INL/MIS-23-75469-Revision-0

Accident Mitigation Based Safety Adequacy Evaluation at MSRs

November 2023

Changing the World's Energy Future

David Eugene Holcomb

Idaho National Laboratory

INL/MIS-23-75469-Revision-0

Accident Mitigation Based Safety Adequacy Evaluation at MSRs

David Eugene Holcomb

November 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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

David Holcomb
Molten Salt Reactor Technology Lead

Molten Salt Reactor PROGRAM

Accident-Mitigation-Based Safety Adequacy Evaluation at MSRs

EPRI MSR Technology User Group
December 13th, 2023
9 AM MST
Virtual

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 prevention of 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

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 lifecycle

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 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

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

Evaluating a Severe Accident That Releases Most Radionuclides into Containment is Key to Siting and Safety Adequacy Evaluation

- Required in multiple places in Code of Federal Regulations (CFR)
- Fuel salt container rupture releases bulk of radionuclides into containment
  - Fission gases are released into containment, minimal pressurization
  - Fuel salt flows down to floor
- MSR designs would ordinarily include sloped fuel salt catch pan to guide fuel salt into lower drain tanks
  - Fuel salt is a low viscosity Newtonian fluid
- Drain tanks are passively cooled
- Transferring fuel salt into drain tanks is ordinary maintenance activity
  - Severe, postulated accident places MSR into a maintenance configuration

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

Functional Containment is a Key to Enabling Demonstration of Adequate Radionuclide Containment

- Multiple layers and mechanisms evaluated together
- Individual layers may or may not be leak tight
- Fuel salt is a non-leak tight barrier that retains some radionuclides
- Different layers may be credited in different circumstances
  - Normally salt-wetted layer may provide containment during normal operations
  - External guard vessel may provide containment during accidents
- Normally salt-wetted layer may not be "code rated" if not credited to perform a safety function during accidents
- Code-rated guard vessel material only needs to withstand salt exposure during accidents

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, and noble metal release)
  - Volatile species also release (e.g., CsI and I_2)

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
- 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 into barrier performance

Barrier Performance Analysis Shows 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

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

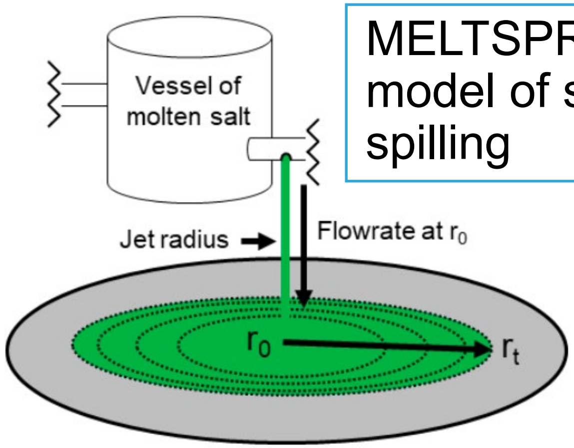
Separate and Integral Effects Tests Remain the Foundation for Evidence of Adequate Performance

- 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



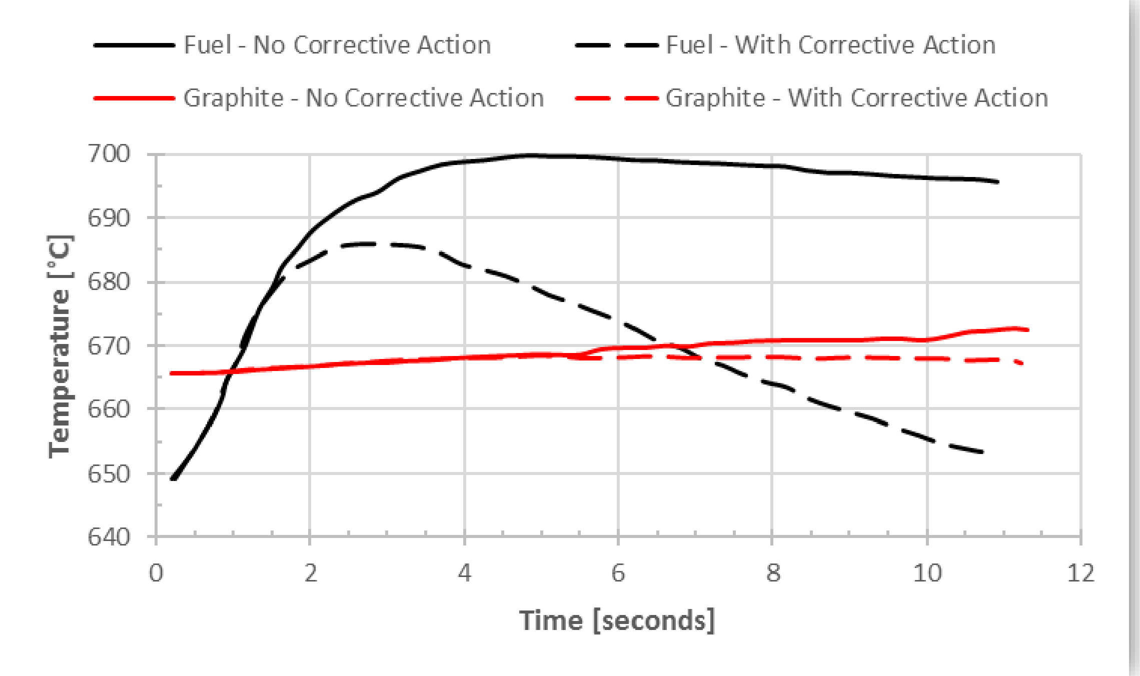
ANL/CFCT-22/15; DOI 10.2172/1873509

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

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

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

MSR Characteristics Alter the Risk Significance of the SSCs

- Reduced core source term
- Increased fission gas source term
- Active systems may not be necessary to perform protection and mitigation functions
  - Capability of bringing the reactor subcritical and decay heat removal will be fully passive and cannot be disabled by control system actions
  - MSRs lack heat transfer or temperature threshold phenomena (e.g., no departure from nucleate boiling or hypothetical core disruptive accidents)
  - Reduced safety significance of active components and I&C
- Avoiding over classification key to avoiding unnecessary costs
  - New American Nuclear Society standard on categorization and classification of SSCs will be an important element of MSR design

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

MHA-Based Safety Adequacy Evaluation Could Substantially Decrease Licensing Time and Expense

- Substantial fraction of the existing license application process is based upon the need to prevent accidents and accident escalation
  - General design criteria are not required in MHA evaluation
- Broad implications throughout plant lifecycle–potentially impacting
  - Need for licensed operators
  - Scope of inspections
  - Need for safety grade instrumentation and protection systems
  - Classification of SSCs

INL

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.