NUREG/CR-XXXX

Fuel Qualification for Molten Salt Reactors

Draft Report for Comment

Office of Nuclear Reactor Regulation

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ABBREVIATIONS AND ACRONYMS

AOO	anticipated operational occurrence
ARDC	advanced reactor design criteria
CFR	US Code of Federal Regulations
BDBE	beyond-design-basis event
DBE	design-basis event
DOE	US Department of Energy
DRACS	direct reactor auxiliary cooling system
FSF	fundamental safety function
GDC	general design criteria
HA	high assay
LEU	low enrichment uranium
LWR	light-water reactor
MSR	molten salt reactor
MIMS	mineral insulated, metal sheathed
MSRE	Molten Salt Reactor Experiment
NE	Office of Nuclear Energy
NPP	nuclear power plant
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PRACS	pool reactor auxiliary cooling system
RVACS	reactor vessel auxiliary cooling system
SAFDL	specified acceptable fuel design limit
SARRDL	specified acceptable radionuclide release design limit
SSCs	systems structures and components
TRIGA	Training, Research, Isotopes, General Atomics [reactor]
TRU	transuranic
U_{nat}	natural enrichment uranium

1 INTRODUCTION

1.1 Purpose

This report supports development of an efficient, appropriate methodology or process for liquid salt fuel system qualification. This report describes the technical issues encountered when developing an adequate understanding of the fuel salt's chemical and physical behavior under both normal and accident conditions. Staff members from the US Nuclear Regulatory Commission (NRC) have defined fuel qualification in terms of adequate understanding of its physical and chemical behavior.

> *Fuel qualification is a process which provides high confidence that 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].

Earlier phases of activities performed at Oak Ridge National Laboratory (ORNL) in support of liquid fuel salt qualification are documented in ORNL/LTR-2018/1045, *Molten Salt Reactor Fuel Qualification and Challenges* [2] and ORNL/TM-2020/1576, *MSR Fuel Salt Qualification Methodology* [3]. This report includes substantial excerpts from the earlier reports to improve overall readability and to serve as a single point of reference.

NRC staff members are developing more general advanced reactor fuel qualification guidance [4]; this report aligns with the safety intents of the more general effort. However, liquid salt fuel has substantial technical differences from solid fuels, and this report describes tailored approaches for achieving the common safety intents when using liquid salt.

Nuclear fuel qualification involves the development of an evidentiary basis to support findings associated with overall nuclear power plant (NPP) regulatory requirements. Fuel performance is an important element in the safety case of both solid and liquid fueled reactors. However, the technical details of how the fuel supports safe plant operation differ substantially between solid and liquid fueled systems. A central purpose for this report is showing how variations in fuel salt properties impact achievement of fundamental safety functions (FSFs) at liquid-salt fueled molten salt reactors (MSRs). This report also provides customized fuel qualification guidance for liquid salt–fueled NPPs to supplement the generic guidance being developed under the NRC's advanced reactor fuel qualification activities. As with the broader advanced reactor evaluation, this report focuses on identification and understanding of fuel life-limiting failure and fuel salt property degradation mechanisms that occur as a result of irradiation during reactor operation.

The interaction of fuel salt with the plant safety-related systems, structures, and components (SSCs) is within scope of fuel salt qualification to the extent that the properties of the fuel salt impact the ability of these SSCs to perform their functions. Similarly, requirements for adequate information on fuel salt performance under accident conditions vary according to specific accident sequences. Consequently, this report includes discussion of the variance in fuel salt performance requirements with SSC configurations and accident sequences. This report does not address whether the SSCs considered provide adequate defense-in-depth or whether the accidents described represent the complete set of accidents.

1.2 Scope

Liquid salt fuel enables a very broad set of reactor designs. MSRs do not have a single configuration or size. Designs are being pursued that range from micro to gigawatt scale. Almost every possible fertile and fissile material combination is being pursued at some level. Table 1 lists key liquid fuel salt MSR design variants.

Table 1 MSR Design Variants

Property	Variant	
Spectrum	• Thermal • Fast	• Time variant • Spatially variant
Fissile/fertile feed	• Th • LEU • $\mathrm{U_{nat}}$	• TRU • HA-LEU-235
Non-fueled coolant	• Fluoride salt • Chloride salt • NaOH	• Pb • Nitrate salt
Moderator	• Internal graphite • NaOH • Heavy water	• External • None
Reflector	• Fertile salt • Liquid lead	• Solid heavy metal
Core configuration	• Channels in graphite • Tubes (connected or partially closed, possibly with fertile materials)	• Open vessel
Fissile material utilization	• Burner • Converter	• Breeder
Passive decay heat removal mechanism	• DRACS • RVACS • PRACS	• Drain tank with DRACS or RVACS
On-site fuel processing	• Physical (bubbling and plate out) • Intense (10 day/core)	• Mild (year/core)
Halide	• Chlorine	• Fluorine
Heat transfer from fuel	• In-core • Integral (in-vessel)	• Loop (ex-vessel)

Given the rapidly progressing MSR development environment, it is not possible to prejudge which designs will be presented for safety evaluation. Consequently, the scope of this document includes a comprehensive set of liquid-fueled MSRs for consideration. The broad scope necessitates a more abstract, somewhat lengthier discussion of the fuel salt qualification issues.

Fuel salt qualification includes definition of the fuel salt's role in achieving safety functions, beginning with the initial receipt of the fuel salt at the plant site until it is transferred to an independent storage facility. The fuel salt includes all radioactive material within the liquid fuel salt at any point in its lifetime until the radionuclides have been stably trapped so that they no longer have a reasonable pathway to either return to the bulk of the liquid salt or to be released in the event of a container rupture. Fuel salt qualification also includes analysis of the following materials:

1. Fission gases and aerosols until their radioactive materials have been adequately trapped,
2. Activated corrosion products that are incorporated into the fuel salt,
3. Plated out materials on the reactor coolant boundary, and
4. Suspended solids within the liquid fuel salt.

Liquid fuel salt is separable from and moves independently of its boundary materials under normal conditions. Fuel salt qualification does not include consideration of the plant SSCs that provide the boundary of the fuel salt system except for the corrosion products that become incorporated into the fuel salt.

1.3 Organization

Section 2 of this report begins with a discussion of liquid fuel salt's operational and safety functions. The report then describes a composition-based methodology for modeling the fuel salt's role in achieving the plant's fundamental safety functions under both normal and accident conditions. Section 2 also describes how variation of the salt's chemical and physical properties can impact safety-related SSCs. Section 3 describes the property information necessary to accomplish the safety intent of liquid fuel salt's nuclear fuel and coolant aspects. Section 4 describes a methodology for determining what fuel salt property information is required to demonstrate adequate plant safety under normal operations and accident conditions.

The report concludes with summary tables detailing the impacts of fuel salt properties on the achievement of the fundamental safety functions, as well as conclusions about the fuel salt property information necessary to model the role of the fuel salt in overall plant safety.

2 ADEQUATE FUEL SALT BEHAVIOR

Fuel salt behavior is governed by its chemistry and physics. 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. Beyond its primary functions, the fuel salt has additional properties that are elements of reactor safety. These include functioning as a neutron moderator and absorber, as well as being a corrosive medium. To qualify liquid salt fuel, an adequate understanding of the fuel salt's chemistry and physics must be developed in order to assess its role in performing the plant's fundamental safety functions (FSFs) under both normal and accident conditions. Fuel salt is directly involved in achieving each FSF.

The FSFs of any nuclear power plant (NPP) are [5]

1. Limiting the release of radioactive materials
2. Removing heat from the reactor and waste stores, and
3. Controlling reactivity.

The principal potential adverse consequence of NPP operation is the release of radioactive materials into the environment. Supporting FSFs include removing heat from the reactor and waste stores and controlling reactivity. Failure to achieve either of the supporting FSFs will eventually result in unacceptable radionuclide release consequences. Therefore, the information necessary to demonstrate adequate heat removal and reactivity control is also necessary to demonstrate adequate radionuclide retention.

Fuel qualification identifies the fuel salt properties needed to model the NPP's fulfillment of the FSFs under normal and accident conditions. This report focuses on identifying and describing fuel salt safety-related performance parameters and degradation mechanisms in terms of their ability to achieve the FSFs. A key issue for liquid fuel salt qualification is the level of understanding of fuel salt properties necessary to adequately assess the fuel salt's role in achievement of the FSFs.

Fuel qualification includes consideration of the fuel salt's role in achieving the FSFs from the time fuel salt arrives at (or is synthesized at) the facility until it is transferred to independent spent fuel storage. Used fuel at MSRs comprises both spent fuel and fuel that is being stored for reuse (i.e., additional fuel produced by breeder reactors, or fuel intended to be returned to service in a replacement fuel salt circuit). Spent fuel at an MSR is any fuel that can no longer adequately perform its operations or safety functions as a result of use in-core. Used fuel salt storage will be part of normal operations for designs that remove fuel salt from the primary loop onsite. The fuel salt will initially be liquid, but it will solidify as its heat generation rate drops.

Demonstrating achievement of the first of the FSFs involves mechanistic analysis of radioactive material transport to the environment. The NRC Commission Paper entitled *Issues Pertaining to the Advanced Reactor (PRISM, MHTGR, and PIUS) and CANDU 3 Designs and Their Relationship to Current Regulatory Requirements* (SECY-93-092) describes the necessary conditions to employ this mechanistic analysis [6]. Specifically, sufficient data are needed to provide adequate confidence in the mechanistic transport approach, including data on the impacts of multiple barriers and pathways. SECY-93-092 also stipulates that the events considered in the mechanistic analyses must bound severe accidents, including design-dependent uncertainties.

Fuel salt also has a role in limiting the harm resulting from beyond-design-basis events (BDBEs). Although the performance of fuel salt during BDBEs is not part of fuel qualification, understanding the performance of fuel salt under BDBE conditions supports mitigation of severe accident consequences. Fuel salt properties and accident phenomena have high degrees of uncertainty under BDBE conditions due to the complex set of interrelated issues. For example, raising the fuel salt temperature would be expected to substantially increase radiative heat transfer. However, mists, fog, or smoke would substantially impede radiative heat transport.

Inadequate decay heat removal following a large fuel salt spill may lead to BDBE conditions. Fuel salt viscosity decreases with increasing temperature, thus spreading out uncontained spills. Fuel salt volatility also increases with increasing temperature. The carrier salt would preferentially volatilize at high temperature. Fuel salt distillation experiments were performed on Molten Salt Reactor Experiment (MSRE) fuel salt to separate the fission products from the carrier salt [7]. The tendency for fission products to remain in the heel would reduce radioactive material transport. On the other hand, the carrier salt vapors would form thermally insulating snow-like deposits on cooler surfaces above spilled fuel salt, thus inhibiting further heat transfer. Cold-wall type decay heat removal systems would become much less effective if they were coated with thermal insulation.

Interacting with water would be undesirable for spilled salt, as rapid water vaporization could generate substantial pressure, stressing exterior containment layers and transporting radionuclides. Moreover, water cooling would not rapidly lower the fuel salt temperature because of the high temperature and high heat flux from spilled fuel salt. The Leidenfrost effect would tend to limit the ability of the water to contact the salt and would provide cooling. However, the Aircraft Reactor Test severe accident testing program demonstrated that plunging fuel salt into a large volume of water primarily resulted in vigorous local boiling, and it also inhibited radioactive material release [8].

2.1 Limiting the Release of Radioactive Materials

Radionuclide transport and accident progression at MSRs are determined by the chemical and physical characteristics of the fuel salt, as well as the plant design features and operational history. During both normal operations and under accident conditions, radioactive material release is restricted by multiple barriers. Taken together, these barriers provide defense-in-depth. Some of the barriers are essentially leak tight, so if a single leak-tight barrier in a release pathway remains intact, then radionuclide release will be adequately prevented. Other barriers reduce the quantity of radionuclides being released, but they are not leak tight. To release radioactive materials into the environment, all of the leak-tight barriers must be breached or bypassed. Alternately, performance of multiple non–leak-tight barriers can be combined to adequately reduce accident consequences. The particular combination of barriers and the credit taken for each barrier will depend on the release pathways of the potential accident sequences for the particular reactor design, the operating state of the reactor, and the choices of the license applicant.

The fuel salt itself is an inherent, non–leak-tight barrier to the release of those radioactive materials that incorporate into the liquid fuel salt as low-vapor pressure molecules. For example, both cesium fluoride and cesium chloride have high solubility within fuel salt and very low vapor pressure at MSR operating temperatures. However, ^{137}Cs is not only a direct fission product; it is also a daughter of the direct fission product ^{137}Xe, which largely separates from the fuel salt into the cover gas. Thus, the fuel salt is a barrier to the release of the ^{137}Cs produced within the liquid fuel salt, but it is not a significant barrier to the release of ^{137}Cs produced in the cover gas.

The amount of radioactive material released into the cover gas is largely determined based on the properties of the fuel salt and the reactor's operating conditions. Consequently, developing an adequate understanding of how materials that originate within the fuel salt can cause the cover gas mixture to stress the barriers is key to understanding the fuel salt's properties. For example, the radionuclides in the cover gas initially produce substantial decay heat that thermally stresses the cover gas container.

Details of a particular plant's accident sequences and its specific requirements for fuel salt accident performance are design specific. There is no universally applicable set of MSR accident sequences given the wide variation in designs under development. However, halide salt characteristics, which support fulfillment of FSFs, are common to any MSR. For example, all fuel salts have high boiling points, low Gibbs free energies, and similar natural circulation heat transfer properties. These inherent salt characteristics allow for a generic approach when determining the required fuel salt properties.

To adequately assess the salt's role in internal accidents that can result in the release of radioactive materials, the fuel salt properties that stress barrier layers must be understood. Barrier layer stresses are any conditions that increase the likelihood of barriers to release radionuclides. For example, an increase in the temperature of fuel salt would cause a higher pressure in the cover gas, thus increasing the pressure stress on the cover gas container, as well as the temperature stress on the fuel salt container. Barrier stress mechanisms can be chronic, such as radiation-induced embrittlement or corrosion, or acute, such as a thermal shock or a steam pressure transient. The performance requirements that apply to materials in continuous or frequent contact with the fuel salt or cover gas during normal operations differ from those that are only in contact for the limited duration of accidents.

Besides fuel salt properties, external events can also challenge the fulfillment of FSFs. For example, if decay heat removal systems or other safety features are prevented from functioning adequately, then barrier failure can result. However, apart from seismic events, containment protects the fuel salt from external events.

Modeling the potential for release of radioactive materials from a specific containment layer requires less information than developing a mechanistic source term. A mechanistic source term includes the chemical and physical forms of released materials. However, stress on a containment layer during relevant accident durations depends only on the physical characteristics of the fuel salt (e.g., temperature and pressure) and not on its chemical composition. Because of its low chemical potential energy (Gibbs free energy) the fuel salt will not have a vigorous chemical reaction with any material. Corrosion and other thermodynamically allowed chemical processes for generating stress on barrier layers progress slowly compared to accident durations. However, the high temperature (high physical energy) of fuel salt could trigger chemical reactions such as ignition of combustible materials in non-fuel salt materials. Therefore, modeling the ability of a containment layer to limit the release of radionuclides under accident conditions does not require knowledge of the radioactive material's chemical form, but it does require knowledge of the chemical environment within containment.

Functional containment [9] is a key concept for MSRs because it enables a license applicant to consider the integrated performance of a set of barriers to radionuclide release instead of relying on imposed requirements for any particular barrier. The usefulness of functional containment for MSRs is based on the design and operational flexibility afforded by liquid salt fuel. For example, high-power density fission can occur immediately adjacent to an MSR barrier layer, thus resulting in significant barrier stresses. Alternately, substantial shielding may be included between the fuel salt and the first barrier, effectively eliminating radiation damage as a stressor to that barrier. A barrier layer with significant operational stresses may not be credited to retain fuel salt radionuclides under accident conditions, yet it may adequately contain the radionuclides during normal operation.

Both the terms *containment* and *barrier* denote structures, features, or mechanisms that prevent or impede the transport of radionuclides. The NRC glossary describes containment as "... enclosure around a nuclear reactor to confine fission products that otherwise might be released to the atmosphere in the event of an accident.". Likewise, 10 US Code of Federal Regulations [CFR] 63.2 defines *barrier* as any material, structure, or feature that prevents or substantially reduces the rate of movement of radionuclides. Functional containment enables the performance requirement of the concrete and steel enclosure in a light-water reactor (LWR) to be distributed across a series of barrier layers. This document describes the physical means to prevent the release of radionuclides into the environment using the terminology of *containment layers* that are composed of *barriers*.

For significant quantities of radionuclides to reach the environment, an MSR's containment performance must be unacceptably degraded. For this to occur, the combination of leak-tight and non–leak-tight containment layers must be damaged or bypassed (by opening a maintenance hatch, for example) to such a degree that they no longer adequately perform their function.

Releasable stored energy is a key concept used for mechanistic accident progression to assess the potential for internal accidents to stress barrier layers and trigger cascading event sequences. Designs with large amounts of releasable stored energy require more robust barriers to contain radioactive materials, and they also require more comprehensive evaluation of accident progression to adequately model triggered/cascading events. Understanding the chemistry and physics involved during fuel salt interaction with barrier layers and materials within containment are crucial to understanding the potential for fuel salt to contribute to radionuclide release.

MSRs operate at temperatures well below the boiling point of the fuel salt. Consequently, the greatest pressure on the fuel salt boundary tends to be the hydrostatic load from the fuel salt column. Fuel salt is in a low chemical energy state, so it cannot chemically react vigorously with any material. The high temperatures and high radiation doses within containment substantially limit the capabilities of materials within containment or serving as containment layers. The plant SSCs must support the intended operational and safety functions. The limited suite of acceptable materials and required plant functions streamlines assessment of how the fuel salt and/or cover gas will interact with each material and minimizes the fuel salt property information necessary to adequately model the interactions.

The following description of the property information necessary to model the fuel salt's interactions with materials is based on performance data. The description is intended to be broadly applicable to MSRs while also being representative of available technology. Designers who select alternate materials must provide equivalent performance information.

2.1.1 Normal Operations

The normally salt-wetted containment layer will be constructed of a high-temperature tolerant alloy that is adequately compatible with fuel salt chemicals and tolerant of neutron flux. During normal operations, the container alloy forms a leak-tight basin for the fuel salt. Cover gas above the fuel salt will be contained within an alloy structure that is tolerant of high temperatures. The structure will be joined to the top of the fuel salt basin and will have adequate compatibility with cover gas chemicals and tolerance of neutron damage.

The fuel salt property information necessary to model normal operations includes the salt's heat generation and heat transfer parameters. The fuel salt corrosivity and erosivity are also important properties that affect the salt's potential to damage the container. The history of the fuel salt temperature is also important input when modeling fatigue and creep of the fuel salt container, as well as mechanical changes to seals and bolted flanges. The fuel salt also stresses the containment via hydraulic mechanisms. The fuel salt temperature, density, and local flow velocity are all needed to calculate the thermal/mechanical stresses on the container.

The fuel salt heat generation is based on fissions and radioactive decay. The fuel salt isotopic composition and distribution must be known in order to perform reactor physics calculations, as well as calculations of energy production from subsequent radioactive decay. Normal operation performance establishes the temperature distribution and radioisotope distribution that would exist at the start of an accident. Establishing the accident's initial conditions is key to assessing accident progression. Initial conditions include details on the startup of passive safety systems, such as the effect of natural circulation initiation upon loss of forced flow. The fuel salt temperature distribution during normal operation also drives the effects of corrosion based on temperature difference. Temperature difference–driven corrosion derives from the differential temperature solubility of corrosion products in the salt. If the concentration of a corrosion product exceeds its solubility limit at the lowest temperature in the fuel salt circuit, then that corrosion product will be deposited in the cold region.

During fuel salt corrosion of the container wall, the least noble component of the alloy is oxidized. Although other corrosion mechanisms are possible via the fuel salt, they occur so rapidly (e.g., dissimilar material corrosion [10]) or are so small (e.g., non-oxidative dissolution of container alloy elements) that they are not practical issues for consideration in comparison to oxidative corrosion. However, non-oxidative corrosion would be a primary stressor for MSRs that employ hydroxide salts [11]. The alloy elements are in their most reduced state, so they are not significantly vulnerable to reductive attack. The fuel salt's redox condition represents its tendency to oxidize or reduce contacting materials. Consequently, knowledge of the fuel salt redox condition is necessary to model its tendency to corrode its container. The fuel salt redox condition can be determined using any method that provides adequately reliable results. Typical assessment techniques include using an electrochemical redox probe, measuring the concentration ratio of the oxidation states of a redox-dependent multivalent element (typically uranium), or measuring the change in the dissolved concentration of the most readily oxidizable element from the container alloy (typically chromium). For example, the MSRE corrosion damage model assumed uniform corrosion and monitored the change in chromium concentration within the fuel salt over time. Corrosion depth was estimated by assuming uniform corrosion and knowing the concentration of chromium in the alloy, the fuel salt, the volume of fuel salt, and the size of the salt-wetted surface. Applicants must provide evidence that corrosion will not result in unacceptable loss of container strength during normal operation.

Fuel salt flow can erode its container by causing suspended hard particles to impact the container's surface. Particles within the salt can be produced via a number of pathways, ranging from contamination to gradual agglomeration of noble fission product atoms into progressively larger clusters. High-velocity fuel salt flow is also necessary for the suspended particles to significantly erode the container. The precise relationships between chemistry, temperature, particle mass, hardness, and fluid velocity necessary to result in significant erosion are complex and depend on the kinetic energy transfer between the suspended particles and the surface. Both particle filtering and nanoparticle plate out mitigate development of significant quantities of suspended particles. Applicants must provide evidence that the rate of erosion by fuel salt is low enough that the probability of barrier failure will not be increased significantly during the container's service life. To generate evidence of lack of erosion, the container's alloy surface could be subjected to wear testing with representative suspended particles under operating fluid flow conditions. The Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets (ASTM G76-18) describes a standard method for conducting erosion tests under simulated service environments.

The cover gas and the liquid fuel salt stress the barriers independently. Therefore, the extent that each one in impedes fulfillment of the FSFs must be considered separately. Temperature is the primary cover gas stressor of the container material. Fission gases are a substantial heat source during the first few hours following generation. The key properties necessary to model the temperature with the cover gas containment are the quantity and composition of the transported radionuclides, along with the temperature and flow rate of any carrier gas used. The noble fission gases have low solubility in fuel salt and represent the dominant energy source within the cover gas stream. The amount of fission gases produced can be derived from reactor physics models.

Cover gases can also generate stress on the barrier by depositing sufficient solid material onto the piping to restrict (block) flow. Cover gases could then build up upstream of the blockage, thus increasing the pressure stress on the barrier. If this is not corrected, then the pressure build-up could result in failure of the inner cover gas containment layer. Much of the deposited material results from volatilization of the fuel salt. ZrF_4 and UCl_4 are examples of fuel salt component materials that have significant vapor pressures at operating temperature, and they are known to form deposits on downstream piping. Daughter products from the decay of fission gases will also accumulate in the cover gas piping.

During normal operation, deposits within cover gas lines would be anticipated to be returned to the bulk of the fuel salt or sent to a waste processing system, such as via a scraping auger in the piping, so this would not lead to stress on the barrier. Applicants must have adequate cover gas line solid deposition information showing that build-up would not produce stress on the barrier, or they must commit to an operational or maintenance method to remove any build up.

2.1.1.1 Tritium

The amount of tritium produced at an MSR is determined according to the fuel salt composition and data from reactor physics models. Tritium production is much greater at MSRs that include lithium or beryllium in their fuel salt. Tritium escapes from the fuel salt boundary during normal operations primarily via permeation of barrier material. The US Department of Energy (DOE) Office of Nuclear Energy (NE) MSR campaign recently reviewed tritium transport phenomena at MSRs [12]. At temperatures above ~300°C, tritium diffuses through structural alloys. Because of the lack of trapping within structural alloys at MSR-relevant temperatures (>500°C), tritium production does not result in significant hydrogen embrittlement. As the tritium is produced at low concentration in the fuel salt, it is transported as a dissolved material within the fuel salt. The salt redox condition determines whether the tritium is chemically bound within the salt. Chemically bound tritium will not appreciably escape through the container walls. Thus, knowledge of the salt redox condition is necessary to model release of tritium through the fuel salt container during normal operations. Some proposed tritium management methods (especially back diffusion of hydrogen through the power cycle heat exchangers [13][14]) will shift the redox condition of the fuel salt, thus altering the amount of tritium released into the cover gas.

Lower temperature structural alloy barrier layers would typically contain tritium. Consequently, escape through the primary heat transport system is the dominant vulnerability for MSR tritium release. MSRs may employ tritium barrier layers to mitigate tritium escape via the heat exchangers. Any tritium barrier materials in contact with the fuel salt must be chemically compatible with the fuel salt. Many common elevated-temperature tritium barrier materials are not chemically compatible with fuel salt. Fluoride salts at elevated temperatures readily dissolve oxides, and silicon carbide would react with uranium in the fuel salt to form uranium carbide. Tritium escape mitigation techniques beyond the salt-contacting surface of the heat exchanger are not impacted by the fuel salt’s properties.

2.1.2 Accident Conditions

The fuel salt or cover gas cannot directly stress exterior containment layers without first breaching an inner containment layer. However, operating the reactor will cause stress on exterior barrier materials by exposing them to radiation and elevated temperatures. The fuel salt is a necessary part of operating the reactor, but the consequent radiation damage of materials not normally in contact with the fuel salt or cover gas are outside the scope of fuel salt qualification, much as radiation damage to the reactor vessel is beyond the scope of LWR fuel qualification.

Seismic events can stress all layers of the fuel salt containment simultaneously. However, without a breach, the fuel salt properties only directly stress the innermost containment layer. The fuel salt density and viscosity are needed to adequately model the additional stress on the reactor vessel caused by seismic motion and subsequent fuel salt sloshing. Fuel salt flow could break off flow control elements. These elements could become suspended in the flow and damage the fuel salt barrier. Fuel salt flow could also cause instrument penetrations to fatigue and fail. Fuel salt density and viscosity are key salt properties necessary to model structural hydraulic interactions.

Following a breach in the fuel salt boundary, the fuel salt and cover gas can directly interact with materials within containment. Since both the fuel salt and cover gas are fluids, a breach of the inner barrier layer can result in the escape of nearly all of the contained materials. Escape could be rapid, as with a rupture, or it could be slow, as with a leak. Breaches above the level of the fuel salt would only release the cover gas, whereas lower breaches would release both fuel salt and cover gas.

Fuel salt has low Gibbs free energy, so by definition, it would not have a vigorous chemical reaction with any material. However, liquid fuel salt can react physically/thermally with contacting materials due to its high thermal energy. Such physical reactions can produce substantial stress on barrier layers.

2.1.2.1 Direct contact materials

The potential materials that are located immediately outside the first barrier layer depend on the reactor’s configuration and material function. All MSRs will employ a fluid to transfer heat to the power cycle and to passively reject decay heat. The heat transfer fluid may completely envelop the fuel salt boundary, or it may only touch a portion of the boundary. Likewise, some designs may employ a fertile breeder blanket salt in some regions and a high atomic number reflector/shielding material in others. Other designs could employ a low atomic number moderator / reflector material adjacent to the fuel salt boundary. Furthermore, other designs must include electrical heaters to provide vessel preheating.

The following examples illustrate the functional diversity of the potential set of materials that may be located immediately outside the first barrier layer.

- MSRs that externally cool the fuel salt in either normal or accident conditions using an unfueled salt in either a pool reactor auxiliary cooling system (PRACS) or fuel-in-tube configuration would have an **unfueled salt** immediately outside of much of the first barrier layer.

- Designs that employ liquid lead as the coolant for a fuel-in-tube configuration or that employ lead as neutron reflector / shielding material may have **liquid lead** immediately outside the first barrier layer, or the liquid lead may be confined within a separate lead compatible alloy.

- A solid, high atomic number material may be employed to serve as a **neutron reflector and shield** immediately outside the first barrier layer.

- Designs that rely upon radiative and convective cooling in the form of a reactor vessel auxiliary cooling system (RVACS) would have an **impure inert atmosphere** immediately outside the first barrier layer.

- Designs that employ direct auxiliary cooling systems (DRACS) within the reactor vessel could have **thermal insulation** immediately outside the reactor vessel.

- Designs seeking to minimize in-core heat transfer may have **vacuum** immediately outside the first barrier layer.

- Designs that include external heaters on the reactor vessel would have **electrical heater materials** immediately outside the first barrier layer.

- Designs that employ an external breeding blanket or internal breeding zones would have **fertile salt** immediately outside the first barrier layer.

- Small thermal-spectrum MSRs may be externally moderated, and spatially variant spectrum designs may also employ an **external high temperature moderator** immediately outside the fuel salt boundary.

The harsh, high-radiation, high-temperature environment immediately outside the fuel salt boundary substantially restricts the characteristics of the materials located immediately adjacent to the fuel salt. The need to perform heat transfer and neutron management further restricts the types of materials that can be located in this area.

Table 2 lists some functional materials that could be employed in the harsh environment immediately outside the fuel salt boundary. A discussion of the consequences of the interaction of the fuel salt with each of the potential functional materials is provided below the table. The discussion includes the fuel salt properties that must be known to adequately model the accident progression. The consequences of a containment layer breach must be evaluated per 10 CFR 50.34(a)(4).

Table 2 Potential Functional Materials and Conditions Immediately Outside the Fuel Salt or Cover Gas Boundary

1. Unfueled liquid coolant
2. Liquid lead or liquid lead compatible alloy

3. High atomic number neutron reflector
4. Semi inert atmosphere
5. Refractory thermal insulation
6. Heater wire
7. Vacuum
8. Fertile salt
9. High temperature moderator

1. Unfueled liquid coolant

Failure of the boundary between the fuel salt and an unfueled liquid coolant would result in mixing of the two liquids. In both PRACS and fuel-in-tube MSR configurations, the coolant will be at a pressure that is equal to or higher than the fuel salt at the start of the accident, so flow will be low volume and inward. Likewise, in loop and integral heat exchanger configurations, fuel salt flow would also tend to be inward as a result of the higher external pressure. However, if the fuel salt pump continues to run, then it may drive some fuel salt into the coolant container [15]. In this case, the coolant salt container would serve as the next containment layer. Large ruptures or uncorrected small breaches in the fuel salt boundary would substantially contaminate the unfueled coolant. To model the spread of contamination, the miscibility of the fuel and coolant must be known. In principle, any liquid with a high boiling point that is also highly tolerant of radiation could be used as the coolant in a PRACS pool. Halide salts are leading candidate materials due to their advantageous characteristics. Other possibilities include hydroxides, carbonates, and nitrates. Because halide salts are at low chemical potential, they would not react vigorously with any liquid. However, graphite would react exothermically with nitrate salts. The fuel's flow characteristics and nitrate salt mixture must be known to model the progress of a nitrate salt inflow accident.

2. Liquid lead or lead compatible alloy

Failure of the boundary between fuel salt and the liquid lead coolant or the reflector would result in the denser lead displacing the fuel salt. Lead has low miscibility with fuel salt, so if loss of flow occurs, then the lead would flow into the fuel salt container and settle to the low point of the hydraulic loop. If liquid lead were to enter the fuel salt pump loop, then the fluid density would increase, and the pumping system performance would be decreased. Knowledge about the miscibility of fuel salt with liquid lead would be necessary to model the accident progression. If the liquid lead is separated from the fuel salt by a double boundary with lead in one duct and fuel salt in a separate adjacent duct, then failure of the fuel salt boundary would bring the fuel salt into contact with the lead container alloy. If the lead container alloy has any solubility in the fuel salt, then introducing a different material system to the boundary of the fuel salt loop would result in the concentration of gradient-driven corrosion. Failure of both boundary layers would result in the fuel salt coming into direct contact with liquid lead.

3. Solid high-atomic-number reflector

If the boundary between the fuel salt and a solid neutron reflector material such as tungsten or iron were to fail, then direct contact between the fuel salt and the neutron reflector material would result. If the neutron reflector material is formed as blocks instead of as a leak-tight basin, then the fuel salt could flow past the neutron reflector. Neutron reflectors must be mechanically thick to ensure that corrosion of a leak-tight basin of neutron reflector material is unlikely to penetrate the reflector during an accident. Knowledge of salt flow and freezing characteristics (viscosity, decay heat generation rate, freezing temperature, and heat of solidification) would be necessary to model salt flow through the cracks within a thick reflector block wall.

4. Semi inert atmosphere

Hot fuel salt can also heat and consequently pressurize gaseous materials within containment. The higher pressure will stress the next containment layer. Atmospheric pressurization is reasonably well described using the ideal gas law. The maximum amount of pressurization possible would result from bringing the entire gaseous volume to the fuel salt temperature. The amount of pressurization would depend on the initial temperature of the gas, the initial pressure within containment, and the temperature of the fuel salt. Containment pressure could reach a few atmospheres if the atmosphere is initially cool (~300 K) and is heated to an elevated fuel salt temperature (~1,000 K). If the gaseous containment is normally operated at an elevated temperature or reduced pressure, then lower peak pressurization would occur. The rate of atmospheric heating is dependent on the contact between the salt and the atmosphere. Modeling the fuel salt flow from a breach and its subsequent interaction with the atmosphere requires knowledge of its thermal and hydraulic characteristics—including viscosity, density, and specific heat—as a function of temperature.

5. Refractory thermal insulation

The consequences of fuel salt interacting with thermal insulation on the exterior of the first barrier material depend on the size of the breach. Based on the performance requirements, the thermal insulation is likely composed of an inorganic nonmetal. Hot fluoride fuel salt would slowly dissolve thermal insulation, making the fuel salt more oxidizing (corrosive). Fluoride fuel salt would also react with silica insulation to generate silicon tetrafluoride gas. Uranium fluoride converting to uranium oxide would also be thermodynamically favorable. For large breaches, fuel salt flow could cause the thermal insulation to detach from the surface of the inner barrier layer. Detached insulation could fall and block the fuel salt's flow from the guard vessel/core catcher into drain tanks, or the insulation could form a blanket layer on top of a salt puddle, thus inhibiting cooling of spilled salt. To model the accident progression, information about fuel salt viscosity and density as a function of temperature would be needed.

6. Electrical heaters

Electrical resistance heaters could also be located immediately outside the first barrier layer. These heaters comprise metal (typically nickel-chromium) wire and ceramic electrical insulation that are welded to mineral insulated, metal sheathed (MIMS) cable. Fuel salt would not react significantly with any of these materials. The electrical heaters would not be expected to form a leak-tight boundary, so the salt would flow past them into the containment.

7. Vacuum

Breach of a vacuum vessel would allow the fuel salt to flow into the vacuum volume. Vacuum insulation is employed to enable the use of lower boiling point hydrogenous liquid moderators (e.g., D_2O) near the hot fuel salt. The volume of the hydrogenous liquid moderator would need to be large enough to ensure that the temperature of the mixed system (fuel salt and moderator) remains below the boiling point of the moderator. This would maintain low pressure and would avoid pressure accidents that would stress exterior containment barriers. Breach of the vacuum would enable hot fuel salt to efficiently transfer heat into the hydrogenous liquid moderator, which could result in vigorous local boiling, potentially breaching the barrier between the liquid moderator and the region under vacuum during normal operation. Information about the fuel's total thermal energy and freezing characteristics (derived from the salt volume, density, viscosity, temperature, heat of fusion, heat capacity, and thermal conductivity) is needed to model the accident progression.

8. Fertile salt

Breach of the barrier between fuel salt and fertile salt would result in mixing of the fuel and fertile salt. For designs in which the fuel salt is at a higher pressure than the fertile salt, the fuel salt could displace absorbing fertile salt, leading to positive reactivity that could subsequently cause stress on external boundary layers. Knowledge of the fuel and fertile salt's flow and mixing characteristics would be required to adequately model the accident progression. Knowledge of the isotopic (fissile and absorber) compositions of both salts would also be necessary input to model the reactivity aspects of the accident progression.

9. High-temperature moderator

Breach of the barrier between the fuel salt and a high-temperature moderator would result in direct contact of the fuel salt and the moderator material. No vigorous chemical reactions would result from fuel salt's interactions with any high-temperature moderator material. Uranium fluoride would react with oxides to form uranium oxide, and it would react with carbides to form uranium carbide. Beryllium would dissolve into the fuel salt, thus increasing its viscosity. Substantial amounts of temperature-dependent fuel salt and moderator information, as well as reaction kinetic information, would be required to accurately model the accident progression.

2.1.2.2 Common SSCs in Containment

MSRs will employ multiple layer or barrier containments to provide defense-in-depth. The materials that come in direct contact with the inner salt boundary may not provide an additional containment layer. Consequently, liquid fuel salt and/or cover gas that escapes from the first barrier may contact additional SSCs within the next leak-tight barrier. This section provides a plant function–based overview of the fuel salt properties necessary to model its interaction with SSCs within the next containment layer.

In some MSR designs, the containment is segmented into separate cells within a robust external containment. A robust external containment layer is needed to meet the safety intents of the NRC's General Design Criteria (GDC) / Advanced Reactor Design Criteria (ARDC) 2, which stipulates that the containment must withstand external events such as high wind loads and wind-driven missiles, as well as the NRC's requirements for aircraft impact assessment (10 CFR Part 50.150), which stipulate that the containment must continue to perform the FSFs following large civilian aircraft impact. A segmented containment limits the potential spread of accidents within the plant, depending on the degree of connection between the cells, and it can also provide radiation shielding between cells. Moreover, separated cells can be operated at different temperatures, with some cells at high temperature and others only maintaining the process piping at elevated temperature.

Reducing the temperature and radiation expands the set of materials and components that may be used in nonreactor cells. For example, cabling that includes organic insulators (similar to cabling used in LWR containments) may be employed in nonreactor cells, resulting in more complex accident progression scenarios. The reduced amounts of radioactive materials within the cells generally decreases nonreactor cell accident significance for achieving plant-level FSFs.

Separation of SSCs from the high-temperature, high-radiation reactor cell environment tends to increase the technical maturity of SSCs. Nonreactor cells, however, can still contain safety-significant amounts of radionuclides. For example, after the first few hours in storage, fission gases are still sufficiently radioactive to present a hazard if released, but they no longer produce large amounts of decay heat. Radionuclides that, under normal conditions, would not return to the bulk of the fuel salt are no longer part of the fuel salt. Therefore, even though accidents involving these radionuclides are important to plant safety, they are outside the scope of fuel qualification.

Some MSRs will process fuel salt to adjust its physical and chemical properties. A portion of the fuel salt is removed from the bulk of the fuel salt to be processed. The properties of the material being processed are largely independent of the fuel salt's properties. Consequently, even though the material properties within the processing cell, are part of overall plant safety, they are not part of fuel salt qualification. However, there must be reasonable assurance that the material reintroduced into the power-generating loop does not contain significant quantities of material that detrimentally impacts the fuel salt's role in achieving the plant FSF. For example, bismuth carryover would rapidly corrode the container's alloy, and/or improper fissile material content could impede reactivity control.

In addition to understanding the harsh environment, information about common plant functions can be used to (1) develop a function-based overview of the SSCs that fuel salt might contact within the next containment layer and (2) to define the fuel salt properties necessary to model accident progression. However, liquid fuel salt, along with the potential for localized radiation and thermal shielding, enables substantial design diversity. Innovative methods may be developed to accomplish the required plant functions. SSCs within containment that are not addressed in the following discussion must undergo an equivalent analysis of their fuel salt property requirements.

The fuel salt property requirement discussions are grouped by plant function. In several instances, multiple alternative SSCs to perform the same function are described. For example, fission within any fuel salt will produce gaseous fission products, many of which will escape from the fuel salt. Some designs incorporate fission gas decay into their reactor vessel or fuel pins (within the reactor vessel), and other designs incorporate an ex-vessel cover gas management system. In all cases, the objectives are to contain the fission gas radionuclides and to transfer their decay heat to an ultimate heat sink.

SSCs within containment will commonly support multiple plant functions. For example, structures formed from reinforced concrete will provide both structural support and radiation shielding. The discussion is limited to the fuel salt properties necessary to enable the plant to accomplish its FSFs. Information outside the scope of fuel salt qualification may be necessary to evaluate the capability of the SSCs to perform their operational functions.

Table 3 lists the common functions performed by SSCs within the containment layer outside the fuel salt container. Materials that may be in direct contact with the fuel salt container are discussed in the previous section.

Table 3 Common Functions Performed by SSCs Within MSR Containment

1. Radiation shielding
2. Thermal shielding
3. Salt pumping
4. Fuel salt content (redox, absorber, and/or fissile) adjustment
5. Reactivity control
6. Fuel salt storage
7. Cover gas decay
8. Decay heat transfer
9. Component and structural cooling
10. Sensing
11. Structural support
12. Radionuclide containment
13. Maintenance components

1. Radiation Shielding

Dense metals such as cast iron or lead are candidates to provide radiation shielding. The metals may be large slabs, or they may be in small pieces such as shot or bricks, and they may be separately contained, as in a shot-filled plate structure. Inorganic refractory material such as sand contained within slab walls is also a candidate material class designed to provide both radiation and thermal shielding. Exposure to the thermal energy of the hot fuel salt would induce stresses on the shielding material or its container. The fuel salt's temperature, heat capacity, density, and heat generation rate would provide the amount of energy that could be transferred to the shielding. Information about fuel salt properties (e.g., viscosity) would be needed to model the fluid heat transfer to the wall. Frozen fuel salt would also provide a heat transfer barrier, so the fuel salt heat of fusion and solid phase thermal conductivity would also be necessary to model accident progression.

Concrete (possibly reinforced) is a candidate material to provide radiation shielding and to serve as a structural material at MSRs. Concrete would not be in contact with fuel salt or cover gases during normal operation, but under accident conditions, it could come in contact in some designs. If hot fuel salt were poured onto unlined concrete, then it would release both free and bound water, as well as carbon dioxide. The amount and rate of gas generation depends on the concrete's temperature, which in turn depends on the salt temperature and the heat transfer characteristics. The kinetics of heat transfer from liquid fuel salt to concrete determines the rate of gas generation. Applicants that elect to employ unlined concrete must provide adequate information on fuel salt thermo-chemical interactions with concrete, as well as the effects on decay heat removal and criticality control, to assess the stresses on barrier layers caused by a fuel spill accident. Just as the use of unlined concrete results in aggravating fuel salt spill accidents, its use is considered unlikely for situations in which large quantities of fuel salt are available. The impact of heat transfer from the fuel salt on protected concrete (e.g., a stainless steel, thermal insulator, concrete layered structure) depends on the heat transfer rate through the lining, which, in turn, depends on the fuel salt's temperature and heat transfer parameters.

2. Thermal Shielding

The purposes for including thermal shielding in containment would be to protect thermally sensitive materials and components, to reduce the parasitic heat loss during power range operation, and to enable initial non-nuclear heat up of the fuel salt container. Thermal shielding within containment would likely be fabricated from an inorganic non-metal similar to thermal insulation, and it would be in direct contact with the fuel salt container. If thermal shielding is in contact with a fuel salt–filled container, then the increased requirements for mechanical integrity in the contacting insulation are increased. Thermal insulation within containment could include materials such as sand within plates, which would provide both thermal and radiation shielding. Whether the insulation is in contact with or separated from the fuel salt container, the same fuel salt properties would be necessary to model the impact of the fuel salt's interaction with thermal insulation on the achievement of the plant FSFs,.

3. Salt Pumping

Fuel salt pumps will have elements in contact with the fuel salt, and they will also have elements within the next layer of containment. Motive power (electrical, hydraulic, or pneumatic) would come from outside of containment. Pumps that work in MSR environments will mostly comprise metals and ceramics. Exposure of pump materials to fuel salt liquid or vapor would not significantly affect the ability of the plant to achieve the FSFs, apart from preventing forced convective decay heat removal due to pump operational failure.

If the fuel salt were to include large, suspended solids (equivalent to loose parts in an LWR), then the fuel salt could cause a rotor lock accident that would produce stress on the pump shaft, potentially resulting in a cascading accident sequence. Frozen chunks of fuel salt could be introduced into the loop as part of a refueling accident.

Electric arc flashes could be caused by electrical shorts in the pump's motor power. Electric arc flashes can generate pressure waves that result from the intense local heating. Information on the fuel salt vapor/aerosol discharge characteristics would be needed to create models for arch flash initiation. A bounding pressure wave calculation can be performed based upon the total energy in the circuit. This approach would circumvent the need to understand the electrical characteristics of the containment atmosphere.

Fuel salt could chemically, thermally, or mechanically damage improperly designed or implemented fluid transfer lines that are used for pneumatically or hydraulically driven pumps. In high-temperature, high-dose rate regions, the motive fluid transfer lines would be pipes (likely stainless steel) that would be robust enough to not be affected by contacting fuel salt.

4. Fuel Salt Content Adjustment

Fuel salt content adjustment is an alternative to full salt processing. A fuel salt content adjustment system would shift the fuel salt redox, absorber, and/or fissile material content towards a more desirable range for operation. Several mechanisms can be used to adjust the fuel salt content. For example, gas can be bubbled through the fuel salt to increase the fission gas release fraction, or a reducing agent such as beryllium can be added to the salt. All transfers to or from the fuel salt must be made through robust transfer lines to withstand the radiation and temperature environment. These lines would likely be of the same composition as the fuel salt container, so they would not be vulnerable to being contacted externally by fuel salt during an accident.

Improper operation of a fuel salt adjustment system could cause or exacerbate an accident due to the resultant fuel salt properties (improper fissile content or redox condition). However, fuel salt properties do not significantly affect whether contact between fuel salt and the adjustment mechanisms would impact the progress of a salt spill accident.

5. Reactivity Control

After the release of fuel salt past the first containment barrier, the fuel salt properties required to model achievement of the reactivity control FSF depend on the safety function of the reactivity control system. In some MSR designs, the inherent properties of the fuel salt would provide adequate reactivity control to achieve the FSF. In these designs, the strong net negative power feedback, combined with the small amount of excess reactivity available, performs the reactivity control FSF, without reliance on external mechanisms. Other MSR designs may rely on external reactivity control mechanisms to perform the control reactivity FSF.

A large break in the fuel salt system would cause the fuel salt to lose critical geometry, so the normal reactivity control system would cease to have a safety function. A breach in the cover gas system could result in solid “snow” deposits forming on control system mechanisms while liquid fuel salt remains in a critical geometry. Only reactor designs with exposed control system mechanisms would be vulnerable to snow deposits. It is anticipated that MSRs would avoid vulnerability to snow deposit fouling of reactivity control mechanisms by means of separately enclosing the mechanisms.

Snow deposits are caused by vaporization of fuel salt components (e.g., ZrF_4 or UCl_4) and fission gas decay. The fuel salt properties necessary to model the snow deposition would be fuel salt composition and temperature to determine the vaporization rate of the low boiling point components, as well as the fission gas production rate for the fission products. Additionally, the heat of vaporization from the volatile components would be necessary to model the deposition. Substantial additional information on plant design and accident progression would be required to assess the amount of material that would be deposited in any location.

6. Fuel Salt Storage

Fuel salt may be stored before or after use within containment. A fuel salt spill may flood the salt storage area. The presence of additional fissile material could result in failure to achieve the FSF to control reactivity. However, for reasonable designs, it is anticipated that criticality accidents involving fuel salt storage would be precluded by geometry and neutron absorption. For example, fuel salt storage would likely be elevated and would have significant salt-compatible neutron absorption nearby. The fuel salt property necessary to model its reactivity contribution would be its composition.

7. Cover Gas Management

MSR designs that feature in-vessel cover gas decay may fail to achieve the decay heat removal FSF following a breach in the reactor vessel. A discussion of the fuel salt properties necessary to adequately model achievement of the decay heat removal FSF following a vessel breach accident is provided in Section 2.2.2 .

Alternatively, MSR designs may include an ex-vessel cover gas decay tank. A break in either the cover gas decay tank or the reactor vessel would allow the fission gas, as well as fuel salt vapors and aerosols within the cover gas, to escape into the surrounding volume. The accident progression modeling requirements would be similar to those required to model a reactor vessel breach.

Under accident conditions, the fuel salt could come into contact with materials within the cover gas scrubbing or filtering system. A diverse set of filtering and/or scrubbing technologies are possible for holding up and reducing the radioactive burden within the cover gas.

One option would be to employ mechanical filters within the cover gas stream to remove non-gaseous components. Both suspended particles and droplets within the cover gas stream would contribute to the heat load on the filter and build-up of material on its surfaces. The fuel salt properties necessary to model accidents involving mechanical filters are the cover gas composition and the aerosol load.

Another option is to employ a hydroxide scrubber to remove non-noble gas materials from the cover gas flow. Fuel salt that contacts hydroxide scrubber fluid would generate hydrogen fluoride and would also form low solubility oxides in the fuel salt (e.g., zirconium oxide and uranium oxide), which may impede fuel salt flow. Additional volatile radionuclides may also be generated due to the fluorine generation (e.g., molybdenum hexafluoride). However, fuel salt interaction with hydroxide scrubber fluid is not an energetic reaction that would result in significant pressure or heat generation. The major FSF challenge resulting from fuel salt contacting the hydroxide scrubber fluid would be that adequate natural circulation decay heat removal would be compromised. Adequate heat transfer information about the combination of fuel salt and hydroxide scrubber fluid must be provided to enable adequate modeling of such an accident. Because information about this type of mixture does not exist and would be difficult to produce, reducing the accident probability beyond the design basis appears to be the likely design approach.

However, any filter or scrubbing system design has a limited impact on fuel salt qualification. Radionuclides that have been trapped sufficiently well to lack a reasonable pathway for return to the bulk of fuel salt during normal operating conditions are no longer part of the fuel salt. Thus, the radionuclides are outside the scope of fuel qualification.

8. Decay Heat Transfer

The plant components intended to transfer decay heat from the fuel salt (including the portion in the cover gas) to the environment will be within the next layer of containment. A number of different mechanisms can be used to transfer the decay heat. However, whether the heat transfer mechanisms are thermosyphons, heat pipes, or other natural convection loops, they all must be enclosed within piping to guide the flow of the heat transfer media within them. Fuel salt contacting stainless-steel piping during an accident does not significantly impair the capability of the piping to perform its function. However, if the fuel salt were to freeze on the heat receptor portions of the decay heat transfer mechanisms, then it could form an insulating layer that could significantly impede heat transfer. Fuel salt freezing can be modeled using its freezing temperature and natural convection heat transfer parameters (viscosity, heat capacity, thermal conductivity, and coefficient of thermal expansion). Note that maintaining a frozen layer within molten salt requires substantial heat removal from the solid due to the good natural convection cooling provided by the salt.

9. Component and Structural Cooling

During normal operations, components such as the pump motor, control drive mechanisms, sensors, and mechanical structures may be actively cooled. GDC 44 also requires that adequate cooling be provided to any SSCs that are important to safety during both normal and accident conditions. A key safety concept for MSRs is to not rely on active components to achieve adequate safety performance under accident conditions. Safety-related SSCs, however, may be actively cooled during normal operations. Following breach of the inner containment layer, hot fuel salt could interact with coolants or other liquids present within containment. The hot fuel salt would cause the coolant temperature to increase and the fuel salt's temperature to decrease. Following a fuel salt breach accident, the safety significance of structural components for fuel salt containers would be substantially reduced: both the safety implications and the strength requirements for supporting a nearly empty reactor vessel would be substantially reduced.

For low boiling point liquid coolants, if insufficient coolant is present (or the heat cannot be adequately transferred to the bulk of the coolant) to lower the ensemble temperature to below the coolant boiling point, then some of the coolant will flash to vapor, potentially resulting in a substantial volume / pressure increase. Mainly for this reason, large MSR designs either avoid significant quantities of low boiling point liquid coolants in or near containment, or they provide very large quantities of coolant to keep the ensemble temperature well below the coolant boiling point. Smaller MSRs may instead elect to provide an adequate expansion volume to accommodate the phase change pressure rise. For such designs, the applicant must determine the maximum potential pressure on the barrier layer resulting from the phase change interaction for the specific combination of fuel salt and coolant. The mass of fuel salt, along with its temperature, density, and heat capacity, are the fuel salt parameters used to determine the available energy for physical reaction with liquid coolants.

Two higher boiling point liquid coolants (alkali metals and nitrate salts) may have adverse consequences from breaches in the barrier between the fuel salt and coolant. The first of these, alkali metals, are strong reducing agents for fuel salts. Contact between alkali metals and fuel salts would result in actinides in the fuel salt converting to metallic form. The chemical reactions between the fuel salt and alkali metals are largely independent of the fuel salt's properties. The resultant actinide metal atoms have low solubility in the highly reducing fuel salt, and they tend to plate out from the fuel salt liquid. The rate and location of the deposited actinides depend on the amount and location of the introduced alkali metals, as well as the flow characteristics of the fuel salt. Plating out fissile materials could result in significant consequences from a small leak between fuel salt and alkali metal containers. Plating out actinides onto surfaces would reduce radioactive material transport. However, concentrating fissile materials into deposits may result in unintended criticality. Unintended criticality is more likely to occur in fast-spectrum reactors with their higher actinide loading. Highly reducing fuel salt would form uranium carbide with a graphite moderator, thus increasing the amount of fissile material in core. The second potential coolant, hot nitrate salt, would react energetically with graphite. The mixing and flow characteristics of nitrate/fuel salt mixtures would be necessary input to model the accident progression of a nitrate salt ingress accident in a graphite-moderated MSR.

If both oxygen and hydrocarbons (lubricants) or other combustible materials are present within containment, then a fuel salt spill could result in a fire. Outside of thermal and radiation shielding layers, organic materials may be employed as part of cabling. Temperature is the fuel salt property involved in causing ignition for situations in which both a fuel source and oxidizer are present. Note that neither hydrocarbons nor sufficient oxygen to support ignition is likely to be present within inerted containment during normal MSR operations.

10. Sensing

The second containment layer will include a number of sensors and their associated cabling. Within the reactor containment cell, the sensors would employ mineral-insulated, metal-sheathed cabling to withstand the radiation and temperature environment. Other cabling may be employed for locations where the temperatures and radiation doses are lower. Many of these cable materials are flammable. However, the sensing and cabling have low total mass limiting the potential additional energy input as compared to the spilled fuel salt and cables, which would require a source of oxygen to support combustion. No sensor or cabling system would be likely to impede the plant performing its FSFs under fuel salt spill conditions.

11. Structural Support

The structural support elements of the plant and the reactor components would be within the next containment layer. Reinforced concrete and steel are the most likely materials to employ to provide structural support at any MSR. The issues arising from fuel salt or hot gases contacting concrete are described in the radiation shielding portion of this document. The major issue arising from fuel salt contacting structural steel members is that they would be weakened by heating. Modeling the heating of the structural members by spilled fuel salt would require information regarding the fuel salt heat transfer properties (e.g., heat capacity, viscosity, specific heat, heat generation rate, and coefficient of thermal expansion as a function of temperature).

12. Radionuclide Containment

The fuel salt or hot cover gas may come into contact with the next containment layer following breach or rupture of the first containment layer. Since corrosion through structural material layers is a long duration event, thermal and mechanical mechanisms are the primary means through which the fuel salt would stress the barrier. The potential for rapid exposure to the fuel salt (e.g., as a result of a fuel salt circuit rupture event) necessitates considering thermal shock resistance, in addition to overall temperature tolerance of the radionuclide containment barriers. The next containment layer is likely to be composed of stainless steel to allow for performance within the MSR's harsh, high-temperature, high-radiation dose environment. In some areas, the stainless steel may only be a liner (catch pan) for a reinforced concrete structure. Fuel salt and/or hot cover gas would challenge the radionuclide containment FSF primarily by heating the containment layer to a temperature high enough to cause it to be within the creep regime.. Consequently, modeling the accident progression will require knowledge of the fuel salt's heat transfer and flow properties.

13. Maintenance Components

Some MSR designs will incorporate fixtures and structures to enable maintenance. As some components (such as an overhead crane) are cumbersome and difficult to decontaminate, during power operations they may be left within the containment but put in a location with the lowest dose and temperature possible. Maintenance components may be damaged by fuel salt contact, but they do not have safety functions during power operations. Consequently, their interaction with fuel salt is not relevant to fuel salt qualification.

2.2 Removing Heat from the Reactor and Waste Stores

The fuel salt serves as the primary heat transfer medium for removing heat from the reactor and waste stores during both normal and accident conditions. As with solid fuels, fuel salt is the source of nearly all the residual heat that must be removed. The liquid phase salt, fission gases, and plated out solids all generate substantial quantities of heat that must be rejected.

Liquid fuel salt is a high heat capacity fluid with low thermal conductivity and a high boiling point. As such, fuel salt must flow to transport substantial quantities of heat. Consequently, the fuel salt's properties related to flow and heat capacity must be known to model its ability to transfer heat. Fuel salt viscosity, density, thermal conductivity, and heat capacity are heat transfer parameters that vary with temperature and salt composition.

The heat transfer properties derive from the fuel salt's composition. Therefore, the fuel salt composition must be maintained within acceptable limits to ensure acceptable heat transfer. Fuel salt is a Newtonian fluid with continuously varying properties, so heat transfer performance assessments that are made at the boundaries of the acceptable property and physical state (largely temperature) envelope provide conservative assessments of heat transfer for states within the boundaries.

The thermochemical and thermophysical properties of fuel salts are fully described by their chemical compositions and temperatures. Consequently, the fuel salt thermophysical property database can be generated using small samples of low- or no-radioactivity materials. Fundamentally, fuel salt composition and temperature measurement are the only data needed to fully specify the fuel salt's thermophysical and thermochemical properties. However, at the current level of scientific understanding, the salt's thermophysical and thermochemical properties should be measured and correlated with fuel salt composition and temperature to develop an empirical database of fuel salt properties [16].

2.2.1 Normal Operations

During normal operations, an MSR can rely upon either safety grade or non-safety grade SSCs to achieve the FSFs. To be within the bounds of normal operation, the plant must be achieving the FSFs. MSRs can transition to accident conditions as a result of inadequate or excessive heat removal.

It is anticipated that adequate heat removal during an MSR's normal power range operations will be performed in a manner similar to that used for other NPPs. For example, adequate heat removal can be assessed by comparing the nuclear heat generation rate with the thermal energy transfer rate into the power cycle and any operating additional heat removal systems. Monitoring changes to the mixed mean temperature of the coolant leaving the fuel salt critical region also provides assurance that heat is being adequately removed during normal operations.

A wider range of fuel salt properties would acceptably transfer heat during normal operations. However, the same range of fuel salt properties may not adequately transfer heat under accident conditions. For example, the heat transfer impact caused by increasing fuel salt viscosity during normal operations could be compensated for by increasing the pumping power. However, the increased viscosity could adversely impact the ability to adequately reject decay heat under loss-of-forced-flow-accident conditions. Even some phase separation and/or partial solidification could be acceptable under forced flow conditions for cases in which the entrained solids would be carried along with the remainder of the fuel salt. Therefore, variations in liquid fuel salt properties during normal operations become important to fuel salt qualification largely to the extent that they have the potential to impact the outcomes of accidents.

Used fuel continues to be fuel salt, so it will continue to be required to support achievement of plant FSFs: that is, it must avoid criticality, provide adequate cooling, and prevent radionuclide escape. Adequate passive decay heat rejection must be provided to avoid damage to the used fuel salt container (likely be made of stainless steel) from thermally induced deformation. Natural circulation of used fuel salt within the storage container will decrease the temperature differences within the fuel salt container. The internal pressure of the fuel salt container will only increase significantly if the fuel salt temperature increases to its boiling point. Fuel salt boiling points are well above the softening temperatures of reasonable container materials, so fuel salt temperature will likely be the limiting container stressor. Once the fuel salt has solidified, it will be suitable for transfer to independent storage and thus will become subject to the requirements of 10 CFR Part

72, Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste.

Fuel salt properties can contribute to accidents that involve loss of the ability to adequately remove heat. For fuel salts with temperature-dependent solubility of materials, materials may be deposited at the lowest temperature portion of their circulation loop. Over time, this can become important for structural materials for which the most easily oxidizable element of the container alloy is dissolved into the fuel salt's higher temperature regions and is then deposited in lower temperature regions. In addition, if the fuel salt were to become significantly oxidizing for even a short period (hours), it could dissolve more oxidation-resistant materials (such as nickel) that would subsequently be deposited at the low temperature portion of the loop. Some materials (such as nickel) are known to deposit dendritically, which could result in substantial flow restriction with limited amounts of material deposition.

Fuel salt properties can also lead to the exacerbation of heat removal imbalance transients. If the power range heat removal system were to operate fully (e.g., via a coolant pump overspeed accident) while the reactor was producing much smaller amounts of heat, then the fuel salt could freeze within the heat exchanger, thus blocking fuel salt flow and preventing further heat transfer. Consequently, information about the fuel salt's freezing properties (e.g., melt point, heat of fusion) will be a required element of fuel salt qualification.

Another mechanism through which fuel salt properties could initiate accidents that involve loss of adequate heat transfer would be via rapid precipitation of actinide oxides from the fuel salt. Fuel salt oxygen exposure can result in the formation of insoluble oxides. Both uranium and plutonium can form insoluble oxides. To minimize actinide oxide formation, fuel salts frequently contain substantial quantities of a readily oxidizable material such as zirconium. Insoluble actinide oxide particles may form deposits that are not adequately cooled.

Another mechanism through which fuel salt properties could lead to accidents that involve loss of adequate heat transfer would be via formation of solid uranium carbide deposits on graphite. If uranium-bearing fuel salt becomes strongly reducing (for example via alkali metal exposure), then uranium fluoride will chemically react with graphite to form uranium carbide. The uranium carbide deposits may block coolant flow channels, thereby resulting in inadequate heat transfer.

Furthermore, heat must be removed from fission gases during normal operations. If the fission gases have been separated from the liquid fuel salt container, then they will require separate cooling. Although the composition of an off-gas stream will impact the solidification characteristics of its constituent gases and suspended aerosols, which in-turn can result in gas system plugging and pressure build up, variations in the cover gas composition would not significantly impact the ability to adequately reject decay heat during normal operation due to the common heat transfer characteristics of any low-pressure, mostly noble gas stream.

Fuel salt properties can also lead to flow accidents caused by inadequate heat removal. The flow distribution characteristics of open cores are influenced by fuel salt viscosity. Recirculation eddy zones can result in fuel salt hot spots. If these hot spots come into contact with the container wall, they can cause thermal damage.

Overall, sufficient fuel salt property information must be available to directly model heat transfer performance and the role of fuel salt in initiating accidents, as well as to establish reactor conditions (including salt properties) at the initiation of accidents.

2.2.2 Accident Conditions

Fuel salt remains the primary heat source and transfer medium in MSRs under accident conditions. All known MSR designs employ some form of natural circulation-based decay heat transfer from the active fuel salt and from waste stores. The requirement to remove decay heat from the salt remains, even if the salt has been removed from the reactor vessel (e.g., sent to a drain tank). Natural circulation-based heat transfer also remains important for heat rejection during accidents in which the fuel salt has escaped from its normal container. Employing passive decay heat rejection under both AOOs and design basis events (DBEs) is central to avoiding the need for electrical power to achieve plant FSFs.

Convection and (to a lesser extent) conduction continue to provide heat transfer from the fuel salt under accident conditions. Hence, the same basic set of heat transfer and fluid flow parameters required under normal operating conditions (albeit for a wider set of temperatures) must be known to model heat rejection under accident conditions.

Radiative heat transfer would only become significant in a limited set of accident conditions in which the fuel salt temperature increases substantially. Radiative heat transfer increases with absolute temperature to the fourth power. At higher temperatures, radiative heat transfer can become important for spilled fuel salt. For accident situations involving radiative heat transfer from a spilled fuel salt pool to outer containment walls, the radiative heat flux is such a strong function of temperature that changes to fuel salt emissivity would be overcome by only a few degrees of increased temperature. In other words, changes to fuel salt properties that occur with use will not significantly impact the fuel salt's ability to reject heat through radiative cooling.

If radiative heat transfer from spilled fuel salt is credited to achieve adequate decay heat rejection, then the salt emissivity must be known. Radiative heat transfer within the containment atmosphere will be inhibited by materials (such as fuel salt vapors and aerosols) suspended within the atmosphere. Radiative heat transfer within the spilled salt will effectively increase the effective thermal conductivity of the salt. However, radiative heat transfer within the salt will be inhibited by internal absorbance, which will become progressively greater as fission products build up in the fuel salt. In addition, suspended particles and bubbles will inhibit radiative heat transfer within spilled salt. Radiative heat transfer from spilled fuel salt could be substantially reduced if a thermally insulating crust or scum layer is formed on the fuel salt pool due to interactions with materials in the containment environment.

Providing reasonable assurance of the fuel salt's continued capability to reject decay heat requires knowledge of changes in the fuel salt's natural convection heat transfer properties. Initially, the capability of a particular reactor design to adequately reject decay heat will be established through thermal and hydraulic modeling and experimentation. Changes to the fuel salt's ability to provide adequate heat rejection arise from changes to the fuel salt's thermophysical properties. Adequate evidence of the fuel salt's ability to provide adequate heat transfer throughout the range of acceptable fuel salt compositions must be available.

Fuel salt decay heat rejection via natural circulation cooling will take place by laminar flow of the fuel salt across a heat exchange surface. Bonilla [17] developed a parameter group that describes the effectiveness of a coolant to dissipate heat via natural convection in the laminar flow regime:

$$\begin{matrix}\text{Laminar heat}\\ \text{transfer effectiveness}\end{matrix} \propto \left(\frac{\beta \rho^2 c_p}{\mu}\right)^{\frac{1}{2}}, \tag{1}$$

where β is the volumetric expansion coefficient $\left(\frac{1}{\rho}\frac{d\rho}{dT}\right)$, ρ is the density, c_p is the heat capacity, and μ is the viscosity.

Natural circulation heat transfer from fuel salt increases with increasing temperature. This is because the heat transfer improvement that occurs due to the decrease in viscosity is greater than the heat transfer reduction that occurs due to the decrease in density. Salt heat capacity does not vary strongly with temperature. Viscosity decreases exponentially with reciprocal temperature, whereas density decreases linearly with temperature [18]. The heat transfer also increases due to the higher driving temperature difference between the fuel salt and the external environment.

Generation of fission gases stops when fission stops. Hence, fission gas cooling is only needed for a limited duration following shutdown. However, initially, the fission gases produce a substantial heat load. Heat must be adequately rejected from the fission gases, if they remain in their normal container, if they have escaped to the next containment layer, and whether or not they are mixed with a cover gas. Vapor phase heat transfer is primarily via convection augmented by radiation at sufficiently high temperatures. A portion of the heat load from the fission gases is a result of subsequent decays of daughter products. The daughter products will either be suspended in the fission gas atmosphere or plated out onto surfaces. The specific mechanisms for adequately removing the fission gas decay heat will be design dependent. The fission gas heat transfer properties can be adequately represented by treating them as noble gases that include the heat load from the fission gas decay and from their daughter products. Thus, the principal information about the fission gases that is necessary to adequately model decay heat rejection is their total heat production rate, which can be obtained from reactor physics models.

Cooling of used fuel salt is likely to be performed using natural circulation mechanisms under both normal and accident conditions, so this would not be impacted by loss-of-power accidents. The advantageous natural circulation characteristics of fuel salts homogenizes fuel salt temperature, minimizing the potential to create hot spots or configurations that are difficult to cool. The same basic hydraulic and heat transfer parameters will be needed to adequately model decay heat removal from used fuel salt: liquidus temperature, viscosity, density, and heat capacity. For immobile material (i.e., frozen or plated out materials), thermal conductivity is also an important heat transfer property.

2.3 Controlling Reactivity

This section describes how variations in fuel salt properties impact achievement of the controlling reactivity FSF at liquid-salt fueled MSRs. To achieve the FSF, MSRs are required to control reactivity adequately such that the plant's operation does not result in unacceptable radiological dose consequences. Adequately controlling reactivity has multiple aspects that are tied to the fuel salt as the medium that contains the fissile material. Qualifying the fuel salt requires developing an adequate understanding of the fuel salt's properties of the fuel salt to model its role in overall plant safety during normal and accident conditions. However, achievement of the FSF is separate from fuel qualification. Unsafe designs can have well understood fuel properties.

Specific safety performance requirements for fuel salt depend on the degree to which its properties can adversely impact the performance of safety-related SSCs under normal operations or accident conditions. The fuel salt itself is an element of performing some aspects of the FSFs, in that it retains some radionuclides, serves as the heat primary transfer medium, and contains materials that impact reactivity (fissile, moderator, and absorber materials).

Fuel salt reactivity–related qualification requirements apply to new, in-use, and previously used fuel salt. Fuel salt will have an allowable range of thermophysical and thermochemical properties to enable adequately safe plant operations. This range of properties will result in an allowable range of compositions. The allowable range of thermophysical and thermochemical properties (and thus composition) derives from the fuel salt's required behavior under normal and accident conditions. Changes in the fuel salt's composition as a result of use become unacceptable if they cause the salt to have unacceptable performance. With regard to the reactivity control FSF, changes in fuel salt properties become unacceptable if they unacceptably adversely impact the ability of the fuel salt to perform its role in achieving the FSFs as a result of reactivity-derived accidents.

Fuel salt properties are only one element of any reactivity-derived accident sequence. Substantial reactivity transients can occur via mechanisms that are largely independent of the fuel salt's thermochemical and thermophysical properties. For example, the control system might improperly insert positive reactivity, or an internal fertile salt container might accidently drain. Relative to achievement of the reactivity control FSF, fuel salt qualification, requires that the fuel salt's properties be sufficiently well known to enable modeling of their impact on the achievement of the FSFs during and following reactivity-derived accidents. Furthermore, any uncertainties in the fuel salt properties must be biased to ensure conservative calculation of the potential radiological dose consequences.

An acceptable means of achieving the controlling reactivity FSF is to sufficiently decrease the potential for accidents that result in unacceptably large reactivity additions. In an MSR, this would include preventing uncontrolled fissile material addition, increased neutron reflection, and/or removal of neutron absorbers. The amount of reactivity and the rate of increase that would be unacceptably large depends on plant design and fuel salt properties.

To continue to achieve the FSF, evolution of the fuel salt composition with use cannot result in reactivity-derived accidents resulting in unacceptable dose consequences. Safety adequacy analysis must focus directly on unacceptable dose consequences; this is because some reactivity-derived accidents can be self-correcting yet can still causing enough damage to impede the functioning of safety-related SSCs. For example, if the redox control system in a graphite-moderated MSR were to cause the fuel salt to become somewhat too reducing, then the UF_3 within the fuel salt would react with the graphite to form UC, thus increasing the amount of fissile material in core. The resultant power increase would increase the number of fissions occurring, which are oxidative, thus shifting the fuel salt oxidization condition back towards an acceptable value.

MSRs tend to have a high tolerance for reactivity excursions, because their fuel cannot be mechanically damaged. MSRs are operated well away from any cliff-edge type phenomena. Increases in fuel salt temperature are a common element of MSR responses to accident conditions (e.g., increased radiative heat rejection and/or higher solubility of fissile materials resulting from higher temperature). Fuel salt qualification requires having an adequate understanding of the salt properties to adequately model accident sequence progression, including the fuel salt's impact on the performance of SSCs credited to prevent unacceptable radionuclide releases (e.g., safety-related SSCs).

2.3.1 Normal Operations

The plant must be achieving the FSFs to be within the bounds of normal operations. Under normal operations, overall net negative, inherent reactivity feedback mechanisms must be sufficiently large and well understood to avoid conditions that might impede the ability of the safety-related SSC to function as designed. In other words, normal operations cannot bring the plant into a state in which it would not be able to respond to DBEs without releasing unacceptable quantities of radionuclides.

The fuel salt contribution to reactivity feedback must be adequately understood to enable conservative modeling of the plant's operation. For example, a fuel salt freeze valve may be an element for providing a passive, net overall negative reactivity feedback in some MSR designs. In such designs, fuel salt heat-up as a result of reactivity transients may be an allowable part of normal operation if transients are slow enough to enable the freeze valve to adequately contribute negative reactivity. Draining the fuel salt into its designed drain tanks would not itself inhibit achieving the FSFs, so this could be considered part of normal operations.

Reactivity control during normal operations can involve both active systems and passive feedback mechanisms. Reactivity control for normal operations includes starting up, power maneuvering, responding to burnup/breeding of fissile materials and/or fission product accumulation, and achieving and maintaining safe shutdown. Some potential mechanisms for reactivity control for normal operations are related to fuel salt properties. For example, thermal expansion of fuel salt out of a critical geometry and/or changes to the moderation ratio are both related to fuel salt thermophysical properties, whereas Doppler broadening of absorption lines is an inherent aspect of the temperature response of all fissile materials.

The requirements for negative reactivity feedback depend on the specific safety characteristics of the design. To achieve the adequate reactivity control FSF during normal operations, the overall plant negative reactivity feedback must be sufficient to prevent damage to safety-related plant SSCs. During normal operations, the plant cannot enter a state in which it is not able to respond to DBEs without an unacceptable radionuclide release. Furthermore, the properties of qualified fuel salt must be sufficiently well known so that the role of the fuel salt in achieving the reactivity control FSF can be modeled. While achievement of the adequate reactivity control FSF under normal operations conditions requires avoidance of reactivity transients that would result in plant states that exceed the design conditions of safety-related SSCs, reactivity transients are not otherwise limited. As with TRIGA (Training, Research, Isotopes, General Atomics) reactors, even substantial positive reactivity transients may not cause the plant to fail to achieve the FSFs if the inherent negative reactivity feedback mechanisms are sufficiently large and timely.

2.3.2 Accident Conditions

MSRs must continue to provide adequate reactivity control throughout the duration of accidents. Accident conditions include damage to safety-related SSCs and events that result in radionuclides not being confined within the locations designated in the plant's safety analysis. The specific requirements for fuel salt in preventing accident escalation and bringing the plant to a safe shutdown condition depends on the plant design features. Safe shutdown requires that unacceptable levels of radionuclides are not being released and that the plant status not be deteriorating (i.e., not on a trajectory towards releasing unacceptable quantities of radionuclides). The role of both fresh and previously used fuel salt must be included in accident progression analysis.

Reactivity control is one element of overall plant safety. However, the plant becoming strongly subcritical as part of accident progression is not a necessary element of overall plant safety. For example, spilling fuel salt from its normal container would likely cause a substantial decrease in reactivity resulting from changes in the fissile material geometry and less effective moderation.

However, the loss of the containment layer may be a more substantial contributor to the risk of radionuclide release. Therefore, the fuel salt remaining within its normal operations container in a low-power critical configuration may present a lower risk of an unacceptable accident outcome. Note that those MSRs operated with minimal excess reactivity fuel would eventually burn out without the provision of either fresh fissile or fertile material. Furthermore, fuel salt changes that result from reactivity increases can result in improved plant safety characteristics such as increased radiative heat rejection, higher solubility of fissile materials, and/or decreased fuel salt viscosity. Therefore, to provide reasonable assurance of achieving the FSFs, the fuel salt must be qualified by developing an adequate understanding of its properties so that its role in overall plant safety can be modeled.

Some accidents can cause the fuel salt's composition to leave its acceptable range so that it is no longer be capable of fully performing its role in achieving the FSFs. The potential for the fuel composition to change during operation is a distinctive characteristic of liquid fuel. Fuel salt qualification requires that the physical and chemical behavior of the fuel be adequately understood to model its role in overall plant safety. Therefore, the fuel salt properties necessary to model the radiological dose consequences of credible accidents that adversely impact the fuel salt composition must be considered as part of fuel salt qualification.

An acceptable method to provide reasonable assurance that there is a lack of unacceptable radionuclide release following a reactivity transient (i.e., achievement of the safety intent of the reactivity control FSF) would be to assess the stress that the transient places on the first credited radionuclide containment layer. If the normally salt-wetted containment layer remains intact, then the fuel salt cannot have placed unacceptable stress on exterior containment layers.

Having the ability to frequently add and/or remove fissile material from the active portion of the fuel salt prevents the need to add substantial quantities of reactivity as part of normal operation. The reactivity worth of MSR control systems tends to be much lower than that of solid fueled reactors, thus decreasing the impact of system failures. However, some MSR designs, especially those that include fertile/breeder salts, have the potential for large reactivity transients from fertile salt loop rupture or rapid draining accidents. Sufficient fuel salt property information must be available to adequately model the progression of any credible reactivity-derived transient.

A mechanistic accident progression evaluation provides one means to evaluate the stress that the fuel salt places on its container layer over the course of a reactivity-derived accident. Fuel salt can stress its container during an accident through changes in its state by

1. Increasing temperature, thus weakening the structural material,
2. Increasing pressure caused by boiling fuel salt,
3. Increased production of fission gases, thus raising cover gas pressure, and
4. Production of a pressure wave due to localized boiling.

Changes in composition over the course of an accident could result in container stresses (e.g., corrosion) that act over periods of time longer than accidents, so these would not be ordinarily be considered as part of accident progression analysis. However, temperature-related composition changes such as low-temperature phase separation / fissile material plate out can be an initiating or aggravating element of a reactivity derived accident.

Most fuel salts have boiling points well above the softening points of available structural materials. Consequently, hydraulic stress-based container creep and failure would occur well before pressurization due to bulk boiling. In addition, fission gas production is slow enough that container pressurization due to fission gas build-up over the limited duration of accident conditions would not provide a substantial stressor. The potential for an unacceptably large pressure wave that could cause the fuel salt container to fail as a result of reactivity transient provides an upper bound to the size of potentially acceptable reactivity transients.

3 LIQUID FUEL REGULATORY BASES

The central difference between liquid and solid fuel qualification derives from the fact that liquid fuel is not a fabricated product. Solid fuel qualification requires developing high confidence that fuel fabricated in accordance with a specification will adequately perform its operational and safety functions. However, liquid fuel salt properties depend upon the fuel's composition and state (primarily temperature). The relationship between fuel salt composition and its properties as a function of temperature provides the information necessary to model the fuel salt's role in overall plant safety. The liquid fuel salt's composition-dependent performance contrasts directly with solid fuel's fabrication-dependent performance.

Another major difference between liquid and solid fuel qualification derives from the fact that the composition of solid fuel is determined prior to use by its fabrication process, whereas the composition of liquid fuel can be adjusted during use. Measurement of the composition and consequent properties of the liquid fuel salt during use enables adjustment of the salt's composition to mitigate damage, and it provides information about the fuel salt composition approach to unacceptable regimes.

As with solid fuel, liquid fuel salt properties can degrade with use. Consequently, fuel salt qualification includes developing an adequate understanding of fuel salt's life-limiting degradation mechanisms that occur as a result of reactor operation. However, fuel damage in solid fuel as compared to liquid salt fuel is conceptually different. Fuel damage is a representation of the mechanisms by which changes in fuel properties result in challenges to the plant's operational or safety functions. For liquid fuel salts, fuel salt damage derives from changes in its composition, as Newtonian fluids cannot be mechanically damaged. Changes to the fuel salt composition can result in adverse changes to chemical and physical properties that challenge achievement of the FSFs.

Shifting of the fuel salt's redox potential outside of an acceptable window is a key mechanism for fuel salt chemical damage. Fuel salt can become much more corrosive with the addition of oxidative contaminants such as oxygen. In addition, the fission process is typically oxidative. Excessive addition of reductive contaminants such as alkali metals can result in plating out of fissile materials or formation of uranium carbide in core, which also challenges the FSF of reactivity control. However, unlike solid fuels, damage to liquid fuels can be repaired as part of normal operations. The fuel salt redox can be adjusted by adding reducing or oxidizing materials to the fuel salt. For example, refueling additions could be in a reducing state to compensate for oxidation during use.

Fuel salt can also become less capable of fulfilling its operational or safety functions because of physical property changes resulting from composition changes. For example, the fuel salt's melting and boiling points and viscosity are all dependent on the salt composition. Moreover, the solubility of actinides competes with those of other actinides, as well as lanthanide fission products. Thus, the homogeneity and phase of the fuel salt could change as its composition changes with use.

Another key difference between solid- and liquid-fueled reactors is the consequences of a breach in the fuel container. The cladding is an integral part of solid fuel. A crack in solid fuel cladding would only tend to release the portion of the fission gases that have escaped the fuel pellets/particles. The container for fuel liquid fuel would be qualified separately from the fuel itself. A breach in a liquid fuel salt container could release essentially all of the cover gases and the liquid fuel salt down to the level of the breach. Thus, a liquid salt–fueled reactor must either be able to continue to achieve the FSFs following leakage of a major portion of its radionuclides and coolant, or the probability of such a leak must be reduced to a sufficiently low level.

Some thermal-spectrum MSR designs for employing the Th/U fuel cycle include both fertile and fissile salt circuits. The fertile salt would only be subject to fuel qualification considerations to the extent that it contains fissionable nuclei. Although thorium is fissionable in a fast neutron spectrum, but it would not fission significantly in a thermal spectrum MSR. However, imperfect and/or delayed fertile salt processing results in small amounts of fissile material in the fertile salt circuit. In realistic designs, the fertile salt would contain much lower amounts of fission products, including much lower amounts of fission gases. While fertile salt can have a significant role in achieving the plant FSF by controlling reactivity through neutron absorption, it has comparatively low significance in terms of radionuclide retention and decay heat removal. As such, fertile salt in thermal spectrum MSRs would be anticipated to be qualified in a manner similar to other reactivity control systems reflecting the fertile salt's role in the overall safety of the facility.

Fast-spectrum MSR designs can also employ separate fertile/breeding salts. Depending upon design parameters, fast spectrum neutrons can cause significant amounts of fissions within the fertile salt (several percent of power generation). Fertile salt would be subject to fuel salt qualification considerations to the extent that it supports the fuel salt's role in achieving the overall plant FSFs.

Unlike solid fuels, liquid fuel salt does not have a mechanically determined lifetime, because liquids are not subject to mechanical damage. Moreover, as part of normal operations, the chemical composition of the fuel salt can be adjusted to mitigate property degradation. The fuel salt's lifetime is the period during which it adequately performs its operational and safety functions, when it

1. Contains adequate quantities of fissile materials,
2. Does not include too many neutron absorbers, and
3. Maintains acceptable thermophysical and thermochemical properties.

The key functional difference between liquid salt and other advanced reactor fuels is that fuel salt serves as both the nuclear fuel and the primary heat transfer media. Therefore, liquid fuel salt must meet the regulatory requirements associated with both purposes. The following two subsections describe the fuel and coolant aspects of the regulatory basis for liquid salt fuel.

3.1 Advanced Reactor Fuel Regulatory Basis

Higher level regulations specify the required performance of plant safety features. Plant safety features are SSCs credited to achieve safety functions [19]. The fuel salt supports the achievement of the safety functions by the plant safety features, in addition to partially performing FSFs itself. For example, fuel salt retains some radioactive materials under both normal and accident conditions, and it plays a significant role in supporting the ability of the other containment features to adequately retain other radionuclides. Thus, the fuel salt does not itself directly comply with the higher level regulations, but it enables the overall plant to do so.

The NRC's *Fuel Qualification for Advanced Reactors (Draft)* lists the regulations associated with advanced reactor fuel performance [4] referring both directly to the CFR and other applicable guidance documents. Specifically, the draft guidance refers to NRC Regulatory Guide 1.232, which provides advanced reactor tailored versions of the GDC from 10 CFR 50 Appendix A in the form of ARDC. Additional guidance documents (e.g., NUREG-0800) are also described as providing acceptable means to meet fuel performance requirements. However, the acceptance criteria provided in existing guidance documents for LWRs is highly focused towards mechanical performance issues, which are not relevant for liquid salt fuel.

Similarly, this document discusses the process to develop reasonable assurance that liquid fuel salt can fulfill its role in enabling the plant to meet the higher level regulatory requirements as described in the CFR.

Fuel-Related Advanced Reactor Requirements [4]

1. 10 CFR 50.43(e)(1)(i) requires that the performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof.
2. 10 CFR 50.43(e)(1)(iii) requires that sufficient data exist on the safety features of the design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.
3. 10 CFR 50.34(a)(1)(ii)(D), 10 CFR 52.47(a)(2)(iv), and 10 CFR 52.79(a)(1)(vi) require an evaluation of a postulated fission product release from the core into the containment.
4. GDC 2 requires that SSCs important to safety be designed to withstand the effect of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunamis, and seiches without losing the capability to perform their safety functions.
5. GDC 10 requires that specified acceptable fuel design limits (SAFDLs) not be exceeded during any condition of normal operation, including the effects of AOOs. ARDC 10 provides an alternative requirement of a specified acceptable radionuclide release design limits (SARRDLs).
6. GDC 26 requires, in part, the ability to achieve and maintain a safe shutdown under postulated accident conditions.
7. GDC 35 requires an emergency core cooling system that provides sufficient cooling under postulated accident conditions.

This section describes methods to demonstrate that liquid fuel salt adequately supports achievement of each of the safety intents of each fuel-related advanced reactor performance requirement.

3.1.1 Performance of Safety Features

To meet the safety intent of 10 CFR 50.43(e)(1)(i), the liquid fuel salt properties that support adequate performance of the plant safety features must be demonstrated through analysis, appropriate test programs, experience, or a combination thereof.

The fuel salt thermophysical and thermochemical properties provide the information necessary to model the salt's role in enabling plant safety features to perform safety functions. The fuel salt properties vary with the salt's composition and temperature. Therefore, the fuel salt properties must be determined across the range of temperatures and compositions that span potential operational and accident conditions. The potential range of fuel salt temperatures and compositions defines its performance envelope. Neither the fuel salt's thermochemical nor thermophysical properties depend on the isotopic composition of the fuel salt, so the property measurements can be made using stable isotopes and nonfissile and/or less radiotoxic isotopes for elements that lack stable isotopes. Analysis would be employed to interpolate the salt properties between measured points.

3.1.2 Sufficient Data

To meet the safety intent of 10 CFR 50.43(e)(1)(iii), the amount and quality of fuel salt property data must be adequate to support both normal and accident conditions, thus modeling the role of the fuel salt in supporting overall plant achievement of the FSFs. Furthermore, the fuel salt property measurements must span all conditions of normal operation, transients, and accident conditions, including the effects of the evolution of the salt composition during operation. Specifying the fuel salt's environmental performance envelope will be part of the fuel salt qualification process.

During normal operations, the fuel salt supports achieving the FSFs via containing the fissile and fertile nuclei that constitute the reactor fuel, including generating heat through the fission and radioactive decay processes and by serving as the reactor's primary heat transfer medium. Correct operation of the cover gas management system, which can contain a substantial fraction of the decay heat, is also part of normal operations. Start-up, shutdown, and maintenance states are also part of normal operations. The role of the fuel salt in achieving the FSFs under both normal and accident conditions is addressed in Section 2 of this document.

A sufficient amount of fuel salt property data must be developed such that plant performance models built from the data adequately demonstrate plant safety. During normal operations, enough salt property data must be available to enable assessment of stresses on the salt contacting barrier layers. Sufficient data must also be available to recognize when the fuel salt properties are approaching the limits of acceptable conditions. Acceptable fuel salt property values are those that enable plant safety features to support achievement of the FSFs. For example, fuel salt viscosity must be demonstrated to be adequately low during normal operation to enable start-up and operation of natural circulation-based decay heat removal systems at the beginning of a loss-of-forced-cooling accident. Additionally, enough fuel salt and cover gas composition data must be developed to enable adequate accident progression modeling, including mechanistic source-term calculation. Specific accident sequences and resulting property value requirements are design dependent. Adequate fuel salt property data also must be available to model the plant's achievement of the FSFs during extended maintenance outages, and more generally, until the fuel salt is transferred to an independent spent fuel storage facility.

To ensure that the fuel salt continues to be capable of performing its safety functions, its thermophysical and thermochemical properties must be determined. The thermochemical and thermophysical properties of fuel salts are fully determined by their chemical compositions and temperatures. Having an adequate database of fuel salt property variation with temperature and composition is central to being able to rely on periodic salt composition measurement to assess the fuel salt's current safety performance capability. However, at the current level of scientific understanding, the salt's thermophysical and thermochemical properties must be measured and correlated with fuel salt composition and temperature to develop an empirical database of fuel salt properties. Section 2 of this document discusses the relationship between the fuel salt properties and achievement of the FSFs.

The required frequency of and the allowed uncertainty in the measurements will be design dependent. The required measurement frequency will depend on how quickly the property value changes and the extent to which the changes affect safety performance. For example, fuel salt reactivity would be expected to require frequent small adjustments, just as the boron dilution is adjusted or rods are progressively withdrawn to compensate for burnup in LWRs. In contrast, salt viscosity varies little with small changes to salt composition, so much less frequent measurement may be required. The rate of composition and thus property change will vary with the power density of the salt and the mechanisms for fission products leaving the fuel salt. In addition, the rate of overall fuel salt composition change will be reduced in designs for which only a fraction of the fuel salt volume is within the critical region. For each particular design, the allowable range of fuel salt properties, as well as the measurement frequency for each property, will be contained in the plant’s technical specifications related to fuel salts.

In some instances, the fuel salt thermophysical properties will change little over the course of use. The total fission product inventory within the fuel salt as a result of escape, decay, and transmutation may remain sufficiently small as to have negligible effect on the fuel salt thermophysical properties. In such cases, it can be demonstrated that the fuel salt’s thermophysical properties containing bounding values of its built-in elements are similar to those of fresh fuel salt. This approach provides adequate information to enable modeling the heat transfer aspects of achieving the FSF under both normal and accident conditions.

Liquid fuel salt is not vulnerable to power rate of change mechanistic issues such as pellet-clad interaction. The fuel salt temperature closely tracks the local power density, and the fuel salt thermophysical properties depend directly upon its temperature. The large margin to fuel salt boiling effectively eliminates the potential to pressurize the fuel salt container under transient reactivity insertion conditions (if the fuel salt has an adequate volume for thermal expansion).

Applicants must perform accident progression evaluations with bounding fuel salt properties to establish required measurement uncertainties. Unlike solid fuel, key elements of the safety performance of liquid salt fuel generally improve during over temperature accident conditions. In particular, the ability to remove decay heat in liquid salt is improved by increasing its temperature by increasing radiative heat transfer and decreasing the salt’s viscosity.

The solubility of materials within the fuel salt is temperature dependent. Sufficient data on fuel salt component solidification and phase segregation must be provided to enable modeling of potential accidents in which the actinide content of the fuel salt exceeds its solubility limit under normal operations or overcooling accident conditions.

The quality of the fuel salt property data must be sufficient to enable modeling the role of the fuel salt in achieving the plant FSFs. The allowable uncertainty of the fuel salt property measurements will reflect the consequences of the uncertainty. The maximum allowable uncertainty in the fuel salt property measurements depends upon the safety consequences of the imprecision. Accident progression models using bounding values of the salt properties can be employed to assess the needed fuel salt property envelope. Because MSRs do not have any identified cliff-edge type accidents, inaccuracies in one element of the salt heat transfer can be traded off against safety margins and component lifetimes. For example, if the fuel salt viscosity vs. temperature curve is offset so that the viscosity is actually higher than predicted at a given temperature, then startup of natural circulation cooling would take longer, and the fuel salt would reach a higher temperature over the course of the accident, resulting in higher stresses on the containment layer. If the barrier retains adequate creep margin to continue to contain the radionuclides, then the property inaccuracy would not significantly impact achievement of the FSFs. However, the extended period of time at a higher temperature would decrease the remaining barrier lifetime.

3.1.3 Containment System Breach Accident Evaluation

Evaluating the consequences of an accident involving the release of a major portion of the radioactive material into containment is required to meet 10 CFR 50.34(a)(1)(ii)(D). This evaluation is also a major component of siting analysis per 10 CFR 100.11(a). For an MSR, releasing a major portion of the radioactive materials in the fuel salt into containment requires breaching the barrier layer around the fuel salt and evaluating the subsequent accident progression.

Breaching the containment layer that is in contact with the fuel salt is the first step towards releasing radionuclides into the environment and thereby failing to achieve the FSF to retain radionuclides. Section 2.1.2 describes the fuel salt property information necessary to adequately model radioactive material containment following a first barrier breach accident.

Breaching or bypassing the fuel salt–contacting containment layer will be within the design basis of MSRs, because a breach in a single containment layer is a credible occurrence. The fluid nature of the fuel salt and cover gas increases the potential radionuclide release fraction from a containment layer breach. A breach in a containment layer would allow essentially all of the gaseous radionuclides within that containment layer to escape into the next containment volume, and liquids down to the level of the breach would also escape.

The radionuclide content of the cover gas and the fuel salt will be design dependent. For example, radioactive materials that have been removed from the cover gas or fuel salt would not be available to be released. Overall, the fuel salt properties must be sufficiently well known to enable modeling of the plant's achievement of the radionuclide release design limits specified in its safety analysis (e.g., 10 CFR 50.67 limits for conventional siting or 10 CFR 20.1302 limits for flexible siting).

3.1.4 Withstand the Effects of External Events

GDC/ARDC 2 requires that SSCs important to safety be designed to withstand the effects of natural phenomena. Seismic events can directly couple to the fuel salt and affected SSCs. Sloshing of the fuel salt during an earthquake would cause stress on the fuel salt's container and supporting structures. Data on the fuel salt's density and viscosity provide the information necessary to model additional loads induced by earthquakes. Designs that include liquid systems coupled to the fuel salt must either incorporate design features to prevent sloshing-induced mixing of the fuel salt and coupled fluid, or there must be enough mixed fuel salt property data to model the consequences of fluid mixing. For example, a sufficiently large earthquake could cause hydroxide media from a cover gas scrubber to slosh into the fuel salt, resulting in adverse changes to fuel salt properties.

Other external events, such as high winds or flooding, lack the mechanisms that would directly affect the fuel salt's properties, and they do not directly impact achievement of the FSFs. The SSCs necessary to achieve the FSF during DBEs, including external events, would be safety-related, so they would be qualified separately from the fuel salt. For example, severe site flooding could unacceptably increase the heat transfer from improperly designed decay heat removal loops, causing the loops to freeze up and cease to perform their decay heat removal function. Losing the ability to adequately reject decay heat would violate an FSF, regardless of the fuel salt properties.

An MSR's safety response to other external events—including fires, floods, high wind events, loss of grid, wind-driven missiles—is not substantially impacted by the fuel salt properties except for events that are so severe as to cause the external barrier layers to fail. An example of such a severe event would be a wind-driven missile that punctures all of the external containment layers. MSR SSCs must be sufficiently robust to credible external events so that achievement of the FSFs would not be impacted by the fuel salt properties.

3.1.5 Adequate Radionuclide Retention UNDER Normal Operations and AOOs.

GDC/ARDC 10 requires that SAFDLs or SARRDLs not be exceeded during any condition of normal operation, including the effects of anticipated operational occurrences (AOOs). Liquid fuel cannot be mechanically damaged, and if conditions occur in which the fuel salt ceases to be in a liquid phase (freezing or vaporization, which would not be likely), there would be no irreversible damage to the fuel. Consequently, liquid salt fuel meets the safety intent of preserving the capability of the fuel to perform its safety functions under both normal and AOO conditions.

Nearly all of the radioactive material and coolant can escape a container from a breach. However, failure of a containment layer does not represent failure of the fuel salt. The plant-level safety intent of the fuel salt radionuclide release design limits in ARDC 10 can be conservatively represented by avoiding unacceptable radionuclide releases (above 10 CFR Part 20.1302 quantities) under normal operations or AOOs. Sufficient fuel salt property information must be provided to enable modeling the role of the fuel salt in developing reasonable assurance that radionuclide release probability is not unacceptably increased by any safety feature failure that is sufficiently likely to be an AOO.

Adequate information may not be available for all designs to ensure that breach or rupture of the radionuclide barrier in contact with the fuel salt during normal operations would have sufficiently low probability to not be an AOO. Inspection methods for fuel salt-wetted reactor vessels are not yet proven, and even coupons for materials in the creep temperature range, where degradation is dependent upon the applied stress, are not yet available.

For cases in which failure of the fuel salt's first containment cannot be shown to have adequately low probability, the fuel salt properties must be sufficiently well known to allow modeling of the containment failure accident progression with sufficient fidelity to demonstrate achievement of plant SARRDLs. The probability of occurrence does not change the set of fuel salt chemical and physical properties that must be known to adequately model the accident progression.

3.1.6 Ability to Achieve and Maintain Safe Shutdown

GDC 26 requires, in part, the ability to achieve and maintain a safe shutdown under postulated accident conditions. The specific set of postulated accidents will be design dependent.

Safe shutdown requires (1) continuing to achieve the FSFs without requiring active heat rejection, (2) ensuring that fuel and waste store temperatures do not increase, and (3) ensuring that container materials remain at or below design limits. The plant situation must also not be degrading, which means that it must not be on a trajectory towards failing to achieve an FSF. For example, the plant must not be headed towards freezing of passive decay heat rejection loops while the fuel salt continues to require convective cooling.

MSR fuel salts have strong negative temperature reactivity feedback coefficients. Doppler broadening of the nonfission resonance capture peaks provides much of the negative temperature reactivity feedback. However, the positive graphite feedback coefficient in graphite-moderated single-fluid ^{232}Th/^{233}U fuel salt cores can be sufficiently large in some designs (due to the change in ratio of ^{232}Th absorption to ^{233}U fission capture as the spectrum hardens within increasing graphite temperature) to balance the negative Doppler feedback [20]. While the lack of a strong overall temperature reactivity feedback could be a significant safety issue for some MSR designs, even for these designs, the fuel salt itself provides strong negative reactivity feedback. A potential fuel salt qualification issue would be the unavailability of sufficiently accurate ^{232}Th resonance absorption data to accurately assess the overall fuel salt Doppler coefficient for designs in which the overall reactor temperature feedback is not negative enough to overcome data uncertainties.

Also, liquid fuel salt would not mechanically impede insertion control elements into the reactor core. Consequently, the ability to achieve or maintain reactivity control would not depend on liquid fuel salt thermophysical or thermochemical properties for postulated accidents in which the fuel salt remains within the normal fuel salt container.

Rupture of the fuel salt boundary will be a postulated accident unless adequate evidence is available to show that its failure would not be credible. Moderated reactors require an optimized moderator and fuel salt configuration to achieve criticality. Consequently, thermal spectrum reactors will be well below critical following a fuel system breach. Fast-spectrum cores contain substantially more fissile material than thermal spectrum cores. Consequently, fast-spectrum fuel salts are vulnerable to becoming critical outside of the fuel salt circuit if they encounter increased neutron moderation, decreased neutron leakage, or decreased neutron absorption. Reactor designs that include a fertile salt would be vulnerable to potentially large reactivity transients as a result of loss of neutron absorption from leakage of the fertile salt. The fuel salt properties necessary to enable modeling of the overall fuel salt contribution to reactivity are its composition and temperature.

The fuel salt properties necessary to achieve the FSFs following a first-layer containment breach are discussed in Section 2 of this document.

3.1.7 Adequate Cooling Under Accident Conditions

GDC 35 requires an emergency core cooling system that provides sufficient cooling under postulated accident conditions. MSR fuel salt will also require cooling during postulated accident conditions.

MSR designs employ a diverse set of fuel salt cooling systems. MSRs may employ active cooling systems during normal operations. However, a key safety concept for MSRs is to not rely on active components to achieve safety functions under accident conditions. MSRs have strong negative temperature reactivity feedback, thus avoiding the potential for sustained overpower transients. Once an MSR is subcritical, natural circulation-based heat transfer will be key to providing adequate heat transfer. The same basic set of thermal and hydraulic parameters are needed to model natural circulation heat transfer performance in any Newtonian fluid: density, viscosity, thermal conductivity, and specific heat as a function of temperature.

3.2 Fuel Salt Coolant Regulatory Basis

The nuclear fuel aspects of the role of liquid salt fuel in demonstrating adequate safety performance is same as for any other reactor. Therefore, the regulatory basis for the nuclear fuel aspects of liquid salt fuel map directly to the regulations described in the NRC Advanced Reactor Fuel Qualification Draft [4]. However, liquid salt fuel also serves as the reactor coolant, so it would also be required to demonstrate compliance with the safety intents of the coolant-related GDCs. This section discusses the fuel salt information necessary to accomplish the safety intent of the coolant-related requirements.

To assess the fuel salt characteristics necessary to comply with the safety intent of the coolant-related GDCs, this document follows the methodology employed in the NRC Advanced Reactor Fuel Qualification Draft. First, the set of GDCs for which fuel salt properties could impact compliance are identified. Next, the characteristics of MSRs are evaluated against the specific wording of the GDCs. For those GDCs in which the wording aligns with the technical characteristics of MSRs, the fuel salt property information necessary to establish compliance with the safety intent of the GDC is then evaluated. For cases in which the LWR-centric nature of the GDCs makes complying with the specific wording inappropriate or unclear, this document applies the advanced reactor tailored wording provided as ARDCs in RG 1.232.

The containment layers surrounding the fuel salt are not part of the fuel salt itself, so they must be qualified separately. Therefore, criteria such as GDC 31, *Fracture prevention of reactor coolant pressure boundary*, are not within the scope of fuel salt qualification.

Liquid Fuel Salt Coolant-Related Design Criteria

1. GDC 4 indicates that SSCs important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operations, maintenance, testing, and postulated accidents, *including loss-of-coolant accidents*.
2. GDC 15 in part requires that the reactor coolant system be designed with sufficient margin that the design conditions of the reactor coolant pressure boundary are not exceeded during any condition of normal operation, including anticipated operational occurrences.
3. GCD 33 requires that a reactor coolant makeup be provided in the event of small breaks in the reactor coolant pressure boundary. As adding additional fuel salt to the reactor in the event of a break would tend to exacerbate accident consequences, GDC would not be directly applicable to MSRs. ARDC 33 provides additional explanation “as necessary to ensure that specified acceptable fuel design limits are not exceeded…”.
4. GDC 34 requires that a system be provided to adequately remove decay heat from the reactor core during normal operations at AOOs. ARDC 35 requires a similar system for postulated accidents.
5. GDC 38 requires the provision of a system to remove heat from containment following a loss-of-coolant accident.
6. GDC 41 requires the provision of a system to clean up the containment atmosphere following postulated accidents.

3.2.1 Withstand Effects of External Events

For MSRs, GDC 4’s requirement to accommodate the effects of a loss-of-coolant accident is similar to 10 CFR 50.34(a)(1)(ii)(D)’s requirement to evaluate the impact of a significant radionuclide release into containment. However, GDC 4 requires MSRs to continue to achieve their FSFs following such an accident. Section 2 describes fuel salt property information necessary to adequately model achievement of each of the FSFs following a fuel salt container breach accident.

3.2.2 Reactor Coolant System Design

GDC 15 requires that the coolant system be designed so that the design conditions of the reactor coolant pressure boundary are not exceeded during either normal operations or AOOs. ARDC removes the pressure from the boundary function to generalize the requirement to both low- and high-pressure coolants. GDC 15 addresses maintenance of the integrity of the coolant boundary under normal and AOO conditions. A key design issue for an LWR coolant pressure boundary is to have adequate strength to contain the coolant pressure. Also, under normal LWR operations, aging-related issues such as fatigue or crack initiation cannot become so severe as to cause the reactor's coolant pressure boundary material properties to go beyond their design boundaries.

A key design choice for MSRs that employ functional containment is the selection of which layer or set of layers comprise the reactor coolant boundary. The layer(s) credited to accomplish the safety function must meet the regulatory requirement of not exceeding their design conditions under normal operations or AOOs. The low reactor pressure (as a result of the high fuel salt boiling point) substantially reduces the coolant boundary strength requirement. If the normally salt–wetted boundary is not credited to accomplish the safety function, then it conceptually becomes a flow guide analogous to the core barrel in LWRs.

Fuel salt properties can cause contacted fuel salt containers to exceed their design conditions via corrosion and/or erosion. Halide salt corrosion of structural alloy materials is dominated by oxidation. Significant structural alloy erosion requires the suspension of hard particles in the salt. Hence, for designs that credit the salt-wetted boundary, an MSR's fuel salt system must be designed such that development of oxidative conditions during normal operations or AOOs will be detected and corrected before causing significant damage to its container. Section 2.1.1 discusses the fuel salt properties necessary to ensure the integrity of its container during normal operations. Neither corrosion nor erosion will progress significantly during the limited duration of AOO conditions.

3.2.3 Reactor Coolant Inventory Maintenance

GDC 33 requires that a system be available to supply additional reactor coolant to prevent exceeding SAFDLs in the event of small breaks in the reactor coolant boundary. ARDC 33 includes the concept that inventory control may not be necessary for some designs to ensure that fuel design limits are not exceeded. Liquid fuel salt cannot be mechanically damaged.

Small breaks in the fuel salt container have limited implications for fuel salt qualification, because the fuel salt property information necessary to model achievement of the FSFs is not significantly impacted by whether a small amount of fuel salt has been spilled.

Small breaks in the fuel salt heat exchanger would tend to cause unfueled coolant salt to flow inward into the fuel salt loop. Adding materials to the fuel salt could have deleterious effects on the ability of the fuel salt to perform its role in supporting achievement of the FSFs, depending upon the compatibility of the two fluids.

Adding fuel salt to maintain coolant inventory during a small break loss-of-coolant accident would generally not be helpful in achieving the FSFs. However, in some MSR designs, the operation of decay heat removal systems may be unacceptably impeded by the partial loss of fuel salt. For example, a DRACS may have its fuel salt heat exchanger near the top of the reactor vessel. Lowering the fuel salt level might prevent effective heat removal by uncovering the heat exchanger.

For MSRs, the safety intent of GDC 33 would be achieved by requiring that systems be available to enable the fuel salt to continue to perform its heat removal FSF following small breaks in the coolant boundary. Systems must be provided, as necessary, for fuel salt to continue to adequately perform its cooling FSF following small breaks in its container. None of the systems would be permitted to deleteriously impact the fuel salt's heat transfer properties.

3.2.4 Residual Heat Removal

GDC 34 requires the provision of a residual heat removal system that will adequately transfer residual heat under normal operations and AOOs to prevent damage to the fuel and its container. While MSRs could employ forced circulation to provide residual heat removal during normal operations and AOOs, forced circulation will increase the heat transfer provided by natural circulation. Consequently, the limiting fuel salt properties will be those necessary for residual heat removal through passive natural circulation as required under ARDC 35. However, fuel salt cannot be mechanically damaged, so the relevant portion of GDC 34 and ARDC 35 is damage to the fuel salt container. While ARDC 35 allows fuel salt container damage to the point at which the damage becomes so severe as to prevent adequate cooling, little difference exists between deformation beyond design limits and deformation so severe as to prevent adequate natural circulation cooling for a liquid coolant, because the container design limits are selected functionally.

The natural convection heat transfer properties of fuel salt must be adequately well known to establish that the performance of the residual heat removal system would be adequate to prevent damage to the fuel salt container under both normal conditions and AOOs. The fuel salt container can be damaged by raising its temperature to the point that its strength decreases and the structure deforms beyond design limits. The natural convection heat transfer properties of fuel salt are discussed in Section 2.2.1 .

3.2.5 Containment Heat Removal

GDC 38 requires that a containment heat removal system be provided as necessary to maintain the containment temperature and pressure within acceptable limits following postulated accidents. For MSRs, the key postulated accident with the potential to raise the containment temperature and/pressure beyond acceptable limits is rupture of the fuel salt container. Both the fission gases and the fuel salt will contain substantial amounts of residual heat–producing material. MSRs will rely upon passive decay heat removal mechanisms following a leak or break in the fuel salt container. A fuel salt container breach accident is the same as the accident described from a radionuclide containment perspective in Section 3.1.3 . The fuel salt properties necessary to adequately model the residual heat removal under accident conditions are discussed in Section 2.2.2 .

3.2.6 Containment Atmosphere Cleanup

ARDC 41 requires that systems to control fission products and other substances that may be released into the reactor containment atmosphere be provided as necessary to maintain achievement of safety functions. MSR fuel salt properties must be sufficiently well known to provide the required information about the quantities and composition of materials released into the containment atmosphere during postulated accidents to enable modeling of the achievement of the FSFs. The fuel salt properties required include the generation of aerosols and the release of fission gases to the extent necessary to adequately model successful achievement of the FSF.

4 FUEL QUALIFICATION ASSESSMENT FRAMEWORK

Developing high confidence that fuel salt chemical and physical behavior are sufficiently well understood under both normal and accident conditions to enable conservative modeling of overall plant radiological dose consequences is similar to developing evidence that meeting the fuel salt performance parameter results in achieving the FSFs. One process for determining what evidence is required to evaluate the plant safety starts with the high-level goal of achieving the plant safety criteria under conservative assumptions. Employing conservative assumptions means performing safety adequacy analysis using the least advantageous credible values of the fuel salt properties. The high-level goal is then logically divided and subdivided into lower tier goals until the fulfillment of each lower tier goal can be directly demonstrated by evidence.

The same goal subdivision and fulfillment assessment process is also currently being applied to solid-fuel advanced reactors [4]. MSR fuel salt performance requirements include a portion of the information required for solid fuel. However, some of the solid fuel performance requirements describe fuel mechanical performance requirements that are not relevant to liquid salt fuel.

Solid fuel performance depends on a combination of composition and structure to provide adequate performance, whereas liquid salt fuel depends only on composition. Liquid salt is not a manufactured item. Hence, one of the two main branches of solid advanced reactor fuel qualification—namely, fuel manufacturing specification—does not apply. Liquid fuel salt's properties depend only on its current composition and state—primarily temperature. The fuel salt composition can be arrived at by any pathway.

The compositions of liquid and solid fuels will change with use. Many MSR designs include the capability to adjust the liquid fuel salt composition to keep its properties within acceptable bounds. From a safety adequacy perspective, liquid fuel salt's composition is only restricted by its impact on the plant's achievement of the FSFs. The fuel salt properties will change with use and with deliberate and accidental adjustments to its composition. A range of properties may result in the fuel salt adequately performing its role in achieving the FSFs.

4.1 Satisfaction of safety criteria under conservative assumptions

The top-level goal for fuel salt qualification is to satisfy the plant safety criteria under conservative assumptions. The primary safety issue arising from NPP operation is the potential for release of radioactive materials into the environment. Containment of radioactive materials is also the leading FSF. The supporting FSFs are important in that failure to achieve them will result in failure to adequately contain radionuclides. Hence, the role of the fuel salt in achievement of overall plant safety is through supporting the functioning of SSCs (including the fuel salt itself) that are credited to achieve the FSFs. From a requirements perspective, fuel salt may not unacceptably impede the adequate functioning of safety-related SSCs.

What constitutes unacceptably impeding adequate functioning of safety-related SSCs depends on the plant state. Under normal operations, fuel salt properties must support demonstration of adequate margin-to-design limits in order to prevent damage to safety-related SSCs. Under accident conditions, the fuel salt properties must not unacceptably impede safety-related SSCs such that they cannot adequately perform their functions.

Fuel qualification addresses the impact of fuel salt properties on achieving the FSFs during normal operation, AOOs, and DBEs. As such, qualification is limited to the fuel salt's impact on the performance of safety-related SSCs. The impact of fuel salt on other classes of SSCs (e.g., non-safety, or non-safety special treatment) is not addressed by qualification.

Unlike the current draft of the assessment framework for solid-fuels for advanced reactors [4, Goal 2.3], liquid salt fuel qualification does not separately specify the ability to achieve and maintain safe shutdown. Adequate reactivity control is an element of both normal operations and accident condition fuel salt criteria, but it is not specified separately as a fuel salt qualification issue. The fuel salt property issues important to achieving and maintaining safe shutdown are integral to its adequate performance under normal and accident conditions. The separate reactivity control issues identified for solid fuel reactors are based upon limiting mechanical damage to the fuel (e.g., maintain coolable geometry and ability to insert control rods), and liquid salt fuel cannot be mechanically damaged.

4.1.1 Margin-to-design limits under normal operations or AOOs

Fuel salt properties must support demonstration, with conservative uncertainty bias, that adequate margin-to-design limits for safety-related SSCs is maintained under conditions of normal operations or AOOs

The role that fuel salt plays in providing margin-to-design limits can be logically divided into developing adequate understanding of the following:

1. The fuel salt performance characteristics that result in sufficient margin from design limits for safety-related SSCs,
2. The relationship between fuel composition and fuel performance characteristics under normal and AOO conditions, and
3. The operational parameters (e.g., temperatures and power distribution) that constitute normal and AOO conditions.

4.1.1.1 Fuel salt performance characteristics

Developing adequate understanding of the fuel salt performance characteristics that result in providing and maintaining adequate margin from design limits under normal operations or AOO conditions for safety-related SSCs requires developing adequate understanding of the following:

1. The range of fuel salt properties that provide adequate margin from design limits for safety-related SSCs, and
2. The mechanisms and rates by which fuel salt degrades the performance of safety-related SSCs.

The higher-level requirement for adequate fuel salt performance characteristics is divided into two sub-tier requirements: those necessary for current performance, and those necessary to maintain adequate future performance.

Fulfilling the requirement to provide and maintain adequate margin from degrading the performance of safety-related SSCs depends on which SSCs are credited to perform safety functions. The same fuel salt at the same plant under the same operating conditions may or may not have acceptable performance characteristics, depending on the safety function allocation selected by the applicant.

A key decision for an applicant is whether the normally fuel salt–wetted layer would be credited as a safety-related SSC. As the components that comprise the normally fuel salt–wetted layer are anticipated to be replaced multiple times over the course of the plant lifetime, the applicant must determine whether they are (1) consumables that can be used to failure or (2) safety-related SSCs for which adequate margin from design limits must be maintained

Noncredited, Normally Wetted Fuel Salt Boundary

For designs that elect not to credit the normally fuel salt–wetted boundary as a safety-related SSC, the fuel salt would not be in contact with credited (i.e., safety-related) SSCs during normal operations or AOOs except during the limited periods following failure of the normally salt-wetted container, such as the time during which the fuel salt flows from the safety-related guard vessel or catch pan into the safety-related drain tank. Thus, for this design choice, fuel salt properties are required to provide adequate margin from damage to both the guard vessel and drain tank, but not the reactor vessel. The viscosity, decay heat generation rate, and temperature of the fuel salt provide adequate information about the fuel salt properties to assess the guard vessel or catch pan and drain tank margin from damage resulting from a fuel salt drain event under normal operations or AOOs.

Safety-Related, Normally Wetted Fuel Salt Boundary

For designs that do elect to credit the normally fuel salt–wetted boundary as a safety-related SSC, the fuel salt properties must result in adequate margin from the boundary design limits. The specific design limits for safety-related SSCs at MSRs will be an element of the plant’s safety analysis. MSRs operate far from any threshold type performance degradation mechanisms. For example, MSRs lack equivalents to rapid cladding oxidation or departure from nucleate boiling. Therefore, their container material degradation represents integrated damage accumulation during normal operations. For example, rather than an absolute maximum fuel salt temperature limit, high-temperature structural alloy performance degradation would be a result of the integrated effects of thermal, mechanical, chemical, and radiation stressors over time.

Fuel salt stresses the materials it contacts via mechanically, chemically, and radiation-based mechanisms. A credited fuel salt boundary has two basic design limits over its service lifetime during normal operations or AOOs, to maintain (1) adequate mechanical strength and (2) a non-brittle response to stressors that could be present during normal operations or AOOs (GDC 31). Using acceptable mechanical design rules and margins, the strength of the boundary must, with conservative bias to the modeling, be sufficient to

1. Result in adequately small deformation over the service lifetime, and
2. Result in a creep-rupture lifetime adequately beyond the service lifetime.

Adequate strength includes both yield strength and tensile strength. The component strength derives from its constituent material’s strength. Both aspects of strength can be adversely impacted by fuel salt properties. For example, component wall yield strength would be impacted by corrosive wall thinning. Wall thinning would be of most significance for thin-walled components such as heat exchanger tubing. Other thermally driven strength loss phenomena such as grain coarsening and/or dissolution of strengthening features in the alloy microstructure must also be accounted for in assessing the strength degradation. At temperatures sufficiently high to be within the creep regime, tensile strength reductions result in decreasing the material creep-rupture lifetime. Neutron irradiation of nickel-based alloys can significantly decrease the material’s tensile strength and thus its ductility. The fuel salt composition, geometry, and power density determine the neutron flux on the container material. Reactor designs that include significant neutron shielding between the fuel salt and the container may reduce the significance of the loss of creep-ductility. The container would still be considered fuel salt wetted if the shielding does not normally provide leak-tight containment (e.g., shielding blocks immersed in the fuel salt). The temperature of the fuel salt in contact with the container wall and the emitted neutron flux and spectrum are the key fuel salt properties for assessing radiation- and temperature-based degradation of the container's material properties.

The fuel salt boundary would become vulnerable to brittle failure if the ductile brittle transition temperature were to be raised sufficiently to be in the range of temperatures within normal operations or AOOs. Fatigue and stress corrosion cracking can also result in brittle type material failures. The fuel salt properties can promote boundary material embrittlement by all of these mechanisms. For example, the fuel salt viscosity and density are significant elements in flow-induced stress on / fatigue of heat exchanger tubes.

Adequate fuel salt thermochemical compatibility information with the structural alloy that comprises a credited, normally wetted fuel salt boundary must be available to conservatively predict the alloy corrosion rate to be able to predict the component strength loss resulting from wall thinning or other material property degradation mechanisms. The material compatibility information may be acquired via an appropriate experimental testing program or via in-situ material performance surveillance. If material coupons are an element of the surveillance program, then the coupons must be at a stress state equivalent to the monitored component, because corrosion rates can be impacted by the stress level of the material. Fuel salt chemical compatibility with the structural material can be significantly impacted by relatively small changes in some fuel salt properties. For example, the chemical state of tellurium changes from a surface deposit to a dissolved element based on the fuel salt redox state, which, in turn, can be changed by oxygen contamination of the fuel salt. Deposited tellurium has been shown to promote surface cracking of some high-temperature alloys [21]. In contrast, deposits of insoluble fission products onto the surface of the container material may have a protective effect. Sufficient data on the performance of the specific material combination within the allowable envelope of fuel salt composition within the normal and AOO temperature range are needed to assess performance acceptability.

The fuel salt is both the heat source and the heat transfer medium. Consequently, adequate alloy thermomechanical property information must be available to conservatively model the impact of the fuel salt's heat transfer on the container material properties. Time, temperature, and stress evolution of alloy thermomechanical properties can be determined through an appropriate experimental program or by relying upon appropriate material codification for a specific alloy.

The fuel salt is the source for the neutrons that can degrade the container's material properties. Hence, the neutron flux and spectrum emerging from the fuel salt must be known to conservatively predict the container material's property degradation. Adequate material response to neutron irradiation under service conditions is needed to be able to conservatively model degradation in the material properties.

Additional complexity is incurred if the credited container includes layers or coatings. The fuel salt temperature and radiation can result in solid-state chemical interactions (potentially generating brittle phases) and diffusive intermixing of the material layers.

Overall, fuel salt properties and operational conditions (e.g., neutron flux, temperature, stress) can have substantial impact on the performance of materials. The material property degradation mechanisms are progressive and interrelated. Relevant time periods for damage accumulation range from several hours to decades. Few structural alloy and fuel salt combinations have the necessary quantity and quality of information to conservatively predict component service lifetime. Even in the case of the MSRE, the loss of creep-ductility was a significant issue identified during post-startup that limited the reactor vessel's lifetime [22].

Substantial amounts of information about fuel salt container material interaction would be required for any fuel salt qualification effort that credits the normally salt-wetted container material as a safety-related component. The fuel salt's performance characteristics that must be within acceptable bounds to provide and maintain adequate margin from design limits during normal operations or AOOs are as follows:

1. Fissile material content
2. Redox condition
3. Viscosity
4. Density, and
5. Heat capacity

4.1.1.2 Adequate understanding of fuel salt composition relationship to performance characteristics under normal operations and AOOs

The fuel salt serves as both the source of fissile material and the heat transfer medium. Consequently, the fuel salt has required nuclear and heat transfer performance characteristics.

The fuel salt's contribution to overall plant reactivity derives from its isotopic composition and temperature. Similarly, the fuel salt's heat transfer performance derives from its elemental composition and temperature. License applicants must provide sufficient data on the relationship of the fuel salt composition to its heat transfer and reactivity feedback properties.

As with any other Newtonian fluid, the heat transfer parameters that are needed to understand fuel salt heat transfer performance are (1) heat capacity, (2) density, (3) thermal conductivity, and (4) viscosity—each as a function of temperature. Under specialized circumstances in which the fuel salt contains substantial quantities of bubbles (either due to sparging or fission gas evolution), the bubble fraction, gas composition, and relative velocity of the bubbles must also be known in order to calculate the resultant heat transfer and impact on reactivity feedback.

The fuel salt heat transfer properties are determined based on its elemental composition and state—largely temperature. The relationships between the elemental composition and thermophysical properties are complex for multicomponent ionic fluid mixtures such as fuel salt. DOE-NE is in the process of constructing a validated database relating fuel salt composition to its thermophysical and thermochemical properties as a function of temperature [23]. This database is intended to provide an acceptable means of relating fuel salt composition to its heat transfer properties.

The fuel salt isotopic composition, in conjunction with reactor physics models, will be used to establish the fuel salt reactivity feedback characteristics. Reactivity feedback will be impacted by the presence of bubbles in the fuel salt caused by the reduction in the effective speed of sound in the fluid. One mechanism for providing reactivity feedback is via thermal expansion of the fuel salt. Thermal expansion occurs at the speed of sound. Consequently, reactor physics models must adequately include the speed-of-sound reduction for designs in which the thermal expansion of the fuel salt is a necessary element for providing timely negative reactivity feedback.

MSRs may experience DBEs at any time. The safety-related SSCs must be able to adequately perform their safety functions throughout the course of the DBE. The fuel salt property limits for normal operations and AOOs will be set based on the requirements for performance during DBEs when only safety-related SSCs can be credited. Forced convection heat transfer enables the fuel salt to accept a wider range of thermophysical properties during normal operations and AOOs than would be acceptable under natural circulation cooling. Therefore, the specific limits for the acceptable fuel salt heat performance parameters will derive from DBE selection and progression evaluation.

4.1.1.3 Operational parameters that bound normal operations and AOOs

The operational parameter envelope specifies the environmental conditions and radiation exposure under which the fuel is required to perform. This goal is satisfied by specifying the environmental conditions (e.g., temperatures and power densities), exposure, and transient conditions that the fuel is expected to encounter under conditions of normal operation, including the effects of AOOs.

4.1.2 Margin to radionuclide release under accident conditions

Under accident conditions, the fuel salt properties must not result in so much degradation of the plant safety-related SSCs that they are unable to perform their functions. Liquid salt fuel itself cannot be mechanically damaged. Fuel salt properties are only dependent upon its composition—not its history. Even following extreme events such as vaporization, upon cooling, the fuel would not be different from fuel that had not been vaporized.

The fuel salt performance requirements under accident conditions can be divided as follows:

1. The fuel salt performance characteristics that result in adequate performance of safety-related SSCs throughout the duration of each DBE are defined.
2. Adequate information about the relationship between fuel composition and fuel performance characteristics under accident conditions is available.
3. The operational parameters (e.g., temperatures and power distribution) that constitute accident conditions are defined.

4.1.2.1 Fuel salt performance characteristics under accident conditions

Fuel qualification requirements depend on the potential accidents at the plant. Specific accident parameters depend on the details of the plant design. Fuel qualification requires understanding the role of the fuel salt properties in degrading the performance of safety-related SSCs throughout the duration of accident conditions.

The FSFs apply to any reactor. Accidents are conditions that challenge the ability of the plant to achieve an FSF to contain radionuclides, provide adequate cooling, and/or control reactivity. Consequently, the same fundamental accident types apply to any reactor. Therefore, a useful approach for developing general MSR accident properties is to extract the safety function from each accident type, possibly beginning with the accepted list of accident types for LWRs.

Chapter 15 of NUREG-0800 lists seven AOOs and postulated accident types:

1. Increase in heat removal by the secondary system
2. Decrease in heat removal by the secondary system

3. Decrease in reactor coolant system flow rate
4. Reactivity and power distribution anomalies
5. Increase in reactor coolant inventory
6. Decrease in reactor coolant inventory
7. Radioactive release from a subsystem or component

The same general types of accidents would be applicable to MSRs, albeit modified to reflect the ability to add or remove fuel during operation and the dual role of the fuel salt as reactor fuel and coolant.

1. Increase in heat removal by the secondary system
2. Decrease in heat removal by the secondary system
3. Decrease in fuel salt flow rate
4. Reactivity and power distribution anomalies
5. Increase in fuel salt inventory or fissile concentration
6. Decrease in fuel salt inventory or fissile concentration
7. Radioactive release from a subsystem or component

Fuel salt must be in contact with a safety-related SSC to degrade its performance. Note, *in contact with* includes coupling via radiation. The normally salt-wetted containment layer is the only SSC that is normally in sufficient contact with fuel salt to result in property degradation. However, under accident conditions, the fuel salt may come into contact with other SSCs, some of which may be safety related. The accident sequence discussion for fuel salt impacting safety-related SSCs is similar to that provided in Section 2 on the accident progression following the fuel salt contacting containment layer failure.

The impact of the of any of the accident types can be evaluated via the mechanisms by which they can adversely impact the performance of safety-related SSCs. The mechanisms by which fuel salt can degrade the performance of safety-related SSCs include the following:

1. Mechanical stress
2. Raising temperature
3. Lowering temperature
4. Changing temperature too rapidly
5. Radiation damage
6. Chemical reactions

Mechanical Stress

Fuel salt can produce mechanical stress on the SSCs that it impacts via both dynamic and static mechanisms. The properties necessary to model the force produced by flow are the salt density and velocity. The fuel salt properties necessary to model the fuel salt's velocity depend on the accident scenario. For example, the velocity of fluid emerging from a small leak could be a drip or a jet, depending on the pressure differential and the fluid viscosity. Therefore, fuel salt density and viscosity as a function of temperature are the fuel salt properties necessary to model induced dynamic mechanical stress on interacting SSCs. Static mechanical stress would be produced by a fuel salt pool in contact with an SSC. It would be necessary to know the fuel salt's density and the pool depth to model the static mechanical force produced.

The fuel salt's high temperature can also result in generating mechanical stress via thermal reactions with materials that come into contact with the fuel salt under accident conditions. For example, cooling water that contacts hot fuel salt would flash to steam, potentially generating substantial mechanical stress. Hot fuel salt can also ignite combustible materials. The fuel salt's heat transfer parameters and the total amount of thermal energy within the fuel salt must be known to adequately model the potential degradation of safety-related SSC performance as impacted by thermal reactions between the fuel salt and materials that it may contact during accident sequences.

Temperature Rise

Hot fuel salt will raise the temperature of materials with which it comes into contact. Raising the temperature of safety-related SSCs could be initiated by either removing too little or too much heat from the fuel salt. Removing too much heat from the fuel salt could result in loss-of-forced-flow cooling by producing local salt solidification and flow blockage.

The amount of temperature rise within the safety-related SSC for any thermal transient depends on the thermal contact parameters (e.g., time, temperature difference, thermal conductivity of materials). Furthermore, the amount of performance degradation for any particular SSC depends on both the particular materials involved and their temperatures. For example, spilling of a liquid fuel salt onto a stainless-steel catch pan would cause the pan's temperature to rise. A sufficiently large temperature rise would degrade the pan's functionality. The amount of temperature rise depends upon multiple parameters, such as the temperature difference between the fuel salt and the catch pan, the duration of the contact, the catch pan's thickness, the materials behind the catch pan, and so on. Heat generated within the salt while in contact with the catch pan could also become important for longer duration contact. Catch pans would either be designed to provide cooling for spilled fuel salt, or they would be sloped to drain spilled salt to a tank for cooling. Modeling the temperature rise and consequent performance degradation of SSCs that come into contact with fuel salt during accident conditions requires knowledge of the fuel salt's heat transfer and flow parameters, as well as its heat generation rate for longer duration contact.

The vapor phase portion of the fuel salt will also contain significant quantities of thermal energy both from decay and prior contact with the hot liquid fuel salt. Under accident conditions, the vapor phase portion of the fuel salt may come into contact with external safety-related SSCs. Sufficient knowledge of the quantities and types of vapor phase fuel salt materials, as well as their temperature and heat transfer properties (and radionuclide deposits from the vapor phase), will be necessary to model temperature-based degradation of the safety-related SSC performance.

Lowering Temperature

Lowering the temperature of safety-related SSCs may degrade their performance. In most situations, contact with fuel salt will increase SSC temperatures. However, during extended accident sequences, the fuel salt may no longer generate sufficient decay heat to keep materials above their ductile-to-brittle transition temperature or to prevent freeze-up of natural circulation heat transfer loops. This could result in cooling safety-related SSCs enough to impede their functioning. Fuel salt heat transfer property, thermochemical and phase separation information, as well as composition information, will be required to model long-term shutdown-based accidents.

Rapid Temperature Change

Contact with hot fuel salt in either liquid or vapor phase may cause rapid local temperature increase that can impede the ability of safety-related SSCs to perform their functions. While the stainless steel that is likely to comprise MSR catch pans and other containment structures is generally resilient to thermal shocks, temperature distributions across structures may result in unacceptable mechanical distortions. For example, rupture of the cover gas piping may result in hot gases contacting containment seals, thus resulting in temperature differences beyond design limits. The fuel salt heat generation and heat transfer properties provide the information necessary to model the role of the fuel salt in the potential accident sequences.

Radiation Damage

The radiation produced by the fuel salt may cause safety-related SSCs to inadequately perform their roles in achieving the FSFs. For example, the fuel salt may activate the heat transfer fluids within residual heat removal systems to such an extent that coolant leaks become safety significant. The neutrons emerging from the fuel salt may also unacceptably damage safety-related SSCs, including those not normally in contact with fuel salt. The fuel salt properties necessary to model radiation-induced degradation in safety-related SSC performance would be the location, flux, and spectra of the emerging neutrons, as well as the exposure duration.

Chemical Damage

The fuel salt is at a low chemical potential energy, so it would not react vigorously with any material. However, contact with some materials may cause the fuel salt to become substantially more corrosive, potentially challenging the achievement of the FSFs. For example, if the fuel salt were to come into contact with electropositive materials such as alkali metals, then the fuel salt would become strongly reducing, potentially causing the actinides in the fuel salt to form carbides with the core graphite and thus challenging the reactivity control FSF. Alternatively, if the fuel salt were to contact significant amounts of electronegative materials such as oxygen, then the fuel salt could become strongly oxidizing, resulting in corrosion of its containment layers. Knowledge of the fuel salt redox condition would be necessary to demonstrate that the chemical reactions with the fuel salt are not producing unacceptable degradation in the performance of safety-related SSCs.

4.1.2.2 Adequate understanding of the fuel salt composition's relationship to performance characteristics under accident conditions

Accidents extend the temperature range over which the relationship between fuel salt composition and performance characteristics must be known. Molten salt performance characteristics are not anticipated to exhibit any threshold type characteristics for hundreds of degrees above normal operating temperatures, thus providing substantial margin for property uncertainties. The key safety issue is to ensure that adequate fuel salt property data exist to span DBE temperatures, which may be substantially higher than the anticipated operating temperatures.

4.1.2.3 Environmental conditions anticipated under design basis events

The operational parameter envelope reflects the environmental conditions and radiation exposure under which the fuel salt is required not to damage safety-related SSC performance to an unacceptable level. This goal is satisfied by specifying the environmental conditions (e.g., temperatures and power densities), exposure, and transient conditions that the fuel is expected to encounter under accident conditions.

5 SUMMARY OF THE ROLE OF FUEL SALT PROPERTIES IN ACHIEVING FSFs

Fuel salt performance parameters are determined by the salt's composition and state. The values of each fuel salt parameter have different degrees of influence on the achievement of the FSFs. Discussions of the role of each specific fuel salt property in achieving the FSF are provided throughout the body of this report. Tables 4 and 5 provide a subjective, integrated summary of the influence of specific performance parameters on achieving each of the FSFs under normal operations, including AOOs and DBEs.

The use of the term *major* in the tables indicates that variations in the property value have a direct and substantial impact on achieving the FSF. For example, fuel salt viscosity is judged to have a major impact on removing heat from the reactor and waste stores, because viscosity is a central aspect of heat transfer. The use of the term *minor* indicates that variations in the property value have an indirect or small impact on achieving the FSF, and the term *negligible* indicates that variations in the property value have an insignificant impact on achieving the FSF. For example, fuel salt viscosity is judged to have a minor impact on limiting the release of radioactive materials from the fuel salt under normal operations and AOOs because viscosity primarily acts through the long-term damage mechanism of the fatigue of fuel salt boundary components. Similarly, the fuel salt's elemental composition is judged to have a negligible effect on controlling reactivity, as the nuclear properties are largely independent of the outer electron configuration. While some inelastic neutron scattering parameters are indeed dependent on electronic bonding, this is judged to be insignificant in liquid salt. The use of the term *varies* indicates that the impact of the parameter is substantially determined by specific design features or accident conditions. Whether damage to a fuel salt–wetted container results in a minor leak that freezes and self-plugs or a significant radionuclide release varies with multiple factors, including the freezing characteristics of the salt.

Separate tables are provided for normal operations, including AOOs and DBEs, because of the differences in the impacts of fuel salt parameters in the restricted range of conditions in normal operations and AOOs when both safety-related and non-safety–related SSCs can be considered vs. the wider range of DBE conditions when only safety-related SSCs can be credited. For example, fuel salt's radiative emission properties have only minor impacts on heat transfer during normal operations when forced flow convective heat transfer is available. However, at higher temperatures (especially when forced convective cooling is unavailable), radiative emission can provide a substantial fraction of heat transfer. It should be noted that, although the tables are intended to provide a convenient starting place to assess the importance of fuel salt parameters in achieving the FSFs, any particular plant may have design features that change the importance of particular parameters for that plant. For example, radiative coupling of heat from spilled salt can be a primary heat transfer mechanism in designs that rely on an RVACS type of heat rejection for spilled fuel salt. In contrast, changes in emissivity may have negligible importance to designs that allow spilled fuel salt to flow into drain tanks that include immersed natural circulation heat exchangers or PRACS-type heat removal. The technical basis columns in both tables provide brief notes and caveats about the parameter summary evaluations.

Table 4 Salt Properties Supporting Achievement of FSFs Under Normal Operations and AOOs

Fuel salt property	**FSF 1 – limit release of radioactive materials**	**FSF 2 – remove heat from reactor and waste stores**	**FSF 3 – control reactivity**	**Technical basis**
Elemental composition	Major	Major	Negligible	Chemical interaction with container / cover gas
Isotopic composition	Major	Negligible	Major	Radionuclide content Nuclear properties
Viscosity	Minor	Major	Negligible	Heat transfer parameter
density	Minor	Major	Major	Heat transfer parameter and quantity of fissile material
Heat capacity	Minor	Major	Minor	Heat transfer parameter
Liquidus temperature	Minor	Negligible	Negligible	Not near freezing except small stagnant lines with limited fission products (if any)
Boiling temperature	Minor	Negligible	Negligible	Not near boiling except small stagnant lines (if any)
Thermal conductivity	Minor	Major	Negligible	Heat transfer parameter
Particulate content	Minor	Negligible	Negligible	Enhanced erosion
Redox potential	Major	Negligible	Minor	Primary corrosion mechanism Potential mechanism for actinide deposition in core
Emissivity	Negligible	Minor	Negligible	Small element of heat transfer
Vapor pressure	Minor	Negligible	Minor	Impacts release of xenon from core also radionuclide escape from small leaks
Phase stability	Negligible	Negligible	Negligible	Not near phase stability boundaries
Bubble content	Negligible	Minor	Major	Reactivity feedback parameter
Aerosol formation	Minor	Minor	Negligible	Snow can block gas flow and thermally insulate structures
Surface tension	Negligible	Negligible	Negligible	Minimal impact during normal operations or AOOs

Table 5 Salt Properties Supporting Achievement of FSFs Under DBEs (especially fuel salt spills)

Fuel salt property	FSF 1 – limit release of radioactive materials	FSF 2 – remove heat from reactor and waste stores	FSF 3 – control reactivity	Technical basis
Elemental composition	Major	Major	Negligible	Chemical interaction with materials in containment
Isotopic composition	Major	Major	Major	Decay heat source Nuclear properties
Viscosity	Minor	Major	Minor	Heat transfer and fuel spreading parameter
Density	Minor	Major	Major	Heat transfer parameter and quantity of fissile material
Heat capacity	Minor	Major	Minor	Heat transfer parameter
Liquidus temperature	Varies	Varies	Negligible	Flow freezing and plugging
Boiling temperature	Minor	Minor	Negligible	Container failure below boiling point
Thermal conductivity	Minor	Major	Negligible	Heat transfer parameter – key if frozen
Particulate content	Minor	Minor	Negligible	Enhanced erosion Natural convection fouling
Redox potential	Major	Negligible	Major	Primary corrosion mechanism Potential mechanism for actinide deposition in core
Emissivity	Negligible	Varies	Negligible	Element of heat transfer whose impact can be blocked
Vapor pressure	Major	Major	Negligible	Quantity of releasable radionuclides Heat transfer issue
Phase stability	Major	Major	Major	Plate out of actinides and other radionuclides
Bubble content	Negligible	Minor	Major	Reactivity feedback parameter
Aerosol formation	Major	Major	Negligible	Snow can block gas flow and thermally insulate structures
Surface tension	Minor	Minor	Negligible	Salt flow and spreading parameter

6 CONCLUSIONS

Adequate understanding of fuel behavior is central to being able to develop conservatively biased, adequate fidelity models of the potential radiological dose consequences of both solid- and liquid-fueled reactors. The performance-based safety metrics embodied in the FSFs are applicable to any reactor. The requirement to limit the release of radioactive materials into the environment under both normal and accident conditions is also applicable to any reactor.

Fuel qualification is a process that develops high confidence that fuel salt properties are sufficiently well known to model their impact on the overall plant's achievement of the FSFs during normal operation, AOOs, and DBEs. The role of the fuel salt in achievement of overall plant safety is through supporting the functioning of SSCs (including the fuel salt itself) credited to achieve the FSFs, or from a requirements perspective, fuel salt must not unacceptably impede the adequate functioning of safety-related SSCs.

Liquid and solid fuel have substantial chemical and mechanical differences that change the implementation of fuel qualification. Liquid fuel serves as both the nuclear fuel and coolant, so the fuel salt must comply with both fuel and coolant requirements. Liquid fuel salt also does not include an exterior radionuclide retention layer (aka cladding). Consequently, failure of an MSR's first containment layer can release a substantial fraction of the liquid and gaseous radionuclides into the next containment layer. In addition, unlike solid fuel, liquid fuel salt does not retain significant quantities of gaseous fission products, thus increasing the releasable fraction of fission gases from a breach. Solid fuel relies upon its structure (at both the macroscopic and microscopic levels) and composition to perform its safety functions. The solid fuel structure depends on both its fabrication process and use history. In contrast, liquid fuel salt properties depend only on the fuel salt's composition and state. The lack of structural dependence means that the fuel salt properties are not dependent on its synthesis method or use history. Furthermore, the composition of liquid fuel salt can be adjusted during use to remain within acceptable bounds.

Fuel salt properties are acceptable for use in normal operating conditions and AOOs as long as they support demonstration of adequate margin-to-design limits for safety-related SSCs. Fuel salt properties are acceptable for use under accident conditions if they do not result in unacceptable damage to safety related SSCs to the point that they cannot adequately perform their functions.

Fuel salt qualification is an element of MSR safety adequacy demonstration. Fuel salt qualification couples with accident progression evaluation and safety-related SSC selection to enable demonstration of achievement of the FSFs. Understanding the relationship between fuel salt composition and properties is key to fuel salt qualification. The precision with which the properties must be known depends on the specific accident sequences and the SSCs credited to perform safety functions. Consequently, fuel salt qualification requirements will differ from one MSR to another.

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