A conceptual approach to MSR safeguards

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1. Introduction

The carbon neutral aspect of nuclear power has increased interest in using the technology to mitigate CO_2. Advanced nuclear power plants (NPPs) are being developed to play an important role in the future of nuclear energy. One of the advanced NPPs, the Molten Salt Reactor (MSR), is receiving considerable attention because its safety features are superior to existing light water reactors (LWRs). For this reason there is a push to bring the MSR to commercialization.

The MSR uses liquid fuel dissolved in molten salt rather than solid fuel in coolant. This feature allows the MSR to be operated at low pressure and refueled on-line. More important, since there is no separate coolant, it has an inherent advantage in preventing core melting, unlike existing NPPs, where loss of coolant can result in a severe accident.

However, since the fuel is liquid, it is difficult to apply existing safeguards, which were mainly designed for solid fuels. This is one of the challenges of MSR operation and poses a potential problem for MSR commercialization. Because the MSR is in the development stage, there is still time to take a safeguards by design approach, which is advocated by the IAEA. This study will focus on one Korean MSR design and determine which safeguards by design applied at other facilities could potentially be applied to the MSR. This study will focus on burnup monitoring of the flowing fuel regarding the depletion and movement of fissile materials: Once the fuel is loaded into the reactor, the burnup will increase until the fuel is discharged. Therefore, if the reactor design includes fuel composition and reactor power, normal operation and off-normal removal of fissile materials can be checked by measuring burnup along with process monitoring.

2. Safeguards challenges for MSR

The most significant feature of the MSR is its use of liquid fuel. There are two types of liquid fuel MSRs. One uses molten salt as a coolant and uses solid fuels, and in the other type, the fuel is dissolved in the molten salt. This study focuses on the second type of MSR which is under development in South Korea.

The current IAEA safeguards inspection system uses item counting for nuclear reactors which cannot be applied to liquid fuel MSRs. The main safeguards issues for MSR fuel are:

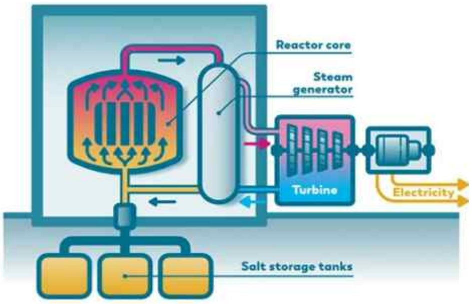
- Continuously flowing material: The fuel is a homogeneous liquid mixture of fuel, coolant, FPs (fission products), and actinides. Unlike conventional NPPs, liquid fuel salts continue to move into and out of the core.
- Continuously changing material (salt and its contents): The salt is solid state before reactor loading and is liquid during normal reactor operations; it remains liquid when discharged due to decay heat, but then becomes a solid again.
- Measurement environment: High radiation, high dose, high temperature environment, with little decay time between the irradiation and measurement.
- Accessibility: Not only the reactor, but the entire containment, will be contaminated, making it inaccessible; new access methods are needed because inspection and measurement will be extremely difficult.

Considering these issues, the on-line safeguards approach is needed and should take into account the continuously flowing and changing fuel salt.

These difficulties are compounded by the fact that there are no commercialized MSRs: As these reactors are still in the development stage, there are no specific reactor designs finalized. This study is to develop a conceptual safeguards approach based on the major features of only one of the MSR designs being researched.

3. Proposed conceptual approach to MSR safeguards

The IAEA said that “the objective of nuclear safeguards is timely detection of diversion of significant quantities of nuclear material and deterrence of such diversion by early detection”. To be exact, it prevents the making of 1 Significant Quantity (SQ), which is defined as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explicit device cannot be excluded". The basic concept for satisfying this is to check whether the total amounts of the nuclear materials entering and leaving the reactor are the same based on the principle of nuclear materials control and accounting (MC&A).

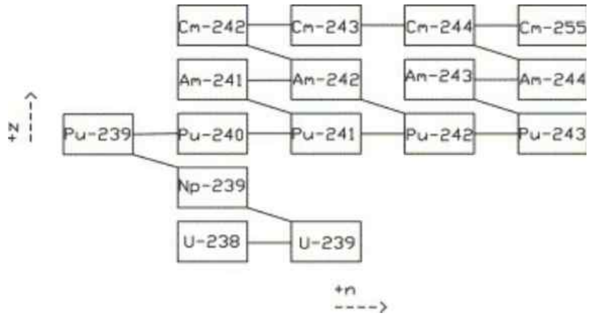


<Fig 1. Example of a MSR scheme>

In the MSR, since the liquid fuel circulates in the system, the flow rate (m^3/s) and total time ($\triangle t$) of flow can be used to determine the amount of nuclear materials loaded into the reactor and discharged out of the reactor. The loaded fuel moves through the off-gas system, and heat exchanger, and then enters the core again. The amount of nuclear materials in the pipes during fuel movement can also be determined by measuring the flow rate and time when the fuel enters and leaves the core. The remaining amount of nuclear materials in the core, except for those moving through the pipes, will undergo a fission reaction in the core. Therefore, by measuring the flow of fuel salt moving into and out of the reactor, the total amount of nuclear materials loading into the reactor can be determined as follows.

- Amount of nuclear materials loading into reactor
  = Amount of materials undergoing fission in reactor core
  + Amount of materials moving in total pipes outside the core

Along with the quantification of mass flow in and out of the reactor, this study proposes the use of burnup monitoring to determine fissile content in the flowing fuel salt at every key measurement point. In order to measure fuel burnup, counting the passive neutron emissions of specific elements was considered. Based on the experiences from pebble bed reactors [Su et al., 2006], Cm-242 and Cm-244 generated through neutron capture from Pu and beta decay are selected as cumulative burnup indicators. As the fresh fuel with zero burnup passes through the core, the burnup increases, and the passive neutron emissions from Cm-242 and Cm-244 begin to emerge. By conuting the passive neutron emissions of Cm-242 and Cm-244 we can determine the cumulative burnup of the fuel.

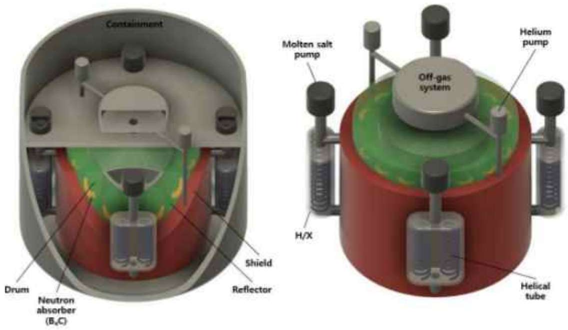


<Fig. 2. Formation chains for actinides>

If the estimated burnup values based on measurements are different from the expected burnup, off-normal operation can be suspected as part of the operation of the proposed monitoring. Detectors with high neutron detection efficiency and good gamma discrimination ability (e.g., fission chambers) should be used for burnup monitoring purposes.

In addition, the off-gas system should be included in the safeguards analysis of the MSR. Because FPs are dissolved in the continuously circulating liquid fuel, some are deposited in the form of particles and some are removed in the off-gas system. Removal of FPs is required in order to maintain the homogeneity of the liquid fuel. The off-gassing is achieved through helium bubbling. Since Pu, Np, and other minor actinides are gasified and separated from the molten salt, removal of these elements through the off-gas system should be considered for nuclear materials accountancy.

This study will examine the feasibility of nuclear safeguards by applying process/burnup monitoring to the MSR design being developed at KAIST. Fig. 3 shows the schematic of the MSR and the main core parameters are shown in Table 1.



<Fig. 3. Reactor core design (KAIST)>

<Table 1. Reactor core parameter>

Parameter	Value
Reactor type	Fast-Spectrum MSR
Fuel salt	$46KCl\text{-}54UCl_3$
U-235 enrichment	19.75w/o
Reactor power	100 MWt
Core temperature	650°C
Reactor life-time	50 years

Depending upon the success of process/burnup monitoring, this study will also evaluate the need for an additional NDA system for MSR safeguards. Such a system may include hybrid k-edge densitometer.

4. Conclusions

This study proposes the use of materials flow monitoring along with burnup monitoring at key measurement points for nuclear safeguards of the MSR. Results of the conceptual analysis through simulations using the KAIST MSR design will be presented at the conference. Examination will include the potential use of the hybrid k-edge densitometer to reduce uncertainty in nuclear materials accountancy.

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