Molten Salt Reactors (MSRs)

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SUMMARY

Molten salt reactors (MSRs) are liquid-fueled reactors that can be used for actinide burning, production of electricity, production of hydrogen, and production of fissile fuels (breeding). Fissile, fertile, and fission products are dissolved in a high-temperature molten fluoride salt with a very high boiling temperature (-1400EC) that is both the reactor fuel and the coolant. The MSR is one of the six advanced reactor concepts identified by the Generation IV International Forum (GIF) as a candidate for cooperative development.[1]

In the last several years, MSRs have been the subject of renewed interest. Liquid-fueled reactors have unique capabilities in terms of burning actinides and thus offer the potential to reduce the long-term radiotoxicity of the waste from production of electricity. This is the primary basis of interest in MSRs by GIF, the French utility EdF[2], the Kurchatov Institute in Russia[3], and several other organizations. In many scenarios, MSRs are used to burn actinides from other power reactors and to produce electricity. There is also a longer-term interest in using the MSR for hydrogen production.

I. BACKGROUND

MSRs were first developed in the late 1940s and the 1950s in the United States for military jet aircraft propulsion.[4] In 1954, the 2.5 MW(t) Aircraft Reactor Experiment (ARE) demonstrated high-temperature operation at 815EC and established benchmarks in performance for a circulating fluoride molten salt (NaF-ZrF_4) system with the uranium dissolved in the salt.

While a nuclear aircraft was never deployed, the ARE was followed in the 1960s by a program to develop a breeder reactor. The Molten Salt Reactor Experiment (MSRE), an 8-MW(t) reactor, demonstrated many of the features required for a power generating reactor: (1) a ^7LiF-BeF_2 salt suitable for breeding applications; (2) graphite moderator compatibility with the fluoride salt; (3) stable performance; (4) Xe/Kr removal from the fuel and trapping in the off-gas systems; and (5) use of different fuels, including ^{235}U, ^{233}U, and plutonium. The MSRE successfully operated for 13,000 equivalent full-power hours between 1965 and 1968. A detailed 1000-MW (e) engineering conceptual design of a molten salt breeder reactor was developed. These programs[5] of the1950s and 1960s demonstrated the technical viability of these concepts. The MSR program was canceled when the United States decided to concentrate its reactor development program on a single concept.

Two primary factors have generated renewed interest in MSRs at the present time: (1) new missions such as actinide burning and hydrogen production, areas in which the MSR has some unique capabilities, and (2) new technologies, such as helium gas-turbine technologies, that may simplify and improve the economics of the MSR relative to other reactor concepts.

II. DESCRIPTION

A schematic of an MSR is shown in Fig. 1. The molten fluoride salt with dissolved fissile, fertile, and fission isotopes flows through a reactor core moderated by unclad graphite to a primary heat exchanger, where the heat is transferred to a secondary molten 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. The heat is generated directly in the molten fuel. The liquid fuel salt typically enters the reactor vessel at 565EC and exits at 705EC and -1 atmosphere (coolant boiling point: -1400EC). The reactor and primary system are constructed of modified Hastelloy-N or a similar alloy for corrosion resistance to the molten salt. Volatile fission products (e.g., Kr and Xe) are continuously removed from the fuel salt.

The secondary coolant loop transfers the heat to the power cycle or hydrogen production facility. The secondary coolant (1) provides isolation between the low-pressure reactor and either the power cycle (if electricity is being produced) or a hydrogen production facility and (2) chemically reacts and traps any tritium that escapes from the primary system. A small cleanup system removes the tritium from the secondary coolant.

The parameters developed for the MSBR conceptual design[6] developed in the late 1960s are shown in Table 1. These parameters are for a large ^{233}U-thorium, liquid-fuel breeder reactor designed for the production of electricity using a steam cycle.

MSRs have a low inventory of fissile materials compared with other reactors because (1) thermal neutron reactors require less fissile inventory than fast reactors; (2) a low fuel-cycle fissile inventory outside the reactor system; (3) little excess reactivity is required to compensate for burnup because fuel is added on-line; (4) direct heat deposition in the fuel/coolant that allows high power densities; and (5) the high-absorption fission products such as xenon are continuously removed.

The choice of molten fluoride salt depends upon the objectives for reactor operation. For operation as a converter reactor for electricity or hydrogen production or for burning of actinides, a salt similar to the ARE salt containing NaF and ZrF_4 could be used. These salts are inexpensive, do not produce tritium, and are relatively nontoxic. The salts have a high solubility for actinides and lanthanides; consequently, in all such fuel cycles (except the breeder reactor fuel cycle), the processing can be done offsite with up to 6 years between reactor refuelings. There is a century of industrial experience with graphite and fluoride salt compatibility; almost all aluminum metal is electrolytically produced using molten cryolite (3NaF-AlF_3) in very large graphite baths at -1000EC.

If the reactor is to be a breeder reactor, the fuel salt characteristics must be optimized, and will almost certainly be a mixture of ^{7}LiF, BeF_2, ThF_4 and UF_4. This mixture provides better neutron economy. A breeder reactor with efficient fuel production also requires on-line processing of the fuel salt because of the nuclear characteristics of breeding fuel with thermal neutrons using the ^{233}U-Th fuel cycle. In a thermal neutron breeder reactor, the breeding reaction is ^{232}Th + n 6 ^{233}Pa 6 ^{233}U. Unfortunately, ^{233}Pa has a moderately large absorption cross section and a half-life of 27 days. If it is left in the reactor, parasitic capture of neutrons by ^{233}Pa will occur, resulting in a significant reduction in the breeding ratio. To avoid this scenario and to obtain high breeding ratios, on-line processing is required for removal of the ^{233}Pa and storage outside of the reactor until it decays to ^{233}U.

Table 1. Design Characteristics of the 1970s Molten Salt Breeder Reactor

Net electric generation	1000 MW	Maximum core flow velocity	2.6 m/s
Thermal efficiency	44.4% (steam cycle)	Total fuel salt	48.7 m^3
Core height	3.96 m	^{233}U	1,500 kg
Vessel design pressure	5.2×10^5 N/m^2 (75 psi)	Thorium	68,100 kg
Average power density	22.2 kW/L	Salt components	^7LiF-BeF_2-ThF_4-UF_4
Graphite mass	304,000 kg	Salt composition (see entry above)	71.7-16-12-0.3 mol %

III. SAFETY

The reactor design characteristics minimize the potential for accident initiation. 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. Fuel is added as needed; consequently, the reactor has low excess nuclear reactivity. There is no need for excess fuel at reactor startup to compensate for fuel depletion or to have excess reactivity to override xenon poisoning. No significant buildup of xenon occurs over time. There is a strong negative temperature coefficient because increased temperatures lower the fuel-salt density and push fuel out of the reactor core. In normal operations, the control rods are fully removed from the reactor.

Many of the driving forces for an accident are reduced compared with those for other reactors. Fission products (except Xe and Kr) and nuclear materials are highly soluble in the salt and will remain in the salt under both operating and expected accident conditions. The fission products that are not soluble (e.g. Xe, Kr) are continuously removed from the molten fuel salt, solidified, packaged, and placed in passively cooled storage vaults. The chemical reaction of fluoride salts, both fuel and secondary system, with water or moisture is relatively benign. The accident source term—the quantity of radioactivity in the reactor core—is less than that in solid-fueled reactors. The primary system is low pressure with a fuel salt boiling point of - 1400EC. This eliminates a major driving force—high pressure—for transport of radionuclides in an accident from the reactor to the environment.

Molten salt reactors use passive emergency core cooling systems. If the molten reactor fuel salt overheats, its thermal expansion causes it to overflow by gravity and be dumped to multiple critically-safe storage tanks with passive decay-heat cooling systems. Freeze valves that open upon overheating of the salt can be used to initiate core dump of fuel. Drains under the primary system also dump fuel salt to the storage tanks if a primary system leak occurs. In MSRs, the primary system is located inside a large insulated sealed hot-box to avoid cold spots in the system. In addition to being the middle layer of a three-level defense-in-depth containment system (primary system, hot box, and containment building), this structure also ensures that any primary-system leak drains to the drain tank system. This design approach allows very large reactors to be built with passive safety systems.

IV. FUEL CYCLE

Four major fuel-cycle options exit to address different goals of reactor operation. The basic reactor remains unchanged except for the salt composition, salt-cleanup systems and off-site fuel cycle operations. Any of the MSRs can be started up using low-enriched uranium or other fissile materials. All ^{233}U fuel cycles require remote handling. With the except the breeder reactor fuel cycle, the processing for all the other fuel cycles can be performed off-site with removal of the fuel salt every few years.

Thorium-^{233}U breeder cycle. The breeding ratio is -1.06, with an equilibrium ^{233}U inventory of about 1500 kg (Table 1). After startup, only thorium is added as a fuel. On-line processing of the fuel salt is required for ^{233}Pa management and efficient removal of fission products.

Denatured thorium-^{233}U breeder cycle.[7,8] The addition of ^{238}U to improve proliferation resistance lowers the breeding ratio to slightly above one and results in a very low fissile plutonium (^{239}Pu and ^{241}Pu) inventory of -0.16 kg/MW(e).

Once-through cycle with minimal chemical processing.[9] The once-through fuel cycle converts thorium to ^{233}U internally in the reactor and uses 20% enriched uranium as fresh fuel to the reactor. The annual fuel consumption is -45 t/GW(e), or about one-fifth that of a light-water reactor (LWR).

Actinide burning.[10] This fuel cycle burns multi-recycle Pu, Am, and Cm from LWR spent nuclear fuel (SNF) or other sources and can produce denatured ^{233}U as a by-product. The penalty for burning actinides in an epithermal neutron flux is partly offset by the greater fission neutron yield of the higher actinides. In this mode of operation, about 10% of the electricity is produced from MSRs that burn the actinides from other reactors in the system.[3]

The fuel cycles[7,10] have very unusual plutonium isotopics with high concentrations of ^{242}Pu. Except when the reactor is used as an actinide burner, the quantities of transuranics are very low compared with those of traditional LWR fuel cycles. When starting with ^{232}Th, many neutron absorptions must occur to produce plutonium or a higher actinide. Much of the current interest in MSRs is a result of the capabilities to burn actinides to reduce waste management burdens. Because they are liquid-fueled reactors, MSRs offer three advantages over solid-fuel reactors in this application:

No isotopic blending. Different lots of SNF have very different Pu, Am, and Cm isotopics. The MSR has a homogeneous liquid fuel. Any fissile material can be fed to the reactor. The very different nuclear characteristics of different batches of higher actinides are addressed by the rate of addition to the homogeneous molten salt. In contrast, in solid-fuel reactors, the quantity and isotopics of the fissile materials in every location of every fuel assembly must be controlled to avoid local overpower conditions that burn out the fuel. With complex mixtures of isotopics, this process is expensive and difficult to accomplish. It requires development of fuels with different actinide compositions, complex designs of reactor cores, and complicated mixing of different batches of fissile materials to produce acceptable feeds to the fuel fabrication facilities.

No fuel fabrication. The higher actinides have small critical masses and high rates of decay heat, representing a serious technical and economic challenge for fuel fabrication. This is a non-issue for a MSR, because no fuel fabrication is required.

Minimal reprocessing. In an MSR, fission products are removed from the molten salt, while actinides remain in the salt. This is the reverse of traditional processing, in which clean fissile materials are extracted from SNF. In an MSR, the cleaned fuel salt is to be mixed back with the salt in the reactor. Some fraction of the fission products must be remove, but there is no reason to fully clean the salt. Processing would be done as a batch process at a collocated or off-site location.

V. ELECTRICITY AND HYDROGEN PRODUCTION

An important characteristic of the MSR is the ability to deliver most of the heat generated at high temperatures. Liquid coolants have high heat capacities and low pumping power costs in comparison with gas coolants. As a direct consequence, liquid-cooled reactors can deliver most of their heat at near-constant temperatures while gas-cooled reactors deliver their heat over a wide range of temperatures due to pumping power limitations. This difference between liquid-cooled and gas-cooled reactors is shown in Fig. 2, in which temperature data are displayed for several different types of reactors. This feature has important implications in terms of electricity production and hydrogen production.

A. Electricity Production

Early designs of the MSR proposed using a steam cycle for electricity production. Current proposals for a MSR use a helium Brayton cycle. The helium Brayton cycle has major advantages over the use of a steam Rankine cycle: simplified balance of plant with lower cost, improved efficiency, reduced potential for salt freezing in the heat exchangers, and simplified control of tritium within the reactor (trapping system is similar to that proposed for many high-temperature gas-cooled reactors).

The multi-reheat recuperated helium Brayton cycle (Fig. 1) has three or more stages of reheat and three stages of intercooling.[11] This is the Brayton cycle equivalent of the traditional multi-reheat Rankine cycle used by fossil-fired power stations. The helium pressure is reduced through three turbines in series, with reheating of the helium to its maximum temperature with hot molten salt before each turbine. Such power cycles are viable only with (1) indirect power cycles to deliver heat before each turbine and (2) liquid-cooled reactors, in which most of the heat from the reactor can be delivered at near-constant high temperatures. Calculations have shown that for the same reactor outlet temperatures, the multi-reheat Brayton cycle increases the thermal efficiency of the MSR to a level 5 to 6% above that of an equivalent gas-cooled reactor using a direct Brayton cycle. For exit temperatures of 705EC (current materials), the corresponding thermal-to-electrical efficiency is 45.5%. At temperatures approaching 1000EC, the efficiencies may exceed 60%.

B. Hydrogen Production

Thermochemical hydrogen production methods[12] require heat at low pressures and very high temperatures—typically above 800EC. These are the same requirements as for the Aircraft Nuclear Propulsion Program, which led to the initial development of MSRs. As a consequence, MSRs are potential candidates for hydrogen production.

VI. RESEARCH AND DEVELOPMENT ISSUES

The Generation IV activities have identified areas requiring major R&D.

Actinide burning. Actinide burning was not the original development goal for the MSR, consequently, significant R&D is required to (1) obtain a better understanding of the solubility of minor actinides and lanthanides in molten fluoride salt fuel for actinide burning missions with high actinide concentrations, (2) develop appropriate separations technologies, and (3) develop methods to produce appropriate waste forms. When the original work on the MSR was conducted, waste management was not a major consideration.

Materials. Several materials of construction have been demonstrated in the laboratory as potentially suitable. However, longer-term tests under irradiation are required before there will be a high degree of confidence in these materials. Current materials are suitable for temperatures up to 750EC. Higher temperatures, such as may be required for hydrogen production, may require new materials. Although the Aircraft Nuclear Propulsion Program developed high-temperature materials, the required lifetimes were significantly less than those required for industrial applications.

Noble metal disposition. Noble metal fission products that do not dissolve as stable fluorides can plate out on heat-exchanger walls as metal or lower-valence metal-metal bonded fluoride clusters. This is an operational issue that scales with the power level of the MSR. In the case of loss of heat sink, the decay-heat load from the metal metals could cause significant damage, leading to loss of integrity of the MSR intermediate heat exchanger. Several methods to address this issue have been proposed but R&D is required to develop an effective control system.

Engineering design. Detailed designs of a MSR have not been produced since 1970s. An updated design (including design trade-off studies) is required to better understand strengths and weaknesses and to develop defensible economic evaluations. The current regulatory structure is designed for solid-fuel reactors, and the MSR design needs to carefully address the intent of current regulations. Work is required with regulators to define equivalence in safety for MSRs. The primary reactor circuit requires remote maintenance; thus, this is a major design issue for an economic reactor.

VII. DEVELOPMENT DIRECTIONS

MSRs can perform different missions: electricity production, actinide burning, hydrogen production, and fissile material production. The development requirements are substantially different for these various missions. The requirements for electricity production and actinide burning are significantly less than those for hydrogen production (higher temperatures) and fuel production (on-line efficient fuel processing). Consequently, MSRs should be viewed as a family of reactors, for which the technology would first be developed for near-term missions with the option of expanding the missions with further development.

Several energy systems require the use of molten salt heat-transfer coolants because of their excellent heat-transfer capabilities and their very low pressure at high temperatures. These systems include (1) the Advanced High-Temperature Reactor[12] for hydrogen and electricity production, which proposes the use of a graphite-matrix coated-particle fuel (similar to gas-cooled reactors) and molten salt coolants and (2) fusion reactors[11] that use molten salt coolants (Peterson 2002). The potential exists for cooperative development programs on molten salt engineering for these diverse applications.

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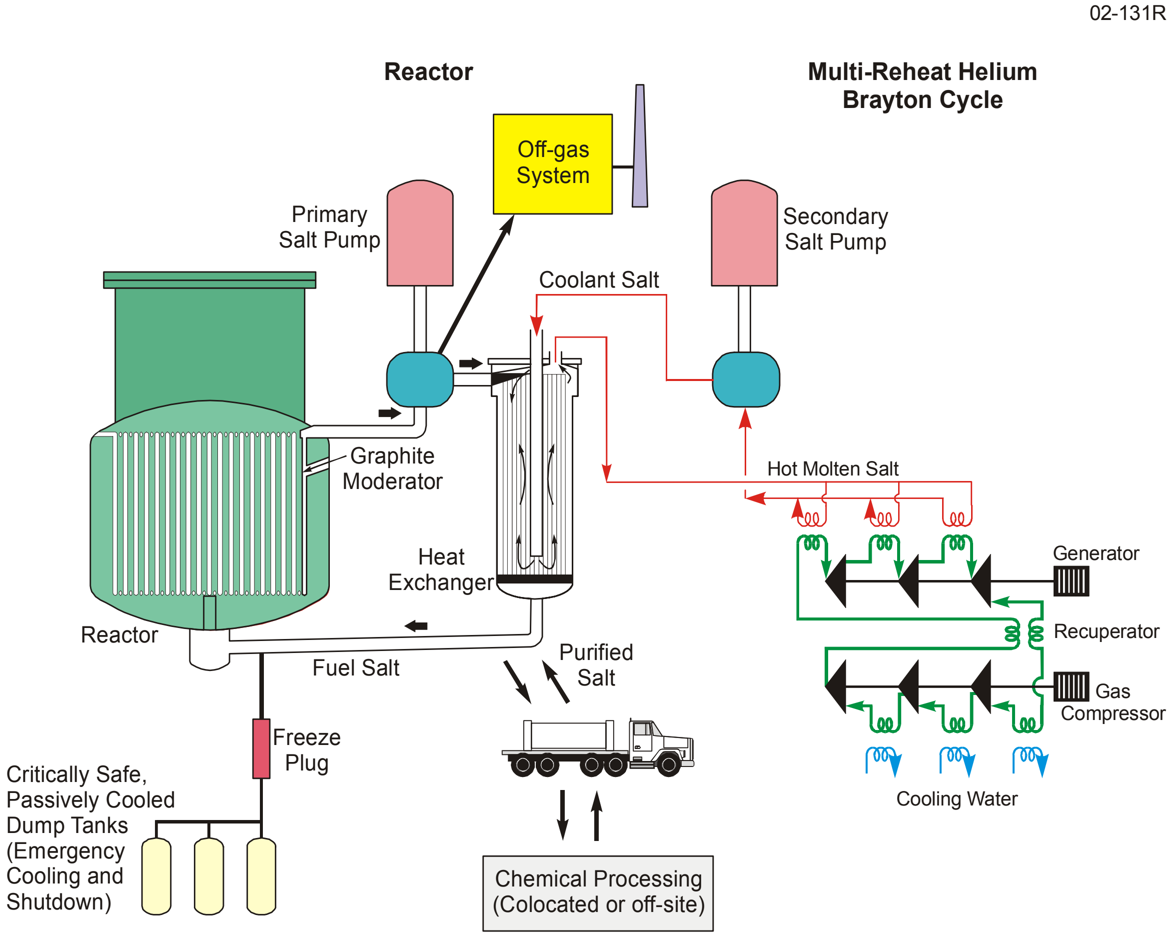

Fig. 1. Molten salt reactor with multi-reheat helium Brayton cycle.

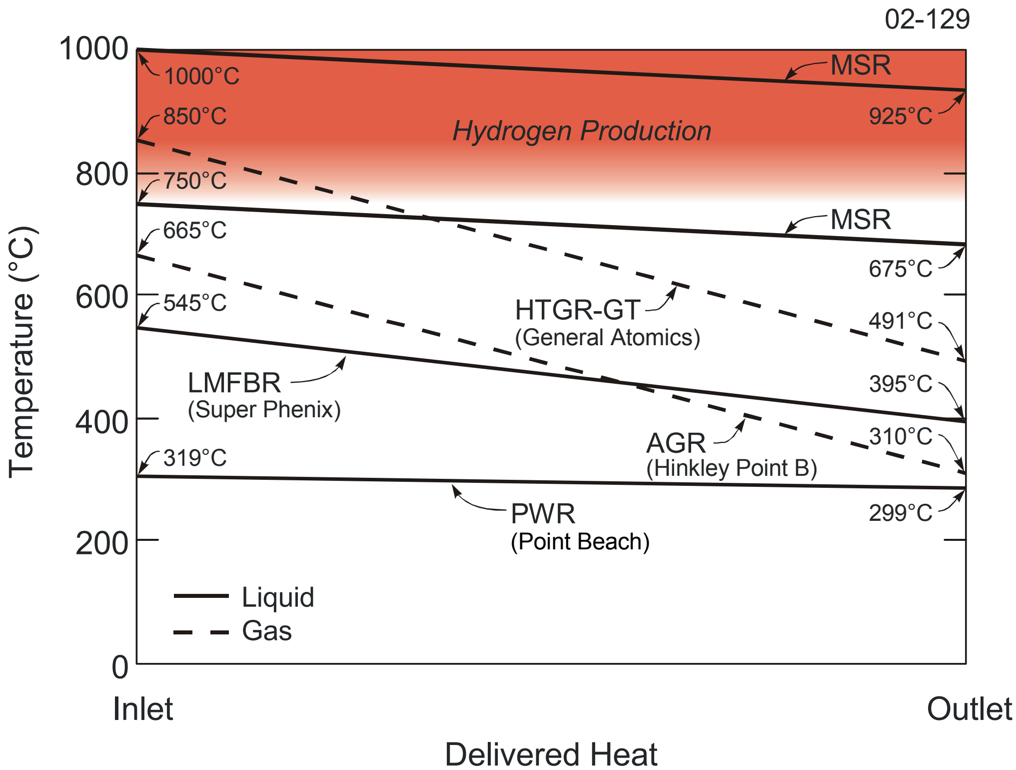

Fig. 2. Temperature of delivered heat from different power reactors.