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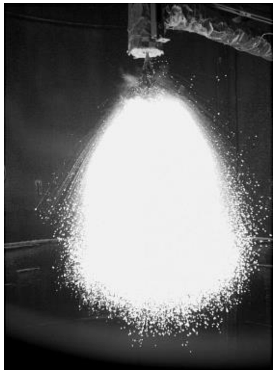

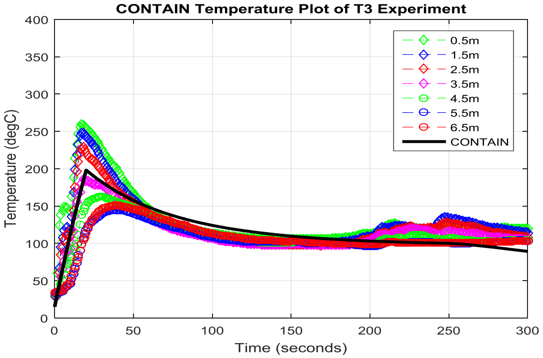

SNL Sodium Fast Reactor Safety Research

Matthew Denman
Andrew Clark
Severe Accident Analysis and Risk and Reliability Analysis

Presentation to TerraPower

July 14th 2016

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Sandia Sodium Reactor Safety Research

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NRC CRBR Sodium Experimental Research

- 1975-1982
- Fuel Vaporization
- Core Debris Coolability
- Accident Precursor Studies

Sodium Fire Experiments

- 2008-2010
- Pool and Spray Fires
- Proof of Capability

Contain-LMR Development

- 1982-1992
- Models sodium fires and aerosol transport
- Contain-LMR used in the GE-PRISM Level 3 PRA
- Multiple Containment and Source Term Assessments

SFR Safety and Licensing Research

- 2009-2016+
- Lead Multi-Lab Gap Analysis
- Contain-LMR ▶ MELCOR
- Mechanistic Source Term
- CREDO Reliability Database
- Dynamic Probabilistic Risk Assessment
- GIF Task Force

Overview

- Sandia Historical NRC Sodium Research
  - ACRR fuel vaporization and debris coolability
  - CONTAIN-LMR development
  - Source term modeling for SFRs
- Sodium Fire Experiments
  - Sodium fire modeling
- Sandia Led CONTAIN-LMR revival
  - MELCOR/CONTAIN-LMR implementation
  - ANL/SNL source term
- SNL's SFR Probabilistic Risk Assessment Research
  - CREDO database
  - Advanced PRA
  - GIF

NRC Sodium Research at Sandia 1975-1992

Experiments to Support Clinch River

- Fuel Vaporization (Energetic Core Disruption)
- Debris Bed Coolability

Contain-LMR Development

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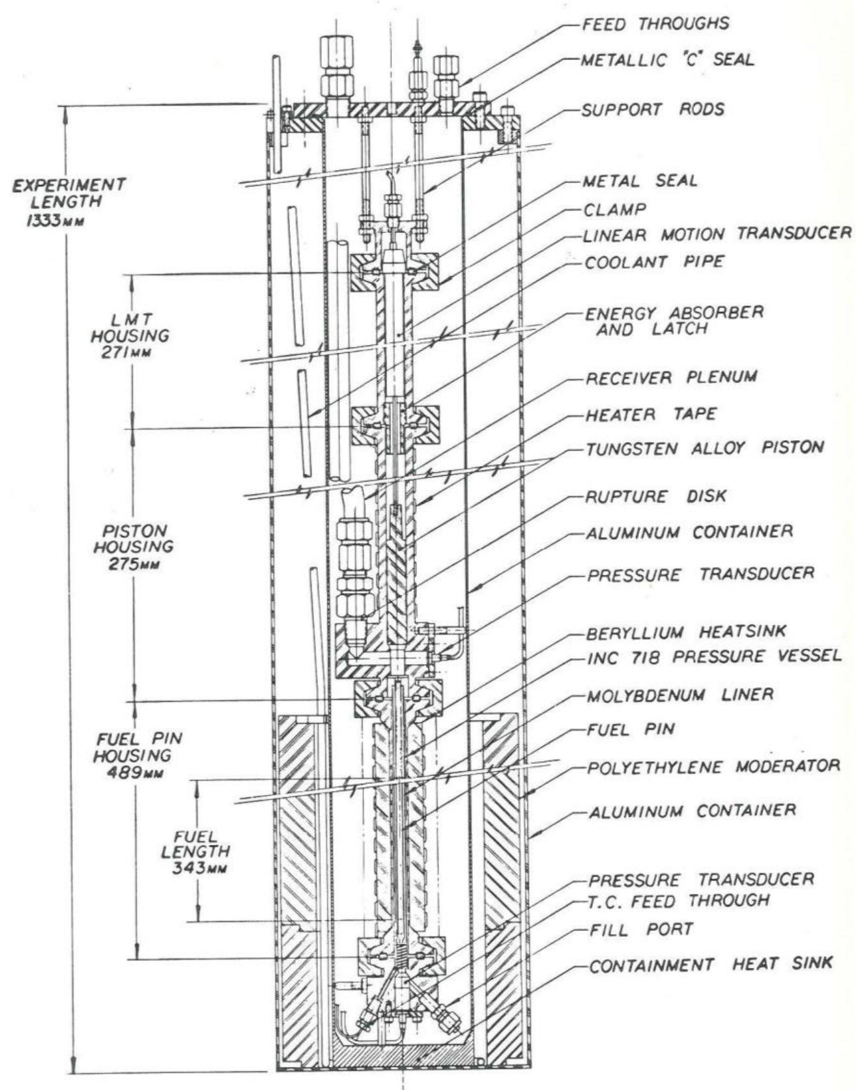
Prompt Burst Excursion Experiments

- Where:
  - Sandia, Annular Core Research Reactor (ACRR)
- Why:
  - Understand mechanical loadings from Hypothetical Core Disruptive Accidents (HCDAs)
- Who:
  - Nuclear Regulatory Commission



PROMPT BURST EXCURSION EXPERIMENT

Figure 1. Instrumented Experimental Package

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Prompt Burst Excursion Experiments

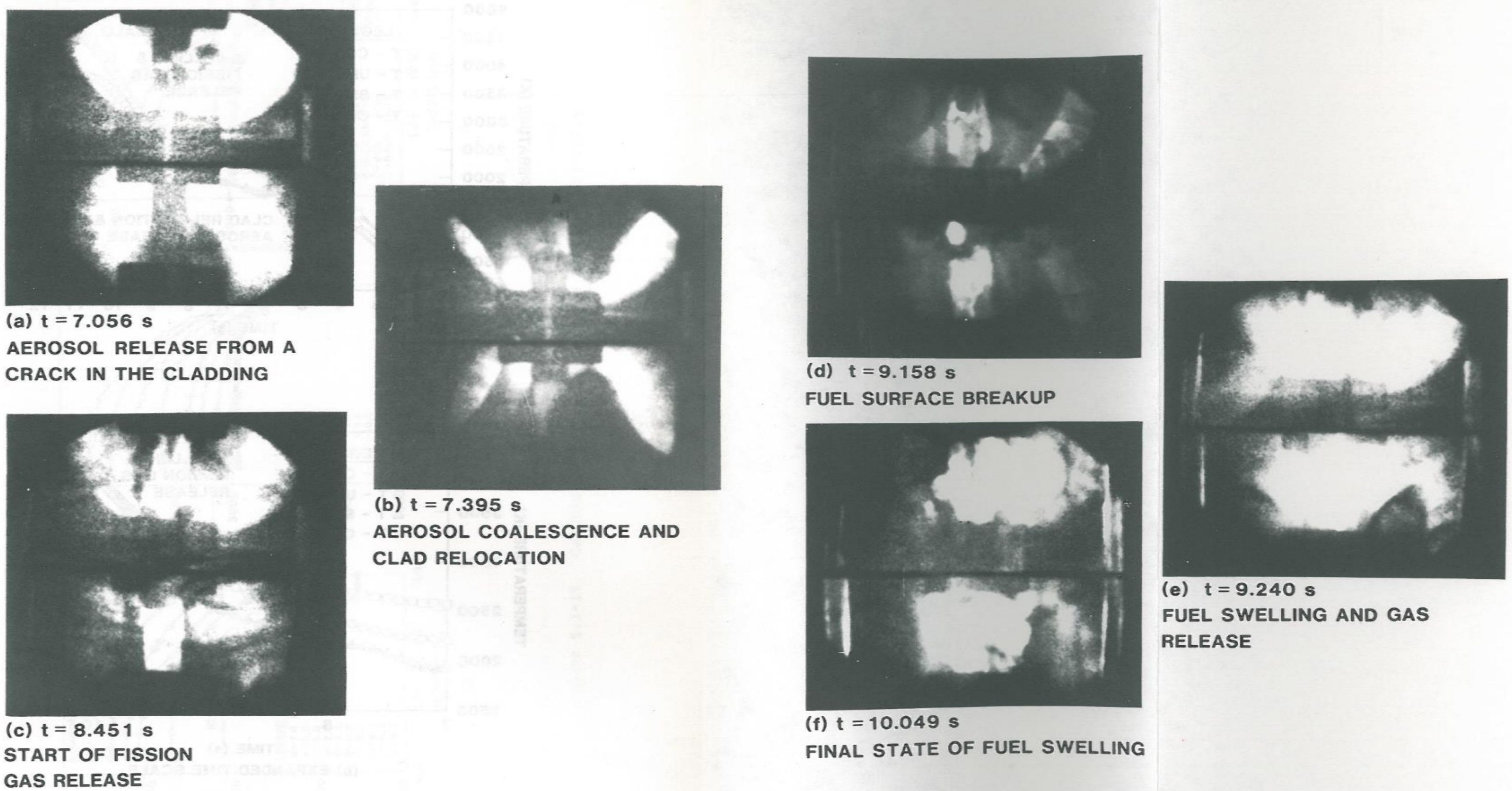


Figure 5.1-13. Photographs Corresponding to Events From Table 5-IV, Experiment FD2.6

Prompt Burst Excursion Experiments

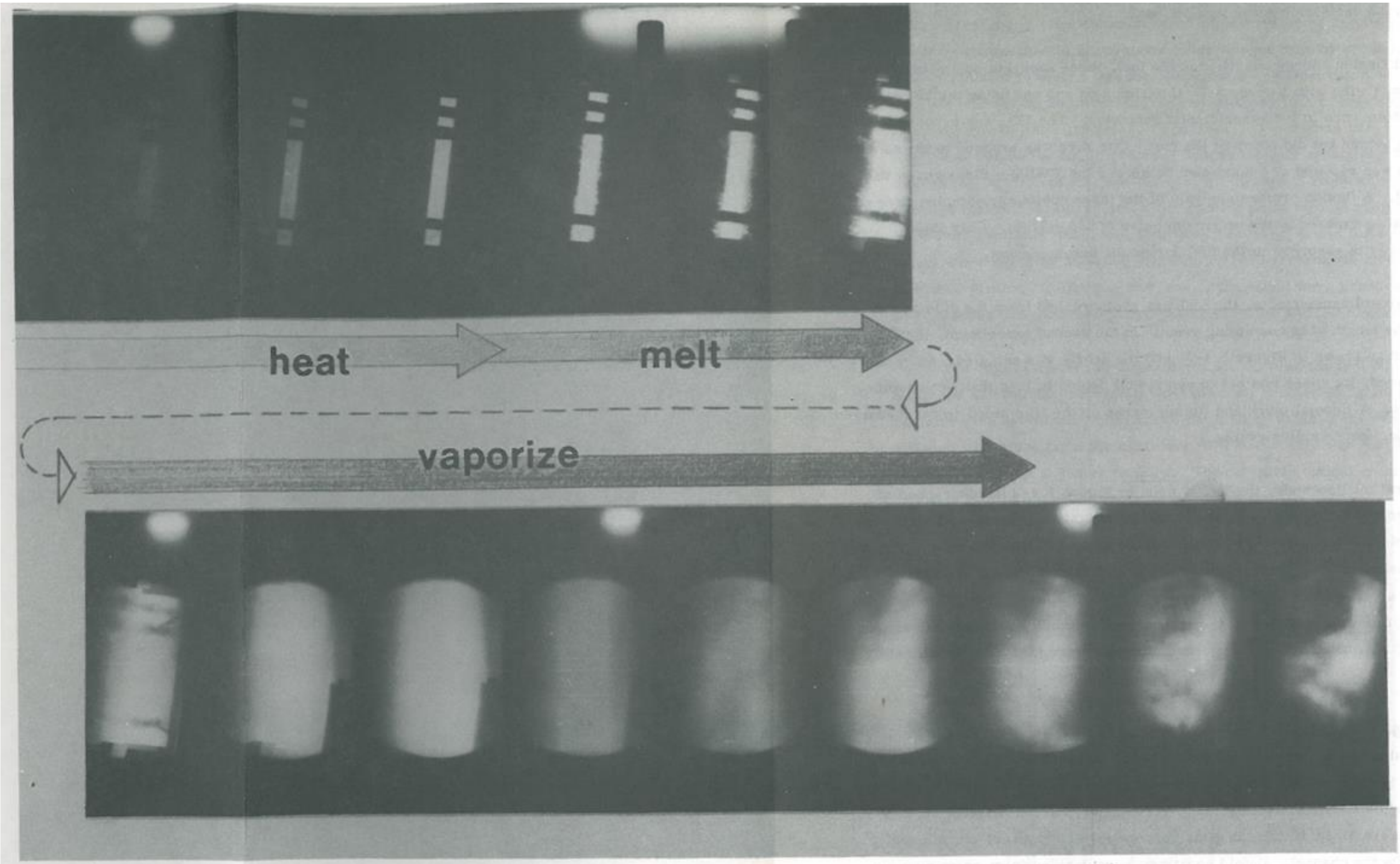


Figure 1.4-2. High-Speed Photographs taken at 3000 Frames/Second Showing a Side View of a Fresh UO_2 Fuel Pin, 20 Percent Enriched with ^{235}U, Vaporizing from a 5-Millisecond FWHM Neutron Pulse. (The resulting fissions deliver 569 cal/gm of thermal energy to the fuel during breakup.)

Prompt Burst Excursion Experiments

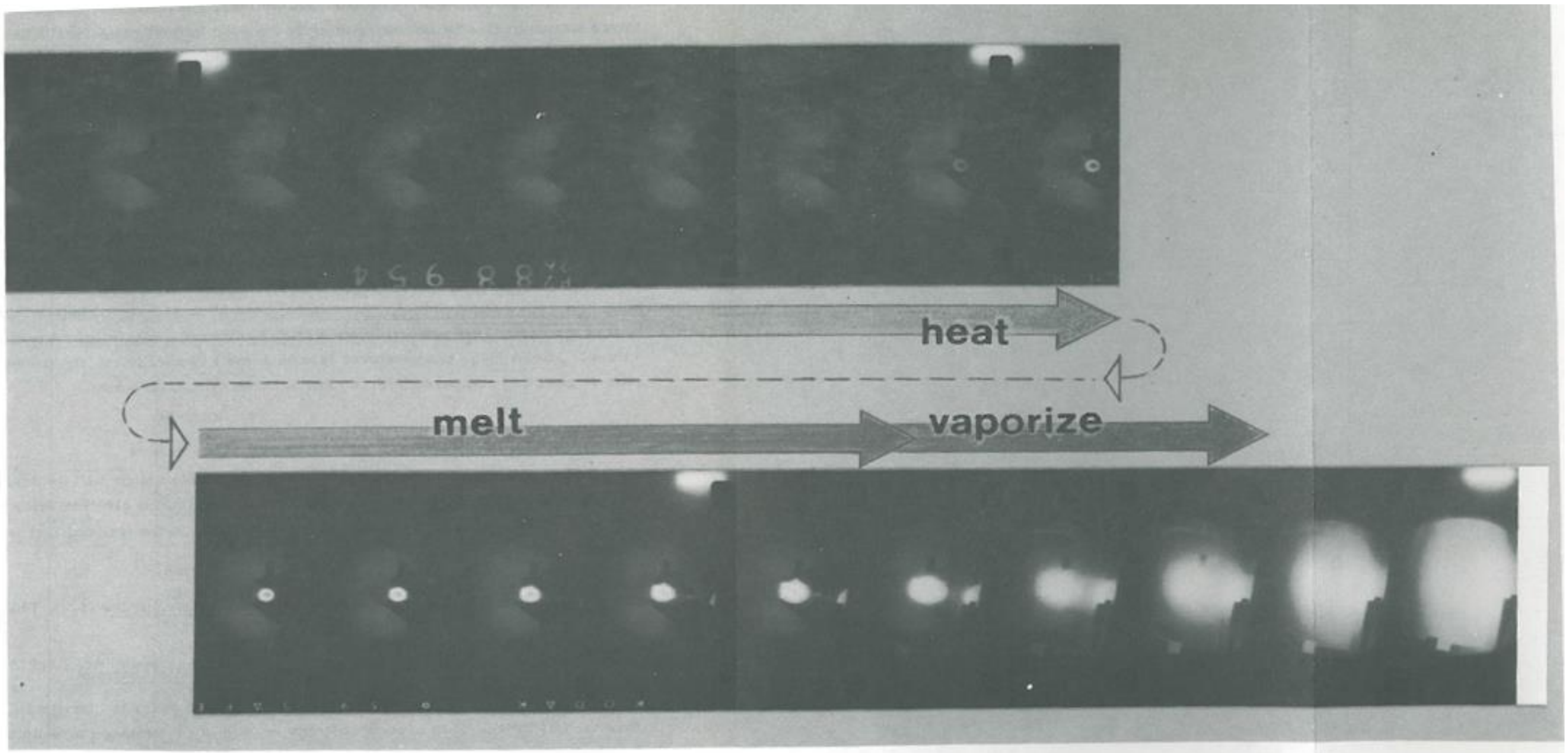
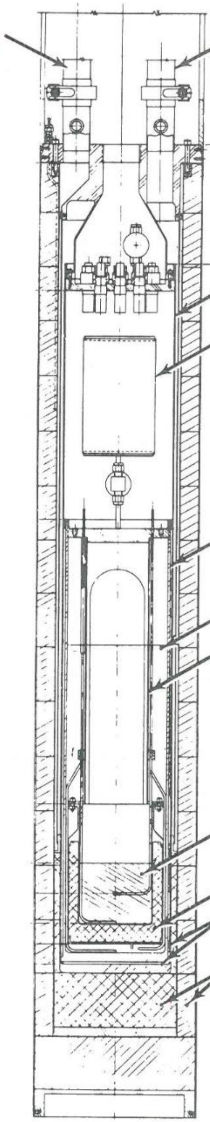


Figure 1.4-3. High-Speed Photographs Taken at 6000 Frames/Second Showing an End View of the Fuel Which Corresponds to the Side View of Figure 1.4-2. (A hole drilled in the end of the fuel was for estimating center line fuel temperatures.)

Oxide Core Debris Coolability Experiments

- Where:
  - Sandia, Annular Core Pulse Reactor (ACPR)
  - Sandia, Annular Core Research Reactor
- Why:
  - Understand how and if core debris can remain coolable post-meltdown
- Who:
  - Nuclear Regulatory Commission



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Oxide Core Debris Coolability Experiments

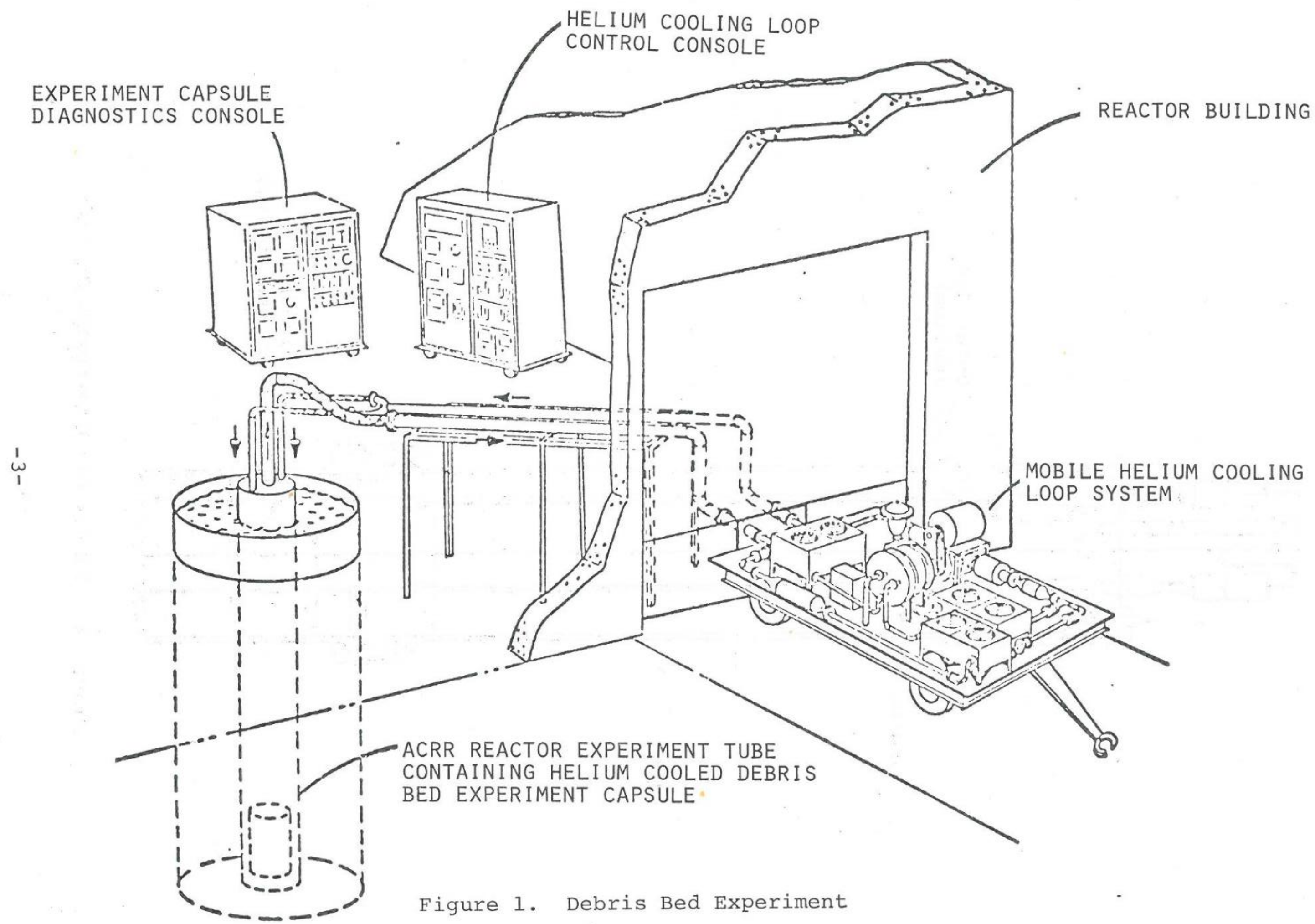

Figure 1. Debris Bed Experiment

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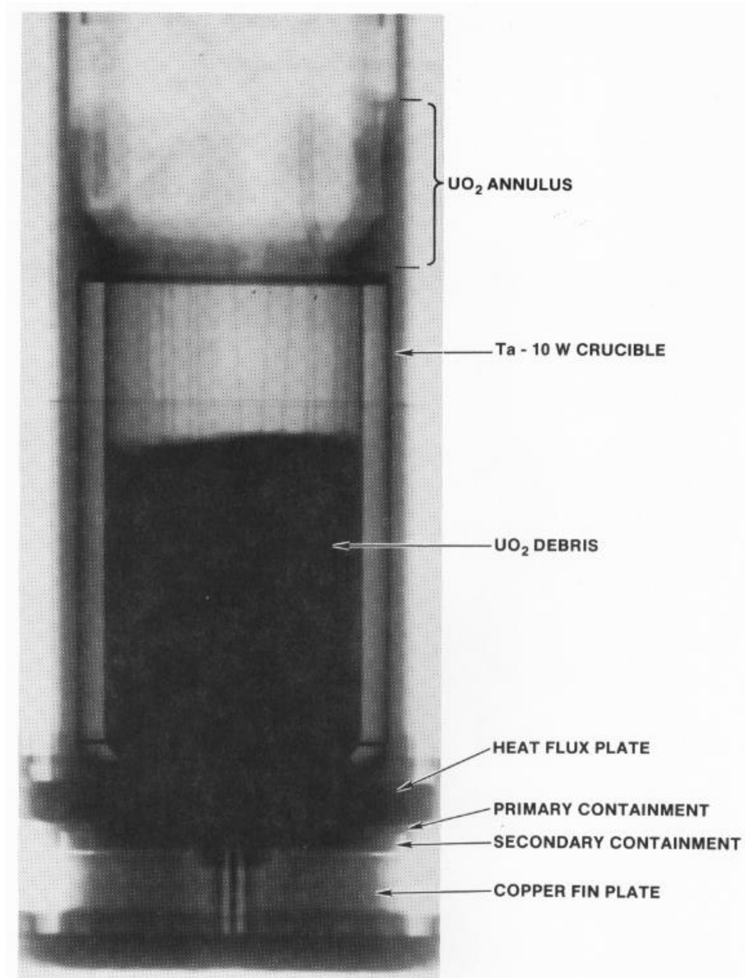
Core Debris Coolabilty (Results)



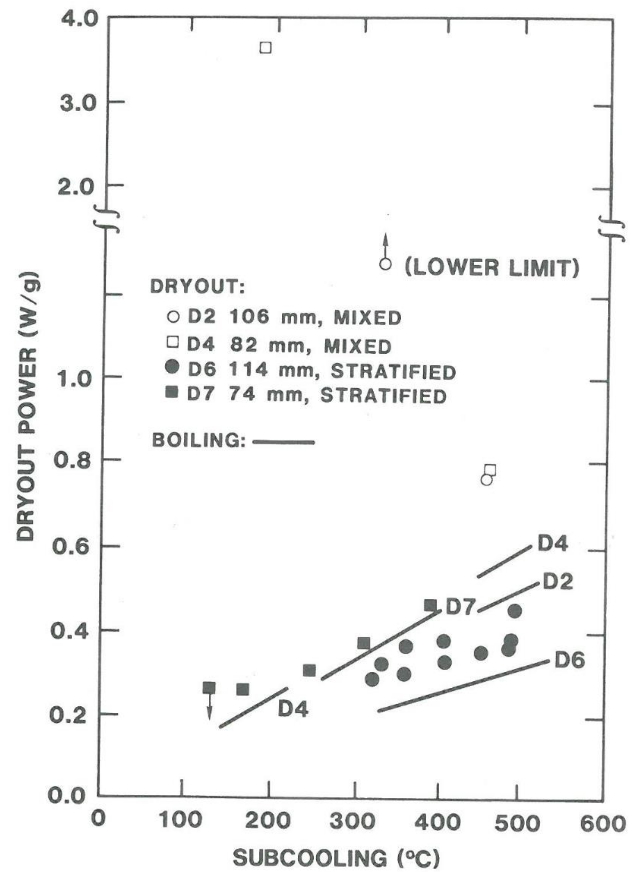


Figure 4-9. Dryout Power vs. Sodium Subcooling for all D-Series Experiments

SAND86-1043
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SNL CONTAIN Code Release History

Version	Date	Improvements
1.0	1984	First Release of Code
1.06	1987	CORCON-Mod2, VANESA, Water dropout,..
1.11*	1991	Moving-grid technique for solving aerosol growth by water vapor condensation
1.12	1991	Add DCH modeling, reactor cavity models for high pressure debris dispersal and vessel blowdown,..
1.2	1995	Film flow on wall structures, energy and mass conservation tracking, CORCON Mod3,..
2.0	1997	Improvements in the DCH and hydrogen burn models

*Note that CONTAIN-LMR was derived from CONTAIN 1.11, but was brought to CONTAIN2.0 standards in 2015.

CONTAIN-LMR Background

- Analysis tool for predicting the physical, chemical, and radiological conditions inside the containment and connected buildings of a nuclear reactor in the event of an accident.
- CONTAIN Code Models
  - Intercell gas flow, including natural circulation
  - Two-phase atmospheric thermodynamics
  - Conduction in structures
  - Convective and radiant heat transfer
  - Condensation/evaporation at structure and pool surfaces
  - Hydrogen combustion
  - Multi-component aerosol processes
  - Transport and decay heating from fission products
  - Ablation of concrete by core debris
  - Does not model reactor core/vessel and accident initiation

PRISM PSAR - Level 3 PRA

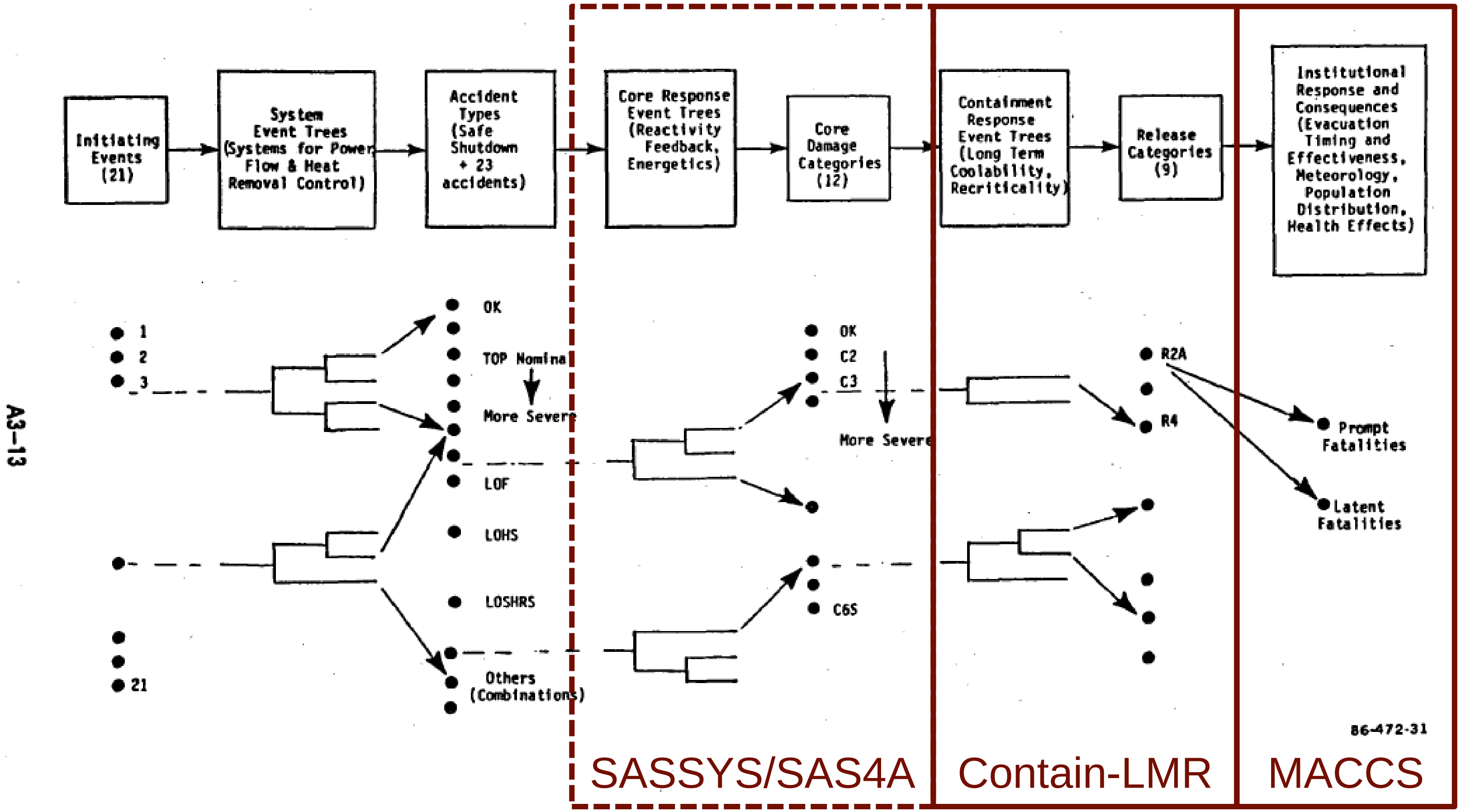

Figure A3.2–1 PRISM RISK MODEL STRUCTURE

Sodium Fire Experiments 2008-2010

- Open-air Burns
- In-Vessel Burns

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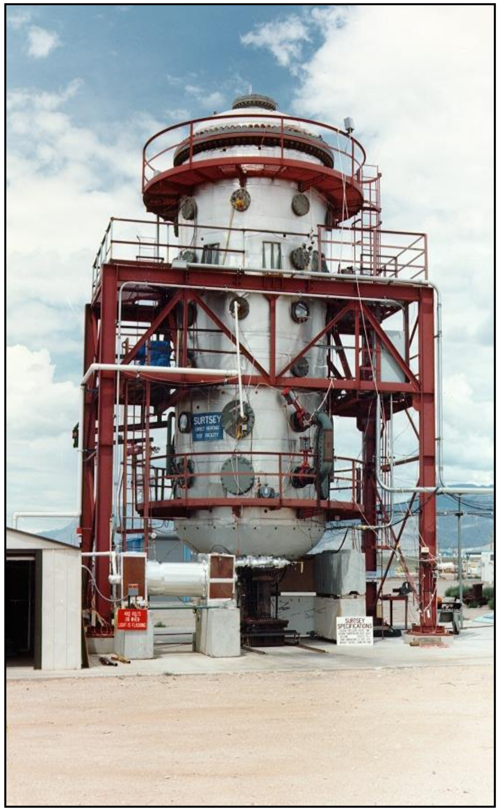
Sodium Fire Testing at SNL

- Goals
  - Establish a general metal fire expertise and analysis capability at SNL to address a key safety issue for the next generation of nuclear reactors.
- Experiments were performed back in 2009 and 2010 at Surtsey Facility; part of LDRD project.
- Sodium Pool Fire Experiments
  - 11 outdoor experiments.
  - Measured surface heat fluxes and pool temperatures.
  - Varied thickness ratio of the stainless steel substrate to the liquid sodium.
- Sodium Spray Fire Experiments
  - 2 outdoor and 2 in-vessel experiments.
  - Measured spray heat fluxes and temperatures.
  - Varied average droplet diameters and sodium temperatures.



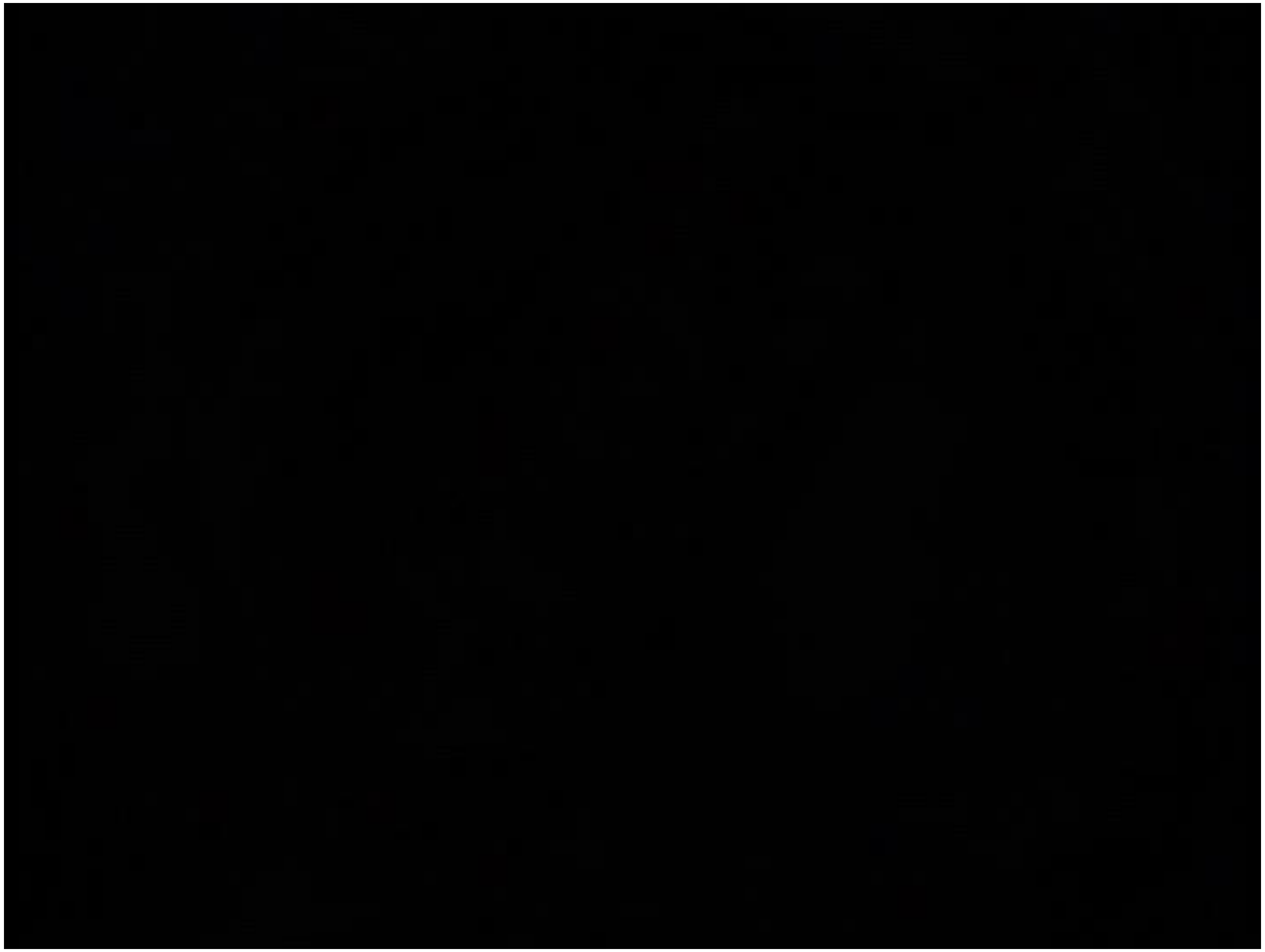
Sodium Fire Test Matrix

Test ID	Open or Closed to the Environment	Pool or Spray	Amount of Sodium (kg)	Average Peak Temperature (°C) (bottom of pan for pool)	Melt Generator Pressure at System Dump Time (psi)
P1	Open	Pool	2.6	320	2.6
P2	Open	Pool	2.6	320	2.2
P3	Open	Pool	4.4	800	2.4
P4	Open	Pool	1.0	780	2.5
P6	Open	Pool	4.8	480	3.2
P7	Open	Pool	7.8	600	3.4
P8	Open	Pool	1.6	220	3.6
P9	Open	Pool	6.0	490	3.6
P10	Open	Pool	11.6	746	3.2
P11	Open	Pool	9.6	648	3.9
T1	Open	Spray	4.0	>1200	310.7
T2	Open	Spray	4.0	880	28.4
T3	Closed	Spray	20	480	307
T4	Closed	Spray	20	1205	307

Outdoor Pool Fire Test

Small Pool Fire

- Time = 0, sodium introduced to pan.
- Time ≈ 4.5 mins, pool fire.
- Time ≈ 8 mins, significant crust formation.
- Time ≈ 13 mins, complete crust formation.



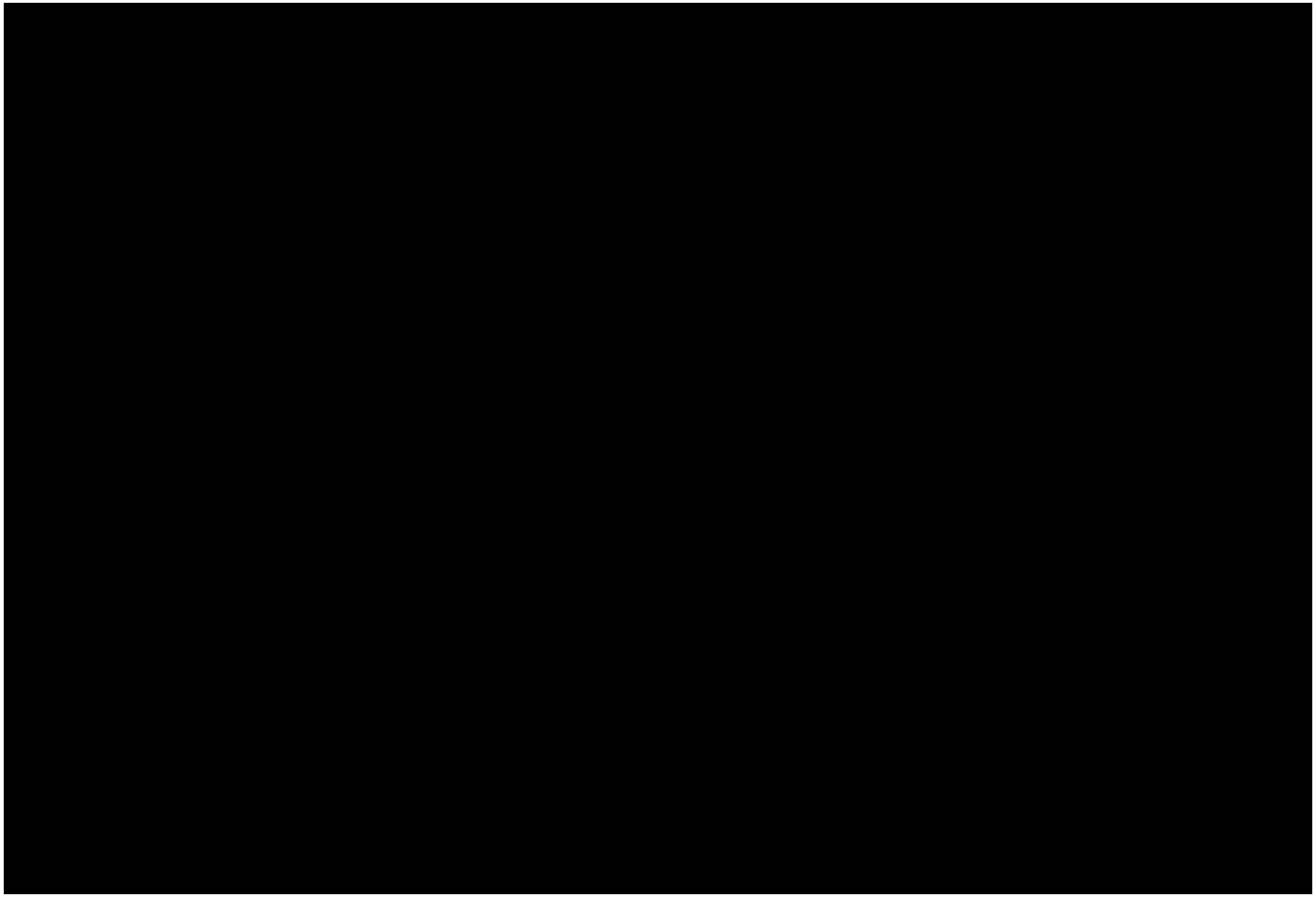
Outdoor Pool Fire Test

Large Pool Fire

- Time = 0, sodium introduced to pan.
- Time ≈ 6.5 mins, pool fire.
- Time ≈ 11.5 mins, significant crust formation.
- Time ≈ 16 mins, complete crust formation.

Outdoor Spray Fire Test

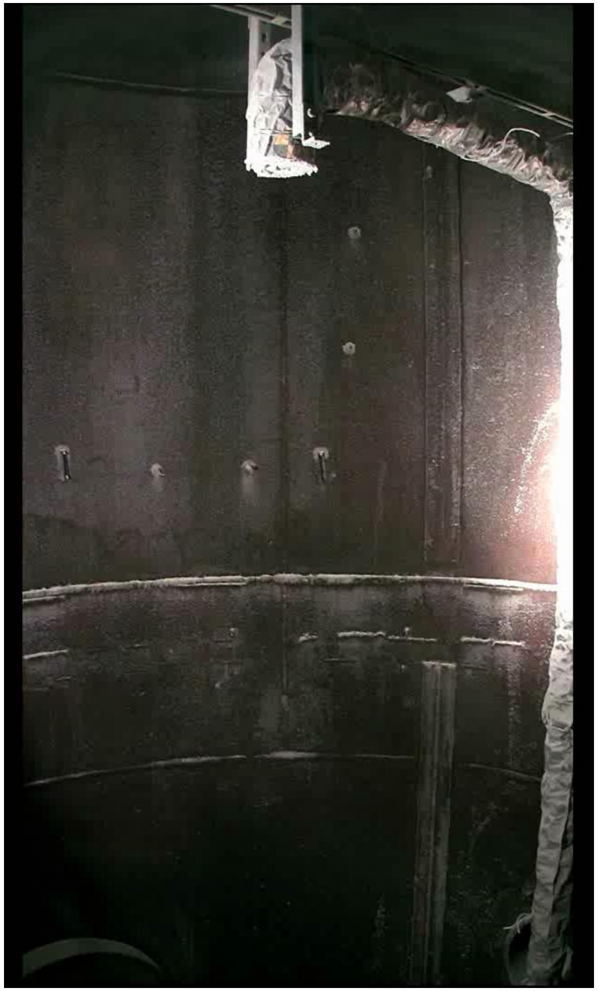
High Pressure Spray

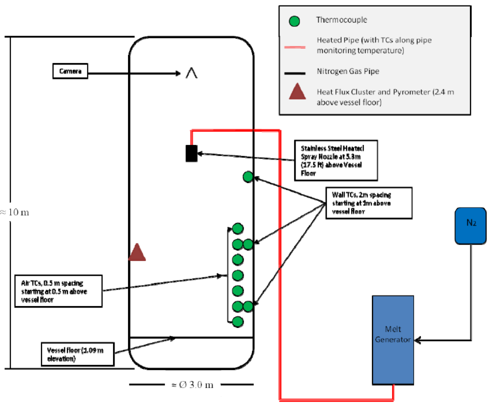


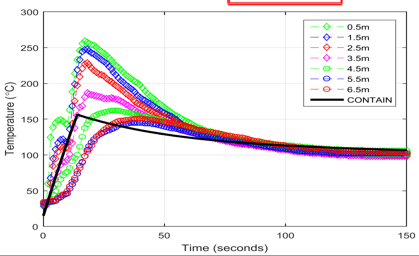
In-Vessel Sodium Spray Fire Tests

T3 Experiment

T4 Experiment







SNL Sodium Fire Testing and Modeling

MELCOR/CONTAIN-LMR

CNWG

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Sodium Models from CONTAIN-LMR

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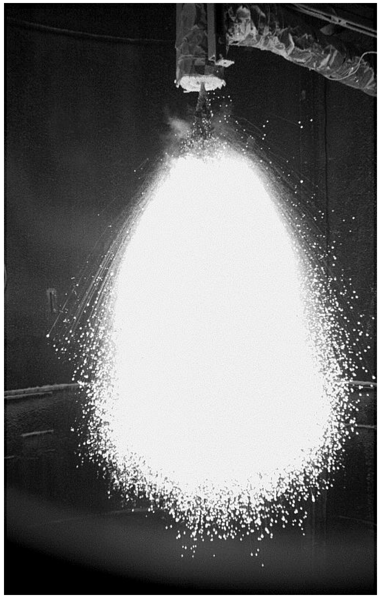
- DOE has funded Sandia for 4 years, starting from FY13
  - We are integrating all sodium physics and chemistry models into MELCOR 2.1 with the sodium coolant fluid capability.
    - Spray fire chemistry
    - Pool fire chemistry
    - Atmospheric chemistry
    - Sodium concrete interaction (SLAM model)
  - Internally, we are upgrading CONTAIN2 (latest version) with CONTAIN-LMR sodium models.
- Expected Schedule:
  - Implementation of all sodium chemistry models by the end of FY16.
  - A combination of experimental, code-to-code and benchmarking studies will be conducted in FY17.

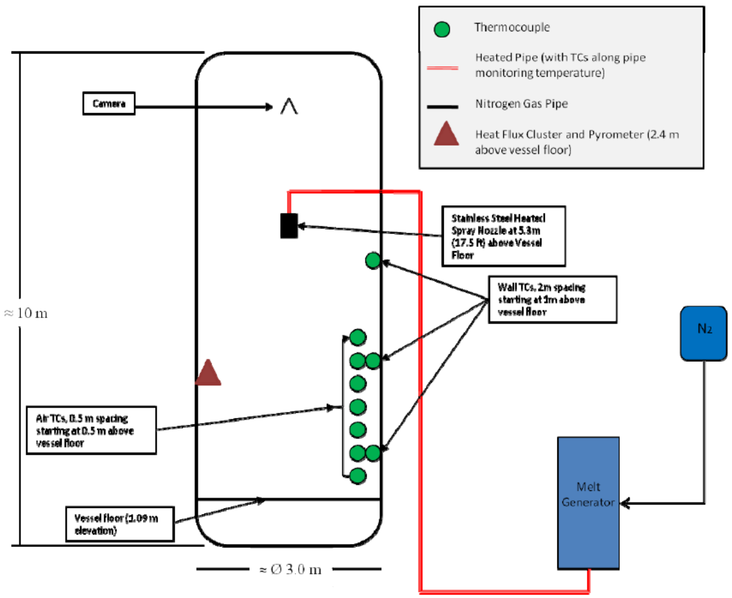
MELCOR/CONTAIN-LMR Integration

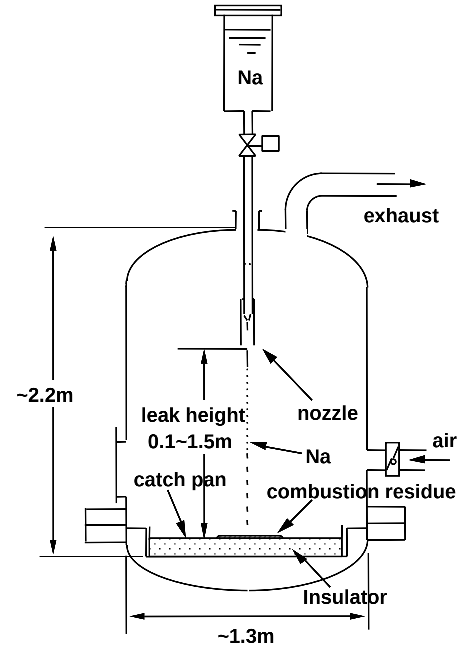
- Motivation:
  - Provide CONTAIN-LMR sodium accident analysis capability under MELCOR integrated severe accident code for SFR source term assessments, level 2/3 PRA, and containment DBA analyses.
- Current Status:
  - Sodium chemistry models from CONTAIN-LMR are being implemented into MELCOR 2.1.
- The MELCOR sodium models will be used in:
  - Trial source term calculations funded by DOE or private vendors.
  - JAEA sodium fire modeling collaboration using SNL and JAEA experiments.
  - Planned MELCOR and ASTEC-Na crosswalk.



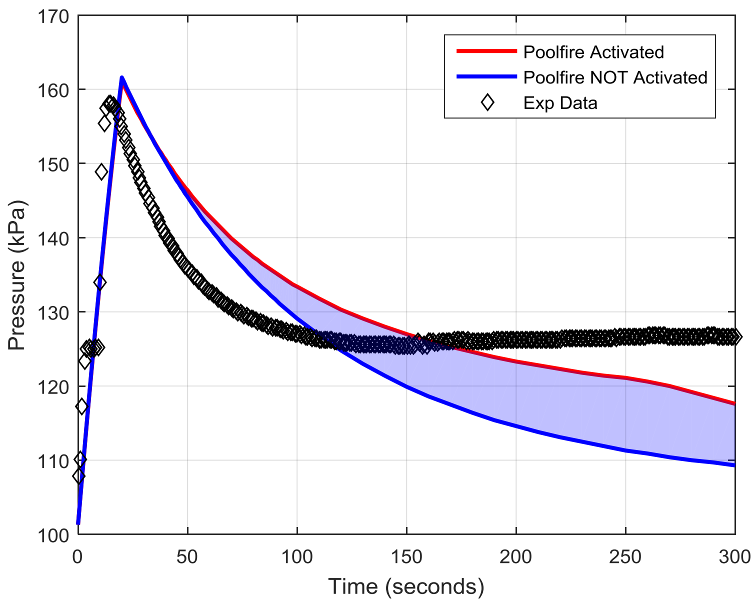
US/Japan Bilateral

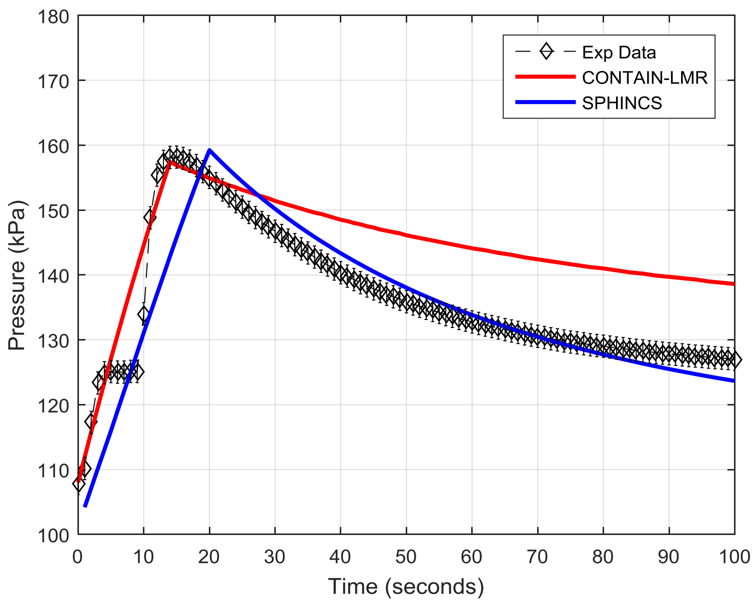
- Conducted under the Civil Nuclear Energy Working Group funded by DOE-NE.
- Focused on modeling:
  - SNL In-Vessel Spray Fire Tests (T3 and T4)
  - JAEA Small Scale Pool Fire Tests (F7-1, F7-2)
- This collaboration allowed SNL to begin modeling sodium fires with CONTAIN-LMR after nearly 20 years of dormancy.



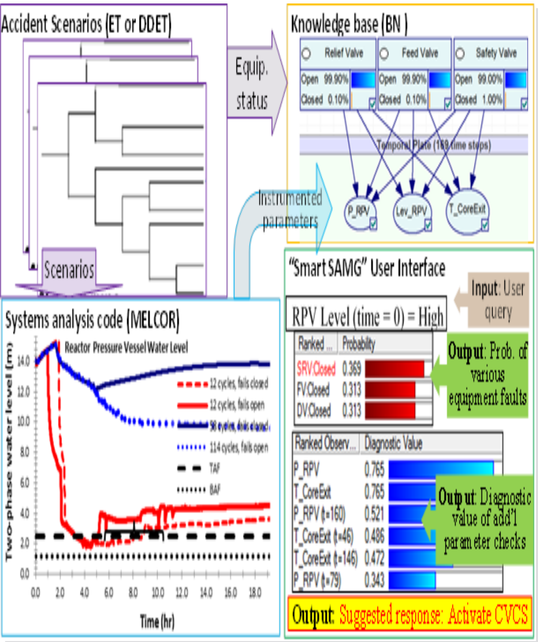


Initial Results for SNL T3 Test





- Modeling the subsequent pool fire is important for reproducing the pressure response for large spray fires.
- SPHINCS pool fire model more advanced than CONTAIN-LMR pool fire model.
  - Better long term pressure response using SPHINCS pool fire model.



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SNL's SFR Probabilistic Risk Assessment Research

CREDO-II

Accident Diagnostics

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Where are we now?
Safety and Licensing Gaps

Planning

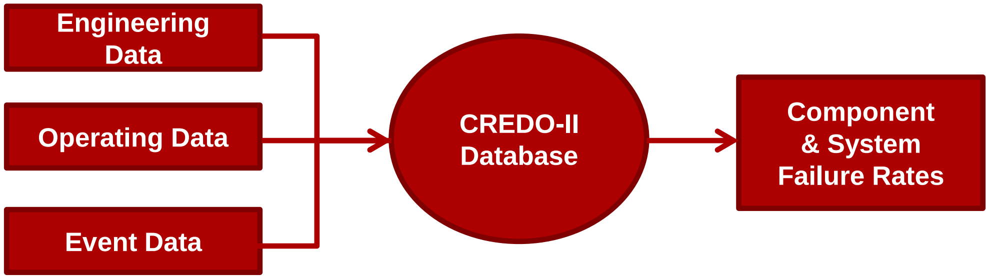
Initial Gap Identification and Rankings (~3 years)

Final Evaluation (~1 year)

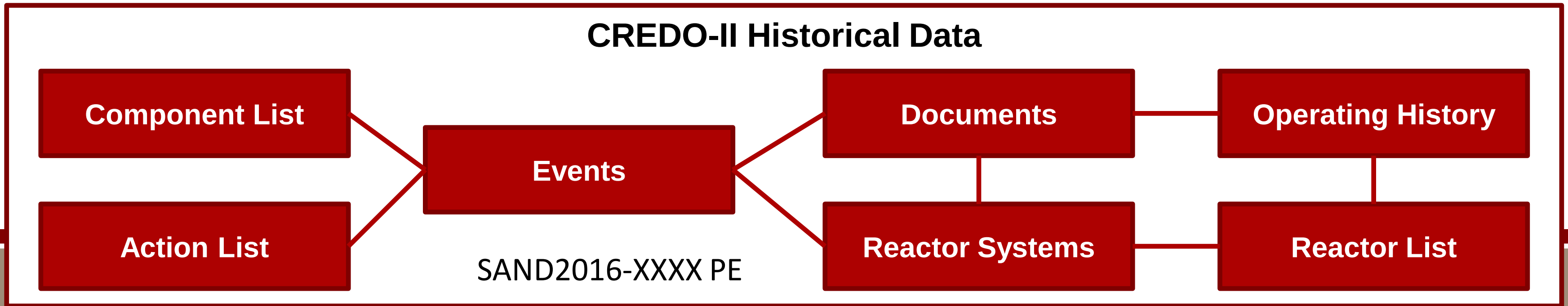
What topical areas are vital to SFR Licensing?

SFR Reliability Assessments

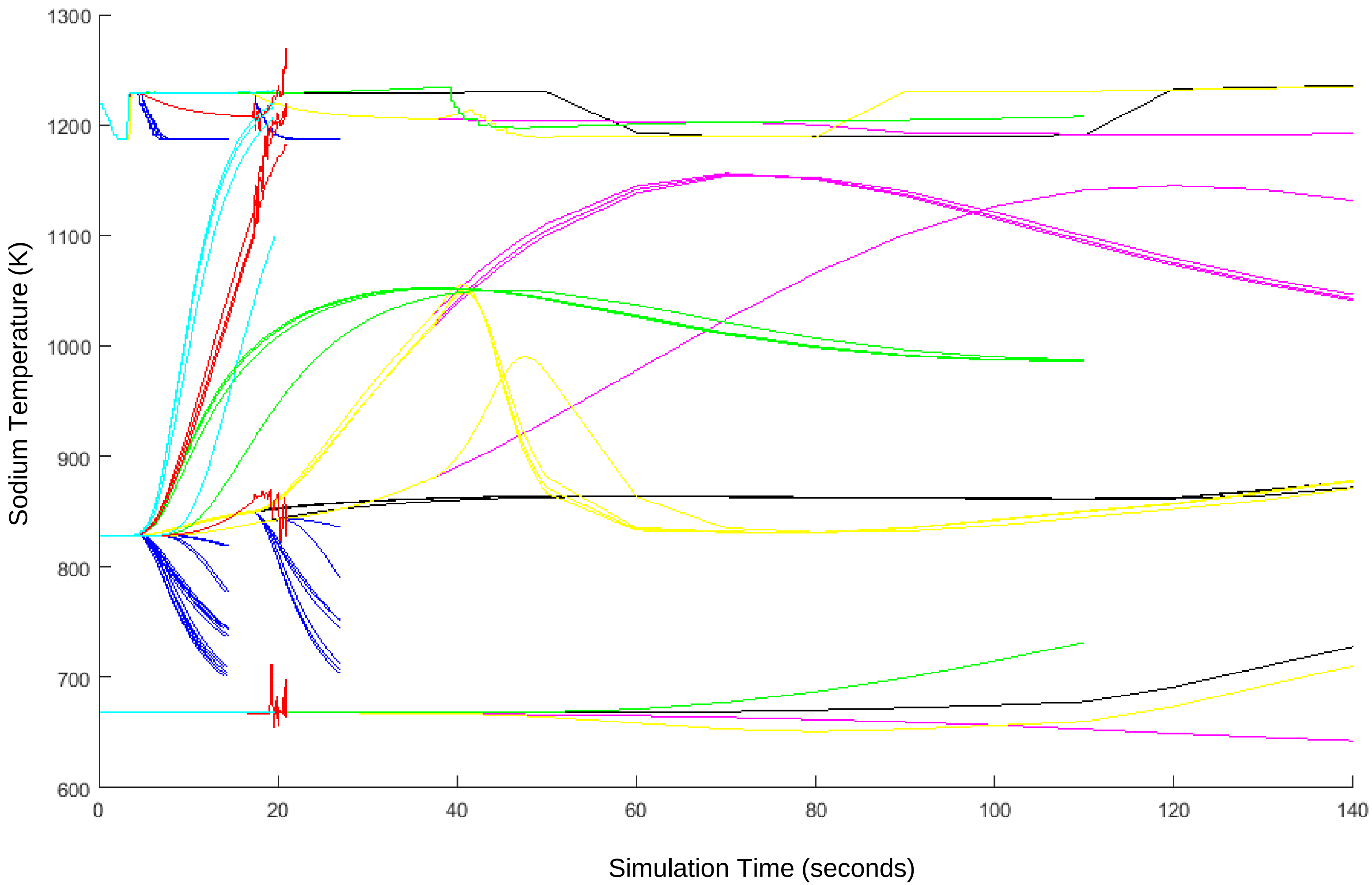
- Centralized Reliability Data Organization (CREDO) – II
  - Funded by DOE-NE under ART - collaborative work between SNL and ANL
- Objectives:
  - Rebuilding sodium reactor component reliability database using primary sources
  - Support future risk assessments
  - Risk-inform future SFR designs



- Data Sources
  - EBR-II (Idaho, 1964-1994)
  - Fermi Unit 1 (Michigan, 1966-1972)
  - FFTF (Washington, 1980-1992)
  - SRE, Sodium Reactor Experiment (California, 1957-1964)
  - HNPF, Hallam Nuclear Power Facility (Nebraska, 1963-1964)
  - SEFOR, Southwest Experimental Fast Oxide Reactor (Arkansas, 1969-1972)



Probabilistic Risk Assessments Research Dynamic Event Trees and Clustering



Summary

- SNL has a long history of sodium reactor safety research.
- SNL knows how to do sodium experiments.
- SNL has been conducting safety research for DOE for the past 8 years:
  - Evaluating licensing gaps
  - Sodium Fire Modeling / Source Term Evaluations
  - Conducting PRA research
  - Supporting the Safety Design Criteria GIF Task Force