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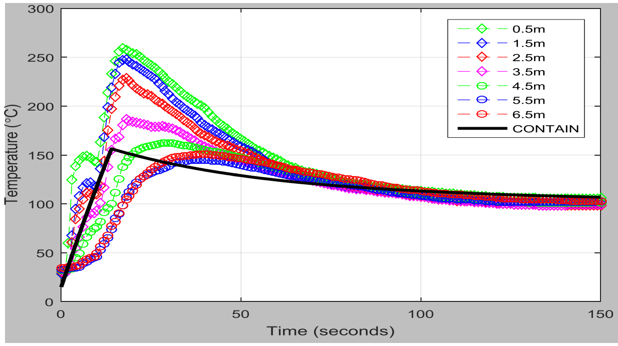

CONTAIN-LMR Sodium Fire Benchmarking

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Civil Nuclear Energy Research and Development Working Group

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National Nuclear Security Administration

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Motivation

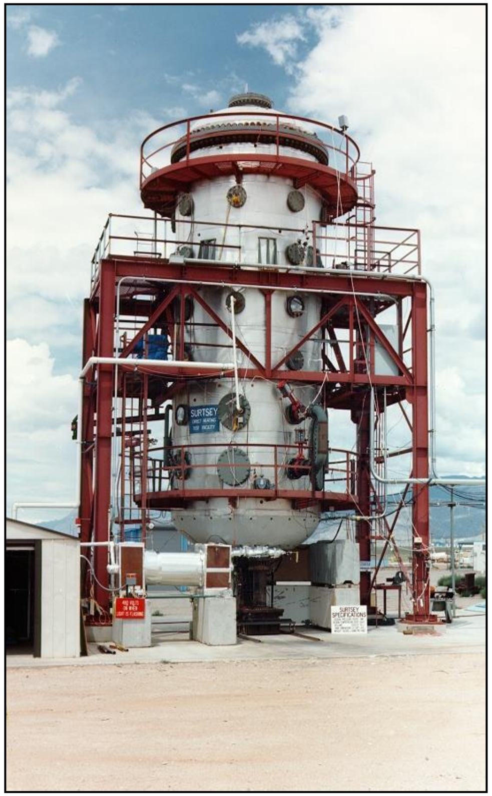
- Understanding and accurately characterizing sodium fires is extremely important:
  - Economics – Unexpected sodium fire behavior can lead to long shutdowns and low capacity factors.
  - Safety – Sodium fires are the primary drivers for radionuclide transport from the reactor to the public for low pressure sodium fast reactor (SFR) systems.
- The US has only recently attempted to regain its sodium fire modeling capability and this collaboration provides a mutually beneficial opportunity for improving both countries sodium fire modeling capabilities.

Objectives

- Review SNL Experiments
- Discuss modeling results for T3 experiment
  - Review the sodium flowrate
  - CONTAIN-LMR sensitivities
  - Two-spray model
- Preliminary modeling results for T4 experiment

Sodium Fire Testing at SNL

- Experiments were performed back in 2009 and 2010 at Surtsey Facility [Olivier 2010].
- 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.



T.J. Olivier, et al., "Metal Fires and Their Implications for Advance Reactors Part 3: Experimental and Modeling Results", SAND2010-7113, Sandia National Laboratories, Albuquerque, NM, (2010).

Test Matrix

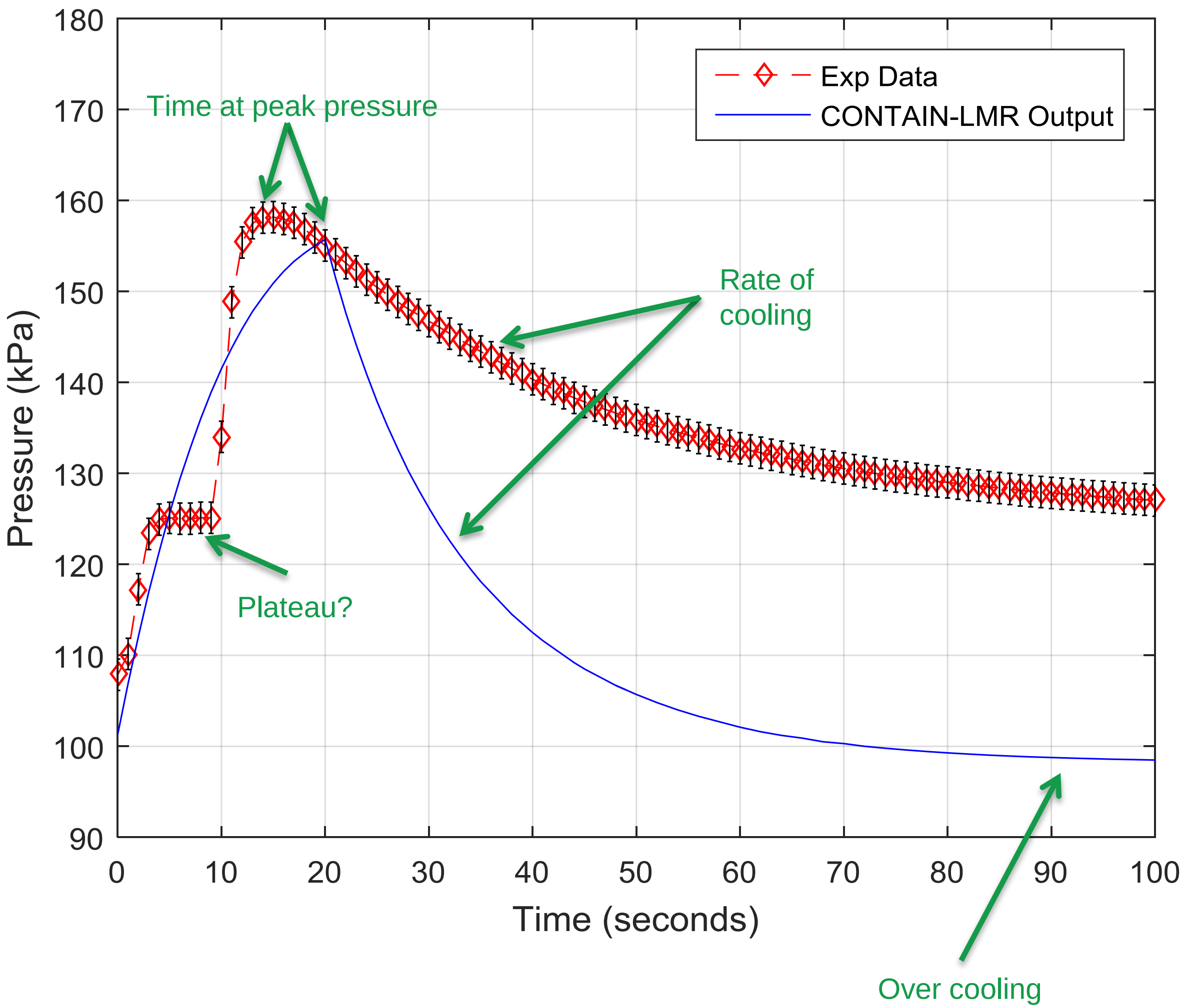
Test ID	Test Originator	Open or Closed to the Environment	Pool/Spray	Amount of Sodium (kg)	Thickness Ratio (liquid sodium/stainless steel)	Average Peak Temperature at bottom of pan (°C)
P1	SNL	Open	Pool	2.6	0.7	320
P2	SNL	Open	Pool	2.6	0.7	320
P3	SNL	Open	Pool	4.4	11.5	800
P4	SNL	Open	Pool	1.0	5.9	780
P5	SNL	Open	Pool	-	-	-
P6	SNL	Open	Pool	4.8	1.3	480
P7	SNL	Open	Pool	7.8	2.0	600
P8	SNL	Open	Pool	1.6	0.4	220
P9	SNL	Open	Pool	6.0	1.6	490
P10	SNL	Open	Pool	11.6	3.0	746
P11	SNL	Open	Pool	9.6	2.5	648
T3	SNL	Closed	Spray	20	-	259
T4	SNL	Closed	Spray	20	-	1205
F7-1	JAEA	Closed	Pool	-	-	-
F7-2	JAEA	Closed	Pool	-	-	-

Updated T3 Information

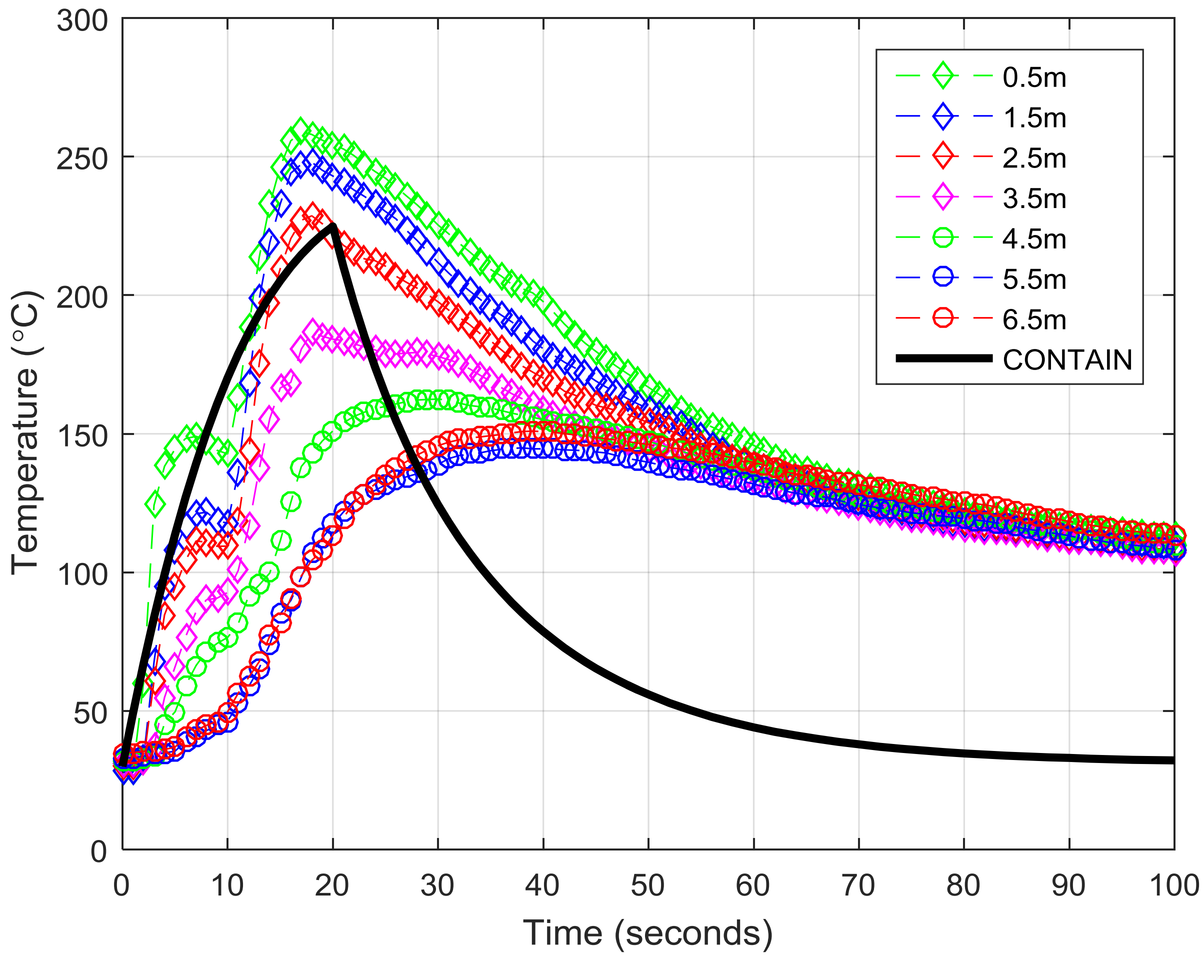
- T3 and T4 experiments conducted inside Surtsey vessel.
  - Thermocouples (TCs) saturated with aerosol products making TC data unreliable.
  - Due to unreliability of TC data, pressure data will be used for verification.
- It was recently communicated to us that the sodium temperature for the T3 experiment was supposed to 500°C, not 200°C.
  - Heater on melt generator (MG) failed when sodium reached 200°C.
    - Decided to go ahead and discharge sodium at 200°C.
  - Additionally, the piping system from MG to nozzle was not purged.

Previous Result Discrepancies

Sodium Mass Injected	20 kg
Duration of Sodium Spray	About 20 seconds
Spray Height	5.3 m
Sodium Mass Flowrate	1 kg/s
Sodium Outlet Nozzle Velocity	9.34 m/s
Outlet Nozzle Pressure	2.01 MPa (291 psi)
Initial Sodium Temperature	200°C
Nozzle Orifice Diameter	1.23 cm
Mean Droplet Diameter (DME)	2.0 mm
Vessel Free Volume	99 m^3
Vessel Thickness	1 cm

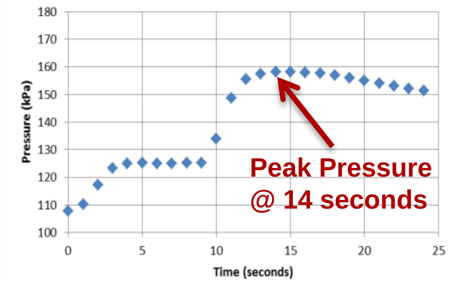


Previous Result, Temperature Plot



Resolving Discrepancies

- CONTAIN-LMR structure inputs not accurate.
  - Updating the structures resolved the rate of cooling and overcooling.
- Time at peak pressure did not align.
  - Based on experimental data, the injection time is more likely about 14 seconds. Thus, $\dot{m} = 1.43\ {}^{kg}/_{s}$



- The sodium temperature and sodium ignition temperature very close to one another.
  - This explains the experimental plateau observed.
- Sodium/water diameter ratio is 2.2 [Accosta 2008] so expected diameter is about 0.8 mm.

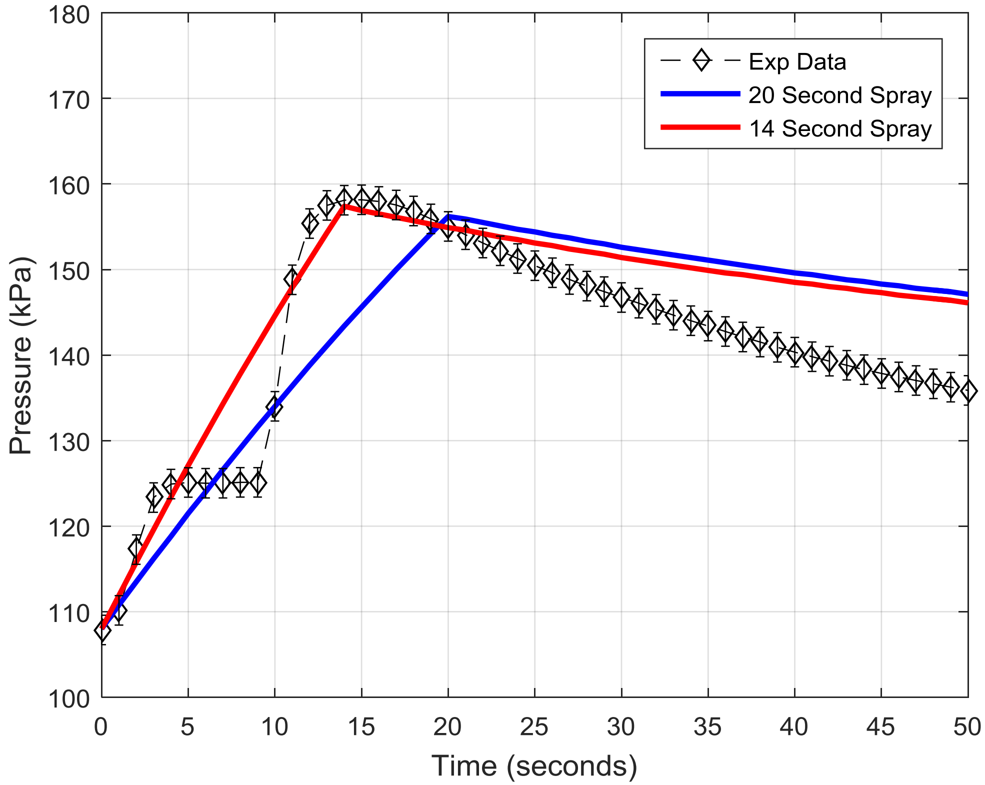
Robert Accosta and Laura Archer, "Studies of Metal Fires: Study of Sodium Spray Fires for Sandia National Laboratories," B.S. Thesis, ME Dept, WPI, Worcester, MA, 2008.

Spray Duration Comparison

- Experimental peak pressure at 14 seconds.
- Unfortunately, spray duration cannot be confirmed by video recordings.
- Long term pressure nearly identical for both spray durations.

T3 Experiment

(Sodium diameter = 2.7 mm)



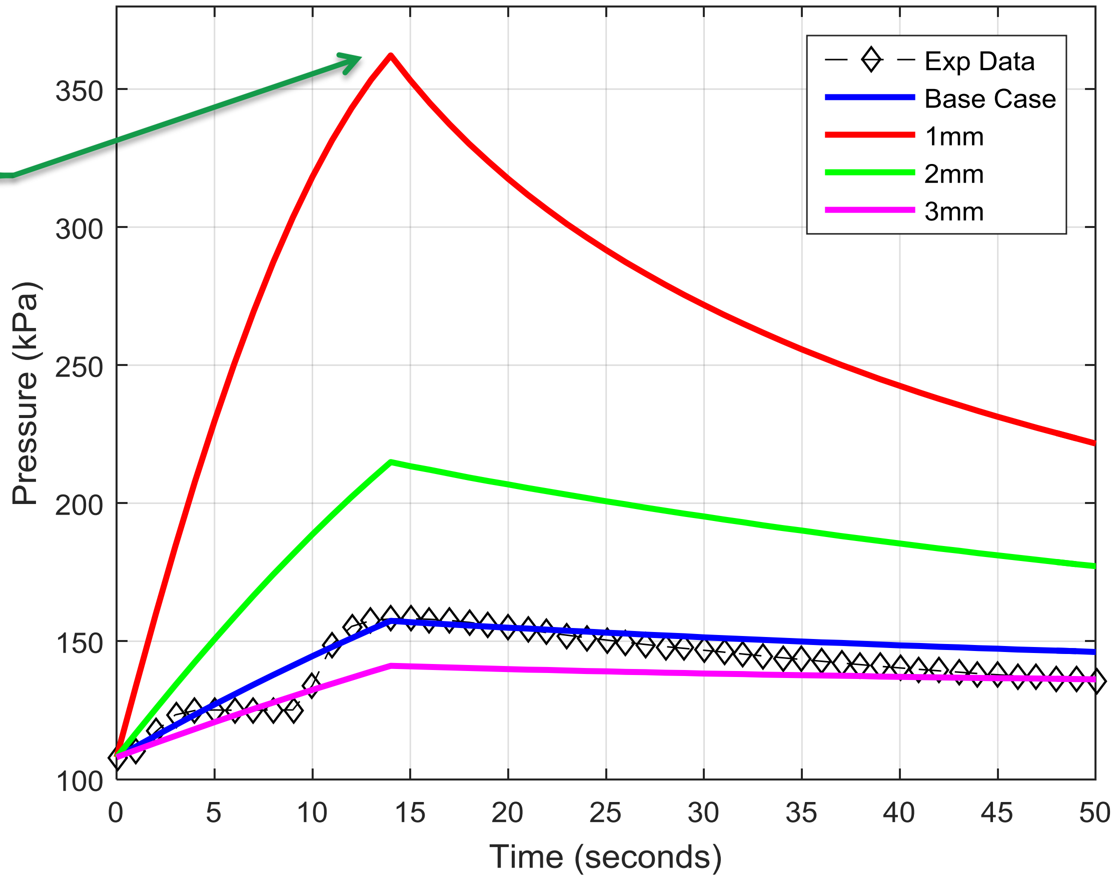
Sodium Droplet Size

<u>Sodium Spray Diameter Uncertainty</u>

- The correlation estimates using nozzle supplier and 2.2 correlation ratio do not align well with experiment.
- Combustion of sodium follows the "D^2" law.
- This leads to results being highly dependent on the user-specified diameter.
- Droplet size distribution follows the Nukiyama-Tanasawa correlation.

T3 Experiment

(Base Case = 2.7 mm)

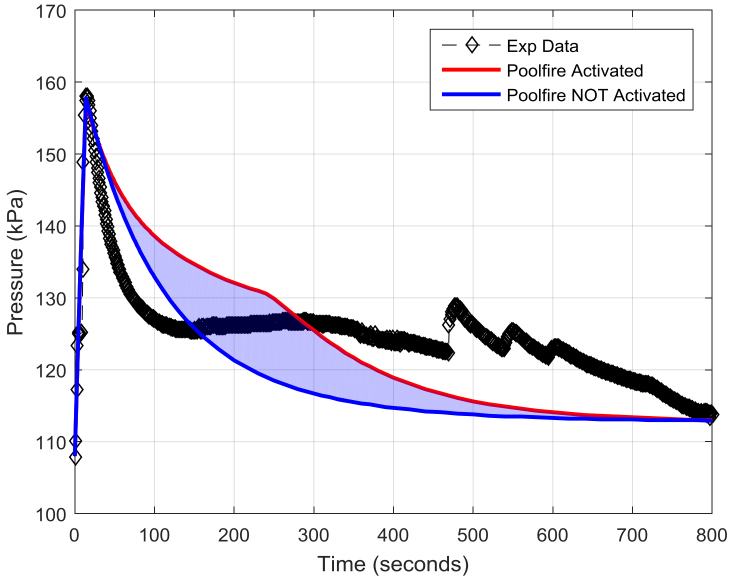


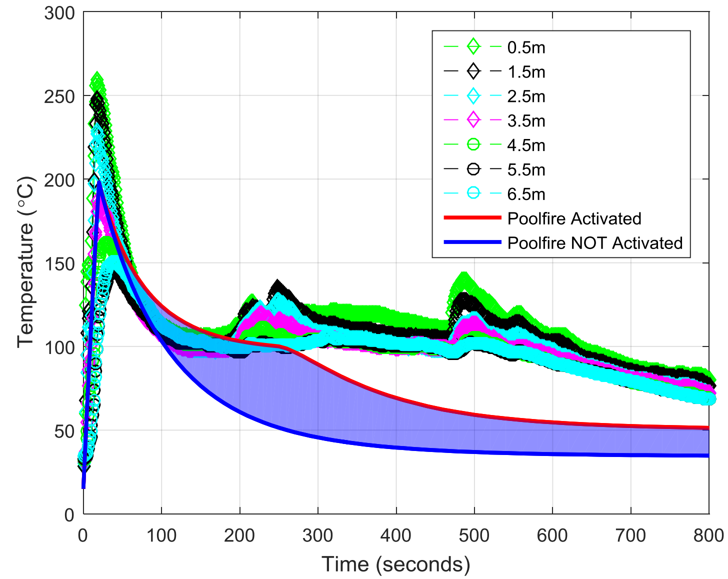
CONTAIN-LMR Inputs (Base Case)

Experimental Parameters	
Sodium Mass Injected	20 kg
Duration of Sodium Spray	Approximately 14 seconds
Sodium Mass Flowrate	1.43 kg/s
Spray Height	5.3 m
Atmospheric Pressure	1.08E+05 Pa
Initial Sodium Temperature	200°C (T3) 500°C (T4)
Vessel Free Volume	99 m^3
CONTAIN-LMR Uncertain Parameters	
Sodium Droplet Diameter (base case)	2.7 mm
Fraction of Na_2O_2 Produced in Spray	1.0
Pool Fire Ratios	0.5, 1.0, 1.0, 0.0

Pool Fire Activation

- Sodium pool fire keyword was previously not activated.
  - If not specified, sodium pool fire will not occur in CONTAIN-LMR.
- Pool fire ratios:
  - *f1 = 0.5*
  - *f2 = 1.0*
  - *f3 = 1.0*
  - *f4 = 0.0*





(Sodium diameter = 2.7 mm)

Pool Fire Keyword

- Four ratios for pool fire keyword in CONTAIN-LMR:
  - *f1 = fraction of the total oxygen consumed that reacts to form the monoxide, as opposed to the peroxide.* Default = 0.5
  - *f2 = fraction of the sensible heat from the reaction that is applied to the pool; the balance, 1-f2, is applied to the atmosphere above the pool.* Default = 1.0
    - Default value assumes user models heat transfer through other modeling options.
  - *f3 = fraction of monoxide,* Na_2O*, that enters the pool as a solid after formation; the balance enters the atmosphere as an aerosol.* Default = 1.0
  - *f4 = fraction of peroxide,* Na_2O_2*, that enters the pool as a solid after formation; the balance enters the atmosphere as an aerosol.* Default = 1.0

Model Uncertainties

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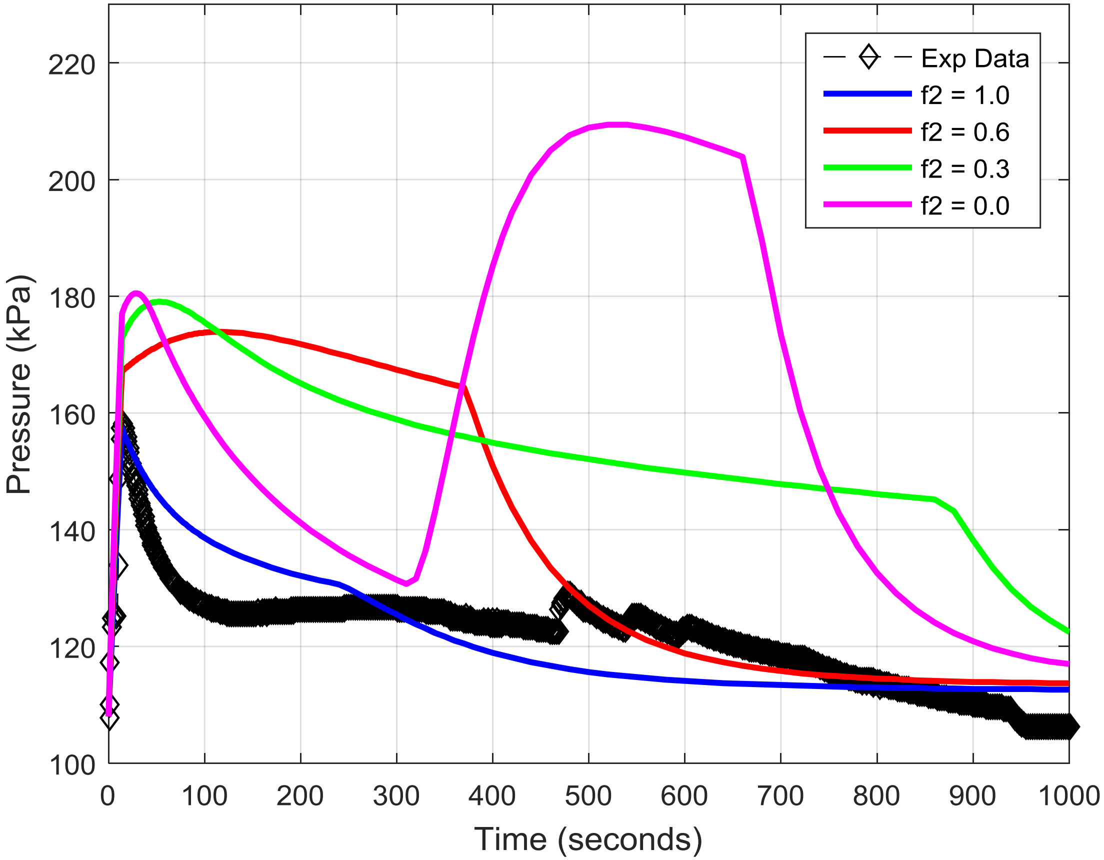
<u>Pool Fire "f2" Ratio</u>

- Recall that *f2* is the fraction of reaction heat added to the pool.
  - Are we modeling all other heat transfer mechanisms in the model?
- Observations:
  - With *f2 = 0.6*, the second experimental pressure drop is observed.
  - With *f2 = 0.3*, the long term pressure drop trend agrees with experiment.
  - With *f2 = 0.0*, the delayed pressure rise is captured (not at the same time though).



Model Uncertainties

Fraction of Peroxide Produced in Spray

- Reactions that are occurring in spray:

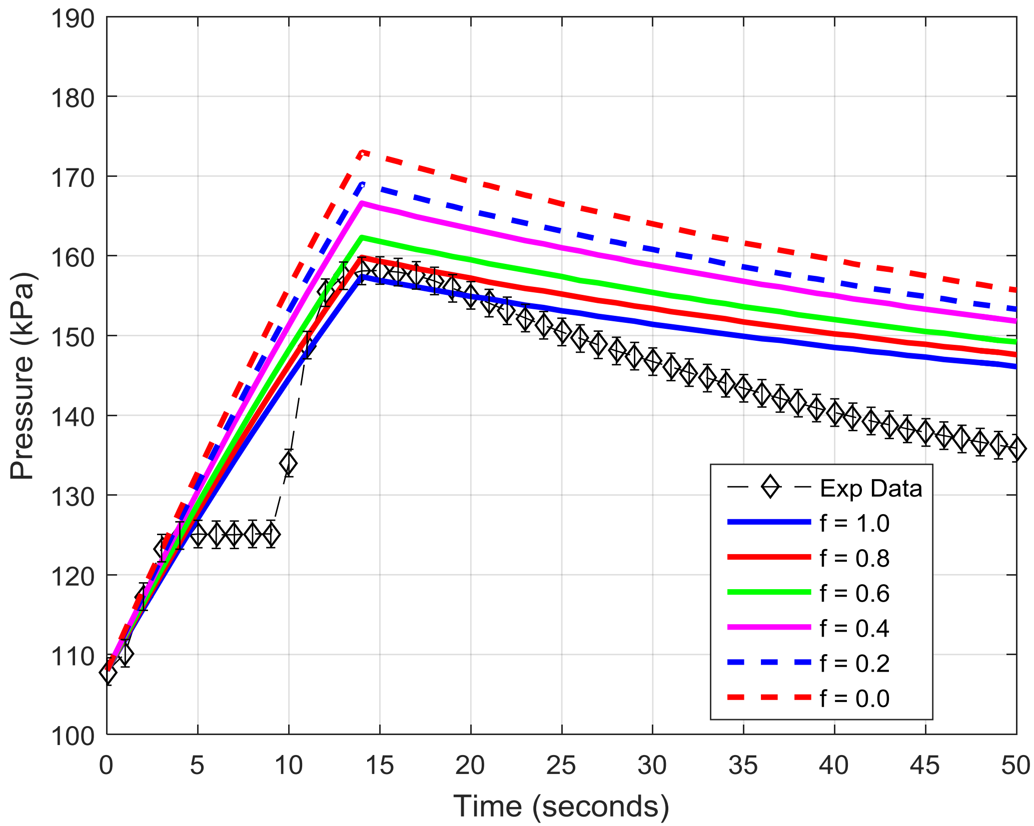
$$2\ \mathrm{Na} + {}^{1}/_{2}\, \mathrm{O_2} \rightarrow \mathrm{Na_2O}$$

$$2\ \mathrm{Na} + \mathrm{O_2} \rightarrow \mathrm{Na_2O_2}$$

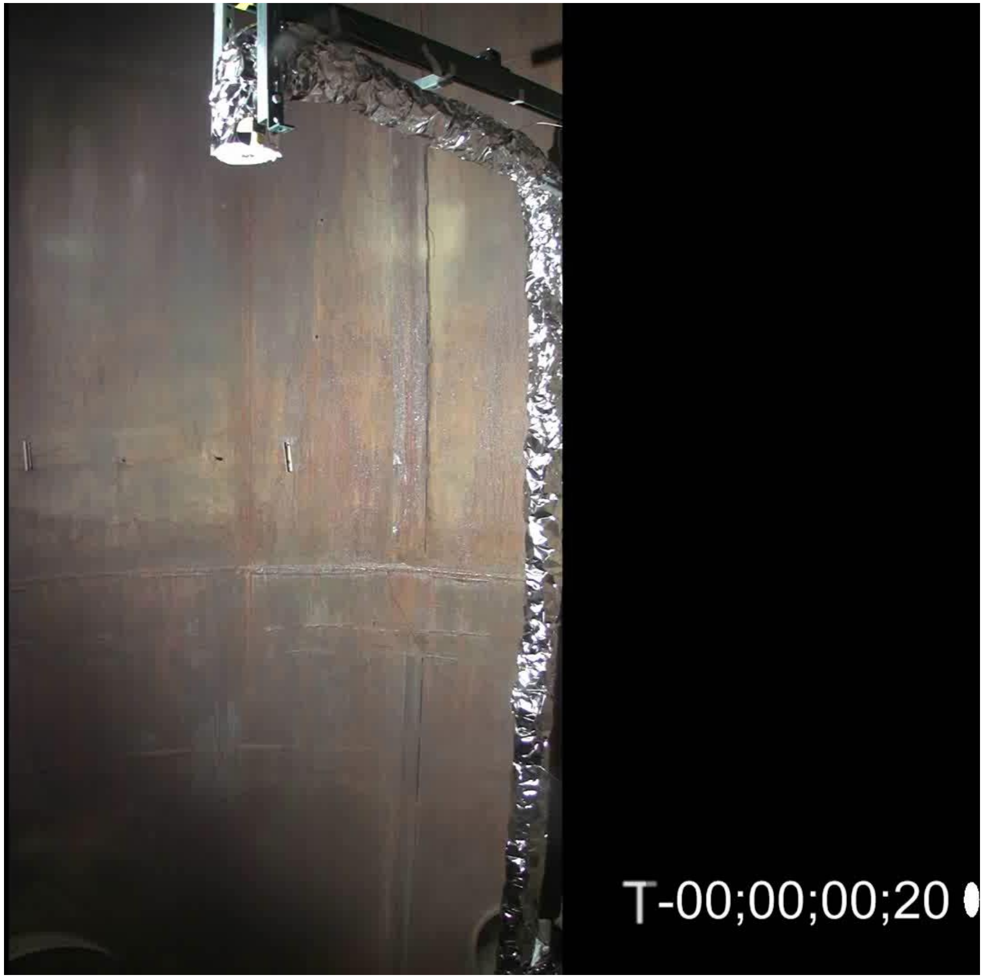
- Fixed ratio of peroxide and monoxide:

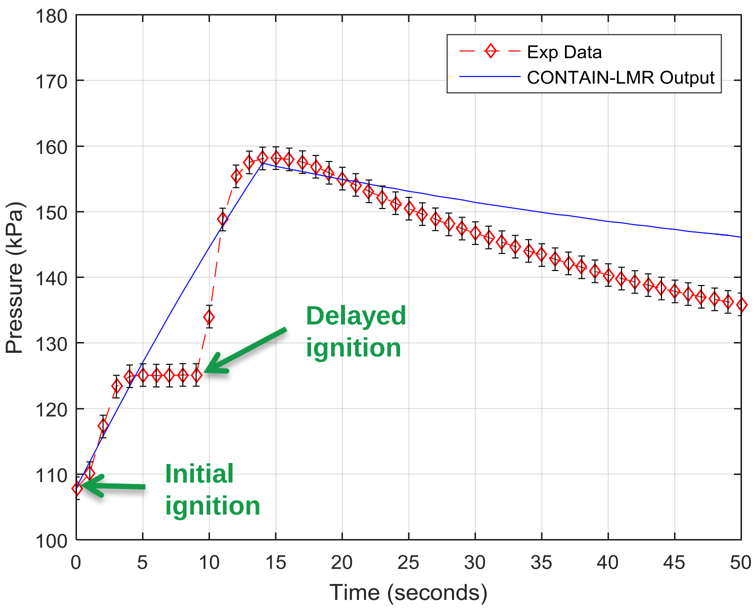
$$\left(\frac{1.3478 \cdot \mathrm{F}_{Na_2O_2}}{1.6957 - 0.3479 \cdot \mathrm{F}_{Na_2O_2}}\right)$$

- No information on reaction products collected from experiment that can be used to estimate the ratio.



Experimental Plateau





Why the Plateau?

- Ignition temperatures for sodium not well-known.
  - Reported anywhere from 120°C to 470°C.
    - However, sodium ignition more complicated than a specific value.
  - One source referenced reports 200°C for droplets [Casselman].
    - Sodium temperature could have been fluctuating around this value.
- Without purging the line, sodium could have been reacting upstream of the spray nozzle.
  - Initial discharge is reacting sodium and reaction products.
- Initial experimental procedure was to have sodium at 500°C but heaters on melt generator (MG) failed.
  - Less likely a possibility due to stationary sodium in MG and high heat conductivity of sodium.

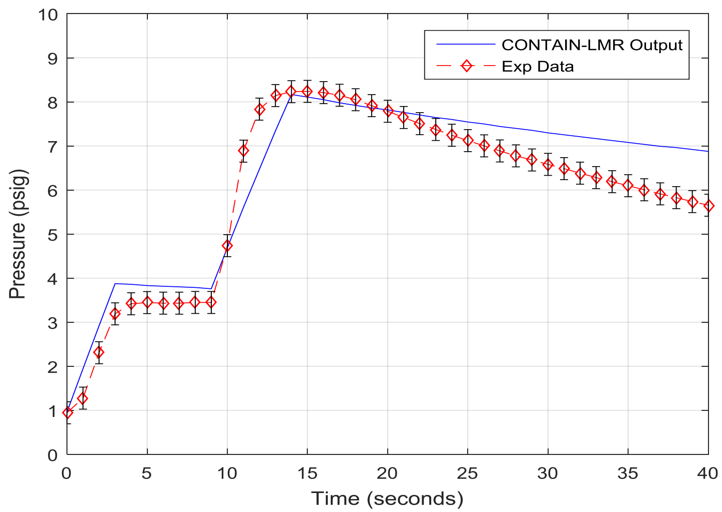
C. Casselman, "Ignition of a Liquid Sodium Pool," DSN/SESTR, Centre de Cadarache, Saint-Paul-lez-Durance, France.

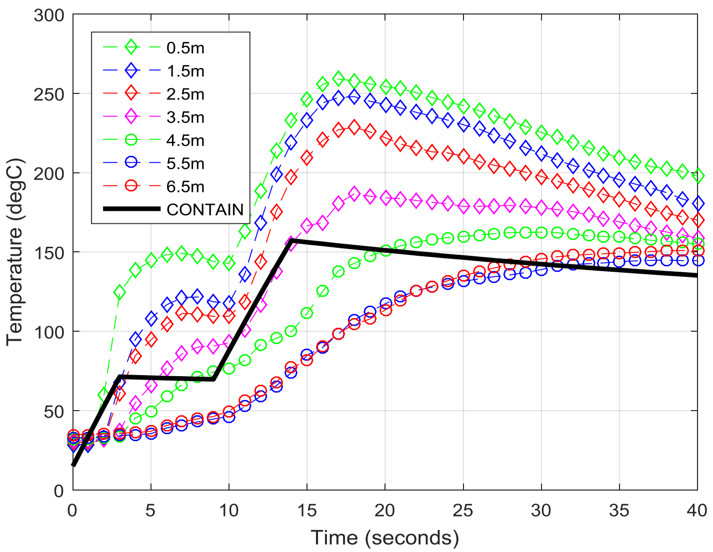
Model Two Spray Fires

- Spray same amount of sodium, but adjust mass flowrate.

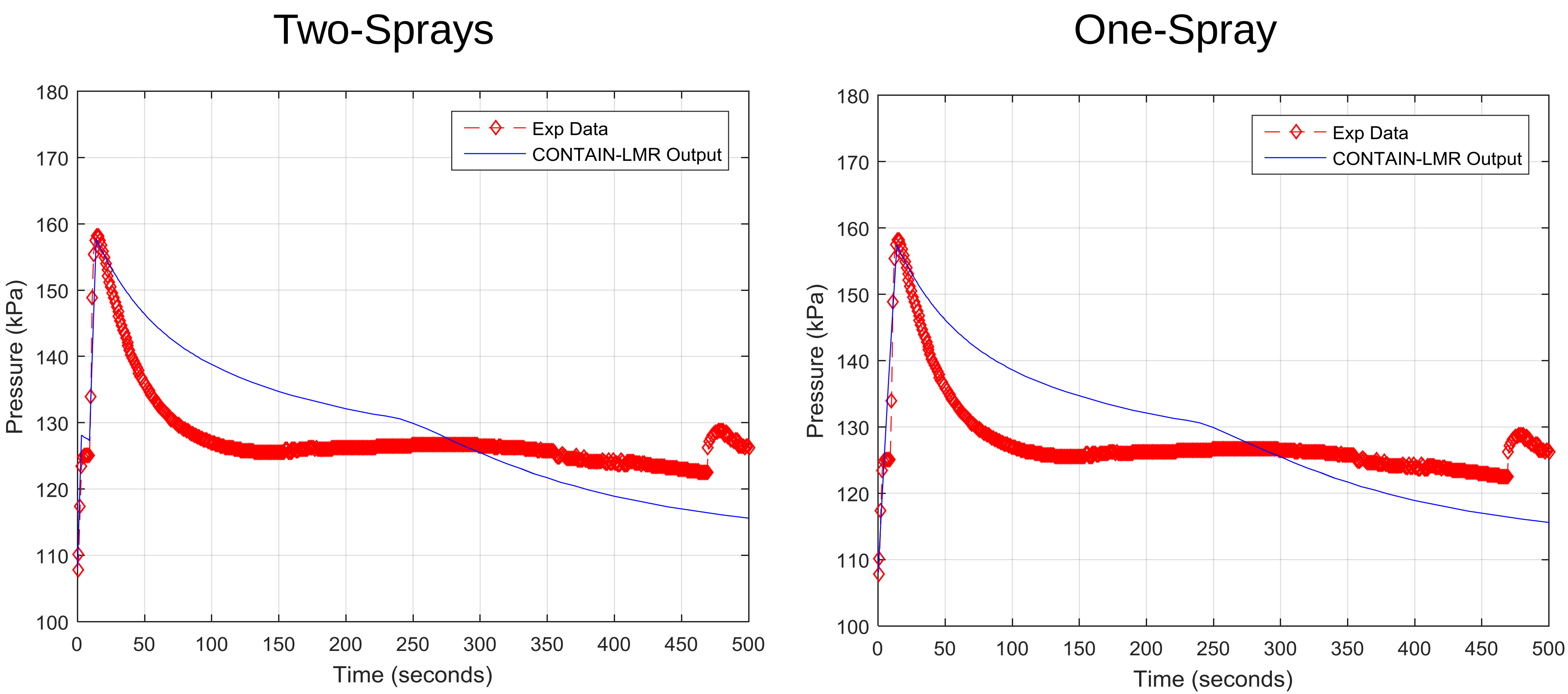
$$\dot{m} = 2.5 \ {}^{kg}/_{s}$$

  - Spray fire source from 0-3 seconds and from 9-14 seconds.
- The defined sodium temperature not compared to sodium ignition temperature.
- No difference in long term pressure because same amount of sodium sprayed.





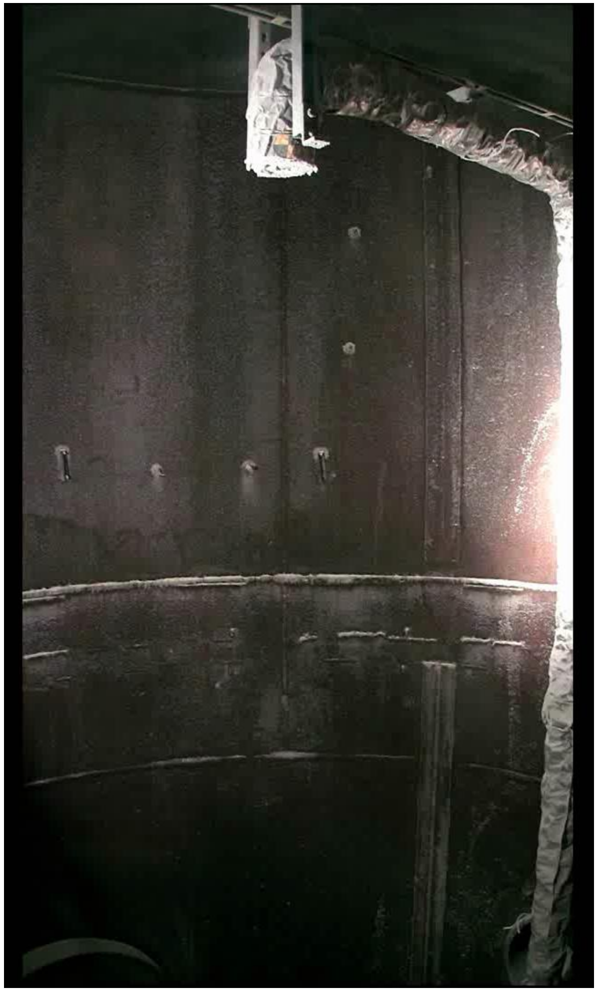
Two-Spray Model, Long Term



T4 Experiment

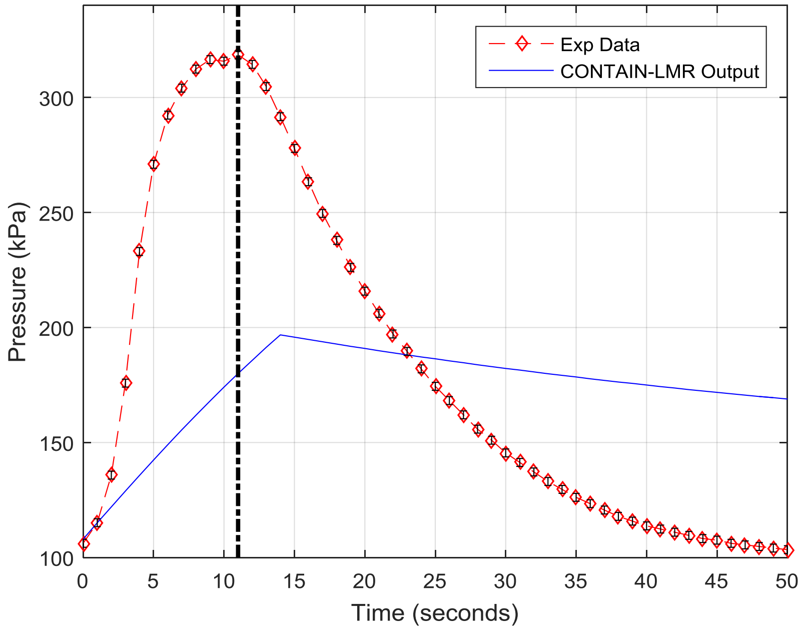
T3 Experiment

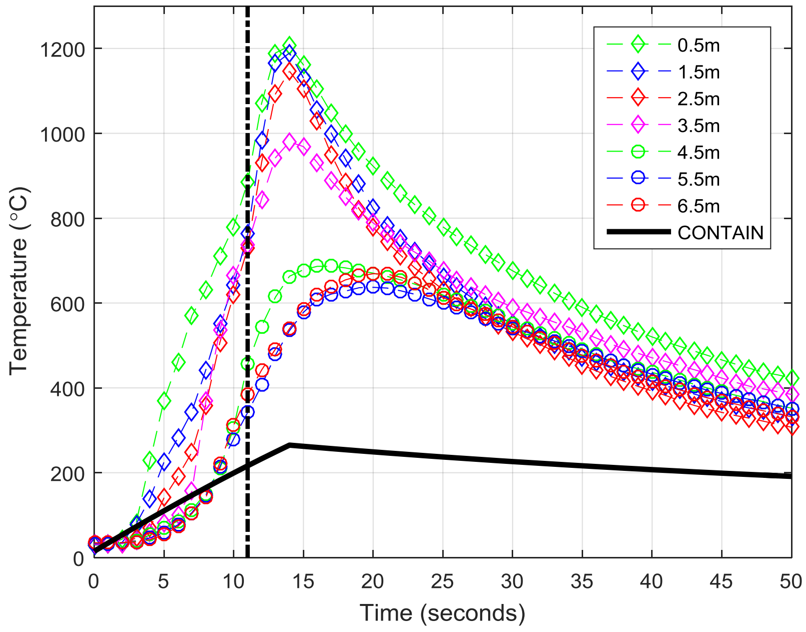
T4 Experiment



T4 Preliminary Results

- Differences between T3 and T4 model:
  - Spray will be continuous, not the two-spray model.
  - Increase sodium temperature from 200°C to 500°C.
  - Port failure in experiment, but not modeled here.





Conclusions

- How the *f2* ratio in pool fire physics affects/interacts with other heat transfer mechanisms in CLMR is not well understood.
  - Are we modeling all heat transfer mechanisms correctly?
- Results are in good agreement when adjusting the sodium droplet diameter.
  - Is this realistic?
- Need better understanding of reaction products.
  - What is the ratio of sodium monoxide to sodium peroxide?
- Why such a mismatch for the T4 experiments?

Future Work

- Adjust T4 data to match data, then compare to T3 inputs.
- Model 3-spray model for T3.
  - First spray → sodium spray fire.
  - Second spray → no spray fire, just adding sodium to pool.
  - Third spray → spray fire.
- Model port failure in T4 experiment.
- Model additional experiments.
- Use pool fire experiments to gain better understanding of pool fire ratios.