Closing the Nuclear Fuel Cycle: Molten Salt Reactors

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INTRODUCTION

The major differences between the light water reactor (LWR) and the molten salt reactor (MSR) are the coolant and the option of liquid fuel. An MSR may be salt-cooled and/or salt-fueled, which determines the state of the fuel: either solid or dissolved into the salt as a liquid. The most apparent advantage of the MSR design is the frozen salt plug drainage system which allows the reactor to be inherently safe. However, as research has progressed, more key features, such as the fuel cycle and waste management involved with the MSR have become apparent.

The purpose of this summary is to outline and discuss the MSR's potential in closing the nuclear fuel cycle and reducing the current volume of stored spent fuel/nuclear waste.

Current MSR Examples

The vendors described in this section are currently designing reactors that are based on molten salt technology and which may be constructed in the next few decades. A set of MSR vendors among the ones whose reactor designs can burn spent fuel and/or actinides include: Copenhagen Atomics, Seaborg Technologies,

RESULTS AND ANALYSIS

New MSR technology and research have revealed advantages in efficiency, safety, and cost. These improvements are partly due to the reactor's ability to operate a closed fuel cycle and to manage waste.

Closed Fuel Cycle

Russia's Molten Salt Actinide Recycler and Transmuter (MOSART), Transatomic Power, and Moltex Energy. In addition to actinides, MOSART utilizes a thorium blanket salt to breed fissile uranium fuel [1]. Flibe Energy, Thorcon Power, and Terrestrial Energy have based their designs heavily on the original Molten Salt Reactor Experiment (MSRE) from the Oak Ridge National Laboratory. Flibe Energy has enhanced the MSRE design to efficiently utilize thorium fuel mixed in lithium fluoride and beryllium fluoride (LiF-BeF_2) salts [2]. Terrestrial Energy has developed a design based on the need for a small modular reactor that is easier, cheaper, and quicker to construct [3]. See the table below to compare these designs.

Comparison of MSR Designs

Table I shows a comparison of selective features of an actinide-burning molten salt reactor (MOSART), Flibe Energy's thorium-fueled MSR, and Terrestrial Energy's uranium-fueled MSRs. Table I shows that molten salt technology is compatible with a wide variety of fuels. A fast neutron spectrum is preferred for burning waste and actinides. The operating temperatures are very much alike since the coolants are similar.

The waste produced in MSRs is mostly fission products-- not actinides-- due to the high burnup. In fact, most reactors with liquid fuel have a 90% or higher burnup rate [1]. As the half-lives of fission products are significantly shorter than those of actinides, MSR waste needs only to be stored for tens or hundreds of years rather than thousands.

Reprocessing spent fuel is much easier and more economical if the fuel is in liquid form. Reprocessing spent fuel recovers fissile and fissionable isotopes to place

TABLE I. Comparison of MSRs

MSR Design	Fuel Cycle	Neutron Spectrum	Operating Temperature (°C)	Thermal Power [MW(th)]	Thermal Efficiency
MOSART	TRU-Th-^{233}U [4]	Fast [4]	600-720 [4]	2400 [4]	40% [5]
Flibe Energy	Th-^{233}U [2]	Thermal [2]	653 [2]	600 [2]	45% [2]
Terrestrial Energy	<5% ^{235}U, ^{238}U [3]	Thermal [3]	600 [3]	400 [3]	45% [3]

them back into the reactor for more energy extraction, thus improving fuel economy and closing the fuel cycle. The waste produced by the LWRs and MSRs themselves can be reprocessed and placed back into the MSRs. The closed nuclear fuel cycle depletes the fuel to a point where radioactivity would become very low.

Waste Management

The appealing features of the MSR, such as its liquid fuel and salt coolant, allow for better management of nuclear waste. Because the MSR is cooled by salt, the operating temperatures have a higher range than those cooled by water. This property increases the burnup and plant efficiency. Also, solid fuel must be replaced often because of radiation damage to cladding. Liquid fuel, as found in MSRs, does not have this problem. Technically the fuel can remain in the reactor forever. Because of these features, burnup of the fuel is relatively high, so the radiotoxicity of the spent fuel is low.

In salt-fueled reactors, waste is much easier to store. Fluoride salts easily undergo vitrification. Therefore, the dissolved fission products in an MSR will be trapped in the salts. The readily formed glass can compactly store spent fuel.

Lastly, The MSR has the potential to burn reprocessed spent fuel and actinides from LWRs and weapon stockpiles. This means that while producing energy, the MSR could simultaneously decrease the volume of nuclear waste.

Safety

The dump tanks at the bottom of the MSR function as an inherent safety feature and storage for excess salt. The unique frozen salt plug and drain tanks in the MSR allow for the reactor to be walk-away safe and meltdown-proof. The drainage process, with few exceptions, does not require cooling, pumping, or any other electricity-powered system. Instead, it solely relies on gravity. In the case of loss of coolant or overheating, the surrounding environment is still safe because of the simple drainage process. The dump tanks also function as storage for excess salt that forms due to expansion in rising temperatures.

The operating pressure of MSRs is near atmospheric pressure. Compared to LWRs, the MSR is very safe in this respect. Loss of pressure or a breech in the containment structure would not spread radioactive materials into the surrounding environment.

MSRs also have the option of utilizing thorium as a fuel. The use of thorium would greatly reduce the proliferation risks associated with nuclear power production. This is because plutonium is rarely produced in thorium fuel cycles.

Areas of Further Research

Because of the lack of research surrounding MSRs, there are still many issues surrounding this technology. Many of these problems relate to materials; however, the following are concerned with the fuel cycle and waste of MSRs.

Online reprocessing may present an obstacle to closing the fuel cycle. Processing all of the salt that flows through in a brief period time will be complex. Plus, the ability to reprocess the fuel on-site leads to proliferation risks. Some nuclear isotopes, especially ^{233}U, may be used for weapons purposes. If online reprocessing is not in place, a once-through fuel cycle may also be utilized in the MSR.

The idea of burning nuclear waste and actinides is a great step for nuclear technology. However, transporting spent fuel and old nuclear weapon material will pose risks related to human health, environment, and proliferation.

The MSR does have great potential toward closing the nuclear fuel cycle and solving the problems associated with nuclear waste. However, more research and development are necessary in the areas of materials, online reprocessing, and accessing spent fuel and waste.

REFERENCES

1. T. GRIFFITHS, J. TOMLINSON, & R. O'SULLIVAN, "MSR review: Feasibility of Developing a Pilot Scale Molten Salt Reactor in the UK," Energy Process Developments Ltd, (2015).
2. A. SOWDER, "Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design: The Liquid-Fluoride Thorium Reactor (LFTR)," 3002005460, Electric Power Research Institute, (2015).
3. D. LEBLANC, "An Overview of the Integral Molten Salt Reactor," *IAEA MSR Workshop*, 1 November 2016, Terrestrial Energy, (2016).
4. C. W. FORSBERG, "Thermal- and Fast-Spectrum Molten Salt Reactors for Actinide Burning and Fuel Production," UT-Battelle, LLC, (2007).
5. NUCLEAR SCIENCE COMMITTEE, "Actinide and Fission Product Partitioning and Transmutation," *Thirteenth Information Exchange Meeting*, Seoul, Republic of Korea, 23-26 September 2014, OECD, (2015).