

Module 10: Safety Analysis and Design Requirements

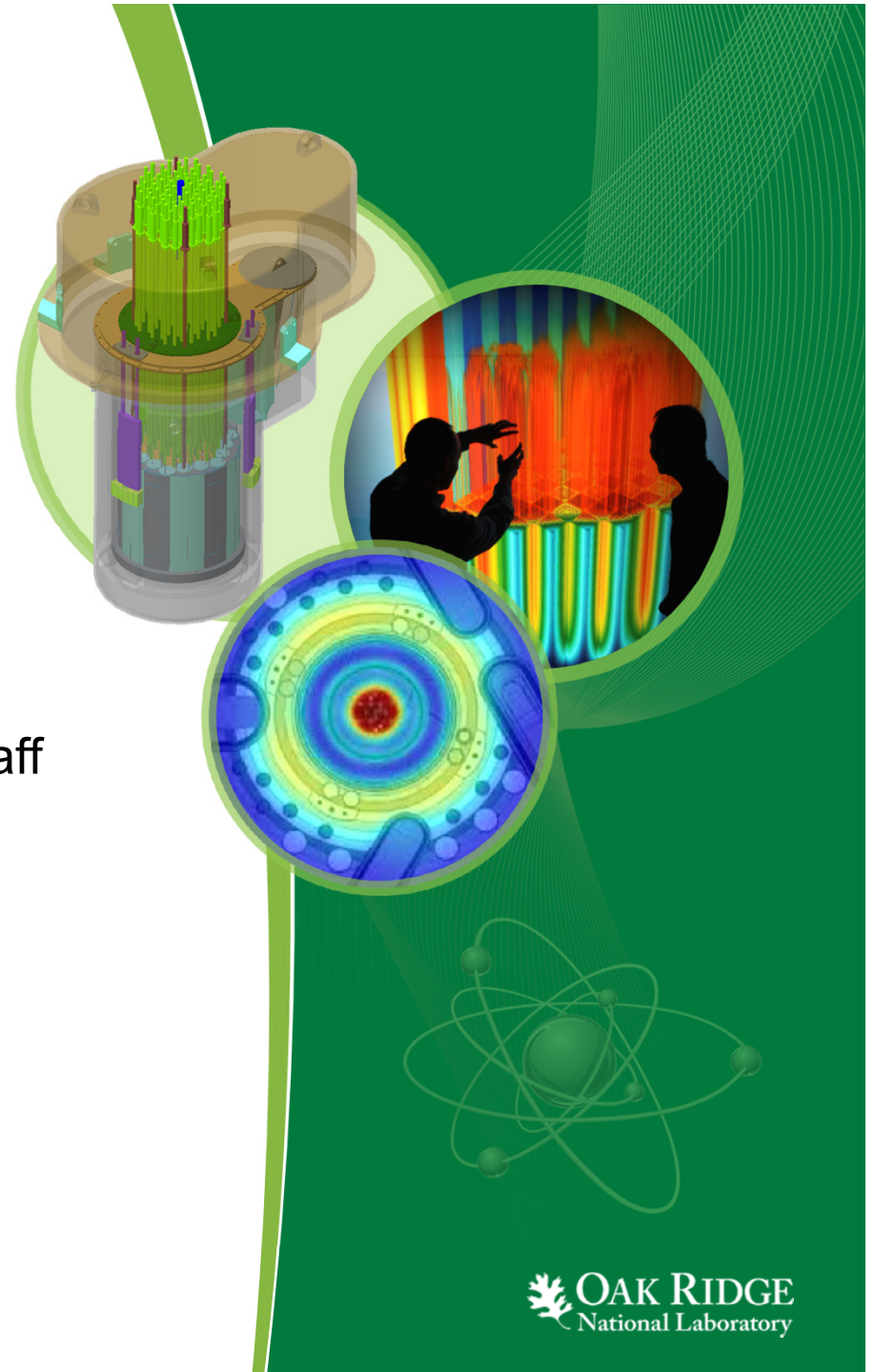
**Presentation on Molten Salt Reactor Technology by:
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Advanced Reactor Systems and Safety
Reactor and Nuclear Systems Division

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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

UNCLASSIFIED
ORNL-LR-DWG 56881

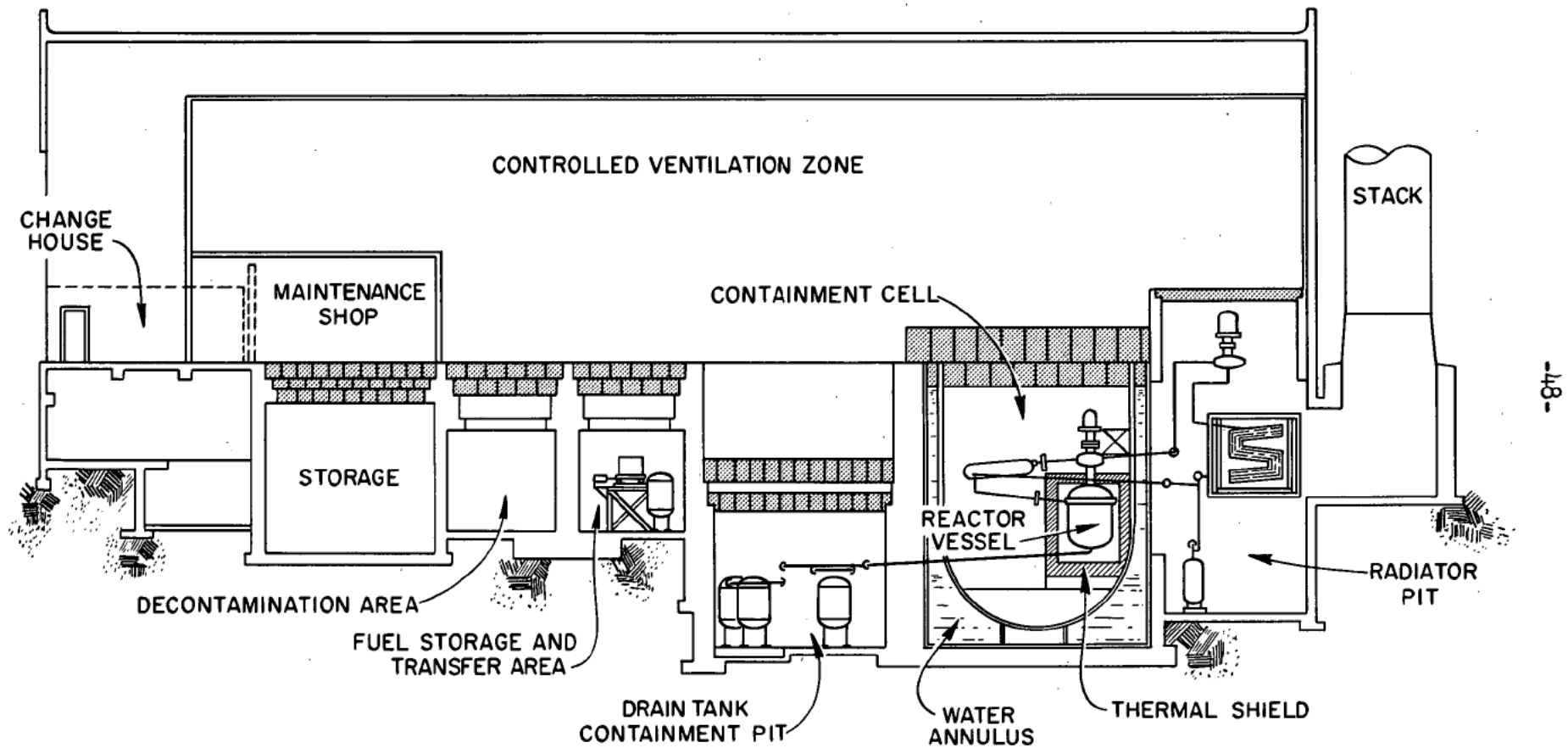


Fig. 17. North-South Sectional Elevation - Bldg. 7503

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 $< 200^\circ\text{F}$ ($\sim 95^\circ\text{C}$): 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

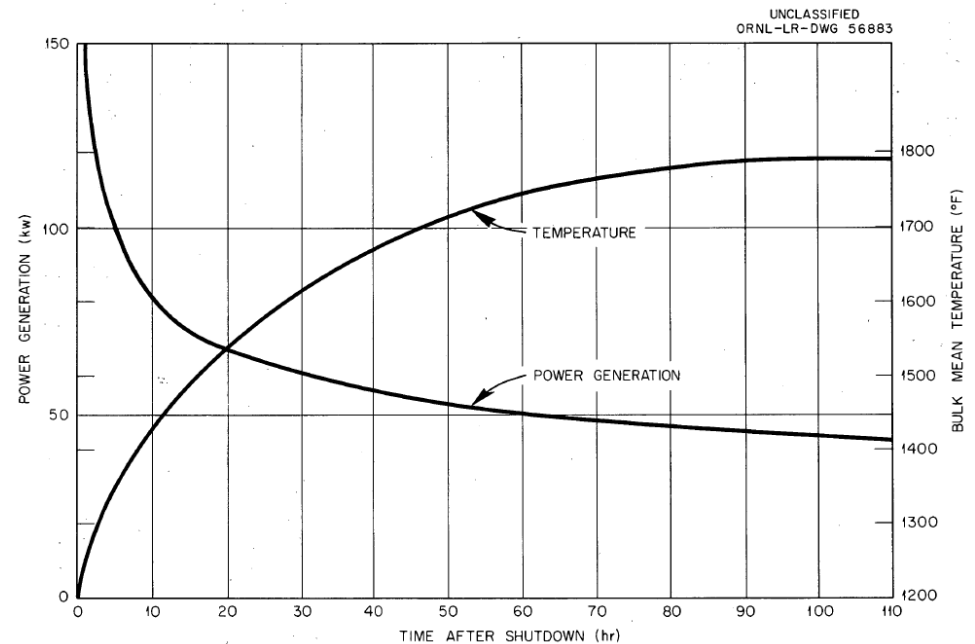


Fig. 21. Afterheat Power Generation and Temperature Rise of Core Vessel vs. Shutdown Time.

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 $k_{\text{eff}} < 1.0$ (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)

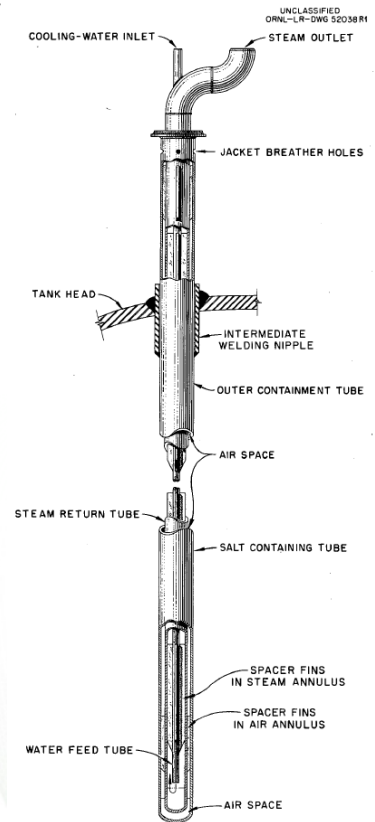
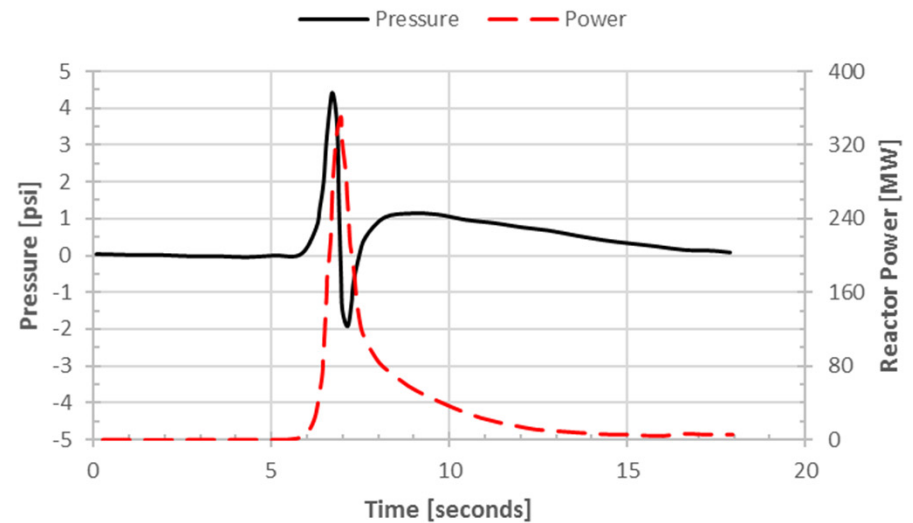
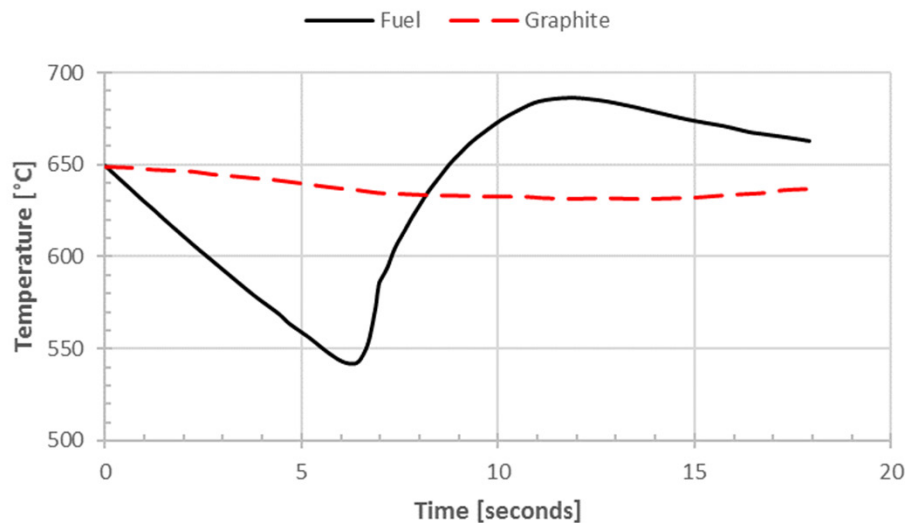


Fig. 9. Cooling Thimble for Primary-Salt Drain Tanks.

MSRE Simulation of Accident Scenarios: Example – Cold Slug

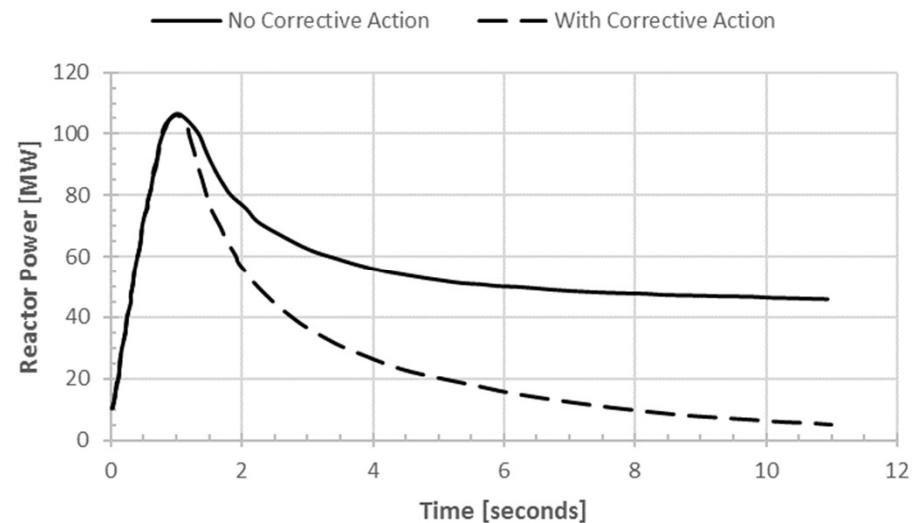
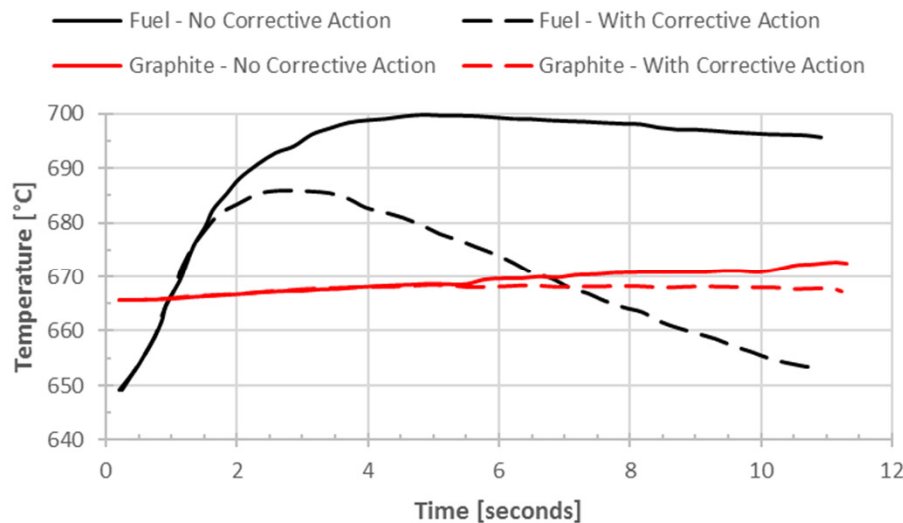
- Worst case scenario for cold slug of 20 ft³ at 480°C (900°F)
- Core initially critical at 650°C (1200°F) with 10 kW of power and no circulating fuel
- Demonstrates inherently safe feedback of the reactor
- Similar tests with control rod action limited peak power to only 0.66 MW



Source: ORNL-TM-251

MSRE Simulation of Accident Scenarios: Example – Reactivity Insertion

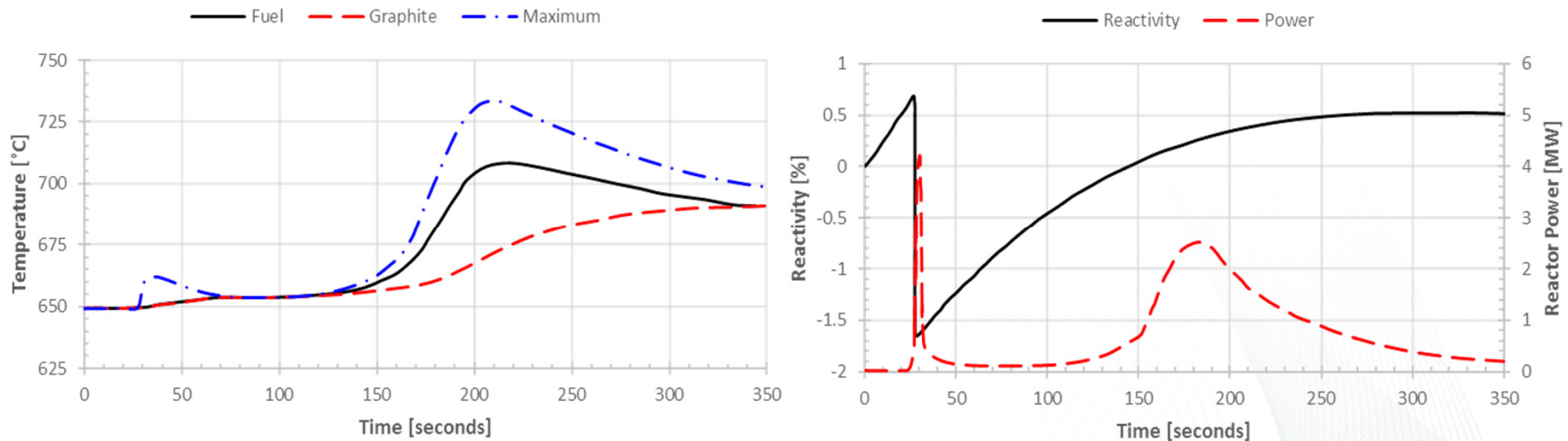
- Reactivity insertion of 0.338% $\Delta k/k$ which makes the reactor exactly prompt critical
- Demonstration with and without corrective action illustrates inherent safety of the reactor
- Corrective action is -0.075% $\Delta k/k$ per sec beginning at 1 s



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

^aFor example, zirconium tends to accumulate with protactinium holdup in reductive extraction processing.

^bParticulate observations suggest appreciable percentages will appear in processing streams.

^cSubstantial 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 MSR
- 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