ABSTRACT

Advanced-High-Temperature-Reactor Spent-Fuel Characteristics and Repository Impacts

Charles W. Forsberg
Oak Ridge National Laboratory*
P.O. Box 2008; Oak Ridge, Tennessee 37831-6165
Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

File Name: HLW05.Abstract
Manuscript Date: October 14, 2006
Abstract Limits: 1500 Words Max (Actual: 1499); 3 Figures/Tables (Actual 3)

Author Notification: December 1, 2005
Draft Paper: January 12, 2006
Author Notification: February 23, 2006
Final Paper Submittal: March 17, 2005

Abstract Prepared for
Session: 7.5 Advanced Fuels and Their Impacts on Disposal
2006 International High-Level Radioactive Waste Management Conference
American Nuclear Society
Las Vegas, Nevada
April 30−May 4, 2006

---

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

ABSTRACT

Advanced-High-Temperature-Reactor
Spent-Fuel Characteristics and Repository Impacts

Introduction

The Advanced High-Temperature Reactor (AHTR) is a large [>2400 MW(t)] liquid-salt-cooled high-temperature reactor with the same safety goals and requirements as modular high-temperature gas-cooled reactors (MHTGRs) with helium cooling and power outputs of ~600 MW(t). Within the U.S. Department of Energy Generation IV Program, the AHTR is being developed as an alternative-coolant very high temperature reactor (VHTR). The VHTR is the high-temperature variant of the MHTGR. The AHTR uses the same type of graphite-matrix coated-particle fuel as MHTGRs; however, the spent nuclear fuel (SNF) burnup is estimated to be 50% higher and the SNF volumes per kilowatt (electric) are projected to be 30 to 50% less. The basis for these different SNF characteristics and the reprocessing or repository implications are described.

Reactor Description

The AHTR [1,2] uses coated-particle, graphite-matrix fuels and a liquid fluoride-salt coolant. The requirements are the same as those for MHTGRs—including the use of passive safety systems that are activated by natural phenomena to provide very high levels of safety. The AHTR is a large reactor [2400 to 3600 MW(t)], whereas the various MHTGRs that are under development are relatively small, with sizes ≤~600 MW(t). Significant work is under way because the capital costs per kilowatt (electric) of the AHTR are estimated to be 50 to 60% of those for the MHTGR, primarily because of economics of scale [2]. As a new reactor concept, the AHTR is in an earlier state of development than the various MHTGR concepts.

The AHTR fuel is the same type that is used in MHTGRs, with fuel-failure temperatures in excess of 1600°C. The optically transparent liquid-salt coolant is a mixture of fluoride salts with freezing points near 400°C and atmospheric boiling points of ~1400°C. The reactor operates at near-atmospheric pressure. At operating conditions, the salt heat-transfer properties are similar to those of water. Heat is transferred from the reactor core by the primary liquid-salt coolant to an intermediate heat-transfer loop. The intermediate heat-transfer loop uses a secondary liquid-salt coolant to move the heat to a thermochemical H_2 production facility to produce H_2 or to a turbine hall to produce electricity. The baseline AHTR facility layout that was developed is similar to that of the S-PRISM sodium-cooled fast reactor designed by General Electric. Both reactors operate at low pressure and high temperature; thus, they have similar design constraints. The 9.2-m-diam vessel is the same size as that used by the S-PRISM.

Several alternative 2400-MW(t) designs are being investigated with peak coolant temperatures between 700 and 1000ºC and corresponding electrical outputs between 1151 and 1357 MW(e).

Higher-Burnup SNF

The AHTR and MHTGRs use the same type of fuel: graphite-matrix coated-particle prismatic fuel. The AHTR fuel burnup is ~50% higher than that of MHTGRs, and thus the SNF volumes are reduced by one-third relative to modular gas-cooled reactors. The AHTR is a large reactor [2400 MW(t)] relative to MHTGRs [600 MW(t)]. The AHTR core is a large right cylinder made of columns of prismatic fuel blocks, whereas MHTGRs have smaller annular reactor cores to assist decay heat removal. Figure 1 shows the layout of prismatic fuel blocks for both core types. The small annular core of the MHTGR implies high neutron leakage (3.5 to 6%) both inward toward a center graphite cylinder and outward toward the reactor vessel. The MHTGR cores are neutronically thin reactor cores. In contrast, the small surface to volume ratio of the large AHTR core implies relatively small neutron leakage (1 to 2%). For nuclear criticality to be maintained, the MHTGR average enrichment of the core must be higher than in an AHTR. If the two reactors have similar initial fuel enrichments, the AHTR can have a lower end-of-life SNF enrichment and a corresponding higher SNF burnup. Table 1 shows relative SNF burnups for the two reactors [3, 4] with similar initial fuel enrichments.

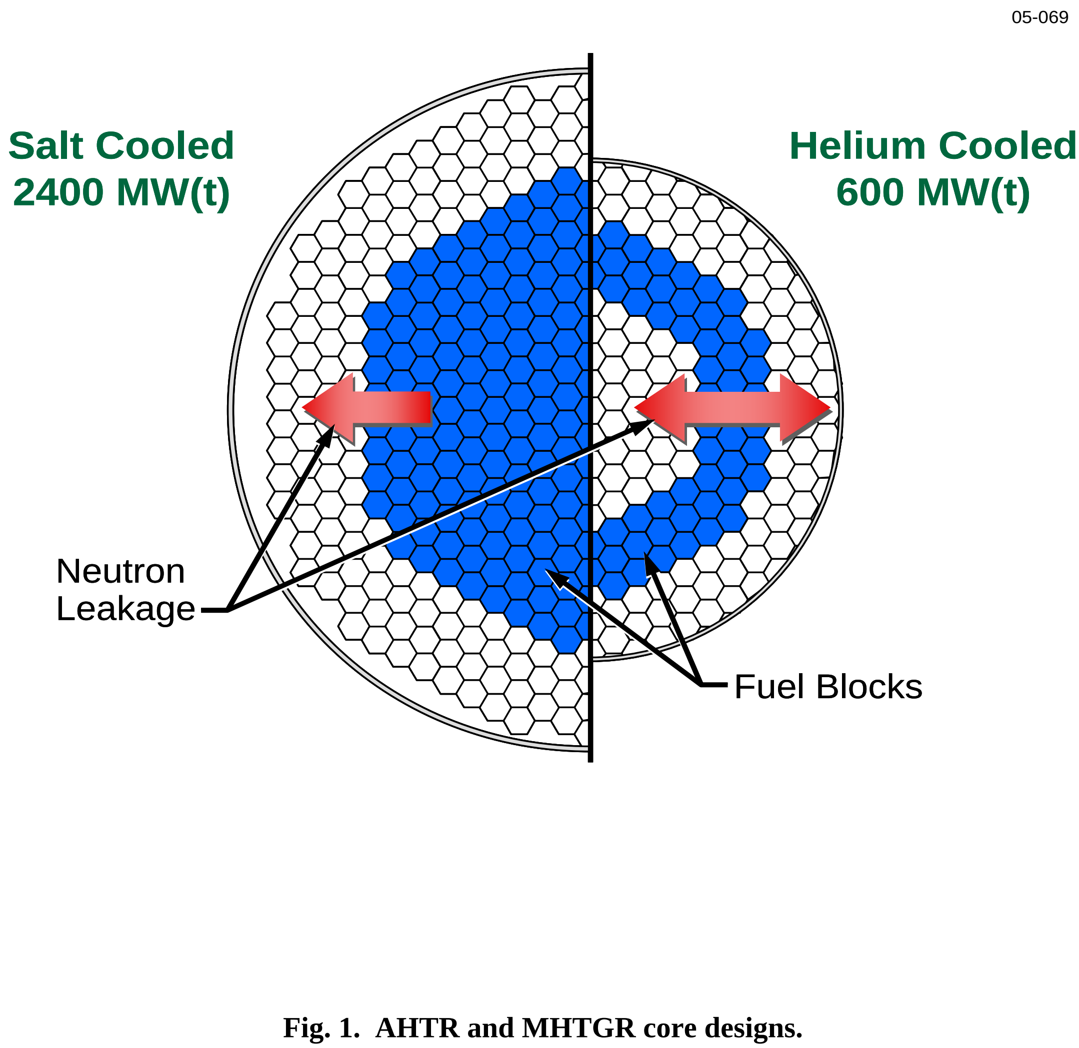

Fig. 1. AHTR and MHTGR core designs.

Table 1. Relative core and fuel cycle parameters for the MHTGR and AHTR with two batch refueling

Parameter	MHTGR	AHTR
Power, MW(t)	600	2400
Total number of fuel columns	102	265
Power density, MW/m^3	6.6	10.2
Specific power density, MW/t	103	158
^{235}U enrichment, %	14.0	15.3
Burnup, GWd/t	100	156

The different reactor core designs are a consequence of the choice of coolants and the common requirement that these advanced reactors have passive decay-heat-removal systems—systems that do not depend upon human actions or active components to ensure removal of decay heat and thus assure fuel temperature limits are not exceeded. During an accident, the decay heat systems prevent excessive temperatures in the reactor core that could damage fuel. For both the gas-cooled and liquid-salt-cooled reactors, decay heat must be removed from the reactor core to the reactor vessel surface, where passive systems dump the heat to the atmosphere. Different types of systems are used (Fig. 2).

- *Helium cooled*. Under accident conditions, decay heat is removed by conduction of heat from the fuel in the reactor core to the reactor vessel. In accidents involving depressurization of the reactor, natural circulation of helium does not transfer significant heat from the reactor core to the vessel. For a maximum allowable fuel temperature before fuel failure, heat can be conducted through a defined thickness of fuel blocks to the reactor vessel without failure of the hottest fuel because of excessive temperature. The thickness of the fuel zone is limited by decay-heat-removal requirements. To build larger reactors, an annual core is used with no fuel in the middle—the fuel thickness is limiting. While the annular zone can be made larger, the maximum size is limited by the size of practical pressure vessels. This restriction results in a power output of ~600 MW(t), with the core shown in Fig. 2.

- *Liquid salt cooled*. Natural circulation of liquid salts can efficiently move heat from anywhere in the reactor core to the reactor vessel. Reactor size is limited by the ability to move heat from the vessel, not the ability to move heat from the fuel to the vessel wall. Large reactors can be built with passive safety, large reactor cores, and more efficient burning of nuclear fuel.

Higher Efficiency

For the same peak reactor coolant temperatures, the AHTR will have higher plant efficiency [5] relative to the MHTGR, which results in greater electricity production per unit of SNF that is produced. This is a direct consequence of using a liquid coolant rather than a gas coolant.

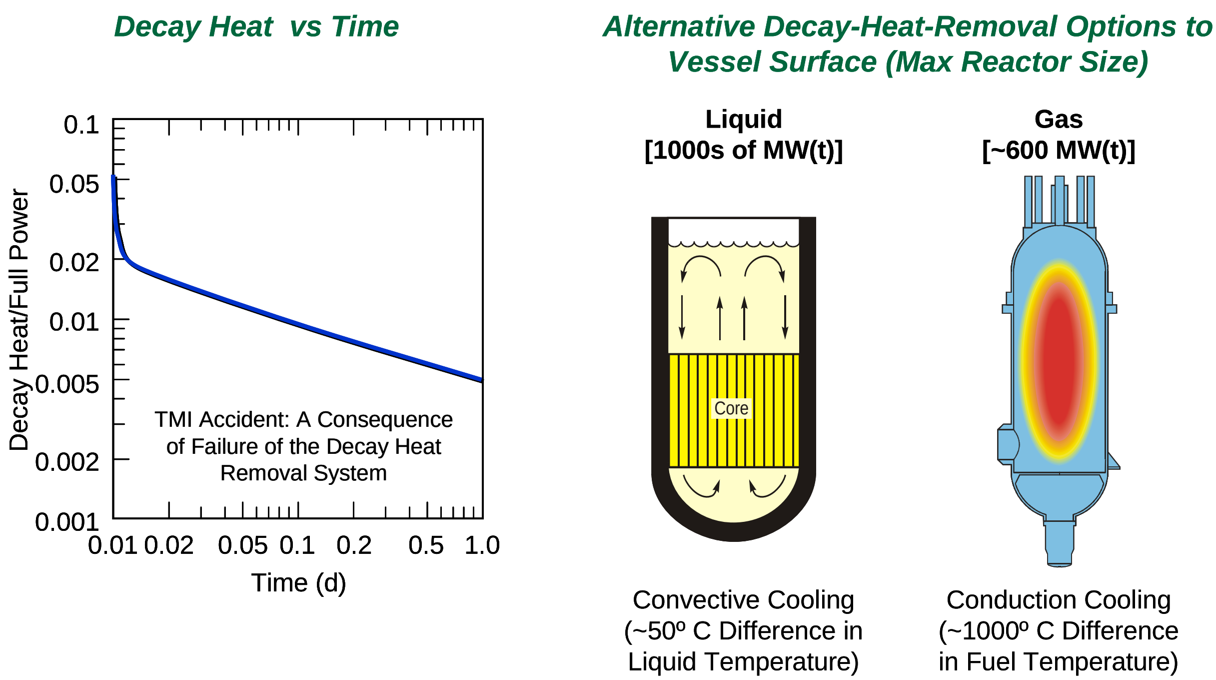

Fig. 2. Passive decay heat cooling systems for the MHTGR and the AHTR.

Gas-cooled reactor systems have high pumping costs relative to those for liquid-cooled systems. Because gas cooling has high pressure losses, practical designs of gas-cooled reactors (such as the General Atomics helium-cooled gas-turbine modular helium reactor and the British carbon-dioxide-cooled Advanced Gas Reactor) have large temperature increases across the reactor core and deliver their heat to the power cycle over a large temperature range. Typical temperature increases across the core are 350°C. In contrast, liquid-cooled reactors such as the French sodium-cooled Super-Phoenix liquid-metal fast breeder reactor and light-water reactors have low pumping costs and are designed to deliver their heat from the reactor core to the power cycle over a small temperature range, typically 100°C or less. The same is true of the liquid-salt-cooled AHTR.

The ideal efficiency of converting heat to electricity is governed by the Carnot cycle, which defines the maximum possible efficiency of any heat engine. The efficiency is defined as

$$\text{Efficiency} = (T_{in} - T_{out})/T_{out},$$

Where T_{in} is the absolute temperature of heat delivered to the power cycle and T_{out} is the absolute temperature of rejected heat to the environment. If heat is delivered over a range of temperatures to the power cycle, the efficiency varies, with higher efficiency associated with high-temperature heat delivered to the power cycle and lower efficiency associated with the low-temperature heat delivered to the power cycle. Unlike gas-cooled reactors, which deliver heat to their power cycles over a 350ºC range, the AHTR delivers most of its heat at a nearly constant high temperature to the power cycle; it therefore has a higher efficiency in converting heat to electricity for any given peak temperature and thus produces less SNF per unit of electricity.

Conclusions

The AHTR is a new high-temperature reactor (with associated uncertainties) that uses the same basic fuel type as MHTGRs. The projected SNF volumes per unit of electricity are expected to be 30 to 50% less than for MHTGRs because (1) the AHTR is a large reactor with a large reactor core that can more efficiently burn fuel and (2) higher plant efficiency is achieved via the use of a liquid coolant. If the fuel is reprocessed, the higher fuel burnup reduces reprocessing costs. If the SNF is directly disposed of, the number of waste packages and the amount of repository space are reduced. The final SNF enrichment is significantly less (higher burnup for equivalent enrichments), thus reducing long-term repository nuclear criticality concerns. Fuel cycle costs will also be reduced by an equivalent amount. There will also be changes in the radionuclide content of the SNF that, in turn, has other repository and reprocessing implications.

References

1. Forsberg, C. W., P. S. Pickard, and P. F. Peterson, 2003, "Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity," *Nucl. Technol,* **144**, 289–302.

2. Forsberg, C. W., P. F. Peterson, and D. F. Williams, 2005, "Liquid-Salt Cooling for Advanced High-Temperature Reactors," *Paper 5401, 2005 International Conference on Advanced Power Plants (ICAPP'05), Seoul, Korea, May 15–19, 2005*, American Nuclear Society, La Grange Park, Illinois.

3. Ingersoll, D. T., K. T. Clarno, C. W. Forsberg, J. C. Gehin, R. W. Christensen, C. B. Davis, G. L. Hawkes, J. W. Sterbentz, T. K. Kim, T. A. Taiwo, and W. S. Yang, September 2005, *Status of Physics and Safety Analyses for the Liquid-Salt-Cooled Very High-Temperature Reactor (LS-VHTR),* ORNL/TM-2005/218, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

4. McDonald, P., et al., September 2003, *NGNP Point Design—Results of the Initial Neutronics and Thermo-Hydraulic Assessments During FY-03*, INEEL/EXT-03-00870, Rev. 1. Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.

5. Forsberg, C. W., P. F. Peterson, and L. Ott, October 2004, "The Advanced High-Temperature Reactor (AHTR) for Producing Hydrogen to Manufacture Liquid Fuels," *2004 Americas Nuclear Energy Symposium*, American Nuclear Society, Miami Beach, Florida.