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U.S. Perspective on Technology Gaps and R&D Needs for SFRs

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Tsuruga, Japan

Presentation Outline

- **Summary of DOE SFR Research Plan to identify and address regulatory gaps for SFRs**
- **Validation of safety modeling: TREAT test database**
- **Examples of recent U.S. experimental work focused on addressing SFR technology gaps**
  - Metal alloy flow and freezing experiments
  - Na-CO2 interaction experiments
  - Sodium fire experiments
- **Summary**

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Sodium Fast Reactor (SFR) Research Plan

What
- Identifies the current state of Safety-Related Gaps for the SFR
- Prioritizes gap closures

Why
- Uncertainties exist regarding DOEs capability to support a SFR license application

How
- Panels were formed in 5 topical areas to elicit the current state-of-SFR-licenseability

Who
- Organized by: Denman (SNL), LaChance (SNL), Sofu (ANL), Flanagan (ORNL), Wigeland (INL), and Bari (BNL)
- Experts included 42 representatives from the DOE lab complex, academia, industry and international bodies

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Summary of SFR Research Plan Recommendations (see SAND2012-4260)

Coordinated Knowledge Management and Preservation Effort

- Documentation of safety related codes and experiments risk being lost
- Piecemeal and underfunded efforts will lead to lost information which may need to be reproduced in the future

Improvements to U.S. safety related codes

- Adequate stewardship and documentation of U.S. safety related codes required for licensing (e.g., LIFE-Metal)
- Modernization of U.S. Codes to satisfy current licensing needs
- Code (e.g., SAS4A) improvements related to seismic response of the entire SFR system will be required post-Fukushima
- Probabilistic safety analysis of containment response capabilities need to be developed for SFRs within the U.S. (i.e., incorporation of sodium phenomena into MELCOR)

Continued U.S. experimental facility utilization, even if on a small scale

- Ensures that future testing capabilities are not lost in budget conscious environments
- Identify testing to address phenomenological uncertainties which could be performed to maintain facilities

Treatment of the Applied Technology (AT) designation must be streamlined

- The current process makes removing AT designations on documents which no longer need to be protected extremely difficult.
- The U.S. NRC is not set up to handle AT documents.

Validation of Safety Modeling: TREAT Test Database

- **Information from past TREAT experiments is valuable for future fast reactor development**
  - Significant information exists from more than 500 one-of-a-kind tests as the basis of much of present knowledge and understanding of transient fuel behavior
  - Many test phenomena are of continuing importance and thus form part of the database of the future
  - Experiments have involved a wide variety/range of complexity: investigations ranging from a focus on individual phenomena to integral effects of multiple interactive phenomena
- **TREAT Test Database — Key features:**
  - Online archive based on open source platform (Linux/Apache/MySQL/Perl/PHP)
  - Search/query forms specific to TREAT test information categories
  - Numerical test instrumentation data from ASCII files
  - Automatic data plotting capability
  - Links to test specific documents

Validation of Safety Modeling: Treat Test Database (cont.)

Common Categories of Observations in TREAT Tests

Off-normal pre-failure fuel behavior	Severe accident fuel behavior
Microscopic and morphology changes	Margins to cladding breach
Constituent redistributions	Pre-failure fuel relocations
Fission gas release	Fuel-coolant interaction effects
Fission product vaporization effects	Coolant voiding
Fuel-cladding chemical interactions	Post-failure dynamics of fuel, cladding, and coolant
Fuel-cladding mechanical interactions	Coolant channel blockage formation

Validation of Safety Modeling: Treat Test Database (cont.)

FUELS (fresh or pre-irradiated)
LWR oxide
SFR oxide
SFR metal alloy
SFR carbide
SFR nitride

COOLING ENVIRONMENTS
Flowing sodium
Stagnant sodium
Flowing steam
Stagnant water
Inert gas

TRANSIENT CONDITIONS
Loss of flow (LOF) accident
Transient overpower (TOP)accident
LOF-driven-TOP accident
Maximum sample heating rate

DIAGNOSTICS
Fast Neutron Hodoscope (fuel motion)
Thermal-hydraulic sensors (T, P, flow)
Optical cameras
Fission-product collection
Neutron radiography/tomography
Post-test metallurgical exams

Core Alloy Flow and Erosion (CAFÉ) Experiments

- **Work sponsored by JAEA and performed at ANL.**
- **Objective: Investigate fundamental flow and freezing behavior of uranium and uranium-alloy melts in contact with metallic surfaces, involving**
  - Dynamic changes in melt composition and properties
  - Chemical erosion / ablation of structure
  - Melting of structure and freezing of melt
  - Flow of melts over newly-solidified compositions
- **Applicable to understanding flow and freezing of molten fuel-cladding alloys within pin cladding, through assemblies, or in contact with ex-core structure.**
- **Provide information for accident code validation and analysis of severe-accident simulation experiments.**

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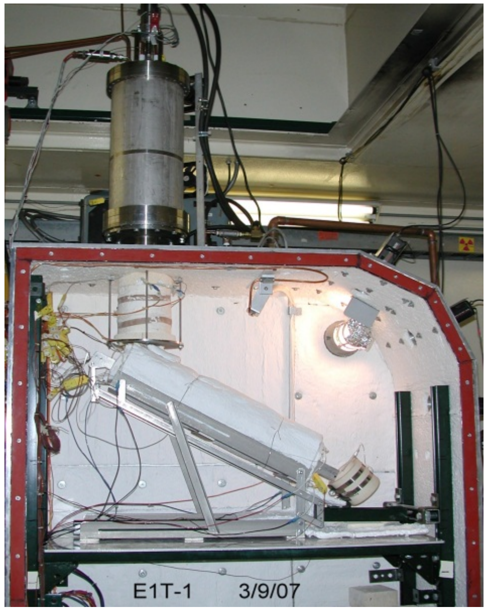
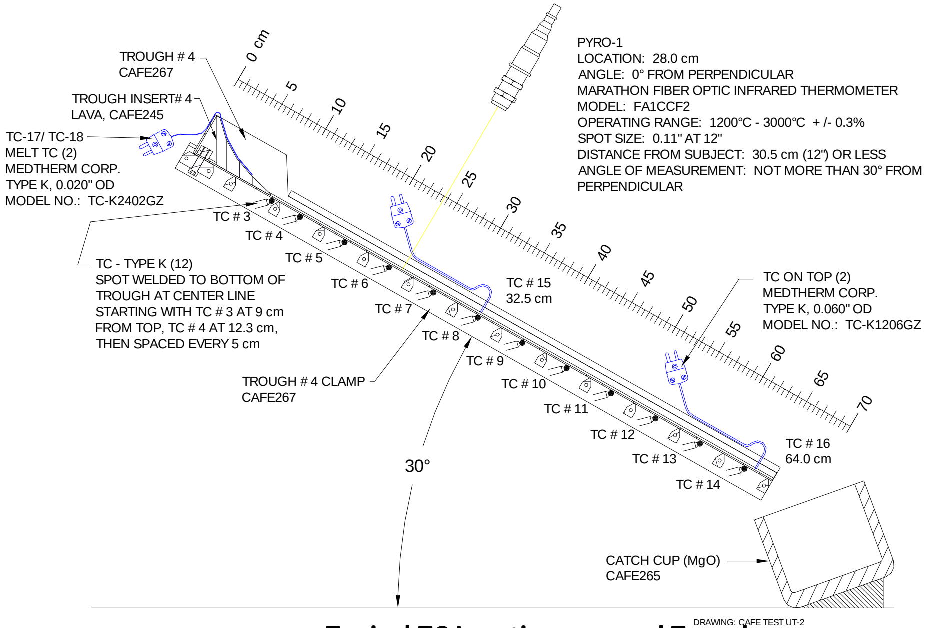
CAFÉ - Approach in Initial Testing

- **Uranium and uranium-iron eutectic melts (generated by induction heating) flowing within open-sided, inclined, stainless steel troughs.**
- **Application to uranium-alloy fuels involving formation of low-melting-point phases with iron-based (e.g., stainless steel) surfaces.**
- **Test rig could also evaluate other melt compositions, surface materials, and contacting configurations.**

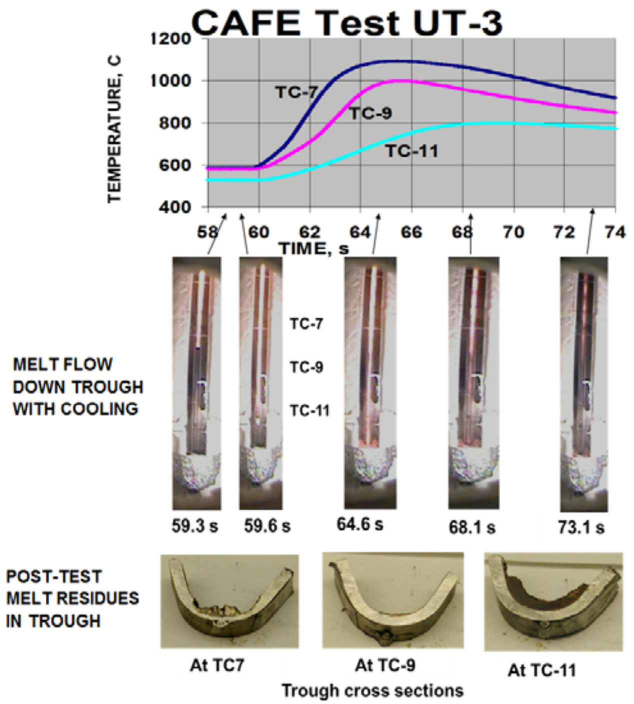




Typical TC Locations around Trough

CAFÉ – Observations and Conclusions

- **Dissolution of structure by flowing melt strongly affects melt flow and correlates with structure when T >1080 C**
- **Frozen crust formation correlates with structure when T <1080 C**
- **Formation of low-melting point compositions strongly affects the melt flow dynamics.**



UT-4 (U melt; 1.2 s above 1080 C)

UT-3 (U melt; 800 C peak)

E1T-2 (eutectic; 11 s above 1080 C)

E1T-1 (eutectic; 0.7 s above 1080 C)

CAFÉ UT-4 Video

ANL S-CO_2 Na Kinetics Experiment (SNAKE)

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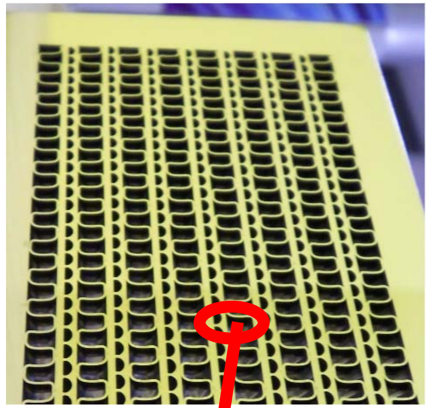
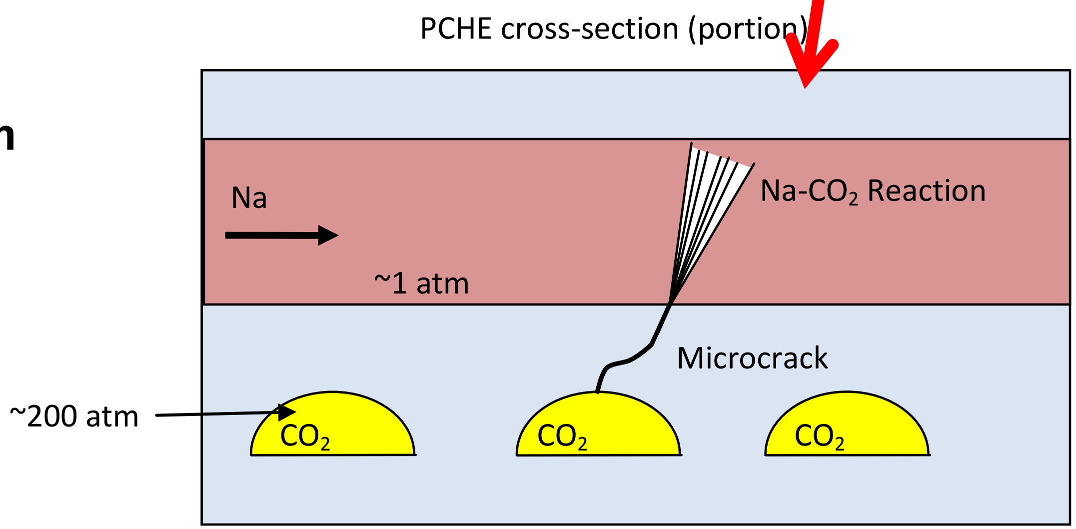
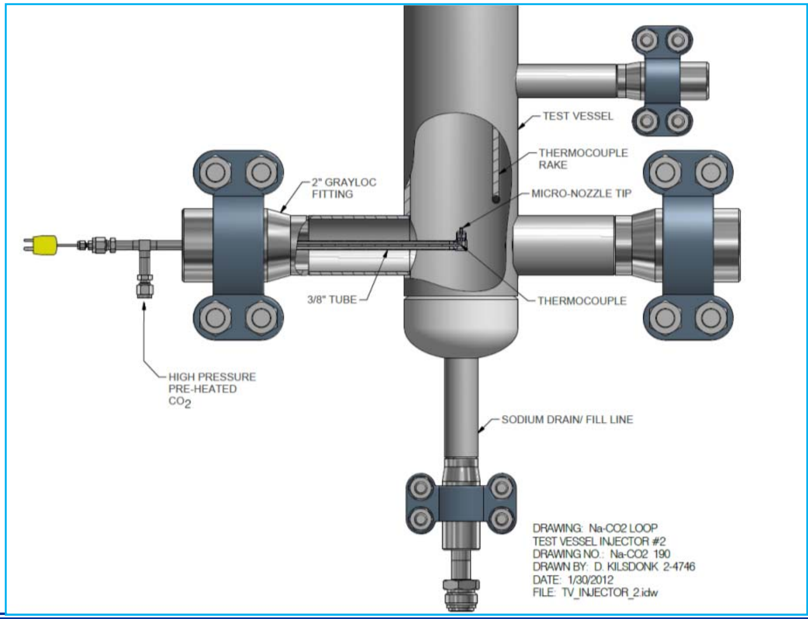
- Investigates potential failure (micro-crack) in Na-CO_2 HX - Printed Circuit Heat Exchanger (PCHE)
- Small inter-stream cracks possible
- Slow leakage rate, potential for chemical reaction
- Potential for increased corrosion in rest of system should reaction products circulate





SNAKE: Major Features

- CO_2 released through stainless steel microcrack (25-100µm) into sodium pool
- Modify sodium pool height (up to 1 m) and temperature (100-510 ˚C)
- Mass spectrometer analyzes product gases
- Post-test evaluation of solid reaction products
- Hardware prep finished; Na loading in July 2012



SNL Sodium Fire Research Program Overview

- **3 year program (2007-2010)**
- **Reactor design and safety assessments**
  - General literature review
  - Reviewed proposed reactor designs
- **Discovery experiments (sodium pool and spray fires)**
  - Identified key but poorly understood phenomena (PIRT)
  - Designed and executed experiments to explore identified phenomena and to support model development and validation
- **Development of analytical tools**
  - Built on existing SNL analysis tools
  - Identified model shortcomings
  - Developed and validated model through comparison with experimental measurements.

Sodium Fire Experiments

- **Results from PIRT and literature review provided insight for experimental design**
- **All experiments relevant to any sodium cooled reactor design**
- **Our Goal:**
  - To bring modern analysis methods (experimental and computational) to bear on metal fire problem for advanced fast reactor applications
  - To develop the expertise and capability need to identify, investigate, and assess key metal fire issues

Experimental Program Overview

- **Sodium Spray Fires Experiments**
  - 2 outdoor and 2 in-vessel experiments
  - Measured spray heat fluxes and temperatures
  - Varied average droplet diameters and sodium temperatures

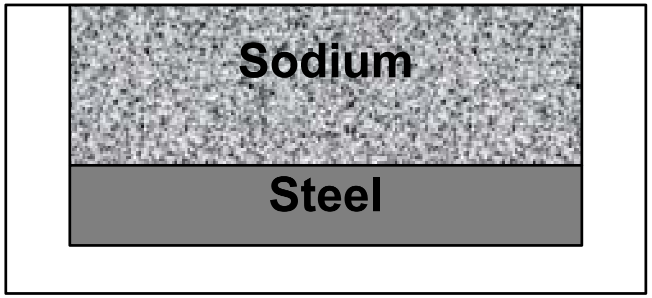
- **Sodium Pool Fire Experiments**
  - 11 outdoor experiments
  - Measured surface heat fluxes and pool temperatures
  - Varied thickness ratio of the stainless steel substrate to the liquid sodium

Sodium Outdoor Spray Test Setup

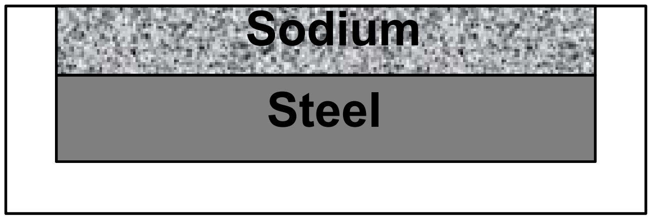
Sodium In-Vessel Spray Test Setup

Sodium Spray Fire Experiments: Indoor Spray Video

Sodium Pool Fire Experiments: Thickness Ratio (Liquid Sodium/Stainless Steel)

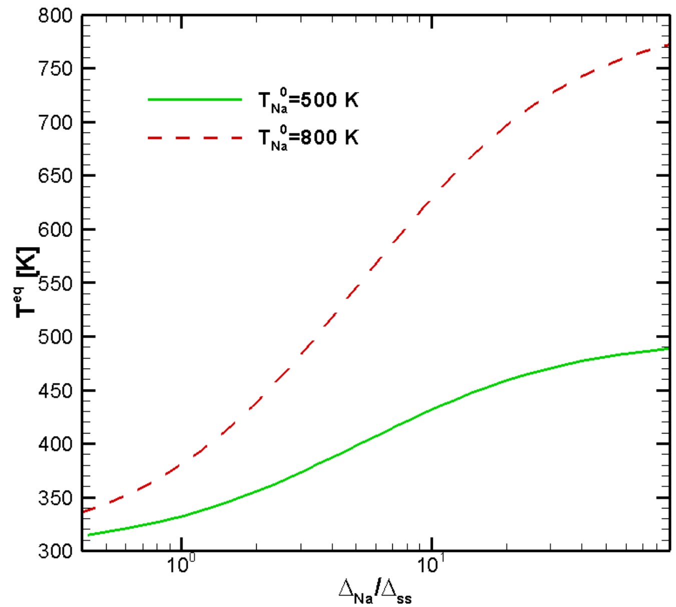


Thick Ratio



Thin Ratio

$$\rho_{\mathrm{Na}} c_{v,\mathrm{Na}} \Delta_{\mathrm{Na}} \left(T_{\mathrm{Na}}^{0} - T^{eq} \right) = \rho_s c_{v,s} \Delta_s \left(T^{eq} - T_s^{0} \right)$$



The thermal equilibration temperature for sodium and steel as a function of the ratio of the thicknesses.

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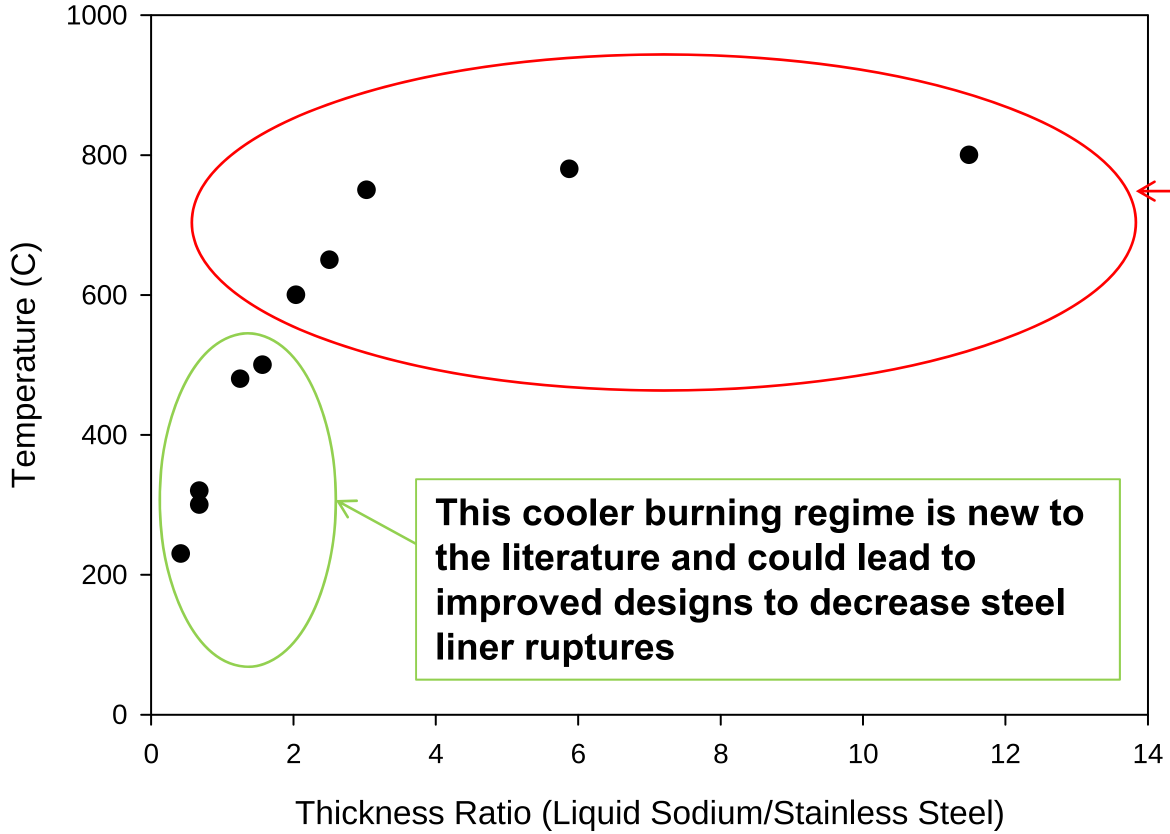
Sodium Pool Fire Test: Results

All Sodium Pool Tests: Measured Peak of Average Bottom Pan Temperature vs Thickness Ratio (Liquid Sodium/Stainless Steel)

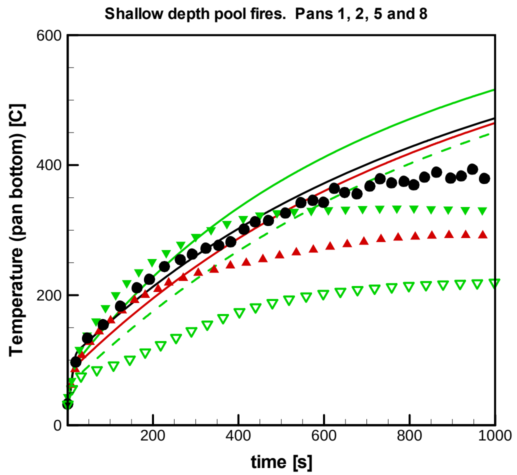


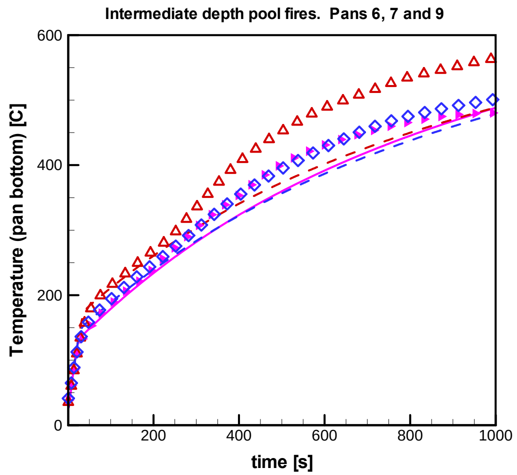
Hotter burning regime which are the typical experiments in past literature

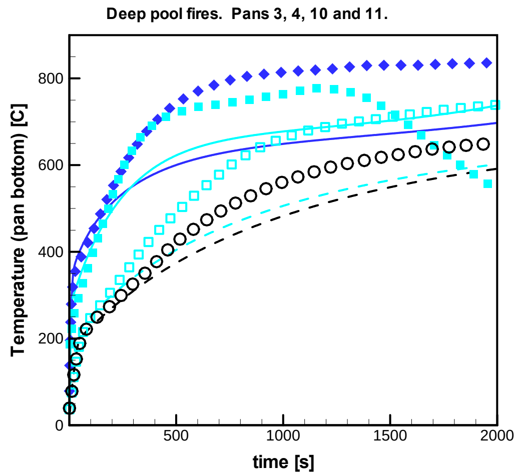
Computational Model Development: Temperature Evolution Predictions

New model can predict shallow pool burning

– **Oxide crust inhibits oxidation heat release.**







Pool Type	Thickness Ratio Range
Shallow	0.4 to 1.0
Intermediate	1.3 to 6.0
Deep	2.5 to 11.5

***Lines are the model predictions and the shapes are experimental data. For comparison, the open shapes go with the dashed lines and the solid shapes go with the solid lines.**

Summary

- **To lay the groundwork for future R&D activities, DOE has developed a Research Plan to identify regulatory gaps and issues for SFRs. Areas include:**
  - Coordinated knowledge management and preservation
  - Improvements to U.S. safety-related codes
  - Continued U.S. experimental facility utilization
  - Treatment of Applied Technology

- **Efforts are being carried out in these various areas to resolve technical issues and to maintain US capability with SFR technology**

Backup Slides

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SNL Sodium Spray Fire Experiments

Test #	T1	T2	S1	S2
Location	In-Vessel	In-Vessel	Outside	Outside
Height of Spray (m)	5.3	5.3	4.6	4.6
Amount of Na (kg)	20	20	4	4
Flow rate (kg/s)	1	1	1	0.5
Median Particle Size Diameter (mm)	between 3 and 5	between 3 and 5	~6	~10
Initial Temperature of Sodium (deg C)	200	500	500	500
Measured Peak Air Temperature (TC's 1 foot from vessel wall for in-vessel and center of spray for outdoor tests) (deg C)	480	1200	>1200**	880
Measured Peak Vessel Overpressure (MPa)	0.006	0.2*	NA	NA
Measured Peak Narrow View Heat Flux (4.8 ft from center of vessel) (kW/m^2)	<1	89	250	40
Notes		*Instrumentation port failure	** TC failed around 1200C	

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SNL Sodium Pool Fire Experiments

Test Number	diameter of pan (in)	height of pan (in)	mass sodium (kg)	base steel thickness (in)	average peak temperature at bottom of pan (deg C)	thickness ratio (liquid sodium/stainless steel)
pan 1	24	2	2.6	0.625	320	0.7
pan 2	24	2	2.6	0.625	320	0.7
pan 3	12	5	4.4	0.25	800	11.5
pan 4	8	7	1	0.25	780	5.9
pan 5	24	2	3.8	0.625	400	1.0
pan 6	24	2	4.8	0.625	480	1.3
pan 7	24	2	7.8	0.625	600	2.0
pan 8	24	2	1.6	0.625	220	0.4
pan 9	24	2	6	0.625	490	1.6
pan 10	24	2	11.6	0.625	746	3.0
pan 11	24	2	9.6	0.625	648	2.5

Technical Issues

- **Sodium Pool Burning**
  - Improved pool burning model requires many poorly characterized parameters. Recommend experimental characterization of:
    - Oxide crust (porosity and composition)
    - Sodium liquid spreading (including freezing)
    - Mass of oxide that sticks (versus aerosolized)

- **Sodium Spray Fires**
  - Based on discovery experiments, improvement for future test series include:
    - Elimination of sodium vapor formation before test. This will allow better heat flux measurements.
    - Other diagnostics: floor vessel temperatures, aerosol characterization, oxygen consumption, spray characterization