A Large Low-Pressure Advanced High-Temperature Reactor (AHTR)

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Abstract—*Oak Ridge National Laboratory, Sandia National Laboratories, and the University of California–Berkeley are developing a new reactor concept for hydrogen and electricity production: the Advanced High-Temperature Reactor (AHTR). The goal is to develop a large economic reactor with passive safety systems that delivers high-temperature heat with the coolant exit temperature (depending upon the specific objectives) between 750 and 1000EC. The safety is to be equivalent to that of a modular high-temperature gas-cooled reactor (MHTGR). The AHTR fuel is a graphite-matrix coated-particle fuel, the type used in MHTGRs. The coolant is a molten fluoride salt with a boiling point near 1400EC. Because of this low-pressure liquid coolant, the type of passive safety systems proposed for liquid-metal reactors (such as the General Electric S-PRISM) can be used. Electricity is produced using a multi-reheat helium or nitrogen Brayton cycle. Depending upon design details, the power output for this passively safe reactor will be between 1000 and 1500 MW(e), with the longer-term potential for even higher power outputs.*

I. INTRODUCTION

As part of the Generation IV International Forum to identify advanced nuclear electrical power generating options for the future, 10 countries (including the United States) examined over 100 reactor concepts. Of the 19 concept sets identified as potentially viable, one new reactor concept was identified—the Advanced High-Temperature Reactor (AHTR). This reactor uses a new combination of existing fuel and coolant technologies that creates the potential for major reductions in electricity production costs and the economic production of hydrogen (H_2) by thermochemical cycles. The key technologies include:

- High-temperature, low-pressure molten-fluoride-salt reactor coolants developed during the U.S. aircraft nuclear propulsion program of the 1950s and the molten salt breeder reactor program of the 1960s.

- Coated-particle graphite-matrix fuel developed for high-temperature gas-cooled reactors.

- Passive safety systems from the proposed modular gas-cooled and liquid-metal-cooled reactors.

- High-efficiency Brayton power cycles.

A series of studies and evaluations have defined the general characteristics of the AHTR. This paper describes the basis for the design of the reactor and summarizes the results of these analyses.

II. MARKET REQUIREMENTS

Two large markets exist for nuclear energy: electricity and H_2. The expected long-term requirements for these markets are the starting point for development of the AHTR. In all markets, there are large incentives to use passive safety systems to reduce costs, improve safety, and increase public acceptance. Passive safety systems do not require human actions or moving parts to ensure their operation. A set of demanding technical requirements exists for H_2 production. In both markets, strong incentives favor the development of large reactors.

In large electrical markets (United States, Europe, Japan, Russia, and China), experience has shown that for several reasons the most economic reactors are large reactors: traditional engineering economics of scale, siting and regulatory costs, and security. The majority of the recently ordered reactors have outputs between 1000 and 1500 MW(e). For a new reactor concept to be competitive in these electrical markets, the reactor should have the potential to be built in large sizes.

In the future, H_2 may become the primary application of nuclear energy. The worldwide demand for H_2 is ~50 million tons per year and growing rapidly. Hydrogen today is used primarily for production of ammonia for fertilizer and conversion of heavy crude oils into liquid fuels. An international effort is under way to develop H_2 as a replacement fuel for transport vehicles.

The present heavy-oil recovery and refinery market for H_2 is sufficiently large to support the deployment of nuclear reactors for H_2 production, assuming the technologies were fully developed and economical. Many experts[1] believe that conventional oil production will peak in this decade and then decrease. The shortfalls in production are likely to be offset by conversion of tar sands and other low-grade hydrocarbon deposits to liquid fuels in Canada, California, and Venezuela. This process requires massive amounts of H_2 because the H_2-to-carbon ratio of these lower-grade oil supplies is low. For example, the H_2-to-carbon ratio of tar sands is ~1, a value that must be raised to 2 if the final product is gasoline. Some perspective[1] on the scale of operations can be obtained by examining the Canadian tar sand development. Production is being raised from its current level of 500,000 barrels per day to 2.5 million barrels per day by 2010. Since 1996, 23 billion dollars has been invested to increase production. An additional 37 billion dollars in new plants and expansions has been announced. If these tar sand deposits are fully developed and natural gas is used to produce the required energy and H_2, the natural gas requirements will be 2 to 3 times the projected Canadian natural gas reserves. The demand of this and other heavy oil projects represents the near-term market for H_2 production and will provide the production technology for a transition to the larger H_2 economy.

If H_2 is to be produced using nuclear reactors, H_2 production systems will impose a set of requirements on the nuclear reactor.

- *Hydrogen production using nuclear energy requires high temperatures*. The leading candidates[2] for low-cost, large-scale H_2 production are thermochemical processes using nuclear heat. These processes involve a series of chemical reactions in which the net result is that high-temperature heat and water produce H_2 and oxygen (O_2). Various studies[3,4] project H_2 thermochemical production costs as low as 60% of those for electrolysis with the long-term potential heat-to-H_2 efficiencies in excess of 60% (i.e., the potential for major improvements over time). Significant development is required before any of these processes can be deployed.

- *Economic production of H_2 requires large chemical plants*. Large economics of scale are associated with chemical plants. Plant size is limited only by market demand or technological limits. In North America, most H_2 is produced by steam reforming of natural gas. New world-class H_2 plants are typically designed to produce 5.7×10^6 m^3/d (200×10^6 ft^3/d) of H_2, with a recent announcement to build a 8.5×10^6 m^3/d (300×10^6 ft^3/d) plant. If we assume that a nuclear thermochemical process (when commercially deployed in 15 to 20 years) is to produce 8.5×10^6 m^3/d of H_2 (the same size as the largest conventional H_2 plant under construction today), the nuclear reactor or reactors must deliver ~2400 MW(t) of high-temperature heat to the process. This assumes the thermochemical process is 50% efficient in converting heat and water to H_2. With the expansion of H_2 pipeline systems with multiple production plants and consumers, larger production facilities may become viable.

  The scaling factor[5] for current natural-gas-fueled H_2 plants is estimated to be 0.66. This implies that if the plant size is increased by 4, the capital cost increases by only a factor of 2.5; that is, the larger facility capital cost is only 62% of that for the smaller facility per unit of capacity. The scaling factor[6] for the hybrid thermochemical process was estimated at 0.54; that is, the larger facility capital cost is only 53% of the smaller facility per unit of capacity. Market and technical factors indicate that the thermochemical process facilities will be very large and couple well to large high-temperature reactors.

- *Thermochemical H_2 plants will likely require molten-salt heat-transfer loops to move heat from the reactor to the thermochemical plant.*

> Safety considerations will likely require significant separation of the nuclear facility from the thermochemical plant with its large inventories of hazardous chemicals. The projected physical size[4] of the thermochemical plants (dimensions of several hundred meters) also implies the transfer of heat over long distances. German studies in the 1970s concluded that molten salts were the fluids most desirable to use—following traditional chemical industry practice for high-temperature heat transfer. Several factors are involved. To transfer equivalent heat, the pipe diameter of a helium heat-transfer loop must be 5 times greater than that for a molten salt heat transfer loop. Larger pipe sizes have higher costs and greater heat losses. Safety factors must be considered as well. In chemical plants, compressed-gas heat-transfer systems are generally avoided because the compressed gas provides a high-energy mechanism to disperse hazardous chemicals if an accident (such as a heat exchanger failure) occurs in the chemical plant.

The requirements of the electrical and H_2 market provide the starting point to define the characteristics of a new reactor. The goal of the AHTR is to meet these requirements.

III. REACTOR DESCRIPTION

III.A. Systems

The AHTR[7] is a high-temperature reactor (Fig. 1) that uses coated-particle graphite-matrix fuels and a molten-fluoride-salt coolant. The fuel is the same type that is used in modular high-temperature gas-cooled reactors (MHTGRs), with fuel failure requiring temperatures exceeding 1600EC. The optically transparent molten-salt coolant is a mixture of fluoride salts, typically containing zirconium, sodium, and other fluoride salts with freezing points near 400EC and atmospheric boiling points of -1400EC. The reactor operates at atmospheric pressure. At operating conditions, the molten-salt heat-transfer properties are similar to those of water, with reactor coolant exit temperatures (depending upon the specific objectives) between 750 and 1000EC. Heat is transferred to a multi-reheat helium or nitrogen Brayton cycle power conversion system for the production of electricity or to an intermediate loop to provide high-temperature heat for H_2 production.

The vessel (Fig. 2) is the same size as that used by the S-PRISM sodium-cooled fast reactor designed by General Electric. However, the AHTR thermal output is 2400 MW(t), rather than the 1000-MW(t) design output of the S-PRISM reactor. The vessel is similar in size to that of the 600-MW(t) MHTGR. Like that of the MHTGR, the AHTR vessel is lined on the inside with graphite so that the fuel and coolant can operate at higher temperatures than the vessel. In the current design, the AHTR, like the MHTGR, has an annular core with coolant flowing downward through the core. 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.

The reactor core physics are generally similar to those 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. Although the AHTR and MHTGR vessels have similar diameters, the AHTR core volume is considerably larger. The larger volume is possible because the coolant is a low-pressure high-heat-capacity liquid rather than high-pressure low-heat-capacity helium. Consequently, the AHTR has no thick-wall pressure vessel or large annular zones for upflow of helium coolant. This added space is available for the reactor core.

For high-temperature operations, materials, and fuels are key technologies. There is a century of large-scale experience in the use of fluoride molten salts. Aluminum is made by electrolysis of a mixture of bauxite and sodium aluminum fluoride salts at -1000EC in large graphite baths. Fluoride salts are compatible with graphite fuels. A smaller nuclear experience base exists with molten fluoride salts in molten salt reactors. Nickel alloys such as modified Hastelloy-N have been qualified for service to 750EC. A number of metals and carbon–carbon composites[8] have been identified for use at much higher temperatures; however, these materials have not yet been fully developed or tested for such applications.

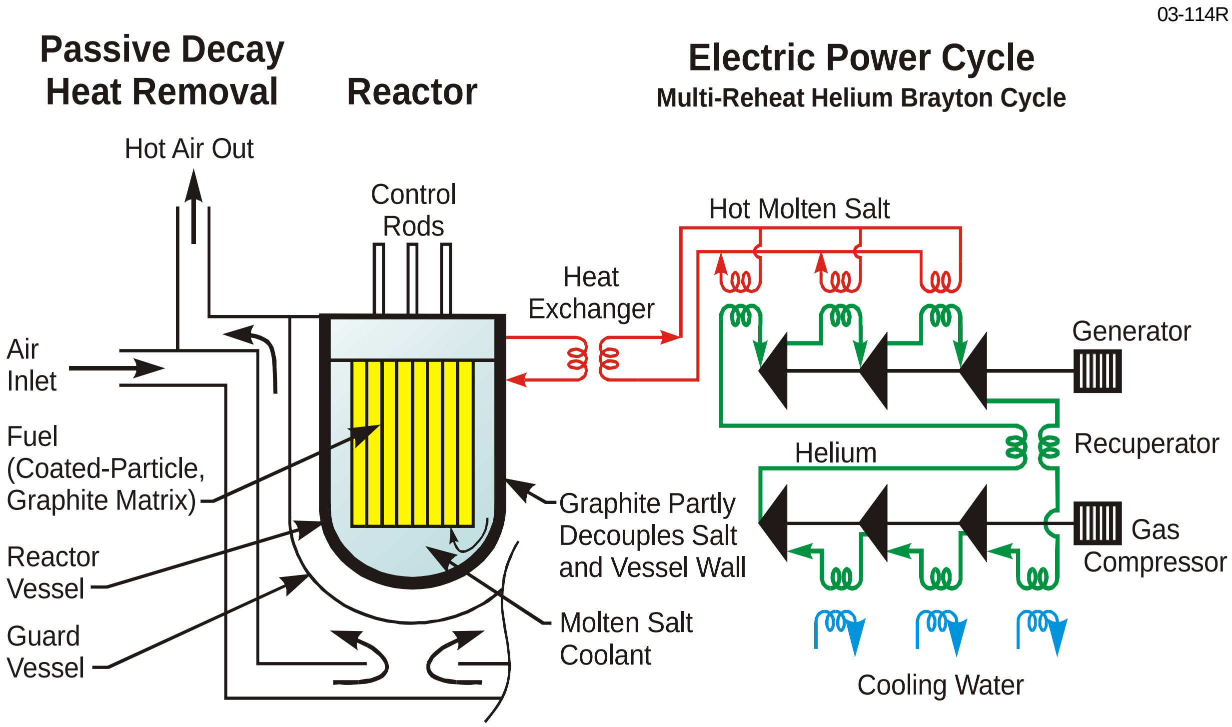

Fig. 1. Schematic of the Advanced High-Temperature Reactor for electricity production.

III.B. Decay Heat Removal

The AHTR uses passive decay-heat-cooling systems. For the analysis herein, an air-cooled passive decay-heat-removal system[7] was examined that is similar to that developed for the General Electric sodium-cooled S-PRISM. The reactor and decay heat cooling system are located in an underground silo. In this pool reactor, decay heat is (1) transferred 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 forth 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.

Several types of passive decay-heat-cooling systems have been developed for different power reactors. In each case, heat is transferred from the reactor core to the reactor vessel surface. Several alternative methods are available to cool the silo walls (natural circulation of air, water baths, etc.). In each case, the reactor thermal output is limited by the ability to transfer decay heat from the nuclear fuel to the outside surface of the reactor vessel (Fig. 3) in an emergency. The use of a molten salt coolant and a high-temperature fuel allows much higher reactor power ratings than those found in other reactors with similar passive safety systems *in the same size reactor vessel*. Increasing the power output for the same plant footprint improves economics. Advances in reactor design has enabled adoption of passive safety systems in larger reactors.

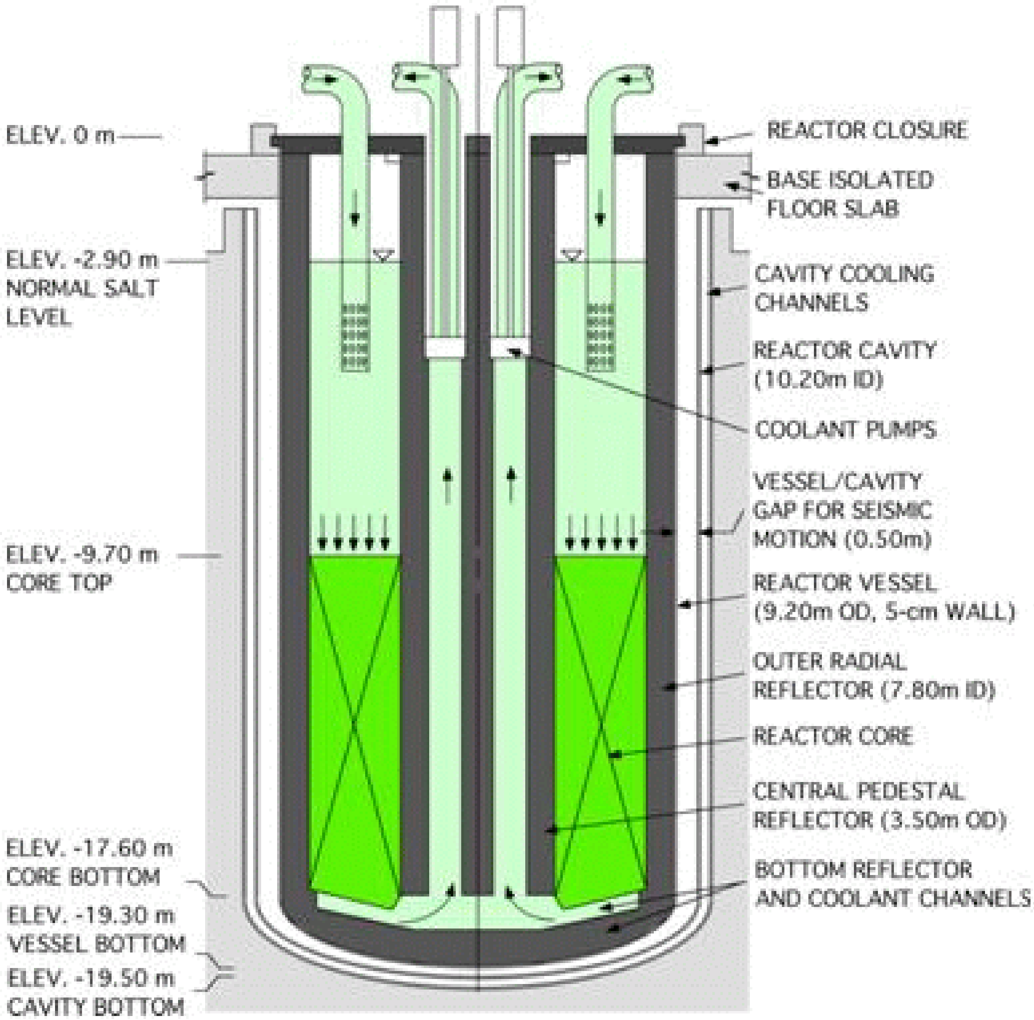

Fig. 2. Schematic of the Advanced High Temperature Reactor vessel.

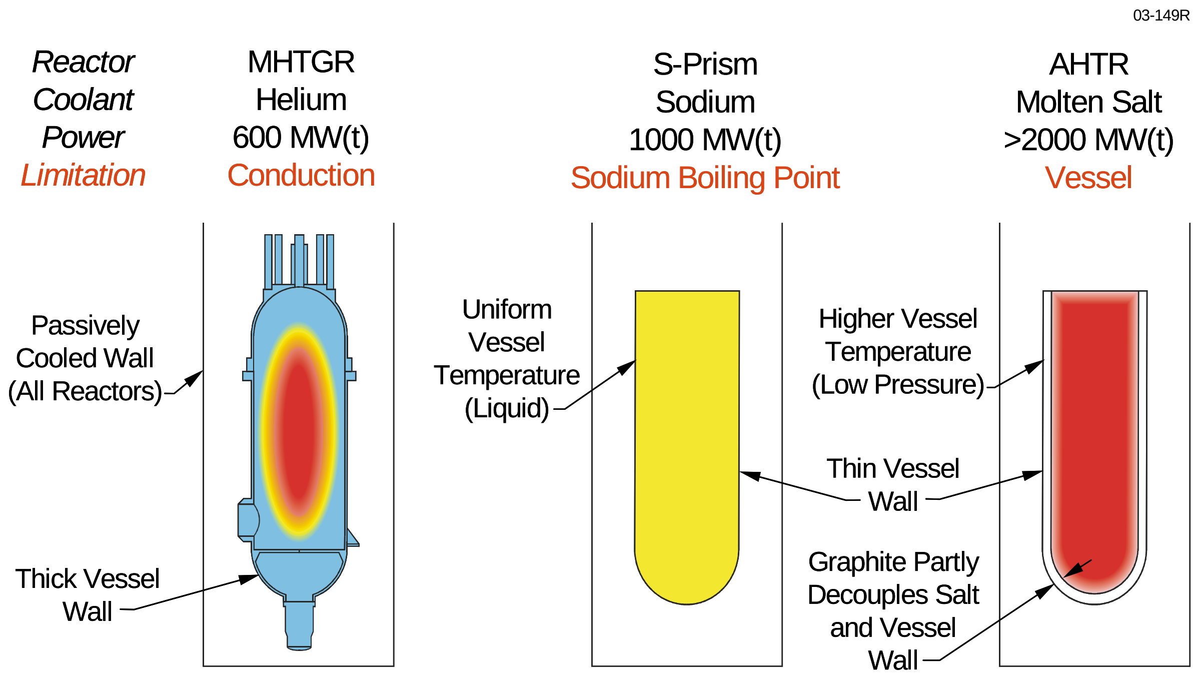

Fig. 3. Evolution of passive decay-heat-removal systems in similar size reactor vessels.

- *MHTGR*. In an emergency, decay heat must be moved from the center of the reactor core to the vessel boundary by conduction and radiation. This process[9] requires a large temperature drop (-1000EC) to transfer heat through the graphite-matrix coated-particle fuel, the graphite reflector, helium flow channels, and a thick-wall pressure vessel. Furthermore, only some surfaces of the reactor vessel are hot and efficiently rejecting decay heat while those parts of the vessel that are far from the reactor core are cool and reject little heat. To ensure that the fuel in the center of the reactor does not overheat and release large quantities of radionuclides in an accident, the nominal power output of the reactor is limited to 600 MW(t).

- *Sodium-cooled reactors (General Electric S-PRISM)*. In an emergency, decay heat is transferred from the center of the reactor core to the vessel wall by natural circulation of sodium. Natural circulation of a liquid is an efficient way to transfer heat to the entire vessel with a temperature drop of a few tens of degrees. The ultimate power limitation of the S-PRISM is that the peak coolant temperature must be significantly below the boiling point of sodium. The heat rejection capability of the S-PRISM is greater than that of the MHTGR because the circulating sodium ensures that the entire surface area of the reactor vessel is at a relatively uniform high temperature for rejecting decay heat. If the fuel in the center of the reactor is not to fail in an accident, the power production must be limited to -1000 MW(t).

- *AHTR*. The decay-heat-removal approach in the AHTR is similar to that in a sodium-cooled reactor. However, in the AHTR the decay-heat rejection rate is limited only by the temperature limits of the low-pressure reactor vessel. Unlike sodium-cooled reactors, AHTR fuel and coolant can go to very high temperatures. With current vessel materials, the vessel temperature can be as high as 750EC. This allows for passive decay heat removal with a nominal reactor power level of -2400 MW(t). (Because of the graphite insulation layer inside the reactor vessel, the molten salt and fuel temperatures can be above the vessel temperatures.)

The ultimate power output of the AHTR is limited by the capacity of the passive decay system; this capacity, in turn, is limited by the reactor vessel temperature. If higher-temperature reactor vessel materials are developed and qualified, vessel temperatures in an emergency may be allowed to increase to temperatures as high as 1000EC. Under such circumstances, it may be viable to have significantly higher thermal power ratings.

III.C. Beyond-Design-Basis Accident

In a beyond-design-basis accident, it is assumed that the air-cooled passive decay-heat-cooling system has failed and that significant structural failures (vessel failure, etc.) have occurred. Decay heat continues to heat the reactor core but decreases with time. To avoid the potential for catastrophic accidents (accidents with significant release of radionuclides), the temperature of the fuel must be kept below that of fuel failure by (1) absorption of decay heat in the reactor and silo structure and (2) transfer of decay heat through the silo walls to the environment. For the MHTGR, the maximum size of reactor that can withstand this accident without major fuel failure is -600 MW(t). Preliminary assessments[10] indicate the potential for a 2400-MW(t) AHTR to have a similar capability because of its low-pressure (relatively chemically inert), high-temperature coolant. If there is vessel failure, the inventory of molten salt coolant in the reactor vessel is sufficient to fill the bottom of the silo and keep the reactor core flooded. The molten salt provides an efficient mechanism to transfer heat from the failed vessel to the silo wall and the environment. As with normal operation, it is the characteristics of the low-pressure liquid coolant that enable enhanced safety in a larger reactor.

Most fission products (including cesium and iodine) and all actinides escaping the solid AHTR fuel are soluble in the molten salt and will remain in the molten salt at very high temperatures. The molten salt prevents any oxidation of the fuel by air ingress. These characteristics provide additional barriers to radionuclide releases.

IV. ENERGY CONVERSION

IV.A. Thermal Characteristics for Energy Conversion

Two reactor coolant temperatures are critical to operations: the peak temperature and the average temperature. The peak temperature determines the requirements for fuels and materials, while the average temperature is a measure of the useful energy that the reactor can deliver for electricity or H_2 production.

As a liquid-cooled reactor, the AHTR has the ability to deliver all the heat at high average temperatures. Because of their much higher volumetric heat capacities, liquid coolants have low pumping power costs in comparison with gas coolants. As shown in Fig. 4, 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. This feature has major implications in terms of materials and fuels. If heat must be delivered at 850EC to a thermochemical H_2 cycle, the peak coolant temperature of the AHTR will be <100EC higher. On the other hand, the peak coolant temperatures of a gas-cooled reactor must be much higher to deliver most of its heat at 850EC.

IV.B. Electricity Production

The reference AHTR design[11] employs a recuperated helium Brayton cycle (Fig. 1) with three stages of reheat and three stages of intercooling. 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. The respective efficiencies at salt exit temperatures of 750, 850, and 1000EC salt are 48, 56, and 59%.

Because delivery of most of the heat at near-constant high temperatures allows the use of more-efficient Carnot-like power cycles, the AHTR has a higher potential efficiency than the MHTGR at the same reactor coolant exit temperatures. The proposed General Atomics MHTGR,[9] with a direct recuperative gas-turbine cycle, has an efficiency of 48% with an exit gas temperature of 850°C. The AHTR, with a indirect recuperative *multi-reheat* gas-turbine cycle (Fig. 1), has an efficiency of 56%—assuming the same temperatures and turbomachinery parameters.

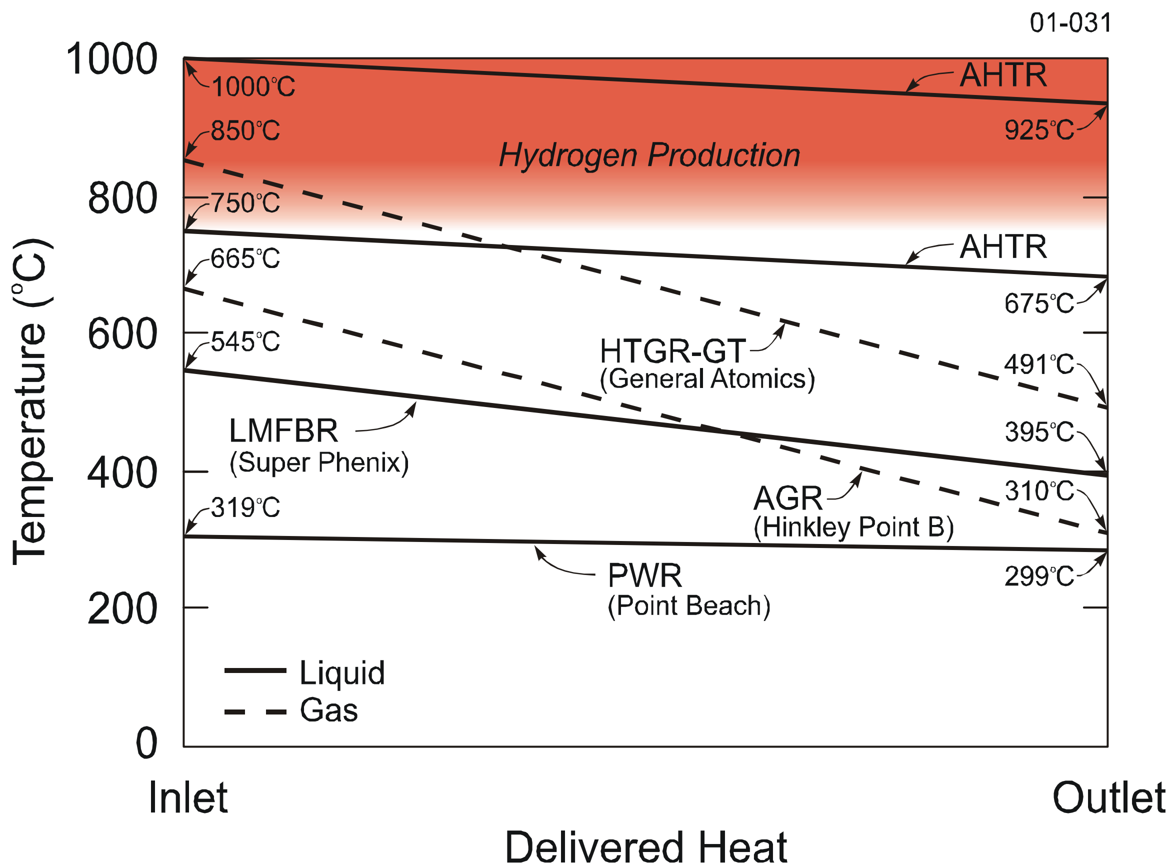

Fig. 4. Temperature of delivered heat from different reactors.

A nitrogen Brayton cycle is being considered as an alternative to helium. The major advantage of the nitrogen Brayton cycle is that the turbomachinery is commercially available—the same as is used by electric utilities in natural-gas combined-cycle plants. However, nitrogen cycles may have slightly lower overall efficiencies.

IV.C. Hydrogen Production

For efficient thermochemical cycles, large quantities of high-temperature heat need to be supplied to a secondary heat-transfer system. The AHTR characteristics match the expected requirements for H_2 production as defined earlier: large size, efficient coupling to an intermediate molten-salt heat transfer loop, and delivery of heat at a relatively uniform high temperature.

V. 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.

The proposed General Electric S-PRISM sodium-cooled fast reactor has a thermal power output of 1000 MW(t), with an electric power output of 380 MW(e). The same size reactor vessel with the same basic type of passive decay-heat-cooling system and similar system configuration can potentially contain a 2400-MW(t) [1150-MW(e)] AHTR core. The larger power output in similar size systems, a consequence of the higher AHTR operating temperatures, indicates the potential for significantly lower costs.

The AHTR has many features in common with the MHTGR (coated-particle fuel, gas-turbine power cycle, high thermal-to-electric efficiency, and passive cooling). While the size of the MHTGR is limited by the constraints of passive decay-heat removal to about 600 MW(t), the AHTR may be scaled in sizes to in excess of 2400 MW(t) with passive cooling. Assuming a 0.7 economic scaling law, this implies a per-kilowatt-electric capital cost that is 66% that of the MHTGR. 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 57% that of the MHTGR.

The economics for H_2 production via the AHTR would be expected to be superior to other alternatives because the AHTR characteristics are designed to match requirements for H_2 production: large size, coupling to an intermediate molten-salt heat-transfer loop, and delivery of heat at appropriate temperatures.

VI. CONCLUSIONS

The AHTR is a new reactor concept. The unique characteristic of the reactor is its combination of a very-high-temperature fuel (graphite-matrix coated-particle fuel) with a low-pressure, very-high-temperature molten-salt-reactor coolant. Combining these two technologies may enable the construction of large reactors with high efficiency, passive safety decay-heat-removal systems, and beyond-design-basis-accident systems designed to prevent major fuel failure. Some of the characteristics of such large reactors have been defined. Preliminary scooping studies have been completed. *However, many uncertainties remain.* The next step is to develop a more detailed preconceptual design to (1) understand the complex technical, safety, and economic trade-offs; (2) provide a credible cost estimate for an n^{th}-of-a-kind plant; and (3) develop a detailed R&D plan that defines all of the issues that must be addressed.

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