

# Liquid Salt Applications and Molten Salt Reactors

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# LIQUID SALT APPLICATIONS AND MOLTEN SALT REACTORS

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**Abstract** – *In the last 5 years, there has been a rapid increase in interest in the use of high-temperature (700 to 1000°C) molten and liquid fluoride salts as coolants and for other functions in nuclear systems. This interest is a consequence of new applications for high-temperature heat and the development of new reactor concepts. These salts have melting points between 315 and 565°C; thus, they are of use only in high-temperature systems. Nitrate salts with a peak operating temperature of ~600°C are the highest-temperature commercial liquid coolant available today; therefore, the development of higher-temperature salts as coolants offers the possibility of new nuclear and non-nuclear applications. These salts are being considered for intermediate heat-transport loops between all types of high-temperature reactors (helium and salt cooled) and hydrogen production systems, oil refineries, and shale oil processing facilities. 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 efficiently into electricity and thus have created the enabling technology for more efficient cost-effective high-temperature reactors. The near-term Advanced High-Temperature Reactor uses a graphite-matrix, coated-particle fuel and a liquid salt coolant. A longer-term potential exists for a liquid-salt-cooled fast reactor that uses metal-clad fuel and a liquid salt coolant. The molten salt reactor (MSR), with the fuel dissolved in the molten salt coolant, is receiving attention because of (1) the advancing salt-coolant technology and Brayton cycles that improve the economics; (2) advances in salt chemistry that enable the development of fast-spectrum MSRs with the safety advantages of large negative void coefficients; and (3) the interest in actinide burning where MSRs avoid the need to fabricate fuel of highly active actinides. Last, there is a developing interest in liquid-wall fusion machines with much higher power densities than solid-wall fusion machines.*

## I. INTRODUCTION

There has been a rapid growth in research and development on high-temperature molten and liquid salts in nuclear systems. This paper describes (1) why the new interest in these technologies has arisen, (2) the four nuclear-related applications, and (3) the work that is under way in each area. Because these programs use the same base technologies, the associated technical developments are 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 discussed in this paper, the materials and corrosion challenges in clean-salt systems (like clean sodium, helium, and water systems) are significantly less than those in salt applications involving many chemical species.

## II. NEW INTEREST IN LIQUID AND MOLTEN SALT SYSTEMS

In the 1950s and 1960s, the United States investigated molten salt reactors (MSRs) in which the fuel was dissolved in the fluoride coolant, 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. The need for high-temperature heat that could be provided with nuclear reactors was limited. Renewed interest in liquid and molten salts has emerged because applications for high-temperature heat now exist, there are changing requirements for nuclear systems, and new technologies have emerged.

- *Oil refining, hydrogen production, shale oil production, and tertiary oil recovery.* Each of these processes requires massive quantities of high-temperature heat. Historically, oil and natural gas have been used to provide this heat. The increased costs of these fossil fuels and concerns about greenhouse climatic impacts have created an interest in new methods to provide high-temperature heat to industrial processes.
- *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 electricity. The traditional utility power conversion cycle has been the steam cycle, with temperatures limited to  $\sim 550^\circ\text{C}$ . 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 scenario. For peak coolant temperatures of 705, 800, and  $1000^\circ\text{C}$ , 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.
- *Breeder reactors and actinide burning.* There is renewed interest in breeder reactors and reactors that can burn actinides. MSRs have unique capabilities in these areas.

Only two coolants have been demonstrated in high-temperature nuclear systems: helium and liquid fluoride salts. Table I lists some of the physical properties of various liquid salt coolants compared to traditional coolants. There are strong economic incentives to use liquid-fluoride-salt coolants. Table II shows the number of 1-meter-diameter pipes required to transport 1000 MW(t) of heat with a  $100^\circ\text{C}$  rise in temperature. Whereas only half a pipe would be required to transport that quantity of heat with a liquid salt, more than 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 alternatives to helium and sodium as coolants in high-temperature heat-transfer systems, including nuclear reactors. Two recent studies [2,3] have compared helium and liquid salts in various systems and provide a more quantitative analysis of the potential economic benefits of liquid salt systems. Recent reports [4,5] evaluate various salts as coolants and provide a review of the status of our knowledge.

**TABLE I.** Physical Properties of Coolants<sup>a</sup>

Coolant	$T_{\text{melt}}$ ( $^\circ\text{C}$ )	$T_{\text{boil}}$ ( $^\circ\text{C}$ )	P ( $\text{kg}/\text{m}^3$ )	$C_p$ ( $\text{kJ}/\text{kg } ^\circ\text{C}$ )	$\rho C_p$ ( $\text{kJ}/\text{m}^3 ^\circ\text{C}$ )	k ( $\text{W}/\text{m } ^\circ\text{C}$ )	$\nu \cdot 10^6$ ( $\text{m}^2/\text{s}$ )
$\text{Li}_2\text{BeF}_4$ (Flibe)	459	1430	1940	2.42	4670	1.0	2.9
59.5NaF-40.5ZrF <sub>4</sub>	500	1290	3140	1.17	3670	0.49	2.6
46.5LiF-11.5NaF-42KF	454	1610	2020	1.89	3820	$\sim 0.6\text{--}1$	1.4
31LiF-31NaF-38BeF <sub>2</sub>	315	1400	2000	2.04	4080	1.0	2.5
71LiF-29ThF <sub>4</sub>	555	-	4470	1.05	4694	1.2	0.67
8NaF-92NaBF <sub>4</sub>	385	700	1750	1.51	2640	0.5	0.5
66.3NaNO <sub>3</sub> -33.7KNO <sub>3</sub>	221		1772	1.53	2710	0.53	
Sodium	97.8	883	820	1.27	1040	62	0.12
Lead	328	1750	10540	0.16	1700	16	0.13
Helium (7.5 MPa)			3.8	5.2	20	0.29	11.0
Water (7.5 MPa)	0	290	732	5.5	4040	0.56	0.13

<sup>a</sup>Salt compositions are shown in mole percent. Salt properties at  $700^\circ\text{C}$  and 1 atm. Sodium-zirconium fluoride salt conductivity and lithium-sodium-potassium fluoride salt boiling temperatures are estimated — not measured. The  $\text{Li}_2\text{BeF}_4$  and NaF-ZrF<sub>4</sub> are potential salt-cooled-reactor coolants. The NaF-NaBF<sub>4</sub> system must be pressurized above  $700^\circ\text{C}$ ; however, the salt components do not decompose. Nitrate properties at  $500^\circ\text{C}$ ; decompose near  $600^\circ\text{C}$ . This nitrate mixture has a composition by weight of 60% NaNO<sub>3</sub> and 40% KNO<sub>3</sub>. Sodium properties at  $550^\circ\text{C}$ . Pressurized water data are shown at  $290^\circ\text{C}$  for comparison. Nomenclature used:  $\rho$  is density;  $C_p$  is specific heat; k is thermal conductivity;  $\nu$  is viscosity.

**TABLE II.** 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 temp, °C	320	545	1000	1000
Velocity, m/s (ft/s)	6 (20)	6 (20)	75 (250)	6 (20)
Number of 1-m-diameter pipes required to transport heat	0.6	2.0	12.3	0.5

Multiple nuclear-related applications of liquid salts are being investigated today and are described in the following sections.

### III. SALT HEAT-TRANSPORT SYSTEMS

Liquid fluoride salts are being developed to transport heat in high-temperature systems such as from any high-temperature reactor to the user. At lower temperatures, nitrate salts have been used on a large industrial scale for 60 years as coolants in heat transport systems in the chemical industry; thus, a large-scale experience base exists for salt-based heat-transport systems. However, because these salts decompose at ~600°C, highly stable salts are required at higher temperatures. 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. Chloride salts are a second option, but the technology is less well developed. Chloride salts are not likely to be used as reactor coolants because of their higher absorption cross sections in the thermal part of the neutron spectrum. 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-AlF<sub>3</sub>) at ~1000°C in a graphite-lined bath. Massive graphite electrodes provide the electricity that converts aluminum oxides to aluminum metal.

Several 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 950°C. For most of these applications, the heat would have to be moved from hundreds of meters to kilometers.

- *Oil refining.* Modern refineries consume ~20% of the energy content of each barrel of oil that is processed. Much of the energy is in the form of high-temperature heat for distillation columns and thermal crackers. High-temperature nuclear heat could replace the expensive oil and natural gas and thus increase the output of liquid fuels per barrel of oil.
- *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 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 by the large physical size of the chemical plant. To minimize the equipment size in the heat transport system (Table II) and the chemical plant, liquid salts are preferred. Within a hydrogen plant, the high-temperature heat is used to drive strongly endothermic chemical reactions in which 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 size [2] of the chemical reactors by up to 80%.
- *Shale oil and tertiary oil recovery.* Within the United States is sufficient oil shale to meet domestic oil demands at current consumption rates for a century. Large deposits of oil shale exist elsewhere in the world. New methods 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 option [6] involves using high-temperature reactors to provide the high-temperature heat through an intermediate heat-transport loop and thus avoid the losses of converting heat to electricity and then back to

heat. The same technology can be used for tertiary oil recovery from old oil fields, where 50 to 70% of the oil remains in the rock and is held in place by capillary action. Heating the rock can vaporize the oil, which can then be condensed near the production wells.

- *Sodium fast reactors.* A primary challenge with sodium-cooled fast reactors is economics. One option [7] that is being examined is a salt-cooled intermediate loop between the sodium-cooled primary system and a supercritical carbon dioxide power cycle—an advanced power cycle with potentially higher efficiency and lower capital costs than the traditional steam cycles. Liquid salts offer two potential advantages: (1) smaller equipment size because of the higher volumetric heat capacity of the salts and (2) no chemical reactions between the reactor, intermediate loop, and power cycle coolants. There is experience with this type of system because the Aircraft Reactor Experiment (the first MSR) used a sodium-cooled intermediate loop.

#### IV. LIQUID-SALT-COOLED REACTORS

Two types of solid-fuel liquid-salt-cooled reactors are being investigated, the Advanced High-Temperature Reactor (AHTR) and the liquid-salt-cooled fast reactor (LSFR).

##### *IV.A. The Advanced High-Temperature Reactor*

The AHTR (Fig. 1) is a relatively new reactor concept [8, 9] that has been under development for several years in the United States. Investigations are also under way in several other countries. There are three design goals: (1) high reactor-coolant exit temperatures (700 to 950°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 light-water reactors (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). A preconceptual point design has been developed.

The AHTR 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. The optically transparent liquid-salt coolant is a mixture of fluoride salts with atmospheric boiling points >1200°C. The reactor operates at near-atmospheric pressure, and at operating conditions, the liquid-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 hydrogen production facility or to a turbine hall to produce electricity using a multi-reheat nitrogen or helium Brayton power cycle (with or without a bottoming steam cycle). Electrical efficiencies are expected to be near 50%. The AHTR capital costs have been estimated to be 50 to 60% those of a modular gas-cooled or liquid-metal-cooled reactor for equivalent electrical output. This is a consequence of economics of scale, higher potential efficiencies, and the higher volumetric heat capacity of liquid salts, which reduces equipment size relative to other coolants.

The 2400-MWt baseline concept has a closed primary loop immersed in a tank containing a separate buffer salt that provides a heat sink for various transients. The temperature of the buffer-salt tank is near the coldest temperature in the primary system. If the intermediate heat-transport loop fails, hot primary coolant exits the primary heat exchanger and dumps heat to the buffer pool through the uninsulated piping from the heat exchanger back to the reactor core. If the primary pumps fail, heat is also rejected from the primary system to the buffer salt through the Pool Reactor Auxiliary Cooling System (PRACS) heat exchangers. The PRACS connects the bottom and top plenums of the reactor core and contains in series a heat exchanger and fluidic valve. The fluidic valve has high flow resistance in one direction and low flow resistance in the other direction. Upon loss of forced circulation, decay heat is removed by natural circulation up through the reactor core and down through the PRACS heat exchangers with heat dumped to the buffer salt. Heat removal from the buffer salt to the environment occurs primarily through Direct Reactor Auxiliary Cooling System (DRACS) heat exchangers.

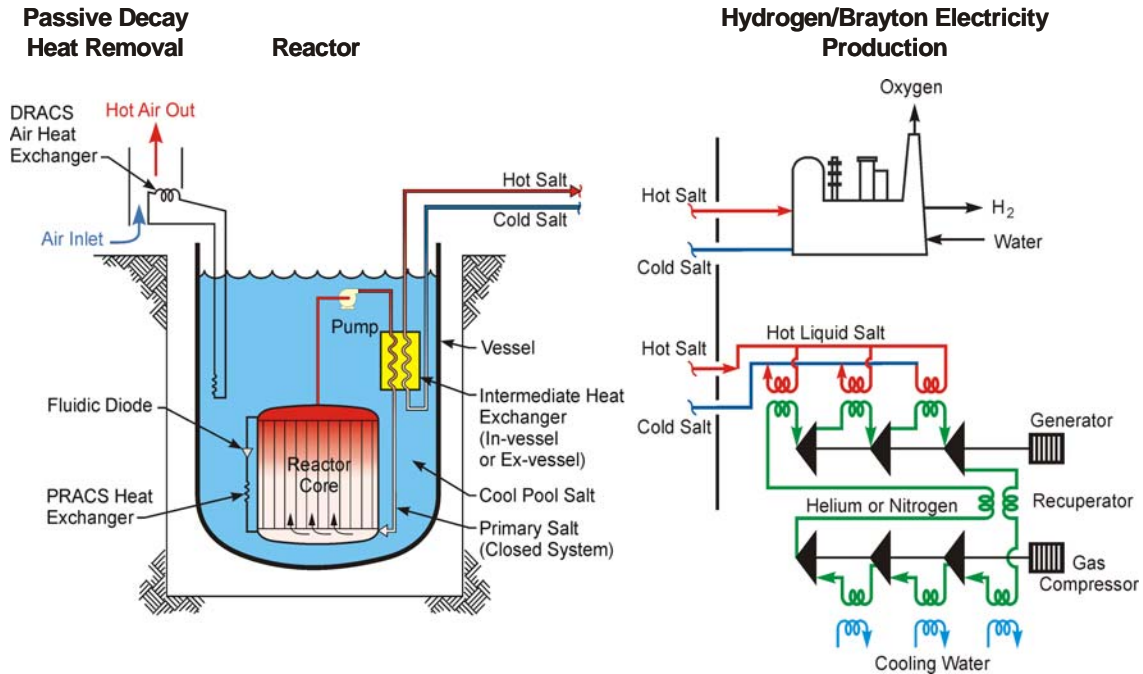


Fig. 1 AHTR layout for hydrogen production or electricity production

#### IV.B. The Liquid-Salt-Cooled Fast Reactor

The LSFR [10] is a new reactor concept with a design that is similar to the AHTR shown in Fig. 1, 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.

The incentive to consider an LSFR is economics. Sodium-cooled fast reactors have been successfully developed and have many attractive features. However, the projected capital costs per kilowatt (electrical) are significantly greater than those of LWRs. The LSFR has the potential for lower costs because (1) the high volumetric heat capacity of the salt (relative to that of sodium) reduces equipment sizes by a factor of 2, (2) the high-temperature closed Brayton cycle increases efficiency by ~20%, (3) there is no potential for sodium–water chemical reactions that generate hydrogen, and (4) the optically clear liquid simplifies in-service inspection and maintenance.

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. The second viability issue is core design, where the fluoride salt softens the neutron spectrum. Work is under way at Oak Ridge National Laboratory, the University of California at Berkeley, the Massachusetts Institute of Technology, and the French Atomic Energy Commission (CEA).

### V. MOLTEN SALT REACTORS

#### V.A. MSR potential and background

Liquid salt technology for nuclear applications emerged in the 1950's with the development of the MSR for aircraft propulsion and then as a breeder reactor. In an MSR, the fuel and fission products are dissolved in the molten salt. Two test reactors were built at Oak Ridge National Laboratory: the Aircraft Reactor Experiment and the Molten Salt Reactor Experiment (MSRE). The favorable experience gained from the operation of the MSRE, an 8-MW(t) experimental reactor operated from 1965-1969, led to a reference breeder reactor design with a thermal spectrum and thorium fuel cycle, the

Molten Salt Breeder Reactor (MSBR). The large research and development effort, combined with the MSRE and large test loops, provided a significant basis for the demonstration of the viability of an MSR breeder concept.

In an MSR (Fig. 2) of the MSBR type, 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.

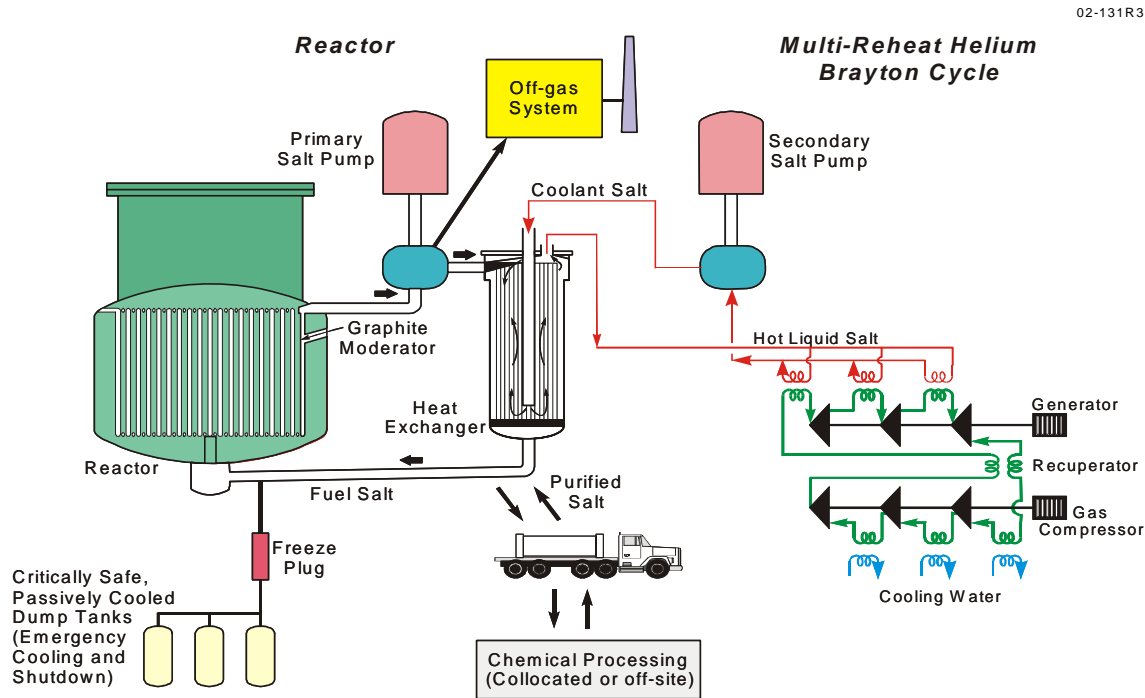


Fig. 2 MSR with multi-reheat helium Brayton cycle

The graphite-to-fuel ratio is adjusted to provide the optimal neutron balance, an epithermal neutron spectrum. In preconceptual 1000-MW(e) designs such as the MSBR, 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 energy conversion system (steam-water or Brayton power cycles) or to a hydrogen production facility.

The liquid fuel provides major benefits:

- *Safety.* Under emergency conditions, the liquid fuel is drained to passively cooled critically-safe dump tanks. Unlike solid-fuel reactors, MSRs can operate in quasi 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 avoids the challenges associated with fuel development, qualification, and fabrication. A wide choice of fuel cycle options is available: burning of actinides from other reactors, a once-through fuel cycle, a thorium-<sup>233</sup>U breeder cycle, and a denatured thorium-<sup>233</sup>U breeder cycle. Some of the options, such as a thermal-neutron-spectrum thorium-<sup>233</sup>U breeder cycle, require online refueling and thus cannot be practically achieved using solid fuels.

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 Ni-based 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.

### *V.B. New directions for MSRs*

The original MSR program was discontinued in the 1970s, when the United States decided to concentrate on a single breeder reactor concept—the sodium-cooled fast reactor. A renewed interest in MSRs has emerged as a consequence of changing goals and changing technologies. There is also a renewed interest in breeder reactors and reactors for burning of actinides to reduce waste burdens for the repository. For actinide burning, MSRs offer the unique advantage of having no fuel fabrication step—an extremely complex task for fuel elements with higher actinides. Simultaneously, several technological changes have occurred: (1) the advancing salt-coolant technology and Brayton cycles that improve the MSR economics and reduce the technological challenges, (2) advances in salt chemistry that enable the development of fast-spectrum MSRs with the safety advantages of large negative void coefficients, and (3) advances in fuel salt processing. Finally, in the last several years, by applying modern design tools to a reactor that had received little attention for several decades, major progress in understanding MSRs and advances in the technology have occurred.

Major work is being conducted in France at CEA and CNRS, with significant programs in the Czech Republic and in Russia at the Kurchatov Institute in Moscow, the Institute of Technical Physics in Snezhinsk, and the Institute of High-Temperature Electrochemistry in Ekaterinburg. Limited work is being done in the United States at Oak Ridge National Laboratory and at the University of California at Berkeley. The performances and design parameters of the MSBR have been revisited in the frame of the MOST (acronym for MOlten Salt reactor Technology) project supported by Euratom in 2002–2004 [11]. The state-of-the-art review of MSR technology performed in MOST has confirmed the fundamental potential of MSR as breeders or burners. In addition, MOST identified the critical issues to be addressed by research and development in response to some deficiencies of the MSBR, particularly core neutronics (uncertainties in the neutron cross-sections of minor actinides in the fast part of the neutron spectrum and on temperature feedback coefficients with low margins to zero), viability of the reprocessing scheme (time to reprocess the whole core, feasibility of technologies), and mechanical integrity of the primary circuit structures for long-term operation, especially graphite lifetime.

A new family of MSR designs has been developed with the common objective of breeding with use of a thorium cycle (see section V.C). In parallel, new conceptual MSR designs (see section V.D) have been developed for transmutation of actinides from LWR spent nuclear fuel (SNF).

### *V.C A new family of MSR breeders with thorium fuel cycles*

A new effort in Europe has been initiated to reexamine the MSR using modern tools and technologies with the goals of development of a modern sustainable and realistic MSR breeder design. France has led this work. The general concept of the Thorium Molten Salt Reactor (TMSR) was developed based on a 2500-MW(t), 1000-MW(e) reactor. The reactor inlet temperature is 630°C with a thermodynamic efficiency of 40%. The core contains a fluoride fuel salt, composed of LiF enriched in  ${}^7\text{Li}$  (99.999%) and heavy nuclei (designated as “HN” in the chemical nomenclature for salts), including the fissile element. The core structures are protected by reflectors, which ensure that 80% of the neutron flux is absorbed. To avoid thermalization of the reflected neutrons, the axial reflectors are made of ZrC. The radial reflector consists of graphite channels containing a binary fluoride salt ( $\text{LiF-ThF}_4$ ) with 28 mol %  ${}^{232}\text{Th}$ . This reflector is a fertile blanket, increasing the breeding ratio via a biannual extraction of  ${}^{233}\text{U}$  from the blanket salt.

Systematic analysis of the effect of such parameters as reprocessing time, moderation ratio, core size, and content of heavy nuclei in the salt has resulted in several attractive reactor configurations, in thermal, epithermal, or fast spectrum in the TMSR family [12]. For these studies, the salt used is a binary salt,  $\text{LiF}-(\text{HN})\text{F}_4$ , with the  $(\text{HN})\text{F}_4$  content set to 22 mole %, corresponding to a melting temperature of 565°C. A helium bubbling system in the salt circuit is assumed to extract the gaseous fission products and the noble metals within 30 s. These early studies of the concept are based on a delayed reprocessing of the total salt volume over a 6-month period with a complete extraction of the fission products and of the transuranic elements (TRU).

One of the key design parameters is the moderating ratio, which determines the neutron spectrum. In MSRs, graphite is the moderator. If it is assumed that the core consists of hexagonal graphite blocks with 15-cm sides and each block contains one channel for flowing molten salt, the moderator ratio can be adjusted by changing the channel radius. Figure 3 shows the influence of the channel radius on reactor core performances in terms of total reactivity feedback coefficient, breeding ratio, graphite lifetime, and initial fissile inventory. The maximum fuel-channel radius shown corresponds to conditions in which no graphite moderator is present in the reactor core.



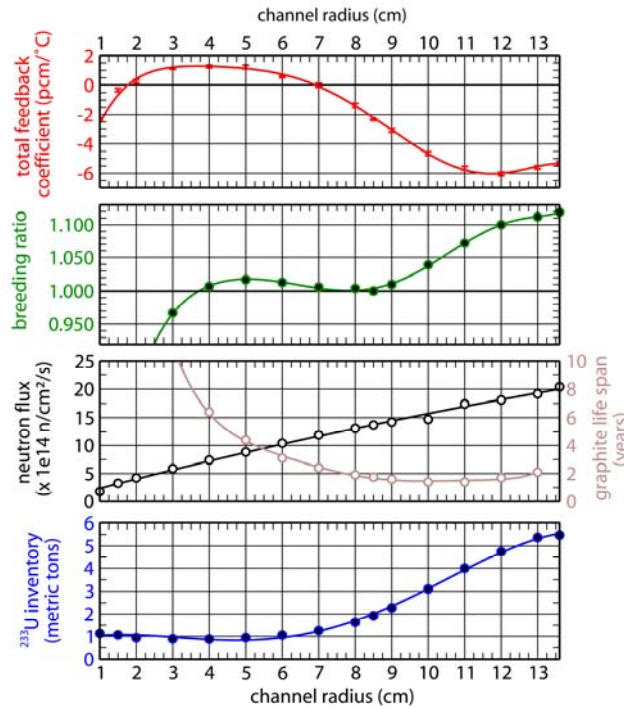


Fig. 3 Effect of fuel channel radius on TMSR performance parameters

For this system and salt composition, a thermal spectrum leads to a low fissile inventory but a positive feedback coefficient, while a fast spectrum implies a high breeding ratio but large fissile inventory. A narrow window with the appropriate ratio of molten salt to graphite with a somewhat hardened spectrum combines self-breeding and negative feedback coefficients with a relatively small initial fissile inventory. There is one other significant neutronic effect in a thermal-spectrum MSR. The feedback coefficients become negative as the hexagon size is reduced (i.e., when the core becomes more homogeneous). This assumes that the volume fraction of the molten salt in the core remains the same. Simultaneously, the breeding ratio is improved because parasitic captures of neutrons in the graphite are reduced, thus enabling design of a thermal-spectrum TMSR.

The parametric studies also led to the conclusion that a fast-neutron-spectrum MSR (FS-MSR) with no graphite moderator was highly promising and had the simplest configuration (see section V.D). Like solid-fuel fast-spectrum reactors, FS-MSRs can have high breeding ratios for either fuel production or actinide burning. Furthermore, FS-MSRs have large negative reactivity coefficients that provide robust intrinsic safety characteristics—a property not found in large solid-fuel fast reactors. If the molten salt is heated or a void is created, molten salt with its fissile material is expelled from the reactor core and the power level decreases. This is a unique feature among fast-neutron systems and has major implications in terms of safety and actinide burning.

*V.D. The potential of a fast-spectrum MSR*

***TMSR: breeder and burner in fast spectrum***

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 no graphite is present in the reactor core. Earlier proposals for FS-MSRs have used chloride salts. However chloride salts have three major drawbacks: (1) a need for isotopically separated chlorine to avoid high-cross-section nuclides; (2) the activation product <sup>36</sup>Cl, which 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 FS-MSR; however, the preliminary analysis indicates a reactor with potentially unique capabilities as a breeder reactor.

An example of an FS-MSR is the “nonmoderated version” of the TMSR, with graphite moderating blocks removed from the core. This reactor has very good neutronic properties in terms of its breeding ratio ( $>1.1$ ) and reactivity feedback coefficients. The operational limitations associated with graphite in the core caused by irradiation are eliminated. The reactor is composed of a single salt channel surrounded by a thorium blanket and two axial reflectors made of ZrC. The ZrC reflectors are used to avoid the use of a moderator material. As a fast reactor, the “nonmoderated” TMSR requires a larger amount of fissile matter than that required by a thermal-spectrum MSR.

Parametric studies evaluated different concentrations of heavy nuclei in the fuel salt and reprocessing [13] rates for the molten salt. These parameters strongly influence neutron energy moderation, actinide solubility, and the initial fuel inventory. A conceptual 2500-MW(t) FS-MSR was developed in which the salt contains 17.5 mole % of heavy nuclei fluorides and 200 kg of heavy nuclei per day is reprocessed. Such TMSRs can be operated with a thorium fuel cycle and be started initially using (1) 4.6 tons of  $^{233}\text{U}$  mixed with  $\sim 37$  tons of thorium or (2) 7.3 tons of fissile plutonium (4.5 mole % plutonium trifluoride) with thorium. In terms of burning efficiency, after about 40 years the TMSRs started with TRU elements become equivalent to TMSRs directly started and operated with  $^{233}\text{U}$ . At this time, 85% of the initial TRU inventories have been burnt. The reactivity feedback coefficients of these fast-spectrum TMSRs are negative for all HN proportions with a reactivity coefficient of approximately  $-7$  pcm/K when at equilibrium for both the  $^{233}\text{U}$ -started and TRU-started TMSRs. This ensures an excellent level of deterministic safety [14].

### ***MSR and actinide burning in fast spectrum***

European theoretical and experimental studies, led by Russia, are under way to examine and demonstrate the feasibility of the MOlten Salt Actinide Recycler & Transmuter (MOSART) system to reduce long-lived waste toxicity and to efficiently produce electricity in a closed fuel cycle. These activities are part of the International Science and Technology Center project 1606, the International Atomic Energy Agency cooperative research program “Studies of Innovative Reactor Technology Options for Effective Incineration of Radwaste” and the Euratom 6<sup>th</sup> Framework Program ALISIA project [15, 16]. MOSART is a single-stream fast-spectrum MSR fueled with different compositions of plutonium and minor actinides from LWR SNF without the use of uranium or thorium.

The start-up and feed material scenarios include plutonium and minor actinides from PWR enriched uranium (scenario 1) or mixed-oxide SNF (scenario 2). The fuel-salt mixture is 15LiF-58NaF-27BeF<sub>2</sub> (mole percent) with a melting point of 479°C. Depending upon the feed material, the salt at equilibrium contains 1.05 to 1.3 mole % of actinide and lanthanide trifluorides. Transient to equilibrium in the 2400-MW(t) MOSART core requires about 10 years. Masses of plutonium and minor actinides in the primary circuit at equilibrium for scenario 1 and scenario 2 are respectively 7320 kg and 9346 kg. The specific salt was chosen, in part, because of its high solubility ( $> 2$ -mole % at 600°C) for actinide and lanthanide trifluorides—a requirement for TRU burning. The salt is sparged for removal of tritium, xenon, and krypton. The salt processing system removes the soluble fission products (rare-earth trifluorides) with an average residence time in the reactor of 300 effective full-power days. More rapid processing would reduce parasitic neutron losses but it would also increase the losses of actinides to the waste stream. The lithium is enriched to 99.99%  $^7\text{Li}$ .

The 2400-MW(t) MOSART system (Fig. 4) has a homogeneous core with intermediate-to-fast neutron spectrum. The core diameter is 3.4 m with a core height of 3.6 m. The core has 0.2-meter radial and axial graphite reflectors. The specific power is  $\sim 43$  W/cm<sup>3</sup>, with an effective neutron flux of about  $1 \times 10^{15}$  n cm<sup>-2</sup> s<sup>-1</sup>. The salt inlet temperature is 600° with an average outlet temperature of 715°C. The core inlet structure is designed to assure (1) the maximum temperature of the solid reflectors is controlled to assure reasonable lifetimes and (2) no reverse or stagnate flow. The mechanical design of the balance of the nuclear system includes four pumps operating in parallel with an out-of-core circulation time of  $\sim 4$  s. Heat is transferred from the primary salt to the power conversion system using a secondary NaF-NaBF<sub>4</sub> salt with a composition of 8–92 mole %.

The safety assessments show that the parameters are favorable for reactor safety, primarily because of the large negative density and fuel Doppler effects. The temperature reactivity coefficients vary from  $-4.125$  (scenario 1) to  $-6.625$  pcm/°C (scenario 2), depending upon the feed. This is for a pure actinide burner with no uranium or thorium. Preliminary calculations of kinetic and dynamic characteristics of the MOSART system indicate that it would exhibit high levels of controllability and safety. The option exists to add a thorium-containing salt blanket to produce fissile material.

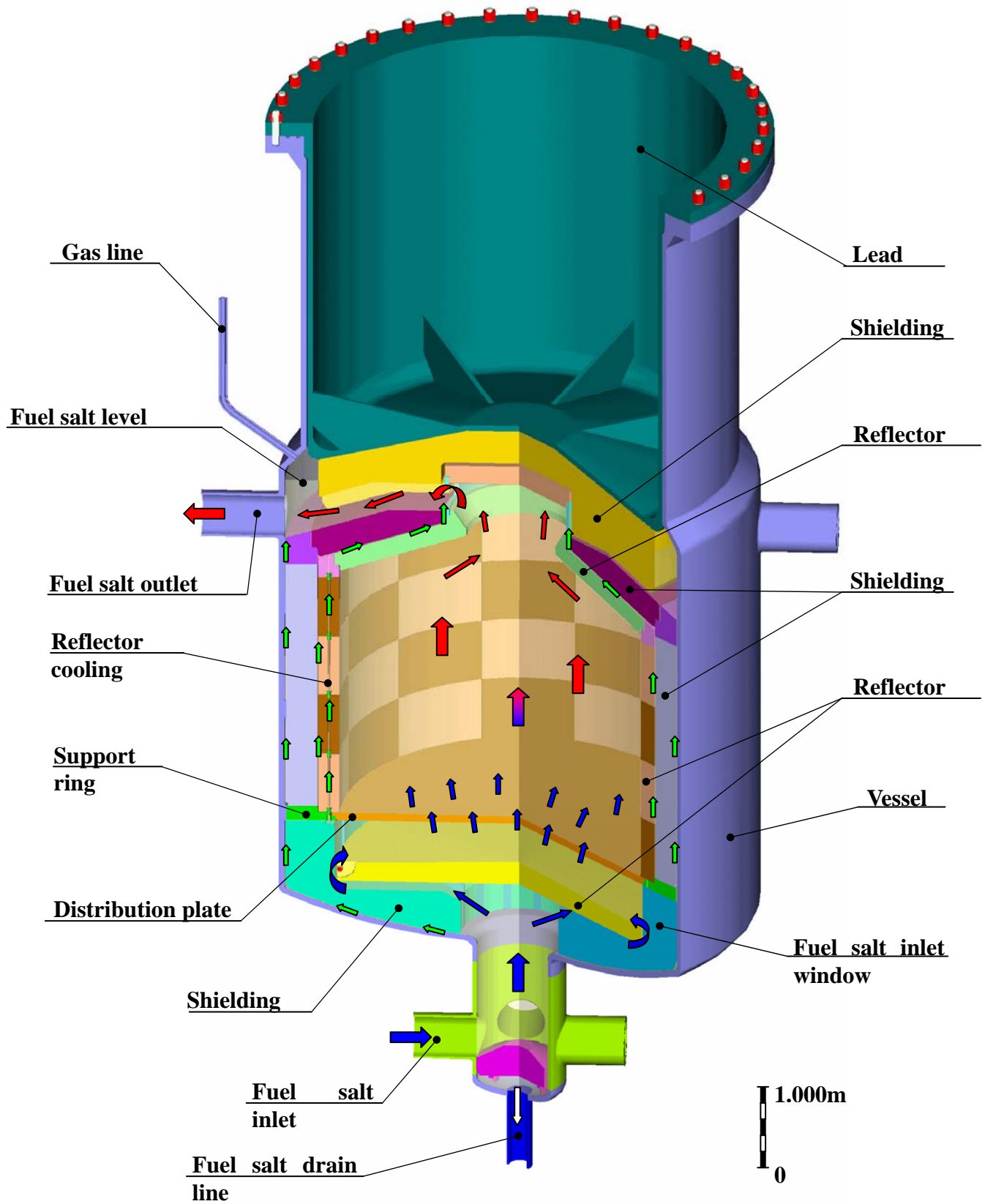


Fig. 4. MOSART core

## VI. FUSION

Liquid salts (primarily lithium-beryllium-fluoride salts) are 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. The economics of a fusion reactor are strongly dependent on the maximum amount of heat that can be removed by the first wall. Liquid salts [17, 18] may be used to form a flowing liquid wall inside the fusion machine to shield structures from fusion neutrons. The use of a liquid wall may allow extremely high power densities relative to solid-wall machines. Most of the initial work is focusing on inertia fusion machines with heavy-ion and laser drivers. Liquid salts are the primary candidates because of their very low vapor pressure.

## VII. CONCLUSIONS

The development and commercialization of a new coolant technology and its use in multiple reactor concepts is a major challenge. However, the increasing demands for high-temperature heat, the ability to convert such heat efficiently to electricity, and the interest in advanced reactors for breeding and waste management are creating the incentives to develop this family of technologies. The use of liquid salts as a coolant technology opens several new frontiers for nuclear energy.

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