

Developments in Molten Salt and Liquid-Salt-Cooled Reactors

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File Name: AHTR Publications: LiqSaltOptions.ICAPP06.Paper
Manuscript Date: February 6, 2006
Final Paper Due Date: March 15, 2006
Abstract Number: 6292

Session 3.11 Status of Advanced Reactor Programs
2006 International Congress on the Advances in Nuclear Power Plants (ICAPP'06)
Embedded Topical in the 2006 American Nuclear Society Annual Meeting
American Nuclear Society
June 4–8, 2006
Reno, Nevada

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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.

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Abstract — *In the last 5 years, there has been a rapid growth in interest in the use of high-temperature (700 to 1000°C) molten and liquid fluoride salts as coolants in nuclear systems. This renewed interest is a consequence of new applications for high-temperature heat and the development of new reactor concepts. Fluoride salts have melting points between 350 and 500°C; thus, they are of use only in high-temperature systems. Historically, steam cycles with temperature limits of ~550°C have been the only efficient method to convert heat to electricity. This limitation produced few incentives to develop high-temperature reactors for electricity production. However, recent advances in Brayton gas-turbine technology now make it possible to convert higher-temperature heat efficiency into electricity on an industrial scale and thus have created the enabling technology for more efficient nuclear reactors. Simultaneously, there is a growing interest in using high-temperature nuclear heat for the production of hydrogen and shale oil. Five nuclear-related applications are being investigated: (1) liquid-salt heat-transport systems in hydrogen and shale oil production systems; (2) the advanced high-temperature reactor, which uses a graphite-matrix coated-particle fuel and a liquid salt coolant; (3) the liquid-salt-cooled fast reactor which uses metal-clad fuel and a liquid salt coolant; (4) the molten salt reactor, with the fuel dissolved in the molten salt coolant; and (5) fusion energy systems. The reasons for the new interest in liquid salt coolants, the reactor concepts, and the relevant programs are described.*

I. INTRODUCTION

There has been a rapid growth in research and development for five applications of high-temperature molten and liquid fluoride salts in nuclear systems. This paper describes (1) why the new interest in these technologies has arisen, (2) the five nuclear-related applications, and (3) the work that is under way in each area—both national and international. Because these programs use the same base technologies, the associated technical developments are closely interrelated and the programs are technologically coupled.

The term *liquid salt* refers to applications involving clean salts. The term *molten salt* refers to applications in which fissile materials and fission products are dissolved in the salt. As will be discussed in this paper, the materials and corrosion challenges in clean salt systems (like clean sodium, helium, and water systems) are significantly less than in salt applications involving many chemical species.

II. NEW INTEREST IN LIQUID SALT SYSTEMS

In the 1950s and 1960s, the United States investigated molten fluoride salts as coolants for aircraft nuclear propulsion and for breeder reactors.¹ While much technical progress was made and two experimental test reactors were successfully built, the programs were ultimately discontinued. Molten and salt-cooled reactors are intrinsically high-temperature machines because the melting points for salts that are useful in nuclear systems have melting points between 320 and 500°C. The need for high-temperature heat that could be provided with nuclear reactors was limited. Renewed interest in molten and liquid salts has emerged because applications for high-temperature heat now exist.

- *Hydrogen and shale oil production.* There is a growing interest in hydrogen production systems^{2,3} that require high-temperature heat to convert water to hydrogen and oxygen. An interest has also emerged in in-situ recovery⁴ of

shale oil, a process requiring that oil shale be heated. Both of these applications require the transfer of high-temperature heat from some type of high-temperature reactor to the user over distances from hundreds of meters to several kilometers.

- *Brayton power cycles.* In the last decade, the technology for Brayton power cycles (using nitrogen or helium) has been developed to efficiently convert high-temperature heat to electricity⁵. The traditional utility power conversion cycle has been the steam cycle with temperatures limited to ~550°C. Limited interest existed in high-temperature reactors, because high-temperature heat could not be efficiently converted into electricity. The development of the technology for high-temperature Brayton cycles has changed this. For peak coolant temperatures of 705, 800, and 1000°C, the respective thermal-to-electric efficiencies for helium Brayton power cycles have been estimated to be 48.0, 51.5, and 56.5%—far higher than those achieved in traditional Rankine steam cycles.
- *Dry cooling.* Major conflicts exist between energy production and water usage. High-temperature reactors with Brayton cycles increase power plant efficiency and make dry cooling of power plants more economically viable.⁶ Current light-water reactors (LWRs) have efficiencies of ~33%. For every kilowatt of electricity, 2 kW of heat is rejected to the cooling towers. If power plant efficiency is increased to 50%, only 1 kW of heat is rejected to the cooling towers for every kilowatt of electricity. In the United States, water shortages exist in both the

arid west and in the east. For example, Dominion Power is proposing a wet/dry cooling tower in its U.S. Nuclear Regulatory Commission (NRC) revised early site permit application for building an additional nuclear reactor at its North Anna site in Virginia. That system is estimated to cost an additional \$200 million over the traditional water-intensive cooling systems. Water limitations, the associated economic costs, and the siting limitations created by the need for water create strong incentives for more efficient reactors that do not consume large quantities of water.

Only two coolants have been demonstrated in high-temperature nuclear systems: helium and liquid fluoride salts. There are strong economic incentives to use liquid-fluoride-salt coolants. Table I shows the number of 1-meter pipes required to transport 1000 MW(t) of heat with a 100°C rise in temperature. Whereas only half a pipe would be required to transport that quantity of heat with a liquid salt, over 12 pipes would be required if the coolant were helium, and 2 pipes would be required for sodium. The liquid salt is at atmospheric pressure, whereas the helium is at high pressure. This comparison provides a crude measure of the size of pipes, valves, and heat exchangers and is an indication of potential economic advantages in using liquid salts as coolants in high-temperature heat-transfer systems, including nuclear reactors, as alternatives to helium and sodium. Two recent studies^{3,7} have compared helium and liquid salts in various systems and provide a more quantitative analysis of the potential economic benefits. Table II⁸ lists some of the physical properties of various coolants.

TABLE I
 Relative Heat-Transport Capabilities of Coolants to
 Transport 1000 MW(t) with a 100°C rise in Coolant Temperature

	Water	Sodium	Helium	Liquid salt
Pressure, Mpa	15.5	0.69	7.07	0.69
Outlet temperature, °C	320	545	1000	1000
Velocity, m/s (ft/s)	6 (20)	6 (20)	75 (250)	6 (20)
Number of 1-m-diam pipes required to transport heat	0.6	2.0	12.3	0.5

TABLE II

Physical Properties 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 · 10 ⁶ (m ² /s)
Li ₂ BeF ₄ (Flibe)	459	1430	1940	2.42	4670	1.0	2.9
0.595NaF-0.405ZrF ₄	500	1290	3140	1.17	3670	0.49	2.6
Sodium	97.8	883	820	1.27	1040	62	0.12
Helium (7.5 MPa)			3.8	5.2	20	0.29	11.0
Water (7.5 MPa)	0	100	732	5.5	4040	0.56	0.13

^aThe composition of the sodium-zirconium fluoride salt is indicated in mole %; its conductivity is estimated—not measured. Salt properties at 700°C. Sodium properties at 550°C. Nomenclature used: ρ is density; C_p is specific heat; k is thermal conductivity; v is viscosity.

Five nuclear-related applications of liquid salts are being investigated today. These applications can be characterized relative to other types of coolants used in nuclear reactors. Figure 1 shows categories of nuclear reactors classified by power output and the peak temperatures of their coolants. 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 helium and (2) low-pressure liquid salts. The high-temperature reactor options differ from other reactors in their use of Brayton power cycles for electricity production and their potential use for the production of hydrogen. High-temperature helium reactors are the near-term high-temperature reactor option because several experimental reactors have been built, two test reactors are operating, and a precommercial prototype reactor is being built in South Africa. Salt-cooled reactors are a longer-term option.

III. SALT HEAT-TRANSPORT SYSTEMS

The first application for liquid fluoride salts is to transport heat from any high temperature reactor to a user. At lower temperatures, nitrate salts have been used on a large industrial scale⁹ for 60 years as coolants in heat transport systems in the chemical

industry; thus, there is a massive practical engineering experience base exists for salt-based heat-transport systems. Nitrate salts are also used today in solar power towers for the transfer of heat from the solar collectors to the power-generating equipment. However, these salts decompose at ~600°C. At higher temperatures, highly stable salts are required. Most of the research on higher-temperature liquid coolants has been focused on fluoride salts because of their chemical stability and relatively non-corrosive behavior. As is true for most other coolants, the corrosion behavior is determined primarily by the impurities in the coolant, not the coolant itself. While large-scale testing has taken place, including the use of such salts in test reactors, there is only limited industrial experience.

However, other industrial experience exists for the use of fluoride salts. Since the 1890s, essentially all aluminum has been produced by the Hall electrolytic process. In the Hall process, aluminum oxide is dissolved in a mixture of sodium and aluminum molten fluoride salts (cryolite: 3NaF·AlF₃) at ~1000°C in a graphite-lined bath. Massive graphite electrodes provide the electricity that converts aluminum oxides to aluminum metal.

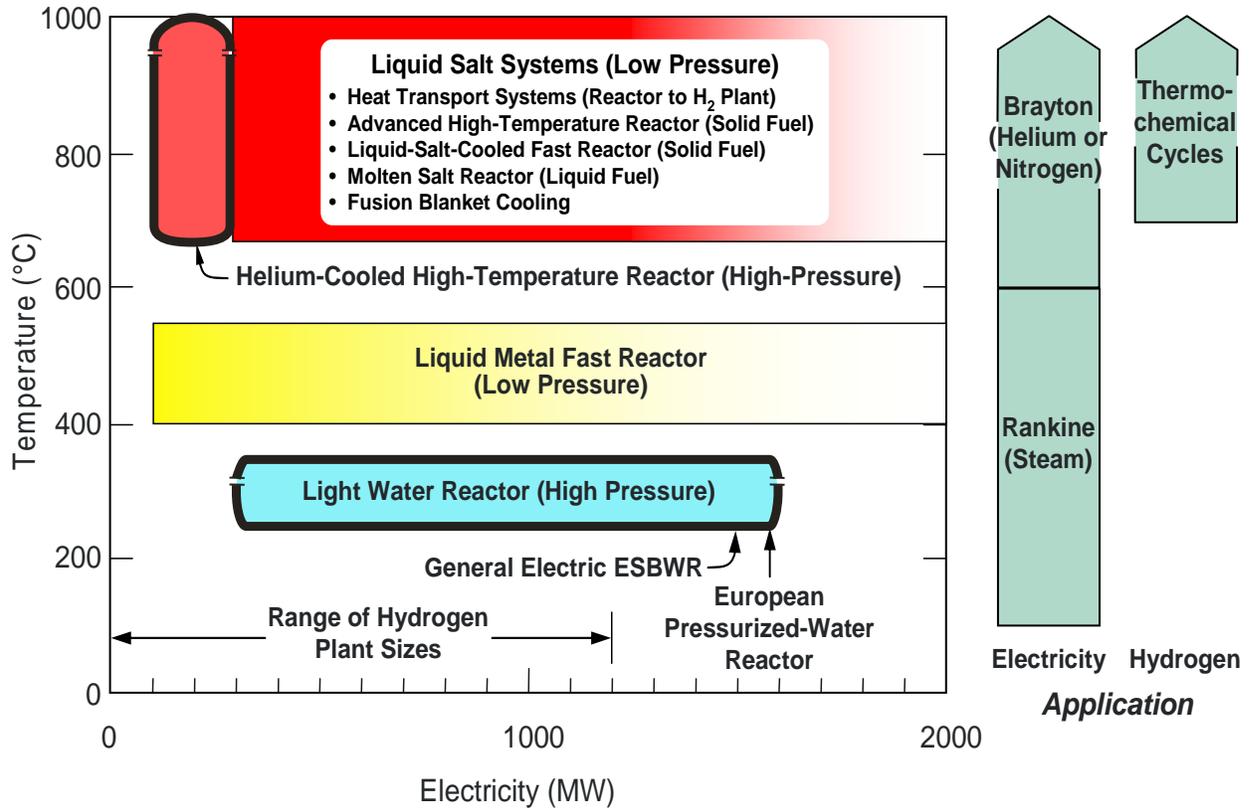


Fig.1. Reactor type vs temperature and power output.

Two incentives exist for developing high-temperature liquid-salt heat transport systems to move heat from high-temperature nuclear reactors (gas cooled or liquid salt cooled) at temperatures from 700 to 1000°C.

- Hydrogen production.* Worldwide, significant work is being conducted on thermochemical hydrogen production methods that convert heat and water to hydrogen and oxygen. The high-temperature heat must be transported hundreds of meters from the reactor to the chemical plant. Heat transport distances are defined by the safety requirement to separate the nuclear plant from the chemical plant and the large physical size of the chemical plant. Liquid salts are preferred to minimize the equipment size in the heat transport system (Table I) and the chemical plant. Within a hydrogen plant, the high-temperature heat is used to drive strongly endothermic chemical reactions, where the size of the chemical reactor

is determined by the rate of heat transfer through the walls of the heat exchangers within the reactor. The use of liquid salt coolants with their superior heat transfer capacity relative to that of helium can reduce the size³ of the chemical reactors by up to 80%.

- Shale oil.* Within the United States there is sufficient oil shale to meet domestic oil demands at current consumption rates for a century. New methods¹⁰ for shale oil recovery are being developed that involve drilling wells into oil shale, using electrical heaters to raise the bulk temperature of the oil shale deposit to initiate chemical reactions that produce light crude oil, and then pumping the oil to the surface. The longer-term option⁴ involves using high-temperature reactors to directly provide the high-temperature heat and thus avoid the losses of converting heat to electricity and then back to heat. Direct heating of the oil shale requires

transferring the heat down wells that are effectively kilometer-long bayonet heaters. To minimize the diameter of the well and pumping costs, a high-temperature heat-transfer fluid that has a very high volumetric heat capacity is required. Liquid fluoride salts have these properties.

Both public and commercial organizations are funding work on liquid-salt heat-transport systems. Experimental work is under way at Oak Ridge National Laboratory (ORNL), the University of California at Berkeley, and the University of Wisconsin at Madison. Studies and analysis are under way at these institutions, as well as at Westinghouse, the University of Nevada at Las Vegas, and other institutions. Significant proprietary activities are also being conducted.

IV. ADVANCED HIGH-TEMPERATURE REACTOR (AHTR)

The AHTR is a new reactor concept that has been under development for several years. There are three design goals: (1) high reactor-coolant exit temperatures (700 to 1000°C) to enable the efficient production of hydrogen by thermochemical cycles and the efficient production of electricity, (2) passive safety systems for public acceptance and reduced costs, and (3) competitive economics relative to both LWRs and modular high-temperature gas-cooled reactors (MHTGRs). The safety goals of the AHTR are identical to those of the MHTGR. The reactor size would be between 2400 and 4000 MW(t). Within the U.S. Department of Energy Generation IV Program, the AHTR is being developed as a liquid-salt-cooled very high-temperature reactor (LS-VHTR), the high-temperature variant of the AHTR that is required for hydrogen production. A preconceptual point design has been developed.^{11, 12}

The AHTR (Fig. 2) is a liquid-salt-cooled high-temperature reactor that uses the same type of coated-particle graphite-matrix fuel that has been successfully used in high-temperature gas-cooled reactors. It represents the near-term liquid-salt-cooled reactor option because of (1) the use of a demonstrated high-temperature fuel and (2) the demonstrated compatibility of graphite-matrix fuels with fluoride salts at high temperatures. 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. Several different salts can be used as the primary coolant, including lithium-beryllium and sodium-zirconium fluoride salts.

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 hydrogen production facility or to a turbine hall to produce electricity. If electricity is produced, a multi-reheat nitrogen or helium Brayton power cycle (with or without a bottoming steam cycle) is used.

The baseline 2400-MW(t) AHTR layout (Fig. 2) is similar to the S-PRISM sodium-cooled 1000-MW(t) fast reactor designed by General Electric. Both reactors operate at low coolant 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 design. The baseline AHTR also uses a passive reactor vessel auxiliary cooling system (RVACS) similar to that developed for decay heat removal in the General Electric sodium-cooled S-PRISM.

The reactor and decay-heat-cooling system are located in a below-grade silo. The decay heat is (1) transferred from the reactor core to the reactor vessel graphite reflector by natural circulation of the liquid salt, (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 to the guard vessel. Radiative heat transfer increases by the temperature to the fourth 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.

In terms of passive decay-heat-removal systems, the AHTR can be built in very large sizes, while the maximum size of a gas-cooled reactor with such systems is limited to ~600 MW(t). The controlling factor in decay heat removal is the ability to transport decay heat from the center of the reactor core to the vessel wall or to a heat exchanger in the reactor vessel. The AHTR uses a liquid coolant, where natural circulation can move very large quantities of decay heat to the vessel wall with a small difference in coolant temperature (~50°C). Unfortunately, when a gas-cooled reactor is depressurized under accident conditions, the natural circulation of gases is not very efficient in transporting heat from the fuel in the center of the reactor to the reactor vessel. The heat

must be conducted through the reactor fuel to the vessel wall. This inefficient heat transport process limits the size of passively safe gas-cooled reactors to ~600 MW(t) to ensure that the fuel in the hottest location in the reactor core does not overheat and fail. The ability to build large passively safe liquid-cooled reactors is a significant economic advantage for liquid-cooled reactors.

The economics of the AHTR have been assessed by several different methods^{13, 14} and indicate the potential for a cost-competitive reactor. Figure 3 shows the result of one assessment that evaluated the relative building volumes, quantities of concrete, and quantities of steel for existing and future reactors per unit of electrical output. All quantities are relative to that required to build a standard pressurized-water reactor (PWR) in 1970. In the figure, the oldest reactors are shown on the left and the most advanced concepts on the right. The first-generation reactors used relatively small quantities of materials. Following the Three Mile Island accident and added safety requirements, there was a significant increase in the quantities of material per unit power output, as seen in the General Electric Advanced Boiling Water Reactor (ABWR) and the Framatome Economic Pressurized-Water Reactor (EPR). However, as technology progressed, the quantities of materials decreased, as seen in the projected quantities of materials for the General Electric ESBWR—the next generation of LWR that is just now being submitted to the NRC for review and licensing.

The two reactors on the right, the MHTGR and AHTR, have not been built. The MHTGR is a near-term option because a number of helium-cooled high-temperature reactors have already been built. On the other hand, no salt-cooled high-temperature reactor has yet been built and thus the need for a test reactor to demonstrate the concept. The assessments indicate that the AHTR capital costs will be between 50 and 60% of those for an MHTGR. This low cost is primarily a consequence of the economics of scale. This finding also suggests that in the long-term, the MHTGR market may be in smaller electrical grids, whereas the AHTR market is in large electrical grids that can operate with reactors with large power outputs.

The AHTR has the potential for improved economics relative to existing LWRs because of several design characteristics: (1) a high-volumetric-heat-capacity coolant, which minimizes equipment sizes; (2) a low-pressure, relatively inert coolant, which reduces the costs of safety and containment systems; (3) high efficiency, which reduces the costs

of the power conversion, associated heat rejection, and decay-heat-removal systems per kilowatt (electric) capacity; and (4) the lower cost of the Brayton power cycle equipment relative to that for Rankine steam cycles.

The development activities have not identified any technical viability issues; however, major technological development challenges remain. The primary uncertainties are associated with materials of construction for heat exchangers and other components. For temperatures to about 750°C, demonstrated code-qualified materials of construction have been proven to be fully compatible with liquid salts. The multiple candidate materials of construction for higher temperatures have not been fully tested or qualified.

Both public and commercial organizations are funding work on the AHTR. The primary interest by the U.S. Department of Energy is for the production of hydrogen (a very high-temperature application), whereas the primary commercial interest is as a potential long-term (2025) alternative to the large LWR. For electricity production, the economics¹⁵ will likely dictate lower peak coolant temperatures (700 to 800°C) and large reactors [4000 MW(t)]. In the United States, work is under way at ORNL, Argonne National Laboratory, Idaho National Laboratory, the University of California at Berkeley, the University of Wisconsin at Madison, and Framatome. In the United States, the development activities have concentrated on use of a prismatic fuel; however, a pebble-bed version is being evaluated in the Netherlands.¹⁶

V. LIQUID-SALT-COOLED FAST REACTOR (LSFR)

The LSFR¹⁷ is a new reactor concept that is less than 2 years old. The design is similar to the AHTR shown in Fig. 2 except that the reactor core is replaced by a modified metal-clad fast reactor core and a fluoride salt is chosen (such as a sodium-zirconium salt) to minimize neutron moderation in the core. The fuel-clad materials limitations imply operating temperatures between 700 and 800°C.

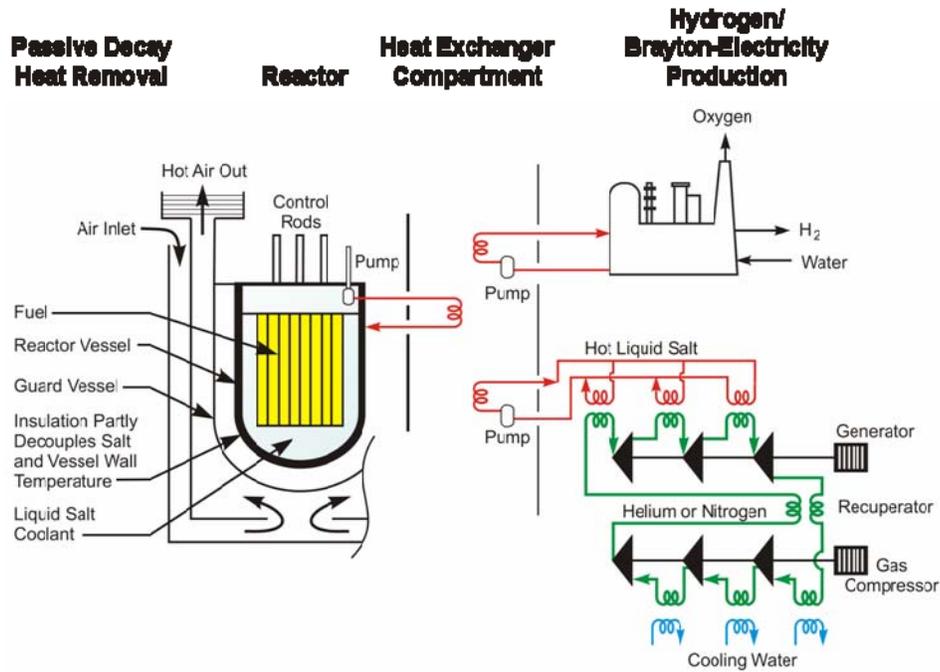


Fig. 2. Schematic of the Advanced High-Temperature Reactor and Liquid-Salt-Cooled Fast Reactor.

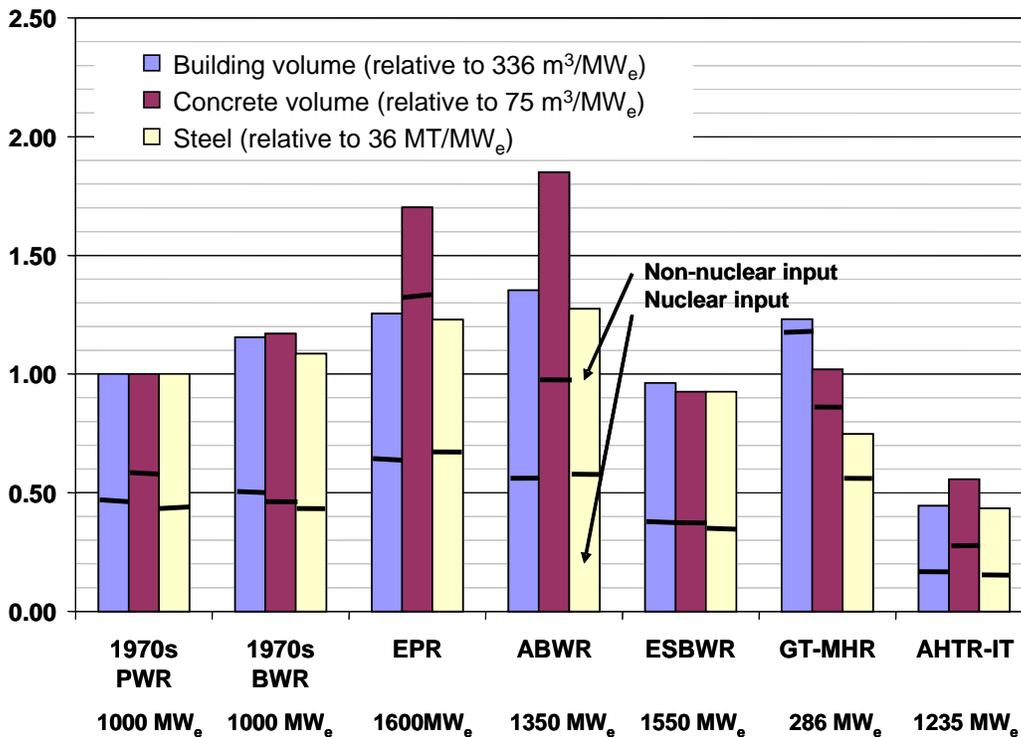


Fig. 3. Relative quantities of materials per unit power output to construct various types and generations of reactors. [PWR: pressurized-water reactor; BWR: boiling-water reactor; EPR: Framatome European PWR; ABWR: GE Advanced BWR; ESBWR: GE Economic Simplified BWR (in licensing); GT-MHR: General Atomics Gas-Turbine Modular Helium Reactor (proposed); and AHTR: Advanced High-Temperature Reactor].

The incentive to consider an LSFR is economics. Sodium-cooled fast reactors (SFRs) have been successfully developed and have many attractive features, such as the capability to produce fuel and destroy long-lived radioactive wastes. However, the projected capital costs per kilowatt (electrical) are significantly greater than those of LWRs. A new fast reactor technology is of interest only if there is a reasonable potential for a major improvement in the economics compared with those of an SFR. The potential for better economics with the LSFR is based on several considerations.

- *Equipment size.* At operating conditions, the volumetric heat capacity of liquid sodium is one-fourth to one-fifth that of water or a liquid salt. This implies large equipment sizes relative to an LWR or an LSFR.
- *Sodium-water reactions.* The chemical reactions of sodium with water that generate heat and hydrogen result in expensive safety and containment systems.
- *Plant efficiencies.* The new EPR has an efficiency of ~37% relative to SFR efficiencies of 40 to 42%. The small difference in efficiency does not compensate for the added complexities of an intermediate heat transport system. Raising the exit temperature of the sodium coolant in an SFR would improve efficiency; however, safety requirements for the SFR require that boiling not occur in the reactor. This limits the allowable temperature of the sodium. The higher-temperature LSFR would have efficiencies between 45 and 50%.
- *In-service inspection.* In-service inspection, particularly to locate loose parts, is difficult in SFRs due to the opaque coolant, whereas liquid salts are transparent and allow optical inspections.

To address these economic challenges, the SFR community is considering technical improvements such as supercritical carbon dioxide power cycles¹⁸ to replace the steam cycle. Such a change would simultaneously increase plant efficiency and eliminate the sodium-water challenge. The alternative is a more radical change in fast reactor technology such as the LSFR.

Two technical viability issues have been identified for the LSFR. A high-temperature metal clad is required. Multiple candidates have been proposed, but none have yet been demonstrated to

meet the requirements for corrosion resistance in a high-temperature liquid-salt environment and to withstand fast neutron radiation damage. This is in contrast to the AHTR, where the in-core graphite-based fuel and components meet both of these requirements. The second viability issue is core design, where the fluoride salt softens the neutron spectrum. Work is under way at ORNL, the University of California at Berkeley, and the Massachusetts Institute of Technology to address these viability issues. Work is also planned at the French Atomic Energy Commission (CEA).

VI. MOLTEN SALT REACTORS

Liquid salt technology for nuclear applications started with the MSR. The technology was first developed for aircraft propulsion and then as a breeder reactor. These billion dollar programs created the base technology, and two test reactors were subsequently built. The relatively trouble free 8-MW(t) MSR Experiment provided an effective demonstration of the reactor technology.

In an MSR (Fig. 4), the molten fluoride salt with dissolved fissile, fertile, and fission isotopes flows through a reactor core moderated by unclad graphite. In the core, fission occurs within the flowing fuel salt, which then flows into a primary heat exchanger, where the heat is transferred to a secondary liquid-salt coolant. The fuel salt then flows back to the reactor core. The graphite-to-fuel ratio is adjusted to provide the optimal neutron balance, an epithermal neutron spectrum. In the preconceptual 1000-MW(e) designs developed in the early 1970s, the liquid fuel salt typically enters the reactor vessel at 565°C and exits at 705°C and ~1 atmosphere (coolant boiling point: ~1400°C). Volatile fission products (e.g., krypton and xenon) are continuously removed from the fuel salt. The secondary coolant loop transfers the heat to the Brayton power cycle or to a hydrogen production facility.

The liquid fuel presents major technical challenges but also provides major benefits.

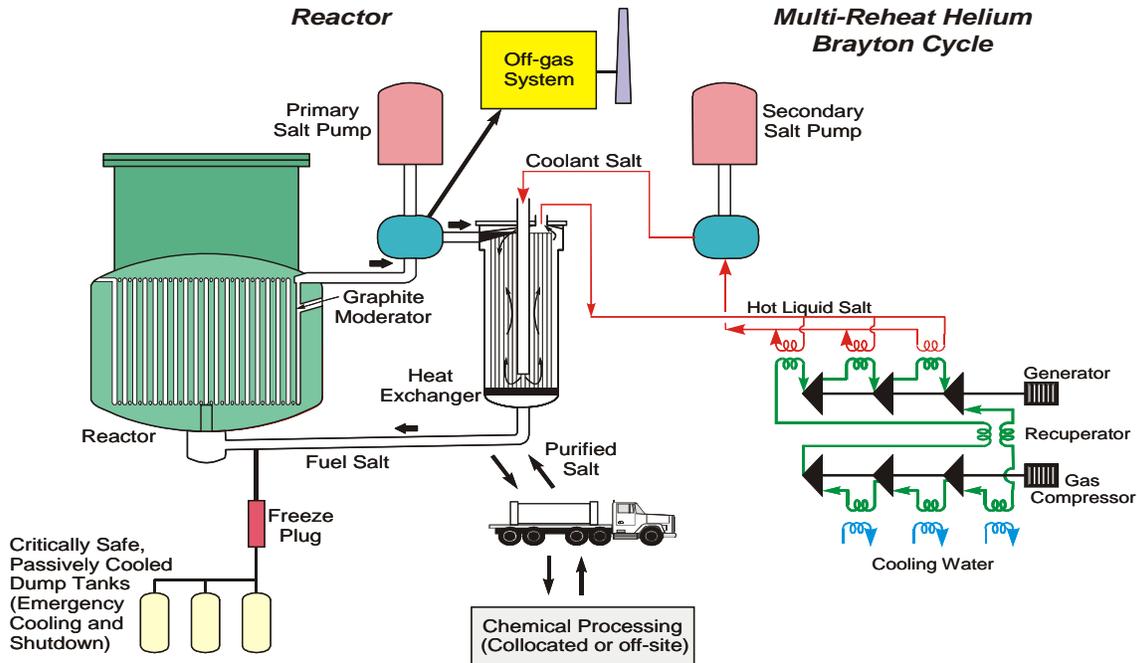


Fig. 4. MSR with multi-reheat helium Brayton cycle.

- Safety.** The MSR liquid fuel provides several safety advantages. Under emergency conditions, the liquid fuel is drained to passively cooled critically safe dump tanks. Unlike solid-fuel reactors, MSRs operate at steady-state conditions, with no change in the nuclear reactivity of the fuel as a function of time. Fission products can be removed online, thus minimizing the radioactive inventory (accident source term) in the reactor core.
- Fuel cycles.** The liquid fuel allows online refueling and a wide choice of fuel cycle options: burning of actinides from other reactors, a once-through fuel cycle, a thorium-²³³U breeder cycle, and a denatured thorium-²³³U breeder cycle. Some of the options, such as a thermal-neutron-spectrum thorium-²³³U breeder cycle, require online refueling and thus can not be practically achieved using solid fuels. Liquid fuels also avoid the challenges associated with fuel development, qualification, and fabrication.

A critical technical distinction between the MSR and other liquid salt applications should be noted. The corrosion rates of systems containing clean

liquid fluoride salts with the proper materials of construction are very low; it is the impurities that are primarily responsible for corrosion. Appropriate alloys of construction have been found for MSRs; however, the peak temperatures may be limited to less than 750°C because the same alloys have low strength at higher temperatures. This constraint does not exist for clean liquid salt systems.¹⁹

In the last several years, there have been major advances in understanding MSRs and advances in the technology by applying modern design tools²⁰ to a reactor that has received little attention for several decades. The technical viability of the MSR depends upon the specific mission. For many applications, it is the unique fuel cycle characteristics of this reactor that make it attractive. In such cases, the viability of the fuel cycle technology determines the viability of the MSR. This finding is in contrast to the AHTR and the LSFR, where the parallel MHTGR and SFR fuel cycles would be used. Major work is being conducted in France, with significant programs in the Czech Republic, and in the Russia at the Kurchatov Institute. Limited work is being done in the United States at ORNL and at the University of California at Berkeley.

There has also been recent work²¹ on a molten-salt fast reactor (MSFR) that is similar to the traditional MSR. Relative to conventional MSRs, two major changes are required to obtain a fast neutron spectrum with a fluoride salt: the fluoride salt composition is adjusted and there is no graphite in the reactor core. Earlier proposals for a MSFR have used chloride salts; but, chloride salts have three major drawbacks: (1) a need for isotopically separated chlorine to avoid high-cross-section nuclides, (2) the activation product ³⁶Cl that presents significant challenges to waste management because of its mobility in the environment, and (3) the more corrosive characteristics of chloride systems relative to fluoride systems. It is premature to judge the viability of the fluoride-salt-based MSFR; but, the preliminary analysis indicates a reactor with potentially unique capabilities as a breeder reactor.

VII. FUSION

Liquid salts (primarily lithium beryllium fluoride salts) are serious candidates for fusion energy machines to remove heat from the fusion reactor, breed tritium, and provide a renewable material for neutron shielding to reduce the mass of solid material exposed to damaging fusion neutron fluences.²² In a fusion reactor, tritium and deuterium fuse together to release energy, neutrons, and helium. The fusion machine must breed tritium to continue operation: ${}^6\text{Li} + n \rightarrow {}^4\text{He} + {}^3\text{H}$ (tritium). The lithium can be a solid in the blanket of the fusion energy machine or exist as part of the coolant. Consequently, low-pressure lithium-containing liquid salts are being considered as coolants for fusion energy machines.

Liquid salts are also being considered for one other application in inertial fusion machines where heavy-ion beams, pulsed electrical power, or lasers are used to compress small pellets to extreme temperatures and cause a fusion explosion. This type of fusion machine produces an impulse on the fusion reactor wall that damages the wall over time. Liquid salts^{23, 24} may be used to form a liquid wall inside the fusion machine to shield structures from fusion neutrons and to absorb shock loads from targets. Because of the requirement that the vapor pressure of the salt must be extremely low to permit focusing of the beams on the target, liquid salts are the preferred option for heavy-ion and laser drivers. As with other fusion applications, the liquid salt is also used to breed tritium.

VIII. CONCLUSIONS

The development and commercialization of a new coolant technology is a major challenge. Three

fundamental changes (Brayton power cycles, incentives for dry cooling, and hydrogen/shale oil production) are creating the incentives to develop a new high-temperature, low-pressure coolant and new large high-temperature reactors. The development and commercialization of such a coolant technology opens several new frontiers for nuclear energy.

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