Generation IV Roadmap Activity
Description of Generation IV Reactor and Fuel Cycle

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Category: Other
Manuscript Date: February 10, 2002

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Submitted to
DOE Generation IV Roadmap Program
U.S. Department of Energy
Washington D.C.

*Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725.

Advanced High-Temperature Reactor for Production of Electricity and Hydrogen: Molten-Salt-Coolant, Graphite-Coated-Particle-Fuel

ABSTRACT

The objective of the Advanced High-Temperature Reactor (AHTR) is to provide the very high temperatures necessary to enable low-cost (1) efficient thermochemical production of hydrogen and (2) efficient production of electricity. The proposed AHTR uses coated-particle graphite fuel similar to the fuel used in modular high-temperature gas-cooled reactors (MHTGRs), such as the General Atomics gas turbine–modular helium reactor (GT-MHR). However, unlike the MHTGRs, the AHTR uses a molten salt coolant with a pool configuration, similar to that of the PRISM liquid metal reactor. A multi-reheat helium Brayton (gas-turbine) cycle, with efficiencies >50%, is used to produce electricity. This approach (1) minimizes requirements for new technology development and (2) results in an advanced reactor concept that operates at essentially ambient pressures and at very high temperatures. The low-pressure molten-salt coolant, with its high heat capacity and natural circulation heat transfer capability, creates the potential for (1) exceptionally robust safety (including passive decay-heat removal) and (2) allows scaling to large reactor sizes [~1000 Mw(e)] with passive safety systems to provide the potential for improved economics.

INTRODUCTION

The AHTR is a new reactor concept to produce high-temperature heat (750 to 1000+°C) for efficient production of electricity and thermochemical hydrogen. The AHTR is based on four technological developments:

1. High-temperature, low-pressure molten-salt reactor coolants from the billion-dollar aircraft nuclear propulsion program of the 1950s and the molten-salt breeder reactor program of the 1960s.
2. Coated-particle graphite fuel developed in the 1970s.
3. Passive safety systems for gas-cooled and liquid-metal reactors developed in the 1980s.
4. Advanced gas turbines—including commercialization in the last five years of magnetic bearing systems that can permit these turbines to be used in closed helium cycles.

NATIONAL AND INTERNATIONAL INTEREST

ORNL and Sandia are actively investigating the AHTR. Some work has also been conducted by the Russian Federation. Japan and several U.S. NERI projects (Brown 2000) are examining methods to produce hydrogen from high-temperature heat.

CONCEPT DESCRIPTION

General Characteristics. 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 GT-MHR. The low-power-density graphite-moderated core also has the long neutron lifetime, slow kinetics, and thermal neutron spectrum characteristic of a GT-MHR. The primary molten salt loop flows 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. The molten salt can be circulated by natural or forced circulation.

The baseline molten-salt coolant is a $^7LiF/BeF_2$ salt, but there are other potential molten-fluoride salts that can be considered. 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, an 8-Mw(th) reactor, operated in the 1960s with a $^7LiF/BeF_2$ molten salt. In these reactors, the fuel was dissolved in the salt whereas the AHTR uses solid fuel.

Neutron absorptions in these salts are low (mb). Atmospheric boiling points for molten salts are near 1400°C. At operating conditions, molten-salt properties are similar to those of water. Molten salts do not react with air or carbon dioxide but will slowly react with water. Fluoride salts are compatible with graphite fuels (Grimes 1970). There is a century of industrial experience with graphite and fluoride salt compatibility—aluminum is electrolytically produced from cryolite ($3NaF\text{-}AlF_3$) in very large graphite baths at ~1000°C. Molten salts are leading candidates for cooling the first wall of fusion reactors (Sagara 2000) and are currently under active experimental study by the DOE Office of Fusion Energy Science.

The excellent heat transfer properties of molten salts, compared with those of helium, reduce the temperature drops between (1) the fuel and molten salt and (2) the molten salt and any secondary system. Comparable calculations for a typical prismatic geometry were made of the temperature drop between the centerline prismatic fuel temperatures and coolant for helium and molten-salt coolants. The temperature drops for helium and molten-salt coolants were, respectively, 415 and 280°C. The better heat transfer capabilities of molten salts (a liquid) compared with those of helium allow reactor designs with higher coolant exit temperatures and power densities than in gas-cooled systems for the same maximum temperature limit in the fuel.

Electricity and Hydrogen Production. An important characteristic of the AHTR is the ability to deliver all the heat at high temperatures (low primary-system temperature-drop with low pumping power). This enables the AHTR to more closely match the temperature requirements of advanced power cycles and hydrogen production. Liquid coolants have good heat transfer capabilities and low pumping power costs in comparison with gas coolants. As a direct consequence, liquid-cooled reactors can deliver most of their heat at near-constant temperatures while gas-cooled reactors generally deliver their heat over a wide range of temperatures due to pumping power limitations. Some examples can demonstrate these differences. The gas-cooled GT-MHR (General Atomics) has a ΔT across the reactor core of 369°C (T_{in} = 850°C, T_{out} = 491°C) while the Advanced Gas-Cooled Reactor (Hinkely Point B) has a ΔT of 355°C (T_{in} = 665°C, T_{out} = 310°C). Liquid-cooled reactors typically have much-lower core-temperature drops. The Point Beach PWR has a ΔT across the reactor core of 20°C (T_{in} = 319°C, T_{out} = 299°C) while a liquid-metal fast reactor (Super Phenix) has a ΔT of 150°C (T_{in} = 545°C, T_{out} = 395°C). The AHTR, as a liquid-cooled reactor, can deliver its heat with small temperature drops (20 to 100 °C) with low pumping power.

Electricity generation. The AHTR has a higher potential efficiency than the GT-MHR because the low primary system temperature drop allows the use of more-efficient power cycles. The current GT-MHR (General Atomics) with a direct recuperative gas-turbine cycle has an efficiency of 48% with an exit gas temperature of 850°C. The AHTR efficiency, using an indirect recuperative multi-reheat Brayton cycle for the same temperature and turbomachinery parameters, is estimated at 56%. Current materials may allow molten salt temperatures of ~750+°C. At these temperatures, it may be feasible to match the efficiency of the GT-MHR with its exit helium temperature of 850°C. At 1000°C, using the same fuel that currently limits the MHTGR to an exit helium gas temperature of 850°C, and taking advantage of the improved heat transfer properties of the molten salt (see above), the efficiency will exceed 59%.

Reheat power cycles (where all of the heat is delivered at a high temperature) have much higher efficiencies than simple power cycles (where the heat is delivered over a large range of temperatures). A modern coal-fired power plant with a typical steam temperature of 565°C has an efficiency of 40+%. The coal plant steam system is supplied almost all of its heat at nearly constant temperature (near 565°C) and uses a high-efficiency multi-reheat Rankine (steam) cycle. Metallurgical constraints limit steam temperatures, although the combustion gas temperatures are far above 565°C. In contrast a GT-MHR, with an exit temperature almost 300°C higher, has an efficiency of only 8 percentage points higher. The GT-MHR, with an exit temperature of 850°C and an inlet temperature of 491°C, delivers its heat to the turbine over a range of 369°C. The wide temperature range, with much of the heat delivered at lower temperatures, limits efficiency to 48% using the best available power cycle.

The reference AHTR design, with the molten salt delivering all of the heat at high temperatures, employs a recuperated helium Brayton cycle (Fig 1) with three stages of reheat and three stages of intercooling (El-Wakil 1971). The helium pressure is reduced through three turbines in series with reheating of the helium to its maximum temperature 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 where most of the heat from the reactor can be delivered at high temperatures. UC Berkeley calculations have shown that the multiple-reheat Brayton cycle increases the thermal efficiency of the AHTR by between 5 and 6 percent above that of the GT-MHR for the same reactor outlet temperature. 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 percent relative to that achieved with high-pressure gas reactors.

Hydrogen production. The Japanese estimates are that costs of nuclear thermochemical hydrogen production will be about 60% of that for nuclear hydrogen production by the electrolysis of water. The AHTR has unique capabilities for thermochemical hydrogen production because it delivers all of its heat at the necessary high temperature and at low pressure. The leading thermochemical processes require heat input from 750 to 850°C (Brown July 2000). The high-temperature step is a chemical decomposition reaction that requires most of the energy input at a nearly constant temperature. Large quantities of lower-temperature heat are not useful for hydrogen production. Furthermore, the high-temperature thermochemical process steps operate at low pressure. For safety reasons (i.e., concerns regarding hazardous chemicals in the hydrogen production system) and to minimize strength requirements on the heat exchangers, it is desirable to operate the heat transfer equipment at low pressures.

Safety Systems. The AHTR has the potential to provide an exceptional robust safety case because of various inherent and passive safety characteristics. Inherent safety characteristics include low core power density, high-temperature-margin fuel, and a high-heat-capacity core. Other inherent safety characteristics of the AHTR include atmospheric pressure operation and efficient liquid-coolant heat transfer. Reactor power is limited by the high-temperature Doppler effect within the fuel. The reactor physics is similar to those of the GT-MHR.

Two alternative methods for passive decay-heat removal exist. The first approach is conduction of heat through the fuel, through the reactor vessel wall, across a gap to the reactor cavity wall, and into ducts embedded in the wall where atmospheric air (moved by natural circulation) rejects the heat to the atmosphere. This approach is used in the GT-MHR (IAEA 1997) and limits the reactor power level to 600 MW(th). Replacement of the thick pressure vessel wall with a low-pressure, thinner vessel allows added heat removal capacity. Using this approach for the AHTR would allow the thermal capacity to be increased to ~800 Mw(th). This approach gives no credit to the heat transfer or heat capacity of the molten salt.

The second approach is a pool-type reactor with passive safety, similar to the General Electric S-PRISM liquid-metal-cooled reactor (Boardman 2000a, 2000b). The size of that reactor is limited by passive decay-heat cooling to ~1000 MW(th). In this pool reactor, decay heat is conducted through the reactor vessel wall, transferred across an argon gap by radiation to a guard vessel, conducted through the guard vessel, and removed from the second wall by natural circulation of air. The radiation heat transfer from the reactor vessel to the guard vessel increases by T^4; thus, a small temperature 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 loses during normal operation but allows radiation heat transfer to increase heat losses if the reactor overheats. The S-PRISM design can remove more heat than in a GT-MHR because of the liquid sodium coolant, which allows transfer of the heat by liquid natural convection from the center of the reactor core (hot-spot location) to the vessel wall. The sodium coolant also allows atmospheric pressure operation.

If the same type of passive cooling system is applied to the AHTR (Fig. 1), the size limits could potentially exceed 2000 Mw(th) because of several factors. First, the AHTR has a higher thermal capacity per unit of vessel volume than the S-PRISM, due to (1) the substantially larger temperature increase permitted for the AHTR fuel and (2) the relative volumetric heat capacity of graphite (3710 kJ/m^3-°K) and Li_2BeF_4 (4680 kJ/m^3-°K) versus sodium (1040 kJ/m^3-°K) and steel (5380 kJ/m^3-°K). The large-heat-capacity core provides added time to allow the decay-heat rate to reach a lower level the before core temperatures peak, thus reducing the capacity requirement for the decay-heat removal system per unit power output. Second, the AHTR operates 200 to 500°C hotter the S-PRISM (500 to 550°C for S-PRISM vs. 750 to 1000+°C for the AHTR). Since natural circulation of cooling air increases with temperature and heat transfer across the argon gap varies with T^4, the higher temperatures allow for more efficient removal of decay heat with heat removal rates adjusted by design of the decay-heat removal system.

The AHTR has potentially outstanding accident-mitigation capabilities. The fuel has excellent high-temperature fission product retention capabilities (same as those of the GT-MHR). Furthermore, many fission products (except noble gases) or actinides escaping the fuel are soluble in the molten salt and will tend to remain in the molten salt at very high temperatures. The chemical inertness and low pressure of the molten-salt coolant eliminates the potential for damage to the confinement structure by rapid chemical energy releases (e.g., sodium) or coolant vaporization (e.g., water).

Fuel Cycles. The fuel cycle options are essentially identical to those of the MHTGR. These include various open and closed low-enriched uranium and low-enriched uranium-thorium fuel cycles.

Economics. The overnight construction costs per MW(e) of capacity for the AHTR have the potential to be ~60% of those for a GT-MHR and significantly less than those of a LWR.

Because the AHTR is a new reactor concept, no bottoms-up cost estimate exists. However, the AHTR has many features in common with the GT-MHR (coated-particle fuel, gas-turbine power cycle, high thermal-to-electric efficiency, passive safety); thus, a relative cost estimate can be made. The AHTR can be built larger than a GT-MHR while maintaining its desirable 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. Assuming a 0.7 economic scaling law, this implies a per-kW(e) capital cost that is 70% of the GT-MHR. The higher potential power conversion efficiency (56% vs. 48%) further reduces the per-MW(e) overnight capital cost to 60% of that for GT-MHR.

The economics are potentially superior to those for large LWRs. The higher thermal efficiency reduces the size and cost of all systems that manage heat loads in the reactor (decay-heat cooling systems, power-cycle heat-rejection systems, etc.). The passive safety systems have potentially lower cost and simpler maintenance. The gas-turbine power cycles have potentially lower capital costs than the comparable stream-turbine power cycles.

EVALUATION AGAINST HIGH-LEVEL CRITERIA

In terms of sustainability goals [uranium/thorium resource consumption (SU-1), waste management (SU-2), and non-proliferation (SU-3)], the AHTR has the potential to be generally superior to LWRs and slightly superior to GT-MHRs. The AHTR uses the same types of fuels and fuel cycles as the GT-HTR; however, its somewhat higher efficiency results in slightly higher sustainability ratings. Because this is a new reactor concept, significantly greater uncertainties exist regarding potential performance.

Worker safety is expected to be similar to that experienced with a GT-MHR (SR-1). Because of the passive safety systems (SR-2), major accidents may not be credible with an AHTR. Therefore, it may be feasible to eliminate emergency evacuation zones (SR-3).

The AHTR has the potential for excellent economics for electric production because of low capital cost (potentially 60% that of a GT-MHR), based on economics of scale and higher thermal efficiencies. The AHTR likewise has the potential for economics superior to those of large LWRs. Because, as a liquid-cooled reactor, the AHTR can deliver all of its heat at very high temperatures, the AHTR has potentially unique capabilities for economic thermochemical production of hydrogen. All the heat is delivered at the needed temperatures.

STRENGTHS AND WEAKNESSES

The potential strengths of the AHTR are that it (1) may provide high temperatures and efficiency for low-cost electricity and hydrogen compared with other nuclear energy options, (2) uses a fuel, coolant, decay-heat removal systems, and power-cycle technologies that are partly or fully developed, thereby reducing R&D requirements, and (3) provides a very robust safety case. The weakness is that achieving the fuel potential for thermal efficiency implies operating at high temperatures which present important engineering challenges. For very-high electric production efficiencies and hydrogen production, new heat-exchanger materials capable of operation above 800°C are required.

RESEARCH AND DEVELOPMENT NEEDS

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 R&D needs are restricted to a relatively limited number of areas. The R&D costs are strongly dependent upon 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 are only a fraction of those for a totally new reactor concept. Four major needs for the AHTR (excluding GT-MHR R&D) have been identified.

1. Temperatures above 800°C will require improved materials of construction. Current materials may allow operation to 750+°C, but better materials are necessary to reach the full potential of the AHTR for efficient electric production and efficient thermochemical hydrogen production.
2. More refined system designs must be developed to understand the trade-offs between high-temperature performance and reliability.
3. Development work is required on high-temperature heat exchangers for both electricity and hydrogen production
4. Significant additional development work is required on the thermo-chemical hydrogen production cycle.

INSTITUTIONAL ISSUES

Strong economic incentives exist for larger plants, while some utilities have expressed a desire for smaller plant sizes. The hydrogen demand in the next several decades is primarily from oil and chemical companies—not utilities. Because these companies represent a different set of customers, a significant effort will be needed to develop the interfaces with the nuclear industry.

TIME LINE FOR DEPLOYMENT

The concept could be deployable in 15 to 20 years.

ASSESSMENT

The AHTR, using (1) passive safety systems and (2) several fully or partly developed technologies, creates the potential for very economic production of electricity. Because of its ability to deliver all of its heat at high temperatures and low pressures, the AHTR may be uniquely suited for the thermo-chemical production of hydrogen. Consequently, a serious examination of the AHTR is warranted.

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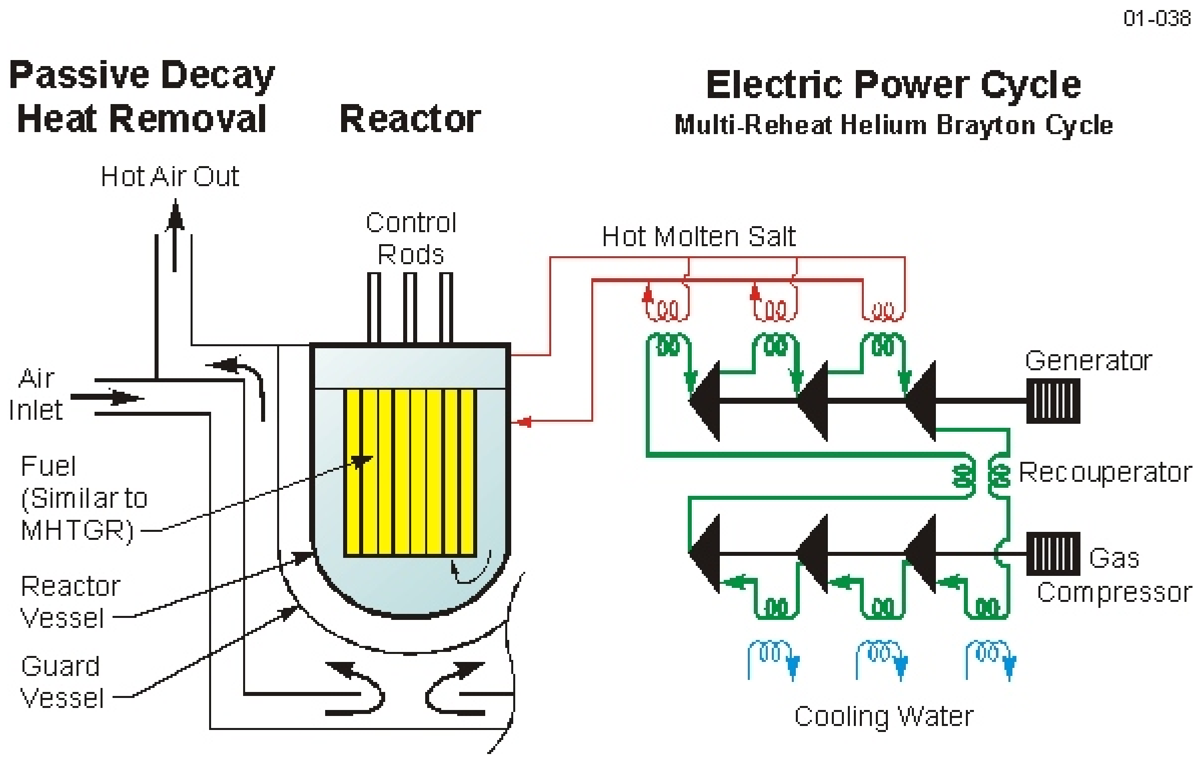

Fig. 1. Schematic of the Advanced High-Temperature Reactor.