SAND2011-8856 C

Understanding Thermal Consequences of Sodium Fires

SAND2011-8856C

Second Joint GIF-IAEA/INPRO Workshop on Safety Aspects of Sodium-Cooled Fast Reactors

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Albuquerque, NM USA

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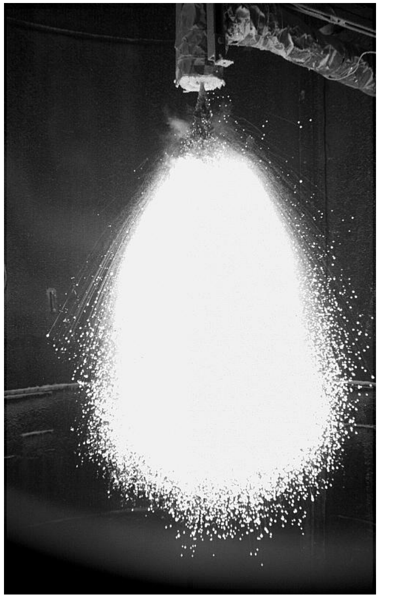
Overview

- Sodium Fire Risk
- SNL Sodium Fire Research Program
  - Expert Gap Analysis (PIRT)
  - Sodium Spray and Pool Fire Experiments
  - Sodium Pool Fire Model
  - Technical Issues

Sodium Fire Risks



- **Significance of the fire hazard:**
  - **Highly reactive and energetic materials**
  - **Critical components vulnerable to thermal damage**
  - **Nuclear materials can be dispersed through vaporization, boiling of other components and through particle entrainment**

- **Hazard mitigation required during regular operation, transportation, maintenance**

SNL's 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.

Insights from Literature Reviews

Previous Sodium Fire Accidents

- **MONJU, Japan 1995**
  - Instrument port failure
  - Sodium leak and fire – ~0.05 kg/s (640 kg total)
  - Facility shut down for 12 years and counting
- **Alermia Solar Power Plant, Spain 1986**
  - Valve maintenance failure – 14 kg/s leak (14 tons total)
  - Spray and pool fire (12 m^2 hole burned in roof)
- **ILONA Sodium Test Loop, Germany 1992**
  - Pressure relief valve failure – 0.2 kg/s leak (4 tons total)
  - Sodium pool fire burns for 14 hours
- **Russian study – categorizes 46 sodium leaks at two reactor facilities (1980's and 1990's)**
  - Dominated by equipment problems/failures
  - Procedural errors also significant cause

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Identify Application Requirements: PIRT Results

- Oxides aerosol, crust, or solution
  - The amount of oxides that is removed from the crust
  - Consequences of the aerosolized oxides on electrical equipment
- Oxygen transport through oxide crusts
  - Important for predicting thermal damage to surfaces on which sodium pools form
- Radiative heat transfer
  - Consequence of thermal load on nearby equipment
- Thermal coupling of sodium pools to surfaces
  - Thermal insult to surfaces below sodium pools
  - Useful for characterizing pool oxidation rate

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**

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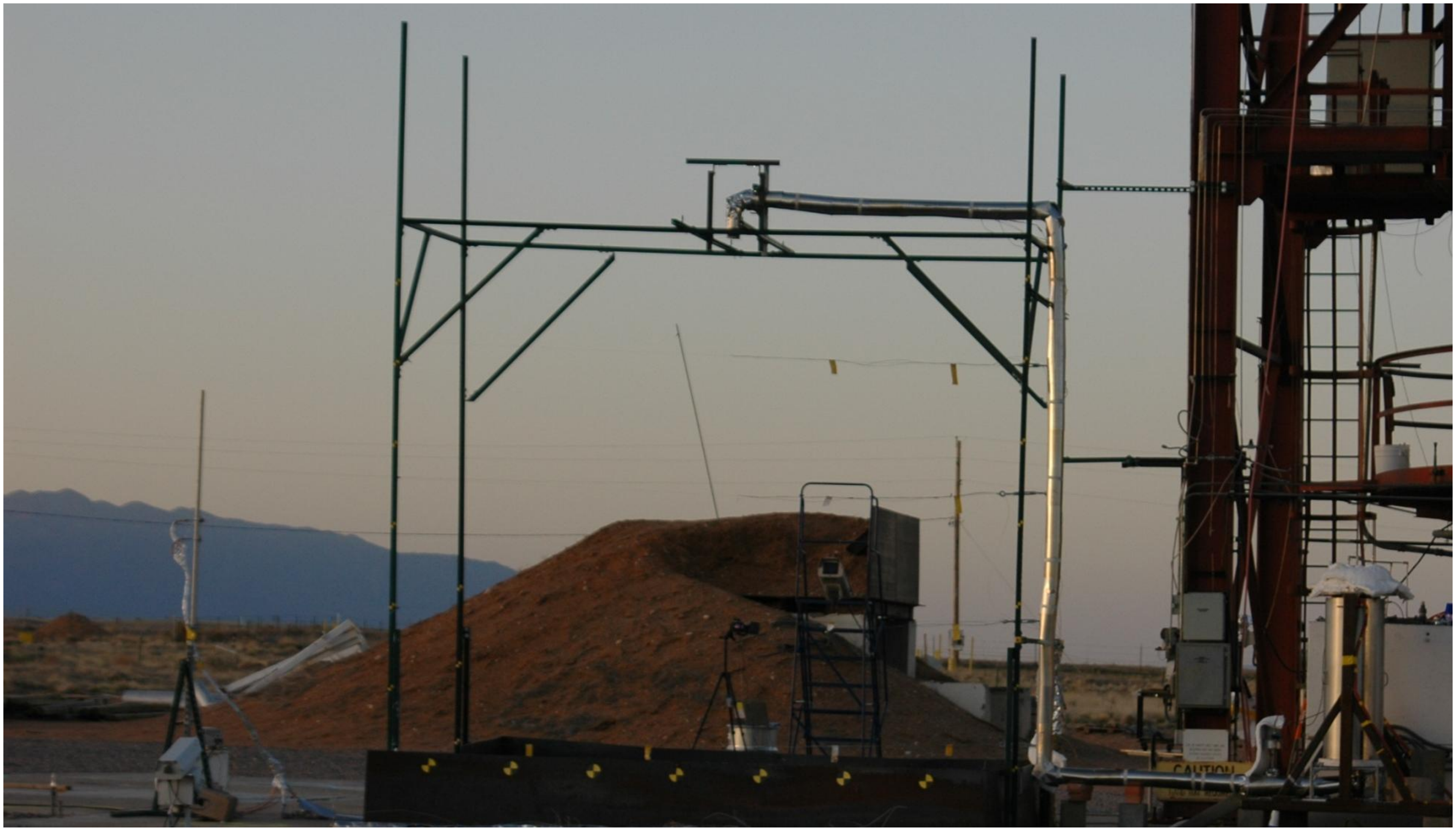
Sodium Spray Fire Experiments

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	

Sodium Outdoor Spray Test Setup



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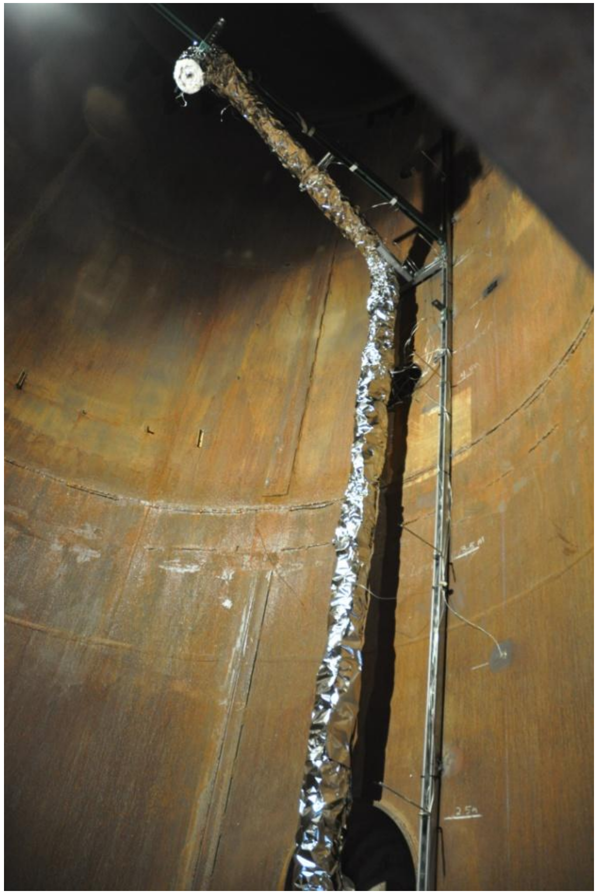
Sodium Spray Fire Experiments: Outdoor Spray Video

Sodium In-Vessel Spray Test Setup



Sodium Spray Fire Experiments: In-Vessel Spray Video

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

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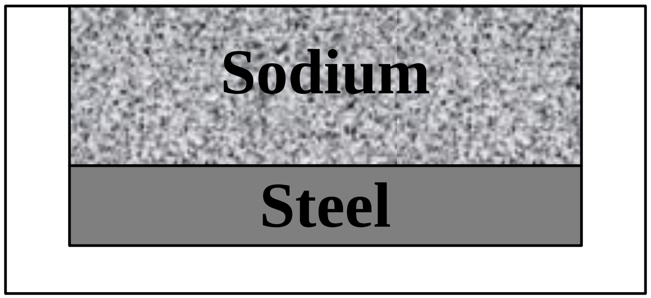
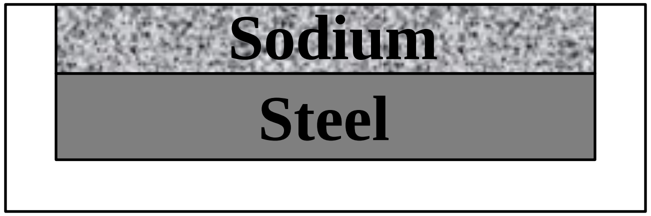
Sodium Pool Fire Experiments: Thickness Ratio (Liquid Sodium/Stainless Steel)

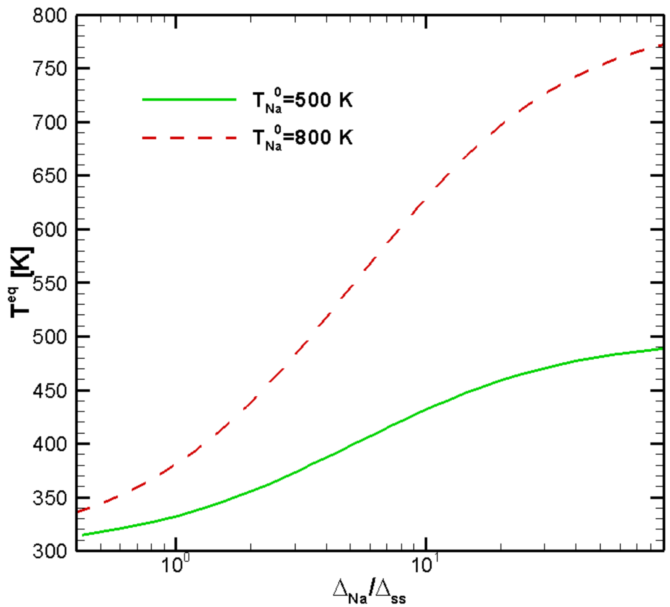


Thick Ratio



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.

Sodium Pool Fire Test

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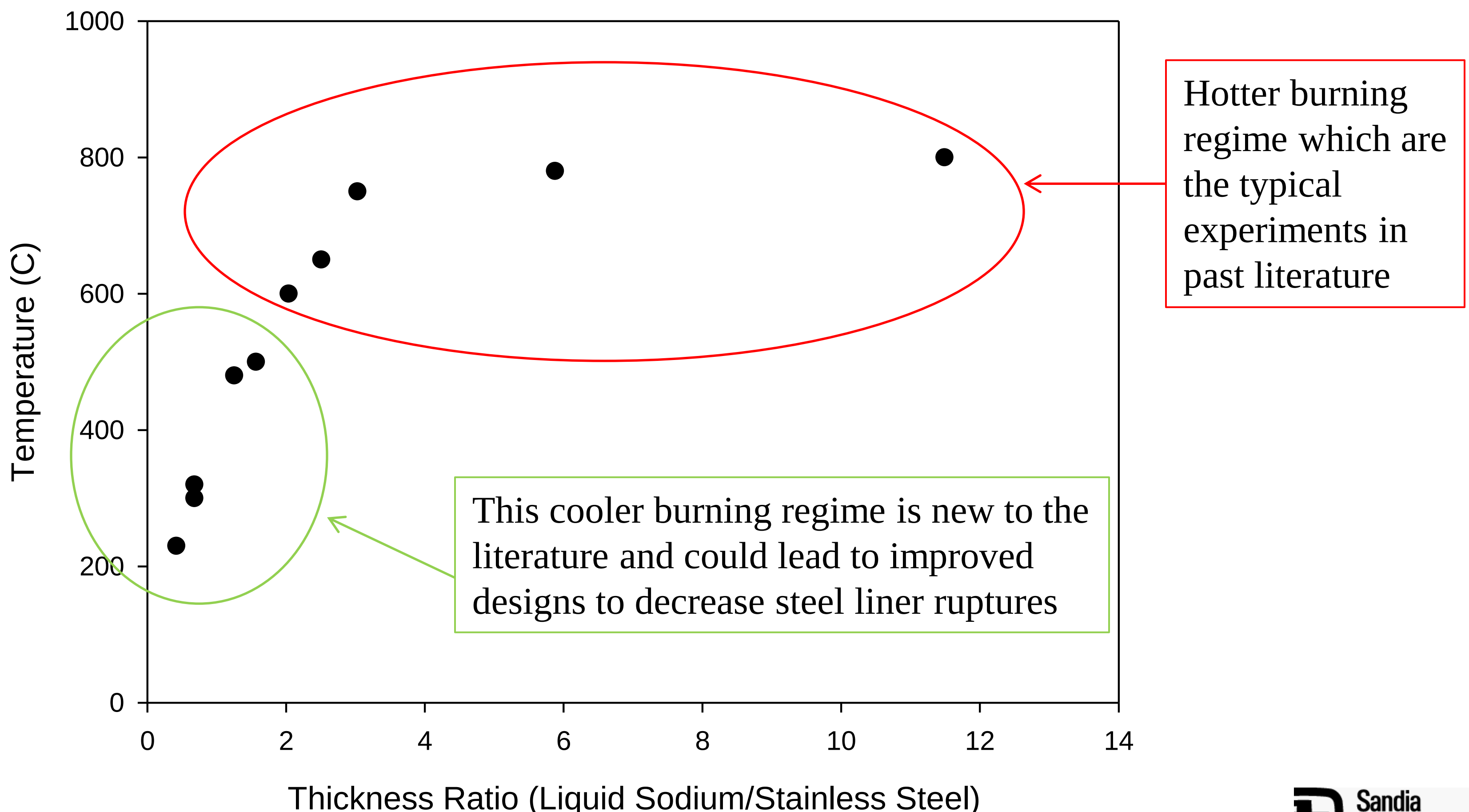
Sodium Pool Fire Test: Results

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



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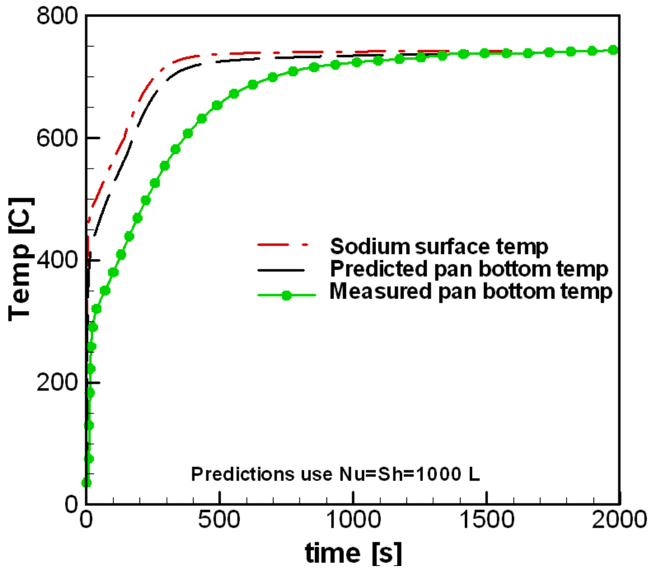
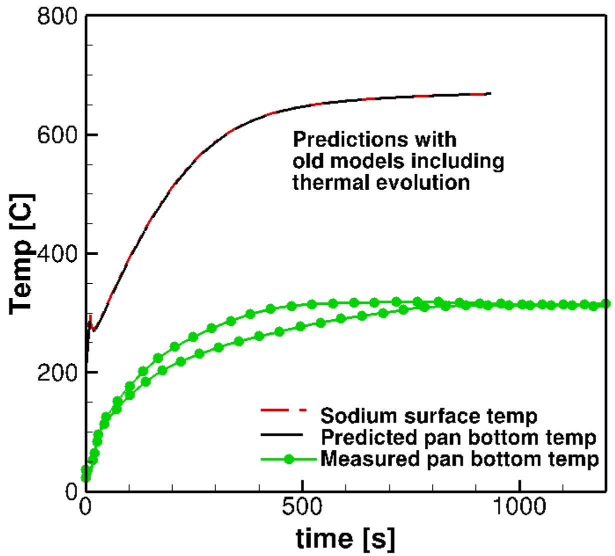
Computational Model Development: Temperature Evolution Predictions

Deep pools

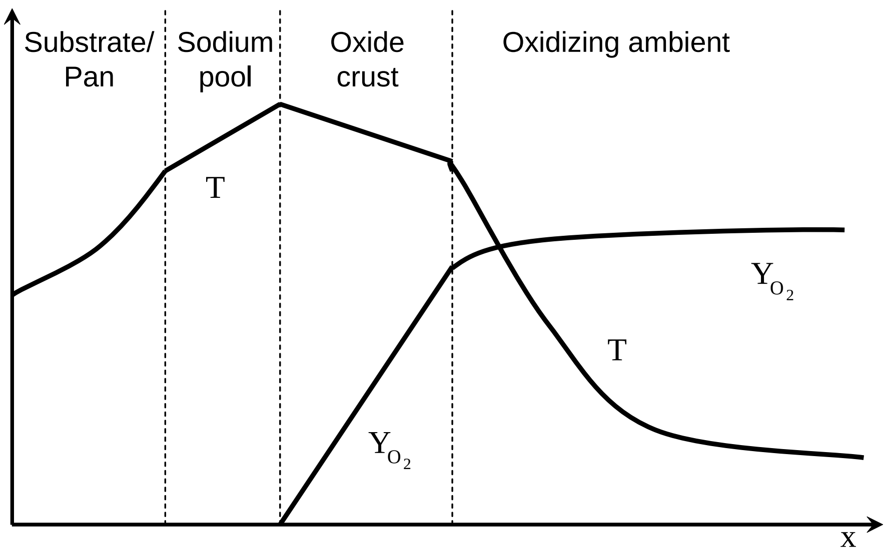


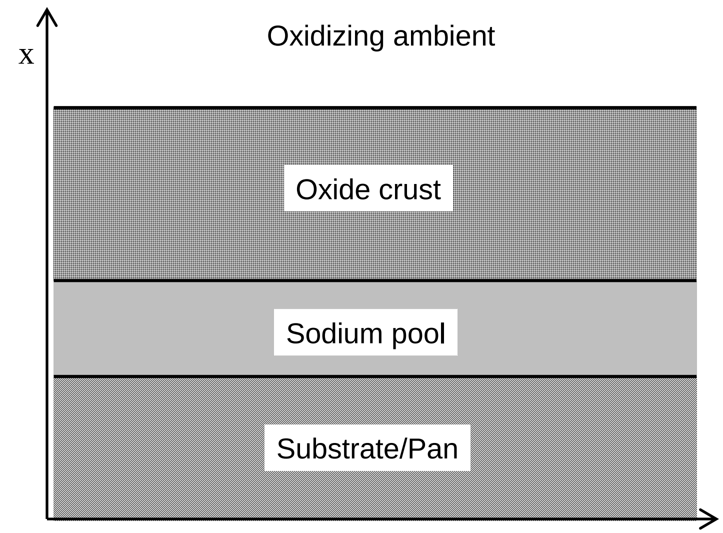
Shallow pools



- **Original model form (from existing literature) can predict deep pool burning, but not shallow pools.**
- **Why?**
  - **Oxide crust inhibits oxidation heat release.**

Model Configuration





- **Thermal evolution driven by heat release versus heat loss**
  - **Heat release determined by oxygen transport to sodium.**
    - **Driving potential is oxygen mass fraction.**
    - **Resistance is across boundary layer and across oxide layer.**
  - **Heat transfer into "pool + pan + ground" versus transfer away from surface.**
    - **Driving potential is temperature difference.**
- **Presence of oxide crust introduces resistance that more strongly resists oxygen transport than heat transport.**

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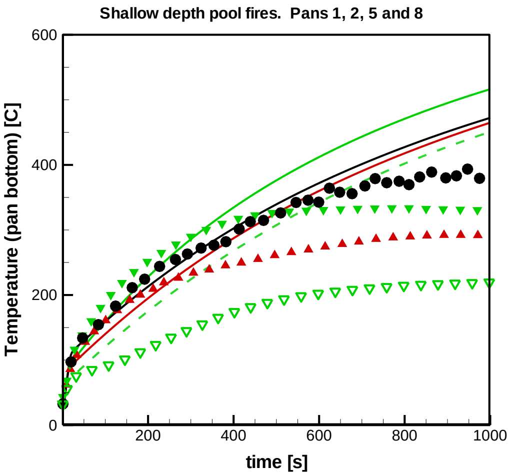
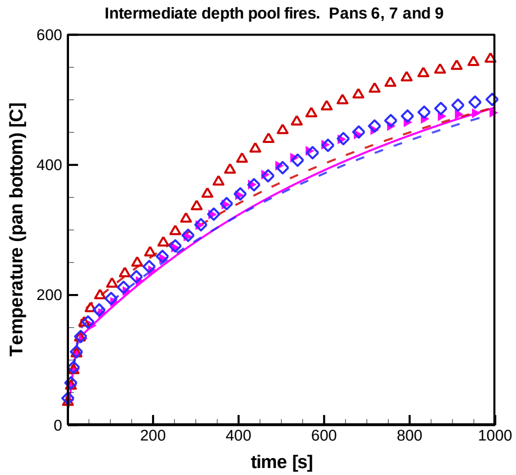
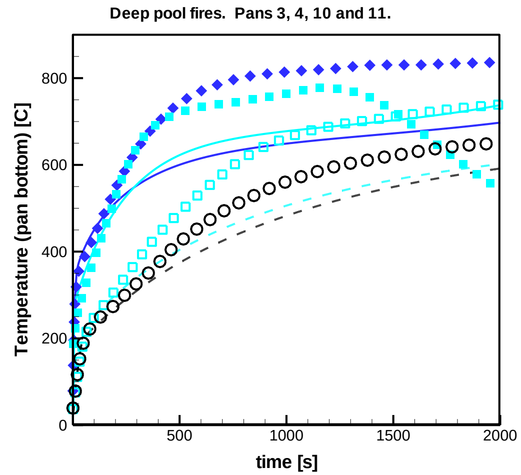
Temperature Evolution Predictions

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.

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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 LDRD 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

Questions/Comments

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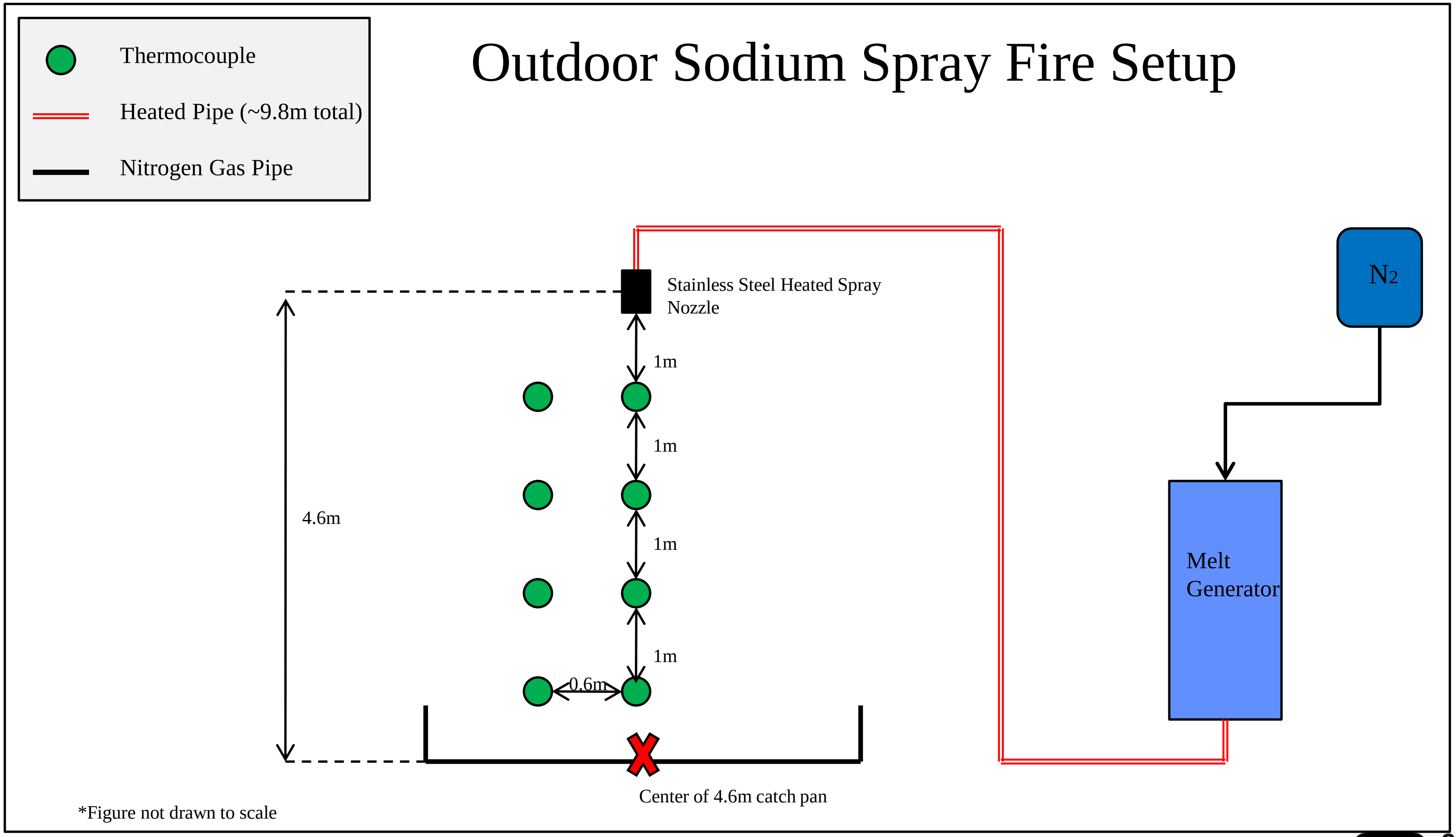
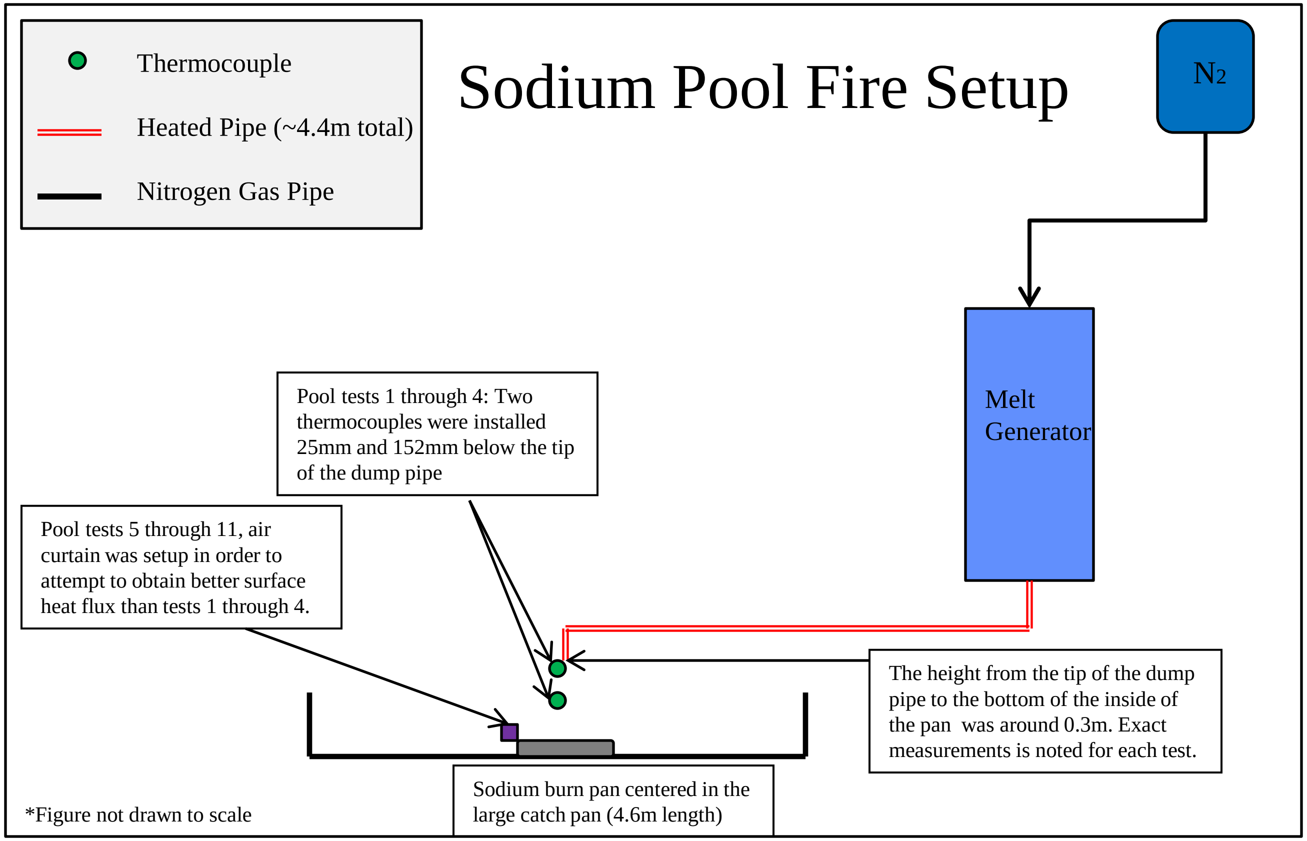
Backup Slides

Facility Info

Outdoor Sodium Spray Fire Setup




Sodium Pool Fire Setup
Thermocouple
Heated Pipe (~4.4m total)
Nitrogen Gas Pipe
N2
Melt Generator
Pool tests 1 through 4: Two thermocouples were installed 25mm and 152mm below the tip of the dump pipe
Pool tests 5 through 11, air curtain was setup in order to attempt to obtain better surface heat flux than tests 1 through 4.
The height from the tip of the dump pipe to the bottom of the inside of the pan was around 0.3m. Exact measurements is noted for each test.
Sodium burn pan centered in the large catch pan (4.6m length)
*Figure not drawn to scale

Inside Test Pan Rake (4 in from center) TCs Details		
Sodium Pool Test	**TC Spacing**	**Number of TCs**
1,2,3,4	N/A	N/A
5	6.35mm (0.25 in)	6
6	6.35mm (0.25 in)	6
7	6.35mm (0.25 in)	8
8	6.35mm (0.25 in)	4
9	6.35mm (0.25 in)	8
10	6.35mm (0.25 in)	15
11	6.35mm (0.25 in)	15

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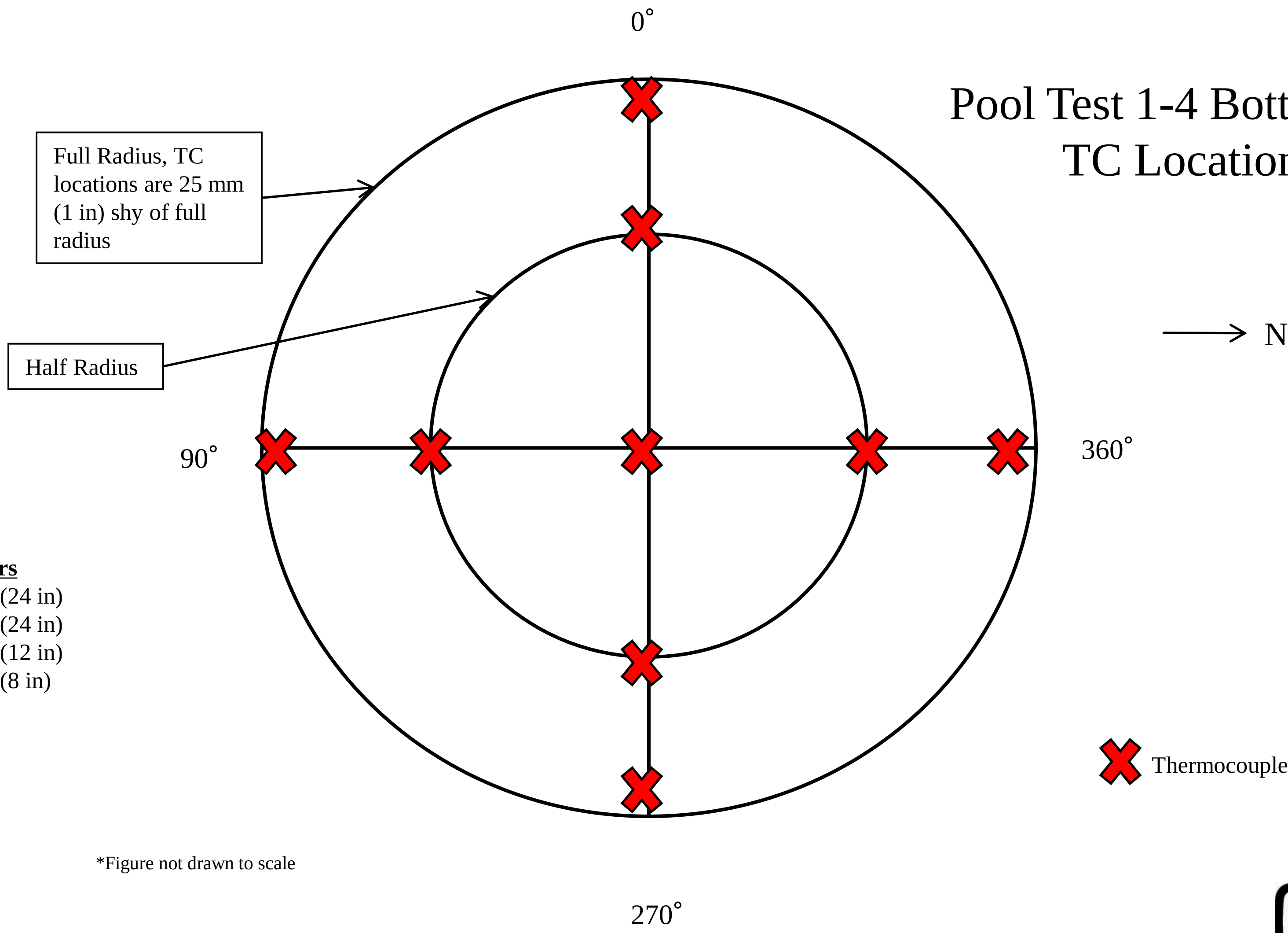
Pool Test 1-4 Bottom Pan TC Locations



Pan Diameters
Test 1: 0.6 m (24 in)
Test 2: 0.6 m (24 in)
Test 3: 0.3 m (12 in)
Test 4: 0.2 m (8 in)

*Figure not drawn to scale

Pool Test 5-11 Pan TC Locations

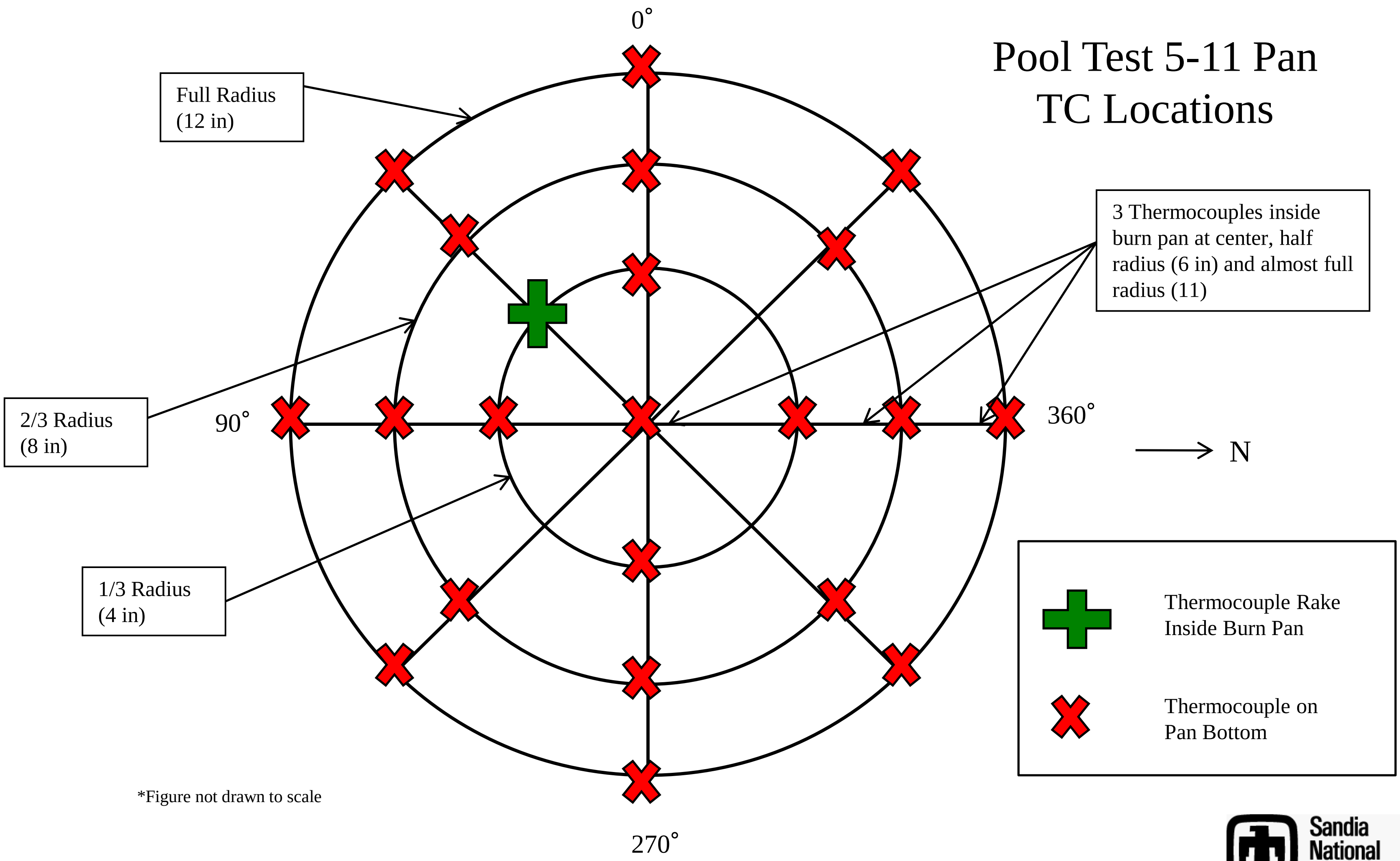
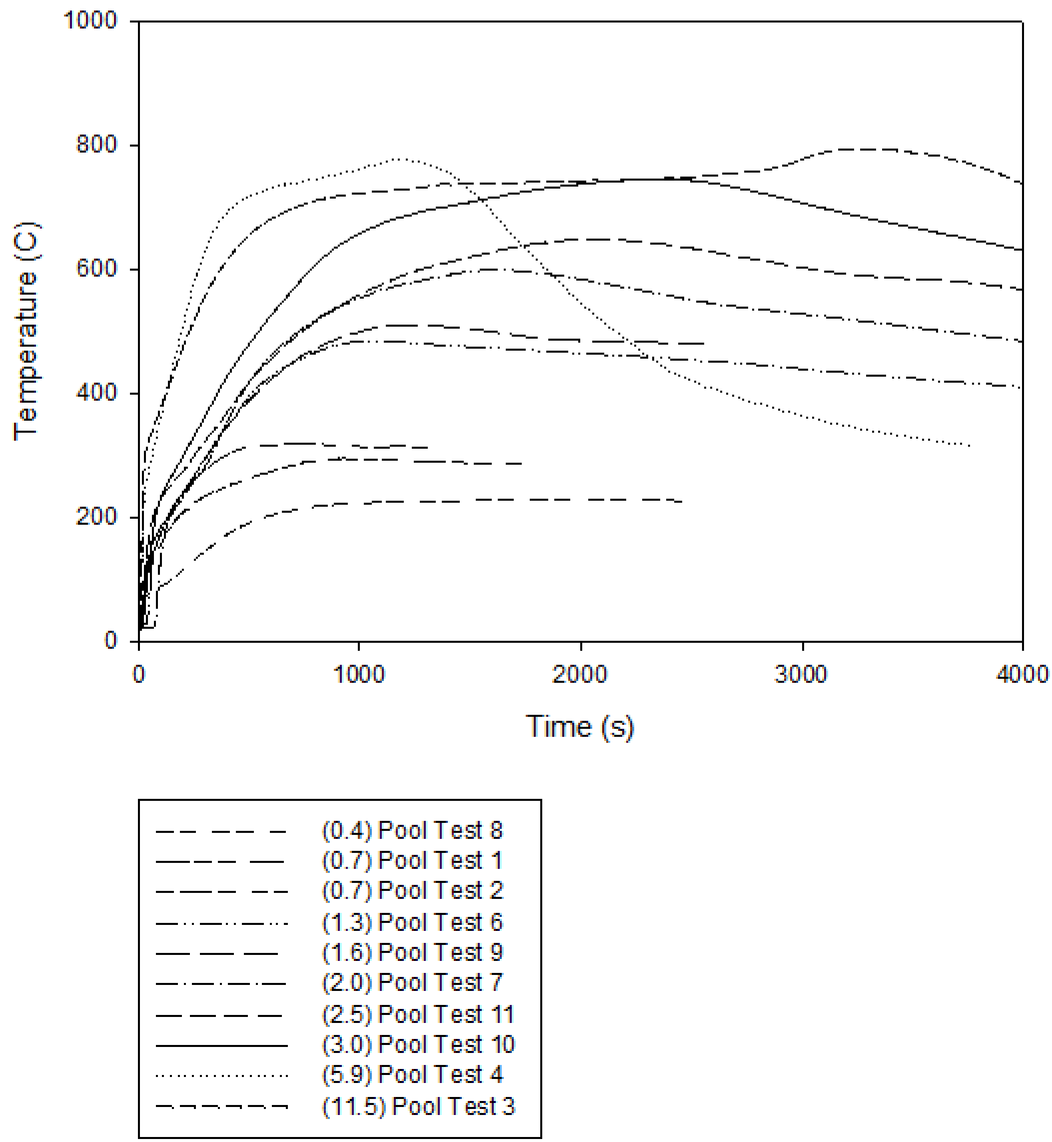
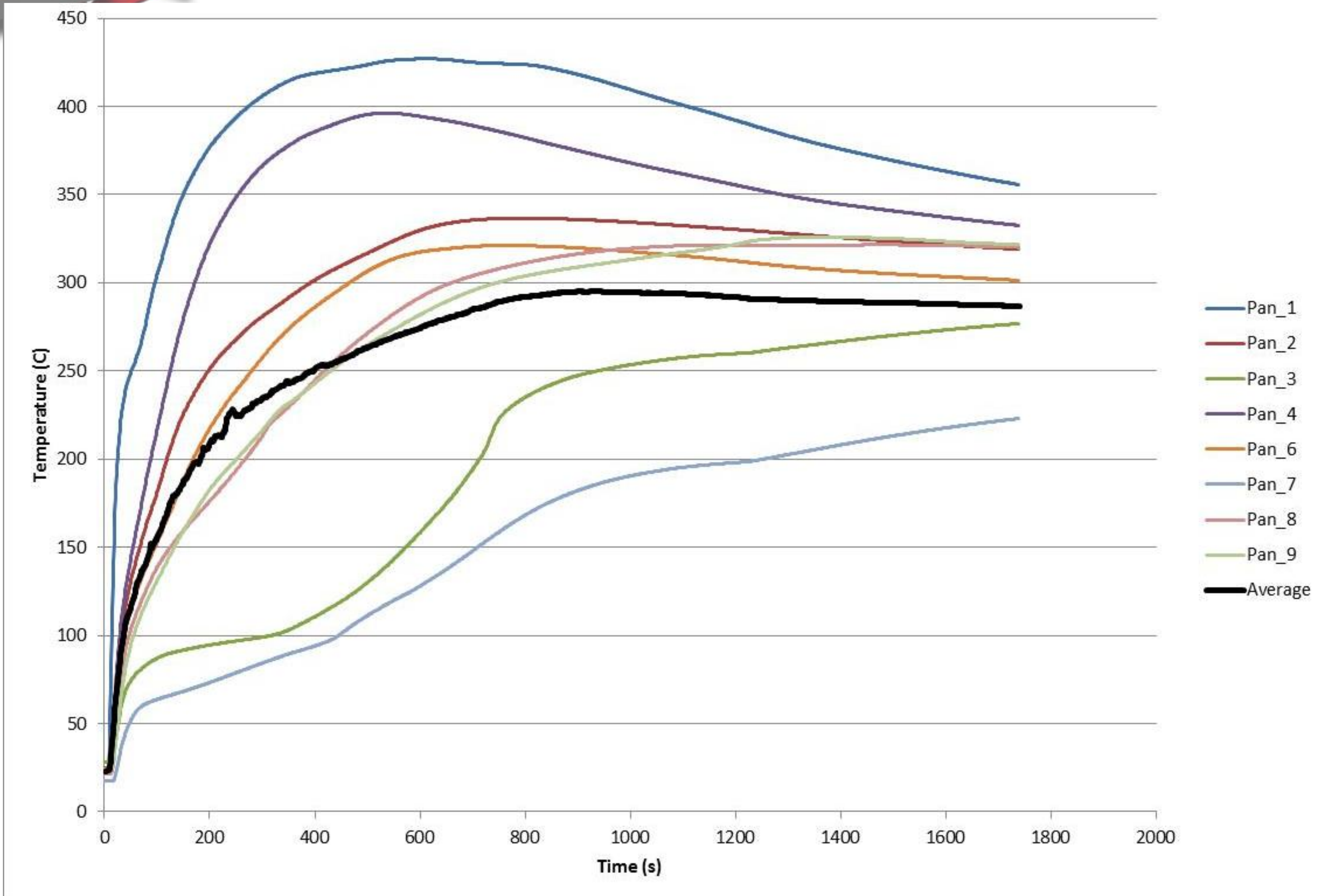


*Figure not drawn to scale



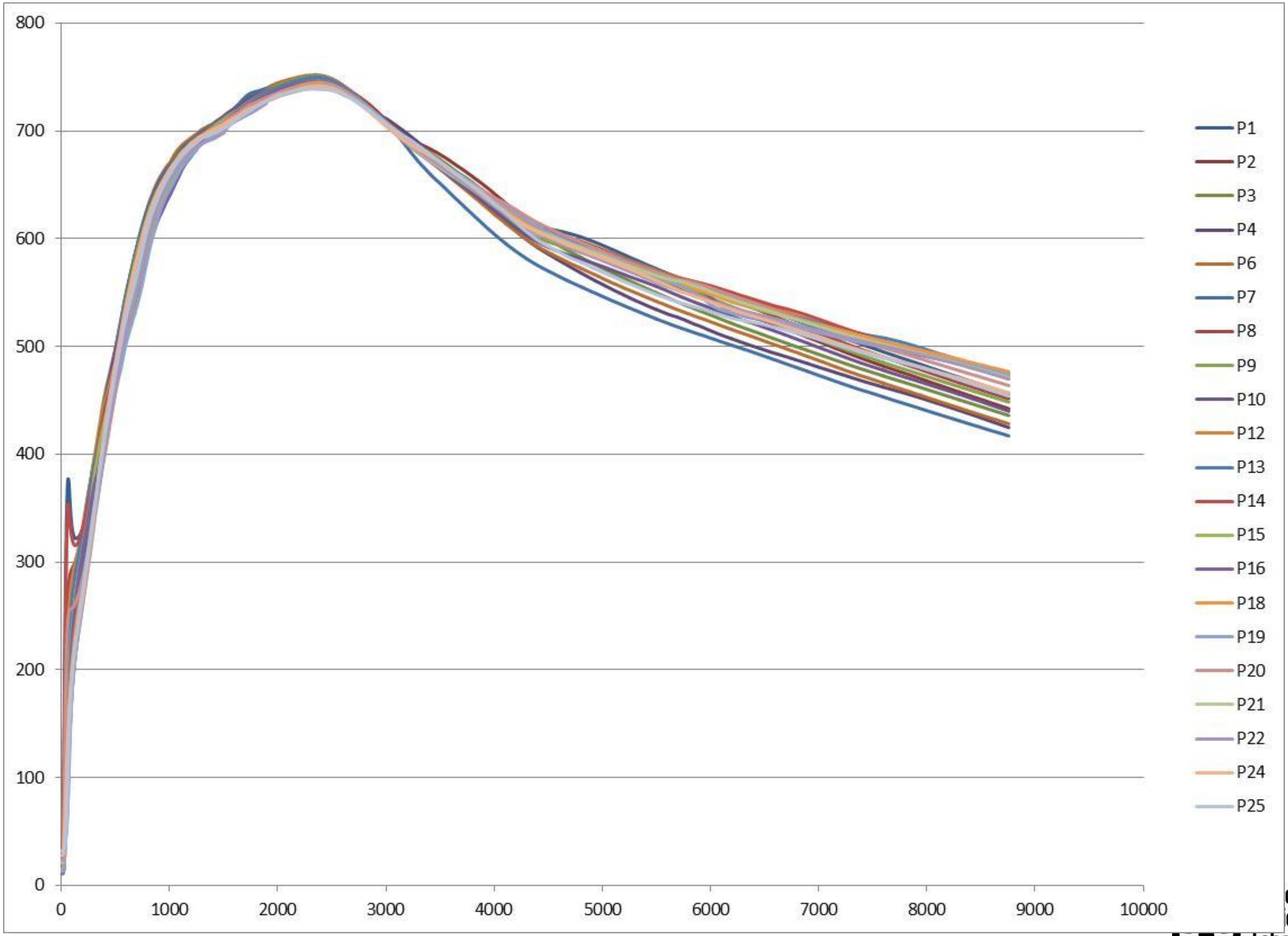
All Sodium Pool Tests Displayed by Liquid to Steel Thickness Ratio: Average Pan Bottom TC Temperatures vs Time

Pan Test 1



450
400
350
300
250
200
150
100
50
0
Temperature (C)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (s)
Pan_1
Pan_2
Pan_3
Pan_4
Pan_6
Pan_7
Pan_8
Pan_9
Average

Pan Test 3



800
700
600
500
400
300
200
100
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0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
P1
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