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Application of Molten Salt Reactor Technology to Nuclear Electric Propulsion Missions

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Abstract

Nuclear electric propulsion (NEP) and planetary surface power missions require reactors that are lightwieght, 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 gas cooled, liquid metal, and heat pipe space reactors.

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.

The ANP design effort led to the development of a homogeneous fluid fuel consisting of uranium tetraflouride (UF_4) dissolved in a NaF-ZrF_4 flouride salt. The first succesful 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.

Table 1: Comparsion of Space Reactor Types

Reactor Type	Heat Pipe	HTGR	LMR	MSR
Coolant Pressure (Pa)	Low	High	Low	Low
$\dot{Q}_{vol}$ (MW/m^3)	Low	Moderate	Moderate	High
T_{fuel} (^{o}K)	1100-1500	1000-1800	800-1600	1100-1400
Fuel Type	UO_2/UN	UC	UN	UF_4-LiF-BeF_2-ZrF_2
K_{fuel} (W/m^2 -^{o}K)	Low	High	Low	High

Advantages of Molten Salt Reactors for In-Space Missions

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

High power density fuel

The dimensions of a reactor are determined by criticality and heat transfer limitations. The ability of effectively remove heat from the reactor is generally the more restrictive criteria on the minimum size. To first order, the size of a reactor is determined by the maximum power density (MW/m^3) 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, are especially limiting. Molten salt reactors, however, eliminate the often large temperature rise across the fuel cladding, fuel pin to clad gap, and the fuel pin itself. The thermal conductivity and viscosity of the flouride salts are similar to water. Table 1 lists some important parameters for various reactor types.

Minimizing 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. Thus, the high power density of MSR's are an advantage in this respect.

High temperature operations and high efficiency Brayton cycles

The closed Brayton cycle is regarded as the the most likely candidate for NEP systems with power levels in excess of 100 KWe. 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. 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 to be a solar dynamic thermal storage system and power conversion system for the International Space Station. This system had a turbine inlet temperature of 1144°K. Advanced turbine technology that would allow inlet temperatures in the 1200-1300°K range are possible 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 very high efficiencies.

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 advocates often refer to the reactor 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 know chemistry techniques, hence the need for expensive fuel fabrication facilities is eliminated.

Safety and ease of control

The magnitude of the negative temperature coefficient (a_T) 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 relatively large volume expansion of the molten salt fluid fuel with increasing temperature leads to temperature coefficients that are several times larger than typically solid fuel reactors.

Research and Development Requirements

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:

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 the melting of the salt during reactor start-up.

Chemistry control

Chemistry control of the molten fluoride salts is vital to minimize corrosion. Remote chemistry analysis and control techniques for long term periods will have to be developed for practical applications of molten salt reactors to NEP and surface power missions.

Summary

Molten salt reactors have several interesting characteristics in terms of economics, safety, operations, and efficiency that make them attractive candidates for in-space propulsion and planetary surface power applications.

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