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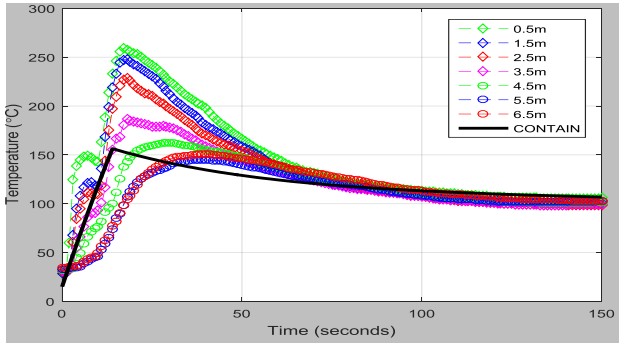

CONTAIN-LMR Sodium Fire Benchmarking

SNL Spray Fire Experiments T3 and T4

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Civil Nuclear Energy Research and Development Working Group

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

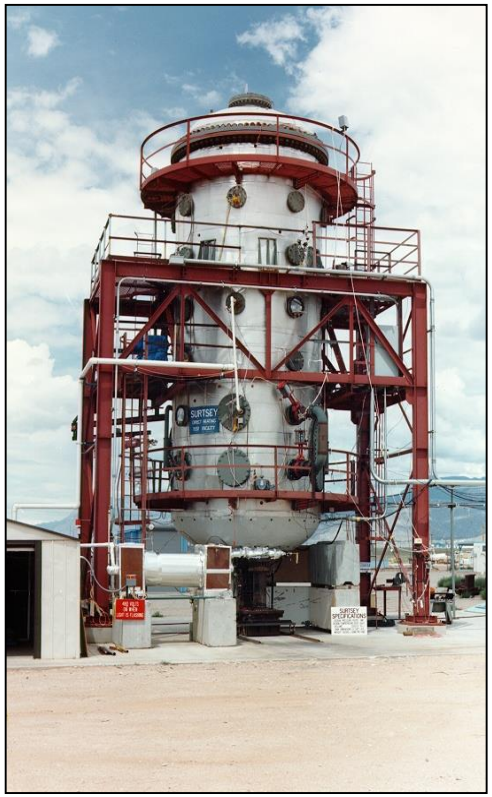
- Understanding and accurately characterizing sodium fires is important:
  - Economics – Unexpected sodium fire behavior can lead to long shutdowns and low capacity factors.
  - Safety – Sodium fires are the primary drivers for radionuclide transport from the reactor to the public for low pressure sodium 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 treatment
- Modeling results for T4 experiment
  - CONTAIN-LMR sensitivities

Sodium Fire Testing at SNL

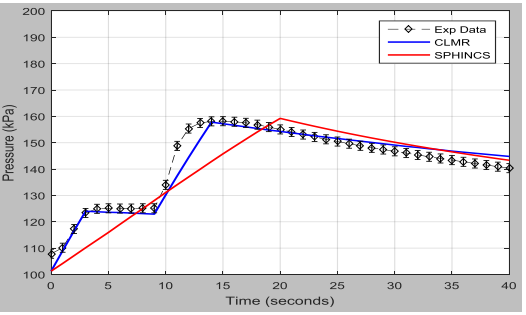
- Experiments were performed back in 2009 and 2010 at Surtsey Facility [Olivier 2010].
- Sodium Pool Fire Experiments
  - 11 outdoor experiments
  - Measured surface heat fluxes and pool temperatures.
  - Varied thickness ratio of the stainless steel substrate to the liquid sodium.
- Sodium Spray Fire 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 (atmosphere)
T4	SNL	Closed	Spray	20	-	1205 (atmosphere)
F7-1	JAEA	Closed	Pool	4.94	-	616
F7-2	JAEA	Closed	Pool	4.94	-	675



Surtsey T3 Experiment

Contain-LMR

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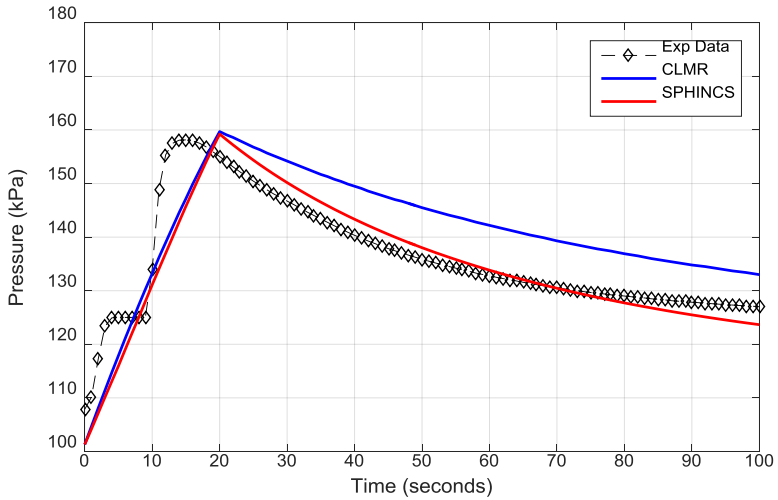
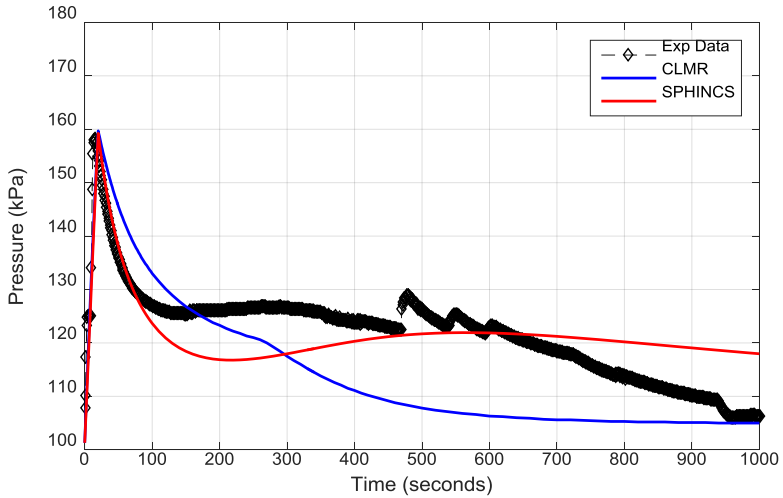
T3 Best Estimate

Terms	CONTAIN-LMR	SPHINCS
Vessel free volume	99m^3	←
Vessel thickness	0.11m(11.0cm)	←
Vessel wall emissivity	0.9 [-]	←
Spray height	5.3m	←
Sodium outlet nozzle velocity	Terminal Velocity	9.34m/s
Initial Sodium temperature	200ºC	←
Mean droplet diameter (volumetric mean)	2.47mm	2.75mm
Sodium pool fire	Activated	← (Ring pool fire)
★ Atmospheric chemistry	Deactivated	?
Initial gas temperature	288.15K	←
Initial gas pressure	101.3kPa A	←
Oxygen concentration (molar fraction)	0.233 [-]	←
Pool fire ratios (*f1, f2, f3, f4*)	0.5, 1.0, 1.0, 0.0	← (Ring pool fire)

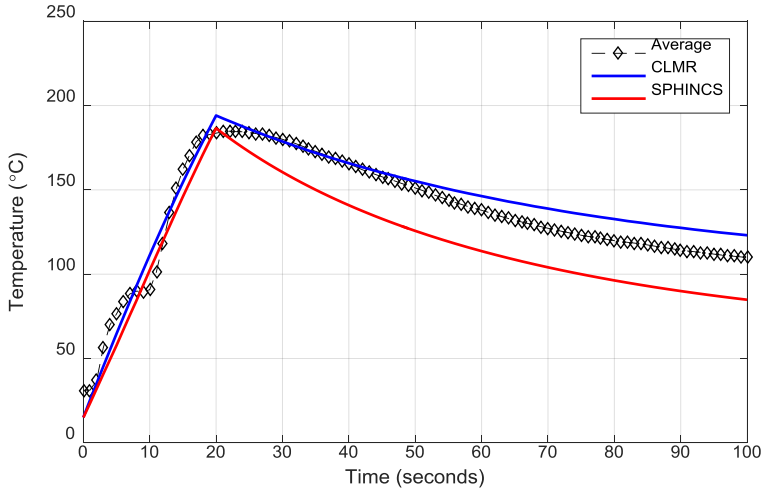
T3 Best Estimate

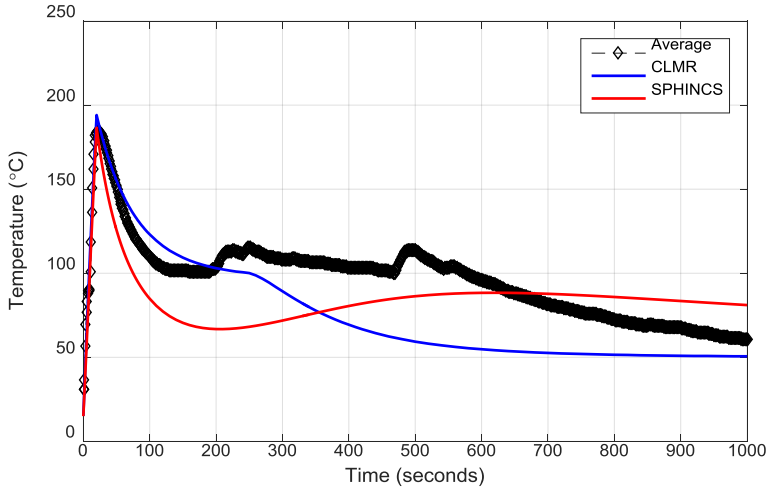
Atmospheric Pressure





Atmospheric Temperature





Atmospheric Chemistry Model

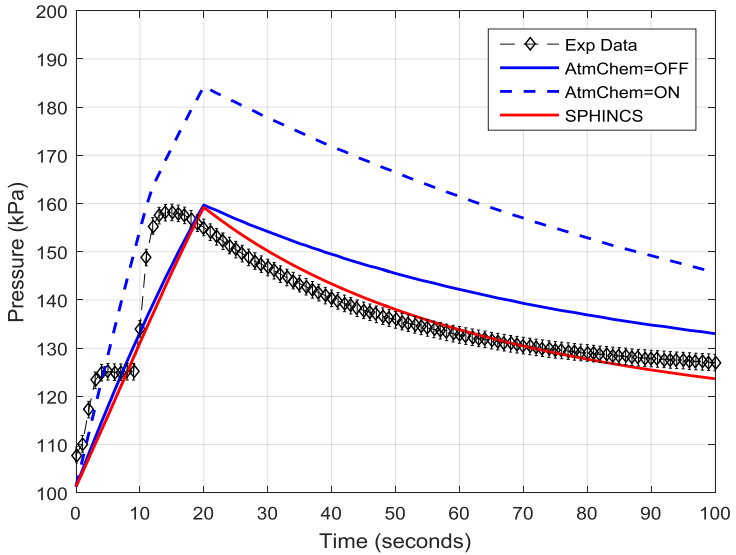
- Atmospheric chemistry can be turned on or off.
- Atmospheric reactions associated with this model:
  - ~~$Na + H_2O\ (liq) \rightarrow NaOH + ½\ H_2$~~
  - ~~$2\ Na + H_2O\ (vap) \rightarrow Na_2O + H_2$~~
  - ~~$2\ Na + ½\ O_2 \rightarrow Na_2O$~~
  - ~~$2\ Na + O_2 \rightarrow Na_2O_2$~~
  - ~~$Na_2O_2 + 2\ Na \rightarrow 2\ Na_2O$~~
  - $Na_2O + H_2O \rightarrow 2\ NaOH$
  - $Na_2O_2 + H_2O \rightarrow 2\ NaOH + ½\ O_2$

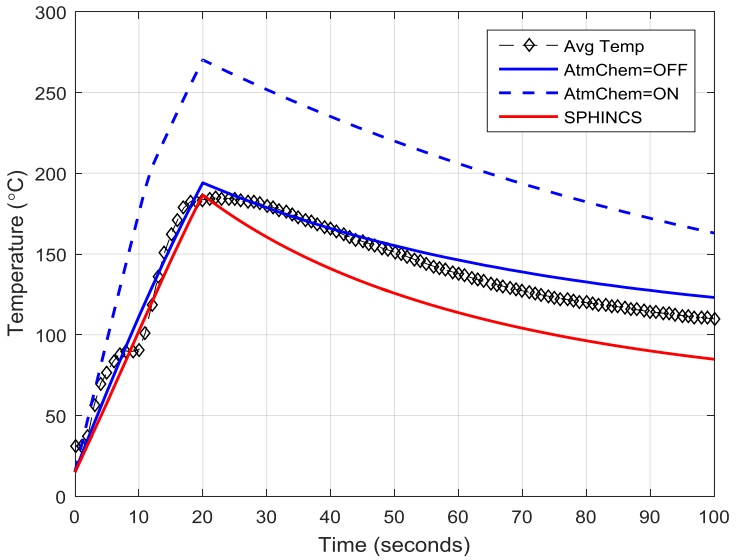
These reactions do not occur in this model since Na is not in the atmosphere.

- Input parameter (frna2o) controls fraction of sodium that produces the monoxide versus the peroxide.
  - Fraction has no effect in current model since first five equations not utilized.

Atmospheric Chemistry Model

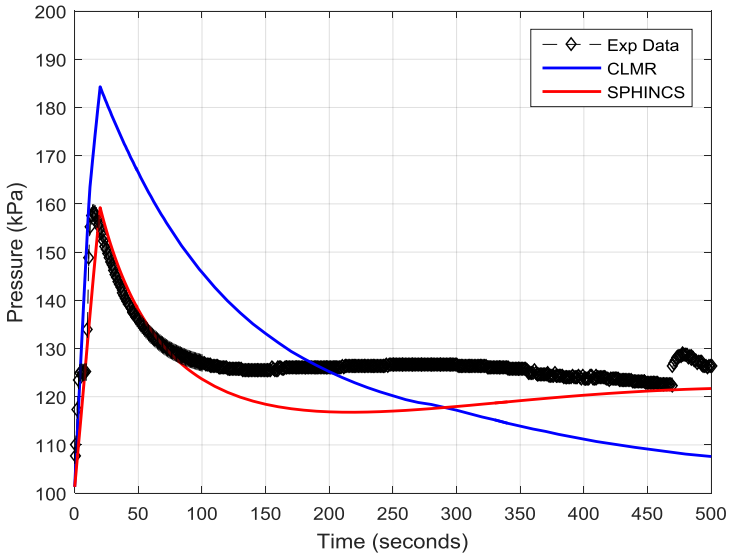
- Atmospheric chemistry model activated – short term results.
- From spray combustion: only sodium peroxide released to atmosphere.
- From pool combustion: only sodium monoxide released to atmosphere.

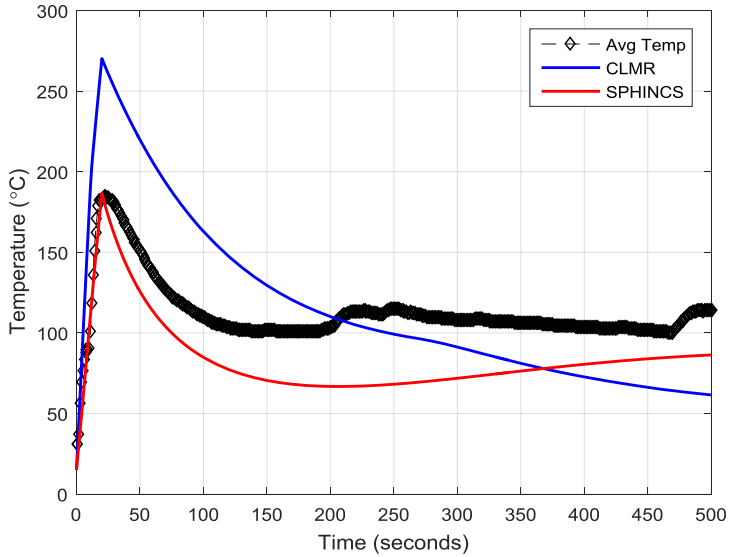




Atmospheric Chemistry Model

- Atmospheric chemistry model activated – long term results.
- Sodium monoxide and sodium peroxide continue to react in the air.
  - Only removal pathway is by aerosol deposition.



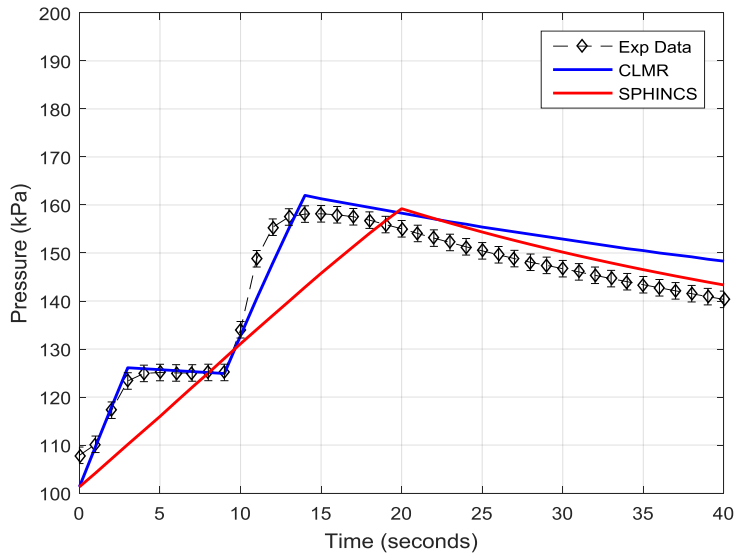


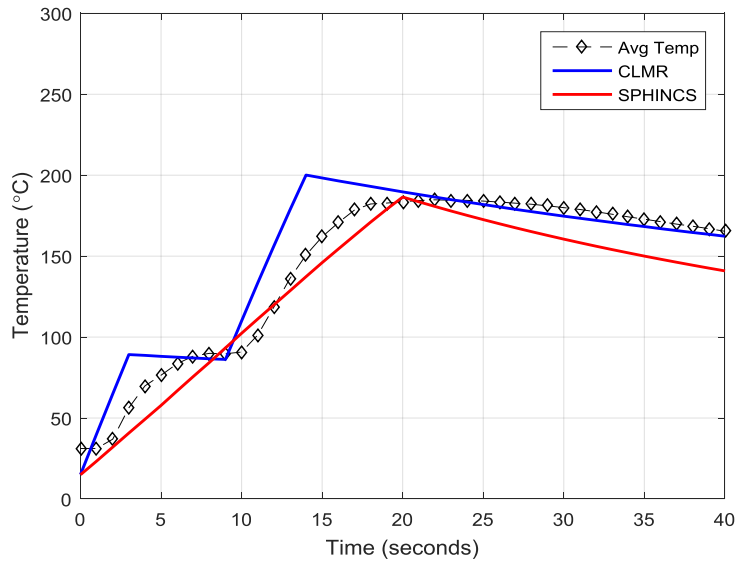
Model Two Spray Fires (1/2)

- 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.
- Diameter unchanged (2.47mm)
- No difference in long term pressure because same amount of sodium sprayed.
- Atmospheric chemistry OFF.



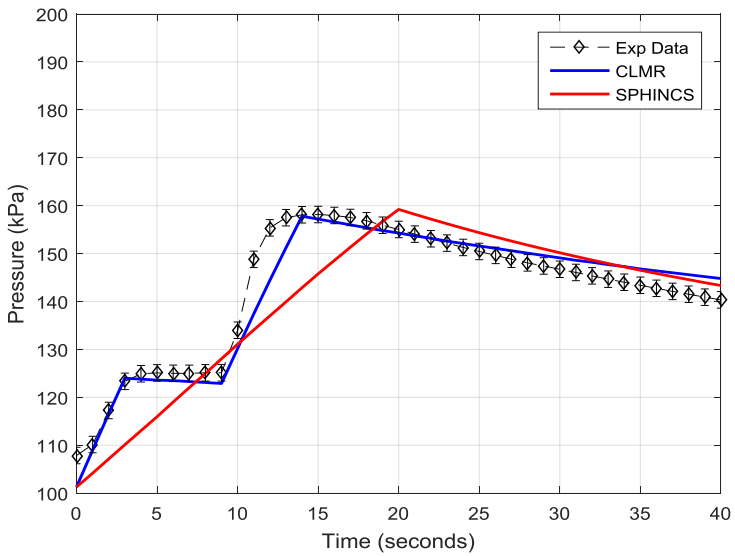


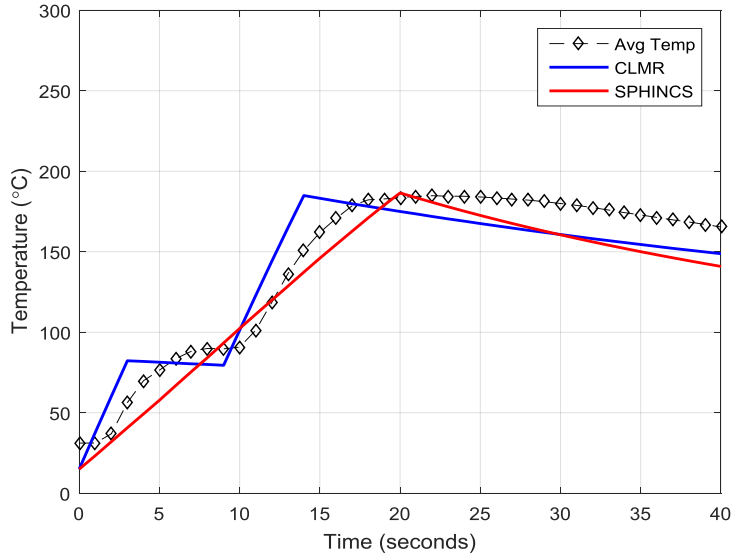
Model Two Spray Fires (2/2)

- 14 second spray with two spray fire sources and one sodium liquid source.

$$\dot{m} = 1.43\ {}^{kg}/_{s}$$

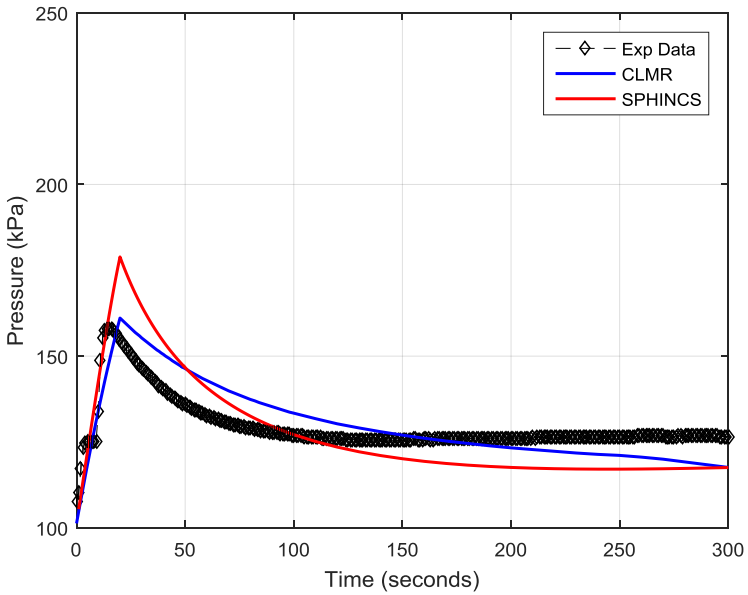
  - Spray fire from 0-3 seconds and from 9-14 seconds.
  - Sodium liquid source (non-ignition) from 3-9 seconds.
- Diameter: 2.47mm → 2.1mm
- No difference in long term pressure because same amount of sodium sprayed.

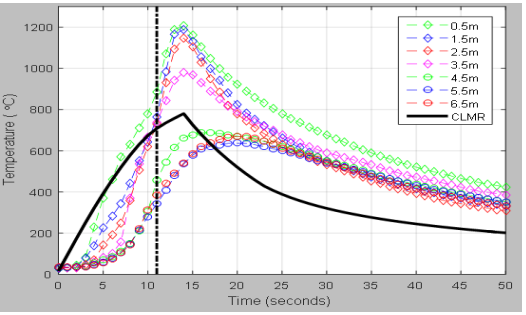




Code-to-Code Comparison

Terms	CONTAIN-LMR	SPHINCS
Vessel free volume	99m^3	←
Vessel thickness	0.01m(1.0cm)	←
Vessel wall emissivity	0.9 [-]	←
Spray height	5.3m	←
Sodium outlet nozzle velocity	*Terminal Velocity*	9.34m/s
Initial Sodium temperature	200ºC	←
Mean droplet diameter (volumetric mean)	2.45mm	←
Sodium pool fire	Activated	← (Ring pool fire)
Atmospheric chemistry	Deactivated	?
Initial gas temperature**	288.15K	←
Initial gas pressure**	101.3kPa A	←
Oxygen concentration (molar fraction)	0.21 [-]	←
Pool fire ratios (f1, f2, f3, f4)	0.5, 1.0, 1.0, 0.0	-





Surtsey T4 Experiment

Contain-LMR

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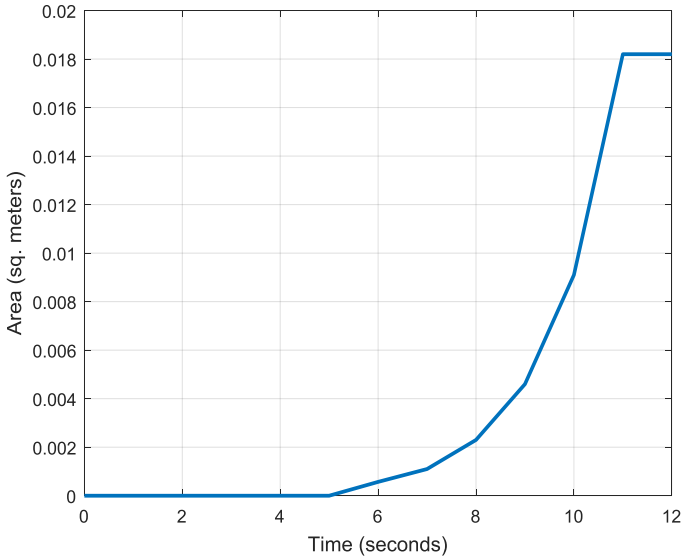
T4 Best Estimate

Terms	CONTAIN-LMR
Vessel free volume	99m^3
Vessel thickness	0.01m(1.0cm)
Vessel wall emissivity	0.9 [-]
Spray height	5.3m
Sodium outlet nozzle velocity	Terminal Velocity
Initial Sodium temperature	500ºC
Mean droplet diameter (volumetric mean)	1.06mm
Sodium pool fire	Activated
Atmospheric chemistry	Deactivated
Initial gas temperature	15℃
Initial gas pressure	108kPa A
Oxygen concentration (molar fraction)	0.233 [-]
Pool fire ratios (*f1, f2, f3, f4*)	0.5, 1.0, 1.0, 0.0

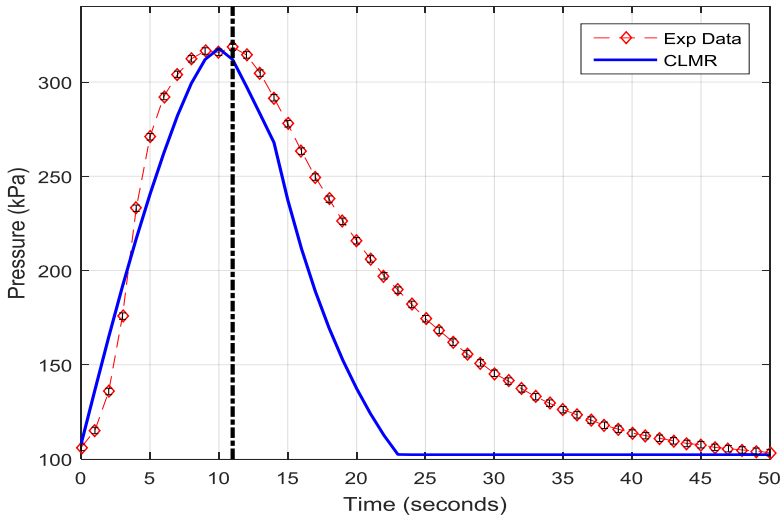
- Port failure at 11 seconds has also been included in the model. Port failure is modeled as a leak-before-break scenario.

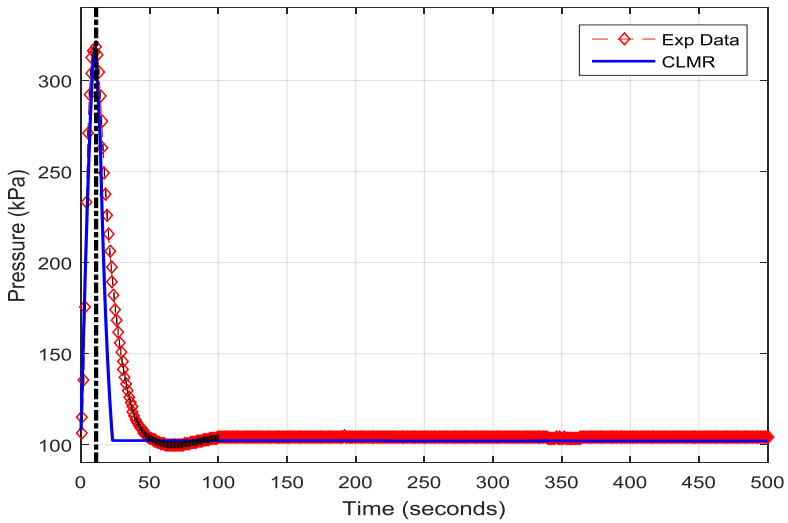


Port Failure Area

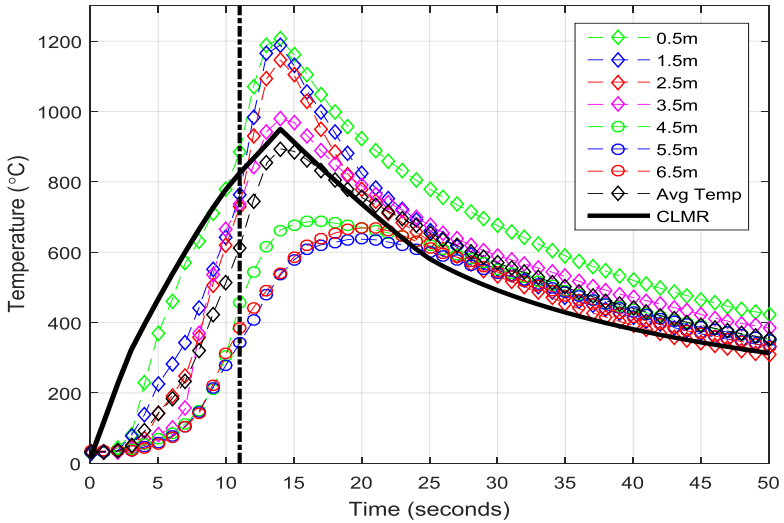
T4 Best Estimate

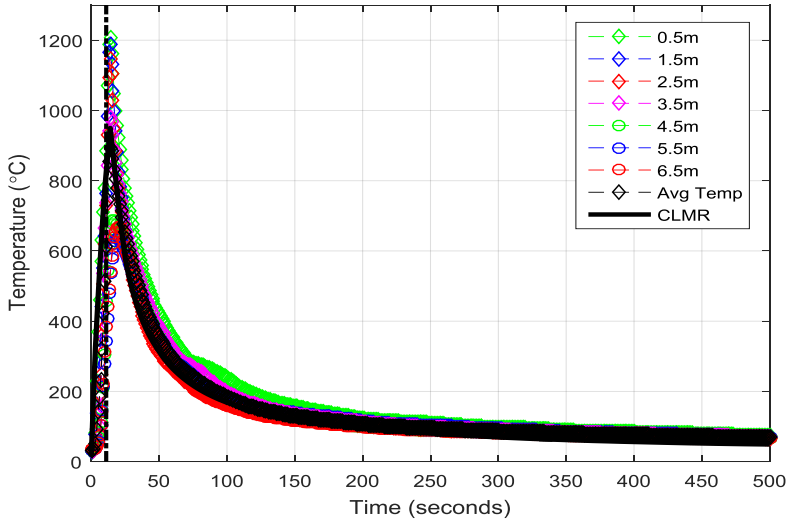
Atmospheric Pressure





Atmospheric Temperature





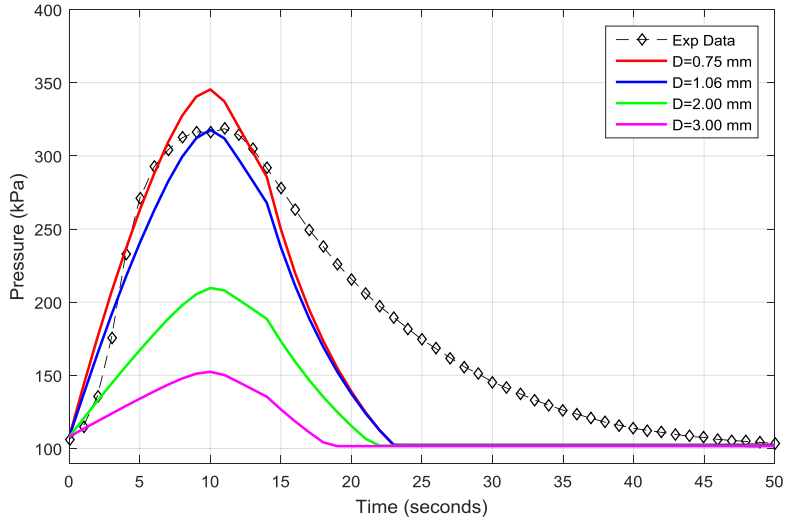
T4 Sensitivities

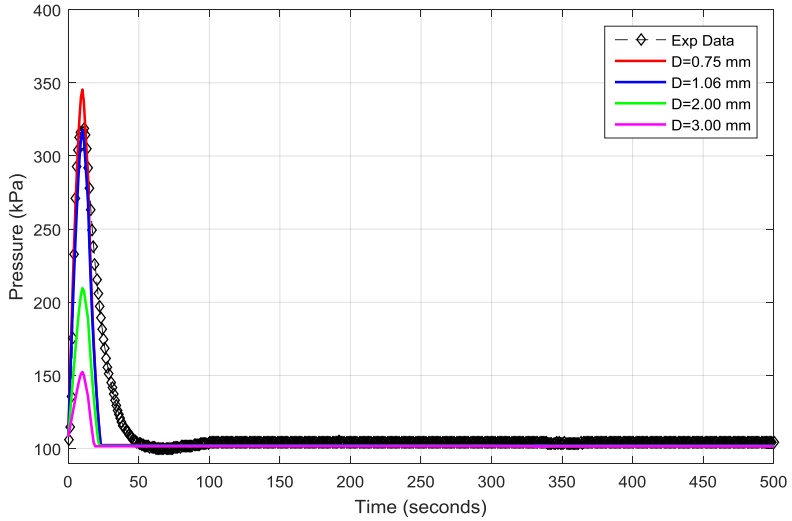
- Spray droplet diameter
  - Diameters of 0.75mm, 2.0mm, and 3.0mm
- Sodium pool fire ratio, *f2* (fraction of rxn heat added to pool)
  - Ratio values of 1.0 (best estimate case), 0.75, 0.5, 0.25, and 0.0
- Atmospheric chemistry activation
  - Atmospheric chemistry turned on or off.
  - Atmospheric reactions associated with this model:
    - ~~$Na + H_2O\ (liq) \rightarrow NaOH + ½\ H_2$~~
    - ~~$2\ Na + H_2O\ (vap) \rightarrow Na_2O + H_2$~~
    - ~~$2\ Na + ½\ O_2 \rightarrow Na_2O$~~
    - ~~$2\ Na + O_2 \rightarrow Na_2O_2$~~
    - ~~$Na_2O_2 + 2\ Na \rightarrow 2\ Na_2O$~~
    - $Na_2O + H_2O \rightarrow 2\ NaOH$
    - $Na_2O_2 + H_2O \rightarrow 2\ NaOH + ½\ O_2$

These reactions do not occur in this model since Na is not in the atmosphere.

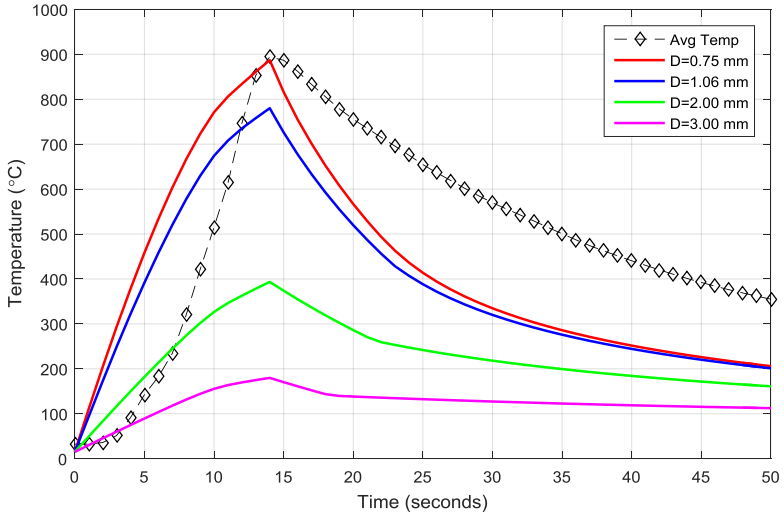
Sodium Droplet Diameter

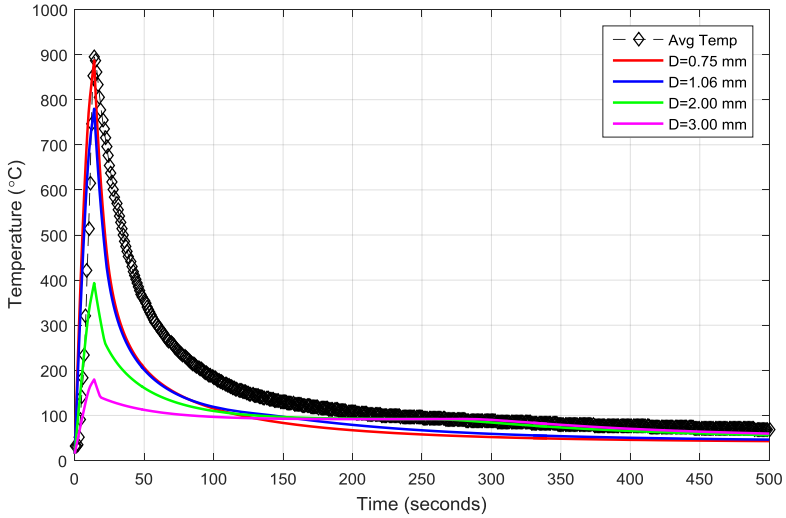
Atmospheric Pressure





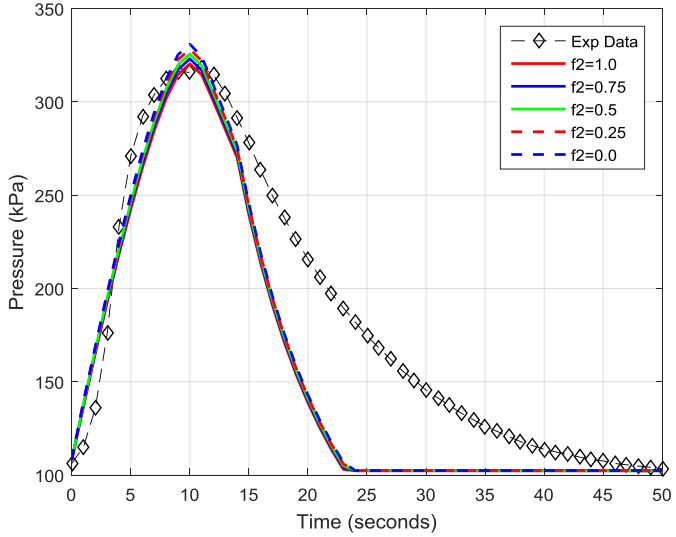
Atmospheric Temperature

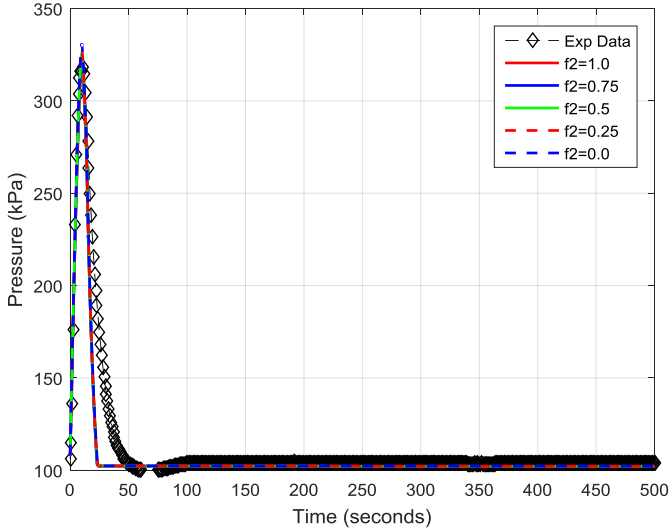




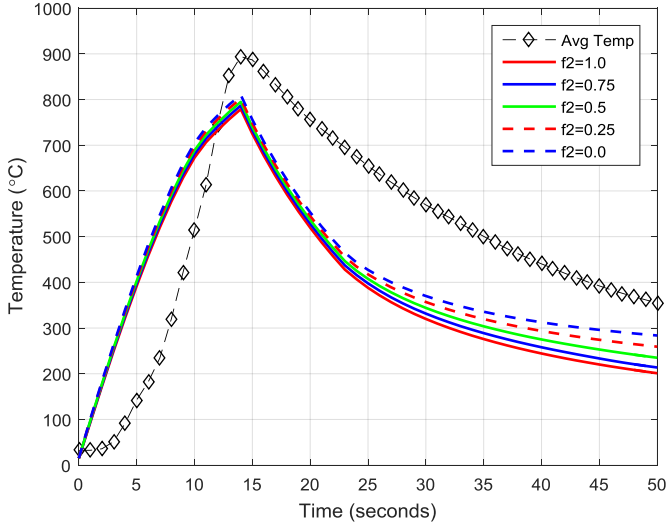
Pool-fire Ratios

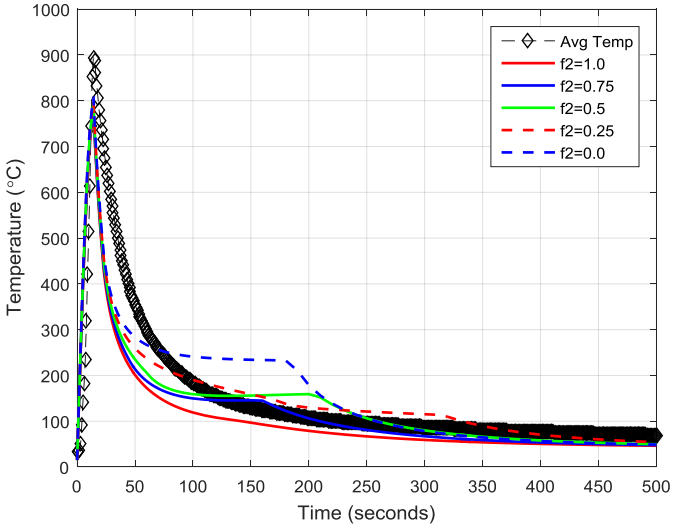
Atmospheric Pressure





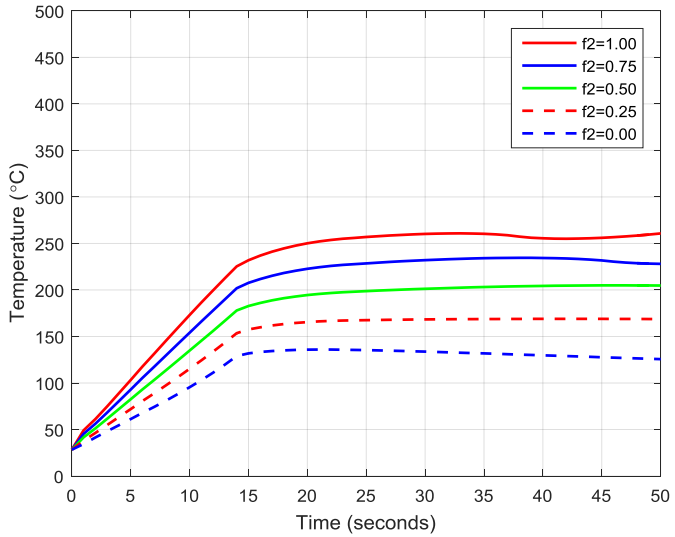
Atmospheric Temperature

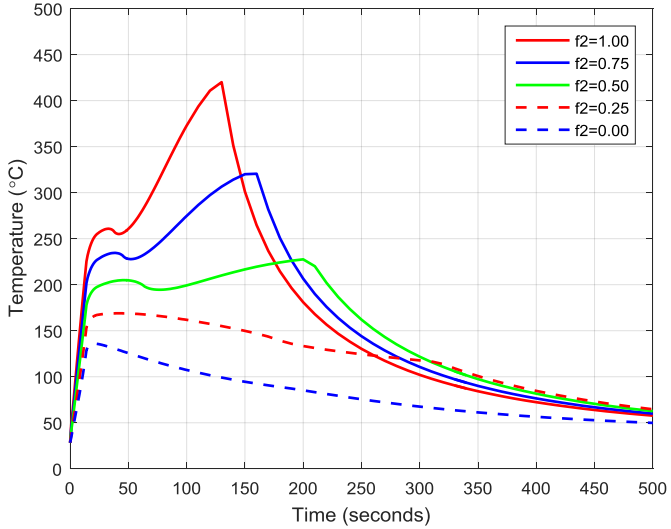




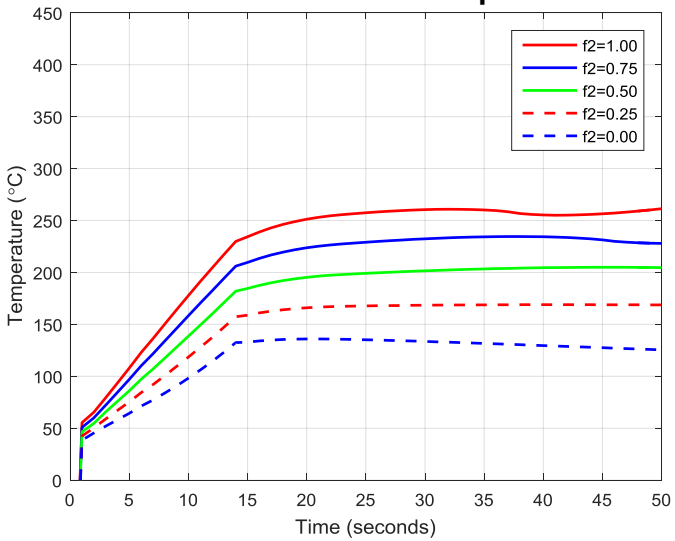
Pool-fire Ratios

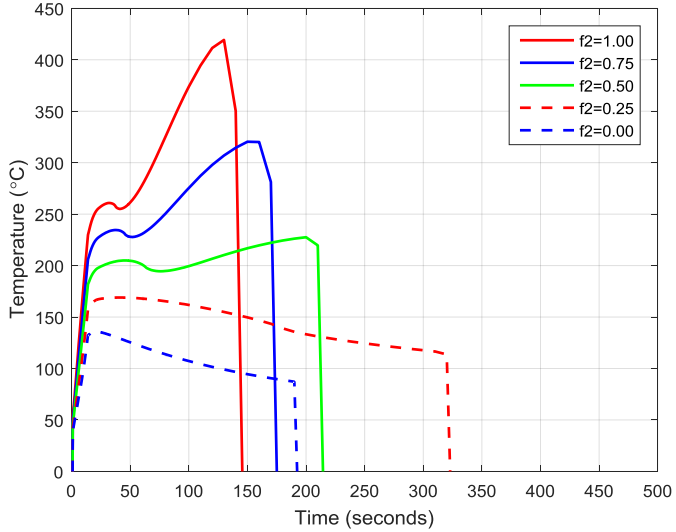
Steel-liner Temperature





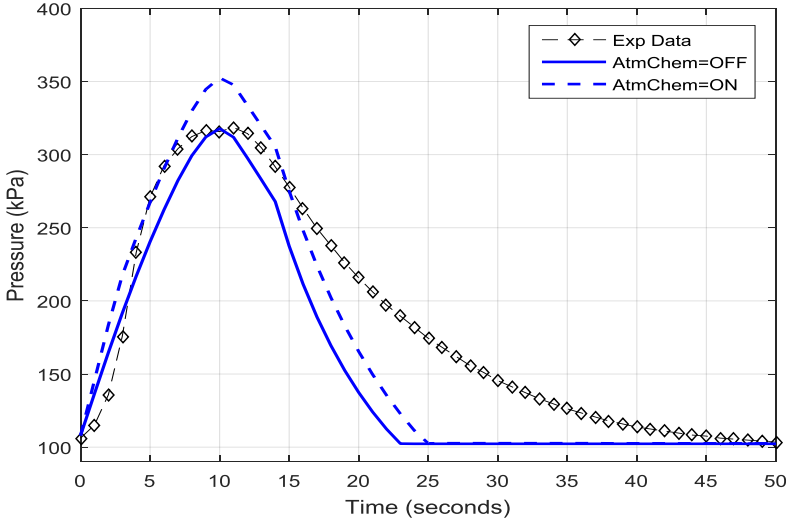
Sodium Pool Temperature

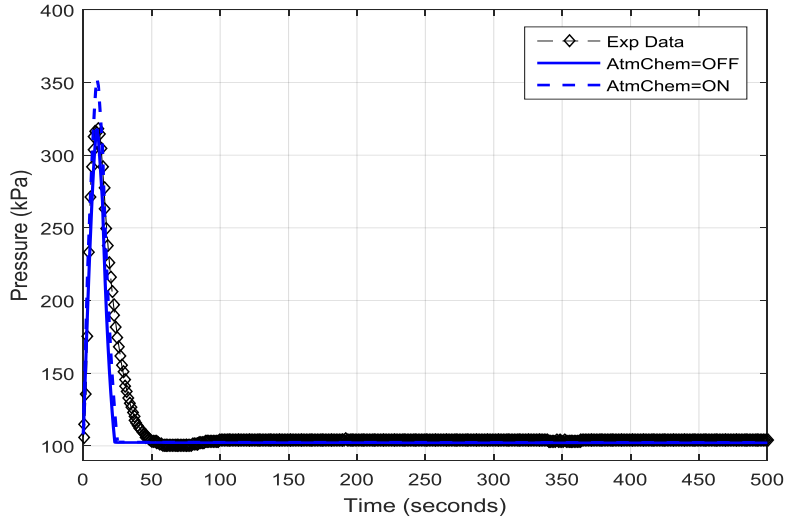




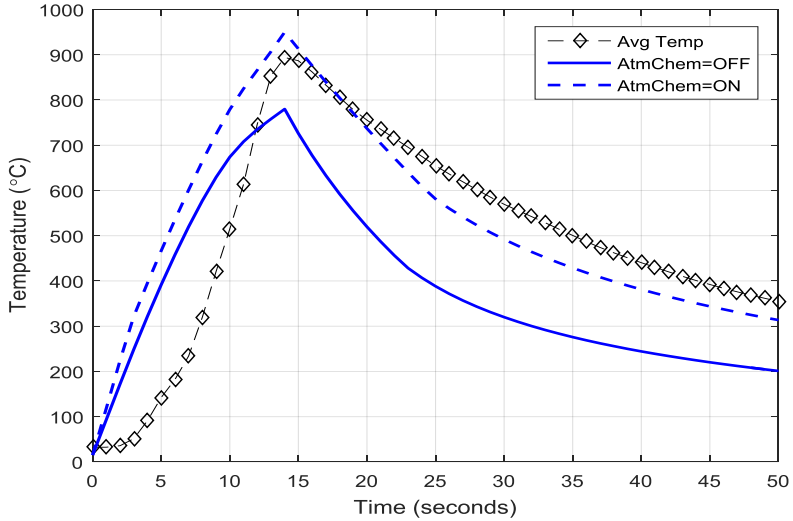
Atmospheric Chemistry Activation

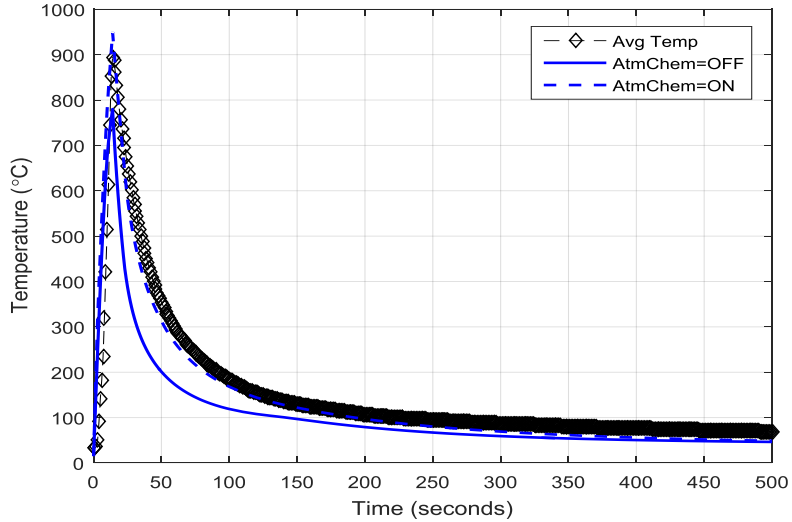
Atmospheric Pressure





Atmospheric Temperature





Summary of T4 Sensitivities

- Spray droplet diameter
  - Significant influence on spray combustion.
  - Slight influence on long term pool combustion for larger diameter droplets.
- Sodium pool fire ratio, *f2* (fraction of rxn heat added to pool)
  - Slight influence on atmospheric pressure.
  - Significant influence on atmospheric temperature; as ratio decreases, atmospheric temperature increases.
  - Significant influence on steel-liner temperature, and sodium pool temperature; as ratio decreases, temperatures decrease.
- Atmospheric chemistry activation
  - Water vapor reactions with sodium monoxide and sodium peroxide have considerable influence on heat added to the atmosphere.

Conclusions T3 and T4

- The T4 model does not accurately predict the depressurization following the port failure.
- Still some unanswered questions about sodium spray fire experiments:
  - T3 and T4 spray duration? 14 second spray or 20 second spray?
  - Sodium temperature at nozzle?
  - Sodium-concrete interactions?
  - Time at which Surtsey vent opening occurs?
  - T3 sodium ignitions?
- JAEA F7 experiments may identify the proper sodium pool fire ratios to use in the T3 and T4 inputs.

Future Work Related to T3 and T4

- Further sensitivity analyses?
  - Initial oxygen and water vapor concentrations?
- Realign base case to have atmospheric chemistry model activated.
- Run models using CONTAIN2-LMR.
- Setup CONTAIN-LMR with DAKOTA[1].
  - Calibration and sensitivity studies.

[1]Adams, B.M., Bauman, L.E., Bohnhoff, W.J., Dalbey, K.R., Ebeida, M.S., Eddy, J.P., Eldred, M.S., Hough, P.D., Hu, K.T., Jakeman, J.D., Stephens, J.A., Swiler, L.P., Vigil, D.M., and Wildey, T.M., "Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.0 User's Manual," Sandia Technical Report SAND2014-4633, July 2014. Updated November 2016 (Version 6.5).