

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

**Modular, Molten-Salt-Cooled, Graphite-Matrix-Fuel
High-Temperature Reactor for Production of Hydrogen and Electricity**

Category: Other
Draft Date: April 26, 2001

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

Modular, Molten-Salt-Cooled, Graphite-Matrix-Fuel High-Temperature Reactor for Production of Hydrogen and Electricity

ABSTRACT

The modular, molten-salt-cooled, graphite-matrix-fuel, advanced high-temperature reactor (AHTR) is designed to provide heat at the conditions (high temperatures and low pressures) necessary to create new nuclear energy options: (1) hydrogen production by thermochemical water splitting (requires 800 to 1000EC heat) and (2) advanced electric production methods (indirect gas turbine cycles and direct thermal-to-electric techniques).

The AHTR would generate up to 600 MW(t) with outlet temperatures of >1000EC. The fuel is a graphite-matrix fuel with the same general characteristics as that developed for modular high-temperature gas-cooled reactors (MHTGRs). Such fuels have been demonstrated at temperatures up to 1200EC. The AHTR fuel cycle would be similar to that for the MHTGR. The coolant would be a molten fluoride salt (2LiF-BeF₂) developed for molten-salt-fueled fission reactors and for cooling the first wall of fusion reactors. It has a boiling point of - 1400EC. Passive safety systems would be used.

INTRODUCTION

World consumption of hydrogen is growing rapidly (Chang 2000) for the production of chemicals (CH₃OH, NH₃) and refining of crude oil into transport fuels. Hydrogen is added to heavy crude oils to (1) produce lighter fuels such as gasoline and (2) remove impurities such as sulfur. As resources of high-quality light crude oils are exhausted, more hydrogen is required to produce an equivalent amount of gasoline per barrel of lower-grade crude oil. Because much of the hydrogen is produced from lower-value refinery streams, an economic outside source of hydrogen would allow the conversion of these hydrocarbons into gasoline rather than to produce hydrogen. This, in turn, would significantly increase the liquid fuel output per barrel of crude oil and reduce crude oil imports. Non-fossil hydrogen would also significantly reduce the quantities of natural gas that is used to produce hydrogen and it would reduce carbon dioxide emissions.

By 2010, it is estimated that if the industrial demand for hydrogen were met through use of nuclear energy with a 50% efficiency, a nuclear fleet equal to the existing nuclear power reactors in the United States would be required (Ogden 1999). Hydrogen has also been proposed as a future transport and distributed-power fuel. These applications would increase the hydrogen demand by one to two orders of magnitude.

Hydrogen and electricity are the only large potential markets for nuclear energy. If use of nuclear power is to expand, reactors must be designed to efficiently produce hydrogen. Many direct thermochemical methods are possible for producing hydrogen with the input of heat and water. High temperatures (800 to 1000EC) are required to ensure rapid chemical kinetics (small hydrogen plant size with low capital costs) and high conversion efficiencies. This application (IAEA 1999) demands a high-temperature, low-pressure, low-cost source of heat.

The development of such a reactor would also enable better methods to produce electricity: indirect Brayton cycles and direct thermal-to-electric conversion techniques. The technologies for efficient direct conversion of heat to electricity are further into the future.

NATIONAL AND INTERNATIONAL INTEREST

Inside the United States, Oak Ridge National Laboratory (ORNL) and Sandia are actively investigating the AHTR. Some work has also been conducted by the Russian Federation. Several NERI projects (Brown 2000) are examining methods to produce hydrogen from high-temperature heat. Japan (Miyamoto 1998) has a major effort to develop thermochemical hydrogen cycles.

CONCEPT DESCRIPTION

General Characteristics. The reactor core consists of graphite-matrix fuel cooled with a molten salt (Fig. 1). The graphite produces a thermal neutron spectrum within the reactor core. The hot molten salt (>1000EC) exits the reactor core, flows to an external heat exchanger, dumps the heat load, and returns to the reactor core. The molten salt is circulated by natural or forced circulation. The high-temperature heat can be used for (1) thermochemical production of hydrogen or (2) production of electricity using either direct or indirect (Brayton cycle) methods.

The highest-temperature fuels that have been developed for power reactors are those for helium-cooled graphite-fuel reactors. These fuels (JAERI 1994, Yan 2000) make possible fuel (not coolant) operating temperatures exceeding 1200EC. The same basic coated-particle fuel would be used for the AHTR.

There are several candidate salts. The baseline salt is $2\text{LiF}\cdot\text{BeF}_2$, the same molten salt (without uranium and thorium) that was used in the molten salt reactor (MSR). This particular salt has excellent nuclear and coolant properties with very low parasitic neutron capture (ORNL 1965, Grimes 1967, Grimes 1970, Cook 1968). Isotopically separated ^7Li is used to minimize tritium production. Except for tritium, no significant activation occurs, and thus no significant neutron or gamma radiation is emitted from the coolant. The vapor pressure is very low (- 1 atmosphere at 1400EC) and the properties improve as the temperature increases. For comparison, sodium as a coolant boils at 883EC. At operating temperatures, the properties of molten salt are similar to those of water. The salt does not react with air or carbon dioxide but will slowly react with water.

Fluoride salts are compatible with graphite fuels (Grimes 1967, Grimes 1970, McCoy 1970). The MSR used unclad graphite to moderate neutrons in the reactor core. This coolant salt (called “FLIBE” in the fusion energy community) is a leading candidate for cooling the first wall of fusion reactors (Sagara 2000). A century of industrial experience has shown that various fluoride salts are compatible with graphite. The best-known example is the production of aluminum in an electrolytic cell. Bauxite is dissolved in cryolite ($3\text{NaF}\cdot\text{AlF}_3$), a fluoride salt, and then electrolyzed to aluminum metal at temperatures near 1000EC. Cell components are made of graphite.

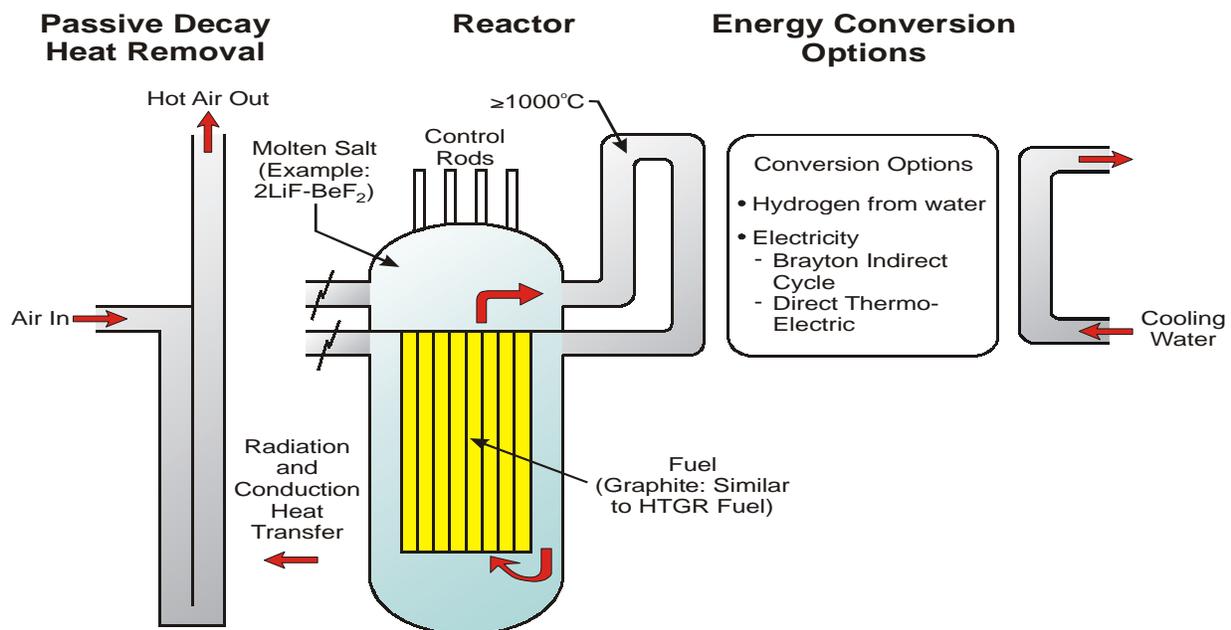


Fig. 1. Schematic of advanced high-temperature reactor.

The unique combination of the graphite fuel form and the molten salt coolant makes possible the very high temperatures. The low-pressure coolant reduces the need for high-temperature, *high-strength* materials in the external heat exchangers, compared with those required in reactors that use high-pressure helium or other high-pressure fluids to transfer heat. The maximum salt outlet temperature can be several hundred degrees higher than that for a gas-cooled reactor with the same graphite fuel and same peak fuel-temperature limits. This is a consequence of improved heat transfer and thus lower temperature drops between (1) fuel and coolant and (2) coolant and secondary systems for the liquid salt (compared with that for helium gas).

The transfer of heat from the primary to secondary system will depend upon the desired application. A secondary heat-transfer loop would be used if the reactor were coupled to an indirect Brayton cycle. The heat-transfer loop isolates the low-pressure primary system from the high-pressure Brayton cycle.

For hydrogen production, a secondary heat-transfer loop or a direct radiation heat transfer may be used. Direct radiation heat transfer involves tubes with molten salt radiating infrared to visible light to tubes containing chemical reagents used for thermochemical hydrogen production. This process becomes viable at high temperatures because radiation heat transfer increases as the fourth power of the absolute temperature. The tubes in any one sheet may be connected via welded metal plates to increase the radiative heat-transfer surface and improve radiation coupling. Such sheets of tubes would be almost identical in design to the boiler-tube curtain walls used in fossil boilers and chemical plants. This method would provide isolation between the molten salt and the highly corrosive chemicals in thermochemical production systems.

Safety Systems. Reactor power is limited by the high-temperature Doppler effect within the fuel. Because the molten salt expands upon heating, an additional negative moderator temperature coefficient is associated with coolant expansion. The reactor physics are similar to those of the MHTGR.

In an accident, the decay heat would be conducted directly from the reactor core, through the steel pressure vessel, and then to the environment via cooling ducts near the reactor vessel. This is identical to the emergency decay-heat-removal system in an MHTGR. In the case of a helium-cooled reactor in an accident, depressurization of the reactor is assumed. This would minimize heat transfer by convective gas currents. For the AHTR, it would be assumed that the molten salt has leaked from the reactor system. In each case, the heat-transfer conditions of the reactor core are essentially identical. For both the AHTR and the MHTGR, this method of passive emergency decay-heat removal limits the total reactor power level to ~ 600 MW(t).

The liquid coolant lowers the potential for radionuclide release by several mechanisms.

- *Low pressure.* In most reactors, a major mode of radionuclide transport in an accident from the reactor core to the environment is entrainment in high-pressure gases leaving the system. With the AHTR, there is no pressured fluid or gas to transport radionuclides to the open environment. This eliminates the primary driving force for radionuclide releases, reduces the forces that can destroy the containment or confinement system, and simplifies isolation of the reactor from the environment.
- *Natural circulation.* The large heat capacity and density allow natural circulation of the coolant to provide decay-heat cooling.

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

EVALUATION AGAINST HIGH-LEVEL CRITERIA

In most cases, the AHTR has characteristics similar to those of the MHTGR. The uranium and thorium consumption will be less than that for an LWR (SU-1) because of the higher neutron efficiency. The graphite fuel block is better than LWR fuel in terms of repository performance and thus reduces the burdens of long-term

stewardship (SU-2). The proliferation resistance (SU-3) is superior to that of an LWR because (1) there is less plutonium in the SNF per unit of energy produced and (2) the plutonium isotopics are less favorable than those of an LWR (i.e., less ^{239}Pu).

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

The AHTR has the potential for good economics (EC-1 and EC-2). Hydrogen production by electrolysis is relatively efficient (~80%). However, when it is combined with the electrical conversion efficiency (ranging from ~34% in current LWRs to 50% for advanced systems), the overall efficiency would be in the range of 25 to 40%. For thermochemical approaches, an overall efficiency of >50% has been projected (Brown 2000).

STRENGTHS AND WEAKNESSES

The strengths of the AHTR are that (1) it directly addresses the requirements for hydrogen production and high-temperature processes to produce electricity and (2) uses existing fuel and coolant technology to reduce the research and development (R&D) requirements. The weakness is that meeting the requirements implies operating at very high temperatures that present serious engineering challenges.

R&D NEEDS

Because the fuel and salt coolant have been developed as part of other reactor concepts, the R&D needs are restricted to a relatively limited number of areas. Four major needs have been identified.

- *Materials.* Improved materials of construction may be required for the primary heat exchangers. Available materials have either high costs or other constraints. Several candidate materials of construction (oxide-dispersion-strengthened alloys such as MA956[®] and PM-2000[®] and modified molybdenum alloys) offer potentially higher performance or lower costs. Some of these materials may allow operations at temperatures as high as 1100°C provided the stresses (pressures) are limited. Most of these materials are currently being developed for other applications.
- *System design.* There are complex trade-offs in system design that are not well understood.
- *Heat exchangers.* The engineering practicality of using radiation heat transfer on a large scale between the reactor and the chemical plant needs to be established. This option, if viable, allows for major simplifications in design and fundamental gains in safety when reactors and chemical plants are connected. For the indirect Brayton cycle, the potential efficiency of high-temperature heat exchangers must be determined.
- *Hydrogen production.* Significant additional development work is required on the thermochemical hydrogen production cycle.

INSTITUTIONAL ISSUES

The demand in the next several decades for hydrogen is primarily from oil and chemical companies—not traditional 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 should be deployable in about 15 to 20 years.

ASSESSMENT

Hydrogen production is the other major market for nuclear energy. The current hydrogen demand, which is large and growing rapidly, may ultimately approach the size of the market for electricity. Production of hydrogen from nuclear energy requires reactors to be built to meet the specific demands of thermochemical water splitting. The same technology opens up advanced thermal-to-electric conversion systems. Because of the potential, a serious examination of the AHTR is warranted.

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