Future Directions: Toward Higher-Temperature Reactors

Charles W. Forsberg
Oak Ridge National Laboratory*
P.O. Box 2008, Oak Ridge, TN 37831-6165
Tel: (865) 574-6783; Fax: (865) 574-0382
E-mail: **forsbergcw@ornl.gov**

File Name: ARWIF05
Manuscript Date: March 14, 2005

Workshop on Advanced Reactors with Innovative Fuels
Nuclear Energy Agency Nuclear Science Committee
Oak Ridge, Tennessee 37831
February 16–18, 2005

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

FUTURE DIRECTIONS: TOWARD HIGHER-TEMPERATURE REACTORS

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

INTRODUCTION

In the last decade, three changes have created incentives for the development of high-temperature reactors: high-temperature Brayton cycles, a need for power plants with dry cooling, and a need for hydrogen produced using nuclear energy. The changing technologies and goals have resulted in a renewed interest in high-temperature reactors. The incentives for high-temperature reactors and the options are discussed herein.

WHY HIGHER-TEMPERATURE REACTORS?

Brayton Power Cycles

For almost a century, the practical technology for converting heat to electricity has been the steam turbine. The last decade has seen the successful deployment of large, efficient, low-cost, high-temperature Brayton power systems—typically using natural gas as a fuel. This has potentially radical implications for nuclear energy. Many high-temperature reactors have been developed; however, the economics have been unfavorable. A primary reason is the steam turbine, which has been limited to a practical peak temperature of ~550ºC. Little economic incentive exists to produce high-temperature heat if the heat cannot be efficiently converted to electricity. The development of higher-temperature open (air) Brayton cycles has created the technology for closed Brayton cycles[1] using nitrogen or helium (with or without bottoming steam cycles) to efficiently convert high-temperature heat to electricity. There is now an incentive to develop higher-temperature reactors to match the new capabilities to convert heat to electricity.

Dry Cooling

Water[2,3] is a primary sustainability issue. In the United States, the largest uses for water are irrigation and cooling water for power plants, with each application using a similar amount of water. Water requirements often dictate power plant siting; thus, only a small fraction of the land area in the United States is considered suitable for siting power plants. The energy–water nexus is a primary sustainability issue that must be addressed for next-generation nuclear power plants.

The challenge of heat rejection using dry cooling is economics. While fossil Rankine steam power plants [totaling 30,000 MW(e)] have been built with dry cooling where water was not available, the costs have been high. These penalties can be drastically reduced with higher-temperature Brayton-cycle nuclear power plants by several different mechanisms.

- *Less heat rejection*. Current light-water reactors (LWRs) have operating temperatures of ~270°C, with an efficiency of ~33%. High-temperature liquid-cooled reactors (see below) that use multireheat Brayton power cycles are significantly more efficient. For peak coolant temperatures of 705, 800, and 1000ºC, the respective plant efficiencies are 48, 51.5, and 56.6%. While the LWR rejects 2 kW(t) of heat per kW(e), the three higher-temperature reactor options reject, respectively, 1.08, 0.94, and 0.77 kW(t) per kW(e). The higher efficiency reduces the capacity requirements of the heat rejection system by about a factor of 2 relative to the LWR.

- *Reduced penalty for higher heat rejection temperatures*. The capital costs of dry cooling systems can be reduced by rejecting heat at a higher temperature but with the penalty of lower plant efficiency. That penalty becomes smaller as the peak temperature of the power cycle increases. For a multireheat Brayton cycle with heat delivered from the reactor by a liquid coolant and a minimum helium temperature of 35°C, the *losses in efficiency* for a 10ºC rise in the compressor inlet temperature were calculated to be 1.5, 1.3, and 1.1%, respectively, for peak coolant temperatures of 705, 800, and 1000ºC.

- *Heat rejection over a temperature range.* Dry cooling involves heating air (i.e., raising the temperature). If the heat from the power cycle is rejected over a temperature range rather than at a single temperature, the appropriate design of countercurrent dry-cooling-tower heat exchangers results in a constant temperature drop across the heat exchangers from the power cycle to the air, which minimizes heat exchanger size. Brayton cycles have this characteristic, whereas Rankine (steam) cycles reject heat at a constant temperature. This Rankine-cycle characteristic is consistent with evaporative cooling, in which water is vaporized at a nearly constant temperature. In the Brayton cycles described herein, the heat is rejected over a 50ºC range, with the helium being cooled from ~85 to 35°C.

Hydrogen Production

The world demand for hydrogen is rapidly increasing. This reflects the decreasing availability of light crude oils and the increased use of heavy crude oils and tar sands for production of liquid fuels. However, converting these heavier feedstocks into liquid fuels requires massive quantities of hydrogen. At the same time, there is a longer-term interest in going to a hydrogen economy where transport energy demands are met with hydrogen. The confluence of these events implies both a growing near-term and a longer-term demand for hydrogen and strong interest in producing hydrogen using nuclear energy.

The leading technologies for the low-cost production of hydrogen using nuclear energy are high-temperature thermochemical cycles,[4] in which, through a series of chemical reactions, high-temperature heat and water yield hydrogen and oxygen. The primary technical challenge is that heat must be provided, depending upon the process, at temperatures between 700 and 850°C. There is now a defined market need to produce high-temperature heat for this market and a need to develop high-temperature reactors.

REACTOR CATEGORIES

There are several categories of high-temperature reactors. Nuclear reactor types can be classified by power output and the peak temperatures of their coolants (Fig. 1). LWRs, such as the General Electric Economic Simplified Boiling Water Reactor (ESBWR), are low-temperature, high-pressure reactors. Traditional fast reactors cooled with liquid sodium operate at medium temperatures and low pressures. Two options exist for high-temperature reactor coolants: (1) high-pressure gases and (2) low-pressure liquids with boiling points above the peak operating temperatures.

Helium is the traditional high-temperature, high-pressure gas coolant and is generally proposed for modular reactors with relatively small output [<300 MW(e)]. Gas cooling is a viable option for small reactors but is difficult to use in large reactors because the low volumetric heat capacity (ρC_p) results in large equipment sizes (pipes, valves, heat exchangers), as shown in Table 1.

Liquid fluoride salts with low nuclear cross sections are the traditional high-temperature, low-pressure liquid coolant. Such salts were originally developed in the 1950s and 1960s for the Aircraft Nuclear Propulsion Program and the Molten Salt Breeder Reactor Program. These programs operated various salt test loops for several hundred thousand hours.

Liquid salts are intrinsically high-temperature coolants because their freezing points are between 350 and 500°C. Except for the special missions of aircraft propulsion and breeding, there was little incentive to develop reactors with these coolants when only steam cycles were available to convert heat to electricity. Special steam cycles are required to avoid freezing of the salt, particularly during startup and transients. In contrast, these systems naturally couple to higher-temperature Brayton power cycles. Four salt-cooled reactor options are being investigated.

- *Advanced High-Temperature Reactor (AHTR).* The AHTR (Fig. 2) combines four existing technologies in a new way:[5] (1) coated-particle graphite-matrix nuclear fuels (traditionally used for helium-cooled reactors and compatible with liquid fluoride salts), (2) Brayton power cycles, (3) passive safety systems and plant designs from liquid-metal-cooled fast reactors, and (4) clean low-pressure liquid-salt coolants. The heat from the reactor core is carried by the clean salt to an intermediate heat exchanger. The intermediate heat transport loop then transfers the heat to a Brayton power cycle. Because the AHTR integrates existing technologies, it is the near-term option for salt-cooled reactors. Liquid salts are compatible with graphite-matrix fuels. Existing code-qualified metals for heat exchangers and other components exist for coolant temperatures up to 750°C. Multiple metal candidate materials have been identified but not fully tested for coolant temperatures as high as 850°C. Major development efforts would be required to develop and qualify metals to 1000°C.

- *Liquid-salt-cooled fast reactor (LSFR).* LSFRs combine the AHTR plant design (Fig. 2) with traditional metal-clad-fuel fast-reactor cores. Only limited exploratory work has been conducted on these reactors.[6,7] The primary technical challenge is thought to be the development of high-temperature clad materials for the reactor fuel. Graphite fuels, such as those proposed for the AHTR, cannot be used in a fast reactor.

- *Molten salt reactor (MSR).* The MSR is a liquid-fuel reactor in which uranium, fission products, and actinides are dissolved in a liquid fluoride salt. The fuel salt flows through a graphite reactor core, which acts as a moderator, and then to an intermediate heat exchanger. This reactor concept was partially developed in the 1970s, and two test reactors were successfully built and operated.[8]

- *Fusion reactors.* Clean liquid salts are major candidates for cooling inertial and magnetic fusion energy systems.[9]

The low-pressure, high-temperature salt coolant is an enabling technology for large high-temperature reactors with passive safety systems for decay heat removal (Fig. 2). The materials challenges for MSRs with the fuel dissolved in the coolant are greater than those for clean-salt applications.

CONCLUSIONS

The development of high-temperature Brayton power systems, the growing incentives for dry cooling, and the growing need for hydrogen have created strong incentives to develop high-temperature reactors. There are two major coolant options: helium and liquid-fluoride salts. Because of the characteristics of helium as a coolant, helium high-temperature reactors are usually smaller modular reactors. Liquid fluoride salts may be the preferred coolants for large high-temperature reactors. The near-term liquid-salt reactor option is the AHTR. Three longer-range options provide long-term fuel sustainability (breeding) and actinide-burning capabilities: LSFRs, MSRs, and fusion reactors.

REFERENCES

1. P. F. Peterson, “Multiple-Reheat Brayton Cycles for Nuclear Power Conversion with Molten Coolants,” *Nucl. Technol.,* **144**, 279–288 (2003).

2. C. W. Forsberg, P. F. Peterson, and H. Zhao, “Sustainability and Economics of the Advanced High-Temperature Reactor,” *J. Energy Eng.* (in press).

3. California Energy Commission, *Comparison of Alternative Cooling Technologies for California Power Plants: Economics, Environmental, and Other Tradeoffs*, PIER/EPRI Technical Report 500-02-079F, EPRI, Palo Alto, California, and California Energy Commission, Sacramento, California (2003).

4. Nuclear Energy Agency, *Proc. OECD/NEA Second Information Exchange Meeting on Nuclear Production of Hydrogen*, Paris, France (2003).

5. C. W. Forsberg, “The Advanced High-Temperature Reactor: High-Temperature Fuel, Liquid-Salt Coolant, and Liquid-Metal Plant,” *1st Int. Conf. on Innovative Nuclear Energy Systems for Sustainable Development of the World (COE INES-1)*, Tokyo Institute of Technology, Tokyo, Japan (October 31-Nove,ber 4, 2004), in press: *Progress in Nuclear Energy*.

6. S. G. Hong and E. Greenspan, "Molten-Salt-Cooled Encapsulated Nuclear Heat Source (ENHS)-Like Reactors," *1st Int. Conf. on Innovative Nuclear Energy Systems for Sustainable Development of the World (COE INES-1)*, Tokyo Institute of Technology, Tokyo, Japan (October 31-November 4, 2004), in press: *Progress in Nuclear Energy*.

7. C. W. Forsberg, P. F. Peterson, and D. F. Williams, "Practical Aspects of Liquid-Salt-Cooled Fast-Neutron Reactors," *2005 Int. Conf. on Advances in Nuclear Power Plants, American Nuclear Society,* Seoul, Korea (May 15-19, 2005)

8. *Nuclear Applications and Technology (*now *Nuclear Technology)*, **8**(2) (entire issue) (1970).

9. R. W. Moir et al., "HYLIFE-II: A Molten-Salt Inertial Fusion Energy Power Plant Design—Final Report," *Fusion Energy*, **25**, 5–25 (1994).

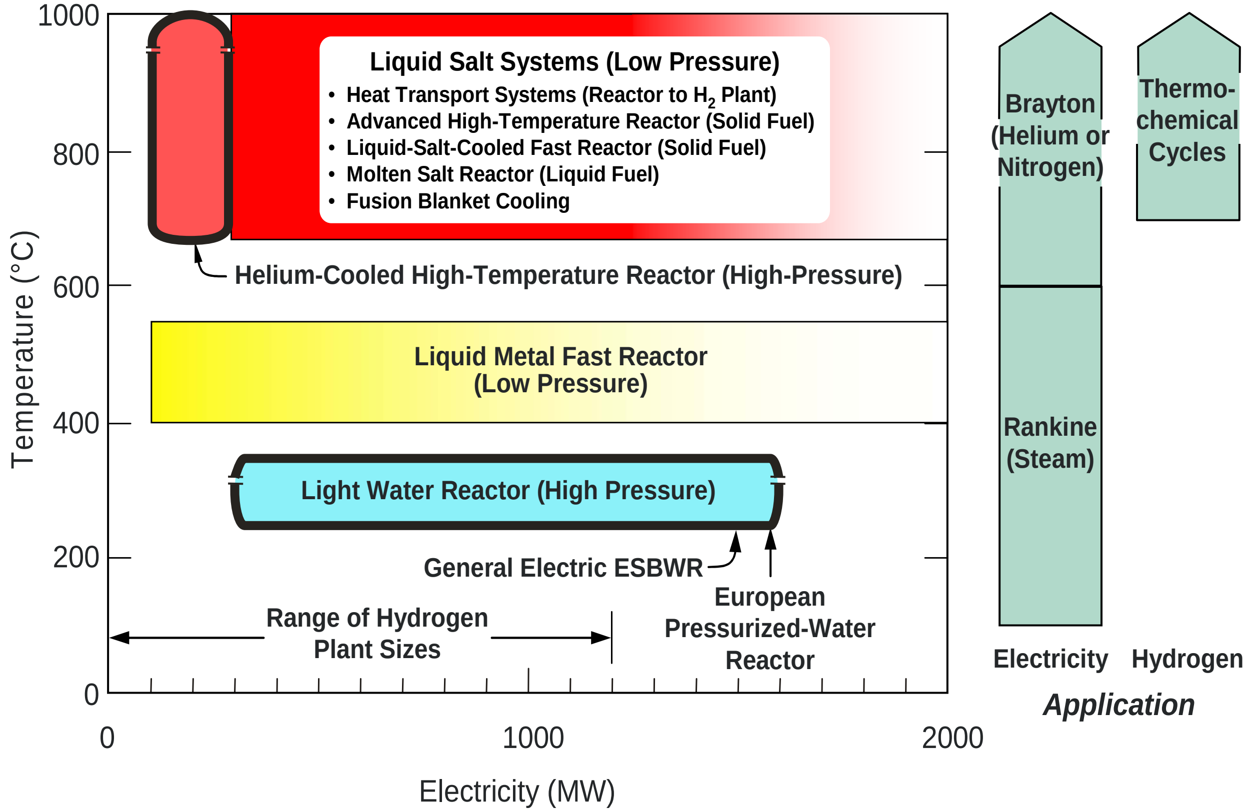

Fig. 1. Reactor type vs temperature and power output.

Table 1. Characteristics of reactor coolants[a]

Coolant	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	C_p (kJ/kg °C)	ρC_p (kJ/m^3 °C)	K (W/m °C)	$v \cdot 10^6$ (m^2/s)
Li_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

[a]ρ is density; C_p is specific heat; k is thermal conductivity; v is viscosity.

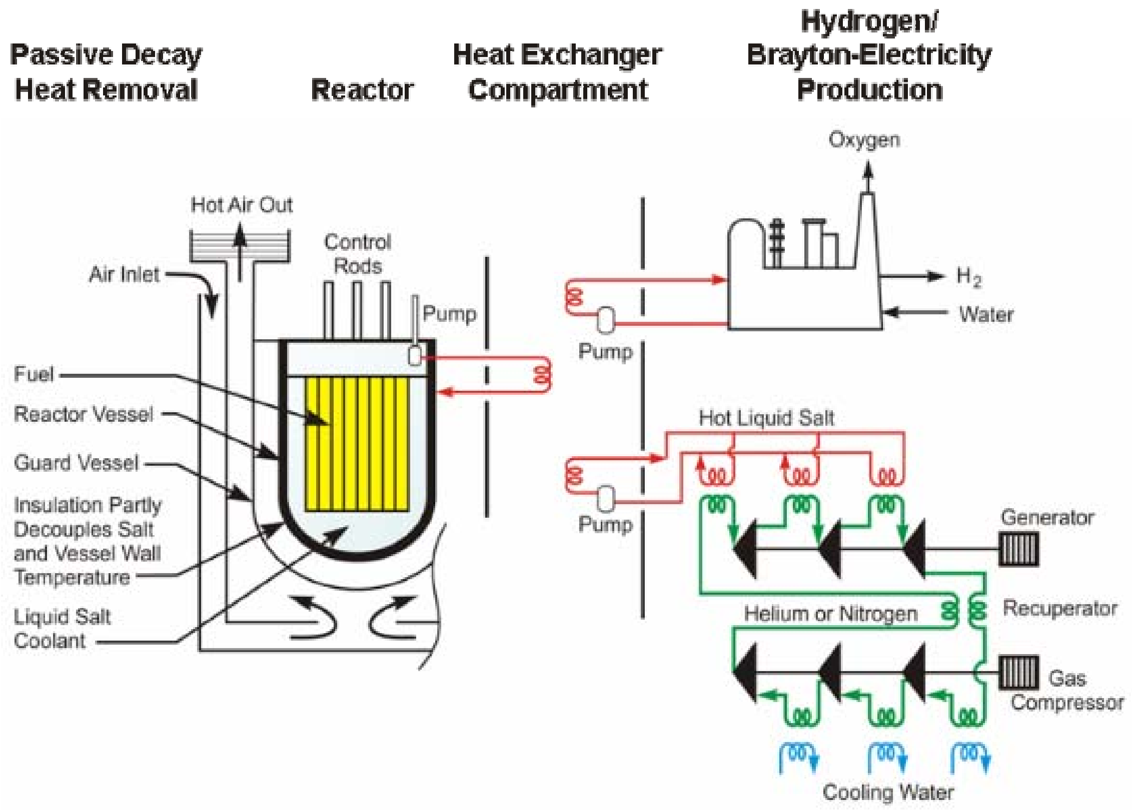

Fig. 2. Schematic of Advanced High-Temperature Reactor and Liquid-Salt-Cooled Fast Reactor.