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]. More than twenty MSR designs are actively being developed around the world. Several of these designs are liquid-fueled and plan to operate within the fast neutron energy spectrum[1].

National regulations will require liquid-fueled MSRs to control and account for nuclear material within a licensed facility. 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 will independently verify these quantities and ensure that the nuclear material and the facility are being used only for peaceful purposes.

One of the key distinctions of a liquid-fueled MSR as compared to other reactors is that in portions of the facility, the nuclear material is in bulk form rather than discrete items. Traditional nuclear material accounting techniques like physical item counting and verification of serial numbers on fresh fuel assemblies are not directly translatable throughout all process streams within liquid-fueled reactors.

Liquid-fueled MSRs are typically designed with low excess reactivity. This provides safety benefits but also means that most MSRs will require the addition of makeup fuel salt while the reactor is operational. The nuclear material in the initial fuel salt and in any makeup fuel salt must be quantified. Additionally, there are distinct nuclear material diversion and reactor misuse scenarios that form the basis of the developed detection methods and overall monitoring system for liquid-fueled MSRs. For example, the IAEA must ensure that fuel salt containing nuclear material is not being diverted through removal 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 [2]. A novel system is being designed to account for nuclear material being added to a liquid-fueled MSR and to monitor for diversion and misuse scenarios related to an MSR feed system.

2. SURVEY OF CANDIDATE MEASUREMENT TECHNIQUES

This initial research aimed to develop a methodology to down-select measurement techniques to meet a specific safeguards goal using an objective decision framework. The initial safeguards goal is to quantify nuclear material in fresh fuel feed and monitor for indicators of diversion and misuse into a liquid-fueled MSR system. Additional assumptions, initially prioritizing US MSR designs, were made to progress the design of an MSR feed monitoring system.

The choice of components used for quantification of total uranium content and ^{235}U mass were first selected through a literature survey of candidate measurement techniques and based on a qualitative ranking via eight figures of merit. Table 1 includes the list of twenty candidate measurement techniques that were evaluated for use in the MSR feed monitoring system. Table 2 includes eight figures of merit that were selected and assessed for each of the twenty candidate measurement techniques [3]. Note that the choices outlined herein are premised upon a liquid-fueled MSR using a low-enriched uranium (LEU) or high-assay low-enriched uranium (HALEU) fuel cycle; the inherently different attributes of

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

other fuel cycles— such as thorium-based breeder designs or a plutonium-based cycle—would warrant separate consideration of the evaluated techniques.

TABLE 1. CANDIDATE MEASUREMENT TECHNIQUES EVALUATED [3]

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 UV-visible-near-infrared spectroscopy	U concentration
Passive neutron	Fissile/fertile mass in measured volume
X-ray fluorescence	Relative elemental abundances (U, etc.)
Bubblers	Total salt volume/mass added and density
Flow measurements	Total salt volume/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 [3]

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 of candidate measurement techniques discussed in section 2, the identified techniques were grouped into four categories according to the information obtained. Within each category, the techniques were comparatively assessed based on the previously identified figures of merit to down-select 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 the uranium concentration within the salt, gamma ray spectroscopy to quantify the ^{235}U enrichment, and weighing systems to quantify the total salt mass added to the reactor. A level sensor could be added as an optional component to confirm the salt volume added to the system and compared with expected salt mass through salt temperature and density conversions [4]. The following sections provide details on the design assumptions pertaining to the MSR system to be monitored and the down-selection and screening process that informed the ultimate component selection.

3.1. K-edge Densitometry

K-edge densitometry application in a MSR feed monitoring system would include an x-ray tube generating x-rays that would penetrate a pipe or tube in which feed salt was being added to an MSR system. A gamma detector would be 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 to quantify uranium concentration primarily based on it not requiring a penetration of 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 use 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 to quantify uranium enrichment were omitted from consideration due to alpha spectrometry and inductively coupled plasma mass spectrometry both requiring a physical sample and are destructive techniques, contrary to the primary goal of this research to design an in-situ monitoring system that could be used by the IAEA Department of Safeguards to monitor for diversion and misuse in a feed system in a MSR. Radiation transport modelling and simulation efforts are currently underway to investigate various trade-offs and to provide an initial proof of concept. The initial step was to characterize the parameter space within which that the gamma spectroscopy measurements could be performed for feed salt monitoring. Parameters include various fuel salt compositions and densities, uranium enrichments, pipe materials and geometries, insulation materials and thicknesses [2].

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 could be used to make this measurement, weighing systems have been selected as the technique to implement as part of the full system design. As a potential complementary measurement for salt volume, liquid level measurements are being examined in tandem for the purpose of monitoring changes in total salt volume.

4. SYSTEM DESIGN AND FUTURE WORK

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

Research is currently underway to continue to develop the design of a MSR feed monitoring system. This includes using modelling and simulation to select specific component features like the passive gamma spectrometry detector technology (e.g., high purity germanium detector) 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 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 in the coming months.

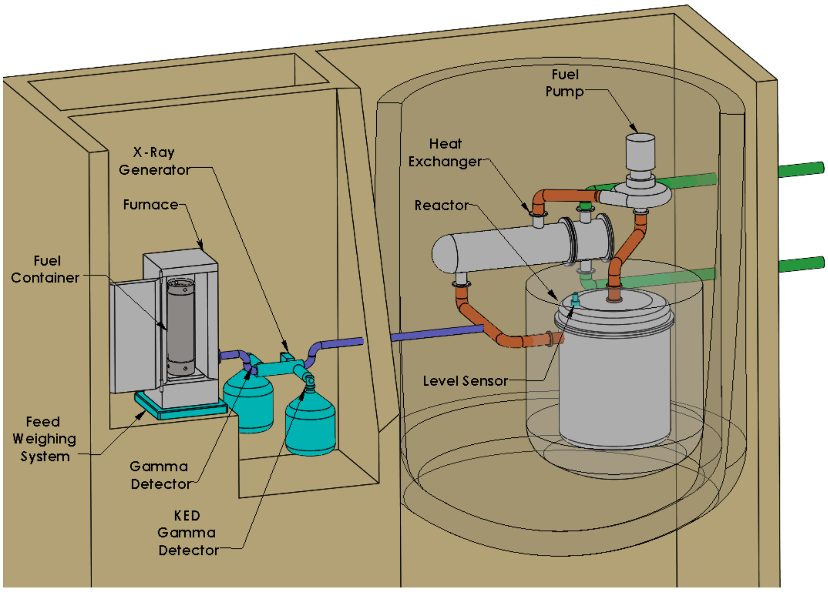

FIG 1. Conceptual design of an MSR feed monitoring system.

5. SUMMARY

A MSR feed monitoring system is under design to quantify nuclear material entering into a 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 components were down-selected for use in a feed monitoring system: gamma spectroscopy (for ^{235}U enrichment quantification), K-edge densitometry (for uranium concentration), and weighing systems (for total salt mass). These components are being further developed through modelling and simulation. Additionally, experiments are being planned for gamma spectroscopy measurements on uranium-bearing, flowing salt representative of the salt composition for a fast chloride molten salt reactor.

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