

# Application of Molten Salt Reactor Technology to MMW In-Space NEP and Surface Power Missions

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## Abstract

*Anticipated manned nuclear electric propulsion (NEP) and planetary surface power missions will require multimewatt nuclear reactors that are lightweight, operationally robust, and scalable in power for widely varying scientific mission objectives. Molten salt reactor technology meets all of these requirements and offers an interesting alternative to traditional multimewatt gas-cooled and liquid metal concepts.*

The ANP design effort led to the development of a homogeneous fluid fuel consisting of uranium tetrafluoride (UF<sub>4</sub>) dissolved in a NaF-ZrF<sub>4</sub> fluoride salt. The first successful demonstration of molten salt fuel was the Aircraft Reactor Experiment, a 2 MW research reactor that operated for 96 MW-hrs. Several different types of salts were developed as part of the ANP program and the Molten Salt Reactor Experiment (MSRE) project. The MSRE was a 8 MW research reactor project to demonstrate the viability of molten salt technology. It operated for greater than 13,000 full power hours.

## I. INTRODUCTION

Molten salt reactors (MSR) were originally conceived as a response to the Aircraft Nuclear Program (ANP) of the late 1950's and early 1960's. The requirements of the program, (i.e. a lightweight, reliable, high temperature reactor) are very similar to the requirements for in-space nuclear electric propulsion and planetary surface power. These missions also require reactors that are lightweight, operationally robust, and scalable in power for widely varying scientific mission objectives.

## II. ADVANTAGES OF MSR TECHNOLOGY FOR IN-SPACE PROPULSION

Molten salt reactors have several advantages over conventional solid pin reactors for in-space power missions. The fluoride salt serves the multiple role of fuel, moderator, and coolant. Fluoride salts are resistant to radiation damage and they do not undergo radiolytic decomposition. They have excellent solubility of uranium and thorium, and they have very low vapor pressures at operating temperatures. There are several specific advantages for space nuclear systems that are discussed below:

Table 1: Comparison of MMW Space Reactor Types

Reactor Type	HTGR	PBR	LMR	MSR
Coolant Pressure (Pa)	$2.758 \times 10^6$	$2.896 \times 10^6$	$1.137 \times 10^6$	< 10
$Q_{vol}$ (MW/m <sup>3</sup> )	57.7	40.5	75.9	6.6-2500
T core-out (°K)	1367	1600	1550	1000-1300
Typical Fuel	UO <sub>2</sub> -Refractory Clad	UC particles	UN-W/25Re	LiF-BeF <sub>2</sub> -ThF <sub>4</sub> -UF <sub>4</sub>

### II.A High power density fuel

The dimensions of a reactor are determined by criticality and heat transfer limitations. The ability to effectively remove heat from the reactor is generally the more restrictive criterion on the minimum size, especially at higher power levels. To first order, the size of a reactor is determined by the maximum power density (MW/m<sup>3</sup>) of the fuel. In conventional solid pin reactors, limitations on heat generation rates are required to prevent exceeding fuel pin centerline temperatures. Ceramic oxide fuels, with their low thermal conductivity values, can be especially limiting in this regard. Molten salt reactors, however, eliminate the often large temperature rise across the fuel cladding, fuel pin to cladding gap, and the fuel pin itself. The thermal conductivity and viscosity of the fluoride salts are similar to those values for water. Table 1 lists some important parameters for various MMW space reactor types. The values listed in the table are not inclusive, but are taken from the open literature to represent typical values<sup>1,2,3</sup>. The power density of a MSR can be anywhere from 5 - 20 times higher than traditional solid pin type reactors.

### II.B. Minimization of reactor shield mass

An important property for space reactors is the ability to scale well with respect to mass for higher power levels. The reactor shield is often one of the largest contributors to the overall system mass of an NEP system. The size of the shield is directly proportional to the volume of the reactor. High power density reactors tend to be very compact in size, hence the shield size (and mass) is much smaller. Again, the high power density of MSR's are an important advantage in this respect.

### II.C. High temperature operations and high efficiency power conversion cycles

The closed Brayton cycle and the liquid metal Rankine cycle are regarded as the two most likely candidates for MMW space nuclear power systems. The efficiency of the Brayton cycle is strongly dependent upon turbine inlet temperature and the compressor inlet temperature, as well as other factors such as regeneration, intercooling, and reheat. The compressor inlet temperature is approximately the same as the radiator heat rejection temperature. The optimum temperature for the low end of the Brayton cycle is generally in the range of 385-475 °K. The turbine inlet temperature is dependent upon the maximum reactor outlet temperature and the heat exchanger design. The ARE experiment operated with a reactor outlet temperature of 1100 °K. Higher temperatures are possible with proper chemistry control. The most highly developed closed Brayton system in recent years is the 25 KWe system developed by NASA/Glenn Research Center. It was designed as a power conversion system for use with a solar dynamic thermal storage system being designed for the International Space Station. This system had a turbine inlet temperature of 1144 °K. Advanced turbine technology that would allow turbine inlet temperatures in the 1200-1300 °K range are projected in the near future. Molten salt reactors have the potential to very effectively use the concept of reheat, in which additional heat is added to the working gas between two or more turbine stages. Brayton cycles with regeneration, and multiple stages of intercooling and reheat are capable of efficiencies in excess of 50%. Liquid metal Rankine systems are also under consideration for power conversion. This cycle is similar to the typical steam cycle employed by the commercial

utility industry, except that potassium is used as the working fluid. Potassium Rankine systems are actually at quite well characterized, as all of the major components (turbine, condenser, alternator and heat exchangers) have undergone many hours of extensive ground testing. One advantage of Rankine systems is that the heat is typically rejected at much higher temperatures (approximately 900°K versus 425 °K for a Brayton cycle). Thus, the radiator mass tends to be much smaller for Rankine systems. Liquid metal Rankine systems may be the preferred option for in-space systems, while Brayton systems may be optimal for planetary surface power sources, since they can take advantage of the available low planetary environment/ground temperatures.

#### *II.D. Economical fuel fabrication, reactor design and construction*

The economics of reactor design, fuel fabrication, and overall development costs are rapidly increasing in importance. Many previous space nuclear reactor programs were terminated due to excessive cost escalation. Molten salt systems have often been referred to as simply "...a pot, a pipe, and a pump..."; in deference to the simplicity of the overall reactor plant. Simple systems are advantageous in terms of economics of design, fabrication, and operational reliability. The latter is especially important for space propulsion systems. Homogeneous fluid fuel reactors are simpler to design than solid fuel pin reactors, in that the fuel pin, cladding and coolant channel unit cell is replaced by a homogeneous fuel salt region. Fuel fabrication is easily performed using well known chemistry techniques, hence the need for expensive fuel fabrication facilities is eliminated.

#### *II.E. Safety and ease of control*

The magnitude of the negative temperature coefficient ( $a_T \approx \frac{1}{k} \frac{dk}{dT}$ ) of any reactor is the most important parameter in reactor control. Reactors with large values of  $a_T$  have greater stability to transients due to the temperature feedback mechanism. The larger the

negative temperature coefficient, the greater the stability of the reactor to power transients. An increase in temperature leads to a decrease in  $k$  which reduces the power level and tends to return the temperature to its original value. Similarly, a decrease in temperature results in a increase in  $k$  which increases the power and again returns the system to its initial value<sup>4</sup>. The power of the reactor is then dependent upon the heat extracted by the energy conversion system. The relatively large volumetric expansion of the molten salt fluid fuel with increasing temperature leads to temperature coefficients that are several times larger than typically solid fuel reactors. The total prompt negative temperature coefficient of reactivity for a typical lithium cooled UN fueled LMR is approximately  $-1.4 \times 10^{-6} \Delta k/k$  per °K of fuel temperature rise<sup>2</sup>. The corresponding value for the MSRE experiment was measured at  $-4.05 \times 10^{-5} \Delta k/k$  per °K. The magnitude of  $a_T$  is approximately 30 times larger for a MSR, hence the reactor is more stable with respect to power transients, and the design of the reactor controls system is much simpler.

### III. RESEARCH AND DEVELOPMENT

The use of molten salt reactors in space leads to unique operational and design constraints. Several areas need that need further investigation to determine the potential of molten salt reactors for space applications are listed below:

#### *III.A. Reactor start-up*

Fluoride salts typically are solid at temperatures below 727-813°K. The actual value is dependent upon the particular chemical composition of the molten salt. The fuel salts will have to undergo a phase change from solid to liquid state before the reactor can be taken to full power. Since the heat is generated within the fluoride salt, the reactor should be able to be started upon from a completely solid state on fission power alone without the need for external heaters. The reactor and primary heat exchanges will

have to be designed so as to facilitate thorough melting of the fuel salt during reactor start-up. Stop and hold points and/or power increase limits may also have to be imposed during reactor startup to ensure that the system temperatures are uniformly above required values. These same considerations also apply to LMR systems.

### III.B. Chemistry control

Chemistry control of the molten fluoride salts is vital to minimize corrosion of the structural components. Remote chemistry analysis and control techniques for long term periods will have to be developed for practical applications of molten salt reactors to unmanned NEP and surface power missions. For manned missions, the presence of a crew will alleviate some of these concerns. Previous reactor operational experience indicated that the corrosion rate increased rapidly with temperature, especially at temperatures in excess of 1000 °K. The remediation and decommissioning of the MSRE experiment has led to an increased understanding of the corrosion rate, especially at higher temperatures, and several solutions have been proposed and are being investigated<sup>6</sup>.

## IV. CONCLUSIONS

Molten salt reactors have several interesting characteristics in terms of economics, safety, operational robustness, and power density that make them attractive candidates for in-space propulsion and planetary surface power applications. Several areas such as chemistry, startup, and overall systems studies need further development are needed in order to determine the full potential of MSR's for space propulsion and power missions.

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## NOMENCLATURE

ARE-Aircraft Reactor Experiment

MSR-Molten Salt Reactor

MSRE-Molten Salt Reactor Experiment

HTGR-High Temperature Gas Cooled Reactor

PBR-Pebble Bed Reactor

LMR-Liquid Metal Reactor

MMW-Multi-megawatt

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