Safeguards Challenges for Molten Salt Reactors

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Abstract

There are now a wide variety of molten salt reactor (MSR) technologies being proposed or developed that are gaining international interest and momentum toward deployment. There are two sub-categories of this class of reactors - those that are liquid fueled (i.e., the molten salt is both the fuel and the coolant) and those that have solid fuel with the molten salt used as coolant only. The liquid-fueld MSRs present unique challenges to current safeguards approaches. These challenges exist because there are currently no conceptual approaches to applying safeguards to unique, tightly coupled nuclear energy systems with the reactor core, balance of plant, and fuel cycle (everything else including salt processing and material separations) combined in a single facility. The application of safeguards to liquid-fueled MSRs will have to take into consideration several technical factors including: the homogeneous mixture of fuel, coolant, fission products, and actinides (with the attendant extremely high radiation field); continuous variation in isotopic concentrations in the fuel salt, including removal (passive or active) of fission products, rare earth elements, and noble metals; high operating temperatures of the fuel salt; online processing where some fraction of the inventory can be removed while the reactor is operational; unique refueling schemes, including the ability to continuously feed the core with fresh fissile or fertile material; the presence of frozen fuel, potentially requiring a different safeguards process from the liquid fuel; and the presence of fuel outside the vessel. Additionally, if the thorium fuel cycle is employed, there will be additional complications since the resulting radiation signatures will be different from those of the uranium-based fuel cycle. The existing IAEA inspection regimes are based on the uranium-plutonium fuel cycle, item counting for nuclear reactors, and bulk material accountancy for the front and back end of the nuclear fuel cycle. These techniques and associated instrumentation for bulk accountancy have been developed predominantly for enrichment, fuel fabrication, and aqueous reprocessing. However, none of these bulk accountancy measures can be directly applied to liquid-fueled MSRs. This paper will explore some of the possible challenges in applying safeguards to molten salt reactors.

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Introduction

Several molten salt reactor (MSR) design variants are currently being proposed. For example, startups in the United States have not only expanded on the original Oak Ridge National Laboratory (ORNL) MSR Experiment (MSRE)[1] design but have also developed possible options using spent nuclear fuel (SNF), uranium-plutonium, transuranics, fast spectrum designs, as well as the original thorium-based concepts. Some European MSR developments (namely, Moltex[2] and Seaborg[3]) focus on disposition of SNF. Similarly, under the Generation IV International Forum (GIF), fast-spectrum MSR developments have been advancing, such as the Russian Molten Salt Actinide Recycler and Transmuter (MOSART) that would have the capability to burn transuranic waste from spent uranium-oxide and mixed-oxide light water reactor (LWR) fuel. China has several approaches underway, including a ^{235}U/Th-based pebble bed solid-fueled MSR (FHR[4]) and a liquid-fueled MSR like the ORNL MSRE/MSBR (Molten Salt Breeder Reactor) designs. Some of the domestic and international designs will use on-site, on-line fuel processing (separation of fissile material from salt or only fission product removal), while others will use an off-site facility either for long-term storage or fuel processing.

The proposed fuel salts for these MSR designs include options from the full range of fissile materials including ^{233}U, ^{235}U (low-enriched uranium-LEU), and SNF (~1% ^{239}Pu, ~1% ^{235}U). Fertile materials are also proposed as fuel salt options and include Th and ^{238}U. All the MSR designs will need fresh fuel containing many significant quantities (SQ) of fissile/fertile materials that must be either manufactured onsite or shipped from an external facility. Safeguards will likely be required at the external facility, during transport to the reactor site, and during any potential on-line processing included in the various MSR designs. Therefore, multiple material balance areas (MBAs) will be needed. Specific attention should be paid to material in-process and material-unaccounted-for (MUF) since liquid and some solid fuels are likely to require bulk nuclear material accountancy methods.

Current Concepts

The unique nature of the MSR concept and its flexibility in design variations has resulted in the diverse MSR designs currently under development. Because of abundant thorium supplies, some designers are continuing to pursue an optimized thorium breeder fuel cycle. Some designs are burner-type MSRs without actinide separations (i.e., Denatured MSRs - DMSRs), which are under development by multiple commercial entities. Some efforts are even seeking to shift between fast and thermal spectrum operation by inserting moderator rods into the core as reactivity changes during operation. Alternatively, fast-spectrum fluoride-salt based MSRs are the leading candidate technology being pursued in the European Union and the Russian Federation. Furthermore, chlorine isotope separation appears to be both technologically feasible

1 https://www.ornl.gov/news/msres-50th

2 http://www.moltexenergy.com/

3 https://seaborg.dk/intro/

4 FHR refers to a **F**luoride salt cooled **H**igh temperature **R**eactor that employs a solid fuel matrix

and not cost prohibitive. Consequently, commercial entities are pursuing fast spectrum $^{238}U/^{239}Pu$ breeder reactors based on ^{37}Cl salts.

Both fixed and mobile fuel forms for solid-fueled MSRs (FHRs) are under consideration. The tri-structural-isotropic (TRISO) particles being developed for gas cooled reactors are currently the leading candidate FHR fuel. TRISO-based pebbles, plates, and fuel compacts embedded within graphite blocks have all recently been considered. The liquid cooling provided by molten salts enables a higher power density than is possible with gas cooling. Consequently, higher amounts of fissile material would be required in the core, which in turn would necessitate either higher enrichment in the TRISO or more frequent refueling. Alternatively, both the silicon carbide and molybdenum-based claddings being developed under the US Department of Energy's (DOE's) accident tolerant fuels program would be compatible with a molten salt coolant enabling a more conventional fuel rod and assembly format employing larger amounts of lower enrichment fuel (<5 wt. % ^{235}U).

Table 1 lists the initial design intents of the publicly described reactors including their associated fuel cycle. Some of the designs are adaptable to other fuel cycles, like the ORNL MSRE that originally ran on ^{235}U and later transitioned to ^{233}U (and introduced ^{239}Pu in its last few fuel additions). For example, the European fast spectrum molten salt reactor (MSFR) employs significant fertile loading while the Russian MOSART concept does not include fertile material, yet otherwise much of their layouts is similar potentially allowing switching between fuel cycles. Other MSR companies exist with non-publicly disclosed design intents and are therefore not included in the table.

Table 1 – Currently proposed molten salt reactors and fuel cycles

Fuel Cycle	**Reactor/Developer**
Thermal $^{232}Th/^{233}U$ Breeder	FLiBe Inc.[5], Copenhagen Atomics[6], Thoreact[7], Alpha Tech Research[8]
Thermal Two Fluid $^{232}Th/^{233}U$ Breeder	Indian Molten Salt Breeder Reactor[9]
Thermal $^{232}Th/^{233}U$ Breeder with Multistage Separations	Chinese TMSR-LF[10]
Thermal Denatured Mixed Thorium and LEU Burner	ThorCon Power[11]
Denatured Thermal ^{235}U Burner	Terrestrial Energy[12]
Fast Fluoride $^{238}U/^{239}Pu$ Breeder	MOSART – Russian Federation[13]

5 http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002005460
6 http://www.copenhagenatomics.com/
7 http://thoreact.com/
8 http://alphatechresearchcorp.com/
9 https://www.ias.ac.in/article/fulltext/pram/085/03/0539-0554
10 https://www.gen-4.org/gif/upload/docs/application/pdf/2017-05/03_hongjie_xu_china.pdf
11 http://thorconpower.com/docs/exec_summary.pdf - p. 19
12 http://terrestrialenergy.com/imsr-technology
13 IAEA-Tecdoc-1626 – Chapter 9

Fast Fluoride Mixed Thorium and Uranium Breeder	MSFR[14]
Fast Chloride $^{238}U/^{239}Pu$ Breeder	TerraPower[15], Elysium Industries[16]
Spectral Shift Actinide Burner	TransAtomic[17]
Mixed Spectrum Thorium Enhanced Actinide Burner	Seaborg Waste Burner[18]
Fast Plutonium Chloride Burner – Fluoride Salt Cooled	Moltex[19]
Fast Chloride Burner – Lead Cooled	Dual Fluid Reactor[20]
Pebble bed solid fuel ^{235}U Burner	Kairos Power[21]

It is not possible in all cases to arrange the various designs from a geographical standpoint. Take as an example the ThorCon Power design - the company owners are based in the Caribbean, they are incorporated in Singapore but with a U.S. affiliate, and their lead developers are in the US. Their planned heavy manufacturing will be in South Korea and they are planning on initial deployment in Indonesia.

In addition, Figure 1 shows the proposed technologies in relation to their main design characteristics (solid fuel vs. liquid fuel, fast vs. thermal spectrum etc.). The figure shows that most designs use salt for both the fuel and coolant, use thorium, and have either onsite or offsite fissile separations capabilities.

[14] Jérôme Serp et al., *The molten salt reactor (MSR) in generation IV: Overview and perspectives*, Progress in Nuclear Energy, 77, November 2014, 308-319

[15] http://terrapower.com/

[16] http://www.elysiumindustries.com/

[17] http://www.transatomicpower.com/wp-content/uploads/2015/04/transatomic-white-paper.pdf

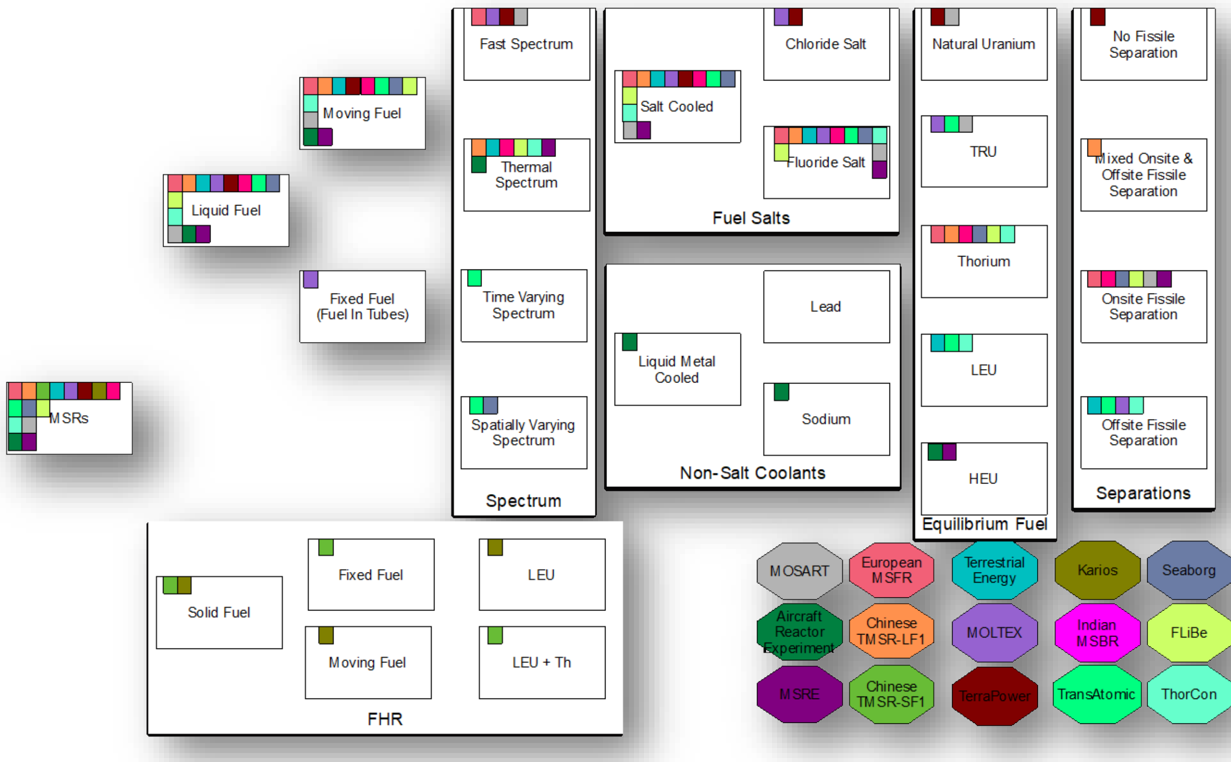
[18] https://seaborg.dk/intro/

[19] http://www.moltexenergy.com/

[20] https://dual-fluid-reactor.org/

[21] https://kairospower.com/

Figure 1 – Main design characteristics of proposed reactors



Key Safeguards and Nonproliferation Issues To Be Addressed

MSR technology exists in a wide variety of designs that may be developed for international deployment. It is possible that within the next decade, initial test reactors might be deployed. The following key questions remain to be answered in understanding the safeguards implications of MSRs:

- *Is the International Atomic Energy Agency (IAEA) and international safeguards system ready for MSRs? If not, what steps should be taken to prepare?*
- *Are the safeguards inspection regimes of today valid for proposed MSR designs and the associated fuel cycles?*
- *Have the appropriate safeguards approaches been determined for MSRs?*
- *Are the safeguards approaches for one MSR design valid for another design?*
- *Is the safeguards technology of today sufficiently mature to meet the verification challenges posed by MSRs and their associated fuel cycles?*
- *Is safeguards technology readily fieldable? For example, are non-destructive assay technologies and other measurement instruments ready for deployment to meet these new verification challenges?*

The following are some of the associated key safeguards and nonproliferation issues that should be considered.

Salt-Fueled MSRs

The nominal MSR fuel form is a homogenous mixture of fuel, coolant, fission products, and actinides. There are currently no safeguards approaches for nuclear power reactors that take this into consideration. Since MSR fuel is not contained in assemblies, it is not possible to perform traditional item counting and visual accountability of the salt fuel. Additionally, there is the potential for online fuel processing whereby some fraction of the inventory can be removed while the reactor is operating. In this case there could be similarities with safeguards approaches for aqueous reprocessing facilities. Salt fuel represents a unique combination of high-temperature and high-radiation environments that will be challenging for measurement techniques and instrumentation.

- The temperature in the reactor or fuel processing plant will always be kept above the melting point of the salt (operating temperatures from 400°C to >800°C).
- Once the reactor has operated, the fuel salt will remain highly radioactive both inside and outside of the reactor core.
- Molten salts can potentially present a highly corrosive environment, which will challenge any monitoring instrumentation.
- The potential for the presence of frozen fuel in the reactor system might require a different safeguards approach to that of liquid salt fuel.
- Fuel salt can in some cases have low fissile concentration in the salt mixture, which implies that a relatively large volume of salt will have to be diverted to produce 1 significant quantity.

Online Fuel Processing and Refueling

There are significant safeguards implications related to the online processing and refueling of salt fuel:

- There will be continuous variation of isotopic concentrations in the fuel salt from both transmutation and online chemical processing. The isotopic concentrations in the reactor system will be both time variation (burnup) and the spatial variation (fission in core and transport/plating through the system).
- There is the potential to have fuel inventory present outside the reactor containment vessel.
- Refueling schemes might include the ability to continuously feed the core with fresh fissile or fertile material.
- Plate-out of rare earth elements in the reactor and in the process piping could complicate inventory tracking.

The following questions arise from the above safeguards implications.

- What will be the form of SNF since it does not accumulate because of online fuel processing?
- How will the fissile material content in the fuel be determined when it is in the reactor, in storage tanks, or in separations processing?

Solid-Fueled MSRs

Even though some MSR designs include the use of solid fuel forms, which are more like conventional reactor designs and therefore traditional safeguards, there are still new safeguards considerations. Because of the variety of fuel forms, the first question that will have to be answered is “what constitutes an item?”

- The theft of solid fuel involves either many items (fuel TRISO particles and/or pebbles) or bulky items (rods or fuel assemblies), which could take place at the fuel fabrication facility or reactor site.
- There is the potential for LEU fuel enrichments to be greater than 5%.
- The recovery of fissile isotopes from fresh or irradiated fuel involves removal of large quantities of carbon for a small yield of nuclear material[22].
- The reprocessing of TRISO fuel in industrial-scale has yet to be demonstrated, therefore, there is no safeguards experience because the flow sheet is unknown.

Thorium Fuel Cycles

There will be different safeguards implications of MSR designs that use thorium fuel cycles compared to other fuel cycles.

- There is limited experience in detecting and measuring ^{233}U. The ^{232}U co-produced with ^{233}U has ^{208}Tl daughter products that emit highly energetic (2.6 MeV) gamma rays with high absolute emission probability. Gamma radiation from ^{208}Tl presents challenges to operation and monitoring.
- Protactinium removal from the reactor can lead to the production of pure ^{233}U, which would be of safeguards concern at the reactor or fuel processing unit. There is also the potential for misuse of the reactor by modifying its fuel salt composition to produce more ^{233}U.
- Some designs require onsite storage for thorium fuel, which must be placed under safeguards.

As noted by Worrall *et al.* (2016[23]), current safeguards technology, concepts, and approaches, will require evaluation and potential future development to adapt them for the large variation in MSR fuel cycles and reactor technologies. Therefore, to move forward with the appropriate

[22] *Very High-Temperature Reactor (VHTR) Proliferation Resistance and Physical Protection (PR&PP).* ORNL/TM-2010/163, August 2010

[23] *Safeguards Considerations for Thorium Fuel Cycles*, Nuclear Technology · Vol. 194 · 281–293 · May 2016

safeguards approaches it must be better understood how the MSR fuel cycles will introduce fissile and fertile materials. This includes the location and distribution of the nuclear material inventory; the rate at which these materials are produced and consumed by the reactors; and how these materials will be changed chemically, physically, and isotopically. These rates, chemical and physical forms, and isotopic composition, as well as resulting signatures and locations, will be different for each of the MSR designs. Thus, measurement requirements and safeguards approaches will have to accommodate these MSR varieties.

Because of the different salt chemistries and fuel processing approaches of the various MSR designs underway, the resulting radiation signatures will also be different. Therefore, to develop measurement methods, it will be necessary to perform assessments of which signatures are most appropriate for MSR safeguards in combination with factors such as how much fissile material is being created. For example, an MSR operating on a thorium-based fuel cycle will have unique gamma radiation signatures. Due to the presence of short-lived fission products in the salt, safeguarding online fuel processing activities will provide an additional challenge for measurement instrumentation due to their high dose. However, these short-lived fission products might provide unique radiation signatures not previously explored for safeguards applications that may point to new safeguards measurements and technology needs.

It is expected that the nuclear material accountancy systems will be able to verify that any MUF is within the range allowable by the IAEA. For MSRs, depending on the flow and physical form of nuclear materials, high-accuracy measurement systems could be needed to meet the IAEA's safeguards timeliness goals for detection of diversion of those materials. If the measurement uncertainties cannot satisfy IAEA requirements, safeguards measures such as Physical Inventory Verification (PIV) might need to occur more frequently or the materials must be separated into smaller throughput streams. Measurement goals are often guided by the International Target Values (ITVs) for measurement uncertainties. Because of the nature of bulk measurement statistics, the MUF will never be zero, but will ideally be statistically close to zero. It should be noted that it will likely be very challenging for an inspector to perform a PIV at an MSR. With multiple nuclear material forms, trace or residual nuclear material quantities in waste salts, and nuclear material loss from irradiation in the reactor core, there is significant room for uncertainty when determining the MUF values. Instead of a traditional PIV inspection, the IAEA might have to rely on technologies and approaches such as continuous monitoring of reactor processes (i.e., process monitoring) to accurately quantify materials (similar in concept to techniques such as hybrid K-edge densitometry or those deployed in commercial reprocessing plants).

As this discussion shows, there will be challenges to the application of safeguards to MSR technology, including measurements and instrumentation because of the difficulty in measuring the highly radioactive fuel salt forms. This may contribute to measurement uncertainties, which will have to be factored into the overall performance requirements. Ultimately, the designs of specific safeguards systems for the different MSRs will determine what must be measured and the corresponding instrumentation requirements.

Moreover, remote and unattended monitoring will likely be required, which will have to be developed. There will be issues with instrument reliability as well as shortened equipment lifetimes and limited access for maintenance and periodic upgrades. As such, there will need to be extensive assessment of current safeguards measurement technology and its applicability to MSRs.

Conclusion

Because of the nature of the IAEA's role in international nonproliferation, limited resources, and legal mandates, the agency is necessarily focused on safeguards verification of the current nuclear fuel cycle and existing nuclear material and facilities. Therefore, the IAEA might not be adequately taking into consideration the potential for future technologies that could appear in the medium to long term. Consequently, the IAEA and its international safeguards system do not have the policies, concepts, approaches, or technologies needed for applying safeguards to MSR designs. Existing IAEA safeguards approaches are largely based on the uranium-plutonium fuel cycle, item counting for nuclear reactors, and bulk material accountancy for the front and back end of the nuclear fuel cycle. These techniques and associated instrumentation for bulk accountancy have been developed predominantly for enrichment, fuel fabrication, and aqueous reprocessing. However, none of these bulk accountancy measures can be directly applied to MSRs, in general, and for salt-fueled MSRs in particular, without evaluation and potential modification.

Additionally, little work has been done to determine which of the current safeguards approaches could be applied to MSRs, which could be modified, and which should be developed. No comprehensive study has been performed that integrates safeguards concepts and approaches and technology development with a detailed understanding of the interplay of the numerous fuel cycle and reactor options. Special attention should be paid to how nuclear material measurements could be made considering the different MSR designs and material flowsheets and what nuclear material measurement methods and technologies need to be developed (destructive/ non-destructive analysis, etc.) given that the nuclear signatures are likely to be notably different from conventional fuel cycles.

A vital consideration for safeguards implementation is the Safeguards-by-Design (SBD) concept. SBD should be applied to designs that are in their early stages of development to maximize their effectiveness and minimize their burden on reactor operations. This could have a significant benefit for safeguards approaches that can be implemented for MSRs and help solve real technical challenges for MSR safeguards. If not considered now, safeguards will have to be applied to mature (or already-built) MSR designs with the attendant shortcomings, reduced effectiveness, and increased cost of such an approach. This could leave the IAEA and the international safeguards regime underprepared to ensure that all nuclear material is accounted for and that there has been no diversion of nuclear material or undeclared production or misuse of facilities. This would likely have a negative impact on the future deployment of this technology worldwide and in non-nuclear weapons states.