UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 – 0001

November 22, 2021

Daniel H. Dorman
Executive Director for Operations
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: NUREG/CR – XXXX, “FUEL QUALIFICATION FOR MOLTEN SALT REACTORS, DRAFT REPORT FOR COMMENT”

Dear Mr. Dorman:

During the 690th meeting of the Advisory Committee on Reactor Safeguards, November 2 - 5, 2021, we reviewed NUREG/CR – XXXX, “Fuel Qualification for Molten Salt Reactors, Draft Report for Comment.” Our Metallurgy and Reactor Fuels Subcommittee also reviewed this matter on October 5, 2021. We had the benefit of discussions with representatives of the NRC staff, Oak Ridge National Laboratory staff, and other stakeholders. We also had the benefit of the referenced documents.

CONCLUSIONS AND RECOMMENDATIONS

1. The behavior of nuclear fuel under normal and off-normal conditions is a key part of the overall safety case for a nuclear reactor. For molten salt fueled reactor concepts, the fuel is dissolved in the molten salt coolant. This different configuration requires a new approach to fuel qualification for molten salt fueled reactors.

2. The NUREG/CR draft report provides a reasonable and practical approach to developing a licensing basis for fuel qualification for molten salt fueled reactors.

3. The NUREG/CR draft report should be issued once comments in this letter are addressed.

BACKGROUND

The behavior of nuclear fuel under normal and off-normal conditions is a key part of the overall safety case for a nuclear reactor. Current NRC requirements for nuclear fuel are derived from solid uranium dioxide (UO_2) fuel pellets in Zircaloy fuel cladding for use in light-water reactors. Recently, the NRC has developed more generic requirements related to fuel qualification for advanced reactor systems (NUREG-2246). For molten salt fueled reactor concepts, the fuel is dissolved in the molten salt coolant. This different configuration requires a new approach to fuel qualification for molten salt fueled reactors. The subject draft report provides a licensing basis for fuel qualification for molten salt fueled reactors.

The draft report is intended to provide guidance to both regulators and to designers about the challenges associated with molten salt fuel qualification. The detail in the document, with its numerous examples, provides context for the complexity associated with some of the challenges and the level of detail necessary (but not always obvious) to resolve the issue as it relates to fuel qualification. Some of those examples are summarized in this letter to highlight the significant differences in the challenges compared to solid fuel qualification.

DISCUSSION

The approach used in the draft report aligns well with the NRC advanced reactor fuel qualification approach in NUREG-2246. It begins by identifying the fundamental safety functions identified in regulatory guide (RG) 1.232 for molten salt reactor systems and then establishing the role of the fuel salt in achieving those fundamental safety functions. Because there are so many potential salts and different reactor configurations (fast, thermal, breeding), the report discusses salt behavior at a very high generic level. Specific examples are used to illustrate potential issues with a specific salt or a specific design approach. Given this complexity, this is a reasonable and practical approach.

The fundamental safety functions for salt fueled reactor systems are identified as: (a) limiting release of radioactive material, (b) removing heat, and (c) controlling reactivity. Although these are the fundamental safety functions identified in RG 1.232, the draft report also considers control of the chemical environment and the potential for chemical reactions, which can be important for molten salt reactors. Alignment with the safety functions proposed in the draft language for Title 10 of the *Code of Federal Regulations* (10 CFR) Part 53 would address this incongruity. This should be noted and a rationale for it in the context of the content of the draft report should be discussed.

The role of the salt in achieving each of these safety functions depends on the chemical and physical behavior of the salt. The key chemical and physical properties of the salt are strong functions of temperature and salt composition. For example, the viscosity of the salt decreases as the temperature increases yet the volatility of the major components in the salt increases as the temperature increases. Understanding the dependency of composition and temperature on the salt properties will be needed to establish allowable range of acceptable properties and hence acceptable levels of temperature and composition of the salt during normal and off-normal operation (e.g., technical specifications).

The draft report does not consider beyond design-basis events as part of fuel salt qualification. It is unclear why the draft report limits the scope in this way since other fuel systems evaluate behavior beyond the design-basis as a means to evaluate the safety margins of the system.

Limiting the release of radioactivity

The use of a functional containment approach is key to limiting the release of radioactivity from molten salt reactors. Under certain conditions, the molten salt is itself an inherent non-leak tight barrier providing significant retention of fission products. Understanding the rate of volatilization and aerosolization as a function of temperature in the salt is critical in establishing the effectiveness of the salt as a barrier and the source term that could emanate from the salt during a spill. While the draft report notes that as the temperature increases, the main salt components are distilled leaving the minor components in the residual "heel," little is said about the actual volatilization process from a chemical standpoint specifically the degree of ideality or non-ideality in the salt. This is important information for developing a model for volatilization from the salt.

The high temperature and high radiation doses associated with molten salts limit the capabilities of materials that can be used for containment vessels or serve as barriers. It may be difficult to qualify the reactor vessel for a given lifetime in the traditional safety sense given the aggressive environment; replacing the vessel during the reactor lifetime or implementing a guard vessel surrounding the reactor vessel may be design solutions. Beyond the salt itself and its containment vessel, it is envisioned that multiple segmented containment cells will be used around the reactor vessel.

The ability of the salt to challenge/damage the retentiveness of the containment vessel and/or barriers must be known. Because the salt can be corrosive under certain circumstances, control of the reduction-oxidation (redox) conditions in the salt is important to assure that the salt does not challenge the integrity of other potential fission product barriers it encounters upon contact. Even with good redox control, because of temperature gradients in the coolant system, temperature driven corrosion could be expected. The solubilities of anticipated corrosion products as a function of temperature must be established and the mechanisms and rate at which the salt degrades the barrier are required to properly establish the safety margin for vessels that contain or come in contact with the molten salt. Solubility limits for relevant fission products and actinides are also necessary to assure that precipitation and agglomeration of fission products in the salt and subsequent deposition are not excessive in cool parts of the system. Of particular concern is that actinides and lanthanide fission products compete in terms of overall solubility in the salt which can result in precipitation of fissile actinides such as plutonium. This complex chemistry needs to be well understood.

Ingress of oxidizing or reducing agents into the salt can affect the chemistry of its constituents. If the salt is exposed to moisture, it can lead to the formation of acids (e.g., hydrofluoric acid , hydrogen chloride). Oxygen ingress can lead to oxide formation in the salt. Addition of a strong reducing agent like alkali metals can lead to the formation of uranium carbide in systems with a graphite moderator. These conditions will have to be accounted for in relevant accident sequences.

The cover gas used to remove fission gases from the salt is another important source term to be accounted for in the safety analysis evaluating the event of its postulated breach. Beyond the fission gases, the volatilization of constituents of the salt (e.g., zirconium fluoride and uranium chloride) and daughter products of the fission gases (e.g., cesium from xenon decay) can form deposits in the cover gas system. The behavior of tritium in lithium containing salts is also a key radionuclide to account for in the safety analysis.

Heat Removal

Because the salt is also the coolant, the ability to remove fission heat from the salt during operation is critical. Salt properties including density, heat capacity, thermal conductivity, and viscosity are needed under forced convection conditions as a function of temperature and salt composition. In addition, in overcooling situations or systems that implement a freeze plug, the freezing point of the salt as a function of composition must be established.

Most molten salt designers would prefer to use passive schemes to remove decay heat to avoid the need for electric power under off-normal conditions. Many different design options are available. As in normal operation, the heat transfer properties of the salt are needed under natural convection conditions to be able to model the accident progression and to evaluate the response of systems, structures and components and containment vessel/barriers.

Being able to model the progression of a spill of molten salt from a break will be important for the safety analysis to demonstrate that the geometry results in a subcritical configuration and to evaluate the thermal challenge of the salt to the barrier. Numerous common functions performed by structures, systems, and components in containment cells could include radiation and thermal shielding, salt pumping, fuel salt content adjustment, reactivity control, fuel salt storage, cover gas management, decay heat transfer, component and structure cooling, sensing, structural supports, and maintenance systems. The progression of a postulated event will be dependent on the specific cell where the break is postulated to occur and the contents of the cell. In this regard, the seals, other connections, insulation, or resident equipment, may be more important than the barrier itself in establishing the event sequence depending on the design.

Developing the required accuracy in models for these events and validating those models will be challenging given the composition and temperature dependency of molten salt properties, the associated uncertainties, and the potential geometries that could occur following a rupture/drainage of the system. In cases where the salt is postulated to spread in a containment cell during and following a break, the surface tension may be necessary to accurately model the melt spreading. This property is not discussed in the document and should be included. For accident cases where radiation heat transfer may be important, the emissivity of the salt is needed. The effect of aerosols emanating from the salt and the potential for surface crust or scum layers from interaction with oxygen can impede radiation heat transfer and must be accounted for in the analysis. If the containment cell contains unlined concrete, chemical interaction of the salt with the concrete producing carbon dioxide and water vapor must be considered.

Reactivity Control

Three key characteristics of molten salt fueled systems need to be demonstrated to show that the reactivity of the system is controlled. First, the reactivity feedback of the system is anticipated to be negative for all salt systems (e.g., thermal expansion of the salt will decrease the reactivity), but the components of the overall feedback need to be well understood as a function of temperature and composition of the salt over its lifetime. Experimental validation will be necessary. Second, with a liquid fuel as a coolant, multi-dimensional thermal-hydraulic effects in the coolant (e.g., eddies, thermal stratification, void formation) can impact reactivity control and must be understood. Additional discussion in this area is warranted. Third, from a reactor control perspective, the effective delayed neutron fraction must be established with its associated uncertainties. The removal of fuel (and hence delayed neutrons) from the core region will reduce the effective delayed neutron fraction. In addition, especially in fast systems where the delayed neutron fraction is smaller than in thermal systems, the effect of fuel removal from the core will be even more pronounced. In cases where buildup of actinides and subsequent fission is anticipated, the uncertainties in the fission properties of higher actinides will introduce additional uncertainty in the effective delayed neutron fraction. An experimental assessment may be necessary to demonstrate that the reactor can be controlled considering the uncertainties. This concern about delayed neutron fraction is not discussed in the report and should be.

For any rupture or drainage events, the geometry of the salt must result in a subcritical configuration so that reactivity control is maintained.

The document notes that for molten salt fueled systems, the plant is not required to be strongly subcritical upon shutdown. This discussion needs additional technical basis given the importance of reactor shutdown in the licensing of solid fueled reactors and the role of shutdown in overall defense in depth.

Licensing Basis

Knowledge of the material properties of the salt and their dependence on temperature and salt composition are critical to assuring that the safety functions discussed earlier are maintained. There should be limits on allowable fuel salt composition and the redox control window to assure that: (a) the material properties are what is documented in the safety analysis, (b) the corrosion is limited to assure integrity of vessels/containers, and (c) adequate margin exists to solubility limits of actinides, lanthanides, and noble metal fission products. Sufficient data with quantified uncertainties over relevant ranges will be required to establish a sound licensing basis.

SUMMARY

The behavior of nuclear fuel under normal and off-normal conditions is a key part of the overall safety case for a nuclear reactor. For molten salt fueled reactor concepts, the fuel is dissolved in the molten salt coolant. This different configuration requires a new approach to fuel qualification for molten salt fueled reactors. The NUREG/CR draft report provides a reasonable and practical approach to developing a licensing basis for fuel qualification for molten salt fueled reactors.

Our comments on the NUREG/CR draft report are that the following are needed:

1. Discussion on the alignment between molten salt safety functions and draft language in 10 CFR Part 53,

2. Additional discussion on beyond design basis fuel salt behavior,

3. More discussion on volatilization behavior from a chemical standpoint (e.g., the degree of ideality or non-ideality in the salt.),

4. Discussion on salt surface tension to needed list of material properties to model melt spreading in the event of a spill,

5. Discussion on the impact of thermal hydraulic phenomena associated with liquid fuel on reactivity control,

6. Discussion on reduction in delayed neutron fraction in molten fuel systems and impact of uncertainty on reactivity control,

7. Discussion of the need for spills to result in subcritical geometries, and

8. Additional discussion on rationale for the salt not having to be deeply subcritical upon shutdown.

The report should be issued once the comments are addressed.

Sincerely,

Signed by Sunseri, Matthew on 11/22/21

Matthew W. Sunseri
Chairman

REFERENCES

1. U.S. Nuclear Regulatory Commission, NUREG/CR-XXX, Fuel Qualification for Molten Salt Reactors, Draft Report for Comment, July 31, 2021 (ML21245A493)

2. U.S. Nuclear Regulatory Commission, NUREG 2246, Fuel Qualifications for Advanced Reactors, Draft Report for Comment, June 30, 2021 (ML21168A063)

3. Regulatory Guide (RG) 1.232, “Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors,” Revision 0, April 30, 2018 (ML17325A611)

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