SECURITY CONSIDERATIONS FOR THE TRANSPORTATION OF MOLTEN SALT REACTOR FRESH FUEL SALT

Jason Karcz
Oak Ridge National Laboratory

Sunil Chirayath
Oak Ridge National Laboratory

Marc Fialkoff
Oak Ridge National Laboratory

Jeff Packett
Oak Ridge National Laboratory

Adam Smith
Oak Ridge National Laboratory

ABSTRACT

Molten salt reactors (MSRs) have rapidly gained interest within the international community as a means of supplying reliable energy because of a variety of factors associated with these advanced reactor design factors such as inherent safety features and efficient fuel utilization. Recent efforts have focused on reactor physics and vendor designs, but the transport security of MSR fresh fuel salt is not well understood and must be explored to determine the most secure methods of shipping such material while adhering to appropriate safety measures. Light water reactor (LWR) fuel rods and assemblies have been successfully shipped worldwide for decades; however, given the anticipated bulk form of advanced MSR fuel and accompanying feed components, new considerations are warranted for conveyance designs. LWR fuel is shipped as pellets within fuel rods or assemblies, but some MSR feed materials will be shipped in bulk, raising new questions about ensuring the physical protection of feed materials in a given conveyance design because of the unique fuel forms, feed compositions, and accompanying salts required for successful reactor operation. This paper provides an overview of security considerations for transporting MSR fresh fuel salt based on anticipated material components and likely conveyance configurations regardless of reactor design. The paper highlights existing information related to fresh fuel salt and feed component properties to explore how these characteristics will affect new conveyance designs. Unique conveyance configurations, such as transporting fresh fuel salt in homogeneous rather than heterogeneous bulk mixtures, are presented to emphasize their impact on transport security. The paper also analyzes anticipated risks of transporting these advanced materials in these conveyance designs and explains the novelty of the attendant risks compared with traditional LWR fuel shipments. Finally, the paper presents new transport security considerations for MSR fresh fuel salt based on the conveyance designs and risks detailed throughout the paper. Ultimately, this paper highlights initial transport security considerations for shipping MSR fresh fuel salt components and stresses the broader need for conducting rigorous research in this space to prepare the international community for securely transporting this material in the near future.

INTRODUCTION

Interest in advanced and small modular reactors has rapidly increased over the past several years. These reactor designs offer efficient, flexible power options to meet future energy demands (IAEA, 2025). To power the reactors, some designs use low-enriched uranium (LEU), and other designs use high-assay low-enriched uranium (HALEU). These fuels come in a variety of forms, such as traditional UO_2 pellets, tri-structural isotropic (TRISO) particles, uranium carbides or nitrides, and uranium halides such as UF_4 and UCl_3. In addition to these innovative fuel forms, many small modular reactor designs use alternative coolants, including liquid metals such as sodium or lead, gases such as helium, or molten salts such as LiF-BeF_2 (FLiBe) or NaCl, which greatly differ from those used in existing water-cooled nuclear reactors (IAEA, 2024).

Although research has been conducted on these types of reactors to varying degrees, transport security information is generally lacking. Information related to the transportation of molten salt reactor (MSR) fuels is sparse; most data focus on reactor design and safety. Some reports have previously assessed the broad needs related to transporting MSR fuel salts; however, security has been assessed against regulatory frameworks rather than in terms of technical risk considerations (Richmond, et al., 2024). Nonetheless, regulatory frameworks inform baseline security requirements for transporting MSR fuel salts and will be further elaborated upon in this paper.

Although MSRs may be seen as over-the-horizon reactors, as they are deployed, transport security operations will be critical to connecting each step of their fuel cycles to ensure material arrives at sites without interference by malicious actors through theft or sabotage of the conveyance. Early research on MSR material transport can elucidate the unique risks associated with this material to mitigate malicious acts by means of innovative transport security solutions. This paper provides high-level considerations for securing MSR fresh fuel salts during transport to support the nuclear transport industry in preparing to move these types of materials internationally. First, the paper examines common fresh fuel salt design properties that may affect packaging and operations. An examination of regulatory and packaging considerations for MSR fuels follows. Next, based on the previous sections, unique risks are assessed and security considerations are provided for various MSR transportation scenarios, including heterogeneous material transport (i.e., MSR fuel separate from salt coolant and moderator), homogeneous transport (i.e., MSR fuel dissolved in salt), and the forms MSR fuel may be transported in (e.g., pellets, powder, bulk solid) (IAEA, 2024). This paper focuses on the security risks associated with decentralized, off-site fuel salt preparation and the conveyance of fuel salts in bulk form. Finally, the paper provides recommendations for future work that can inform the transport security of MSR fuels. Ultimately, the paper highlights technical considerations and needs for securely transporting MSR fuels.

MOLTEN SALT REACTOR FUEL CHARACTERISTICS

The two common MSR fuel salt compounds that use HALEU are LiF-BeF_2-UF_4 (referred to as FLiBe fuel) and NaCl-UCl_3. Fuel salt transport to reactor sites varies depending on the MSR design. For example, the nuclear material part of the salt, UF_4 or UCl_3, can be transported separately instead of combining it with FLiBe or NaCl, respectively. Alternatively, the mixed salt can be transported with the nuclear and nonnuclear parts together. In this latter case, the mixing is done at a fuel fabrication facility; in the former case, salt mixing is done at the reactor site where the fuel feed is prepared. The uranium fractions of FLiBe fuel and NaCl-UCl_3 are substantially different, and the differences affect various aspects of transport security, including material attractiveness, security levels, and associated physical protection measures. For example, NaCl-UCl_3 salt generally has about twice the uranium fraction of FLiBe-based uranium fuel salt, which affects criticality safety in terms of how many containers are needed for transporting the fuel and the associated security detail for protecting such a conveyance.

CONVEYANCE DESIGNS FOR THE TRANSPORT OF FEED MATERIAL

Regulatory Considerations

Although the transport of radioactive materials is regulated under a complex network of international conventions and guidance, the possibility of transporting unirradiated MSR fresh fuel salt introduces novel questions. In 2023, the International Atomic Energy Agency (IAEA) acknowledged that further work was needed on the transport safety and security of advanced reactor fuels, including molten salts. The IAEA noted that—given the diversity of fuel forms, particularly for molten salts—various transport packages need to be designed and qualified. Additional considerations for molten salts include whether the salt is in solid or liquid form, which, in turn, requires further analysis of the behavior of the salt in the transport package and how the material will react under accident conditions (IAEA, 2023).

In the United States, one of the few regulatory analyses currently available was developed by Pacific Northwest National Laboratory (PNNL) and focuses on front-end considerations for molten salt fuels, including transportation (Richmond, et al., 2024). The PNNL analysis of 10 CFR Part 71, *Packaging and Transportation of Radioactive Materials*, focused primarily on safety considerations during the transport of unirradiated molten salt. The analysis acknowledges that when molten salt fuel is transported, it will be required to meet the physical protection requirements outlined in 10 CFR Part 73, *Physical Protection of Plants and Materials*. In the present paper, two specific findings from the PNNL analysis are important to consider. First, to date, the Nuclear Regulatory Commission "has not yet approved package design for [Molten Salt Reactor] salt fuel materials." Second, the PNNL report assumes that MSR salt fuels will be transported in a Type B(U) package (unirradiated fissile material) (Richmond, et al., 2024).

The Orange Book, more formally known as the United Nations *Recommendations on the Transport of Dangerous Goods*, provides countries with guidance for developing transport regulations for the transport of dangerous goods. For provisions regarding the transport of nuclear and other radioactive material, the IAEA provides recommendations in *Regulations for the Safe Transport of Radioactive Material* (IAEA Safety Standards Series No. SSR-6 [Rev.1]). Although molten salt fuels will most likely fall under the provisions of Class 7 transport and guidance from the IAEA, the forms the nuclear fuel materials are in may include other hazard classes, such as corrosive substances (Class 8). The Orange Book provides guidance for the appropriate safety and security measures attached to handling goods that fall under multiple dangerous goods classes. For security, Chapter 1.4 of the Orange Book lays out general security recommendations for transporting dangerous goods, including nuclear material. For nuclear material, Chapter 1.4 provides a footnote that links the Orange Book security recommendations with those found in IAEA Nuclear Security Series (NSS) No. 13, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities* (INFCIRC/225/Revision 5) (United Nations, 2023).

Regarding nuclear security, no analysis to date indicates which security guidance applies to MSR fuel. The starting point for international guidance for transport security is NSS No. 13 (IAEA, 2011) and the supporting implementation guide, NSS No. 26-G, *Security of Nuclear Material in Transport* (IAEA, 2015). For MSR fuel, a graded approach will be applied, consistent with NSS No. 26-G (IAEA, 2015).

As noted in the 2024 PNNL analysis, further security analysis is needed to evaluate whether existing international guidance accounts for the different forms of molten salt fuels (solid vs liquid) and whether some fuel forms are more attractive targets for theft or sabotage. Additional transport security considerations include the specific physical protection measures needed for the various forms of molten salt fuels and an understanding of how such material can be transported across multiple modes of transport (including rail, maritime, and air, if permitted).

Operational Considerations

For shipments of MSR fresh fuel salts, innovative packaging strategies must be tailored to a variety of fuel characteristics, including chemical composition, radiological characteristics, and thermal properties. MSRs deviate from traditional reactor fuel systems but use materials that can be processed into liquid or solid form to create fresh fuel salt.

Heterogeneous MSR fuel shipments may be similar to traditional shipments of nuclear fuel in that the fuel is separate from the coolant salt and transported as LEU or HALEU. Such configurations may allow for more familiarity in modeling and securing shipments based on historical operating experience in moving traditional nuclear fuels.

For homogeneous MSR fuel salts, the feed material will be consolidated into a single mixture. Consequently, special attention must be focused on maintaining transport conditions to keep the material in a stable form and prevent leakage or inadvertent reactivity by sealing the containment with inert gas atmospheres. Because of the nature of this type of configuration, further research may be needed to determine optimal design specifications for moving this type of material. Additionally, because the bulk of a reactor's feed material will be included in this type of configuration, more robust security measures may be necessary because of impacts on energy security if such a shipment is stolen or sabotaged. Risks associated with these two types of configurations are analyzed in greater detail in the following section.

UNIQUE RISKS FOR TRANSPORTING MOLTEN SALT REACTOR FEED MATERIAL

Security insights for most MSR risks must be derived from conceptual designs and historical experimental data. Limited full-scale MSR data are available, and new data must continually be reviewed as this technology matures. Depending on the MSR design (i.e., homogeneous or heterogeneous), transport needs vary greatly. Understanding and mitigating risks is essential for the safe and secure movement of these materials between suppliers, fabrication sites, and reactor facilities.

MSRs represent a diverse group of advanced reactor concepts being pursued by many developers. Salts can be used to support several significant reactor core functions, including fuel, coolant, or moderator functions. At a high level, MSRs themselves can be categorized as homogeneous or heterogeneous. Homogeneous MSRs notably lack any separation between the fuel and coolant salts, effectively combining these two reactor functions in the core. Conversely, heterogeneous MSRs include structural materials designed to separate the fuel salt from the coolant or moderator (IAEA, 2024). However, the fuel salt itself remains a homogeneous mixture to ensure consistent reactivity.

Most MSR concepts currently under consideration use fluoride, chloride, or mixed halide carrier salts because of characteristics such as favorable melting temperatures, fuel solubility, and neutron economy. Salt-fueled reactors can include fissile and fertile isotopes in the salt mixture depending on the operational goals. Fuel salt composition varies significantly among reactor developers and is often a proprietary mixture specific to the reactor design. Because of the potential wide diversity in the composition of MSR fuel salts, transportation conveyances and security requirements may also vary but be proportional to the uranium fraction in each fuel salt mixture. Fuel salts are likely to be optimized based on performance objectives and strictly managed to control impurities. Fissile material makeup will be a factor in material attractiveness; developers are considering several fuels, including enriched uranium, plutonium, and thorium depending on the fuel cycle. Use of HALEU with enrichment up to 20% is also anticipated to challenge regulatory limits on production, transport, and use (IAEA, 2024).

MSR fuel salts have lowered barriers for extracting fissile material, and this characteristic is a key security concern with this technology. Additionally, diversion of fuel salts containing fissile material is inherently more difficult to monitor and detect when compared to traditional solid reactor fuels. Fuel salt can be prepared off-site and transported to the point of use or prepared on-site. Fuel salt prepared at an off-site salt processing facility is purified, mixed, and stored in containment vessels in noncritical configurations. Once the fuel has been dissolved into the salt, the fissile material is less attractive for theft, but the fissile material may be easier to access than traditional cladded fuel forms because of its bulk nature. The fuel salt is then cooled and solidified into a stable form for transport. Consequences of sabotage are likely to be lower while the fuel is in a solid state, having less potential for dispersal. Sabotage risks for fresh fuel salts are related more to chemical hazards associated with the salt and less to the radiological risks posed by the fresh fuel (McFarlane, Taylor, Holcomb, & Poore, 2019).

Fresh fuel salts for MSRs will likely be in bulk form or in a form similar to that of traditional light water reactor (LWR) fuel shipments (i.e., pellets). However, differences in transporting MSR fuel salts in these forms pose unique safety and security risks.

Heterogeneous fuel shipments are likely to pose risks similar to those associated with LWR fuel shipments. Heterogeneous fuels are likely to be transported in similar fuel assemblies or in powder form to a fuel salt processing location on the MSR site or in a specialized facility as an intermediate step before being sent to the reactor. When shipped as assemblies, MSR fuels will have better defined geometries that reduce the risk of material dispersion and minimize unexpected criticality risks during transport. However, heterogeneous MSR fuel shipments of bulk powder may require further attention to conveyance designs to minimize the associated risks. Powdered fuels pose an inhalation risk and may present risks similar to those associated with liquid fuels if released (McFarlane, Taylor, Holcomb, & Poore, 2019).

Homogeneous bulk shipments of MSR fuel salt may have relatively high radiation doses because of dissolved fissile content within the salt coolant, especially from neutron or gamma emissions from salts that contain ^{233}U or Pu. The nature of these salts presents a high potential for reactivity. Depending on the halogen present in the salt, HF or HCl may be formed if the material comes into contact with moisture because of the hygroscopic properties of the fuel salt. These properties may also result in altered material integrity and characteristics in transit if moisture is present in the container. Although robust regulations cover container leakage and integrity, the corrosive nature of fuel salt may cause damage to the containment, resulting in an increased risk of moisture interacting with the material. Additionally, unpredictable geometry and moderation of MSR fuel in bulk form may lead to unexpected criticality risks if shipments are not properly configured and monitored (Maheras, et al., 2023). Halide-resistant alloys that line the containment may mitigate such risks by minimizing the corrosive effects of the salts that can lead to material release or hygroscopic reactions.

SECURITY CONSIDERATIONS FOR MOLTEN SALT REACTOR CONVEYANCE DESIGNS

The risks mentioned in the previous section are not an exhaustive list but rather are factors that highlight several of the nuances of transporting MSR fuel salts that differ from transporting traditional fuel assemblies and must be accounted for. Although the foregoing risks are largely safety-related, appropriate security measures must be implemented to prevent thefts or sabotage of MSR fuel salts that may lead to such safety risks.

Operationally, based on reactor designs and IAEA categorization schemes, MSR fuel salts are likely to be Category II (HALEU) or Category III (LEU) shipments, depending on the fissile content of the salt. Security measures that would apply to HALEU shipments include developing transport security plans, real-time shipment tracking (e.g., satellite tracking), two-way communication capabilities, adequate detection and delay measures (e.g., electronic intrusion detection and robust locking mechanisms), and armed guards, depending on State requirements (IAEA, 2015).

These security measures are based on recommendations for traditional shipments of nuclear material and do not address security measures for the corrosive salt component of MSR fuel salt or other unique hazards such as hygroscopic reactions with halide salts. Because these hazards are not present in traditional fuel shipments, these may become new targets for adversaries and must be addressed when planning transport security operations. Although MSR fuel shipments are potentially nonradioactive (in the heterogeneous scenario) and non-fissile, their link to national energy infrastructure may justify the need for added security measures. MSRs cannot fully operate without fuel salt coolant, so a loss of coolant would be an impediment to energy security. The Orange Book is clear that the fissile material qualifies as Class 7, but subsidiary hazards (i.e., Class 8 for FLiBe or NaCl) must also be addressed (United Nations, 2023). Strategies for addressing these hazards may include additional monitoring or access controls for MSR conveyances; however, these conveyances should be assessed further to understand the overlap between nuclear security measures and principles and chemical security measures. Table 1 summarizes anticipated conveyance configurations, fuel forms, packaging considerations, risks, and regulatory issues that will affect transport security for MSR fresh fuel salts.

Table 1. MSR Feed Material Transport—Anticipated Packaging Types and Risk Profile Alignment[1]

Material type	Form	Fissile content	Packaging type (IAEA)	Key risk categories	Regulatory notes
Enriched fluoride salt (e.g., FLiBe fuel)	Solidified bulk (pre-melt)	High (^{235}U, ^{233}U)	Type B(U) or B(M)	Radiological, **security**, chemical (HF risk), criticality, thermal	Requires fissile material certification; likely to need special arrangements.
Pu-bearing chloride salt	Solidified bulk	Very high (^{239}Pu)	Type B(M) (possibly with enhanced shielding)	Radiological, **security**, criticality, chemical	High security category; real-time tracking and safeguards mandatory.
Th–U fuel salt blend	Bulk granular or solid	Medium (^{233}Th, ^{233}U)	Type B(U)	Radiological criticality (because of ^{233}U), thermal	May require fissile modeling and criticality control documentation.
Coolant-only salt (e.g., NaCl-$MgCl_2$)	Bulk solid or liquid	None (non-fissile)	Type A (possibly industrial package Type 2 or 3)	Chemical (corrosive), thermal (freezing)	Lower regulatory burden, but containment still required because of corrosive potential.
Fuel pellets or rods (^{235}U or ^{233}U)	Solid, fabricated	High	Type B(U)	Radiological, **security** criticality, thermal (minor)	Similar to conventional fuel transport, with well-established pathways.
Powdered fuel for heterogeneous MSRs	Solid powder	High	Type B(U) with fixed geometry	**Security,** inhalation risk, criticality (geometry control), contamination	Special inner containment may be required to avoid dispersion.

FUTURE WORK

Currently, no Nuclear Regulatory Commission–licensed packaging options exist for transporting MSR fresh fuel salts (Richmond, et al., 2024). This fact, combined with the lack of MSR fuel salt transportation standards, creates opportunities to begin or continue researching MSR fresh fuel salts and their effect on transport security. For example, fuel salt characteristics and U concentration and, in turn, ^{235}U can vary depending on the MSR design. This situation calls for a detailed analysis of fuel salt transport containers (geometry and permitted amount of salt) from the perspective of not only criticality safety but also security (e.g., sabotage opportunities). Such information can reinforce the importance of the safety–security interface

[1] Security risks bolded for visibility

and indicate how the concept of safety informs the assessment of security risks and vice versa. Additional information is needed to assess MSR supply chains, and transportation research is needed to ensure supply chain security for future reactor deployment.

Although most existing research is safety-focused, it can still inform security decision-makers. The benefits of such research are twofold: information for package designs and further assessments of unique risks related to MSR fuel salts. Understanding MSR fuel salt geometries based on the form in which the material will be transported can drive modified or new package designs for these types of fuels. This package design phase presents opportunities for incorporating security measures (e.g., embedded sensors or innovative structural mechanisms) that enhance security at a lower cost, reducing the security burden during transport operations. Additionally, researchers should assess and test technologies for mitigating the unique risks of MSR fuel salts (compared with more traditional LEU shipments), exploring how such technologies can be integrated with nuclear security principles. Table 1 shows a clear overlap between nuclear security and the new chemical hazards posed by MSR fuel salts, a crossover that could be explored to determine the most appropriate technologies and techniques for protecting MSR fuel salts during transport.

Finally, most research for advanced and small modular reactors has focused on front-end operations, but MSRs will create waste streams distinct from those of traditional LWRs. These waste streams may pose new or unknown security risks during transport, including higher radiological consequences, different contamination pathways, and unique proliferation concerns because of the different burnup levels of new fuel types—concerns that should be assessed early to develop robust transport security plans for moving such waste.

CONCLUSIONS

Although MSRs are a promising reactor type with favorable design characteristics, uncertainties around transporting fuel salts remain prominent, with no clear solutions. Transport safety is often the focus of research; however, transportation safety research can be used to understand MSR fuel salt properties and risks and how they will translate to securing these materials during transport. This paper provided a high-level overview of security considerations for transporting MSR fuel salts, how existing frameworks may drive physical protection requirements, and unique risks that must be addressed to effectively transport these materials to their destinations. Early-stage planning for transporting MSR fuel salts will enable early assessment of security risks posed by these innovative fuel types and help maintain necessary operations for robust national and energy security worldwide.

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REFERENCES

Forsberg, C. W., Peterson, P. F., & Zhao, H. (2004). An Advanced Molten Salt Reactor using High-Temperature Reactor Technology.

IAEA. (2011). Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5).

IAEA. (2015). Security of Nuclear Material in Transport. Vienna: International Atomic Energy Agency.

IAEA. (2018). Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. SSR-6 (Rev.1). Vienna: International Atomic Energy Agency.

IAEA. (2022). Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2018 Edition). Vienna: International Atomic Energy Agency.

IAEA. (2023). Considerations for the Back End of the Fuel Cycle of Small Modular Reactors. Vienna: International Atomic Energy Agency.

IAEA. (2024). Small Modular Reactors Catalogue.

IAEA. (2024). Status of Molten Salt Reactor Technology. Vienna: International Atomic Energy Agency.

IAEA. (2025). Small Modular Reactors. Retrieved from https://www.iaea.org/topics/small-modular-reactors

Maheras, S. J., Rigato, A. B., Adkins, H. E., Todd, D. R., Kaiser, K. I., Arm, S. T., . . . Thomas, K. M. (2023). Technical Information Needs and Regulatory Considerations for Front-End Transportation Activities of HALEU Fuel Feed Material.

McFarlane, J., Taylor, P., Holcomb, D., & Poore, W. P. (2019). Review of Hazards Associated with Molten Salt Reactor Fuel Processing Operations.

Richmond, D., Thomas, K., LaHaye, N., Lowry, P., Napier, J., Short, S., & Todd, D. (2024). Assessment of Technical Information Needs and Considerations for Front-End Activities for Molten Salt Fuel Types.

United Nations. (2023). Recommendations on the Transport of Dangerous Goods. United Nations.