molten salt will require special design features. There is significant experience from the operation of sodium-cooled fast reactors, Russian lead-cooled submarine reactors, and the Molten-Salt Reactor Experiment. The AHTR uses a pool-type reactor vessel that reduces some of these challenges. As with other high-temperature liquid-cooled reactors, the reactor will be refueled with liquid covering the reactor core. In this context, the AHTR has two advantages over sodium- and lead-cooled reactors: (1) molten salts are transparent and (2) the fuel has a lower power density and thus a lower rate of volumetric decay heat generation.

III. REACTOR CORE

III.A. Reactor Configuration

Figure 2 provides a pre-conceptual design configuration for the AHTR, which is used herein to estimate potential safety, economic, and performance benefits from this class of reactors. The details will be described later. The AHTR vessel exterior dimensions are chosen to be identical to S-PRISM reactor vessel dimensions. The S-PRISM was developed by General Electric as a sodium-cooled reactor. The AHTR and S-PRISM are both low-pressure reactors. The AHTR pre-conceptual design takes advantage of the well-developed high-temperature, transportable, seismically base-isolated characteristics of the S-PRISM reactor vessel design.

As does the GT-MHR, the AHTR uses a graphite liner to thermally isolate the reactor vessel from the reactor core under normal and accident conditions. To maximize the core diameter, the AHTR coolant return (or alternatively supply) occurs through ducts located inside a central pedestal that extends through the annular core and coolant pool to the top of the reactor. The AHTR core design follows that of the GT-HTR, which also has an annular reactor core and central pedestal with no fuel. With its larger core diameter, and the same 7.9 height as the GT-MHR core, the pre-conceptual AHTR core volume is 300 m^3, 3.4 times larger than the 87 m^3 permitted by the GT-MHR reactor vessel configuration.

At 2400 MW(th) with a 90EC temperature rise across the core, the AHTR primary flow rate is 6.2 m^3/sec (97,000 gpm). This can be compared to the substantially larger 20 m^3/sec (330,000 gpm) of a conventional 4-loop, 3340 MW(th) [1140 MW(e)] Westinghouse PWR. With a flow velocity of 6.0 m/sec, the AHTR primary flow can be accommodated using four primary circuits of 0.56-m diameter.

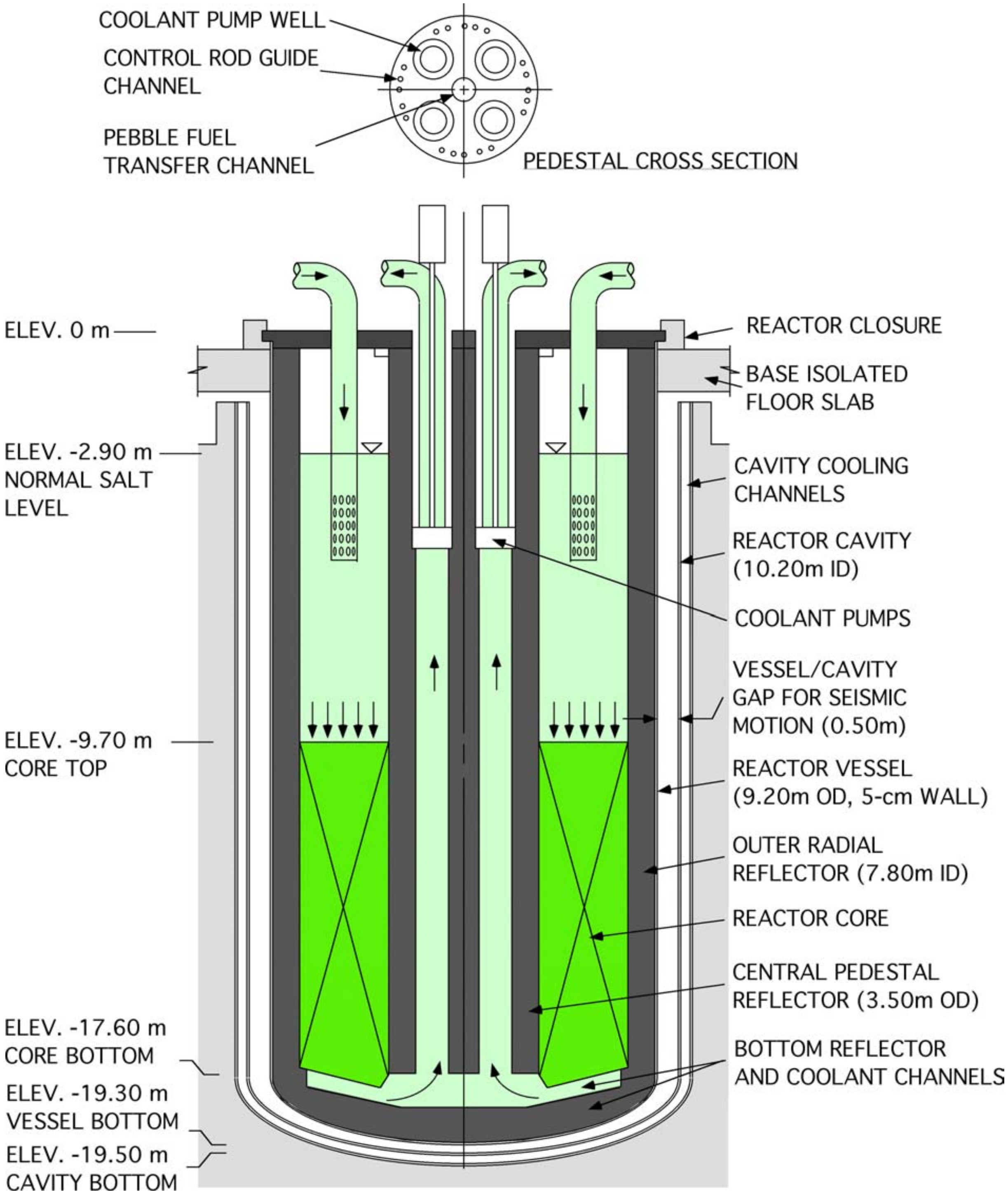

Fig. 2. Pre-conceptual AHTR vessel, based on the S-PRISM reactor vessel.

III.B. Fuel Characteristics

The AHTR coated-particle, graphite-matrix fuel is essentially the same as that used in all helium-cooled gas reactors, including the GT-MHR [3]. The uranium fuel particles are coated with multiple layers of carbon and silicon carbide, a system that prevents release of radionuclides at very high temperatures. Currently available coated-particle fuels can operate at temperatures up to 1250EC. Under off-normal conditions, fuel temperatures of 1600EC can be tolerated for limited periods of time (~100's of hours) before fission product releases become significant.

The coated particles are incorporated into a graphite-matrix fuel compact, which, in turn, is incorporated into a graphite-matrix fuel assembly. Several shapes of fuel assemblies have been used in helium-cooled reactors: hexagonal block, pebble bed (small balls), and long cylinders (Peach Bottom Reactor). The different designs reflect different operational goals. Pebble beds allow on-line refueling by the slow movement of balls through the reactor core. Hexagonal blocks allow wide latitude in the volumetric ratio of fuel, coolant (molten salt), and moderator (graphite). Figure 3 shows the fuel assembly used in the operating High-Temperature Engineering Test Reactor [9] in Japan. This 30-MW(th) helium-cooled test reactor and its fuel are designed to reach very high helium exit temperatures (950EC) to investigate high-efficiency electricity and H_2 production. While the use of a coated-particle graphite-matrix fuel is required for compatibility with the molten salt and to obtain the desired temperatures, the optimal geometry of the fuel assembly will depend upon detailed design trade-offs between performance, fuel costs, safety, and other factors.

III.C. Reactor Core Physics

The AHTR reactor core physics is similar to that of a GT-MHR or PBMR because helium and molten-salt scattering and absorption cross sections are generally small compared with total absorption in the core. Molten-salt nuclear cross sections (mb) are larger than those for helium but an order of magnitude smaller than those of water. The moderating effect of the molten salt is dependent on the salt composition and will be more significant for the Li and Be salts. For most configurations, the molten salt does not significantly change neutronic characteristics from those expected in a He-cooled graphite-moderated core. The void coefficient of reactivity was evaluated since the molten-salt atom density is higher than helium and the effect could potentially be significant. A series of neutronic calculations were conducted for prismatic fuels to confirm the existence of workable designs [10]. Figure 4 illustrates the results, showing the total core void coefficient as a function of the uranium-to-carbon ratio and the consequences of adding boron or thorium.

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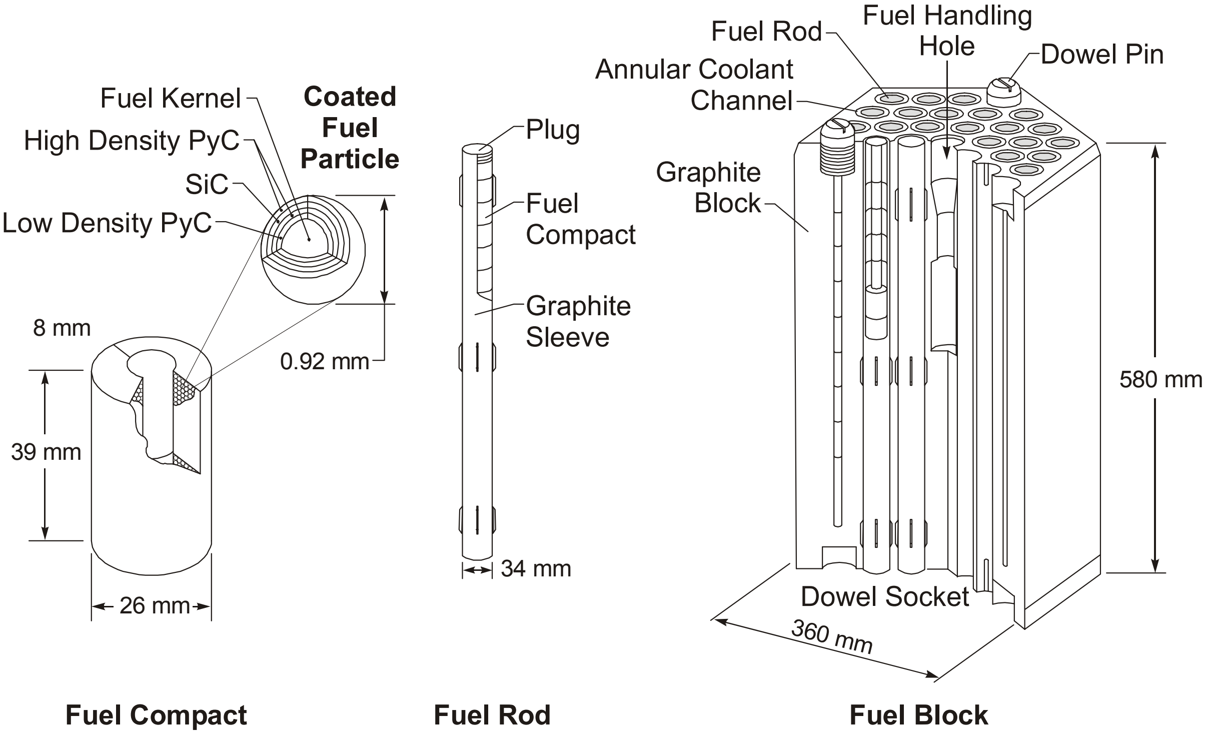

Fig. 3. High-temperature engineering test reactor fuel designed for 950EC exit helium temperatures.

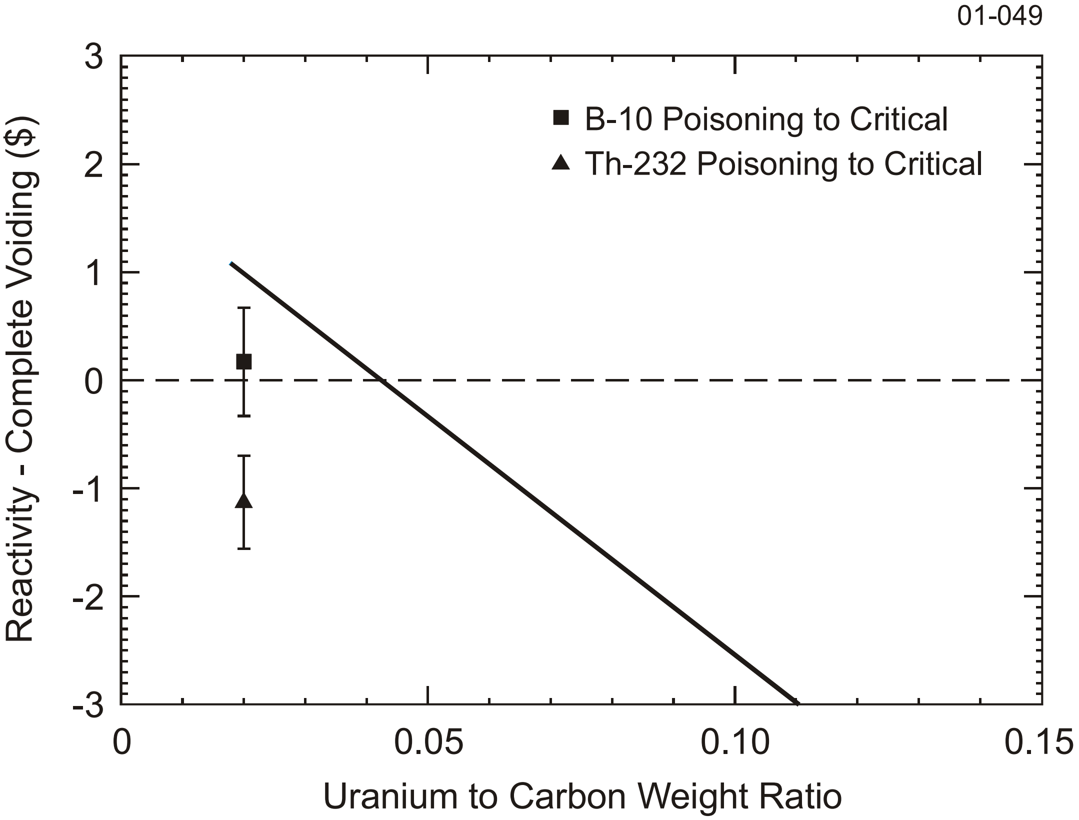

Fig. 4. Void reactivity for the 10% coolant fraction AHTR. (Li_2BeF_4 salt; 10% ^{235}U enrichment; core radius = 300 cm; core height = 600 cm; volume fraction salt = 0.1; radial reflector = 100 cm molten salt; carbon axial reflector = 100 cm; temperature = 900EC; fresh core).

The coolant void reactivity coefficient was analyzed for a core with a 10% Flibe ($^7Li_2BeF_4$) coolant fraction, a ^{235}U enrichment of 10%, and U/C weight ratios ranging from 0.02 to 0.1. The results show that for U/C ratios <~0.05, complete voiding of the coolant from the core could result in a positive reactivity addition. For a U/C equal to 0.02, voiding the complete core resulted in a reactivity addition of ~$1.00. For these very dilute fuel loadings, the effect of voiding the molten salt coolant is positive, since the decrease in absorption in the coolant is more important than the negative effect of the loss of moderator. As the fuel concentration is increased to provide more realistic excess reactivity values and longer core burnup times, the relative importance of the absorption and moderation in the Flibe is reversed and the overall void coefficient is then negative as the uranium to carbon ratio exceeds -0.05. The addition of absorbers to reduce k_{eff} to near unity, or the addition of fertile fuel materials to increase conversion ratios and burnup, also result in negative void coefficients. Although the magnitude of the total reactivity swings is relatively small, the results are consistent with the expectation that over moderation can create the potential for positive void coefficients whereas under moderation can lead to negative void coefficients. Such studies define the design parameters required for safe core design.

The intrinsic characteristics of this system allow the designer of the reactor core many options. The volume fraction of the fuel, coolant, and moderator can be independently varied. Burnable absorbers can be added to the fuel, the coolant (as rare earth fluorides), or the graphite. The efficient heat transfer compared with that of gas cooling allows variable coolant channel dimensions for prismatic fuels.

IV. SAFETY SYSTEMS

The AHTR has the potential to provide a robust safety case because of various inherent and passive safety characteristics. Inherent safety characteristics include moderate core power density, high-temperature-margin fuel, a high-thermal-inertia core, efficient decay-heat removal based on effective heat transfer of the molten salt (which requires no moving parts or control activation signals), atmospheric pressure operation, and efficient liquid-coolant heat transfer. Reactor power is intrinsically limited by negative temperature feedback (Doppler effect) within the fuel. The reactor physics and kinetics are similar to that of the GT-MHR. A series of systems are designed to remove decay heat and provide protection in beyond-design-basis accidents.

IV.A. AHTR Core Thermal Inertia

One of the most important safety characteristics of a reactor is its thermal inertia. If a reactor has an appropriately large thermal inertia, it will take days before the decay heat raises the reactor temperature sufficiently to cause fuel failure. This (1) provides time for operator action, (2) reduces the requirements on the decay heat removal system, and (3) provides time for short-lived radionuclides to decay away. The AHTR has a very large thermal inertia because it combines the efficient natural-circulation liquid heat transfer of the S-PRISM with the high-temperature capabilities of the GT-MHR. The other reactors have significantly lower thermal inertia because they do not use as efficiently the thermal inertia of the materials inside their respective reactor vessels.

- *GT-MHR*. In the GT-MHR, under design-basis depressurization loss-of-cooling conditions, large radial and vertical temperature gradients exist within the reactor vessel. Under depressurized conditions, the GT-MHR peak fuel temperature reaches 1560EC after 60 hours while the peak temperatures of the reactor vessel are under 600EC. Large temperature gradients are needed to remove the decay heat. If the reactor remains pressurized with better heat transfer in the reactor vessel, the core temperature peaks at only 1240EC at 50 hours, due to the more uniform core temperature caused by natural convection of the high pressure helium coolant [11]. Most of the mass in the reactor is far below allowable peak temperatures and not efficiently used to maximize thermal inertia.

- *S-PRISM Thermal Inertia.* In the pool-type S-PRISM reactor, the thermal capacity of the coolant and structures is used efficiently because natural circulation of the sodium greatly reduces temperature gradients to <30EC between the core outlet and the reactor vessel midwall at the time of peak core temperature at 30 hours [12]. However, the S-PRISM thermal inertia is limited by the lower volumetric heat capacity of sodium compared to molten salts (Table 1) and by the much lower peak core temperature permitted in the S-PRISM (670EC vs 1600EC for the GT-MHR).

To quantify the thermal inertia capabilities of the AHTR, the following question was asked: What would be the thermal power output of an AHTR with (1) a reactor vessel similar in volume to the 600-MW(t) GT-MHR (e.g., Fig. 2) and (2) the same rate of temperature change. While a detailed thermal design has not yet been performed, a simplified analysis indicates that the AHTR can have a power output of ~2400 MW(t) with a similar volume of reactor vessel. The analysis assumed that the AHTR vessel shown in Fig. 2 would be the same size as the S-PRISM vessel—a vessel designed for a liquid coolant. Due to transportation limits, the vessel volumes of the S-PRISM (1000 MW(t), 9.2-m diameter, 1260 m^3) and the GT-MHR (600 MW(t), 8.4-m diameter, 1210 m^3) are almost identical.

The equivalent AHTR thermal power was estimated by comparing the volume and heat capacity of materials that can be coupled to the core by convective heat transfer in the two reactors. An AHTR with the same 9.2-m diameter, 5.0-cm thick vessel as the S-PRISM, and with a 0.65-m thick graphite liner and reflector, has an effective annular core diameter of 7.8 m. Conversely, the GT-MHR's effective core diameter is only 4.9 m because of the (1) 0.22-m thick vessel wall, (2) inner core barrel for helium down flow and vessel thermal conditioning, and (3) graphite reflector. In the vertical direction, the GT-MHR heats the 1.6-m thick graphite reflector, located above the 7.9-m high core. Conversely, the AHTR provides a 6.8-m deep molten-salt pool above the core. Thus the ratio of the active volume to absorb heat of the AHTR, relative to the GT-MHR, is 4.1, e.g. $[(7.8/4.9)^2 \times (6.8+7.9)/(1.9+7.9)]$. Furthermore, in the GT-MHR, a significant fraction of the thermally-active volume is occupied by helium, which has negligible heat capacity. Conversely, in the ATHR all of the active volume is occupied by graphite or by molten salt, which has a larger heat capacity than graphite (Table 1).

IV.B. Reactor Cavity Cooling System (RCCS) Decay Heat Removal

Thermal inertia can slow the temperature rise in the reactor core; however, decay heat removal is ultimately required. As indicated above, the thermal capacity of the AHTR core is more than a factor of 4 greater than the 600-MW(t) GT-MHR, while maintaining a peak core temperature of 1240EC at 50 hours. The acceptable thermal power of the AHTR is then limited by the peak decay-heat removal capacity of the RCCS. The 600-MW(t) GT-MHR RCCS has a peak capacity that matches the decay heat output at the time of peak core temperature 50 hours after loss of cooling. To achieve the same 50-hour duration at 2400 MW(t), the AHTR RCCS must have a heat removal capacity four times that of the GT-MHR.

Several alternative methods exist for enhanced passive decay-heat removal. The coolants for the RCCS can be either ambient air (e.g. S-PRISM, GT-MHR) or water (e.g. PBMR). Because each provides different advantages and disadvantages, no final selection has been made for the AHTR. The characteristics of the AHTR RCCS are somewhat different than that of the GT-MHR or S-PRISM. Consequently, while scooping estimates of RCCS performance were be made, major work will be required to develop and demonstrate these systems.

IV.B.1. AHTR RCCS Using the S-PRISM Approach

The AHTR RCCS (Fig. 1) could use the same design approach as the General Electric S-PRISM liquid-metal-cooled reactor [12, 13]. In this pool reactor, decay heat is (1) transferred to the reactor vessel boundary by natural circulation of sodium, (2) conducted through the 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 the second wall by natural circulation of air. The rate of heat removal is controlled primarily by the radiation heat transfer through the argon gas from the reactor vessel to the guard vessel. Radiation heat transfer increases by T^4; thus, a small rise in the reactor vessel temperature greatly increases heat transfer out of the system. The argon gap acts as a thermal switch to limit heat losses during normal operation but allows radiation heat transfer to increase heat losses if the reactor overheats. The sodium coolant also allows operation at atmospheric pressure. The S-PRISM design can remove more decay heat than that of a GT-MHR because of the liquid sodium coolant, which allows transfer of the heat by efficient liquid natural convection from the center of the reactor core (hot-spot location) to the vessel wall. The large temperature drops from the center of the reactor core to the reactor vessel in gas-cooled reactors are avoided. The size of the S-PRISM reactor, using this passive decay heat cooling system, is limited to ~1000 MW(th).

If the same type of S-PRISM passive cooling system is applied to the AHTR (Fig. 1) with the same size of reactor vessel (same cooling surface for decay-heat removal), the reactor output could potentially exceed 2000 MW(th). The AHTR operates 200 to 500EC hotter than the S-PRISM (500 to 550EC for the S-PRISM vs 750 to 1000+EC for the AHTR). Because natural circulation of cooling air increases with temperature and because heat transfer across the argon gap varies with T^4, the higher temperatures allow for greater decay-heat removal for a decay-heat removal system of the same size, i.e., a reactor with the same size vessel. Studies have been done on the performance of this type of system as a function of temperature [14]. These studies indicate that the heat rejection capability of this type of system will be more than doubled at 750EC for a given reactor vessel. However, detailed studies have only been conducted to ~700EC.

IV.B.2. AHTR RCCS Using the GT-MHR Approach

The AHTR RCCS can use the same design approach as the GT-MHR. The RCCS of the GT-MHR is similar to the S-PRISM except there is no guard vessel. Cooling air goes directly through cooling panels embedded in the reactor cavity wall. Inside the GT-MHR reactor vessel the cooling ducts and graphite reflector are arranged to partly insulate the reactor vessel from the reactor core. As a consequence of these design features, the reactor vessel temperature is much lower than the reactor core. The high pressures of the GT-MHR require a thick-wall pressure vessel. Such massive vessels are very expensive and difficult to construct using high-temperature materials. High-vessel temperatures are avoided by this design. While a similar graphite liner is used to limit the vessel temperature of the AHTR, because it is much thinner it can be constructed of high-temperature materials, like the S-PRISM, and sustain much higher temperatures and heat fluxes than the GT-MHR.

The RCCS capabilities of an AHTR with this type of design can be estimated based on the RCCS GT-MHR design [11]. A simplified analysis indicates the potential to remove up to six times as much heat in a vessel of similar size. There are several factors.

- *Effective Vessel Surface Area.* The ATHR vessel surface can be heated more uniformly than that of the GT-MHR, which rejects heat primarily in the radial direction by conduction from the 7.9-m high core. In the AHTR vessel, the liquid coolant assures only small temperature differences within the reactor. The effective use of the bottom of the AHTR vessel, and the vertical surfaces all the way to the top of the 6.8-m deep salt pool, can effectively double the useful vessel surface area for heat transfer.

- *Heat Transfer.* Radiant heat transfer dominates heat removal from the reactor vessel under accident conditions, and varies with the fourth power of the temperature. Increasing the peak vessel temperature from 497EC (GT-MHR peak temperature) to 750EC would increase the radiant heat flux by approximately a factor of three. There are other methods to enhance vessel cooling. Because the AHTR operates at atmospheric pressure, there is no thick-wall pressure vessel. Heat transfer can be improved by adding fins to the vessel [14]. Fins are effective on thin-wall vessels but not thick-wall vessels where the thick wall is the primary resistance to heat transfer. As cooling efficiency improves, the option exists to add more insulation (graphite liner) to the inside of the vessel and operate the vessel at lower temperatures relative to the molten salt coolant.

While the potential for highly effective RCCS heat removal exists for the AHTR, detailed design will be required to optimize and maximize its heat removal capability. There are multiple RCCS cooling options, including operating the reactor vessel at lower temperatures than the molten salt coolant. Scaling of both the thermal inertia and RCCS heat removal capability of the AHTR suggest that reactor thermal power >2000 MW(t) should be achievable with a vessel of the same volume as the GT-MHR or S-PRISM.

IV.C. Beyond-Design-Basis Accidents

Among solid-fuel reactors, the AHTR has potentially unique accident-mitigation capabilities. First, the high-temperature fuel has the same excellent high-temperature fission product retention capabilities as the GT-MHR. Second, most fission products and all actinides escaping the fuel are soluble in the molten salt and will remain in the molten salt at very high temperatures. Fluoride salts were chosen for the liquid-fueled molten salt reactor, in part because actinides and fission products dissolve in the molten salt at very high temperatures [2]. Third, the chemical inertness and low pressure of the molten-salt coolant eliminate the potential for damage to the confinement structure by rapid chemical energy releases (e.g., sodium) or coolant vaporization (e.g., water). Last, the molten salt excludes access of air to the solid fuel. This avoids concerns about graphite oxidation and prevents direct transfer of radionuclides from fuel to air.

V. ELECTRICITY AND HYDROGEN PRODUCTION

V.A. Thermal Characteristics for Energy Conversion

An important characteristic of the AHTR is the ability to deliver all the heat at high average temperatures without high pumping requirements. Liquid coolants have high heat capacities and low pumping power costs in comparison with gas coolants due to their much higher volumetric heat capacities (ρC_p in Table 1). As shown in Table 2 and Fig. 5, liquid-cooled reactors deliver most of their heat at near-constant temperatures while gas-cooled reactors deliver their heat over a wide range of temperatures due to pumping power limitations. If a gas-cooled reactor were to deliver most of its heat over a similar small temperature range, the energy consumption in circulating the gas would use a significant fraction of the plant output. The AHTR, as a liquid-cooled reactor, can deliver its heat with small temperature drops (40 to 100EC) with low pumping power costs.

TABLE 2. Reactor exit and entrance temperatures (EC) for different coolants

Reactor/Type/Status	Coolant	T_{out}	T_{in}	Delta T
Point Beach [15]/pressurized water reactor/operating	Liquid, water	319	299	20
Super Phoenix/fast reactor/closed	Liquid, sodium	545	395	150
Hinkely-Point-B [15]/advanced gas-cooled reactor/operating	Gas, carbon dioxide	665	310	355
GT-MHR [3]/high-temperature gas-cooled reactor/proposed	Gas, helium	850	491	369

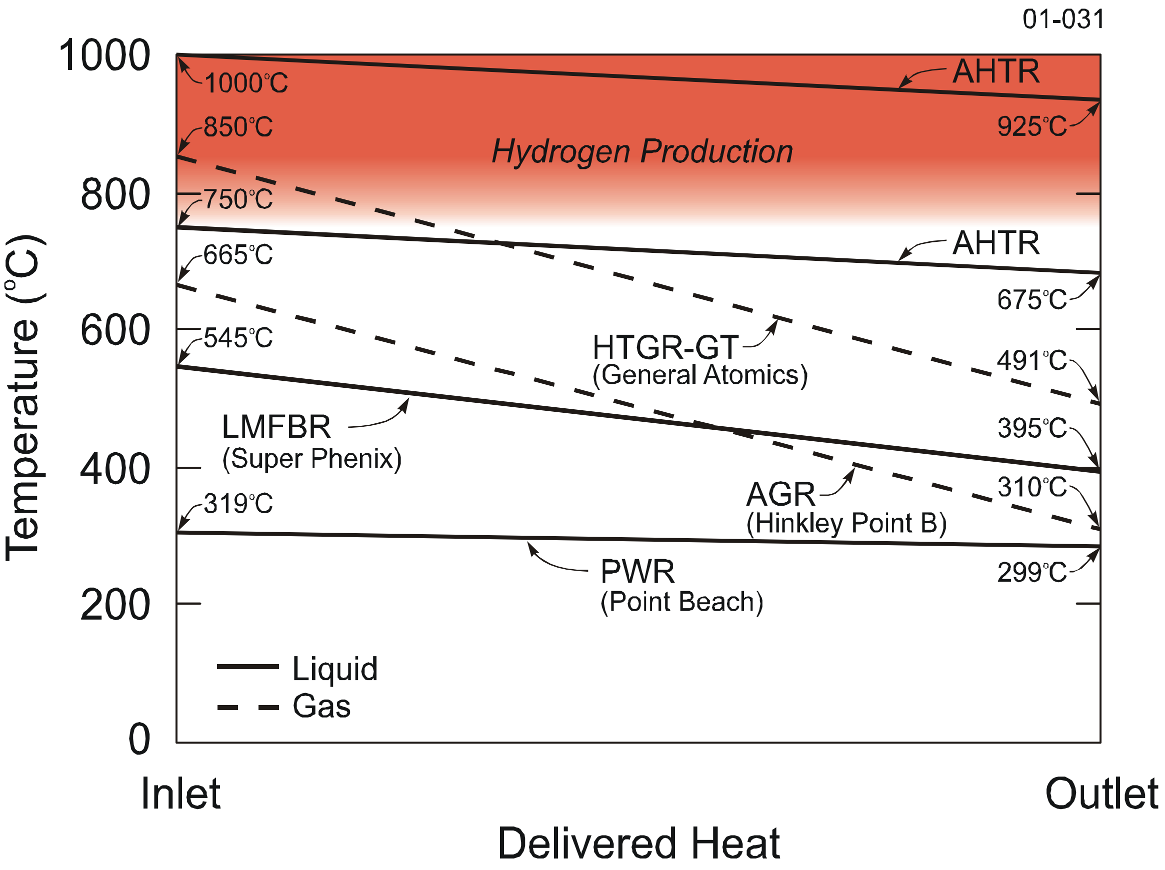

Fig. 5. Temperatures of delivered heat from existing and proposed reactors.

V.B. Electricity Production

The AHTR has a higher potential efficiency than the GT-MHR at the same reactor coolant exit temperatures because delivery of most of the heat at near-constant high temperatures allows the use of more-efficient Carnot-like power cycles. The benefit of these advanced cycles is increased efficiency, resulting in up to 20% increased electrical output for the same thermal power. The cost of this improvement is some increased system complexity. Molten salt coolants present the most promising approach to take advantage of this potential benefit.

The proposed General Atomics GT-MHR [3], with a direct recuperative gas-turbine cycle, has an efficiency of 48% with an exit gas temperature of 850EC. The AHTR, with a indirect recuperative *multi-reheat* gas-turbine cycle (Fig. 1), has an efficiency of 56% [16]—assuming the same temperatures and turbomachinery parameters. Current materials may allow molten salt temperatures of -750+EC. At these temperatures, the AHTR matches the efficiency of the GT-MHR, with its exit helium temperature of 850EC. At 1000EC that might be obtained with advanced materials, using the same fuel that currently limits the GT-MHR to an exit helium gas temperature of 850EC, and taking advantage of the improved heat transfer properties of the molten salt (see above), the efficiency of the AHTR can exceed 59%.

The reference AHTR design employs a recuperated helium Brayton cycle (Fig. 1) with three stages of reheat and three stages of intercooling [15]. The helium pressure is reduced through three turbines in series, with reheating of the helium to its maximum temperature with hot molten salt before each turbine. Such power cycles are viable only with (1) indirect power cycles to deliver heat before each turbine and (2) liquid-cooled reactors, in which most of the heat from the reactor can be delivered with low pressure drops at near-constant high temperatures. Calculations [16] have shown that for the same reactor outlet temperatures, the multiple-reheat Brayton cycle increases the thermal efficiency of the AHTR by between 5 and 6% above that of the GT-MHR with a traditional Brayton cycle. The potential reduction in the reactor vessel conditioning heat load, due to the low-pressure operation of the AHTR, potentially increases the AHTR thermal efficiency by an additional 1 to 2% relative to that achieved with reactors operated at high pressures.

The differences in pressures between the power cycle and the primary system require appropriate design features to ensure that no over-pressurization of the reactor occurs. These include (1) use of an intermediate salt heat transfer loop, (2) minimization of the helium inventory in the power cycle, (3) pressure relief valves for small leaks, and (4) burst relief valves for large leaks. Alternatively, if an intermediate salt loop is not used, then a large low-pressure gas volume can be part of the primary system to accept the entire helium inventory.

V.C. Hydrogen Production

The world [17-19] uses 50 million tons of H_2 per year, primarily for fertilizer production and the conversion of lower-grade crude oil into transport fuels. The demand is growing rapidly. Many oil refineries, other H_2 users, and merchant H_2 plants are now connected by pipelines. The projected market for traditional H_2 applications is sufficient to support the development of nuclear methods to produce H_2. Furthermore, large-scale R&D efforts are under way to develop H_2 fueled vehicles. The energy required to produce the H_2 for transportation would be approximately equivalent to that used to produce electricity.

The largest H_2 plants that are under construction [20] have capacities of 200 million standard cubic feet per day and operate on natural gas. Hydrogen can be produced from water and high-temperature heat (see below). A 1600-MW(th) reactor would be required to produce the energy to manufacture 200 million standard cubic feet per day—assuming 50% efficient conversion of thermal energy to H_2. By the time the AHTR could be deployed, its proposed size [2000+MW(t)] will match the production capacity requirements of a conventional H_2 plant.

There are several methods currently being considered to produce emission-free hydrogen from nuclear energy. The primary candidates [21] are thermochemical cycles and electrolysis, including high-temperature electrolysis. The thermochemical production of H_2 involves a series of chemical reactions with the net result of heat plus water yields H_2 and oxygen. The incentive for thermo-chemical production of H_2 is that the potential economics of scaling may be significantly better than those for electrolysis of water with electricity. The Japanese estimates [9] are that the cost of nuclear thermochemical H_2 production could be as low as 60% of that for nuclear H_2 production by the electrolysis of water. At the most fundamental level, thermochemical H_2 production involves conversion of thermal energy to chemical energy (H_2) while electrolysis involves conversion of thermal energy to electricity and subsequent conversion of electricity to chemical energy. The additional conversion step adds cost and introduces additional inefficiencies. Efficient H_2 production places severe requirements on the reactor, which the AHTR is designed to meet.

Many types of thermochemical processes for H_2 production exist [22]. All of the competitive processes require heat input at temperatures above 750+EC. The sulfuric acid processes (sulfur-iodine, Westinghouse, Ispra Mark 13) are the leading candidates. In each of these processes, the high-temperature low-pressure endothermic (heat-absorbing) reaction is the catalytic thermal decomposition of sulfuric acid to produce oxygen:

$$H_2SO_4 \ 6 \ H_2O + SO_2 + \tfrac{1}{2} O_2.$$

Based on current technology, temperatures in the range of 800 to 1000EC are needed to drive the sulfuric acid decomposition reaction sufficiently to completion for efficient H_2 production. (There is research underway that may lower these temperatures to 700EC.) After oxygen separation, additional chemical reactions are required to produce H_2. The leading candidate for thermochemical H_2 generation, the sulfur–iodine process (Fig. 6), has two additional chemical reactions:

$$I_2 + SO_2 + 2H_2O \ 6 \ 2HI + H_2SO_4 \ (\sim 120\text{EC})$$

and the H_2-producing step

$$2HI \ 6 \ H_2 + I_2 \ (\sim 450\text{EC}).$$

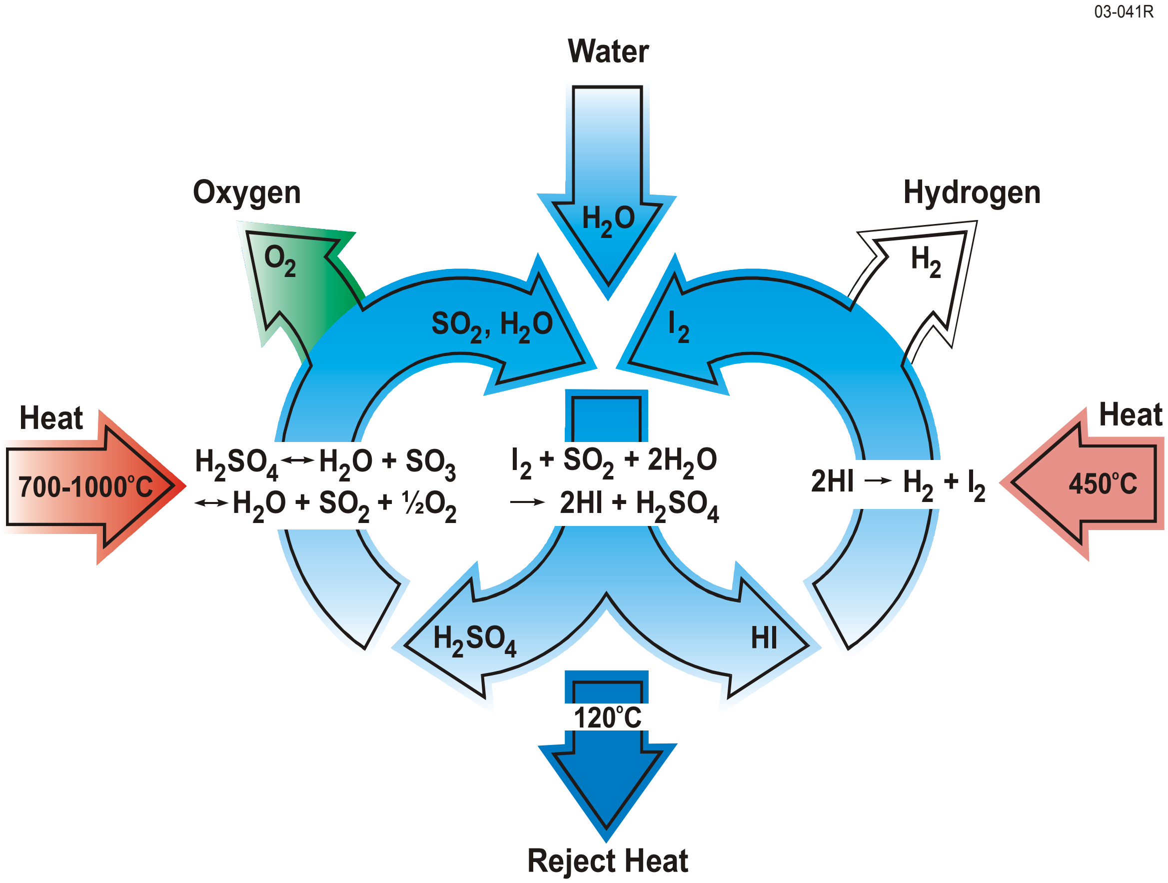

Fig. 6. Iodine-sulfur process for thermochemical production of H_2.

The design of the interface between the reactor system and the H_2 plant is significantly different from that for heat transfer to the high-pressure helium power conversion system. For the H_2 plant, the heat is transferred to a chemical reactor for the disassociation of H_2SO_4. The high-temperature step is an equilibrium process. Low pressures and high temperatures yield dissociation products, while high pressures and low temperatures favor formation of H_2SO_4; thus, the chemical reactor must operate at high temperatures and relatively low pressure. Chemical dissociation is a near-constant-temperature process that requires that heat be supplied at a near-constant temperature. Because large quantities of lower-temperature heat are not useful for H_2 production, the use of liquid-cooled reactors, rather than gas-cooled reactors, is favored.

If the heat is needed at 750EC, the maximum temperature of the molten salt may be as low as 800EC. In contrast, if a gas coolant is used to provide the heat to the sulfuric acid dissociation step, the maximum temperature of the coolant may exceed 1000EC to limit costs of pumping the gas coolant through the reactor and chemical plant (Fig. 5). Considerations involving process, safety (potential release of hazardous chemicals in the H_2 production system), and materials (reduced strength of materials at high temperatures) all indicate that an optimized chemical reactor (heat transfer equipment) should operate at relatively low pressures and at temperatures only slightly above those needed for the chemical reactions. These high-temperature and low-pressure requirements match the AHTR capabilities.

The production of H_2 requires isolation of the reactor from the chemical plant, probably using an intermediate heat transfer loop between the primary reactor coolant and the thermochemical cycle. Efficient heat transfer is required in this intermediate loop to minimize temperature loses and pumping power requirements. The high heat transfer and low pressures characteristics of the molten salts are among the best coolant choices to meet these requirements.

Another candidate for H_2 production from nuclear energy is high-temperature electrolysis (up to -900EC). In this process [23, 24], thermal energy is used to produce high-temperature steam. Electrolysis of the steam yields H_2 and oxygen. High-temperature heat significantly reduces the quantities of the more expensive electricity required for electrolysis by providing high-temperature steam and additional heat directly to the electrolytic cells. Equally important, the high temperatures may result in better chemical kinetics within the electrolyzer, which reduces (1) equipment size and (2) inefficiencies. The reactor requirements for delivery of heat (temperature, pressure, isolation) are similar to those of the above-described thermochemical cycles. The currently projected costs for high-temperature electrolysis are higher than those for other methods of H_2 production, but future research may result in significant improvements.

VI. FUEL CYCLES

The fuel cycle options are essentially identical to those of the HTGR. These include various open and closed low-enriched uranium and low-enriched uranium–thorium fuel cycles. Prismatic fuels use periodic refueling, while pebble fuels permit continuous refueling.

VII. ECONOMICS

To be viable, a reactor must be economic. The AHTR is a new reactor concept; thus, no bottoms-up cost estimate exists. However, some relative comparisons were made to determine if the potential exists for good economics. There are several approaches that can be used.

- *Traditional scaling laws*. The AHTR has many features in common with the GT-MHR (coated-particle fuel, gas-turbine power cycle, high thermal-to-electric efficiency and passive, and reactor vessel volume). The AHTR can be built with a higher power output than a GT-MHR while maintaining the desired passive safety features. While the size of the GT-MHR is limited by passive decay-heat removal constraints to about 600 MW(th), the AHTR may be scaled to in excess of 2000 MW(th) [>1000 MW(e)] with passive cooling and similar reactor vessel size. Assuming the traditional 0.7 economic scaling law, this implies a per-kilowatt-thermal capital cost that is 70% that of the GT-MHR. If a further adjustment is made for the higher efficiency (56% vs 48% assuming the same peak coolant exit temperatures), the per-megawatt-electric overnight capital cost is 60% that of the GT-MHR.

- *Size comparisons*. The AHTR physical size is similar to the GT-MHR and S-PRISM; but the energy output is larger. The S-PRISM module has a thermal power output of 1000 MW(th), with an electric power output of 380 MW(e). The GT-MHR module has a thermal output of 600 MW(th), with an electric power output of 285 MW(e). The same size vessel should be sufficient to reject the decay heat from a 2000+ MW(th) [1000-MW(e)] AHTR core. A size comparison would indicate that the nuclear island of the AHTR would be only slightly more expensive than the S-PRISM or GT-MHR whereas the power conversion system and balance of plant would scale with the traditional scaling laws (above). Such an analysis yields more favorable economics than the traditional economics-of-scale approach with AHTR per kilowatt capital costs approximately half those of the GT-MHR.

Fuel costs would be expected to scale linearly with fission power. Higher efficiency in converting thermal energy to electricity should reduce fuel costs. Operating costs will have economics of scale. Significant development and engineering is required before a fully credible bottoms-up economic analysis can be completed.

VIII. UNCERTAINTIES AND R&D REQUIREMENTS

Development of a new high-temperature reactor is a major undertaking. However, because the fuel, molten-salt coolant, decay-heat removal systems, and power-conversion technologies have been partly or fully developed as part of other reactor concepts, the major AHTR R&D needs are restricted to a limited number of areas. The R&D costs are strongly dependent on the development of the GT-MHR, which shares the fuels and helium gas-turbine technology of the AHTR. If an ongoing GT-MHR program exists, the development costs for the AHTR would be expected to be a fraction of those for a totally new reactor concept. The AHTR is a logical next step in development of coated-particle fuel reactors beyond the GT-MHR. Several major needs for the AHTR have been identified.

- *Materials*. Materials are the greatest challenge for all high temperature reactors, including the AHTR. With the use of a liquid coolant with its better heat transfer characteristics, the reactor and corresponding materials temperatures are lower for a given temperature of delivered heat than comparable gas-cooled reactors. This reduces some of the materials challenges compared to gas-cooled reactors. However, many challenges remain. Current materials allow operation to 750EC and may be extended to higher temperatures. The materials for this application have good performance in the laboratory, but significant added testing is required before large-scale commercial use. Operating temperatures much above 800EC will require improved materials of construction. There are strong incentives to increase the temperature to reach the full potential of the AHTR for efficient electric and thermochemical H_2 production. Oxide dispersion-strengthened alloys (such as MA-754 or MA-956) and carbon-carbon composites [25] are among the candidates for operating temperatures from 900 to 1000EC. The excellent chemical compatibility of carbon with molten salts creates new materials options—provided that the composites can also be designed to withstand the ingress of oxidizers. The graphite fuels, and potentially the carbon-carbon composites, can operate at much higher temperatures.

- *System design*. Detailed system designs must be developed with supporting experimental work to understand the trade-offs between high-temperature performance, reliability, and various design choices (molten salt composition, core power density, etc.). An important component of this work is selection of the preferred salt among several related fluoride salts. This involves tradeoffs between neutronics, cost, operations (melting point, coolant radiation levels, ease of chemistry control), heat transfer, and other parameters.

- *Heat exchangers*. Significant development work is required on high-temperature heat exchangers for both electricity and H_2 production. The development of the chemical reactors/heat exchangers for H_2 production may demand radically different heat exchangers compared to those traditionally used in the power industry.

- *RCCS systems*. The thermal power of the AHTR will be limited primarily by the heat removal capacity of the RCCS. Detailed design and heat transfer optimization are needed to maximize the potential RCCS performance.

- *High-temperature thermochemical or thermoelectric H_2 cycles*. Significant additional development work is required on efficient high-temperature H_2 production cycles.

IX. CONCLUSIONS

As a new family of high-temperature reactors, the AHTR is defined by two characteristics: (1) a high-temperature fuel and (2) a low-pressure liquid coolant. Our studies indicate that a reactor with these characteristics has the potential for significantly improved economics for the production of electricity and H_2. Because heat is delivered at temperatures and pressures that match process requirements, the reactor may have unique potential for the thermochemical production of H_2. As with all new reactor concepts, there are major uncertainties (materials, thermochemical H_2 cycles, etc.) and many alternative design possibilities. Significant work will be required before the characteristics of and potential for this new family of reactors are well understood.

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