Module 13: Regulatory Issues and Challenges

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Fluid-Fueled Molten Salt Reactors (MSRs) Provide Unique Challenges to Regulation

- Aspects of MSRs not present in water-cooled nuclear systems
  - Potentially highly corrosive behavior (requires careful redox control)
    - Compatibility of salts with reactor materials (at high temperatures and radiation conditions)
  - High melting point
  - High boiling point (low pressure)
  - Large volumetric heat capacity
  - Significant quantities of fuel outside the reactor core
    - Heat exchanger, various tanks, pumps, possible associated fuel processing, possible continuous addition/removal of fuel
  - Distributed delayed neutrons (mobile fuel)
  - Noble gas fission products evolve out of the salt into cover gas; noble metal fission products plate out onto surfaces; fuel salt retains most other fission products, but not all

Fluid-Fueled MSRs Provide Unique Challenges to Regulation (cont'd)

- Aspects of MSRs not present in traditional nuclear systems
  - Salt vapor deposition in cover gas lines
  - Potential for larger volumes of high activity components (filters and replaced components)
  - Fuel composition continuously changing
  - Fuel performs cooling function
  - Strong prompt negative reactivity feedback with increasing temperature for most designs
  - Tritium production (especially lithium fuel salts)
  - Presence of bubbles (fission product gasses) passing through the core
  - Beryllium hazard for Be-based salts

Regulatory Issues/Challenges of Molten Salt Reactors

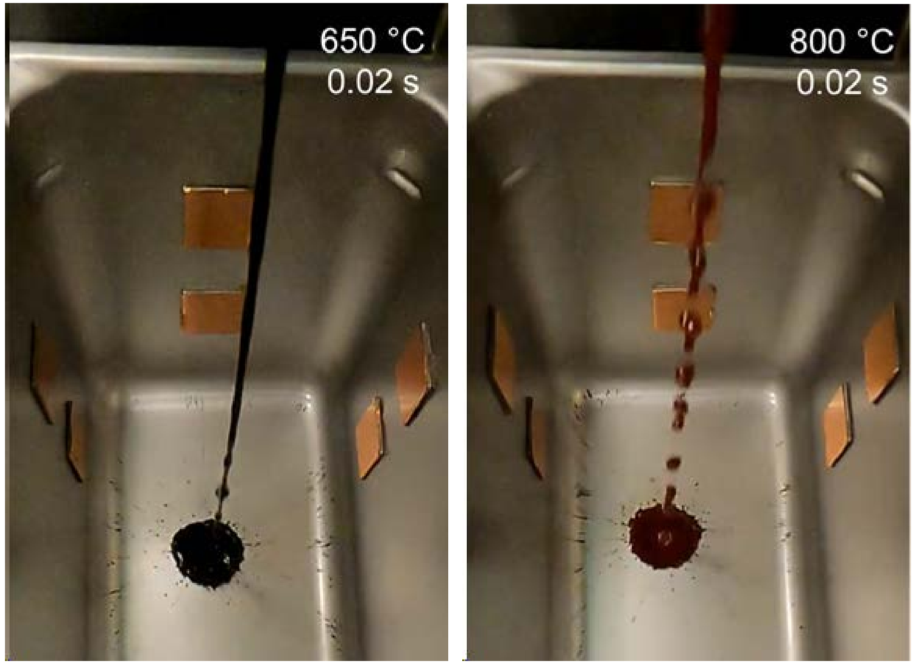
- MSR safety analysis/licensing strategy or framework needs to be developed
  - Principal design criteria are needed
  - Major phenomena have recently identified and ranked
    - ORNL/TM-2021/2176 – Molten Salt Reactor Fundamental Safety Function PIRT
  - Accident sequences and initiating events identification exercise performed
    - ORNL/TM-2019/1246 – Molten Salt Reactor Initiating Event and Licensing Basis Event Workshop Summary
  - Qualified safety analysis tools are not yet available
    - Identification of safety analysis codes (applicability of LWR tools?)
    - Operational experience does not exist
    - Nonprototypic (scaled) separate and integral effects tests need to be used
      - Quality data and benchmarks need to be developed
    - Need for test and prototype reactors (MSRE may be used for similar designs)
  - Mechanistic source term needs to be developed
  - Tritium control criteria will be necessary (particularly in lithium salt systems)
  - Be control for Be-based salts will be necessary

Regulatory Issues/Challenges of Molten Salt Reactors (cont'd)

- Systems, structures, and components (SSCs) must be carefully chosen
  - High temperature tolerant
  - Radiation damage resistant
    - Interior shielding/reflection common design element
  - Corrosion resistant
    - Fuel salt-wetted SSCs may need to be clad to assure salt compatibility in addition to high temperature and high radiation tolerance
  - Replaceable using remote tooling
  - Leak-tight gaskets and valves remain unproven
  - Instruments will require long leads to signal processing due to high radiation and temperatures
  - Tritium retention
  - Some materials may be difficult to obtain (isotopic separation, alloys)
  - Materials need to be qualified for nuclear use

Component Failure-On-Demand Accident Progression Models Do Not Align Well With MSR Characteristics

- Passive systems tend to experience performance degradation instead of abrupt failure
  - For example - slower initiation of natural circulation cooling or decreased coolant flow
- MSRs lack cliff-edge type accident phenomena
- Consequences of performance degradation tend to be increased stresses on other SSCs
  - For example – Decreased natural circulation cooling flow results in higher vessel temperature which increases material creep
    - Heat transfer increases substantially at higher temperatures
    - Substantial time/temperature margin to vessel failure
- MSRs have limited data available to quantify specialized component failure probabilities

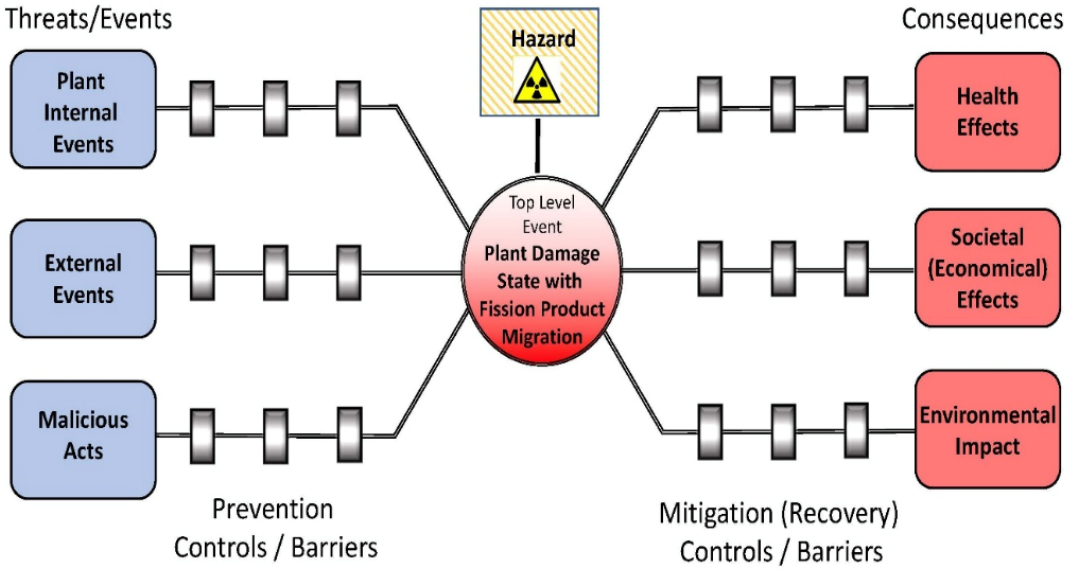


NaCl-UCl_3 salt pours at 650 °C and 800 °C showing increasing radiative emission

Source – ANL/CFCT-22/32

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

- 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

Source – ML18115A367

- 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

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 maximum credible accident as means to demonstrate adequate safety was the credible potential for severe accidents in large LWRs that could not be reasonably contained
  - Maximum hypothetical accident 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

Prescriptive Regulatory Language Embodies Characteristics of Large LWRs

- MSRs will require exceptions to inapplicable regulatory language – for example
  - Mitigation of beyond design basis events - 10 CFR 50.155
    - Prescriptive language (fuel damage, spent fuel pool monitoring, etc.) – adopted in 2019
  - NRC Inspection Manual – employs increase in core damage frequency to determine acceptance criteria
  - Maintenance rule – 10 CFR 50.65
    - Focuses on individual component performance not impact of component degradation on overall safety
  - Containment leakage testing – 10 CFR 50 Appendix J
    - Primary containment stressor at MSRs is elevated temperature instead of pressure
    - Globally heating containment would substantially stress other components

Passive Safety Characteristics Substantially Impacts SSC Classification

- Reactor vessel is a key safety element at LWRs
  - Current regulations mandate compliance with ASME BPVC for LWRs (10 CFR 50.55a)
    - ASME BPVC focuses on adequate material strength over time at temperature
    - Does not include primary material stressors at MSRs – chemistry and radiation
- Fuel salt container (reactor vessel) is only one barrier layer in an MSR functional containment strategy
  - Most MSR designs are anticipated to be able to continue to achieve adequate containment following fuel salt container breach
    - Guard vessel and/or sloped catch pan leading to cooled drain tank
  - Performance requirements for materials that only need to endure fuel salt contact for for accident durations are much different

Regulatory Guidance Needed to Align AEA Language With MSR Characteristics

- AEA Section 123 a (7) indicates that no material containing plutonium, uranium-233, or other nuclear materials that have been irradiated (except for low-enrichment uranium) can be "altered in form or content" without prior approval
  - After start-up fuel salt will include either ^{233}U or ^{239}Pu – not LEU
  - On-line refueling, redox control of salt, solid particle filtering, draining to a critically safe shape, or allowing to freeze all alter fuel salt form or content
- Need performance-based regulatory guidance to provide the prior approval necessary

Means of Obtaining Principal Design Criteria based on Advanced Reactor Design Criteria (ARDC)

- ARDC 1–5 Overall Requirements
  - No change required
- ARDC 10 First fission product barrier is not the cladding but the reactor vessel and associated piping, gaskets and seals, heat exchangers, pumps, and valves as well as any tanks or clean up systems than contain fuel
  - Definition of a Specified Acceptable Fuel Design Limit (SAFDL) or Specified Acceptable Radiological Release Design Limit (SARRDL) is the challenge
  - Any or all of these systems may contain fuel during normal operation
  - AOOs affecting these components or systems may be different for each system and are not necessarily related to core events
  - How will on-site reprocessing systems, if any, be addressed?
- ARDC 11–13 and 17–19 Generally applicable
- ARDC 14 and 15 Reactor Coolant Boundary and Coolant System Design
  - Definition of reactor coolant boundary and coolant system is the challenge
- ARDC 16 Containment
  - Likely the containment will be leak tight, could have multiple adjacent containments all potentially within exterior containment layers

Means of Obtaining Principal Design Criteria based on ARDC (cont'd)

- ARDC 17 Electrical Power
  - Current designs employ passive shutdown and heat removal systems which do not require off-site or on-site electrical power
- ARDC 21–25 Protection System Functions, Reliability, Testability, Independence, Failure Modes, Separation, and Reactivity Control Malfunctions
  - May require rethinking how these are applied across the spectrum of MSR designs
    - For example: MSRs, such as those with drain tanks, may not have a scram system using neutronic poisons (MSRE); as a result of draining the core, the shutdown, residual heat removal, and emergency core cooling functions are transferred to systems outside the reactor core
- ARDC 26 and 27
  - Reactivity control system may be only used to control temperature and not for shutting the reactor down
    - For example: In the MSRE, control rods were used to control the temperature, but shutdown was achieved by draining the salt from the reactor core region
- ARDC 28 and 29 Generally applicable

Means of Obtaining Principal Design Criteria based on ARDC (cont’d)

- ARDC 30–33 Coolant Boundary Quality, Fracture Prevention, Inspection, Coolant Inventory Maintenance
  - Definition of coolant boundary will have impact on these ARDC
  - Inspection may be very difficult (radiation and thermal environment)
  - Inventory maintenance may need to be defined (drain tanks)
- ARDC 34–37 RHR and ECC Inspection and Testing
  - RHR is required of all systems that may possibly contain fuel or fission products – multiple RHR systems (designs may differ based on the function and/or system)
  - Definition of a postulated accident will determine which are ECC and which are RHR
  - Inspection and testing may be difficult (radiation and thermal environment) and/or require draining and flushing the fuel salt
  - RHR systems may be shared or independent (heat sink)

Means of Obtaining Principal Design Criteria based on ARDC (cont'd)

- ARDC 38, 39, 40, 41, 42, 43 Containment Heat Removal, Inspection and Testing and Containment Atmosphere Cleanup, Inspection and Testing
  - Applicable, but there may be multiple containments (e.g., for distributed source terms)
  - Inspection and testing may be difficult (radiation and thermal environment) and possibly require draining and flushing the fuel salt
- ARDC 44–46 Structural/Equipment Cooling, Inspection and Testing
  - Multiple structures requiring cooling
  - Inspection and maintenance may be difficult (radiation and thermal environment)

Means of Obtaining Principal Design Criteria based on ARDC (cont'd)

- ARDC 50–53 Containment Design, Fracture Prevention, Leakage Testing, Testing and Inspection
  - Applicable but may be multiple containments of differing design
  - Inspection and testing may be difficult (radiation and thermal environment)
- ARDC 54–57 Containment Penetrations and Isolation
  - Will be design dependent; it may be necessary in designs using drain tanks to not have isolation except for multiple parallel freeze plugs
  - Testing and inspection may be difficult (radiation and thermal environment)

Means of Obtaining Principal Design Criteria based on ARDC (cont'd)

- ARDC 60–63 Fuel Storage and Handling and Radioactivity Control
  - These ARDC probably take on more importance for a MSR
    - Fuel storage systems may be directly connected to the reactor
    - Much different from conventional used fuel pool or dry cask storage
    - Inaccessibility compared to current LWR (affects inspection and testing)
    - May store fuel temporarily that will be reused in the reactor, processed, or used in subsequent reactors
    - Fuel forms will be different from those in any other reactors
    - Doses likely to be higher because there is no hold-up time
    - Design criteria of other systems related to fission product storage, handling, and control required (e.g., like "other systems" in ARDC 61)
  - ARDC 64 Monitoring Radioactive Releases
    - Applicable to MSRs

Potential Additional (70 Series) MSR-Specific Design Criteria (examples)

- Intermediate Coolant System
- Fuel Salt and Cover Gas Purity Control
- Salt Receiving, Storage, and Processing Systems
- Salt Leakage Detection
- Salt Heating Systems
- Salt/Water/Organics Reaction Prevention Mitigation
- Fuel Salt System Interfaces
- Cover Gas Inventory Maintenance

MSRs Will Require a Significant Change in Current Regulations and Guidance

- Revision of ARDC
- Adaption of the Standard Review Plan
- System descriptions and functions will need to be revised
  - Allocation of safety functions will need to be revisited
- Accident sequences and initiators will be unique
- Categorization/classification of equipment
- Fuel qualification
- Mechanistic source terms
- Which regulations apply where? 10 CFR 50, 10 CFR 70, or combinations of both
  - MSR-specific safeguards regulations will also need to be established
- Others will be identified as the MSR designs progress