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MSR Safety Adequacy Demonstration US Contributions Towards a Common Goal

June 2023

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Changing the World's Energy Future

Idaho National Laboratory

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MSR Safety Adequacy Demonstration

US Contributions Towards a Common Goal

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

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GIF MSR pSSC Safety Collaboration is Limited to Exchange of Open/Fundamental Information

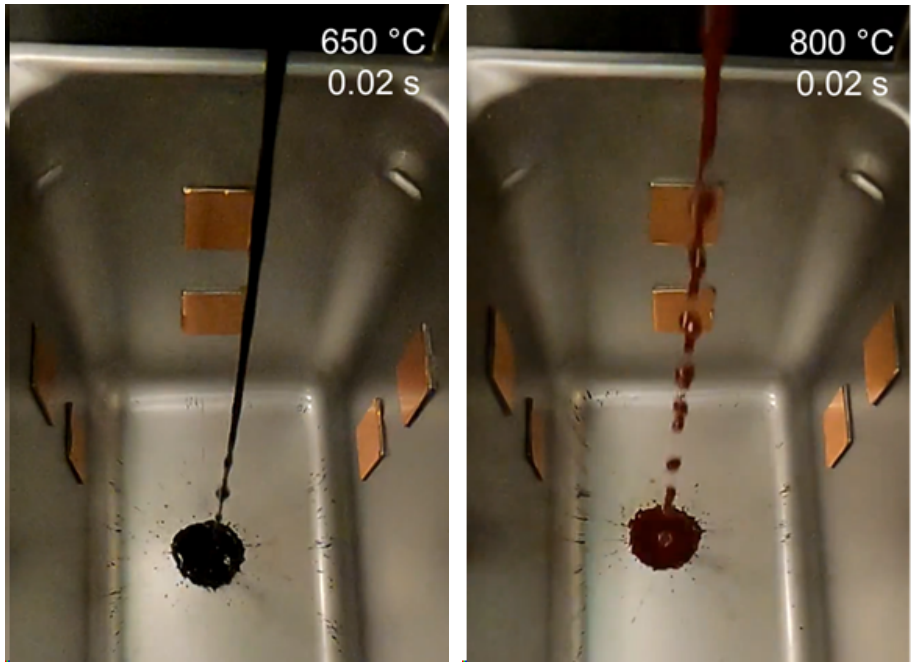
- Focus of collaboration is on developing and exchanging information suitable for providing technical basis for safety adequacy assessment
  - Multiple alternative methods for safety adequacy assessment are possible
- Technical basis derives from fundamental data – for example
  - Fuel salt thermophysical and thermochemical properties
  - Safety system, structures, and component (SSC) performance
  - Accident progression experiments and simulations
- Employing open data for safety adequacy decisions can increase public acceptance of nuclear power
  - Accident progression demonstrations have not yet been at sufficient scale to necessitate collaborative activities

Efficient and Effective Safety Adequacy Demonstration is Key to Widespread MSR Deployment

- Molten salt fuel and coolant provides desirable performance and safety characteristics
  - Characteristics can be leveraged to decrease cost and time necessary to develop reasonable confidence of adequate safety
    - Low pressure; low chemical potential energy; partial radionuclide retention; negative reactivity feedback; effective natural circulation heat transfer
- Acceptable safety continues to depend on fundamentals
  - Quality assurance
  - Good design, proper construction, adequate maintenance
- Substantial technical differences from other reactor classes necessitate
  - Distinctive systems, structures, and component (SSC) performance information
  - Customized tools and analysis methods

MSR Campaign Activities Focus on Decreasing Risks Common to Multiple Developers

- Fuel salt containment failure is key step in accidents that may lead to release of radionuclides
- Very limited prior testing has been performed to demonstrate accident progression phenomena for molten salt spills
  - Salt spill testing led by ANL
  - Results fed into MELCOR (SNL) and NEAMS tools
- Focus is on developing the information necessary to model accident progression – heat transfer, splashing, aerosol formation, radionuclide release (including non-radioactive surrogates in spills)
  - Seeking to identify key factors for future larger-scale, integrated testing



$NaCl\text{-}UCl_3$ (66-34 mol%) salt pours at 650 °C and 800 °C showing increasing radiative emission

Source – ANL/CFCT-22/32

Performance-Based Requirements are Key to Enabling Innovative Means to Achieve Acceptable Performance

- Builds from understanding of the chemistry and physics of the plant SSCs and their performance under accident conditions
- Assessing achievement of fundamental safety functions (FSFs) is central to performance-based safety analysis
  1. Contain the radionuclides
  2. Provide adequate cooling
  3. Control the reactivity
- Functional containment (reliance on a set of barriers whose collective action provides adequate containment) provides substantial design flexibility
  - Barrier role may vary with plant state

US Government is Sponsoring Development of MSR Safety Tools and Technical Information

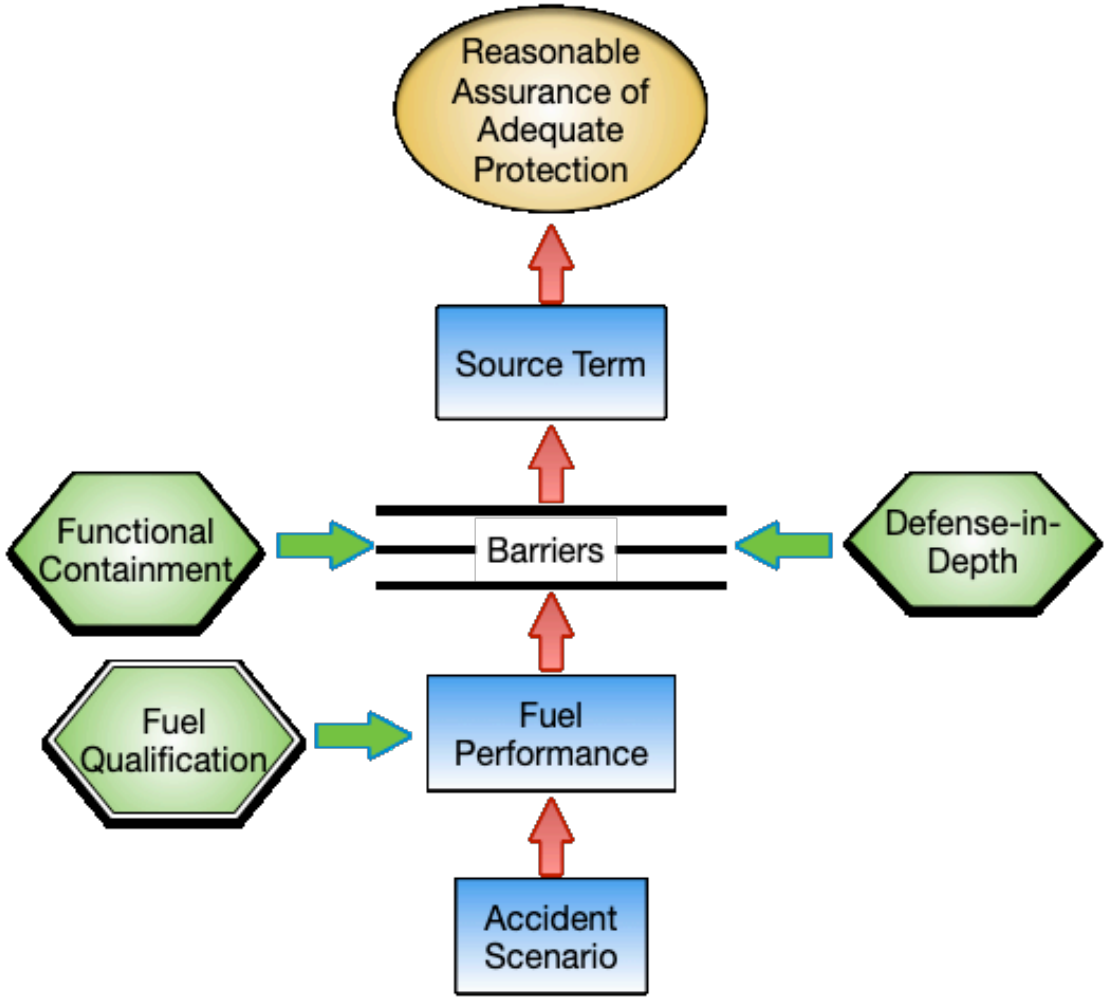
- Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) both provide support
  - Much of the support is via adding MSRs to pre-existing nuclear energy support mechanisms and evaluation capabilities – for example
    - Nuclear Energy Advanced Modeling and Simulation (NEAMS – e.g., SAM, Mole, Yellowjacket, etc.) tools
    - NRC Code Suite (TRACE, MELCOR, SCALE)
    - Nuclear Energy University Programs (NEUP)
    - Gateway for Acceleration of Innovation in Nuclear (GAIN) vouchers
- Activities can be grouped into three broad categories
  1. Preventing and mitigating accidents
  2. Understanding and modeling accident phenomena
  3. Developing safety adequacy analysis tools and methods

Preventing and Mitigating Accidents are Key Safety Elements Throughout a Plant's Lifecycle

- Safety adequacy analysis emphasizes evaluation of plant response to credible accidents including internal and external events
- Accident scenario development begins with assessing "What can go wrong?" – i.e., looking for accident initiators
  - DOE-NE sponsored an MSR initiating event workshop in 2019
  - Broadly supported by national laboratory, universities, industry, and regulators
- Understanding SSC degradation is key to preventing and mitigating accidents
  - DOE supports multiple condition monitoring activities including:
    - Electrochemical sensors for on-line assessment of concentration of corroded materials in salts
    - Evaluating erosive characteristics of flowing salts via thin layer activation

Understanding Fuel Salt Properties and Behavior Underlies Safety Analysis

- NRC has recently sponsored development of fuel salt qualification methodology
- 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



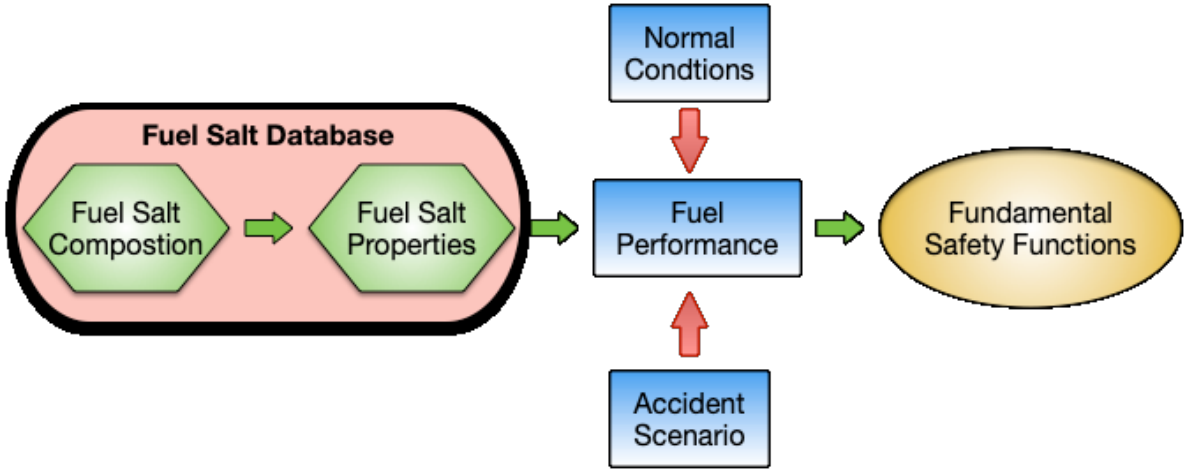
Source: US MSR Fuel Salt Qualification Process Presentation to Advisory Committee on Reactor Safeguards November 3rd, 2021, ML21321A165

Fuel Salt Thermophysical and Thermochemical Properties Database Under Continuous Development

- Fuel salt properties derive from its 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



Source: US MSR Fuel Salt Qualification Process Presentation to Advisory Committee on Reactor Safeguards November 3rd, 2021, ML21321A165

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

Understanding and Modeling Accident Phenomena Enables Developing Confidence that Consequences are Acceptably Small

- Derives from understanding the properties of those SSCs credited to perform safety functions
- DOE-NE sponsored an MSR fundamental safety function focused Phenomenon Identification and Ranking Table (PIRT) development exercise in 2021
  - Provides broad identification and ranking of key aspects of MSR safety
  - Guided expert elicitation remains a central element of safety assessment
    - PIRT panel composed of ~20 experts from several national laboratories, reactor developers, universities, and regulators

Validating Predictions Through Separate and Integral Effects Tests Remains Foundational to Establishing Reasonable Assurance of Adequate Protection

- DOE-NE is supporting limited scope separate and integral effects testing
  - Instrumented, unirradiated salt spills
  - MELTSPREAD code updated to include fuel salt
- Significant emphasis on vapors and aerosols released from fuel salt
  - Higher potential for release due to higher mobility
  - Instruments and models being developed
- Tritium distribution, movement, and release models being experimentally validated
- Natural circulation decay heat transfer demonstrations performed over past decade are applicable to MSRs (performed largely for other advanced reactors)

Industry Consensus Standards Can Improve Design and Safety Analysis Efficiency

- Balloting is currently underway for an American Nuclear Society standard on liquid fueled MSR design safety (ANS 20.2)
  - Substantial background information on MSR safety
  - MSR focused design criteria that maintain the safety-intent of the general design criteria from 10 CFR 50 Appendix A for LWRs and NRC Regulatory Guide 1.232 for advanced reactors
  - Guidance for applying probability-based risk evaluation similar to the NRC Regulatory Guide 1.233 process
- Material surveillance test articles are under development that can support extension of ASME BPVC to include environmental effects and updating ASTM E531 – *Standard Practice for Surveillance Testing of High-Temperature Nuclear Component Material*

NRC Requires Capability to Indefinitely Store Used Fuel In the Event a Repository Never Becomes Available

- Used fuel salt requires stabilization
  - Radiolysis of deeply frozen salt will generate halide gases pressurizing containers
  - Unstabilized fluoride salts may release UF_6 while chloride salts will release ^{36}Cl
- DOE-NE has supported technology demonstrations of fuel cycle and waste form development
  - Dehalogenation possible to increase storage density
    - Phosphate or oxide waste glasses
  - Glass or metal encapsulated waste forms
    - Halide or oxide crystals

MSR Safety Adequacy Evaluation Would Be Unnecessarily Costly and Lengthy Without Specialized Information and Customized Tools

- MSRs are currently being developed by industry
- US government needs the capability to efficiently and effectively evaluate whether proposed plants would represent an unacceptable risk to the public or the environment
- DOE-NE and NRC activities enable developers to improve their designs and to develop evidence that their proposed plants meet safety requirements
  - Development of fundamental scientific information such a thermophysical and thermochemical properties of halide salts is a longstanding government function
  - Accident progression demonstrations – especially those involving significant quantities of fissile materials – are more practical at DOE facilities

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