INL/MIS-23-75615-Revision-0

MSR Safety, Accident Scenarios, and Fuel Qualification

November 2023

Changing the World's Energy Future

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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November 29th, 2023

Avignon, France

DOE-NE – CEA Collaboration Discussion

Molten Salt Reactor PROGRAM

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

- Contain the radionuclides
  - Functional containment important concept
- Provide adequate cooling
  - Both active and used fuel
- Control reactivity
- Safety functions must be achieved under both normal operations, including anticipated operational occurrences, and design basis accidents
  - Designs must consider mitigating consequences of beyond design basis events
- Safety functions must be achieved throughout the plant’s life cycle

Preventing Unacceptable Releases of Radioactive Materials is the Principal Safety Function

- Challenges to containment and the systems, structures, and components (SSCs) employed to prevent and/or limit releases are distinctive to molten salt reactors (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 the critical circuit
  - Containment, cooling, and criticality control provided by the guard vessel or storage/drain tank
- Tritium can be released through intact containment layers during normal operations

Either Accident Mitigation or Prevention Can Result in Adequate Safety

- Earliest nuclear power plants relied on accident mitigation
  - Containment
  - Remote siting
- Safety adequacy evaluation transitioned to preventing accidents and accident escalation upon realization that some accidents could not be reasonably contained at large light-water reactors (LWRs)
  - Much of the content for license applications derives from the need to prevent accidents and accident escalation
- Plants that mitigate the worst credible accident do not need to demonstrate accident prevention to achieve adequate safety

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 (MHA) 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 fundamental safety functions (FSFs) will continue to be achieved following the MCA

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
  - Release of fission gases does not result in high pressure in next containment layer
- Temperature and mechanical force (pressure) are key barrier stressors
  - Barrier stress during accident is independent of chemical composition of leaked material
- Thermomechanical 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

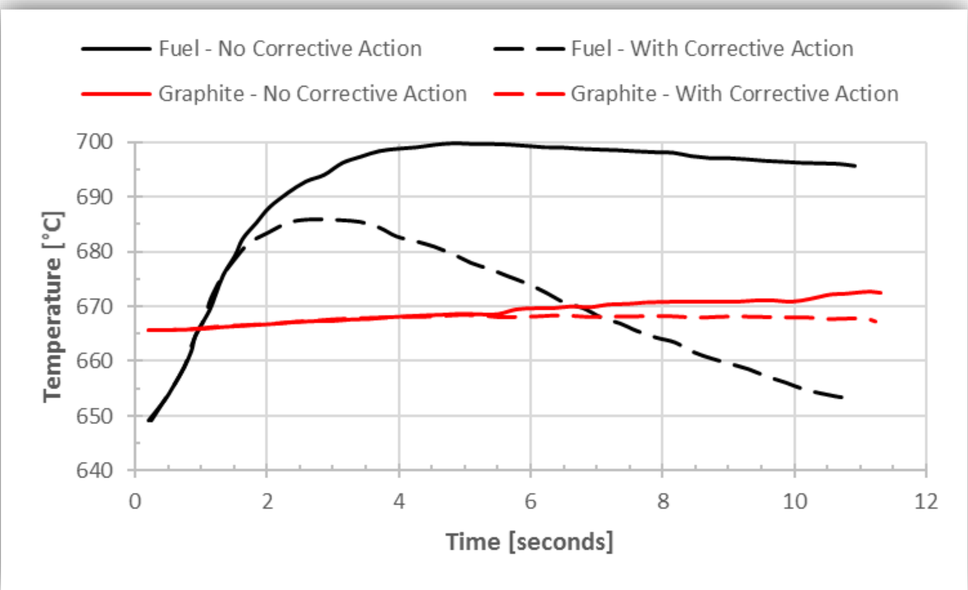
- Lines-of-defense methodology has wide applicability to reactor safety evaluation
  - Key requirement is to have an adequate number of sufficiently strong barriers based upon the potential accident consequences
  - Applied to the EU molten-salt fast reactor – DOI: 10.1051/epjn/2019031
  - Currently 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 into barrier performance

Passive Safety System Performance Poorly Represented By Component 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

MSRs Tolerate Substantial Reactivity Excursions Without Damage

- Fuel salt cannot be mechanically damaged
  - Core damage frequency inapplicable
  - Unacceptable reactor vessel creep requires large temperature excursions (hundreds of degrees) for extended times (thousands of hours)
- Large, rapid feedback mechanisms are negative
  - – Fuel salt temperature (spectral) and density
    - Net negative (density component may be positive or negative)
  - – Moderator temperature
    - May be negative or positive
  - – Moderator thermal expansion
    - Negative but longer timescale
  - – Changes in flow rate
    - Stable, depending on design



MSRE Temperature Response to Prompt Critical Insertion

Source: ORNL-TM-251

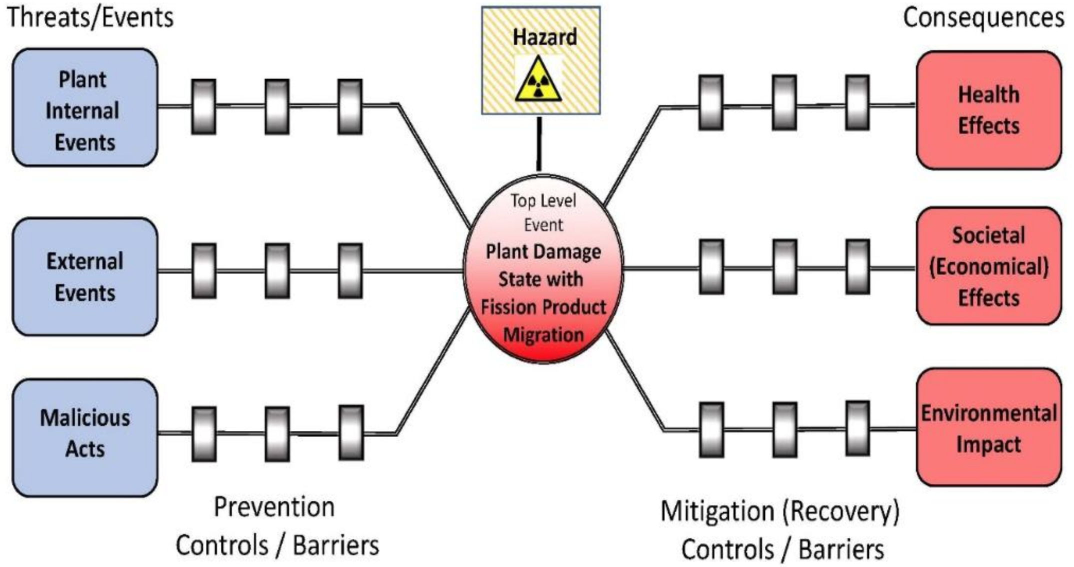
MSRs Designs Can Avoid the Potential For Phenomena That Prevent Reasonable Severe Accident Containment

- Proper design is required to avoid the credible potential for substantial pressurization or fire which could result in accidents that breach containment layers
  - Avoid significant quantities of phase change materials (e.g., water) and combustible materials in or near containment
- Primary rational for departing from containment of the MCA as means to demonstrate adequate safety was the credible potential for severe accidents in large LWRs that could not be reasonably contained
  - MHA remains the central safety element for non-power reactors
- Plants need to be adequately robust against severe external events
  - Requirement to withstand large, civilian aircraft impact necessitates substantial external event shielding
- Loss of control of all energy sources (thermal, electrical, and mechanical) within containment bounds potential accidents (e.g., fuel salt containment failure, accompanied by station blackout, and pump rotor lock)
  - No proposed MSRs require electrical power to achieve FSFs
  - Fast spectrum designs need to ensure that fuel repositioning during accidents does not result in re-criticality

Functional Containment Has Technical Similarities to Lines-of-Defense Evaluation

Source – ML18115A367

- Functional containment approved for MSRs by SRM-SECY-18-0096
- Functional failure modes and effects analysis (FFMEA) of the containment function aligns with functional containment
  - FFMEA integrates with master-logic diagrams to determine specific lines-of-defense (barriers)
  - Barriers in bow-tie representation can include controls, programs, or hardware serving to prevent or mitigate the top-level event



Bow-tie representation of barrier assessment

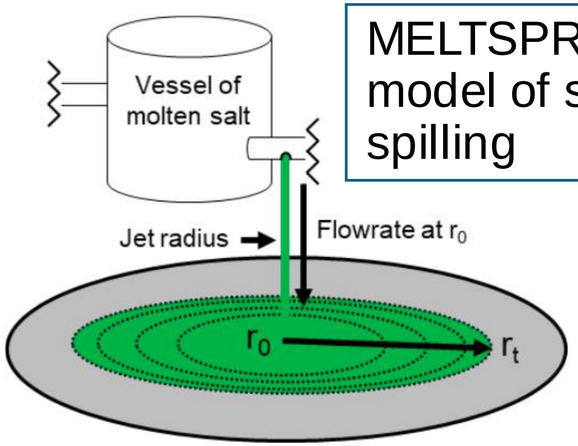
- Barrier performance adequacy at accident termination provides success criteria for both methods
  - Components and mechanisms are represented as elements of barriers
  - Beyond design basis events includes consideration of mitigation measures
- Lines-of-defense method employed internationally to assess defense-in-depth adequacy

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

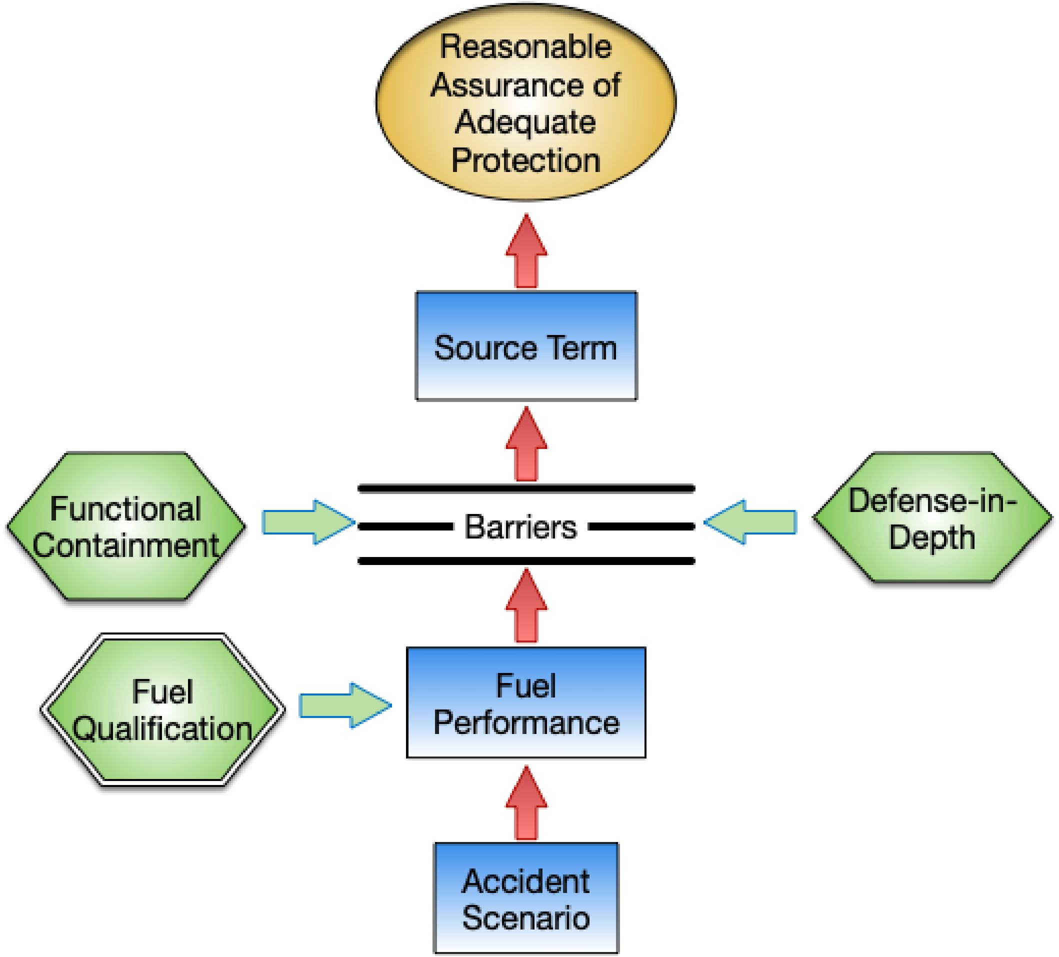


MELTSPREAD model of salt spilling

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

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)

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

- Specific accident sequences are design dependent
- Basic operational and FSFs 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
  - Thermal energy transfer, chemical reactions, and mechanical processes

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

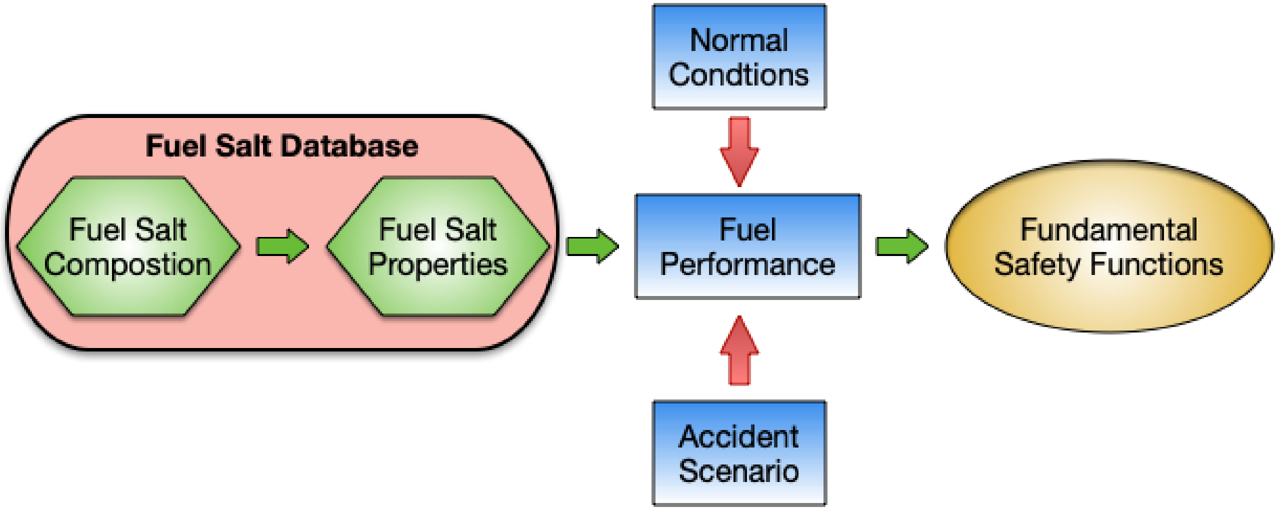
Small minimally radioactive liquid fuel salt samples provide representative physical and chemical properties

Fuel Salt Thermophysical and Thermochemical Properties Database Under Continuous Development

- Fuel salt properties derive from their composition and state (primarily temperature)
- Database provides information necessary to model the performance of the salt under normal and accident conditions
  - Database is publicly available

<u>Physical Properties in Database</u>

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



Access available at https://mstdb.ornl.gov.

Performance Based Safety Adequacy Evaluation is Key to Regulatory Efficiency for Widely Varying Designs

- 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

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Thank you

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