AN IN SITU FEED MONITORING SYSTEM FOR MOLTEN SALT REACTORS
With Fast Neutron Energy Spectrum Molten Salt Reactor Applications

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1. INTRODUCTION

Molten salt reactors (MSRs) are one of the six promising advanced reactor technologies selected for further research and development by the Generation IV International Forum [1,2]. More than twenty MSR designs are actively being developed around the world. Several of these designs are liquid-fueled and intended for operation within the fast neutron energy spectrum.[1]

National regulations will require liquid-fueled MSRs to control and account for nuclear material within licensed facilities. Additionally, states with comprehensive safeguards agreements with the International Atomic Energy Agency (IAEA) are obligated to declare nuclear material quantities within facilities. In return, the IAEA Department of Safeguards independently verifies these quantities and provides assurance that the nuclear material and facility are being used only for peaceful purposes.

One key distinction of liquid-fueled MSRs compared with other types of reactors is that in portions of the facility, the nuclear material is in bulk form rather than discrete items. Traditional nuclear material accounting techniques such as physical item counting and verification of serial numbers on fresh fuel assemblies do not translate directly to all process streams within liquid-fueled reactors.

Liquid-fueled MSRs are typically designed with low excess reactivity. This feature provides safety benefits but also means that most MSRs require the addition of makeup fuel salt while a reactor is operational. The nuclear material in the initial fuel salt and in any makeup fuel salt must be quantified. Additionally, distinct nuclear material diversion and reactor misuse scenarios form the basis of the detection methods and monitoring systems developed for liquid-fueled MSRs. For example, the IAEA provides assurance that fuel salt containing nuclear material is not being diverted from the system, that the feed salt matches the reported actinide concentrations and uranium enrichment, and that no additional fertile material is being introduced into the system [3]. Measurement systems currently used for nuclear material control and accounting are not directly applicable to achieving MSR safeguards goals. This paper concerns a system being designed to account for the nuclear material added to liquid-fueled MSRs and monitor for diversion and misuse scenarios related to MSR feed systems.

2. SURVEY OF CANDIDATE MEASUREMENT TECHNIQUES

The initial research aim was to develop a methodology for down-selecting measurement techniques to meet a specific safeguards goal using an objective decision framework. The initial safeguards goal was to quantify nuclear material in the fresh fuel feed into a liquid-fueled MSR system and monitor for indicators of diversion and misuse. Additional assumptions, such as the types of nuclear material contained in fresh fuel salt, which initially prioritized US MSR designs, were made to advance the design of an MSR feed monitoring system.

The components chosen to quantify total uranium content and ^{235}U mass were first selected using a literature survey of candidate measurement techniques and a qualitative ranking via eight figures of merit. Table 1 lists the 20 candidate measurement techniques that were evaluated for use in the MSR feed monitoring system. Table 2 lists the eight figures of merit that were used to assess each of the 20 candidate measurement techniques [4]. The choices outlined herein were premised on a liquid-fueled MSR using low-enriched uranium (LEU) or high-assay low-enriched uranium (HALEU) fresh; the

[1] For example, TerraPower's Molten Chloride Fast Reactor, NAAREA's XAMR, and Stellaria's Stellarium.

inherently different attributes of other fuel cycles (e.g., a thorium-based breeder design or a plutonium-based cycle) would warrant separate consideration of the evaluated techniques.

TABLE 1. CANDIDATE MEASUREMENT TECHNIQUES EVALUATED [4]

Measurement Technique	Quantity Measured
Active neutron – delayed gamma Active neutron – neutron multiplication Gamma spectroscopy	Fissile mass in measured volume
Alpha spectrometry Gamma spectrometry Inductively coupled plasma mass spectrometry	^{235}U enrichment
Electrochemical sensor Hybrid K-edge densitometry K-edge densitometry Laser-induced breakdown spectroscopy Laser-induced fluorescence Inductively coupled plasma mass spectrometry Raman spectroscopy Ultraviolet-visible-near-infrared spectroscopy	U concentration
Passive neutron	^{234}U mass in measured volume
X-ray fluorescence	Elemental composition
Bubblers	Total salt volume or mass added and density
Flow measurements	Total salt volume or mass added
Level measurements	Total salt volume added
Weighing systems	Total salt mass added

TABLE 2. FIGURES OF MERIT USED TO EVALUATE CANDIDATE MEASUREMENT TECHNIQUES [4]

No.	Figure of Merit
1	Reasonably achievable uncertainty
2	Measurement time to achieve reasonable uncertainty
3	Capital equipment cost
4	Facility burden
5	Maintenance intensity
6	Technological maturity
7	Human capital requirements
8	Introduction of a path for potential nuclear material removal

3. COMPONENT SELECTION

Based on the results of the survey and evaluation of candidate measurement techniques discussed in Section 2, the identified techniques were grouped into four categories. Within each category, the techniques were compared based on the figures of merit in Table 2 to down-select to the system components deemed most promising for future development. Three system components were selected for further development into an MSR feed monitoring system: K-edge densitometry to quantify uranium concentration within the salt, gamma ray spectroscopy to quantify ^{235}U enrichment, and weighing systems to quantify the total salt mass added to the reactor. A level sensor could also be used to confirm the salt volume added to the system and compare it with expected salt mass through salt temperature and density conversions [5]. The following sections provide details on design assumptions pertaining to the MSR system to be monitored and the down-selection and screening process that informed component selection.

3.1. K-edge Densitometry

The application of K-edge densitometry in an MSR feed monitoring system includes an x-ray tube generating x-rays that penetrate the pipe or tube through which feed salt is being added to the MSR system. A gamma detector is aligned on the opposite side of the pipe. The enhanced attenuation of transmitted x-rays at the K-edge energy of uranium in the uranium-bearing molten salt within the pipe is used to determine the elemental concentration of uranium within the salt. K-edge densitometry was selected as the best option for quantifying uranium concentration because it does not need to penetrate the MSR system (i.e., it does not require physical contact with the salt and may not require any modification of the piping, such as the installation of a window).

3.2. Passive gamma spectroscopy

Passive gamma spectroscopy was chosen as the measurement technique for determining uranium enrichment within the liquid fuel salt. The two other candidate measurement techniques for quantifying uranium enrichment—alpha spectrometry and inductively coupled plasma mass spectrometry—were omitted from consideration because they require the taking of physical samples and are destructive techniques. Both of these factors were contrary to the primary goal of this research, which is to design an in situ monitoring system that can be used by the IAEA Department of Safeguards to monitor for diversion and misuse in an MSR feed system. Radiation transport modelling and simulation efforts are currently underway to investigate these trade-offs and provide initial proof of concept. The initial step was to characterize the parameter space within which gamma spectroscopy measurements can be performed for feed salt monitoring. Parameters include various fuel salt compositions and densities, uranium enrichments, pipe materials and geometries, and insulation materials and thicknesses [3].

3.3. Weighing systems

Quantification of total uranium content within the fuel salt requires that the total salt mass be measured in situ along the flow path. Although several different techniques can be used for this measurement, weighing systems were selected for implementation as part of the full system design. Liquid level measurements are being examined as a potential complementary measurement for salt volume to monitor changes in total salt volume.

4. SYSTEM DESIGN AND FUTURE WORK

Quantitative and qualitative design criteria have been determined for a monitoring system that quantifies total uranium and ^{235}U masses and monitors the feed pipe into an MSR system for indicators of diversion or misuse. Components are being integrated into a multimodal system design, and modelling and experimental research are underway to determine optimal features for each design criterion. Figure 1 depicts the integration of feed monitoring system components into a nominal MSR design.

Research is currently underway to continue to develop the design of an MSR feed monitoring system. This research includes using modelling and simulation to select specific component features such as the passive gamma spectrometry detector technology and optimize monitoring system design parameters such as the shielding thickness between the x-ray tube and the pipe and the pipe and the gamma detector. Additional modelling and simulation efforts are underway to determine the limitations of the system design. Hardware components have been procured, and experimental measurements on representative materials (i.e., uranium-bearing flowing salt in a pipe) are planned.

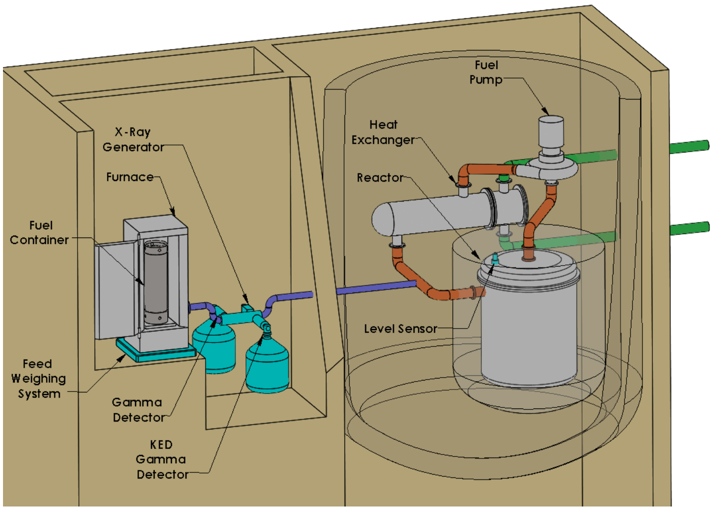

FIG 1. Conceptual design of an MSR feed monitoring system.

5. SUMMARY

An MSR feed monitoring system is being designed to quantify nuclear material entering an MSR in initial and makeup fresh fuel salt and monitor for indicators of relevant diversion and misuse scenarios. Candidate measurement techniques were surveyed against eight figures of merit, and three component measurement techniques were down-selected for use in a feed monitoring system: gamma spectroscopy to quantify ^{235}U enrichment, K-edge densitometry to measure uranium concentration, and weighing systems to quantify total salt mass. These components are being further developed through modelling and simulation. Experiments are planned for gamma spectroscopy measurements on uranium-bearing flowing salt representative of the salt composition of a fast chloride MSR.

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