Module 7: Safety Concepts and Fuel Qualification

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Module Focuses on MSR Safety Concepts and Fuel Qualification

- Organized around SSCs employed to accomplish fundamental safety functions (FSFs)
  - Regulatory issues and accident progression covered other modules
  - Applicable to both commercial facilities and research and test reactors
- Draws from recent DOE-NE sponsored activities on MSR accident initiation and accident progression phenomena
  - ORNL/TM-2019/1246 – Molten Salt Reactor Initiating Event and Licensing Basis Event Workshop Summary
  - ORNL/TM-2021/2176 – Molten Salt Reactor Fundamental Safety Function PIRT
- Includes issues from NRC sponsored report on MSR technical and safety considerations outside of guidance documents – ORNL/TM-2022/2555
- Includes insights drawn from draft of the ANS MSR design safety standard
  - Proposed standard undergoing balloting and review
- Describes the process for liquid fuel qualification
  - Compares with advanced reactor solid fuel qualification (NUREG-2246)

MSRs Have the Same Fundamental Safety Functions as Any Nuclear Power Plant

1. Contain the radionuclides
   - Functional containment important concept
2. Provide adequate cooling
   - Both active and used fuel
3. Control reactivity

- Safety functions must be achieved under both normal operations, including AOOs, and design basis accidents
  - Designs must consider mitigating consequences of beyond design basis events
- Safety functions must be achieved throughout the plant lifecycle

Preventing Unacceptable Releases of Radioactive Materials is the Principal Safety Function

- Challenges to containment and the SSCs employed to prevent and/or limit releases are distinctive to MSRs
  - Functional containment provides substantial flexibility on how to achieve containment
  - Low pressure systems do not require massive, high-strength containments
    - Protection from external events and radiation shielding necessitate substantial structures
- Different license applicants can elect to credit different SSCs to perform containment for the same plant design
  - Normally salt-wetted layer may or may not be credited to provide containment under accident conditions
- Performance requirements for normally salt-wetted, credited containment layers are substantially different than for those that do not contact salt during normal operations
  - Accident response may include removing fuel salt from critical circuit
  - Containment, cooling, and criticality control provided by guard vessel or storage/drain tank
- Tritium can be released through intact containment layers during normal operations
  - Mitigation methods covered in waste streams module

Fission Gases, Vapors, and Aerosols Are Primary Labile Radionuclides

- Nearly all radionuclides in head space can be released through a containment layer crack in connected designs
  - Large, early releases of fission gases to the environment would be unacceptable
- ~40% of fissions have fission gas in decay chain
  - Almost 80% of heat load is generated in first hour
  - <1% of total fuel salt heat load after 2-days
- Fission gases have low solubility in fuel salt
- Amount of fission gas release substantially impacted by sparging to remove ^{135}Xe
  - Much less important in fast spectrum systems
  - Most ^{137}Cs is daughter of ^{137}Xe ($t_{½} \approx 3.82$ min) so forms in head space
- Aerosols can be generated by multiple mechanisms – e.g., splashing, decay recoil, noble metal release
  - Volatile species also release - e.g., CsI

Releasable Stored Energy Bounds Potential Accidents

- Key issue is establishing that a particular accident is the maximum credible accident (MCA)
- Credible accidents at MSRs cannot be larger than the complete release of the stored chemical and physical energy
  - Severe, highly improbable, external events can result in more extreme accidents
- Primary rationale for abandoning MCA for power reactor licensing was the potential for large accidents at LWRs that could not be contained
  - Maximum hypothetical accident remains basis for research and test reactor safety evaluation
- Maintaining low-pressure is key to continuing to provide adequate containment
  - Avoiding significant quantities of phase change material (e.g., water) and combustible materials key to avoiding potential to generate high pressure or significantly damage safety-related SSCs
- MCA can be represented as a combination of reactor vessel failure accompanied by pump rotor lock and station blackout
- Safety objective is being able to provide reasonable confidence that the FSFs will continue to be achieved following the MCA

MSRs Rely Upon Low-Pressure to Limit Driving Force For Radionuclide Dispersal

- Fuel salt is at low chemical potential energy so will not chemically react vigorously with containment materials
  - Fuel salt is in maximum reactivity configuration
- Fuel salt is at high temperature so can react physically with containment materials
  - Reactions of concern are phase change and ignition/combustion
- MSRs are anticipated to avoid use of significant quantities of phase change materials, high pressure, or combustible materials near containment
  - Necessitates secondary coolant loop to connect to power cycle
  - Component cooling performed with non-water-based mechanisms
    - MCA of MSRE involved simultaneous structural cooling water leak (optimal amount for maximum pressure) and abrupt, complete fuel salt system rupture

MSR Accident Progression Aligns With Barrier Failure Analysis

- Failure of interior barrier causes radionuclides to contact next barrier layer
- Stress on next barrier layer is physical (as opposed to chemical) for realistic barrier materials (e.g., stainless steel)
  - Corrosion of structural barriers is slow compared to accident durations
- Temperature and mechanical force (pressure) are key barrier stressors
  - Barrier stress during accident is independent of chemical composition of leaked material
- Thermo-mechanical analysis can be employed to assess barrier stress
- Accident success criteria based upon minimally stressed barrier layers
  - Adequate heat rejection and reactivity control under accident conditions also required

Lines of Defense Analysis Generalizes Barrier Failure Analysis to All Accident Sequences

- Lines of Defense methodology has wide applicability to reactor safety evaluation
  - Key requirement is to have an adequate number of sufficiently strong barriers based upon the potential accident consequences
  - Applied to the EU molten salt fast reactor – DOI: 10.1051/epjn/2019031
  - Currently being employed for both Jules Horowitz (LWR) and ASTRID (SFR)
- MSRE Safety Analysis for ^{233}U operation was based upon adequate barrier performance under identified accident conditions
- Provides deterministic method for assessing adequate defense-in-depth based upon potential accident consequences and barrier strength
  - Probabilistic insights can be used to provide insights onto barrier performance

Passive Safety System Performance Poorly Represented By Failure-on-Demand Models

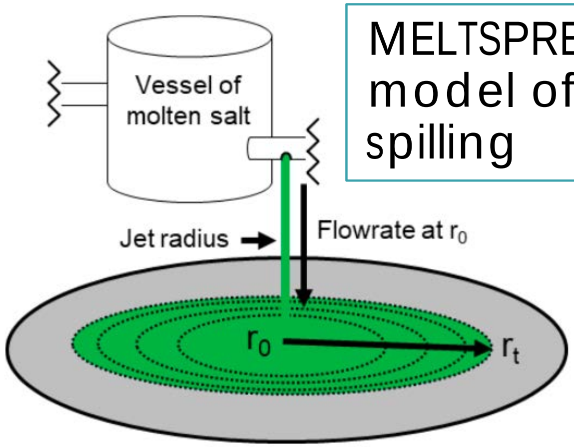
- MSRs lack cliff-edge type accident phenomena avoiding need for rapidly responding safety systems
  - Fuel salts are hundreds of degrees from boiling
  - Unacceptable reactor vessel creep requires substantial temperature excursions for hundreds to thousands of hours
  - Liquid-fuels cannot be mechanically damaged
    - MSRs can be designed as prompt burst type reactors
- MSR safety responses tend to be passive and progressively initiated – e.g., startup of buoyancy-driven natural-circulation cooling
  - Failures tend to be partial and time dependent – e.g., slower initiation or reduced flow
  - Do not match the failure on demand models employed for rapid, actively-driven safety systems

Separate and Integral Effects Tests Remain the Foundation for Evidence of Adequate Performance

- Most safety-significant phenomena for MSRs are well known
  - Historic MSR program
  - Use of halide salts in industry
- MSR accident responses may rely on complex, interrelated phenomena for which there is much less experimental evidence
  - Example – Heat transfer from a spilled salt pool depends on the salt surface condition and intervening materials as well as the natural circulation based heat transfer loop
    - Crust or dross formation on spilled salt, atmospheric mists, and/or snow formation on receiving heat exchanger all could have significant impact on heat transfer
  - Designers likely to minimize impact of uncertainty through plant design – e.g., by providing a floor drain to a cooled, subcritical tank
- DOE-NE continues to perform fuel salt spill experiments and modeling

Unfueled FLiNaK flowing through floor drain

ANL/CFCT-21/22; DOI 10.2172/1830306



MELTSPREAD model of salt spilling

ANL/CFCT-22/15; DOI 10.2172/1873509

Neutron Embrittlement and Corrosion are Key MSR Structural Material Challenges

- Requirements for high-pressure reactors focus on adequate structural material strength and degradation in strength over time (creep-fatigue)
  - Physics and chemistry of MSRs results in different dominant degradation mechanisms – radiation damage and corrosion
  - Surveillance coupons likely to be important element of establishing adequate performance
    - DOE-NE currently developing MSR surveillance specimens and procedures
- Material degradation consequences are also substantially different
  - Even brittle MSR vessel rupture may not generate a substantial pressure stress on next containment layer
  - Leaks and result in release of all fission gases and liquid fuel down to leak level
  - Bolt creep and gasket corrosion make flanged connections prone to leaks
    - High fissile content fuel salt (e.g., fast spectrum MSR fuel salt) could become critical following leaks/spills due to increased moderation

MSRs May Be Defueled As an Accident Response

- Defueling is a design option – FSFs must be achieved within or outside of active circuit
- Multiple alternative methods proposed to remove fuel salt from active circuit

1. Normally open drain in parallel with refilling pump
   - Pump fills reactor vessel faster than drain during normal operation
   - Fuel salt accumulates in drain tank if pump ceases to function
2. Gas pressure differential with goose neck below reactor vessel
   - Gas accumulator employed to blow fuel salt into storage tank
   - Latched (electro-magnetic), mechanically-driven gas-valve in head space
3. Freeze valve with gravity drain
   - Not likely to freeze full flow path (lesson learned from MSRE)
     - Excessive stress on components due to freeze-thaw
     - Slow activation
   - Mechanical valve element frozen in place (e.g., poppet ring frozen)
   - Loss of active cooling opens valve

Liquid Salt Fuel Enables Substantial Flexibility in Decay Heat Rejection and Reactivity Control

- Natural convection passive decay heat rejection loops
  - Direct Reactor Auxiliary Cooling loops (DRACS)
  - Reactor Vessel Auxiliary Cooling (RVACS)
- Liquid salt filled second containment layer
  - Primary circuit immersed in large tank/pool of coolant salt
  - Large volume of liquid salt provides thermal storage and radiation shielding
- Fuel salt displacement as shutdown mechanism
- Sparging as reactivity control mechanism
  - Inert gas bubbles provide small negative reactivity

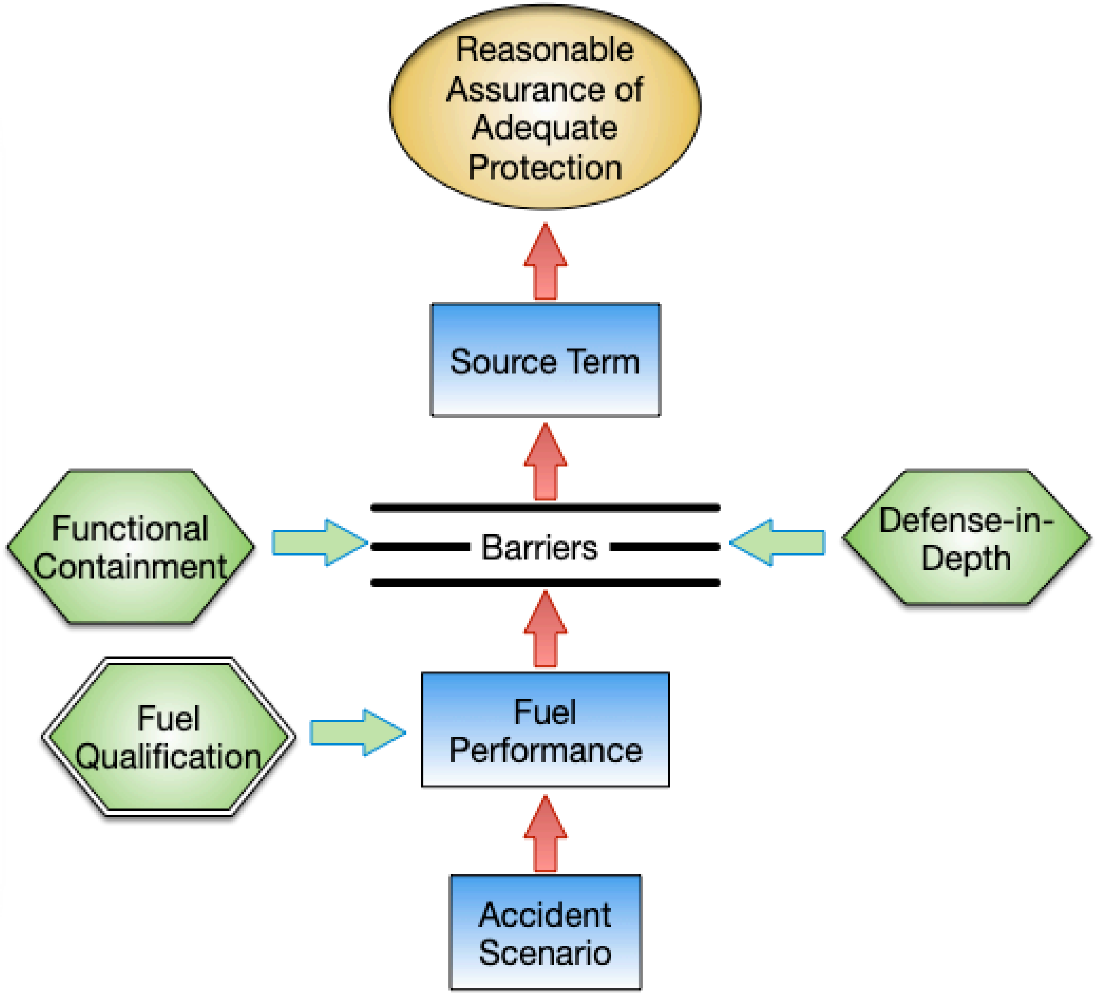
Performance Based Safety Adequacy Evaluation is Key for Efficient MSR Evaluation

- Fundamental safety concepts are the same for all reactors
- Liquid fuel salt results in substantial technical differences in how the FSFs are achieved
  - Widely varying SSCs
- Performance-based rules embody the objective rather than prescribing the implementation method
- Prescriptive rules are based upon the technologies available when written
- MSR technologies and configurations continue to rapidly evolve
  - Substantial effort would be required to developed prescriptive rules for each configuration

Fuel Qualification is an Element in Achieving Sufficient Understanding of Fuel 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."*

- NRC Presentation on Possible Regulatory Process Improvements for Advanced Reactor Designs, August 3rd, 2017 (ML17220A315)



Liquid Fuel Has Substantial, Fundamental Differences From Solid Fuel

- Liquid salt fuel
  - Serves as nuclear fuel and primary heat transfer media
  - Must meet requirements for both purposes

Liquid Fuel	Solid Fuel
Chemically damageable - may be reparable during use	Mechanically damageable
Composition may be adjustable during use	Composition set prior to use
Properties depend on composition and state	Properties depend on fabrication process
Container breach could release nearly all radionuclides	

Common Salt Properties and Plant Functions Enable a General Liquid Fuel Salt Evaluation Method

- Specific accident sequences are design dependent
- Basic operational and fundamental safety functions are common to any nuclear power plant
- Halide salt characteristics are common to any MSR
  - High boiling points (low pressure)
  - Low Gibbs free energy (low chemical potential energy)
  - Natural circulation heat transfer properties
- Fuel salt interacts with its container layers via common chemical and physical mechanisms - for example via
  - Thermal energy transfer, chemical reactions, and mechanical processes

Key Issue is “What Constitutes Fuel Salt?”

- Fuel salt does not come in discrete elements (rods or assemblies) and moves independently of its container during normal operations
  - Cladding and fuel assembly structures are qualified as part of solid fuel
- Fuel salt includes all of the material containing fissionable elements or radionuclides that remain in hydraulic communication, but does not include the surrounding systems, structures, or components
  - Salt vapors and aerosols remain part of the fuel salt system until they become adequately trapped
  - Container corrosion products become part of the fuel salt
- Fresh and used fuel salt in on-site storage are within scope

Functional Containment is Important to How MSRs Provide Adequate Radionuclide Retention

- Barrier performance must be degraded to release radionuclides into the environment
  - Performance degradation can occur through failure or bypass
- Fuel salt properties that stress barriers cause them to be more likely to release radionuclides - for example
  - Increased temperature increases radionuclide vapor pressure in cover gas and well as decreasing strength of container
- Different performance requirements for materials normally in contact with salt versus those that only need to withstand accidents

Fuel Salt Boundary Breach Accident Progression Part of Performance Based and Deterministic Fuel Qualification

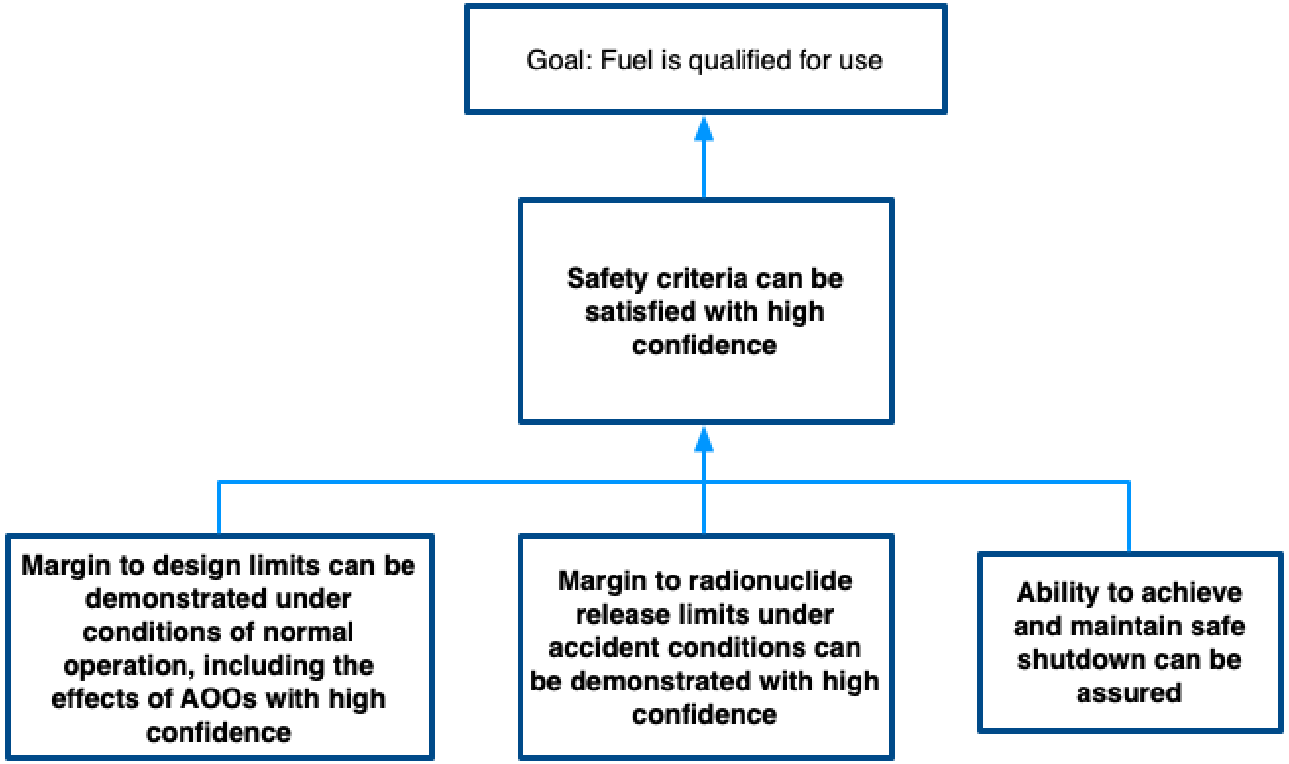
- Multiple locations in the Code of Federal Regulations require evaluation of a postulated fission product release from core into containment
- Fuel salt or cover gas cannot directly stress exterior containment layers without first breaching an inner containment layer
- High radiation and high temperatures immediately outside fuel salt boundary substantially circumscribes characteristics of materials adjacent to fuel salt container
- Focus is on fuel salt properties that must be known to adequately model accident progression and interaction characteristics with materials within containment

Fuel Related Advanced Reactor Requirements Are Similar for Liquid and Solid Fuel

- Example
  - 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
  - Fuel salt thermophysical and thermochemical properties provide the information necessary to model its role in enabling plant safety features to perform safety functions
  - Fuel salt properties vary with both composition and temperature
  - Fuel salt properties need to be determined across the range of temperatures and compositions that span potential operational and accident conditions
  - Quality of the fuel salt property data needs to be sufficient to enable modeling the role of the fuel salt in achieving the plant FSFs

Liquid Salt Fuel Assessment Framework Follows Template Developed for Solid Fueled Advanced Reactors

- Top-down approach used to decompose top level goal of *fuel is qualified* to lower level supporting goals
  - Qualifying fuel develops high confidence that the fuel will adequately perform its role in enabling the facility to achieve its safety objectives
- Lower level supporting goals are further decomposed until clear objective goals are identified that can be satisfied with direct evidence



Qualification is Based Upon Understanding the Chemical and Physical Properties of Representative Fuel Samples

- Liquid state significantly changes the physical behavior of fuel
  – Liquids do not accumulate internal stresses
    - No history dependent properties
  – Flow homogenizes fluid properties
    - No position dependent properties
    - No size dependent properties
- Chemical and physical properties are set by elemental composition and temperature
  – Independent of isotopic content

Small minimally-radioactive liquid fuel salt samples provide representative physical and chemical properties

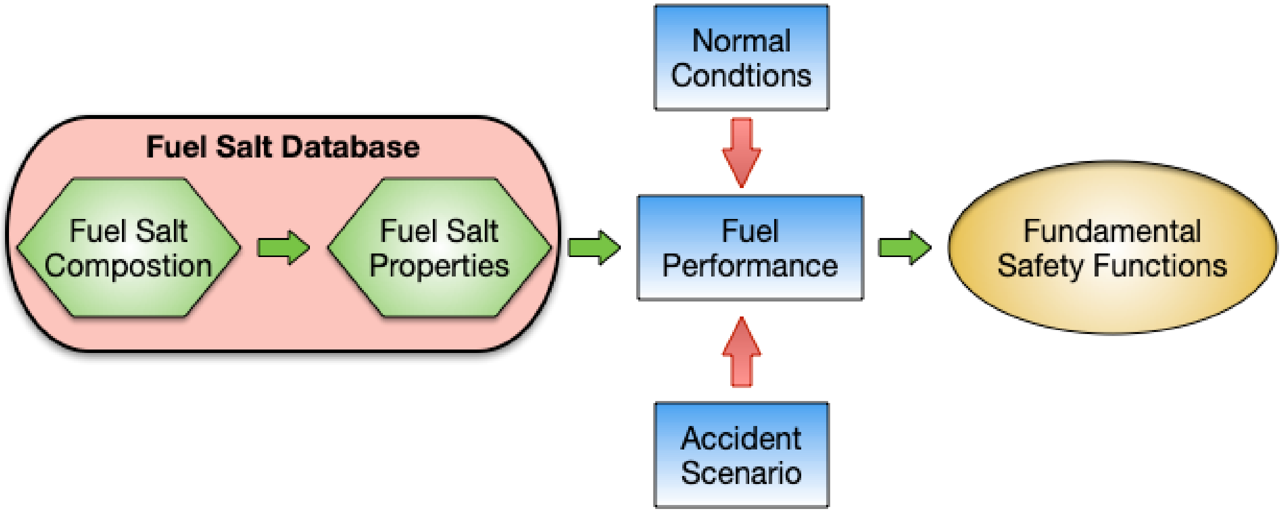
Fuel Salt Thermophysical and Thermochemical Properties Database Under Continuous Development by DOE-NE

- Database relates composition to physical and chemical properties as a function of temperature
  – Database development guided by modeling and simulation
  – Requires appropriate quality assurance for both new and existing data

- Safety evaluations / accident models performed with bounding values to establish acceptable performance range

<u>Physical Properties in Database</u>

- Melting temperature
- Boiling temperature
- Density
- Thermal Conductivity
- Heat capacity
- Viscosity
- Thermal Conductivity
- Surface Tension
- Viscosity



Fuel Salt Supports the Plant SSCs in Achieving the FSFs and Regulatory Requirements

- Qualification focuses on identification and understanding of fuel salt property degradation mechanisms that occur as a result of irradiation during reactor operation
  - Property repair (composition adjustment) may be incorporated into normal operation
- During normal operations and AOOs fuel salt properties must result in sufficient margin from damage to safety-related SSCs
- Under accident conditions the fuel salt properties must not result in sufficient damage to safety-related SSCs to prevent them from achieving their function