GEN IV International Forum[SM]

MOLTEN SALT REACTOR SAFETY ANALYSIS- A U.S. PERSPECTIVE

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26 August 2020

Meet the Presenter

Dr. David E. Holcomb is a distinguished member of the technical staff and distinguished inventor at Oak Ridge National Laboratory (ORNL). Dr. Holcomb currently represents the U.S. and serves as a vice chair of the provisional system steering committee for the Generation IV International Forum on MSRs, chairs the American Nuclear Society's working group developing a design safety standard for liquid fueled MSRs (ANS 20.2), and provides technical oversight of DOE's university projects on MSRs.

He is a past chair of the American Nuclear Society's Human Factors, Instrumentation, and Controls Division.

Dr. Holcomb has been a staff member at ORNL for more than 25 years and is currently a member of the Reactors and Nuclear Systems Division. He has in the past served as the ORNL team lead for space reactor instrumentation as part of the Jupiter Icy Moons Orbiter program.

Dr. Holcomb has served as an Adjunct Assistant Professor at the University of Tennessee, Knoxville, in the Nuclear Engineering Department since 1995 and is a current member of the nuclear engineering program advisory board for the Ohio State University.

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Efficient and Effective Safety Evaluation is Critical to Reduce Financial Risk for Investment in MSRs

- Significant time and resources are required to develop and deploy a new reactor class
- Existing LWR centric framework would be difficult to apply
  - Multiple initiatives to modernize advanced reactor licensing
- Liquid fueled reactors are distinctive even among Generation IV nuclear energy systems

Goals for Generation IV Nuclear Energy Systems

Safety and Reliability

1. Generation IV nuclear energy systems operations will excel in safety and reliability
2. Generation IV nuclear energy systems will have very low likelihood and degree of **reactor core damage**
3. Generation IV nuclear energy systems will eliminate the need of offsite emergency response

There were two people at the [Manhattan Project] metallurgical laboratory, Harold Urey, the isotope chemist, and Eugene Wigner, the designer of Hanford, both Nobel Prize winners who always argued that we ought to investigate whether chain reactors, engineering devices that produced energy from the chain reaction, ought to be basically mechanical engineering devices or chemical engineering devices. <u>And Wigner and Urey insisted that we ought to be looking at chemical devices—that means devices in which the fuel elements were replaced by liquids.</u>

The Proto-History of the Molten Salt System - Alvin M. Weinberg

US Federal Law Does Not Prescribe How to Demonstrate Adequate Reactor Safety

- Delegates authority to Nuclear Regulatory Commission (NRC)
- Two regulatory guidance documents (RG 1.232 and RG 1.233) supporting commercial advanced reactor safety adequacy assessment recently approved
  - Both deterministic and probabilistic methods are acceptable
  - Methods remain based upon identifying principal design criteria, identifying licensing basis events, classifying systems, structures, and components, and considering defense-in-depth
- Alternate safety evaluation path available for non-power reactors – NUREG 1537
  - Safety adequacy based limiting effects of postulated maximum hypothetical accident (MHA)
  - MSR specific version currently under development

Safety Analysis is a Required Element of Licensing

- Commercial nuclear power plant (NPP) safety analysis requires applicant to provide sufficient information to the NRC to reach a conclusion of reasonable assurance of adequate protection of the public and the environment
- NRC Safety goals
  - Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear **no significant additional risk** to life and health
  - Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and **should not be a significant addition to other societal risks**

Potential Safety Impact to Public From Nuclear Power Plants (NPPs) Is Increased Exposure to Radiation

- Primary reactor safety function is avoiding release of radionuclides
  - Basis for NRC quantitative health objectives
  - Title10 Code of Federal Regulations (CFR) Part 20 provides specific requirements
- Two supporting safety functions that could lead to radionuclide release
  - Control reactivity
  - Reject decay heat

Safety Analysis Starts By Developing Understanding of Plant Design and Operation

- What are the intended functions of the plant systems, structures, and components (SSCs)?
  - How do the requirements change with operating state?
    - Power range, startup, transition, refueling, maintenance, decommissioning
- Preliminary hazard assessment provides basic understanding of what can go wrong
  - Where are the radionuclides?
  - Where are the energy sources?
    - High pressure, high speed moving parts, reactive chemicals, …
  - What are relevant common and external hazards?
    - Fire, flood, earthquake, blackout, …

> When eating an elephant take one bite at a time.
>
> – *Creighton Abrams*

Deterministic MSR Safety Adequacy Demonstration Stems From Current LWR Licensing Pathway

- Based upon adaption of LWR general design criteria to advanced reactors
  - RG1.232 does not include MSR specific design criteria
  - Does include specific criteria for sodium and high-temperature gas cooled reactors
- American Nuclear Society (ANS) working group 20.2 is attempting to formulate MSR specific design criteria
  - Includes substantial conservatism in initial version
  - Significant time and effort required to develop and validate minimum acceptable design criteria

Probabilistic MSR Safety Adequacy is Based Upon Quantitative Accident and Risk Modeling

- Data driven approach provides high-fidelity understanding of NPP risks
- MSRs have much less reliability or accident progression data than other advanced reactors
- MSRs have much more diverse potential configurations than other advanced reactors
- Reliability of passive safety systems is more difficult to quantify
  - Progressive and partial degradation does not align well with conventional PRA techniques
  - Advanced methods have not yet been approved

Existing Regulations Provide Alternative Pathway for Safety Adequacy Assessment for Advanced Reactors

- 10CFR50.43(e) indicates that reactors that use simplified, inherent, passive, or other innovative means to accomplish their safety functions will be approved only if:
  - Performance of each safety feature has been adequately demonstrated
  - Interdependent effects among the safety features have been demonstrated to be acceptable
  - Sufficient data exist on the safety features
- Analysis, test programs, experience, or a prototype reactor can be employed to obtain the required information
- MSRs require additional data on safety performance to employ 10CFR50.43(e) method!

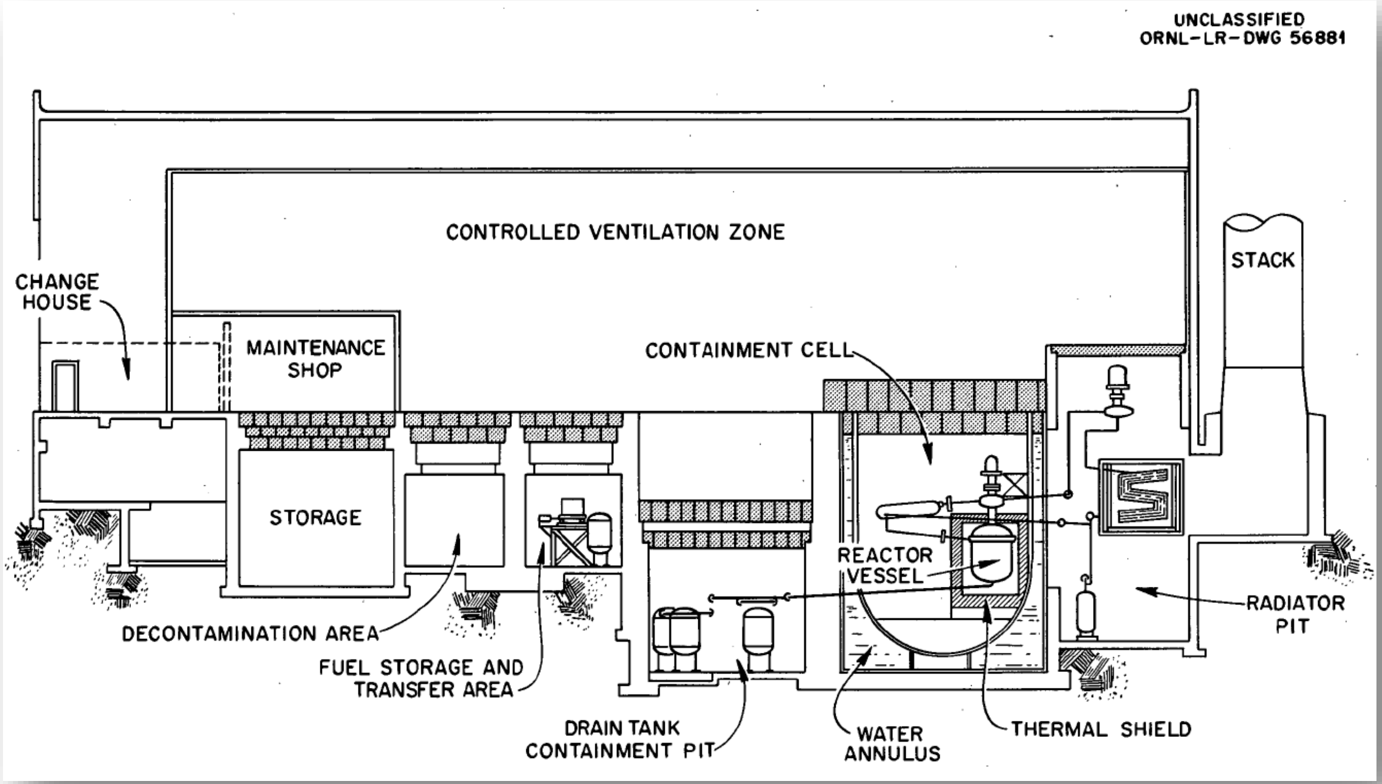
Evaluating Risk is the Central Component of NPP Safety Adequacy Analysis

Risk – The Possibility that Something Undesirable Will Happen

- Defense-in-depth is a primary mechanism to accommodate uncertainty
  - What if we are wrong?

Functional Containment Provides Performance-Based Evaluation of Radionuclide Retention

- Multiple barriers - some of which are not normally stressed
  - Barrier performance requirements depend on their safety function
- Segmented containment
  - Limits accident scope
- Independent barriers
  - Failure of single barrier does not substantially stress other barriers
  - Minimizes potential for cascading or escalating failures



Multi-Layer, Segmented Containment at Molten Salt Reactor Experiment (MSRE)

Everything Depends on **Quality**

- Were the SSCs built according to the design?
- Was the design correct?
- Were the materials correct?
- Has the plant been operated and maintained according to plan?
- Little historical MSR data was acquired under a modern quality assurance plan

> **Give them quality. That's the best kind of advertising.**
>
> ***– Milton Hershey***

MSRs Present Different Safety Analysis Challenges Than Other Reactor Classes

- Radionuclides distributed across plant
  - Solid fuel concentrates radionuclides in core and used fuel pool
  - Gaseous fission products inherently separate from fuel salt
  - Integrated fuel salt processing possible
  - Salt wetted components have limited lifetimes resulting in unconventional high-activity waste stream
- Less (and dated) operating experience
  - Only one prior reactor operating for significant period
    - MSRE ~7.34 MWth operated from 1965-69
  - No large-scale reactor or component demonstrations
  - No fast spectrum systems demonstrated
  - Minimal prior accident performance demonstrations

MSR Risks Have Substantial Overlap with those of Fuel Cycle Chemical Processing Facilities

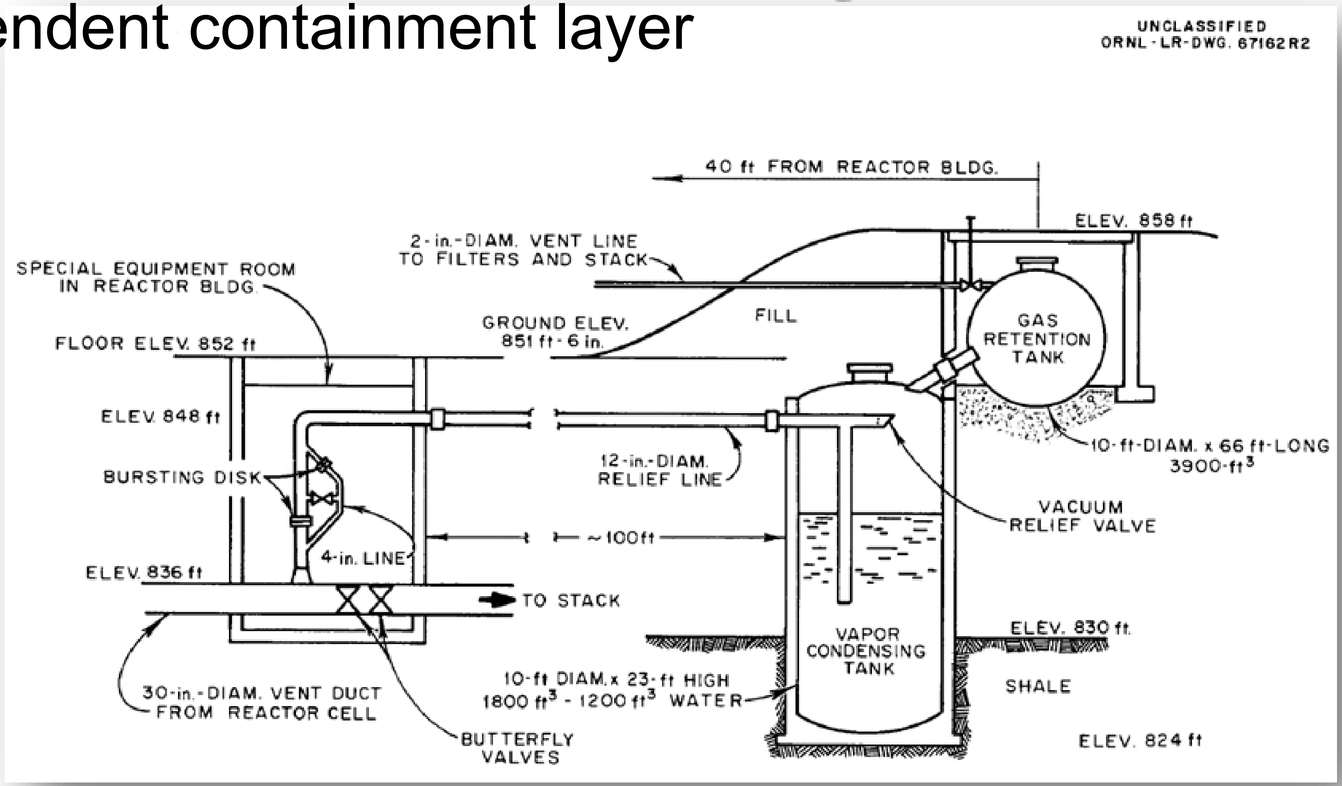
- Both contain large quantities of radionuclides without large inventories of accessible high pressure or pressure generating fluids
  – Key difference between fuel cycle facility and reactor risks
  – Power cycle fluids separated by heat transfer loop (protected by rupture disks)
- Safety adequacy of fuel cycle facilities is regulated under 10 CFR Part 70
- Process Hazard Assessment (PHA) is central to fuel cycle facility safety adequacy assessment
  – NUREG 1513 describes how to perform PHA (referred to as integrated safety assessment) for fuel cycle facilities
  – Proven method to provide reasonable assurance of completeness for accident identification
- PHA does not quantify risks so is not sufficient to evaluate severe accident consequences

Original Reactor Safety Adequacy Evaluation Methodology Was Based Upon Containing MCA

- Safety adequacy of the first commercial reactors was evaluated by a combination of hazard assessment and containment of the maximum credible accident
- As light water-cooled reactors (LWRs) became progressively larger in the 1960s the credible potential for catastrophic accidents necessitated shifting safety focus to preventing accidents and mitigating their consequences
  - Escalating and cascading accidents represent substantial portion of the risk
- Reasonably designed MSRs lack the historically identified mechanisms that could result in catastrophic accidents (WASH-740)
  - High pressure
  - Interaction of hot metals with water (steam or hydrogen explosions)

MSRE Employed MCA for Siting Evaluation

- MCA was based upon a dual, independent containment layer failures
  - Water spill to pressurize containment sufficiently to induce significant leakage in second containment layer
    - Pressure relief and radionuclide capture using rupture disk isolated vent line to suppression pool and gas retention tank
    - Potential for manual final venting



  - MSRE had two quasi leak-tight containment layers plus low leakage reactor building / confinement
    - Dose following MCA was due to residual postulated leaks (1%/day) in exterior containment due to pressurizing to 2.7 atmospheres (39.9 psi)
    - Required continuing to actively vent reactor building to disperse radionuclides

MSRs Have Readily Apparent, High Degree of Passive Safety

- Strong inherent retention of radionuclides
  - Low pressure!
    - Large margin to boiling
    - Minimal amounts of water or other phase change materials within containment
    - Power cycle separated from core with rupture disks along piping
  - Fuel salt retains many radionuclides
    - Up to 40 % can be released into cover gas
      - Only recent production available for release remainder trapped outside of fuel or incorporated into fuel
    - Fuel salt chemically binds most non-noble gas fission products
    - Other radionuclides plate onto salt wetted surfaces
  - Fuel salt is in low chemical energy state (low Gibbs free energy)
    - Minimal chemical reactions with environmental materials

MSRs Have Readily Apparent High Degree of Passive Safety (contd.)

- Effective negative reactivity feedback
  - Fuel in maximum reactivity configuration
  - No hypothetical core disruptive accident
  - Substantial margin to structural damage
    - MSRs considered as prompt burst reactors
- Effective passive decay heat rejection
  - Fuel salt has advantageous combination of heat capacity, thermal expansion, and viscosity for natural circulation cooling
  - High temperature facilitates radiative cooling
- No operational cliff-edge effects

MSRs Retain the Potential of Containing All Credible Accidents At Any Scale

- Avoiding potentially cascading accidents (especially accident sequences that pressurize containment) key consideration
  - MSRE type suppression pool – capture tank system would be quite large for commercial-scale plants
- System immaturity necessitates additional conservatism (design requirements) to ensure containment survival
  - High degree of passive safety minimizes additional cost
  - Reliable quantitative performance data and models would decrease required conservatism
- Additional requirements intended to prevent single event from damaging all containment layers – e.g. core catcher or guard vessel employed to maintain decay heat removal capability following vessel rupture

Assuring that Bounding Accidents Envelope All Credible Accidents is Key to Demonstrating Adequate Safety

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- PHA incorporates multiple methods (Hazard and Operability study (HAZOP), Failure Modes and Effects Analysis (FMEA), Layer of Protection Analysis (LOPA), etc.)
  - Relies upon expert judgement from multiple people with diverse technical backgrounds
  - Same basic process as an early phase PRA
- In order to have consequences (release radionuclides) an accident needs to rupture or bypass all containment layers
  - High resiliency of MSRs enables use of highly unlikely postulated accidents for safety assessment
  - Commercial MSRs will not have a single MCA, but a series of bounding accidents as they have significant amounts of radionuclides in multiple locations

Advantageous Characteristics Lowers Plant Capital and Operating Expenses

- Low pressure substantially lowers cost for barriers
  - Thin walled (~cm) metal tank versus massive reinforced concrete structure
    - Likely below-grade due to large civilian aircraft impact potential
- Passive decay heat rejection not using power cycle avoids power cycle SSCs needing to be safety related
  - Safety-related SSCs confined to nuclear island
- Large margin to damage
  - Reactivity accidents unlikely to damage SSCs
  - Large margin to fuel salt boiling
  - No equivalent to anticipated transient without scram
  - No accidents yet identified requiring rapid operator or active equipment response

Maintaining Low-Pressure Under Accident Conditions Key to Avoiding Potential to Rupture Containment Layers

- MSRE substantially reduced pressure through interconnecting to a large tank via rupture disks
  - Reactor built in an existing small containment
- Process physics and chemistry dictate pressure generation mechanisms
  - Without large amounts of phase change materials, MSRs lack mechanisms for significant pressure generation
- Lack of adequate decay heat rejection could fail all containment layers without requiring pressure generation
  - Adequate decay heat rejection under severe accident conditions required to avoid radionuclide releases

Dual Simultaneous Containment Layer Failure Accident Employed At MSRE Provides Baseline MCA for MSRs

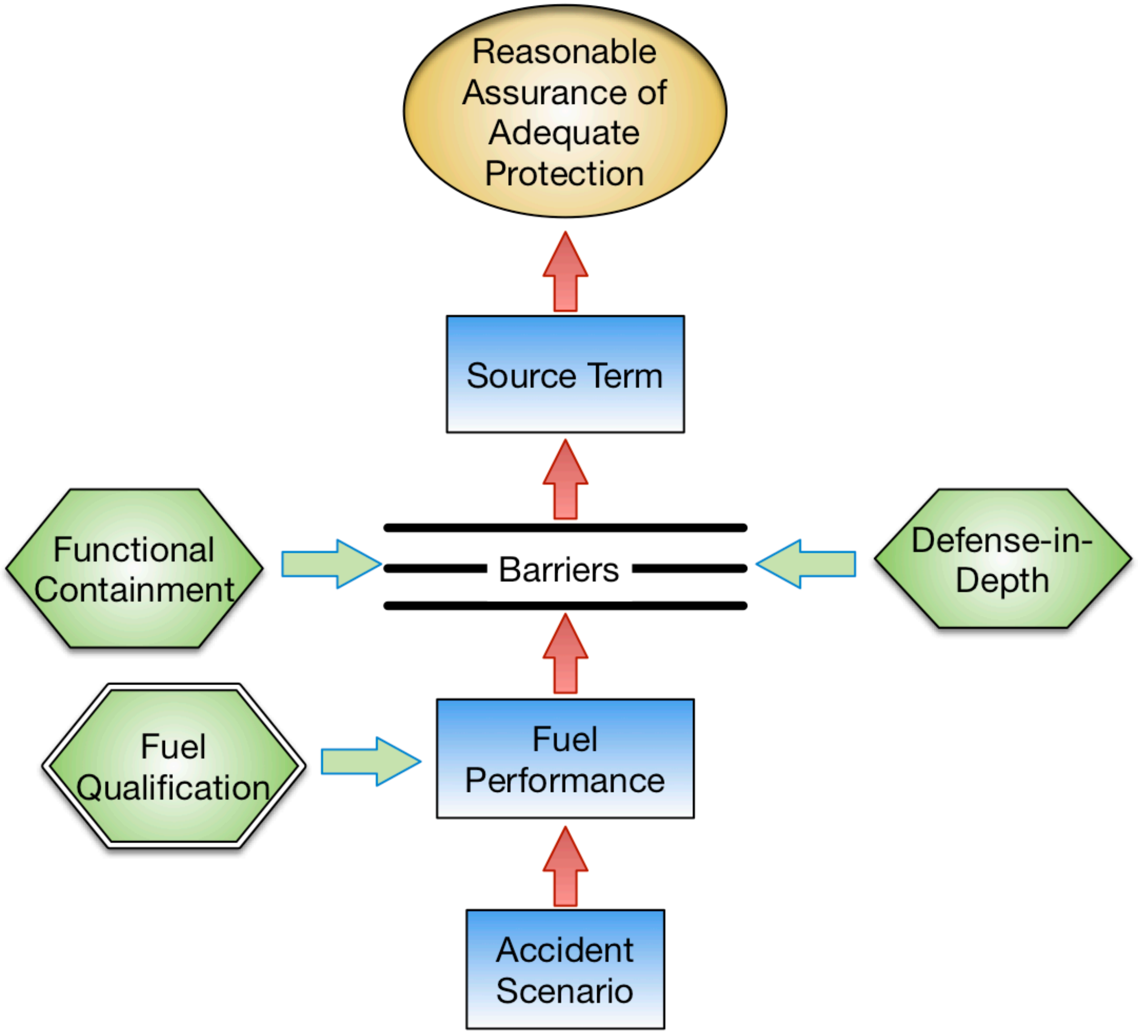
- More conservative than conventional single failure criterion
- Basic physics and chemistry are similar for any MSR
- Lack of adequate data resulted in very conservative source term estimate
  - Iodine trapping in suppression pool unaccounted for
- Electricity generating MSRs will have high-pressure power-cycle fluid connected via heat transfer loop
  - Requires rupture disks to isolate pressure

MSRs Currently Lack Adequate Decay Heat Transport Data to Provide Reasonable Assurance of Adequate Protection for Larger Systems

- As MSRs become larger, additional data is required to provide reasonable assurance that decay heat can be adequately rejected under some accident conditions
  - Lack of adequate decay heat rejection could cause multiple layers of containment to fail
  - Different data requirements for different decay heat rejection systems – DRACS, RVACS, PRACS, drain tanks, guard vessels, core catchers are all possible variants
- Demonstrating technologies for decay heat rejection under degraded conditions is a key next step to enable MSR safety evaluation

Qualified Fuel Salt is Key to Reliably Modeling MSR Performance

- Need to understand the chemical and physical behavior of the fuel salt adequately to model its performance in both normal and accident conditions
- Currently key focus of US national MSR activities is to develop adequate data to qualify fuel salt
- NRC is currently supporting activities to define acceptable liquid fuel salt qualification methods



Fuel Salt Data Quality Assurance Represents Potential Stumbling Block to Fuel Qualification

- Little (if any) fuel salt property data was generated under a nuclear-grade quality assurance program
  - Data has been generated by multiple institutions worldwide
  - Quality assurance information may no longer exist
- Unclear how to make most appropriate use of prior work
- Regulations require appropriate level of quality assurance reflecting the importance to safety
  - Fuel performance is very important to safety
- Will need sensitivity and uncertainty analysis as well as accident progression modeling tools to establish data requirements
  - Amount of validation required remains to be determined

Mechanistic Source Term Methodology for MSRs is Key to Understanding Containment Performance Adequacy

- NRC has established requirements for advanced reactors to employ a Mechanistic Source Term
  1. The performance of the reactor and fuel under normal and off normal conditions is **sufficiently well understood** to permit a mechanistic analysis.
  2. The transport of fission products can be **adequately modeled** for all barriers and pathways to the environs, including specific consideration of containment design.
  3. 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**.

Simulation and Modeling Tools are Needed to Perform Evaluations

- To provide initial conditions for accident progression evaluation
  - Reactor physics (radionuclide generation and consumption),
  - Fuel salt & cover gas motion and heat transfer,
  - Auxiliary system performance (fueling, defueling, salt treatment, plate out, etc.)
- To automate MST calculations for plant designs and scenarios
- Wide diversity of configurations substantially expands modeling requirements
- NRC reactor physics and hydraulics tools already exist that are suitable to model MSRs (SCALE, TRACE)
- New tools needed to provide radionuclide accountancy throughout containment – current activity to develop tool

Implementing MST Models into NRC Accident Modeling Tool is Underway

- MELCOR is NRC accident progression modeling tool
- MSR MST models are currently being developed and implemented into MELCOR in US national MSR program
- Distributed radionuclide configuration at start of accident is distinctive aspect of MSRs
- MELCOR requires further capability extension to accommodate diverse set of potential MSR configurations
  - Will provide building blocks for stakeholders to analyze particular designs under specific scenarios

MSR Safety Adequacy Evaluation Capabilities Are Advancing on Many Fronts

- Don’t yet have a complete and mature set of capabilities
- Preferred method for MSR safety adequacy demonstration will evolve as experience is gained with the technology
- Need to continue to advance fuel salt property understanding, modeling tool capabilities, as well as safety evaluation methodologies
- Distributed radionuclide configuration during normal operations necessitates a new material accountancy tool
- Most significant experimental hole is lack of data to model decay heat removal following fuel salt boundary rupture

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Upcoming Webinars

22 September 2020	Maximizing Clean Energy Integration: The Role of Nuclear Renewable Technologies in Integrated Energy Systems	Dr. Shannon Bragg-Sitton, INL, USA
28 October 2020	Global Potential for Small and Micro Reactor Systems to Provide Electricity Access	Prof. Amy Schweikert, Colorado School of Mines, USA
19 November 2020	Neutrino and Gen IV Reactor Systems	Prof. Jonathan Link, Virginia Tech, USA