Thermal- and Fast-Spectrum Molten Salt Reactors for Actinide Burning and Fuel Production

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**

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THERMAL- AND FAST-SPECTRUM MOLTEN SALT REACTORS FOR ACTININDE BURNING AND FUEL PRODUCTION

Charles W. Forsberg

Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831, forsbergcw@ornl.gov

In a molten salt reactor (MSR), the fuel is dissolved in a fluoride salt coolant. The technology was partly developed in the 1950s and 1960s. With changing goals for advanced reactors and new technologies, there is currently a renewed interest in MSRs. The new technologies include (1) Brayton power cycles (rather than steam cycles) that eliminate many of the historical challenges in building MSRs and (2) the conceptual development of several fast-spectrum MSRs that have large negative temperature and void coefficients, a unique safety characteristic not found in solid-fuel fast reactors. Earlier MSRs were thermal-neutron-spectrum reactors. Compared with solid-fueled reactors, MSR systems have lower fissile inventories, no radiation damage constraint on attainable fuel burnup, no spent nuclear fuel, no requirement to fabricate and handle solid fuel, and a single isotopic composition of fuel in the reactor. These and other characteristics may enable MSRs to have potentially unique capabilities and competitive economics for actinide burning and extending fuel resources. The status, unique characteristics, and recent worldwide advances in MSRs are described.

I. INTRODUCTION

In a molten salt reactor (MSR), the fuel is dissolved in a fluoride salt coolant. The concept[1] of the MSR was developed in the 1950s and two small thermal-neutron-spectrum MSRs were successfully built in the 1960s. The first reactor was part of a program to build a nuclear-powered aircraft, whereas the second reactor was built to test the concept of a molten salt breeder reactor (MSBR). The programs ended in 1976 when the United States decided to concentrate on a single breeder reactor concept—the sodium-cooled fast reactor. Today a renewed interest in MSRs exists for several reasons:

- *Goals.* The goals[2] for advanced reactors have changed in directions that match the intrinsic capabilities of MSRs.
- *Technological advances.* Major advances have taken place in the component technologies[3] of MSRs and the development of new MSR concepts such as fast-spectrum MSRs to extend fuel supplies[4] and burn actinides.[5]
- *Salt-cooled reactors*. Fluoride salts[6] have been developed as clean coolants to use (1) in high-temperature and fast reactor concepts using solid fuel, (2) in fusion reactors, and (3) as a high-temperature heat-transport fluid. These other applications are developing technologies that further advance the required MSR technologies.

While the nuclear power goals—economic and safe electricity production—remain unchanged, several other long-term goals[2] for advanced reactors have changed since the 1960s, when there were large MSR programs.

- *Actinide burning for waste management*. There is growing interest in destroying actinides accumulated in light-water reactor (LWR) spent nuclear fuel (SNF) to reduce the long-term hazards of SNF, destroy the radionuclides that dominate long-term repository risk to the public, and reduce the size of the repository. The specific goals have not been defined; however, the key radionuclides are plutonium, neptunium, and americium.
- *Fuel sustainability*. Historically, advanced nuclear research programs have emphasized the development of breeder reactors with high breeding ratios because it was thought that uranium was very scarce. Today it is recognized that there are large uranium resources and that the economics do not require breeder reactors with high breeding ratios. What is desired is an economically viable transition strategy to advanced reactors with sustainable fuel supplies.
- *Nonproliferation*. A much greater emphasis presently exists on development of reactors and associated fuel cycles with greater proliferation resistance.

Decisions on actinide burning may have major impacts on the preferred methods to ensure fuel sustainability. When viable, the first rule of waste management is to avoid the generation of wastes. Two fertile materials (^{232}Th and ^{238}U) can be converted to fissile materials and form the basis of a long-term sustainable closed fuel cycle. Thorium-232 plus a neutron yields fissile ^{233}U and ^{238}U plus a neutron yields fissile ^{239}Pu. The uranium–^{239}Pu fuel cycle generates large quantities of transuranic (TRU) actinides. The thorium–^{233}U fuel cycle generates almost no TRU actinides, because it takes many neutron captures to convert ^{233}U to a TRU isotope. If society requires that actinides be destroyed to assist waste management, serious consideration must be given to fuel cycles that minimize both the production of actinides and the costs associated with actinide destruction. Under such conditions, reactor systems that can be started using LWR actinides and convert to thorium–^{233}U fuel cycles must be considered.

Changing goals imply that the choice of the optimum reactor system may change. All solid-fuel reactors have a common set of constraints and limitations. MSRs have fundamentally different characteristics than all solid-fuel reactors. If the common solid-fuel-reactor constraints and limitations are major barriers to meeting potential future goals such as actinide burning, the MSR offers the alternative approach that bypasses those challenges. This paper describes how the changes in goals, the intrinsic characteristics of MSRs, and advances in MSR technology may offer alternative viable solutions for burning of actinides and long-term fuel sustainability.

II. MOLTEN SALT REACTORS

In an MSR (Fig. 1), the molten fluoride salt with dissolved fissile, fertile, and fission isotopes flows through a reactor core. Historically, MSRs have been thermal-neutron reactors in which neutrons in the reactor core were moderated by unclad graphite. Today both thermal- and fast-spectrum MSRs are being investigated.

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. In the preconceptual 1000-MW(e) designs developed in the early 1970s, the liquid fuel salt typically enters the reactor vessel at 565ºC and exits at 705ºC and ~1 atmosphere (coolant boiling point: ~1400ºC). Volatile fission products (e.g., krypton and xenon) are continuously removed from the fuel salt. The secondary coolant loop with a liquid salt in a modern MSR would transfer the heat to (1) a hydrogen production facility or (2) a Brayton or supercritical carbon dioxide cycle for electricity production. The term liquid salt denotes a clean fluoride salt that does not contain fissile materials, fertile materials, or fission products.

Compared with solid-fuel reactors, the MSR has many unique characteristics. Under emergency conditions, the liquid fuel is drained to passively cooled critically safe dump tanks. Via the use of freeze valves (cooled sections of piping) and other techniques, this safety system can be passively initiated upon overheating of the coolant salt. MSRs operate at steady-state conditions with no change in the nuclear reactivity of the fuel as a function of time. Fuel is added or subtracted as required. Last, fission products can be removed online and solidified. This process can minimize the radioactive inventory (accident source term) in the reactor core and can significantly reduce the risks from reactor accidents.

In the context of MSRs, fission products can be divided into several categories. Volatiles, such as noble gases, and insoluble fission products (primarily noble metal fission products) are released from the molten salt and thus must be captured and converted into appropriate waste forms at the reactor. The other fission products and the actinides are highly soluble in the salt and can be separated from the salt at the reactor. Alternatively, the salt can be transported offsite to a separate salt processing facility to separate fission products from the salt with recycle of the salt.

The liquid fuel allows online refueling and a wide choice of fuel cycle options that define the characteristics of the reactor. The reactor can be deployed (1) as an actinide burner to destroy actinides from other reactors, (2) as a burner reactor with a once-through fuel cycle, (3) as a thorium–^{233}U breeder cycle, (4) as a denatured thorium–^{233}U breeder cycle, or (5) in several other roles. Some of the options, such as a thermal-neutron-spectrum thorium–^{233}U breeder cycle, require online refueling and thus cannot be practically achieved using solid fuels.

The limited economic studies that have been conducted indicate a potentially competitive reactor system when the system includes both the reactor and associated fuel cycle. Compared with other reactor types, there are stronger economic incentives for large sites with multiple MSRs to allow the use of common services such as off-gas treatment systems and salt processing systems for multiple reactors. Large economics of scale are associated with these chemical processing operations. The characteristics of the salt also facilitate the economics. All of these salts have high volumetric heat capacities relative to other reactor coolants. These physical properties[7] result in small equipment (pipe diameter, valve size, heat exchangers, etc.) relative to those for reactors that use other coolants. Table I provides a comparison of different reactor coolants.

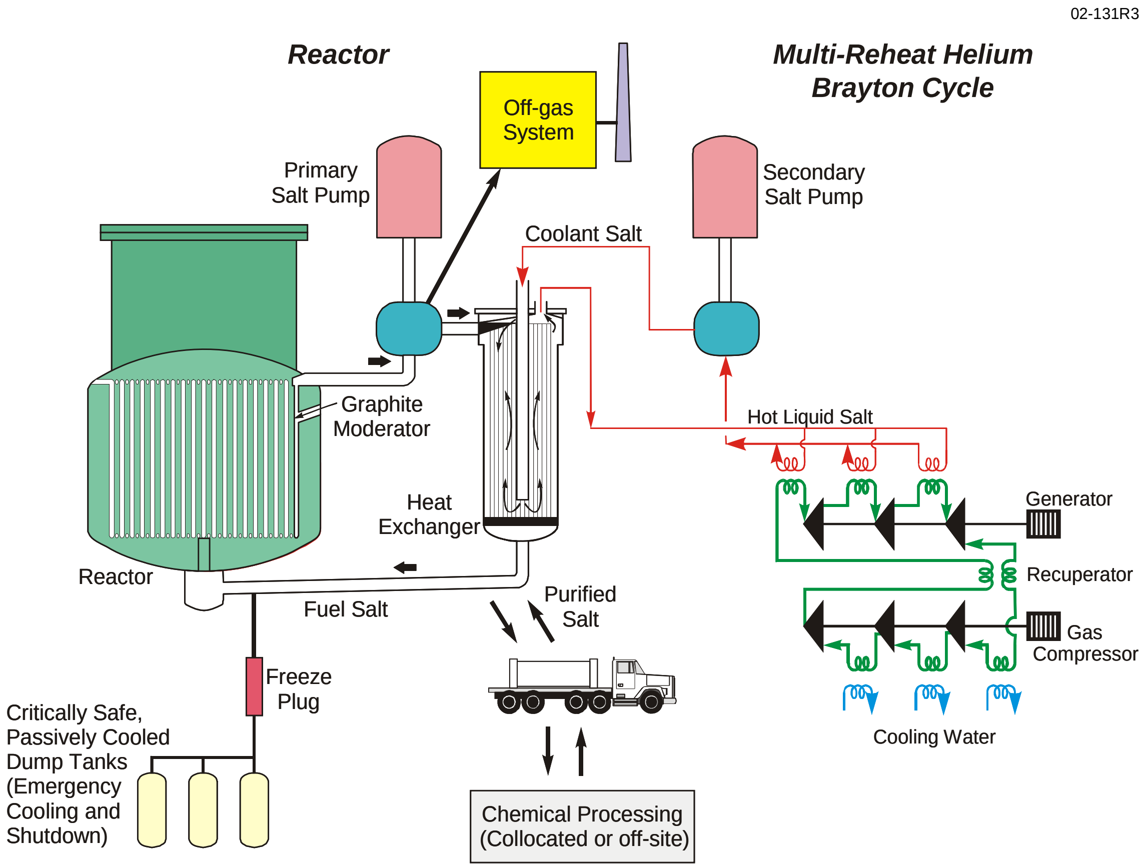

Fig. 1. MSR with multi-reheat helium Brayton cycle.

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 1000-MW(t)	0.6	2.0	12.3	0.5

III. NEW TECHNOLOGIES

The rebirth in interest in MSRs is partly driven by recent technological developments[3] that are expected to significantly improve the viability and economics of MSRs. Examples include:

- *Brayton power cycles.* Because of the melting points of molten salts (350 to 500°C), MSRs are intrinsically high-temperature reactors. When MSRs were first developed, steam cycles were the only power cycle options. Coupling steam cycles to MSRs was complicated because of the need to avoid freezing of the salt, diffusion of tritium through hot heat exchangers from the MSR into the steam, and other constraints. The development of closed helium and nitrogen Brayton power cycles has eliminated many of these technological challenges[3] (salt freezing, tritium migration, etc.), significantly improved power plant efficiency, and reduced capital costs. Power cycles now exist that match the characteristics of MSRs.

- *Fast-spectrum MSRs.* Fast-spectrum MSR concepts have been recently developed with unique capabilities in terms of actinide burning[5] and fuel production.[4] This is partly a consequence of a broader understanding of fluoride salt chemistry. The preferred salt is determined primarily by three factors: physical properties that determine its behavior as a coolant that must flow through the reactor core and heat exchangers, the neutronics, and the chemistry. Different salts have different properties; thus, a viable molten salt for a thorium–^{233}U breeder MSR is different from the optimum salt for actinide burning. The development of fast-spectrum MSRs requires salts with (1) higher solubilities for fissile and fertile materials and (2) less neutron moderation.

- *Safety.* Unlike solid-fuel fast reactors, fast-spectrum MSRs have large negative temperature and void coefficients because as the temperature rises or voids are formed, the fuel salt is expelled from the reactor core.[4-5] The choice of salt determines the thermal expansion coefficient of the salt; thus, salt selection strongly impacts temperature and void coefficients. This is a unique safety advantage for a fast-spectrum MSR and may enable such reactors to burn only waste actinides with zero production of actinides—something that is not practical with traditional solid-fuel fast-spectrum reactors that require some quantity of ^{238}U or ^{232}Th for acceptable nuclear-reactivity safety.

IV. FUEL CYCLE

MSRs use a liquid fuel that has major implications in terms of the fuel cycle. For actinide-burning missions, the use of a liquid fuel has several unique advantages.

- *Isotopics.* The isotopics of the actinides, particularly the higher actinides, vary significantly between different batches of LWR SNF, with major differences in nuclear properties. If the higher actinides are to be recycled in a solid-fuel reactor, the fissile and isotopic content of each fuel pellet must be tightly controlled to prevent fuel-clad hot spots that can damage the fuel in the reactor. This requires that the fuel fabricator mix many batches of recycle actinides to obtain a homogeneous mixture for fuel fabrication—a difficult and expensive task because of the properties of these actinides: very high activity, small critical masses, and high rates of decay heat generation. In an MSR, each batch of actinide fuel feed is a small fraction of the core inventory and can be slowly added to the entire reactor inventory. The difficulties of variable actinide feed materials are avoided because all feeds are blended with the entire actinide inventory in the reactor and the liquid fuel cannot be damaged by excessive temperatures.

- *Fuel design and fuel fabrication.* The fabrication of solid fuels containing high-burnup plutonium with ^{238}Pu, americium, and higher actinides is difficult because of the high activity and decay heat associated with these isotopes. In particular, americium presents major challenges because (1) americium oxides are volatile at higher temperatures, which complicates fabrication of fuel pellets, and (2) the radioactive decay of americium generates large quantities of helium in fuel assemblies over time. No fuel fabrication is required for an MSR, thus avoiding the fuel fabrication challenges. All of the actinides, including americium fluorides, are highly stable in fluoride salts.

- *Inventory.* MSRs have lower fissile inventories (Table II) than other reactor systems. This is a consequence of several factors: (1) no large out-of-core SNF inventories that must be cooled before transport to reprocessing plants; (2) high power densities, which are a consequence of no power-density limits imposed by solid-fuel peak temperature constraints; (3) online addition or subtraction of fissile materials for reactivity adjustments; and (4) removal of high-cross-section fission products (such as xenon) from the reactor core. In solid-fuel reactors, the fuel must have excess fissile material to overcome the effects of fuel burnup and the buildup of neutron-absorbing fission products between refuelings. Minimizing the actinide inventories minimizes many of the risks and costs associated with actinide burning.

TABLE II. Fissile Inventories [Mg/GWe in Reactor] of Different Reactor Systems[a]

	Reactor	Reactor and Fuel Cycle	Commentary
MSR (thermal/epithermal)	1.45	1.45	Thorium Molten Salt Reactor (EU)
MSR (Fast)	5.5	5.5	Thorium Molten Salt Reactor (EU)
Pb FBR	6.7	20.1	BREST (Russia)
Na FBR	4.1	12.3	European Fast Reactor
He GFR	5.7	17.1	Gas-Cooled Fast Reactor (France)

[a]For all fast reactors, the ^{239}Pu equivalent mass is given (multiply it by 1.5 to find the total plutonium inventory). Thermal, epithermal, and fast refer to the neutron spectrum. FBR = fast breeder reactor; GFR = gas-cooled fast reactor; EU = European Union.

The system characteristics of MSRs provide several unique barriers to strengthen proliferation resistance. A full assessment of an MSR will require consideration of both the reactor and any associated processing facilities.

- *Isotopics*. After startup and operation for some time, all the fuel salt has only one composition—that of high-burnup fuel with poor fissile isotopics for use in weapons. If the MSR is being used for actinide burning, any batch of "new" actinides is diluted with the inventory of high-burnup actinides upon its addition to the reactor. In contrast, in solid-fuel reactors wide variations are present in the fissile isotopics between fuel elements and along the length of each fuel element. If the fuel is diverted, parts of the SNF will be low-burnup fuel with isotopics that are more favorable for use in weapons.

- *Fissile inventory*. The low fissile inventories and lack of SNF (1) reduce the MSR safeguards footprint to the reactor site and (2) imply that any major diversion of fissile material would shut down the reactor for power generation. Once a system is operating, there is no need for enrichment services or reprocessing of LWR fuel to provide added fissile material.

- *U-233 isotopics*. All thorium–^{233}U fuel cycles produce the impurity ^{232}U with its decay product, which emits a 2.6-MeV gamma ray. This phenomenon has two implications: it (1) the high radiation levels complicates the fabrication of weapons with ^{233}U and (2) produces a very bright signal that makes it much easier to detect ^{233}U than it is to detect plutonium. Such high-gamma fissile materials would be a major challenge if fabricating solid fuels; but, are a much smaller constraint with molten salts.

For long-term sustainability the goal has been to develop breeder reactors. All of the reactor concepts in Table II are breeder reactors. The low fissile inventory for an MSR system relative to those for other reactor types implies that a very large number of MSRs can be started up from the actinides within the existing worldwide SNF inventories. Because of the smaller quantities of actinides that are required, the low fissile inventories imply that if actinides from SNF are used to start up MSRs, the initial fissile-fuel cost of an MSR per unit electric output is relatively insensitive to the cost of reprocessing LWR SNF. Strategically, the small fissile startup inventories for MSRs imply that the world is rapidly producing enough SNF to provide the fissile inventory for a global MSR economy.

However, major challenges exist in developing reliable and economic systems to process the molten salts. Furthermore, the implications of these radically different systems are only partly understood because (1) the new technologies are creating new MSR options, (2) the goals for reactors are changing, and (3) only very limited studies have been done since the 1970s.

V. REACTOR OPTIONS

Three different classes of MSRs (Table III) that use fluoride salts are currently being investigated. All produce electric power. There are many variants that depend primarily upon the fuel cycle associated with the reactor. The different reactors have different salt compositions that reflect the different missions.

TABLE III. Classes of Molten Salt Reactors

Characteristic	Molten Salt Breeder Reactor	Thorium Molten Salt Reactor	MOSART
Mission	Power (breeder)	Power (breeder)	Actinide burner
Neutron flux	Thermal-Epithermal	Fast	Fast
Core design	Graphite moderator	Tank with no internals	Tank with no internals
Salt composition[a] [mol %]	67^7LiF-33BeF	80^7LiF-20(HN)F_4	58NaF-15^7LiF-27BeF_2
Thermal power [MW(t)]	2250	2500	2400
Electrical power [MW(e)]	1000	1000	1100
Inlet temperature (°C)	565	630	600
Outlet temperature (°C)	705	730	715
Active core diameter (m)		1.25	3.4
Active core height (m)		2.6	3.6
Notes	Original design for a thorium–^{233}U fuel cycle	Startup on LWR actinides or ^{233}U with long-term transition to thorium–^{233}U fuel cycle	Feed: LWR UO_x or MOX actinides

[a]Heavy nuclides

V.A Molten Salt Breeder Reactor (MSBR)

Between 1950 and 1976 a large MSR development program was conducted in the United States, two test reactors were successfully operated, a design of a 1000-MW(e) reactor was completed, and plans were developed to construct a demonstration reactor. Multiple large-scale test rigs and other tests were conducted in support of these programs.

The MSR was originally developed for the aircraft nuclear propulsion program, where a very high power density was required to minimize the reactor size and hence the weight of the reactor shielding. It was then developed as an MSBR in parallel with the sodium-cooled fast reactor. Ultimately, it was decided to concentrate efforts on the development of a single breeder reactor concept—the sodium-cooled fast reactor. These billion-dollar programs created the base MSR technology. The relatively trouble-free 8-MW(t) Molten Salt Reactor Experiment (MSRE) provided an effective demonstration of many aspects of the reactor technology.

The traditional MSBR, as described above, has graphite in the reactor core with a thermal-epithermal neutron spectrum. The graphite-to-fuel ratio is adjusted to provide the optimal neutron balance, an epithermal neutron spectrum. Most of the reactor technology was demonstrated during the operation of the MSRE; however, the development of the associated fuel cycle lagged behind the development of the reactor. Although the chemistry of the fuel cycle was demonstrated, many of the steps were not demonstrated on an engineering pilot scale. It is likely that there major changes in the fuel cycle would result from changing goals and advances in chemistry and process equipment design.

V.B Thorium Molten Salt Reactor (TMSR)

The original MSR project ended in 1976. The performances and design parameters of the MSBR were reexamined using modern methods by the MOST[8] (acronym for MOlten Salt reactor Technology) project supported by Euratom in 2002–2004 using modern methods. The project (1) confirmed the potential of the MSR as breeders or burners and (2) identified the critical issues to be addressed by R&D in response to some deficiencies of the MSBR—particularly, core neutronic stability (uncertainty in temperature feedback coefficients in thermal-spectrum MSRs with low margins), 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.

The combination of modern computational methods, more complete nuclear-property cross sections, and a more complete understanding of fluoride salt chemistry enabled the project to explore a wide variety of MSR designs, with systematic analysis of the effect of such parameters as reprocessing time, moderation ratio, core size, and content of heavy nuclei in the salt. This resulted in several attractive reactor configurations[9] for MSBRs with (1) thermal, (2) epithermal, or (3) fast spectrums.

These developments led to the concept of the Thorium Molten Salt Reactor (TMSR) using a binary salt, LiF-$(HN)F_4$, with the $(HN)F_4$ content near 22% (eutectic point), corresponding to a melting temperature of 565°C. In this terminology, "HN" refers to the heavy nuclides—thorium, uranium, and actinides. The analysis suggested that the fast-neutron-spectrum version (no graphite moderator) was the most promising and had the simplest configuration. The use of a relatively simple LiF-$(HN)F_4$ salt avoids toxic beryllium and may simplify process flowsheets.

Traditional thermal-spectrum MSRs require relatively rapid processing of the molten salt if they are to be breeder reactors. The fast-spectrum MSRs has a higher breeding ratio that enables the reactor to be a breeder reactor with much lower rates of molten-salt processing to remove fission products. This significantly reduces the requirements and hence the costs associated with molten-salt processing.

The TMSR has several unique characteristics: (1) a reactor core that has nothing but flowing molten salt with no internals subject to radiation damage and (2) large negative void and temperature coefficients. While the vessel liner will receive high radiation doses, it is a relatively simple component that is replaceable. A major safety challenge in solid-fuel fast reactors is that loss of the coolant results in a positive power coefficient. However, in MSRs, because molten salts expand, the creation of a void pushes fuel salt out of the core and shuts down the reactor. This is a unique safety advantage of fast-spectrum MSRs.

Fuel cycle assessments indicated that such a reactor could be started with ^{233}U or other actinides (plutonium, americium, and curium) from an LWR and would evolve into a reactor operating on a thorium–^{233}U fuel cycle. For startup evaluations of LWR actinides, an actinide composition corresponding to pressurized-water-reactor (PWR) SNF 5 years after reactor discharge was used: 87.5% of Pu (^{238}Pu: 2.7%, ^{239}Pu: 45.9%, ^{240}Pu: 21.5%, ^{241}Pu: 10.7%, and ^{242}Pu: 6.7%); 6.3% of Np: 5.3% of Am: and 0.9% of Cm. In effect, this is a reactor that can burn LWR actinides while transitioning to a thorium fuel cycle based on ^{233}U that produces almost no actinides because of the many neutron captures required to convert ^{233}U to plutonium.

V.C MOlten Salt Actinide Recycler & Transmuter (MOSART)

In parallel, a series of theoretical and experimental studies were undertaken in Europe to demonstrate the feasibility of MSRs to reduce long-lived waste toxicity and to efficiently produce electricity in a closed cycle. This work was led by the Kurchatov Institute in Russia as part of International Science and Technology Center project 1606 and the International Atomic Energy Agency–coordinated research "Studies of Innovative Reactor Technology Options for Effective Incineration of Radioactive Waste" and European Union ALISIA project in the European Commission 6th framework program.[10]

The single-stream MOSART concept is a fast-spectrum (no-moderator) MSR fuelled with compositions of plutonium plus minor actinide trifluorides from PWR SNF—either once-through SNF or mixed-oxide (MOX) SNF. The MOSART salt contains no uranium or thorium and thus is a pure actinide burner. As a consequence, the reactor destroys the maximum quantities of actinides per unit of energy output. The basis for this advanced actinide burner MSR is the use of the sodium–lithium–beryllium fluoride salt with its high solubility for actinides. The salt composition is chosen to match the requirements for an actinide burner fuelled only with actinide fluorides. Safety analysis[11] have confirmed the favorable behavior of the MOSART concept during unprotected transients.

V.D Once-Through MSR Actinide Burners

Traditional actinide-burning strategies for both liquid-fuel and solid-fuel reactor systems involve burning the actinides along with processing the fuel for recycling of the actinides back to the reactor. Another strategy proposed has been proposed by Dr. Charles Bowman[12]—burning LWR TRU in a once-through MSR that does not have a molten salt processing plant. In this concept, MS with TRU from LWR SNF is continuously added to the reactor. An equal volumetric rate of molten salt is continuously extracted from the reactor along with actinides and fission products and is disposed of as waste. This avoids most of the costs of processing the molten salt.

The TRU transmutation capability of molten salt reactors of different designs was investigated at the University of California, Berkeley, and compared with the transmutation characteristics of solid-fuel reactors.[13–14] It was found that a core without graphite moderator is the preferred design option: it offered the best neutron balance and most compact design and alleviated the graphite-lifetime problem. It was also found that the transmutation effectiveness improves with increasing power density and that the shorter the LWR spent fuel cooling time is, the better becomes the MSR neutron balance. The optimal MSR design offers a high transmutation capability—fissioning of as high as 99.8% of the TRU feed. This is possible because of the choice of molten salt, a fluoride salt with sodium that allows for high concentrations of fission products in the salt. The transmutation capability of the MSR is also rated[13–14] in terms of final waste radiotoxicity, decay heat, spontaneous fission neutron emission, fissile weight %, and ^{237}Np inventory.

The transmutation properties of a critical MSR were consistently compared with those of three types of solid-fuel reactors: lead-cooled fast reactor (LFR), the sodium-cooled fast reactor (SFR), and a PWR. It was found that the fast-reactor spectrum gives the best transmutation performance, followed by the MSR and PWR spectra. Assuming that 0.1% of the actinides fed into the molten-salt processing plant or discharged to the solid-fuel recycling plant are lost to the waste stream, it was found that the MSR has the highest fractional transmutation—due primarily to its high specific power. The SFR and the LFR had the second- and the third-highest fractional transmutations.

VI. OTHER CONSIDERATIONS

VI.A Fast-Spectrum MSR Accident Criticality Safety

Two reactivity-based safety issues are associated with fast-spectrum reactors: reactor control and criticality safety under accident conditions. As noted earlier, fast-spectrum MSRs have large negative temperature and void coefficients because liquid fuel is expelled from the core if voids are formed or if the temperature increases. The other criticality safety challenge associated with fast reactors is that criticality can occur under accident conditions if the fissile materials leak from the primary system and come near neutron moderators—such as concrete. The critical masses in thermal-neutron environments are much lower than those in fast reactors. For a liquid-fuel reactor with mobile fuel, such accident criticality scenarios are of particular importance.

A strategy to ensure accident criticality safety for fast-spectrum MSRs has been developed based on technology being developed for the Advanced High-Temperature Reactor (AHTR). The AHTR is a high-temperature reactor[15–16] that uses coated-particle fuel (the same fuel used in gas-cooled high-temperature reactors) and liquid-fluoride-salt coolants. Because both systems use liquid salt cooling, they face a series of common challenges. The plant layout that was developed for the AHTR[17–18] is applicable to the fast-spectrum MSR and provides protection against nuclear criticality[19] in an accident.

Figure 2 shows a common plant layout for the AHTR and a fast-spectrum MSR. The major differences are that (1) the AHTR uses solid fuel rather than liquid fuel used by the MSR and (2) the MSR has dump tanks for the molten salt—a feature that does not exist in the AHTR. In either system the closed primary reactor system is in a pool of lower-cost liquid "buffer" salt. The primary salt coolant does not mix with the pool buffer salt. Instead, the primary system salt (the primary salt coolant for the AHTR and molten fuel salt for the MSR) goes through the reactor core, the intermediate heat exchanger, and the primary pumps before returning to the reactor core. The buffer-salt pool is cooled with a direct reactor auxiliary cooling system (DRACS), the same technology used in some sodium-cooled fast reactors. During normal operation, the buffer salt is at the same temperature as (or at a lower temperature than) the coldest primary salt.

If the intermediate heat exchangers do not remove the reactor heat, hotter primary coolant exits the heat exchangers. The temperature difference between the primary salt in uninsulated pipes and the buffer salt then dumps decay heat to the pool. Decay-heat removal can be enhanced by a secondary loop containing a fluidic diode and a heat exchanger that is connected between the top and bottom plenums of the reactor core. The fluidic diode allows high primary-system salt-coolant flow in one direction with low pressure drops but low primary-salt flow in the other direction with high pressure drops—the normal condition when the pumps are operating. If the pump stops, hot salt from near the top of the reactor flows by natural circulation down the loop and through a heat exchanger, dumps its heat to the pool, and enters the bottom of the reactor core plenum.

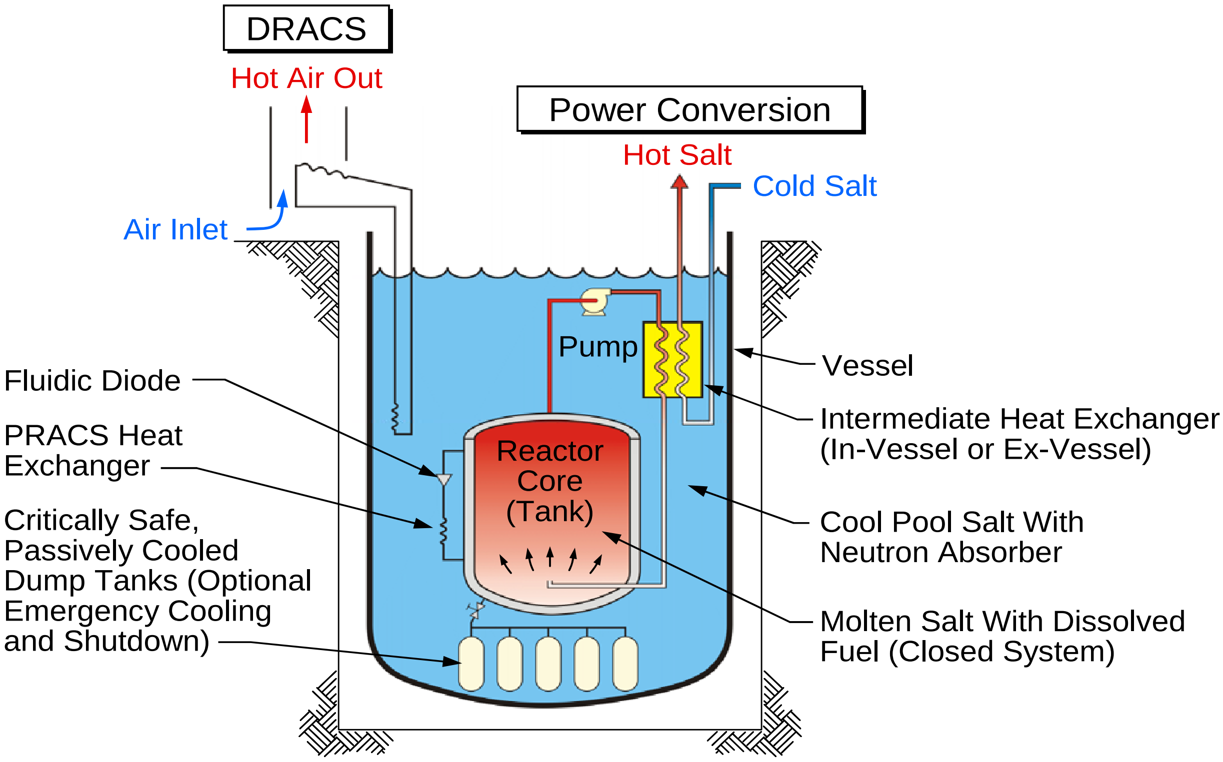

Fig. 2. General plant configuration for the AHTR and fast-spectrum MSR (Dump tanks only for fast-spectrum MSR). PRACS = pool reactor auxiliary cooling system.

If a primary system leak occurs in the fast-spectrum MSR, (1) the molten salt leaks into the buffer-tank salt or (2) the buffer-tank salt leaks into the primary-system molten salt. The buffer-tank salt contains the same salt or a different salt than the primary system except that it has a high concentration of rare-earth neutron absorbers. Criticality is avoided by mixing two salts with very similar chemistries but different nuclear properties. The similar chemistry ensures that no mechanisms exist to separate the rare earths and fissile materials. For the MSR, the buffer tank would likely include dump tanks under the core to drain the fuel salt to critically safe, passively cooled tanks during maintenance and under some accident conditions.

The tank-within-the-tank configuration has several other benefits. In a beyond-design-basis accident with vessel failure, the pool salt provides a method to ensure long-term decay-heat removal by filling the space between the vessel and silo with liquid salt. This assures heat can be transferred to the ground without excessively high temperatures in the reactor. The pool salt tank has the primary insulation. There is high assurance that temperatures are maintained above the melting points of the salts because of the high heat-capacity of the pool salt and the lower surface area for heat losses of the pool vessel versus the primary system. Because these fluoride salts are transparent, the outside of the primary system can be inspected by optical methods[20–21] from the buffer salt tank even when the tank is full of salt.

VI.B MSR Operating Temperatures

There are two constraints on MSR operating temperatures. The minimum temperature is determined by the temperature required to have good physical properties of the salt as a coolant. This temperature is typically 50 to 100°C above the melting point[7] of the salt. The peak operating temperature of a MSR is limited by the materials of construction because the boiling points of these salts are all above 1200°C—temperatures far above the limits of materials of construction.

Three materials have good corrosion resistance to molten salts: high-nickel alloys, molybdenum, and carbon. The temperature limits for high-nickel alloys, the current material of construction, are about 750°C. This implies a 100 to 150°C temperature rise across the reactor core. Molybdenum alloys can operate at higher temperatures but are expensive and very difficult to fabricate. The recent development of carbon composites for vessels and heat exchangers may ultimately allow much higher MSR temperatures. This has major implications.

- *Very high temperature reactor*. With higher-temperature materials of construction, the MSR is a very high temperature reactor and can meet the needs for high-temperature heat.

- *Economics*. Because no solid fuel is present, no limits on reactor power-core density exist. However, there are limits on how fast molten salt can be pumped through the reactor core. When molten salt leaves the reactor core, it removes some of the delayed neutron fraction in the fuel that is used to control the reactor. Reactor-control considerations limit linear flow rates through the core. However, if the molten salt can be heated by 300°C across the core rather than 150°C, the power density can be doubled with the same flow rate through the reactor core. Raising temperatures raises the reactor power level and electrical plant efficiency but may not change the reactor size. Other changes occur, such as higher radiation damage to the reflector.

VI.C. Chloride-Salt MSRs

Since the 1950s there have been multiple proposals for MSRs using chloride salts. Recent studies in France have begun to provide an understanding of the characteristics of a chloride salt. The French concept is called REBUS[22] and uses a classical plutonium fuel cycle with trichlorides of uranium and TRUs dissolved in the sodium chloride: that is, 45 mol % (U + 15.6% TRU)Cl_3 + 55 mol % NaCl. Natural chlorine (composition: 75.4% ^{35}Cl and 24.6% ^{37}Cl) is used. The use of a chloride salt, with its higher atomic number, results in a harder neutron spectrum.

Two major advantages are associated with the use of this type of salt. The higher breeding ratio enables a breeding ratio significantly greater than one with relatively small rates of salt processing required to remove fission products because higher equilibrium fission product loading is allowed in the salt. The million tons of depleted uranium in storage could provide the fuel after the initial fissile loading.

However, there are major challenges: (1) a significantly smaller knowledge base for corrosion resistant materials in chloride salts compared to fluoride salts, along with a somewhat more complex salt chemistry[7, 23]; (2) a higher fissile inventory relative to other MSR concepts; (3) higher melting points of the salt; and (4) the choice of what chloride salt to use. REBUS uses natural chlorine with 75.4% ^{35}Cl and 24.6% ^{37}Cl 24.6%. In the fast-reactor spectrum, ^{35}Cl captures 5 times more neutrons than does ^{37}Cl. Furthermore, the ^{35}Cl generates ^{36}Cl, a long-lived radionuclide that complicates waste management. Thus, there are major neutronic and waste management incentives to use isotopically separated ^{37}Cl, as part of a longer-term MSR concept.

VII. CONCLUSIONS

Advanced reactors can be divided into two categories: solid-fuel reactors and liquid-fuel reactors. Because MSRs are liquid-fuel reactors, they (1) have fundamentally different capabilities and characteristics from solid-fuel reactors and (2) do not have the same potential common-mode failures (such as economic fabrication of higher-actinide fuels) that exist for all solid-fuel reactors for missions such as actinide burning. For some specific missions, such as burning actinides, MSRs offer unique advantages such as no fuel fabrication, a single isotopic composition in the reactor core, and burning actinides without the use of thorium or ^{238}U with secondary production of actinides. This feature minimizes the number of actinide-burning reactors to other power reactors.

There have been major advances in MSR technology within the last decade. Modern computational tools have enabled the exploration of alternative MSR concepts that, in turn, have enabled development of new concepts such as fast-spectrum MSRs. Simultaneously, experimental measurements have improved our knowledge of molten salt properties. New salt compositions have made possible fast-spectrum and once-through actinide-burning MSRs—reactor concepts that require molten salts with much higher solubilities for fission products and actinides. New technologies developed in other industries, such as Brayton power cycles, have eliminated many of the challenges associated with MSR concepts of the 1970s.

However, our understanding of MSRs is significantly less than that for solid-fuel reactors. There have been a limited number of recent studies and the new technologies (such as fast-spectrum MSRs) are effectively creating new reactor system options that have not been previously studied and assessed.

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