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Fuel Salt Qualification and Associated Fuel Cycle Opportunities & Issues

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NRC staff have defined fuel qualification as *a process which provides high confidence that the physical and chemical behavior of fuel is sufficiently understood so that it can be adequately modeled for both normal and accident conditions, reflecting the role of the fuel design in the overall safety of the facility. Uncertainties are defined so that calculated fission product releases include the appropriate margins to ensure conservative calculation of radiological dose consequences* [1]. The Advisory Committee on Reactor Safeguards (ACRS) has accepted the methodology described in NUREG/CR-7299 [2] as an acceptable method for fuel qualification for molten salt reactors. The fuel salt qualification process described in NUREG/CR-7299 is based upon understanding the role that the fuel salt plays in achieving the fundamental safety functions, which in-turn is based on the fuel salt thermophysical and thermochemical properties.

Fuel salt links the chemical and physical behavior of the fuel to the overall facility safety. In a salt fueled MSR, the fuel salt has two primary operational functions: (1) to contain the fissionable and fertile nuclei that constitute the nuclear fuel, and (2) to serve as the reactor coolant. The fuel salt supports achievement of each of the fundamental safety functions. Fuel salt supports containing radionuclides by chemically binding most of the radioactive material and by not causing unacceptable stresses on the plant systems, structures, and components (SSCs) that provide containment. Fuel salt supports removal of decay heat through its heat transfer properties, notably including its buoyancy driven heat transfer characteristics. Fuel salt supports reactivity control through both through its high tolerance of reactivity excursions (cannot be mechanically damaged and large temperature margin to boiling) and its negative reactivity feedback. The liquid state of the fuel also facilitates draining the fuel salt from the critical region to subcritical, passively cooled tanks as a safety response.

The first parts of an application for a commercial nuclear power plant license, including for its siting evaluation, requires evaluation of an accident in which a substantial fraction of the fission products leak from the core into the containment. As having a sloped catch pan guiding spilled fuel salt flow to cooled, subcritical drain tanks would be a typical feature of MSRs, even a complete reactor vessel failure would only drive the plant into a maintenance configuration, with its fuel salt in drain tanks, but would not significantly stress containment. Note, however, that MSRs have substantial design variability and not all designs will include all potential features.

The properties of fuel salt need to be understood well enough to be able to enable modeling the role of the fuel salt in overall plant safety under both normal and accident conditions. Fuel salt properties are determined by its composition and state (largely temperature). Fuel salt qualification is dependent on development of an adequate quality map of the fuel salt composition to properties. Fuel salt will have a range of acceptable properties that result in adequate plant safety. Developing the fuel salt acceptable property envelope is a key aspect of accident progression modeling. For example, the fuel salt would need to provide adequate buoyancy driven heat transfer following a loss of forced flow accident. Fuel salt properties such as viscosity, heat capacity, and density as a function of temperature are needed to model heat transfer.

Fuel salt qualification applies from the time the salt is brought on site until it is transferred to an independent spent fuel storage facility. Fuel salt includes the vapors and aerosols released from the bulk of the fuel salt until their radionuclides have been adequately trapped such that they have no reasonable means for release or return to the bulk of the fuel salt. Fuel salt circulates independently from its container. Fuel salt qualification only considers container materials to the extent that they become incorporated into the fuel salt (e.g., via corrosion).

MSR facilities will incorporate fuel cycle elements outside of power operation. Current regulations (NUREG-2157 [3]) require the ability to store fuel on-site indefinitely in the event that a permanent repository never becomes available. The fuel salt composition and consequently properties change due to irradiation. A principal difference between liquids and solids is the relative ease of access to the constituent materials. Unlike solid fuel, liquid salt composition can be changed during operation. Nuclear fuel only becomes waste when it can no longer perform its functions. The content of MSR fuel salt can be adjusted as part of normal operations. Consequently, fuel salt does not have a predetermined lifetime and with sufficient processing (composition adjustment) can continue to be used indefinitely.

The reactor and fuel cycle are inherently more deeply integrated in liquid fueled systems. Liquid fuel salt composition can be altered for multiple purposes. For example, material can be added to the fuel salt to adjust its redox condition to maintain low corrosivity. Other likely adjustments to the fuel salt composition are to remove parasitic neutron absorbers (chiefly fission products) and to add or remove fissile and/or fertile materials to achieve the desired reactivity.

The historic molten salt breeder reactor program was focused on achieving breeding using a thermal neutron spectrum and the thorium-uranium fuel cycle. As thermal spectrum molten salt breeder reactors (TS-MBSRs) have the potential for highly desirable characteristics for cost-effective energy production, especially not requiring the use of high assay low-enrichment uranium or uranium enrichment at all once following fuel cycle startup, they are currently receiving significant development consideration. While TS-MSBRs can achieve all the Generation IV nuclear energy goals, they remain immature, and both non-breeding and fast spectrum MSRs are also options for MSR development and deployment.

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1 US Nuclear Regulatory Commission. 2017. Public Meeting on Improvements for Advanced Reactors, August 3, 2017. Washington, DC, https:/www.nrc.gov/docs/ML1722/ML17220A315.pdf (accessed November 2018)

2 D. E. Holcomb, W. Poore, and G. F. Flanagan, *Fuel Qualification for Molten Salt Reactors*, NUREG/CR-7299, ORNL/TM-2022/2754, December 2022

3 U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, NUREG–2157, *Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel – Final Report*, Volume 1, September 2014