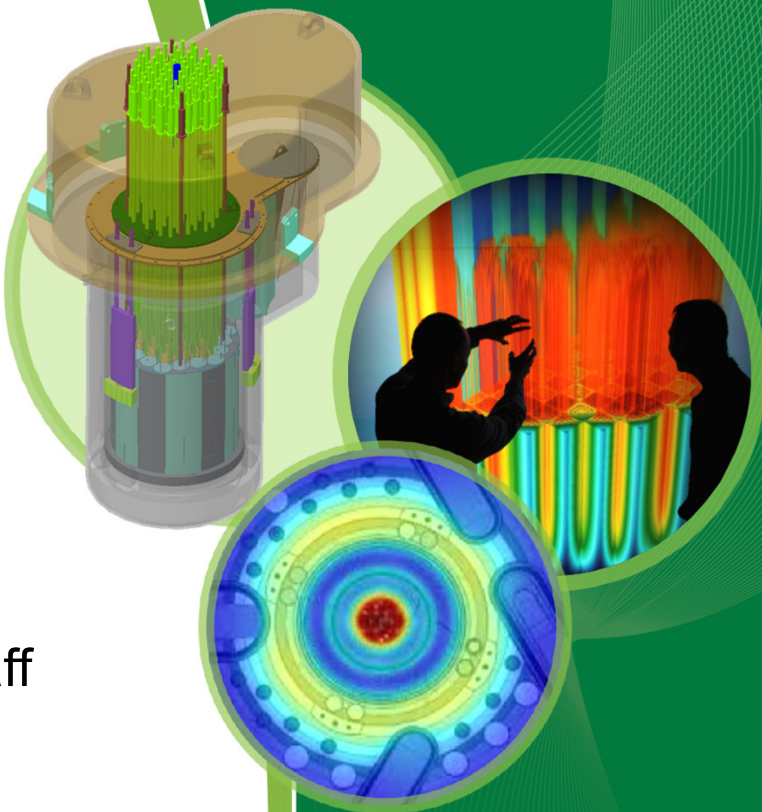
Module 10: Safety Analysis and Design Requirements



Presentation on Molten Salt Reactor Technology by:
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Module Objective

- Identify events and accident sequences specific to MSRs
- Identify issues associated with the analysis and prediction of plant responses, particularly with respect to releases of fission products that could pose a hazard to the surrounding population and the environment
- Show the differences of MSR accident sequences and those of LWRs
- Identify protected events, unprotected events, and severe accidents
- Identify and evaluate phenomena affecting the behavior of plants under accident conditions

MSRE Produced a Hazards Analysis which Identified the Types of Off-Normal Events that Might Occur in a MSR

- Low pressure systems reduce the possibility of energetic events, phase changes
- Core is in an optimal configuration from a geometric and fissile material loading perspective
  - Strong negative reactivity coefficients
- Based on experience with the Aircraft Reactor Experiment, Aircraft Test Reactor, and two Aqueous Homogeneous Reactors (I/II)
- Served as the basis for the more detailed accident analysis
- Reactor core accidents may not be the principal contributor to dose to the public
- Source terms are distributed between the reactor core and other process or storage systems
- Significant events can occur in the noncore systems and not affect the reactor core and vice versa

MSR Schematic

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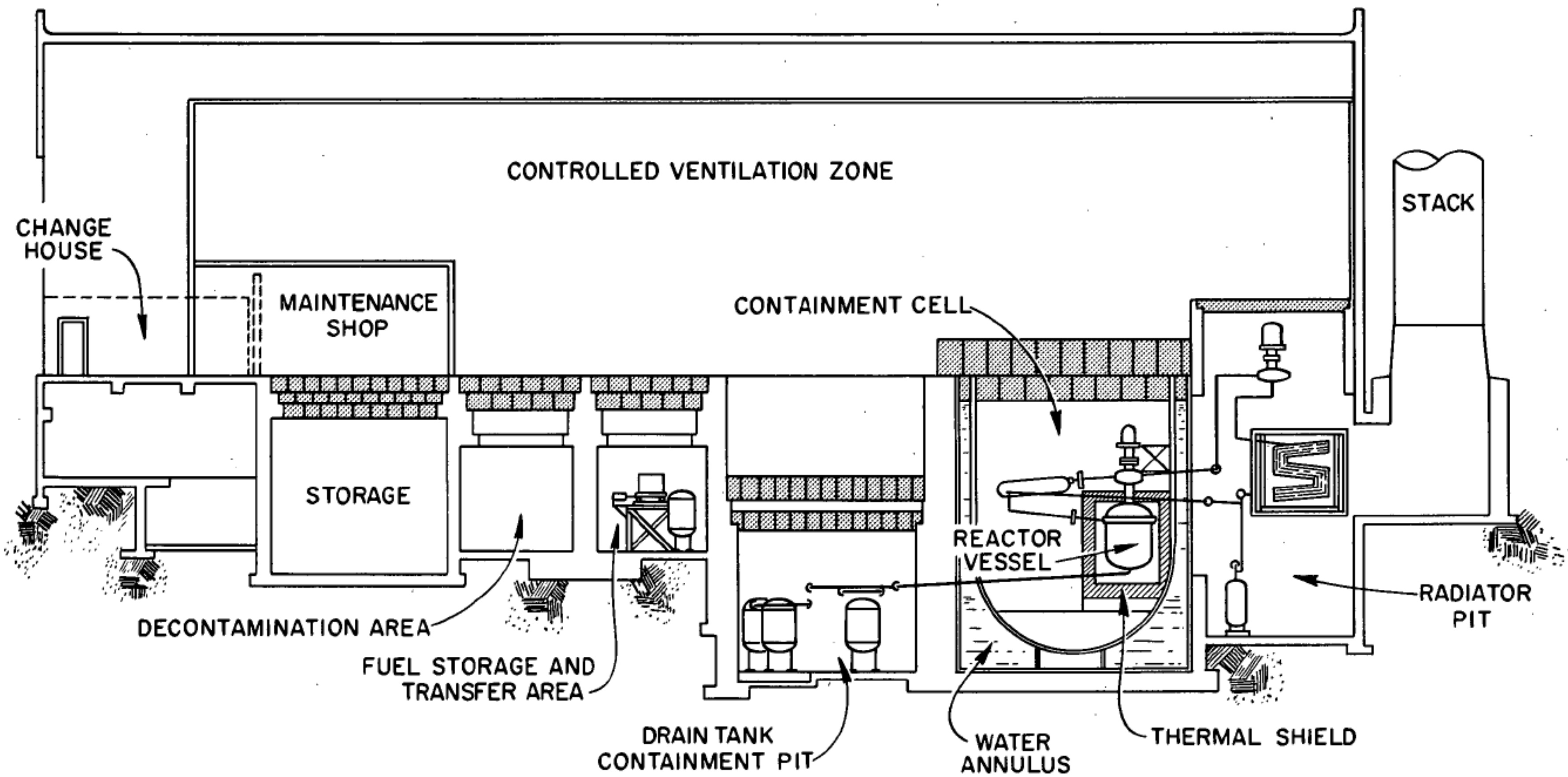

Fig. 17. North-South Sectional Elevation – Bldg. 7503

The Process Hazards Analysis Used a Barrier Approach to Accident Progression

- Discussion of accident progression in MSRs tends to focus on a “barrier” approach as opposed to the traditional LWR “component failure” approach
- A barrier approach focuses on events that can cause source terms to move between barriers
- Will focus on distributed source barriers due to source terms not only in the fuel salt loop but also in other areas such as offgas systems
- The MSRE evaluated the severity of accident scenarios by focusing on whether the primary or secondary containment is damaged
  - Most postulated MSRE core accident scenarios are benign due to the intrinsic nature of the system and the fuel salt

MSRE Primary Containment Accidents and Evaluation of Consequences

- Reactivity excursions
  - Startup accidents: poison not present to counteract excess reactivity, cold fuel slugs
    - No poison results in premature criticality, continue filling - core temperature rises, power is reduced by inherent reactivity feedback (unprotected)
    - Cold fuel slug – core temperature rises, power is reduced by inherent reactivity feedback
  - Graphite issues
    - Permeation of fuel into the graphite would occur slowly (if at all) and can be monitored
    - Large amount of permeation could lead to central graphite burning if vessel opened to air; mitigation strategies available to prevent air ingress (inert cells before maintenance)
    - Graphite shrinkage under irradiation (slow change easily detected and compensated for)
- Fuel separation
  - UO_2 precipitation (oxygen ingress and chemical control is lost)
    - Core temperature rises in event of slug of ^{235}U through core
- Core temperature rises all < 200°F (~95°C): within acceptance criteria

MSRE Primary Containment Accidents and Evaluation of Consequences

- Flow stoppage
  - All pumps fail, instantaneous flow stoppage in fuel loop
    - Core temperature rise due to additional delayed neutrons in core
    - Passive systems (e.g., cooling, draining) mitigate consequences
- Complete control system failure
  - Sudden removal of control poison
    - Core temperature rises but inherent feedbacks limit the rise
    - Primary containment damage unlikely
    - Passive systems mitigate consequences

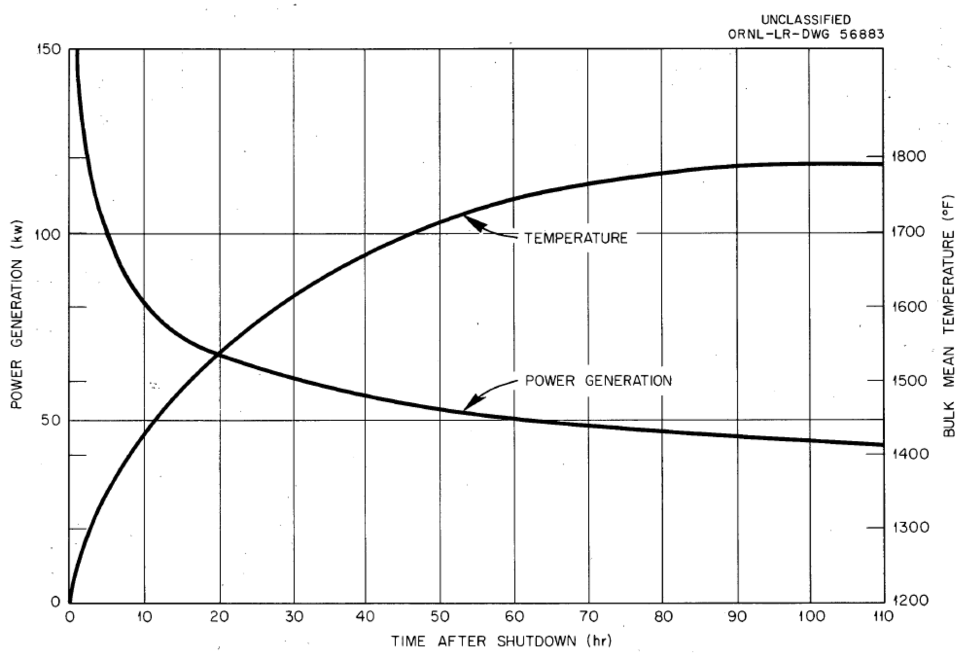

Fig. 21. Afterheat Power Generation and Temperature Rise of Core Vessel vs. Shutdown Time.

MSRE Primary Containment Accidents and Evaluation of Consequences

- Drain tank hazards
  - Loss of decay heat removal and potential critical fuel configurations
    - Flooding of area outside drain tank would act as a neutron reflector
    - Precipitation of fuel due to oxidizing agent present
    - Combined effects still produce $k_{eff} < 1.0$ (0.85)
    - Loss of decay heat removal - passive systems mitigate consequences (passive water cooling)
- Other
  - Freeze valve and freeze flange damage (pipe rupture)
  - Excessive wall temperatures (from electric heater malfunction)
  - Excessive stress from thermal cycling or gamma heating
  - Vessel and other components
  - Overheating and possible combustion of fission product absorption beds (charcoal) - passive cooling below combustion level (submerged in water)
  - Corrosion: not significant for MSRE (redox control)

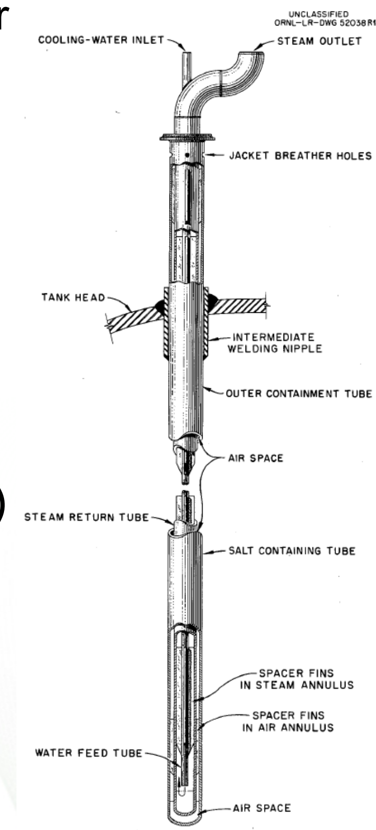

Fig. 9. Cooling Thimble for Primary-Salt Drain Tanks.

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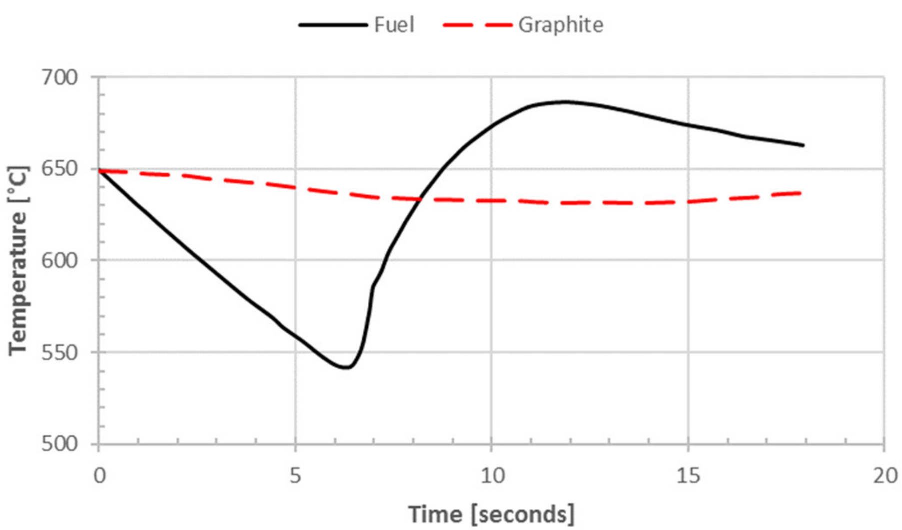
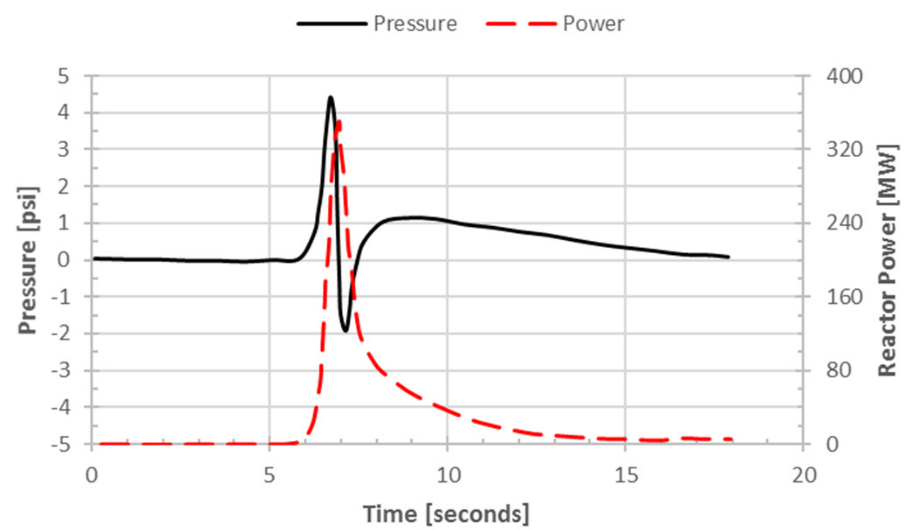
MSRE Simulation of Accident Scenarios: Example – Cold Slug

- Worst case scenario for cold slug of 20 ft^3 at 480°C (900°F)
- Core initially critical at 650°C (1200°F) with 10 kW of power and no circulating fuel
- Demonstrates inherently safe feedback of the reactor
- Similar tests with control rod action limited peak power to only 0.66 MW





Source: ORNL-TM-251

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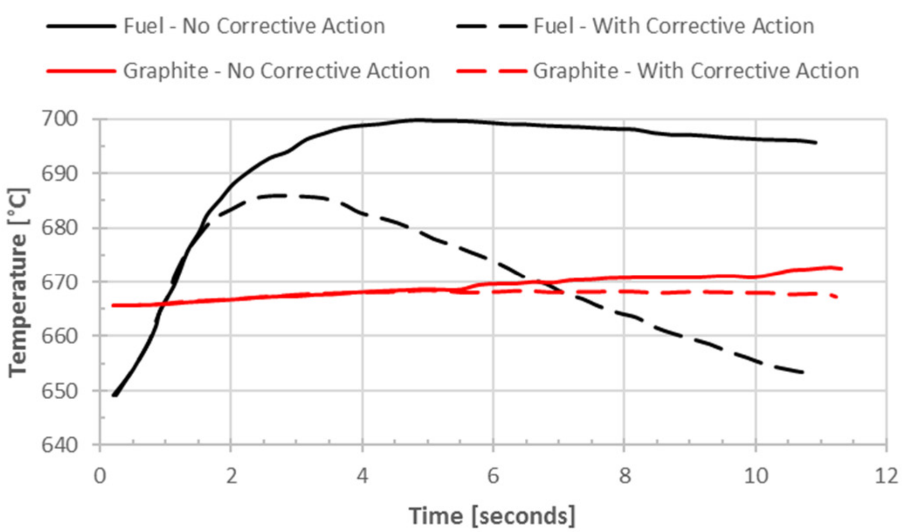
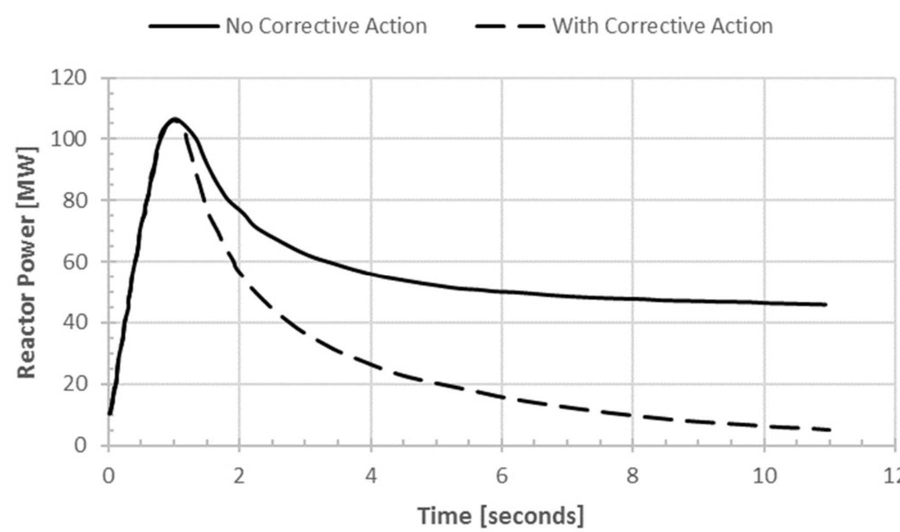
MSRE Simulation of Accident Scenarios: Example – Reactivity Insertion

- Reactivity insertion of 0.338% Δk/k which makes the reactor exactly prompt critical
- Demonstration with and without corrective action illustrates inherent safety of the reactor
- Corrective action is -0.075% Δk/k per sec beginning at 1 s

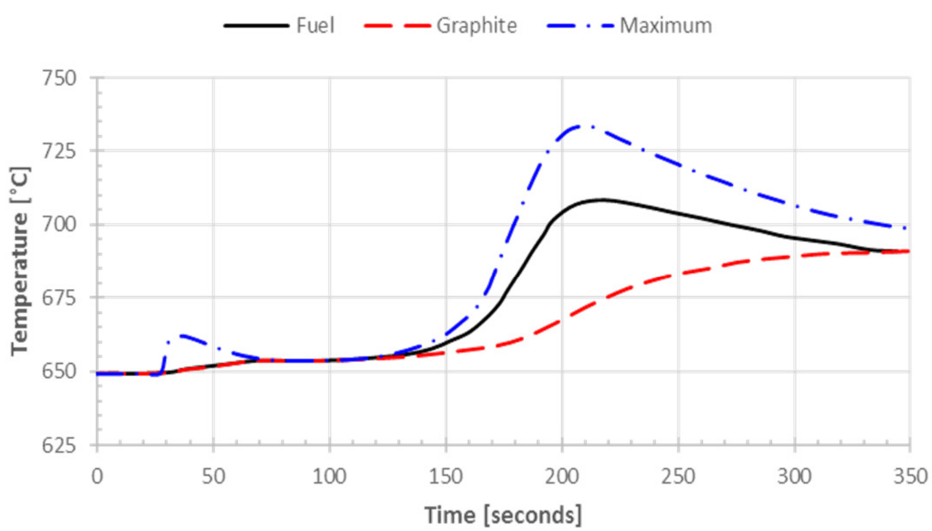


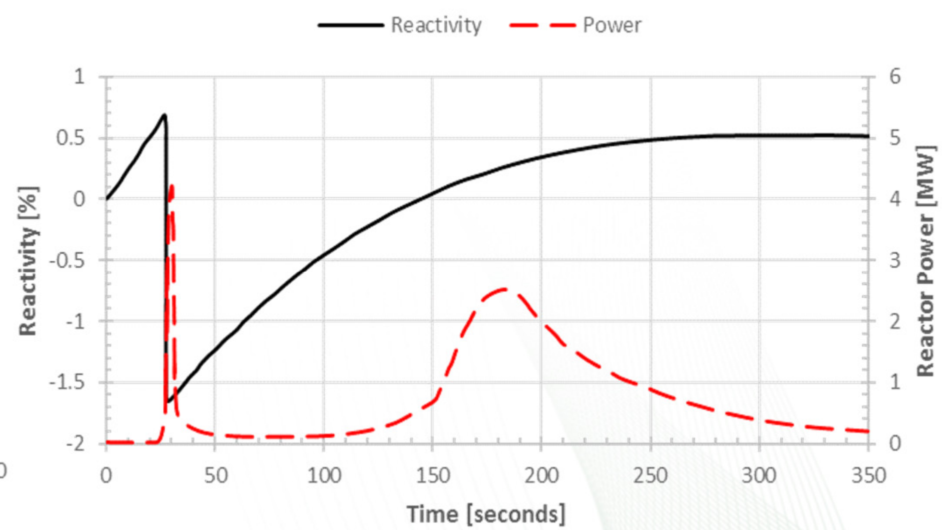


Source: ORNL-TM-251

MSRE Simulation of Accident Scenarios: Example – Fuel Filling Accident

- Maximum reasonable filling accident
  - Fuel composition is least favorable for safe filling (most excess reactivity)
  - Gas supply overpressured from 40 psig to 50 psig (increases salt addition rate)
  - 1 of 3 control rods fails to insert. Other 2 rods automatically insert when power reaches 150% of design power (see transient at ~30 seconds)
  - Only 1 of 3 valves (the gas addition valve) functioned properly
- Maximum temperature safely within tolerated range





Source: ORNL-TM-497

External Hazards Not Extensively Evaluated for MSRE

- Location not subject to severe earthquakes
- Location not subject to flooding

Final Safety Analysis of MSRE (ORNL-TM-732)

- In addition to reactivity events the SAR examined
  - Loss of Flow
  - Loss of Heat Sink
  - Decay Heat Removal
  - Criticality in Drain Tanks
  - Freeze valve and flange failures
  - Excessive wall temperatures
  - Corrosion
  - Salt spillage
  - Be release from a leak
- Most probable accident- small leak into secondary container
  - Radiation monitors would alarm and shut down reactor
  - Airborne activity pumped from secondary containment through clean up system and filters released up the stack did not exceed maximum permissible dose on-site

Final Safety Analysis of MSRE (cont.)

- Maximum Credible Accident
  - Break in drain line (1 ½ inches) 10,000 lbs. salt released to secondary containment
  - Or Break in 5-inch fuel line (4,000 lbs. salt released)
  - Assumed both total 10,000 lbs. (4,000 from fuel and 6,000 from drain line in 280 sec.
  - Simultaneous spillage of water into secondary containment to maximize steam pressure
  - 110 psig (no venting)
  - Rupture disk opens at 20 PSIG to vapor condensing system
  - Maximum pressure in secondary containment is 39 psig (no rupture)
  - 1% leakage at 39 psig
  - Dose offsite (3,000 m) is 6 rem from Iodine under worst meteorological conditions
    - 10% iodine, 10% solids,100% nobles

Lessons Learned from MSRE Hazards Assessment

- Traditional LWR accident scenarios may need to be reevaluated for applicability to MSRs
- Accidents generally progress slowly
- Strong negative reactivity feedback makes many accidents benign
- Filling and draining events need to be considered
- Distributed delayed neutrons result in more narrow margins to prompt criticality
  - Results in insertion of reactivity during flow blockages
  - MSRE showed no indications of instability as a result of delayed neutron distribution

Determination of Mechanistic Source Terms Will Be Challenging

- Distributed source terms
  - Core
  - Drain tanks
  - Offgas system and storage
  - Pumps/heat exchangers
  - Purge tanks
  - Spent fuel storage
  - Drain lines and valves
- Core accidents are only one of many contributions to releases
  - Many potential releases are not a result of traditional core accidents (Chapter 15)

Determination of Mechanistic Source Terms Will Be Challenging (cont.)

- SECY-05-0006 “Second Status Paper on the Staff’s Proposed Regulatory Structure for New Plant Licensing and Update on Policy Issues Related to New Plant Licensing”
  - Scenario-specific source terms may be used for licensing purposes
  - Scenarios should be selected from design specific PRA and include consideration of uncertainties
  - Based on verified analytical tools
  - Scenarios used for licensing decisions should reflect scenario specific timing, form, and magnitude of radioactive material released for fuel and coolant
    - Credit natural and/or engineering attenuation mechanisms

MSR's Distributed Source Terms and Unique Retention Capabilities Will Make It Difficult to Address All the Scenarios

- Timing of events could range from sudden (rupture of gaseous fission product holdup tank) to long term (leaks in liquid drain line)
- Form of release will vary from gases to hot liquids to solids
- Events could range from overheating due to loss of heat removal to external events involving more than one source
- Core events may not result in the dominate source
  - Accident scenarios derived from PRA may not be the maximum source term
- Since fuel salt composition is changing with time the natural phenomena retention mechanisms may change as well
- Low pressure impacts the driving force challenging containment

Fission Product Distributions Were Determined from the MSRE

Table 12.3. Indicated distribution of fission products in molten-salt reactors

Fission product group	Example isotopes	Distribution (%)				
		In salt	To metal	To graphite	To off-gas	Other
Stable salt seekers	Zr-95, Ce-144, Nd-147	~99	Negligible	< 1 (fission recoils)	Negligible	Processing[a]
Stable salt seekers (noble gas precursors)	Sr-89, Cs-137, Ba-140, Y-91	Variable/$T_{1/2}$ of gas	Negligible	Low	Variable/$T_{1/2}$ of gas	
Noble gases	Kr-89, Kr-91, Xe-135, Xe-137	Low/$T_{1/2}$ of gas	Negligible	Low	High/$T_{1/2}$ of gas	
Noble metals	Nb-95, Mo-99, Ru-106, Ag-111	1–20	5–30	5–30	Negligible	Processing[b]
Tellurium, antimony	Te-129, Te-127, Sb-125	1–20	20–90	5–30	Negligible	Processing[b]
Iodine	I-131, I-135	50–75	< 1	< 1	Negligible	Processing[c]

[a]For example, zirconium tends to accumulate with protactinium holdup in reductive extraction processing.

[b]Particulate observations suggest appreciable percentages will appear in processing streams.

[c]Substantial iodine could be removed if side-stream stripping is used to remove I-135.

Source: ORNL-4865

Important Considerations

- Traditional LWR approach to accident progression is not expected to be the same for MSRs
- Source terms will be present outside of the primary fuel/coolant loop (i.e., in the offgas system)
- Secondary containment or other barriers will be required to account for decay heat removal in systems not directly associated with the primary fuel/coolant loop
- Consequences of breach of secondary containment need to be investigated (severe accident and releases)
- External impacts (e.g., natural disasters and aircraft crashes) on an MSR needs to be investigated

Summary

- MSRs have highly favorable intrinsic safety responses to accident scenarios
- The explicit integration of passive safety systems into the design process mitigates many of the severe accident scenarios
- Special consideration will need to be given to the distributed source terms in MSR systems that is not present in LWRs
- Proper evaluation of bounding events and their impact on an MSRs operation needs to be studied