ELECTRIC POWER RESEARCH INSTITUTE

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

Molten Salt Reactors

INTRODUCTION

Growing interest and investment in new nuclear reactor development span a wide range of designs that include light-water small modular reactors (SMRs) and numerous non-water-cooled reactors. Of these advanced reactors (ARs), molten salt reactors (MSRs) represent the most diverse class with respect to fuel forms, neutron spectra, and primary coolant chemistries. MSRs are also among the least mature of AR technologies with respect to demonstration. While immature relative to high-temperature gas-cooled reactors (HTGRs) and sodium-cooled fast reactors (SFRs) that have operated at commercial scales and provided sustained electricity to grids, MSR technology has been successfully tested and operated at experimental scales with construction and operation of two experimental reactors at Oak Ridge National Laboratory during the 1950s and 60s [1, 2].

MOLTEN SALT REACTOR HISTORY

Molten salt reactor technology was initially pursued as high temperature heat source to power aircraft for extended strategic operations without refueling and resulted in the first MSR demonstration—the Aircraft Reactor Experiment (ARE). The ARE represented a short duration proof-of-concept test, incorporating Inconel as the primary structural material, beryllium oxide (BeO) as the moderator, and NaF-ZrF_4-UF_4 as the fuel salt [3, 4]. ARE testing in 1954 included operation for 100 hours up to 2.5 MW_{th} with steady state outlet temperatures up to 860°C, demonstrating stable, self-regulating MSR operation at very high temperatures. The Aircraft Nuclear Propulsion program was cancelled prior to subsequent testing and in-flight demonstration of nuclear propulsion, but as an interesting aside, an operating reactor was flown on a test aircraft to evaluate shielding requirements and feasibility.

The Molten-Salt Reactor Experiment (MSRE) followed the ARE and was designed to operate at a larger scale for a longer period of time to evaluate the technology for land-based commercial power generation (Figure 1) [1, 2]. The MSRE employed Hastelloy N as the primary structural alloy, unclad graphite as the moderator, and LiF-BeF_2-ZrF_4-UF_4 as the fuel salt. The MSRE started up on enriched urnanium-235 in 1965 and later (in 1968) became the first reactor to operate using uranium-233, which was recovered from thorium irradiated in other reactors.

Over its five-year life, the MSRE operated for 20,000 hours at a maximum power of 7.4 MW_{th} with core outlet temperatures up to 650°C. The secondary system, using clean LiF- BeF_2 (Flibe) salt, was never intended to generate electricity and instead dumped heat directly to the environment via salt-to-air heat exchangers. Examination of MSRE materials and components indicated compatibility of the salt-moderator-metal alloy system over reactor operation. Further demonstration of MSRs was curtailed in the early 1970s in favor of continued development of SFR technology, although conceptual work continued at ORNL for another decade.

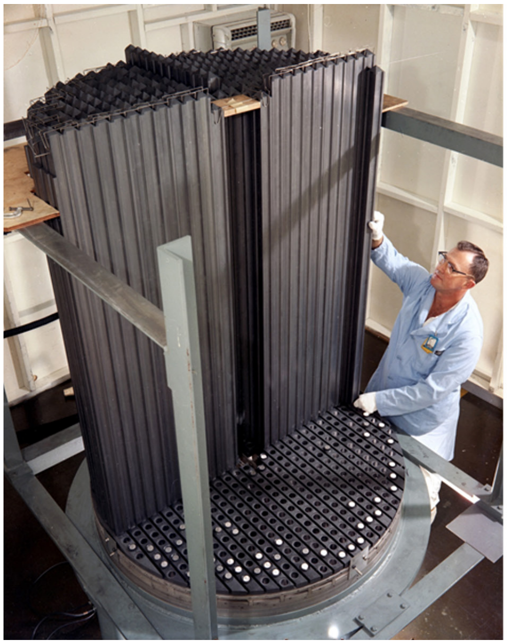
Key Terms

Molten salt: Salt or salt mixtures that when heated beyond the melting point can be used as a heat transfer fluid and thermal energy storage medium in a variety of energy technologies, including nuclear, fossil, and solar-thermal plants.

Molten salt reactor: A class of nuclear fission reactors that use molten salt as the primary system coolant (for solid-fueled designs) or as the primary coolant and nuclear fuel carrier (for liquid-fueled designs).

Fuel salt: Molten salt that contains isotopes of uranium, plutonium, and/or other actinides that functions as the nuclear fuel and, in the case circulating liquid-fuel systems, the primary system coolant as well.

Coolant salt: Molten salt that is used exclusively for heat transfer and does not contain fuel material.



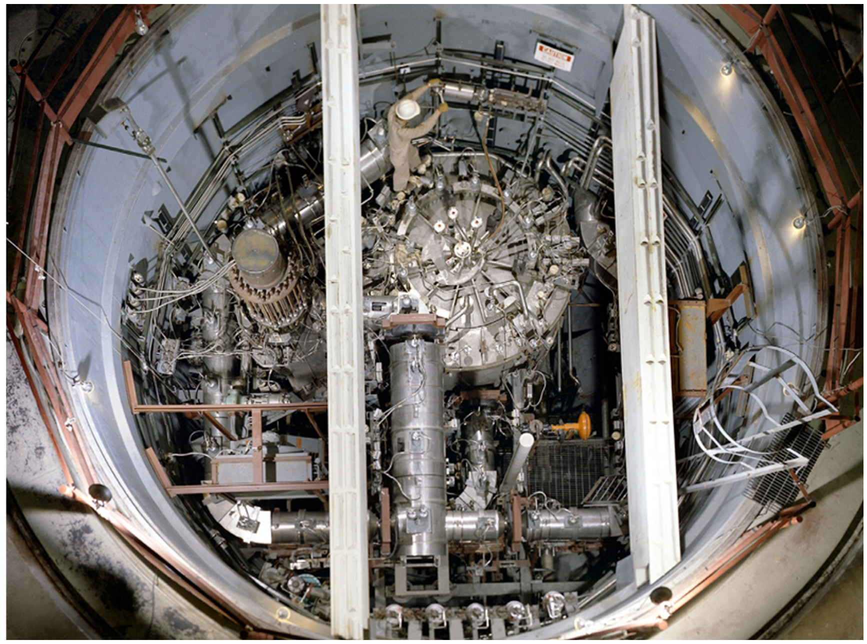


Figure 1. LEFT – Assembly of the core of the Molten-Salt Reactor Experiment, illustrating scale and configuration of core internals. RIGHT – View from above of MSRE reactor cell containing primary system. Pictured are the reactor vessel in upper center, heat exchanger in lower center, and fuel salt pump in left center of image. Scale indicated by worker on top of reactor vessel [Source: Oak Ridge National Laboratory for the U.S. Atomic Energy Commission, ca. 1964.]

Early Promise of Homogeneous Reactors – The MSR Precursor

Early evaluations by the U.S. Congress' Joint Committee on Atomic Energy identified a top-five list of most promising reactor concepts for civilian power production from approximately 80 candidates. The homogenous reactor, the precursor to liquid-fueled MSR designs, ranked number one on the list but was also recognized as requiring the longest lead time for commercialization [JCAE, 1954]:

The consensus of opinion for achievement of economically competitive atomic power as expressed by the witnesses and correspondents is as follows: (No. 1 is most promising No. 5 least promising.)

No. 1 Homogeneous reactor
No. 2 Fast breeder reactor
No. 3 Boiling reactor
No. 4 Sodium graphite reactor
No. 5 Pressurized-water reactor

SALT COMPOSITION

The choice of the primary system salt composition confers important benefits and limitations to an MSR design. While there are many properties and effects to consider, a general list of requirements for fuel-bearing and primary coolant salts includes the following attributes [5]:

- A reasonably low melting point, typically below 550°C for practical MSR applications;
- High boiling point, typically greater than 1000°C;
- Isotopic and elemental compositions featuring adequately low parasitic neutron absorption, which is particularly important for thermal-spectrum MSRs;
- A sufficiently high coefficient of thermal expansion to provide strong negative reactivity feedback and efficient natural circulation;
- Sufficient solubility of fissile fuel components to create concentrations to support criticality as intended and reduce likelihood of precipitation resulting in unintended criticality;
- Stability at all temperatures and under irradiation;
- Low vapor pressures at operating temperatures;
- Moderate to high heat capacity and acceptable thermal conductivity; and
- Acceptable compatibility with contacting materials and components.

Fluoride Salts for Thermal Spectrum MSRs

Fluorides are the salt chemistry of choice for thermal-spectrum MSRs [6]. Table 1 lists three common fluoride salt compositions used in MSRs that operated (ARE and MSRE) and are commonly incorporated into thermal MSR designs. Binary salts are often preferable as they can exhibit much lower melting points than their individual components.

Table 1. Fluoride salts for thermal MSRs

Salt Composition	Acronym	Also Know As
$LiF - BeF_2$	FLiBe	Flibe
$NaF - ZrF_4$	NaFZrF	Nafzirf
LiF – NaF – KF	FLiNaK	Flinak

The prevalence of lithium and beryllium fluoride mixtures is no coincidence; the isotope 7Li and elements Be and F (featuring only one stable, naturally-occurring isotope each—9Be and 19F respectively) are among the few nuclides to exhibit favorably-low thermal neutron capture cross-sections to support MSR operation in the thermal neutron energy spectrum [7].

Chloride Salts for Fast MSRs

For fast-spectrum MSRs, chloride salts are the most common constituents of fuel and coolant salts due to their lower costs (the result of an abundance of supply—think table salt) and the significantly higher solubility of actinide fuel constituents relative to fluorides; however, fluoride salts can also be used and are proposed for some fast MSR systems [8]. Chlorine does have an important disadvantage; one of its two naturally occurring isotopes, ^{35}Cl, is a strong parasitic neutron absorber and is significantly more abundant (approximately 75%) than its more neutron-transparent counterpart, ^{37}Cl. Moreover, an important byproduct of neutron absorption by naturally-occurring ^{35}Cl is the isotope ^{36}Cl; as a long-lived, water soluble radionuclide, disposal of ^{36}Cl-bearing waste can be a disproportionate risk driver for geologic disposal due to its 300,000 year half-life and high mobility in the environment.

Sodium chloride is the most common fuel-bearing salt for fast MSRs. Sodium is found in nature as a single, neutronically-compatible isotope, ^{23}Na. Other suitable cations for chloride salts are K+, Ca^{2+}, Mg^{2+}, Pb^{2+}, Sr^{2+}, and Ba^{2+}.

The Diverse MSR Family

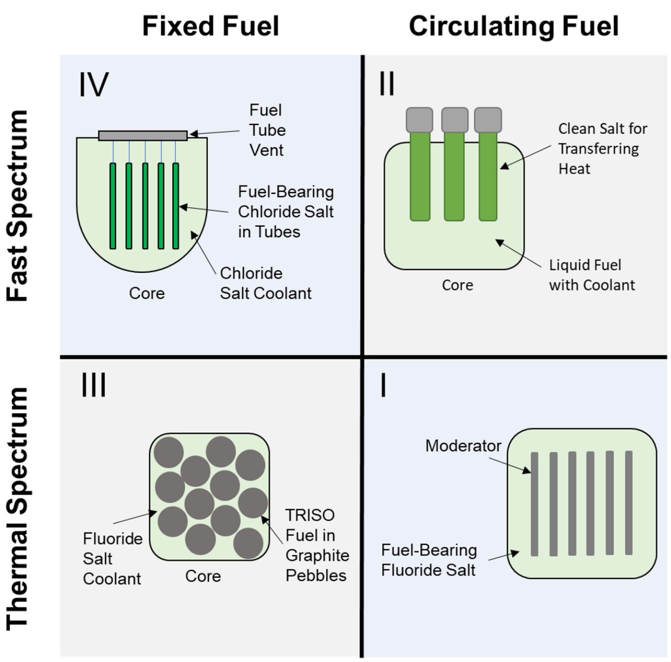


Figure 2. No other family of reactor designs features the diversity of MSRs—spanning four distinct quadrants of design space for neutron spectra (thermal and fast) and fuel form (fixed and circulating).

WHAT SETS MOLTEN SALT REACTORS APART?

Diversity of Technology and Attributes

Molten salt reactors represent the broadest category of reactor, encompassing designs with stationary and flowing fuels; thermal and fast neutron spectra; and the ability to use uranium, plutonium, and other actinides as fuel—including spent fuel from other reactors. Liquid-fueled MSRs also claim the unique distinction of being the only design to operate as breeder reactors in the thermal spectrum—via the thorium—uranium-233 fuel cycle.

Utilization of liquid fuel eliminates the need for fuel fabrication infrastructure. Online refueling and polishing of fuel-salt to remove fission gases, noble metals, among other problematic constituents, also enable high plant capacity factors.

This diversity is reflected in the designs under development in the private sector, here organized by Sectors from Figure 2.

I. Circulating fuel – thermal spectrum: The original molten salt reactor concepts, including ARE and MSRE, were based on fissile fuel material dissolved in fluoride salts circulated through the core and heat exchangers. Current developers and designs include: Flibe Energy's Liquid Thorium Fluoride Reactor (LFTR); Terrestrial Energy's Integral Molten Salt Reactor (IMSR),

II. Circulating fuel – fast spectrum: Elysium Industries' Molten Chloride Salt Fast Reactor (MCSFR); TerraPower's Molten Chloride Fast Reactor (MCFR).

III. Fixed fuel – thermal spectrum: Kairos Power is developing a solid-fueled molten salt-cooled design, also termed a fluoride-salt-cooled high-temperature reactor (FHR). FHRs combine the performance and safety of HTGR fuel, i.e., TRISO-coated particle fuel fabricated into prismatic blocks or pebbles, and the favorable properties of molten salts, i.e., high thermal inertia, high boiling point, and low operating pressure [9].

IV. Fixed fuel – fast spectrum: Moltex Energy's Stable Salt Reactor (SSR) occupies the fourth quadrant with a design in which fuel-bearing molten salt is contained in vented fuel tubes – similar to the assemblies of fuel rods fuel used in light water reactors [10].

Safety and Resilience

Molten salts are recognized for their chemical compatibility with other coolants and environmental contaminants, including air and water. All MSRs benefit from the high heat capacity and boiling points of molten salt. Within wide-ranging operating envelopes, there is no phase change regardless of if the salt is used as a coolant alone, or if fuel is incorporated.

Liquid fueled designs are able to self-regulate and operate with large negative temperature and void coefficients of reactivity. This was demonstrated during the MSRE when a control rod was intentionally removed from the core without a significant power excursion. In situations in which increases in reactor reactivity are of concern, freeze plugs can be incorporated that melt above a defined salt temperature and thereby allow fuel to drain into tanks for added safety margin [11].

Advanced Power Conversion Technologies

With typical core outlet temperatures at or above 650°C, MSRs and other high-temperature reactors could couple with power conversion technologies beyond the traditional Rankine steam cycle. Of particular interest are supercritical CO_2 (sCO_2) power cycles, which offer compelling benefits, including increased conversion efficiencies, on the order of 45% at 600°C [12].

Table 2. Global landscape of molten salt reactor developers and designs. List is intended to be illustrative, not exhaustive.

Developer(s)	Country	Coolant-Fuel Form	Capacity (MW_{th})	Neutron Spectra
Elysium Industries	USA	NaCl-(UCl_3, $PuCl_3$, or $ThCl_3$) Circulating	110-2700	Fast
Moltex Energy	UK	NaCl-(UCl_3 and $PuCl_3$) Static	750	Fast
TerraPower	USA	High-actinide content Chloride salt Circulating	~3000	Fast
French National Center for Scientific Research	France	LiF-(ThF_4,UF_4 and/or PuF_4) Circulating	3000	Fast
Seaborg Technologies	Denmark	Unspecified Fluorine-(ThF_4,UF_4 and/or PuF_4) Circulating	250	Fast
Institute for Solid State Nuclear Physics	Germany	Pb-(UCl_3 and $PuCl_3$) Circulating	3000	Fast
Copenhagen Atomics	Denmark	LiF - High-actinide content Fluoride salt Circulating	100	Thermal
ThorCon	USA	FNaBe-(UF_4 and ThF_4) Circulating	557	Thermal
Terrestrial Energy	Canada	LiF(Be or Na)-UF_4 Circulating	400	Thermal
Flibe Energy	USA	FLiBe-(UF_4 and ThF_4) Circulating	650	Thermal
Kurchatov Institute	Russia	FLiBe-($TRUF_3$ and ThF_4) Circulating	2400	Thermal
SINAP & Chinese Academy of Sciences	China	FLiBe-(UF_4 and ThF_4) Circulating	100	Thermal
SINAP & Chinese Academy of Sciences	China	FLiBe-(TRISO) Pebble Bed	100	Thermal
Kairos Power	USA	FLiBe-(TRISO) Pebble Bed	320	Thermal

FLEXIBLE APPLICATIONS

Nuclear power plants that operate at higher temperature offer greater flexibility in terms of missions beyond electricity generation. High temperature reactors like MSRs can produce hydrogen via efficient technologies such as high-temperature steam electrolysis and thermochemical methods.

Coupling to molten salt heat storage systems would allow an MSR plant to operate in concert with variable generation renewables [13; 14]. This option is very convenient to integrate, as solar salts match the temperature range of an MSR closely [15].

Radioisotope production may be viable due to the online refueling system in liquid fueled designs, allowing fission products for medical and industrial applications to be harvested and processed.

Many potential applications, including remote arctic villages, mining operations, and even space exploration, require reliable, uninterrupted energy supplies for long durations. As shown in Table 2, MSR designs offer scalable energy production and reactor size for flexible operation and deployment options.

CHALLENGES AND BARRIERS ASSOCIATED WITH MSRS

In a 2019 study, EPRI identifies knowledge gaps associated with material properties for commercial MSR applications [16]. Key findings include the need for material property data, including corrosion performance for relevant chemical environments and under irradiation and tritium retention, particularly in lithium-based salt systems.

EPRI Perspective

Molten salt reactors, while less mature than other concepts, do share the use of molten salt heat transfer fluids with other energy technologies, such as concentrated solar power (CSP), fusion, and thermal energy storage systems for repurposing older fossil plants. In light of the growing opportunities for cross-cutting research, development, and demonstration activities, EPRI is prioritizing scouting and collaborative projects on topics that benefit multiple generation technology domains. These areas to date include demonstration of process hazard analysis (PHA) methods for safety assessment of multiple MSR designs; evaluating material property data and manufacturing methods for MSR applications; and developing first-of-a-kind guidelines for molten salt chemistry.

EPRI RESOURCES ON MOLTEN SALT REACTORS

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