Generation IV Roadmap Activity
Description of Generation IV Reactor and Fuel Cycle

Molten Salt Reactors (MSRs) for Production of Electricity with Fissile, Fertile, and Fission Products Dissolved in a Fluoride Salt

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Molten Salt Reactors (MSRs) for Production of Electricity with Fissile, Fertile, and Fission Products Dissolved in a Fluoride Salt

MSRs are liquid-fueled reactors for the production of electricity in which the fissile, fertile, and fission products are dissolved in a molten salt. Typically, the fuel is a mixture of lithium-7 fluoride, beryllium fluoride, thorium fluoride, and uranium fluorides that flows through a reactor core moderated by unclad graphite. The reactor operates at high temperatures (-700EC exit temperature) and at low pressures (boiling point -1400EC) with high thermal efficiency (44%). Volatile fission product poisons (e.g. Xe, Kr, and I) are continuously removed from the molten fuel. An MSR can be operated as a converter, a breeder, or an actinide burner. This description does not include concepts for chloride molten salt reactor concepts that have been proposed as fast-neutron reactors.

INTRODUCTION

Many studies (e.g., *Nuclear Technology* February 1970), experiments, and test loops were undertaken on MSRs in the 1950s and 1960s. This work led to construction of the Molten Salt Reactor Experiment (MSRE), an 8-MW(t) reactor, that demonstrated the technology first using a fuel with ^{235}U fluorides dissolved in molten salts and later using a fuel with dissolved ^{233}U fluorides. The MSRE successfully operated for 13,000 equivalent full-power hours between 1965 and 1968. A detailed conceptual design of a 1000-MW(e) Molten Salt Breeder Reactor (MSBR) was developed and became the primary backup for the liquid-metal fast breeder reactor. MSR research was terminated in the mid-1970's in the U.S. because of a programmatic decision to focus on only one breeder concept.

The MSBR is a large [>1000-MW(e)] ^{233}U-thorium, thermal neutron, liquid-fuel breeder reactor designed for the production of electricity. It can be built in any size with passive emergency core cooling. It has a high efficiency (44%). The MSBR and its associated fuel cycle have a very low inventory of fissile materials because (1) thermal neutron reactors require less fissile inventory than fast reactors and (2) no fuel-cycle fissile inventory exists outside the reactor system. The reactor has a very-low fissile resource demand compared with a light-water reactor (LWR) because (1) it has a low reactor fissile inventory at startup, (2) little excess reactivity is required to compensate for burnup, and (3) it is a breeder reactor that produces its own fuel. An MSR generates few transuranics because it uses a thorium-^{233}U fuel cycle in which many neutron captures are required to produce Pu, Am, and Cm. The wastes contain very low concentrations of actinides because only fission products are extracted from the molten salt. The actinides remain in the molten salt until they are fissioned. MSRs can be built with once-through, actinide-burning, and other fuel cycles. These reactors share most of the characteristics of the MSBR.

NATIONAL AND INTERNATIONAL INTEREST

The French utility EdF (Vergnes 2000) is investigating the MSRs as a power reactor and as a power reactor to burn actinides from LWRs. Studies under way in Russia and Japan are investigating the potential for MSRs to burn minor actinides. In the U.S., there are investigations of MSRs for power production and for burning of actinides from LWR SNF. The U.S. Accelerator Transmutation of Waste Program is investigating molten salt targets for actinide burning that have most of the characteristics of an MSR.

CONCEPT DESCRIPTION

General Characteristics. In the late 1960s, a conceptual design of a 1000-MW(e) MSBR (Fig. 1; Table 1) was developed (Robertson 1971). The basic design characteristics of the MSR remain unchanged today. The fuel is a liquid mixture of lithium-7 fluoride, beryllium fluoride, thorium fluoride, and uranium fluorides. Other salt mixtures are possible—this particular salt was proven during the MSRE and offers the best neutron economy and breeding performance. During operation, most fission products and all actinides form fluorides in the liquid. The liquid fuel salt flows upward through vertical channels into the unclad graphite core. The graphite moderates the epithermal spectrum that is characteristic of the salt, such that criticality occurs only in the reactor core. The heat is generated directly in the molten fuel. The liquid fuel salt 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 for corrosion resistance to the molten salt.

Table 1. Characteristics of a large molten salt reactor

Net electric generation	1000 MW		Maximum core flow velocity	2.6 m/s
Thermal efficiency	44.4%		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 %

The fuel flows through a primary heat exchanger, where the heat is transferred to a secondary molten salt coolant ($NaBF_4$-NaF), and back to the reactor core. The secondary coolant (1) provides isolation between the low-pressure reactor and the high-pressure steam cycle and (2) chemically reacts and traps any tritium that escapes from the primary system. A small cleanup system removes the tritium from the coolant. The heat-transfer fluid flows to a steam generator to produce steam and back to the primary heat exchanger.

A steam cycle converts the heat to electricity. The plant's electrical efficiency is -44%. This high efficiency, compared with that of an LWR, is a consequence of the high reactor operating temperatures. The proposed French MSR (Vergnes 2000) will operate at a higher temperature (-800EC) with a helium gas turbine power cycle.

There are two fluid-fuel cleanup systems. A high-efficiency gas-stripping system incorporated into the primary circulation pumps removes noble gases (xenon, krypton, etc.) and tritium. The noble gases, particularly certain xenon isotopes, are strong neutron absorbers. Without the quick removal of the gases, the neutrons absorbed by these gases would prevent the reactor from being a breeder reactor. Noble gas removal was fully demonstrated in the MSRE. A salt-cleanup system (1) removes lanthanides and other fission products from the salt and (2) controls its composition. The salt cleanup system has been demonstrated in the laboratory.

Safety Systems. 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 also 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 box to avoid cold spots in the system. This design 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. For solid reactors to be passively safe, their core dimensions and corresponding power levels must be relatively small.

The accident source term—the quantity of radioactivity in the reactor core—is less than that in solid-fueled reactors. Fission products are continuously removed from the molten fuel salt, solidified, packaged, and placed in passively cooled storage vaults. More important, the more mobile elements are removed and solidified. The primary system is low pressure. This eliminates a major driving force—high pressure—for transport of radionuclides in an accident from the reactor to the environment.

The reactor has low excess nuclear reactivity. The fissile material content of the fuel is controlled so that no need exists for excess reactivity to compensate for fuel depletion. No excess reactivity is required to override xenon poisoning because no significant buildup of xenon occurs over time. There is a strong negative temperature coefficient. In normal operations, the control rods are fully removed from the reactor.

Fuel Cycles. There are four major fuel cycle options—depending upon the goals. The basic reactor remains unchanged except for the salt-cleanup systems and off-site fuel cycle operations. All of the MSRs can be started up using low-enriched uranium or other fissile materials. All ^{233}U fuel cycles require remote handling, even of the clean uranium. The production of ^{233}U also results in the creation of ^{232}U, with its decay product that generates a 2.6-MeV gamma ray and results in high secular-equilibrium radiation levels (100s of R/hr) even for separated uranium. The denatured fuel cycles contain sufficient ^{238}U to ensure the ^{233}U and ^{235}U are non–weapons usable by isotopic dilution.

- *Thorium-^{233}U breeder cycle*. The breeding ratio is -1.06 with an equilibrium ^{233}U inventory of about 1500 kg. After startup, only thorium is added as a fuel.

- *Denatured thorium-^{233}U breeder cycle (Engel 1978; Engel 1979).* The addition of ^{238}U to improve proliferation resistance lowers the breeding ratio to slightly above one and results in a fissile (^{239}Pu and ^{241}Pu) plutonium inventory of -0.16 kg/MW(e). The system does not have the capability for plutonium removal from the salt. The plutonium inventory is low compared with that of an LWR.

- *Denatured "once-through" cycle with minimal chemical processing (Engel 1980).* 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 a fifth that of an LWR.

- *Denatured burner to destroy actinides from LWRs* (Greenspan 2001). This fuel cycle burns Pu, Am, and Cm from LWR SNF or other sources. It can produce denatured ^{233}U as a by-product. The penalty for burning actinides in a thermal neutron flux is partly offset by the greater fission neutron yield of the higher actinides.

Except when the reactor is used as an actinide burner, the quantities of transuranics are low compared with those of traditional LWR fuel cycles. It takes many neutron absorptions to produce plutonium or a higher actinide starting with thorium. The fuel cycles have very unusual plutonium isotopics with high concentrations of ^{242}Pu (Table 2). This is a result of a fuel cycle that never removes the actinides from the reactor—only the fission products. The unusual plutonium isotopics add a significant barrier for their use in nuclear weapons.

Table 2. MSR plutonium isotopics (%)

Isotope	Weapons grade	Reactor grade[a] (PWR)	Denatured MSR breeder[b]	LWR Actinide Recycle in MSR[c]
^{239}Pu	93.	56.6	30	4.5
^{240}Pu	6.5	23.2	18	17.9
^{241}Pu	0.5	13.9	14	5.0
^{242}Pu	0.0	4.7	38	70.2

[a]PWR SNF also has 1.3% ^{238}Pu: [b]Engel 1978: [c]Includes 2.3% ^{238}Pu (Greenspan 2001); isotopics are dependent upon choice of coolant and operating temperature that control solubility limits.

EVALUATION AGAINST HIGH-LEVEL CRITERIA

As a breeder reactor having a fuel cycle with very low inventories of fissile materials, MSRs place minimal requirements (SU-1) on uranium and thorium resources. The MSR intrinsically destroys actinides and thus minimizes long-term stewardship burdens (SU-2). Limited analysis does not allow for a reliable estimate of proliferation resistance (SU-3); however, the combination of low fissile inventories and unusual isotopics indicates potential advantages.

High levels of worker safety (SR-1) are projected because the highly hazardous materials are handled remotely with minimal manned maintenance. Experience (NEA 2000) in reprocessing facilities shows that facilities using remote operations (as required for an MSR) have significantly lower radiation exposures than traditional reactors. Major accidents may not be a credible scenario with an MSR (SR-2) because of the passive safety systems and reduced reactor core inventory of actinides and fission products. Therefore, the potential exists to eliminate emergency evacuation zones (SR-3). One uncertainty, however, is the potential for smaller releases associated with the processing systems.

MSRs have the potential for good economics (EC-1 and EC-2) because of (1) high resource utilization, (2) high efficiency with smaller secondary-side systems, and (3) economics of scale. Very large capacity per reactor is possible because of the characteristics such as low pressure, passive safety at any size, and many secondary systems (salt processing, remote maintenance, etc.) that are almost independent of reactor size. A detailed cost estimate prepared for a 1000-MW(e) MSBR before the Three Mile Island (TMI) accident showed somewhat better economics than those for an LWR.

STRENGTHS AND WEAKNESSES

The strengths of the MSR are minimum resource consumption, potentially excellent economics, and excellent safety. The major uncertainties are associated with (1) the absence of any detailed evaluation of MSRs since the time preceding the TMI accident, even though major changes in nuclear power requirements have occurred; (2) the need to conduct larger engineering tests (such as irradiation of materials of construction) on selected system components; and (3) confirmation or development of systems that meet current requirements.

RESEARCH AND DEVELOPMENT (R&D) NEEDS

The MSR has been demonstrated on a small scale—the MSRE. Although the major development program was concluded around 1970, a small research program was continued to address the major unresolved scientific issues. The latter program demonstrated, on a laboratory scale, viable solutions to these issues. However, several activities are required before commercialization. A significant effort is needed to carefully examine all aspects of the technology in terms of today's requirements. Development tests (e.g., corrosion tests of materials of construction under realistic conditions, tests of tritium control, graphite irradiation tests, etc.) are required to confirm laboratory results. The concept needs to be updated in areas where new technologies (developed in the last 30 years) may allow simplification or improvement of the design—particularly in the treatment of waste. A detailed proliferation analysis is required. Finally, a reliability and economic analysis of the MSR is required.

INSTITUTIONAL ISSUES

For 40 years the nuclear industry has chosen solid-fuel reactors with ^{235}U/^{239}Pu fuel cycles. MSRs are fundamentally different. The "rulebooks" and traditional ways of thinking must be reconsidered for a system presenting such different characteristics.

TIME LINE FOR DEPLOYMENT

The concept should be deployable in about 20 years.

ASSESSMENT

MSRs, which offer a different approach to nuclear power, have the following characteristics: (1) an MSR is a thermal rather than fast high-conversion or breeder reactor; (2) most fuel cycle activities are coupled to the reactor; (3) the passive safety system is size independent; (4) liquid fuels, rather than solid fuels, are used; and (5) the reactor uses a ^{233}U rather than ^{239}Pu fuel cycle. As such, MSRs have unique capabilities. A reevaluation of the MSR, along with relevant R&D studies to assess its potential in terms of today's requirements, is appropriate.

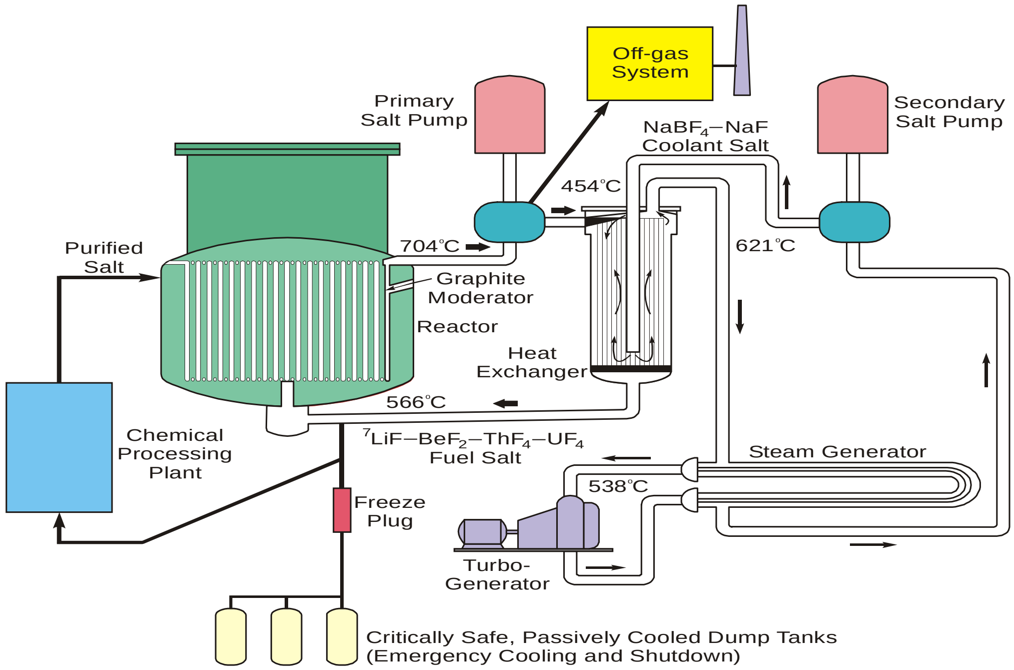

Fig. 1. Molten Salt Breeder Reactor.

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