NRIC National Reactor Innovation Center

Fuel Salt Information Needed to Support Safety Adequacy Assessment

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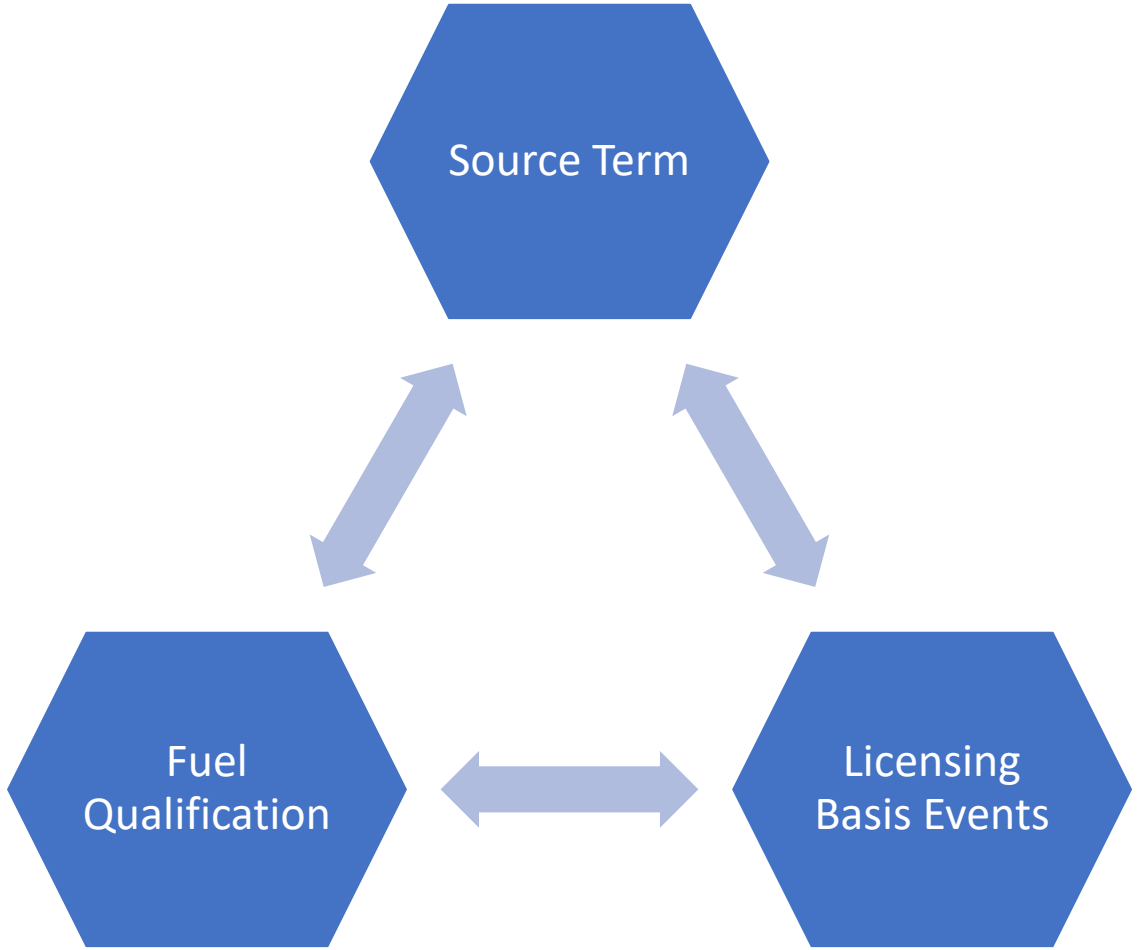
Common Salt Properties and Plant Functions Enable a General Liquid Fuel Salt Evaluation Method

- Specific accident sequences are design dependent
- Basic operations and fundamental safety functions (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

Fuel Salt Qualification is an Element of MSR Safety Adequacy Evaluation

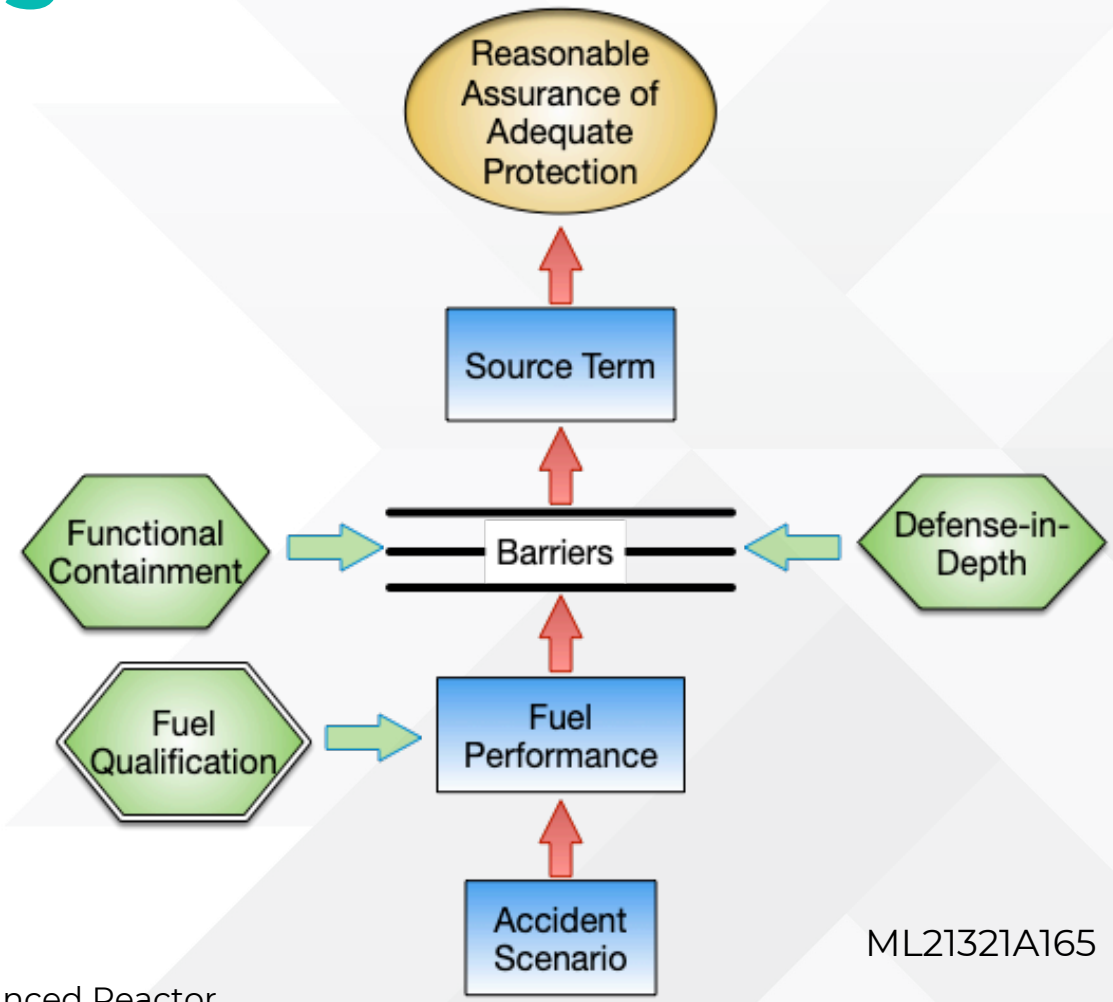


- DG-1353 or maximum hypothetical accident approach can be used to identify licensing basis events[1]
  - Accident progression models and tools
  - Barrier performance
- Advanced reactor siting criteria based upon radiological consequences from design-specific characteristics[2]
  - Bounding simplifications may be possible[3]

[1] Non-Light Water Review Strategy Staff White Paper Draft, ML19275F299,
[2] NRC Staff White Paper, Population-Related Siting Considerations for Advanced Reactors, ML19163A168
[3] ACRS Review of Draft SECY Paper, Population-Related Siting Considerations for Advanced Reactors, ML19277H031

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."

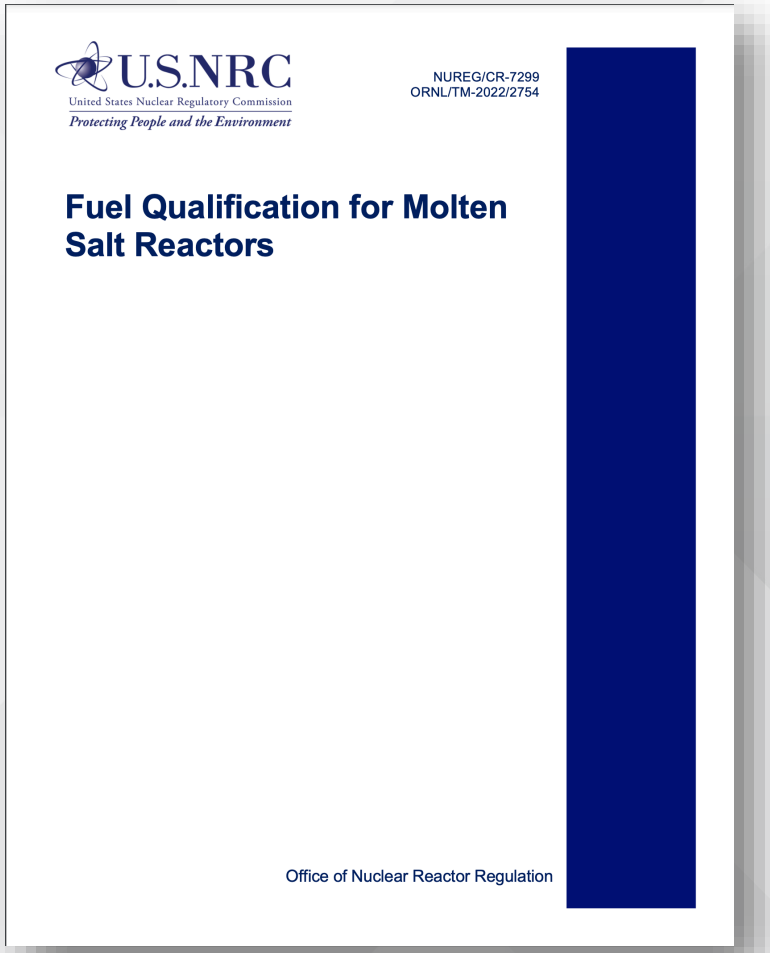


ML21321A165

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

NUREG/CR-7299 Approved as an Acceptable Method for Fuel Qualification for Molten Salt Reactors

- Fuel salt qualification is a primary end use for fuel salt property data and models
- Fuel salt qualification process based upon maintaining fuel salt properties within an acceptable range that results in plant achievement of fundamental safety functions
  - Under both normal and accident conditions
- Significant departure from solid fuel qualification process
  - Aligned with more general non-LWR fuel qualification guidance in NUREG-2246
- Provides the technical basis for fuel salt property database development
  - Includes rationale for measurement ranges and uncertainty limits



Fuel Salt Properties are a Significant Part of Establishing a Mechanistic Source Term

- SECY-92-092 (ML040210725) establishes requirements for advanced reactors to employ a mechanistic source term (MST)
- The performance of the reactor and fuel under normal and off normal conditions is **sufficiently well understood** to permit a mechanistic analysis.
- The transport of fission products can be **adequately modeled** for all barriers and pathways to the environs, including specific consideration of containment design.
- The events considered in the analyses to develop the set of source terms for each design are selected to **bound severe accidents and design-dependent uncertainties**.

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
- Approved for MSRs in SECY-18-0096: *Functional Containment Performance Criteria For Non-Light-Water-Reactors* (ML18115A157)

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

- Multiple locations in the U.S. 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

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 FSFs will continue to be achieved following the MCA

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	

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

Key Issue is “What Constitutes Fuel Salt?”

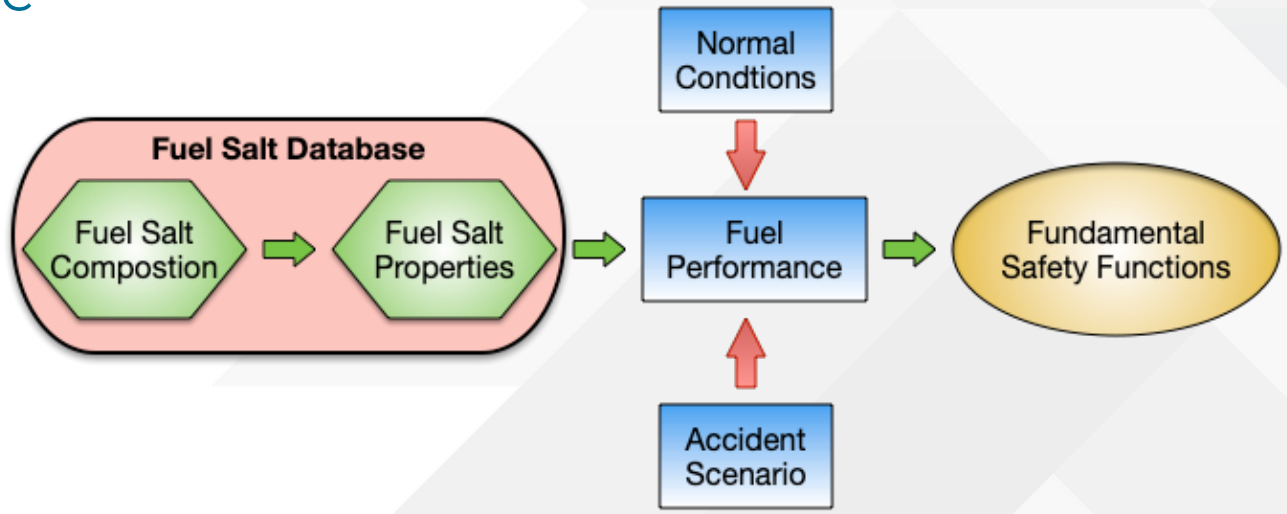
- Fuel salt does not come in discrete elements (rods or assemblies) and moves independently of its container during normal operations
  - Cladding and fuel assembly structures are qualified as part of solid fuel
- Fuel salt includes all of the material containing fissionable elements or radionuclides 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

DOE 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

Physical Properties in Database

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



ML21321A165

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

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Salt Property Measurement Is Central to Populating the Database

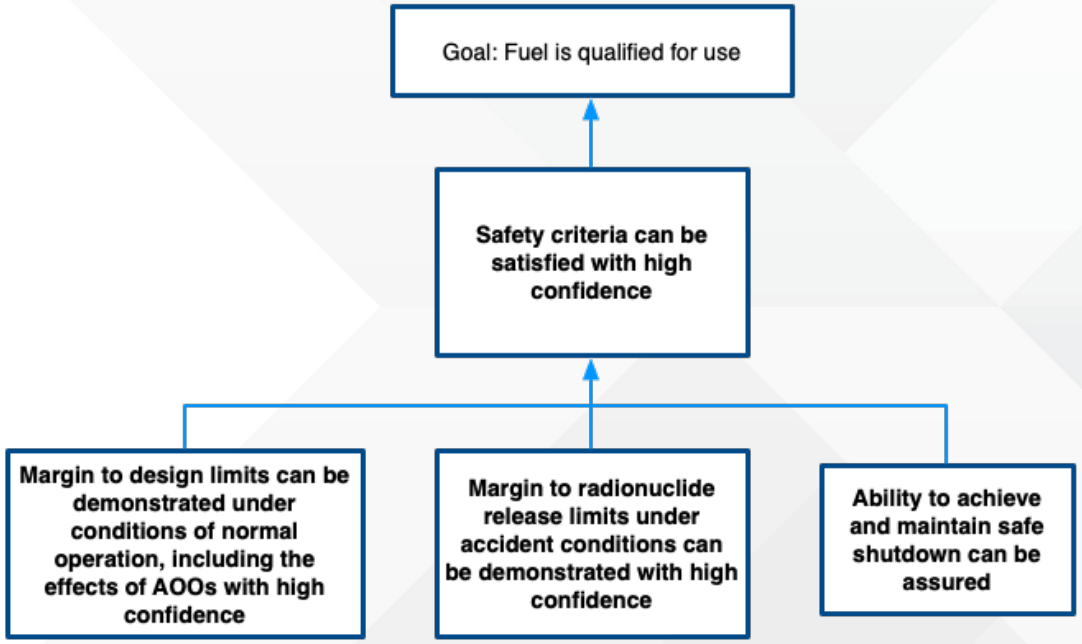
- General understanding of halide salt thermophysical and thermochemical properties is well established
  - Salt property values can be significantly impacted by technical details of the measurement method (purity, volatility, bubbles, etc.)
    - Details of quality control frequently unavailable or not adequately reported in both historical and more recent measurements
  - Necessitates substantial design and operational conservatism
- Given the number of potential salt components, the measurement campaign will continue for several years
  - Salt property measurement roadmap recently developed
- DOE-NE continues to expand its salt property measurement capabilities including by sponsoring the development of innovative sensors and measurement techniques

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



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

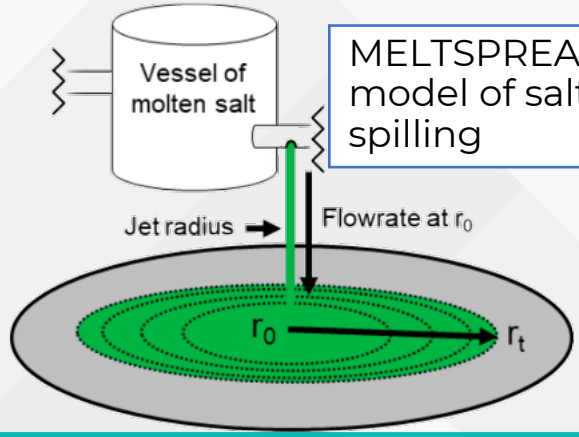
- Qualification focuses on identification and understanding of fuel salt property degradation mechanisms that occur as a result of irradiation during reactor operation
  - Property repair (composition adjustment) may be incorporated into normal operation
- During normal operations and AOOs fuel salt 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

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

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Periodic Fuel Salt Property Assessment Will Be an Element of Reactor Operations

- Analogous to material surveillance coupons
  - Compare measurement to prediction
- Frequency of property measurement depends on potential rate of change and how close salt composition is to allowable limits
  - Chromium composition was measured weekly at MSRE
  - Uranium content was inferred from reactivity impact
  - MSRE did not accumulate sufficient fission products to require reassessing most properties: density, viscosity, etc.

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