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Update on Recent Efforts for the HyRAM Toolkit

Literature Data Validation and Unconfined Overpressure in HyRAM

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Codes & Standards Tech Team Meeting

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Recent HyRAM Changes and Releases

HyRAM 3.0 – Released October 2020

- Enabled cryogenic releases
  - Changed Abel-Noble equation of state to use CoolProp package (similar to RefProp)
- Accumulation calculation improved
- Overpressure harm inputs clarified

HyRAM 3.0.1 – Released January 2021

- Updated two-phase speed of sound calculation
- Other bug fixes

Upcoming: HyRAM 3.1

- Updated two-phase speed of sound calculation
- Input validation for probability distributions, clarification that pressure is absolute

Changing equation of state and other updates gave slightly different results for the same inputs

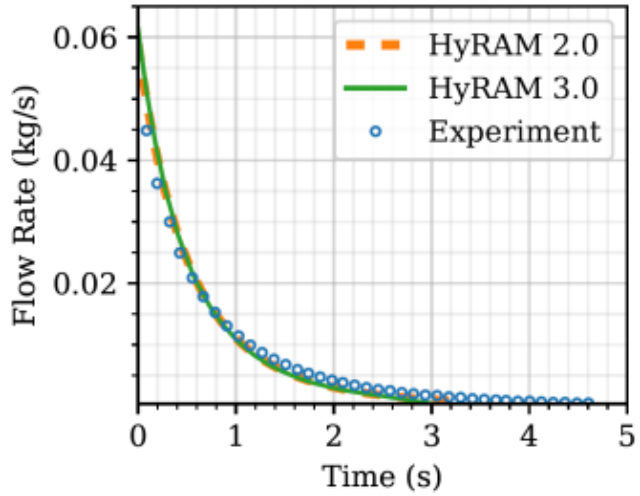
Validation with Literature Data

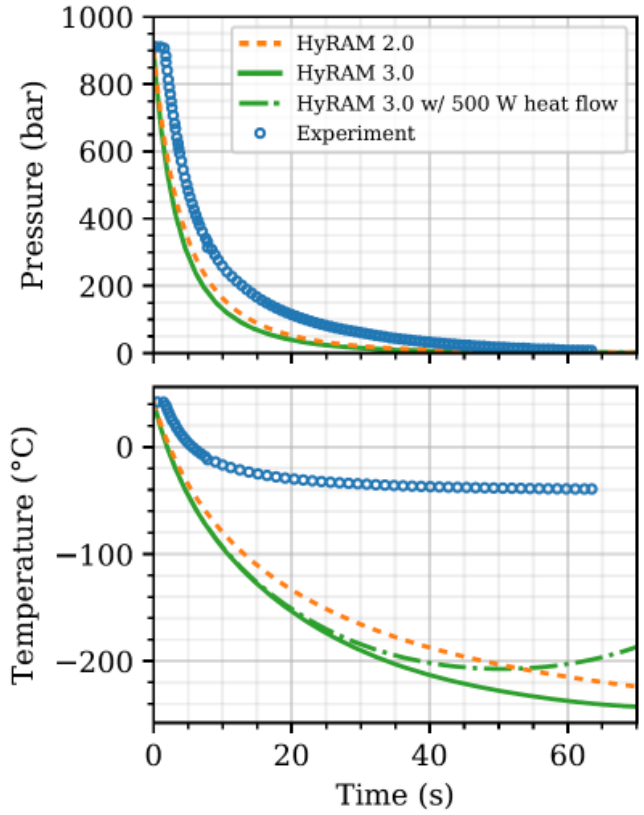
Validation of HyRAM Physical Release Models

- All models included in HyRAM included validation data in their original publications
- Since the updated models returned different results, wanted to do a wider search for comparison data
  - Include all validation efforts in a single publication
- 4 Physical Models in HyRAM:
  - Blowdown (tank emptying)
  - Unignited Jet Plume
  - Ignited Jet Fire
  - Accumulation in Enclosure
- Also specifically considered cryogenic releases
  - Although not in comparison to prior version of HyRAM

Validation of Tank Blowdown

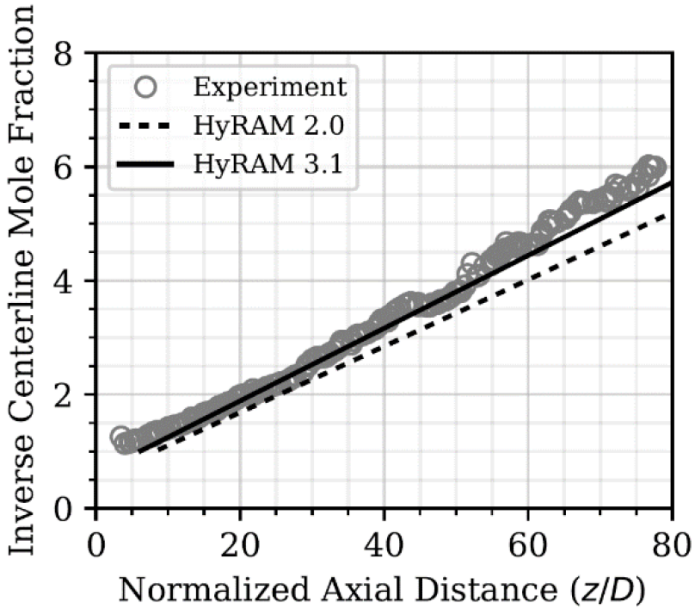
- Mass flow rate over time matches well
  - This is a risk-significant metric
- HyRAM slightly underpredicts tank pressure over time
- HyRAM predicts significantly different tank temperature over time
  - Temperature may not be risk-significant
- Differences due to simplifying assumptions in HyRAM models:
  - Isentropic (reversible) flow
  - Adiabatic tank
- Only minor differences between HyRAM 2 and HyRAM 3

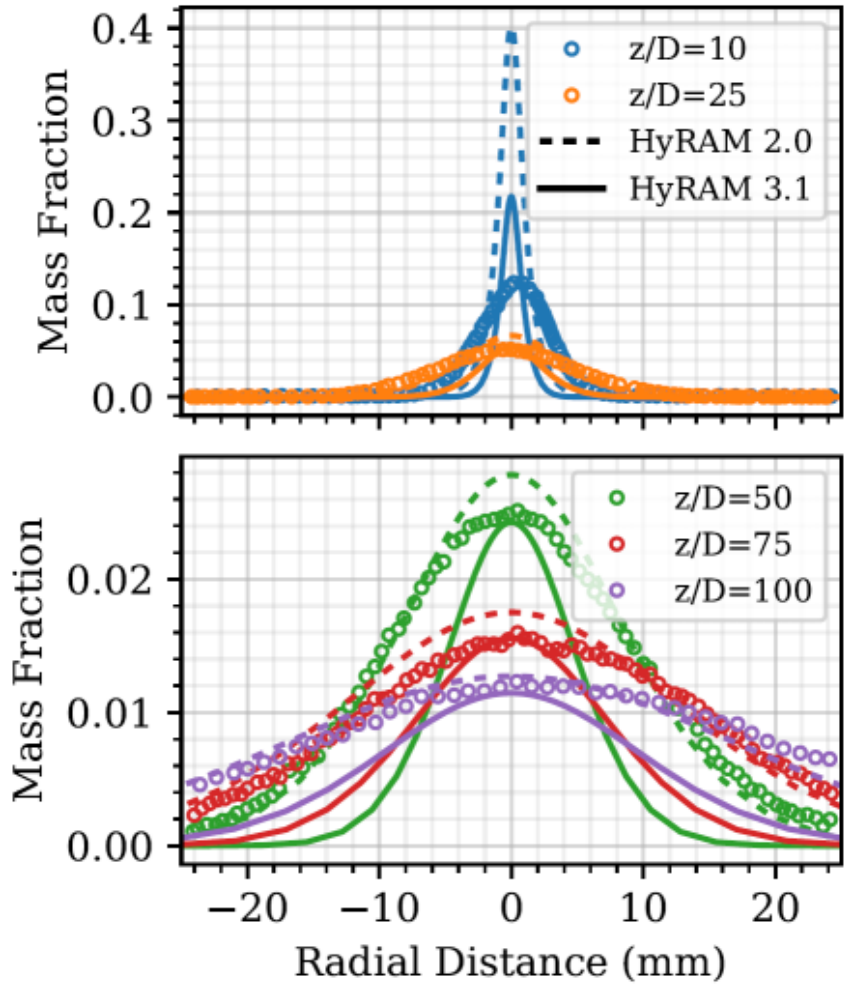




Validation of Unignited Jet Plumes

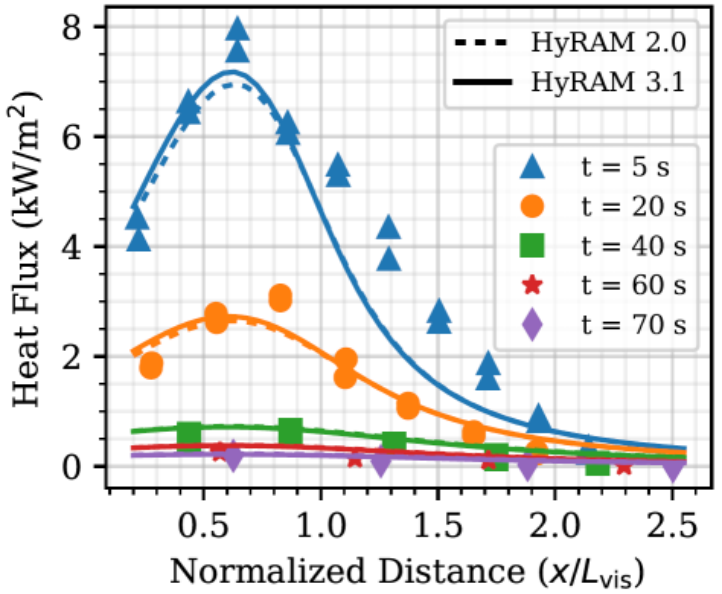
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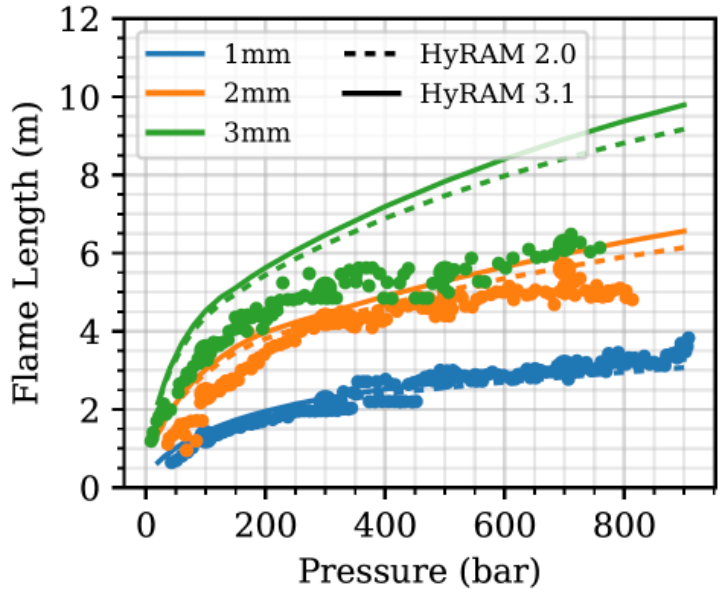




Validation of Ignited Jet Fires

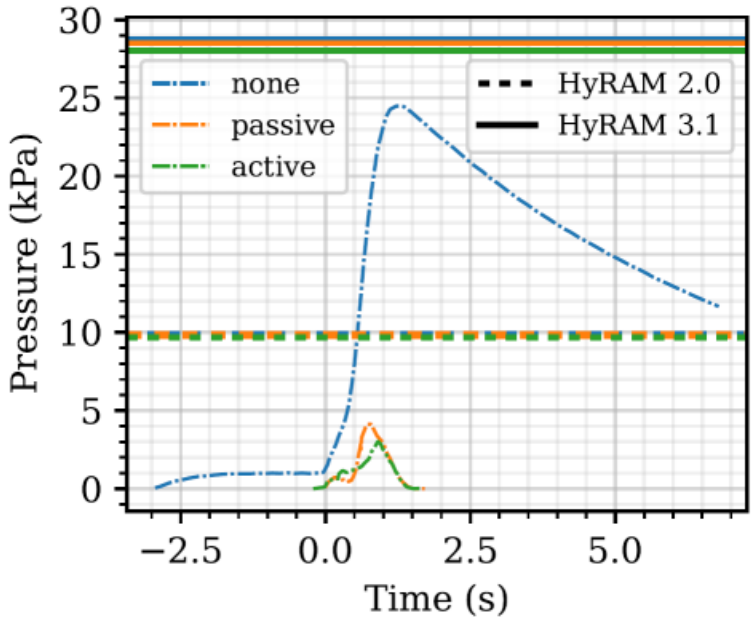
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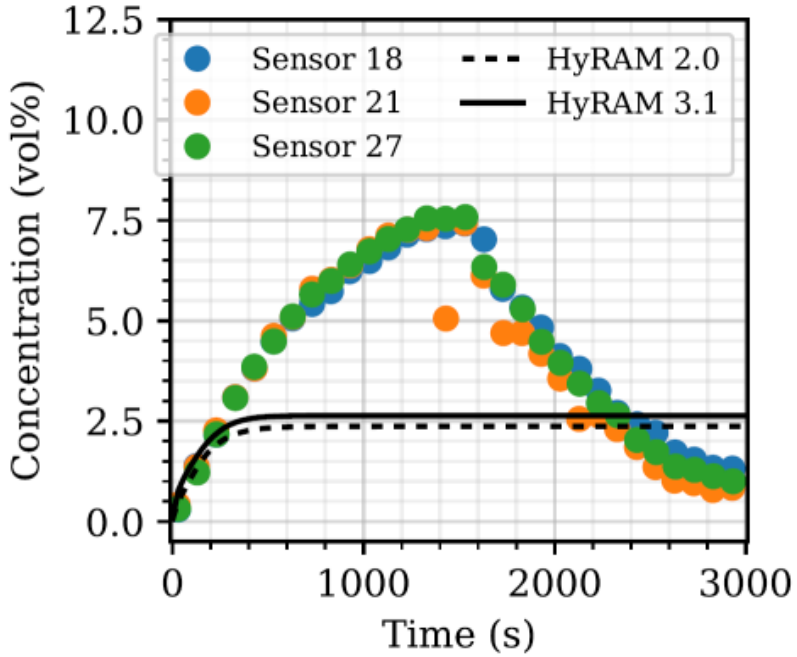




Validation of Accumulation Behavior in Enclosures

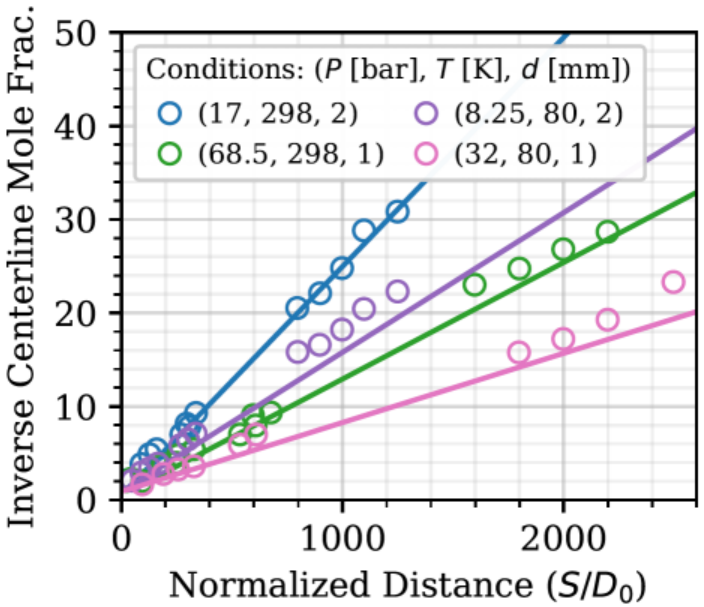
- Concentration measurements inside enclosures can vary significantly based on sensor location
  - Uniform layer assumption does not always capture this
- Limited validation data available for overpressure
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- Limited data and limited model applicability
  - Accumulation model should be used with caution

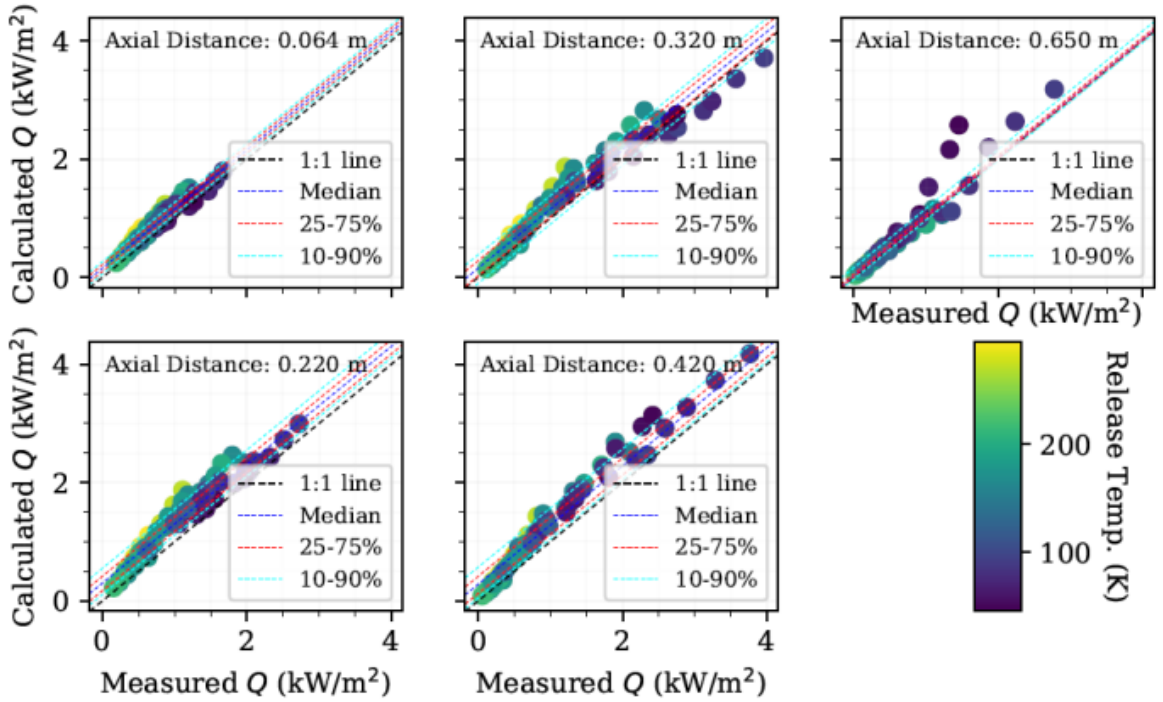




Validation of Cryogenic Releases

- HyRAM 3 had good matches to PreSLHy data (not shown) for mass loss
  - Not very good match to temperatures
- Good agreement to concentration measurements
- Good agreement to heat flux and flame length





Summary of Validation of HyRAM Physical Release Models

- HyRAM 3 generally predicts behavior more accurately than HyRAM 2
  - May result in less conservative values for concentration at a given distance
- Neither version of HyRAM predicts plume widths or tank temperatures very well
  - Neither aspect currently used in risk calculations
- Both versions of HyRAM match heat flux and flame length data well
- Neither version of HyRAM predicts accumulation particularly well
  - Wide variability in data
  - Limited data for overpressure estimation
- HyRAM 3 matches well to cryogenic release data

Unconfined Overpressure Model Comparisons

Leak Outcomes – Event Tree

Probabilities on what could happen given a leak

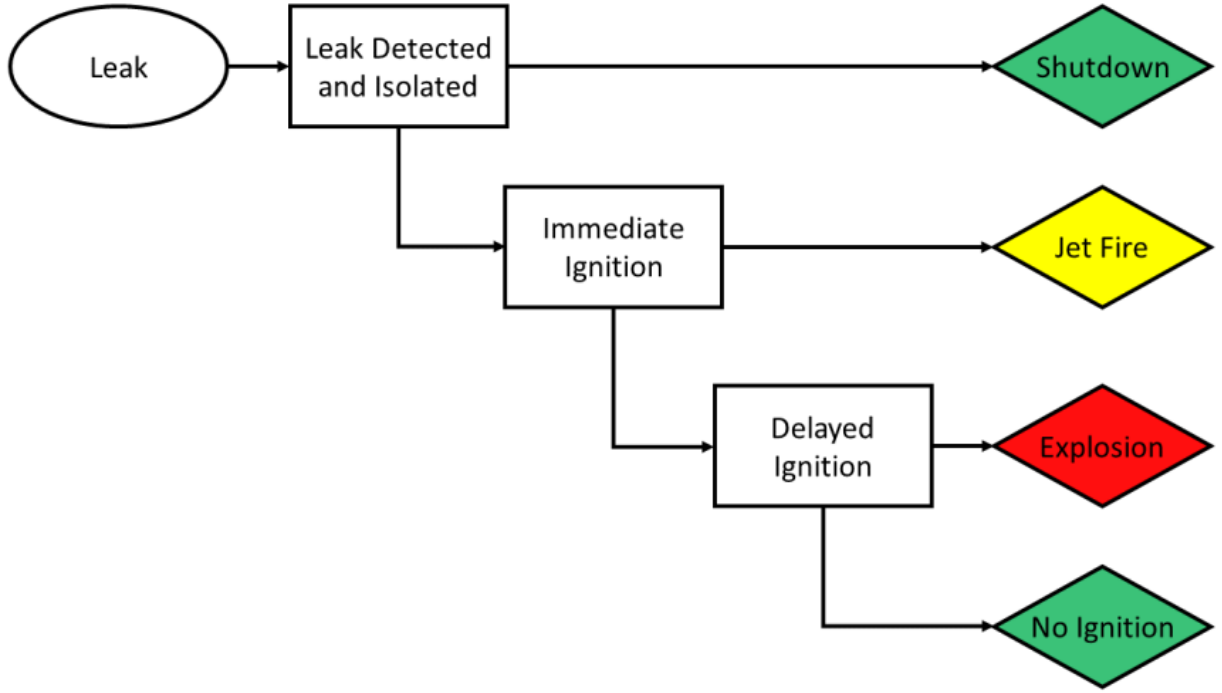
Leak Detection and isolation credit is single input (0.9 default)

Immediate and Delayed Ignition probabilities as a function of flow rate (calculated)

Probabilities multiply down tree

4 outcomes for each leak size

H_2 Release Rate (kg/s)	*P*(Immediate Ignition)	*P*(Delayed Ignition)
<0.125	0.008	0.004
0.125 - 6.25	0.053	0.027
>6.25	0.230	0.120



Overpressure Harm – Currently Basic Inputs

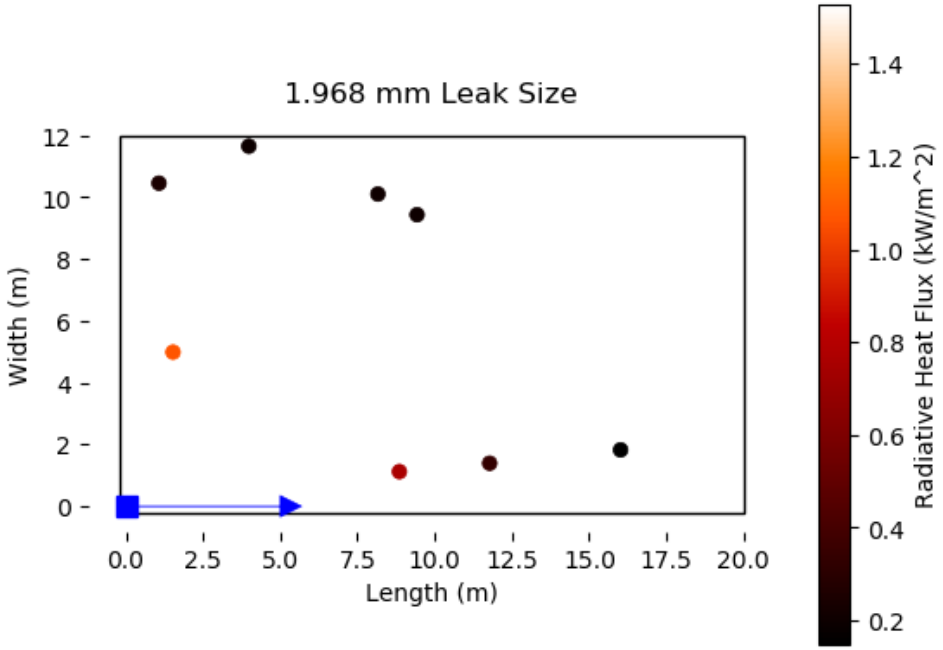
Peak overpressure and impulse are specified for each leak size
- Must be calculated separately, outside HyRAM

These values are applied to each occupant position
- Regardless of distance away from leak

Units: Pa

	Variable	0.01% Leak	0.1% Leak	1.0% Leak	10% Leak	100% Leak
▶	Peak Overpres...	2500.0000	2500.0000	5000.0000	16000.0000	30000.0000
	Impulse	0.0000	0.0000	0.0000	0.0000	0.0000

Versus: Thermal Harm from Jet Fire Heat Flux – Calculated Effects

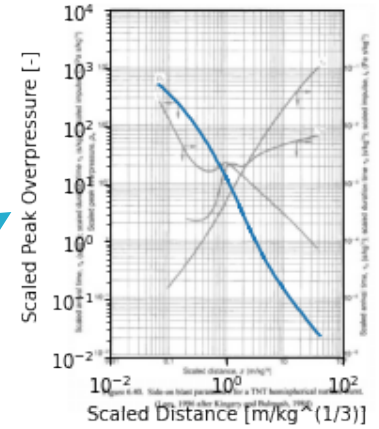


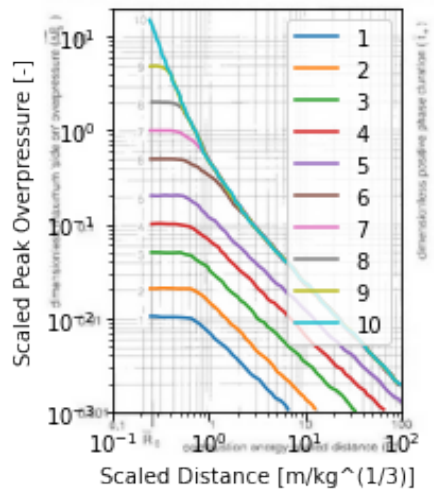
Based on Jet Flame Physics model
- Based on information on pipe size and pressure/temperature

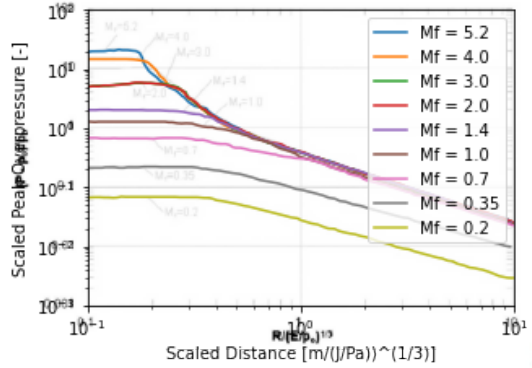
Determines heat flux from leak at every occupant point
- For each leak size

Model Descriptions – Blast Curves

- TNT Equivalence
  - Calculate equivalent mass of TNT: $W_{TNT} = \alpha_e \frac{W_f H_f}{H_{TNT}}$
  - Calculate scaled-distance: $\bar{R} = \frac{R}{W_{TNT}^{\frac{1}{3}}}$
  - Read scaled-overpressure (or impulse) from plot
- TNO Multi-Energy
  - Calculate scaled-distance: $\bar{R} = \frac{R}{(E/P_0)^{1/3}}$
  - Read scaled-overpressure from plot
    - Based on curve number
- Baker-Strehlow-Tang (BST)
  - Calculate scaled-distance: $\bar{R} = \frac{R}{(E/P_0)^{1/3}}$
  - Read scaled-overpressure (or impulse) from plot
    - Based on flame speed





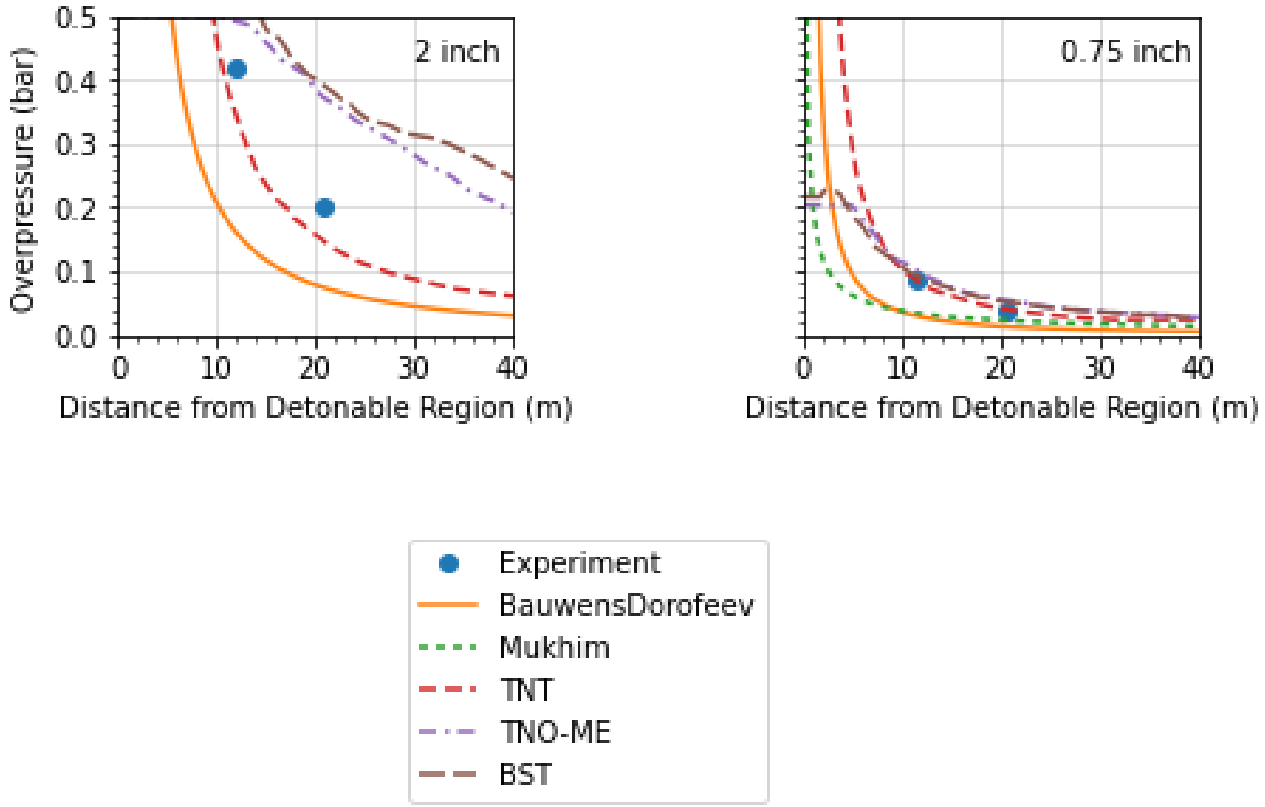


Model Descriptions – Recent Models

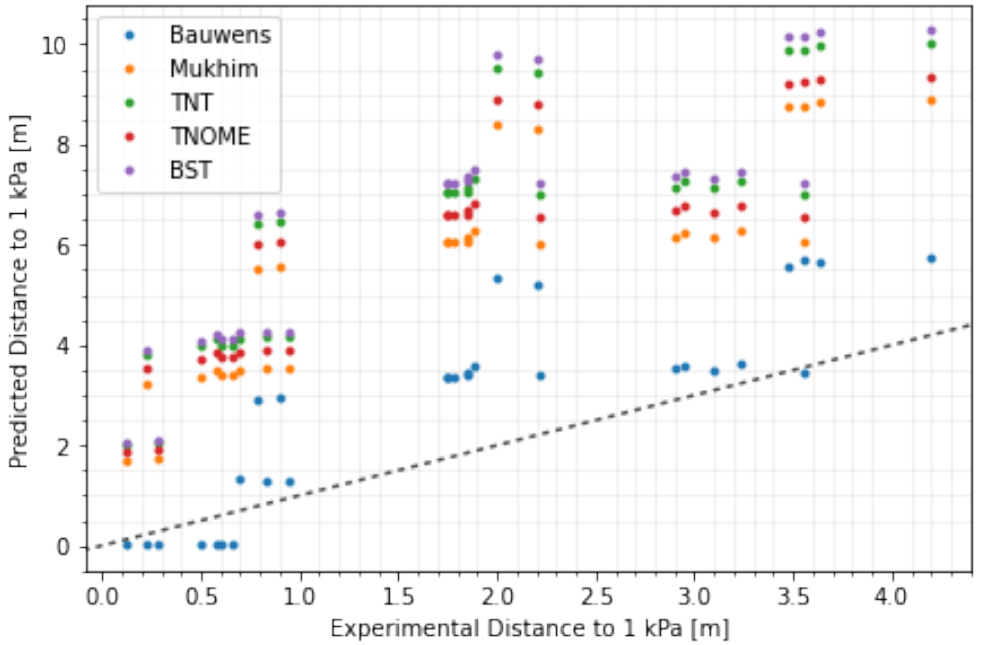
- Mukhim et al. Journal of Loss Prevention in the Process Industries 52, March 2018, p. 99-107
  - Compared TNT, TNO-ME, and BST methods to experimental data (pre-mixed H2)
  - Calculate scaled-distance: $\bar{R} = \frac{R}{(E/P_0)^{1/3}}$
  - Calculate scaled-overpressure from:
    - $p_s = A * \bar{R}^B$
    - Where:
      - $A = 0.0000006948(V * C)^3 - 0.0000807(V * C)^2 + 0.002943(V * C) + 0.02095$
      - $B = -0.7072$
- Bauwens and Dorofeev
  - ICHS 2019 Paper 279
  - Calculate detonation cell size based on equivalence ratio throughout plume
  - Calculate detonable mass based on cell size gradient
  - Calculate scaled distance: $R^* = \frac{R p_0^{1/3}}{E^{1/3}}$
  - Calculated scaled overpressure: $P^* = \frac{0.34}{(R^*)^{4/3}} + \frac{0.062}{(R^*)^2} + \frac{0.0033}{(R^*)^3}$

Literature Data Comparisons (1/3)

Bauwens and Dorofeev, ICHS 2019 paper ID 279

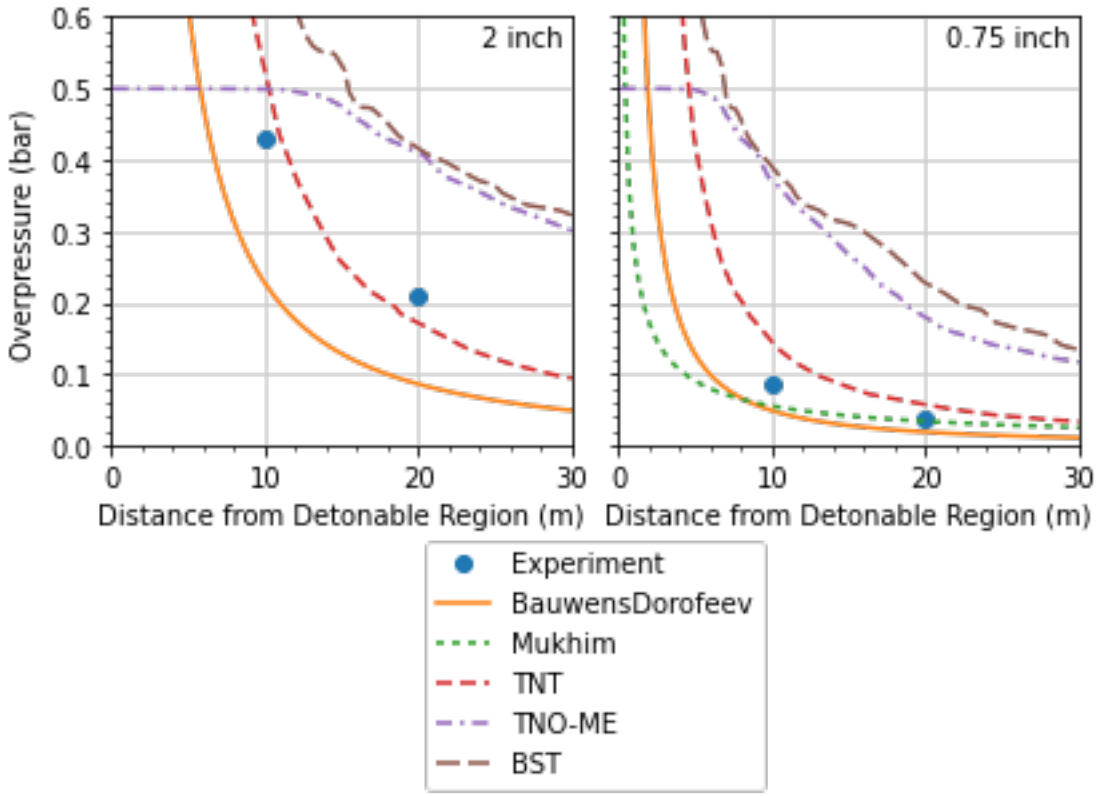


Kobayashi et al., IJHE 45(7), 2020, pp. 5098-5109

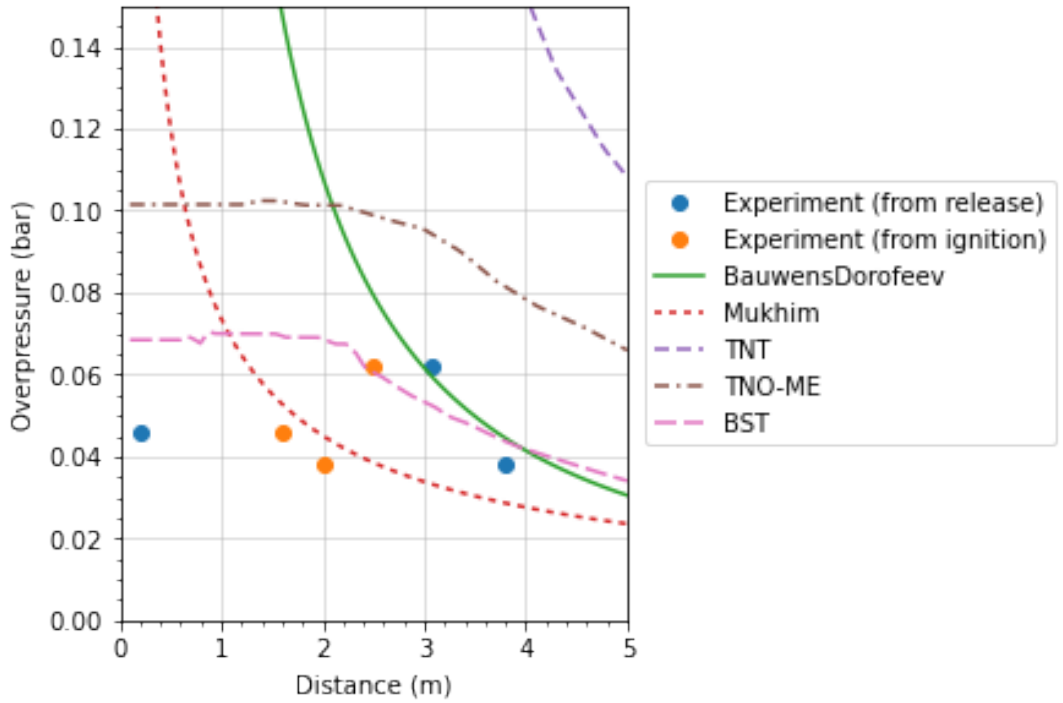


Literature Data Comparisons (2/3)

Jallais et al., Process Safety Progress 37(3) p. 397-410

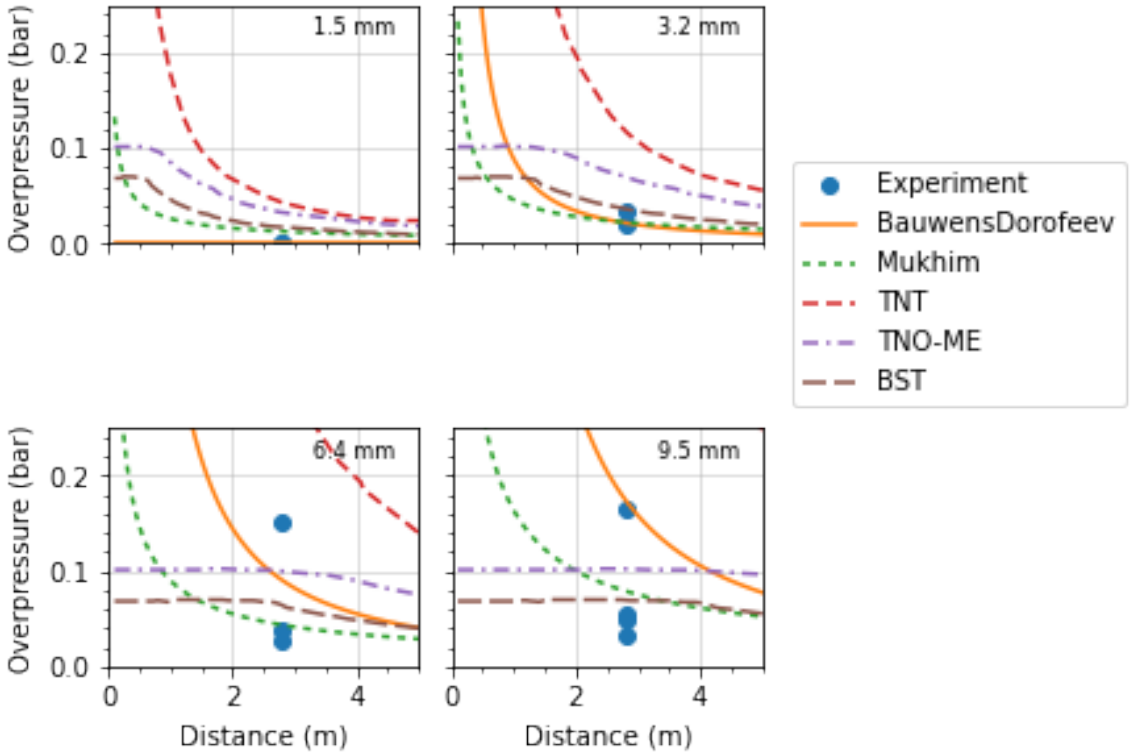


Daubech et al., Journal of Loss Prevention in the Process Industries 36, 2015, p. 439-446

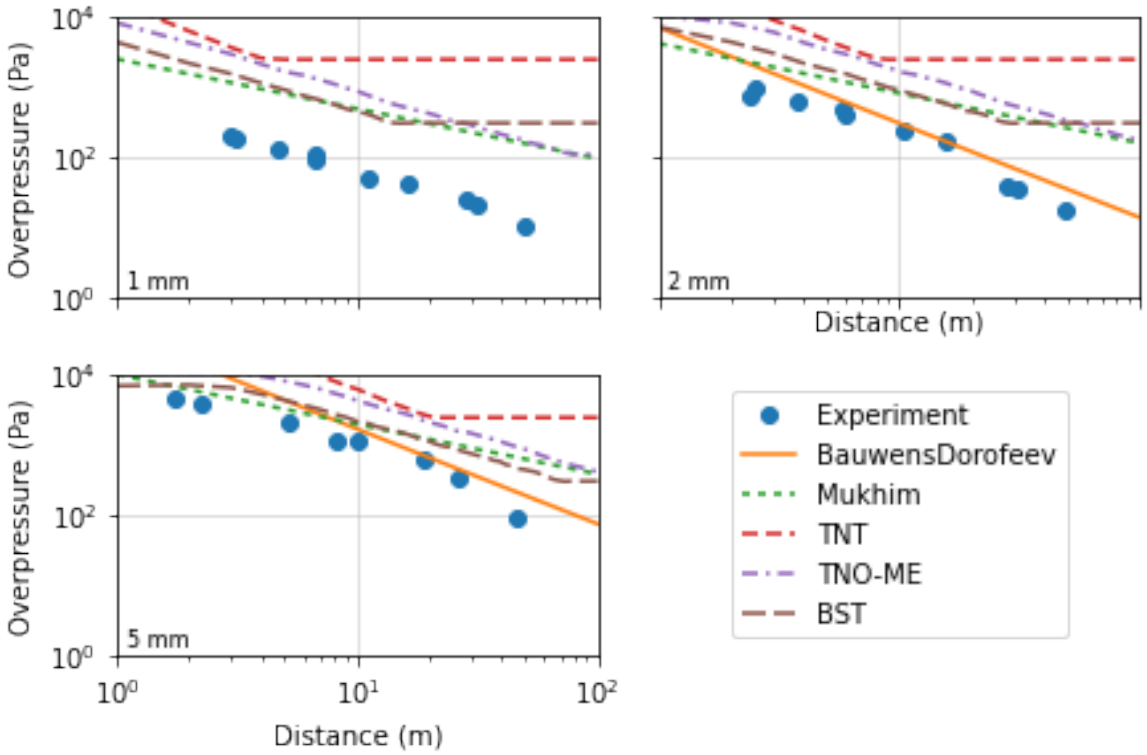


Literature Data Comparisons (3/3)

Royle and Willoughby, IJHE 36(3), 2011, p. 2688-2692



Takeno et al., IJHE 32(13), 2007, p. 2144-2153



Summary of Unconfined Overpressure Model Comparisons

Comparisons to literature data for overpressure from unconfined jet plumes

TNT, TNO, and BST usually conservative
- Can be better scaled with different flammable limits (e.g., Jallais et al. suggest 10-75%)

TNO-ME and BST depend a lot on curve selection

Mukhim et al. and Bauwens/Dorofeev models underpredict some data
- Mukhim et al. overpredicts data for very large releases

Blast curves (TNT, TNO-ME, and BST) developed as general models
- Mukhim et al. and Bauwens/Dorofeev models developed as H2-specific
- Mukhim et al. probably the least transferrable to other fuels? (fit based on flammable volume)

Next Steps:
- TNT, BST, and Bauwens will be incorporated into HyRAM
  - TNT and BST are more general models that provide both overpressure and impulse results
  - Bauwens/Dorofeev model hydrogen- and jet plume-specific

Thank You!

Questions?

Backup Slides

Overpressure Fatalities – Overpressure Probits

For each occupant,

Calculation of probability of a fatality:

- $P(fatality) = F(Y|\mu = 5, \sigma = 1) = \Phi(Y - 5)$

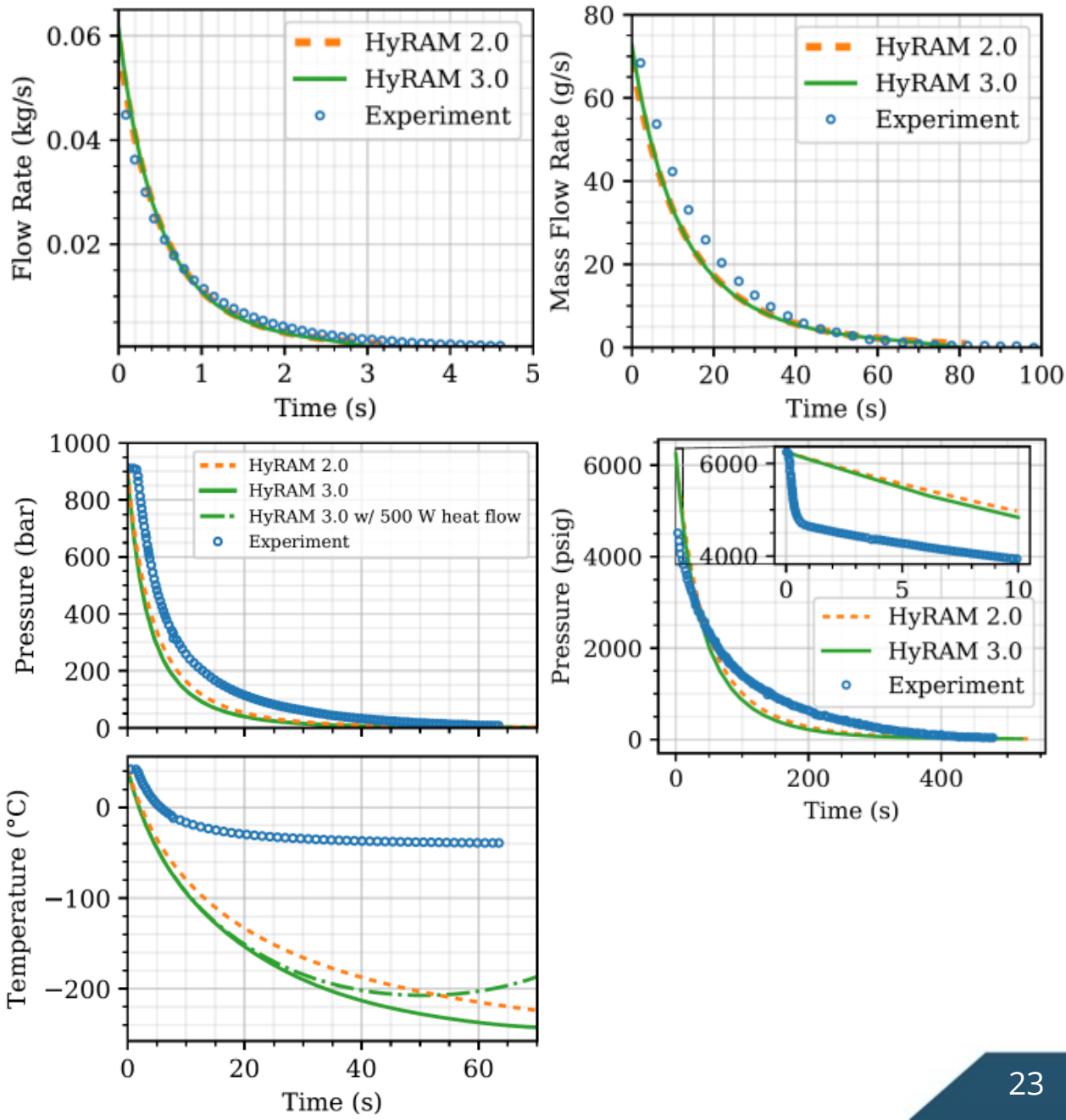
Based on **peak overpressure (P_s)** and **impulse (i)**:

Model	Equation
Eisenberg – Lung Hemorrhage	$Y = -77.1 + 6.91\ln(P_s)$
HSE – Lung Hemorrhage	$Y = 5.13 + 1.37\ln(P_s \times 10^{-5})$
TNO – Head Impact	$Y = 5 - 8.49\ln\left(\frac{2300}{P_s} + \frac{4 \times 10^8}{P_s i}\right)$
TNO – Structure Collapse *	$Y = 5 - 0.22\ln\left[\left(\frac{40000}{P_s}\right)^{7.4} + \left(\frac{460}{i}\right)^{11.3}\right]$

* default

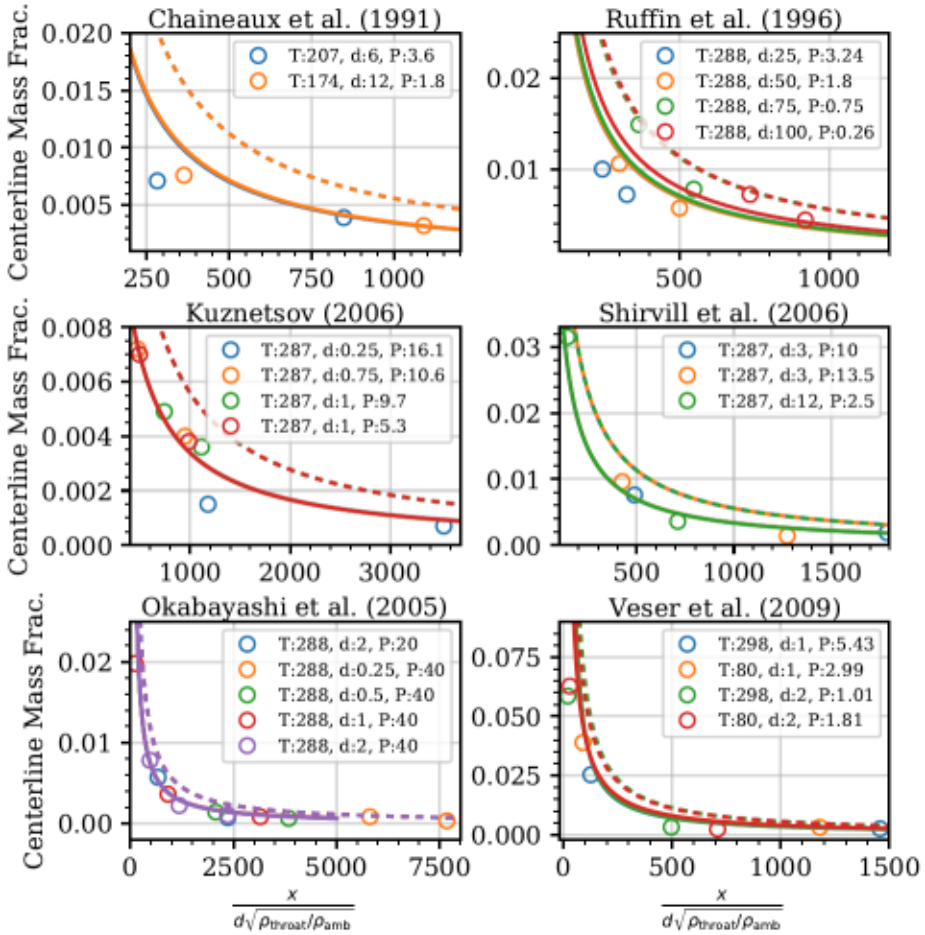
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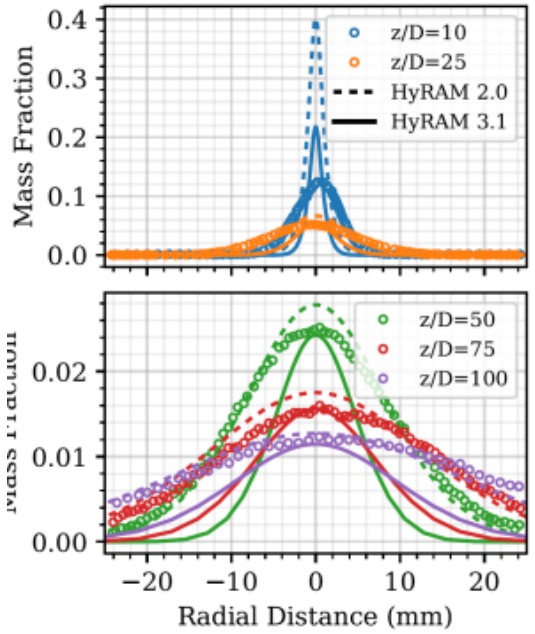
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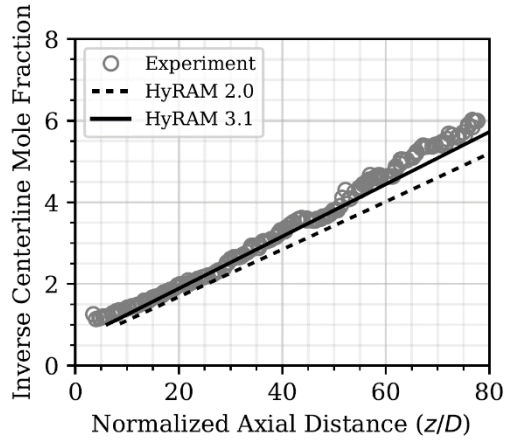


Validation of Unignited Jet Plumes

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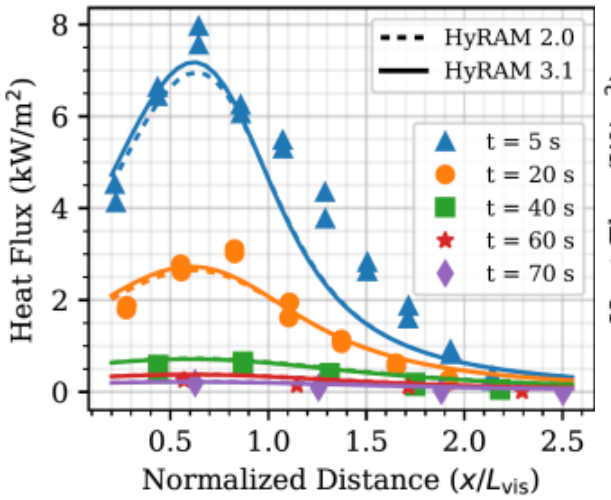


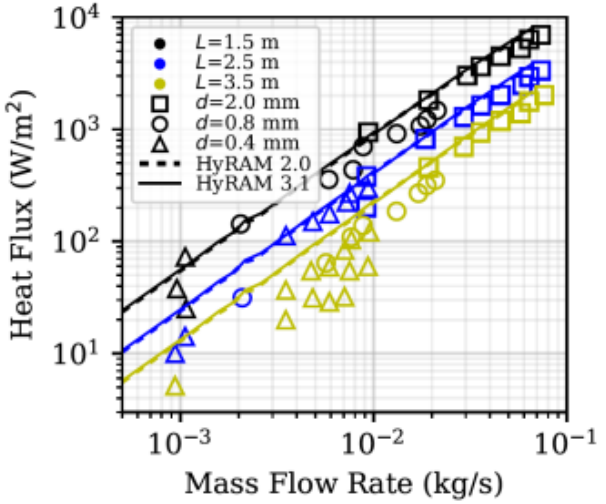


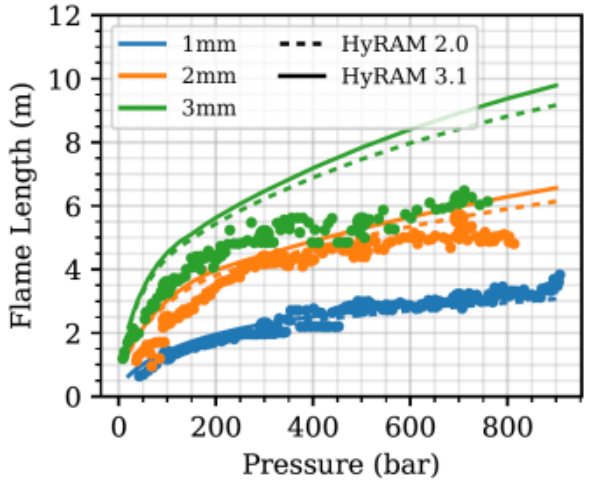


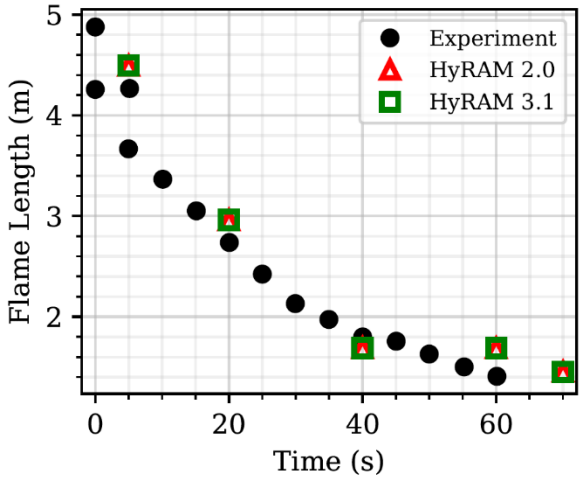
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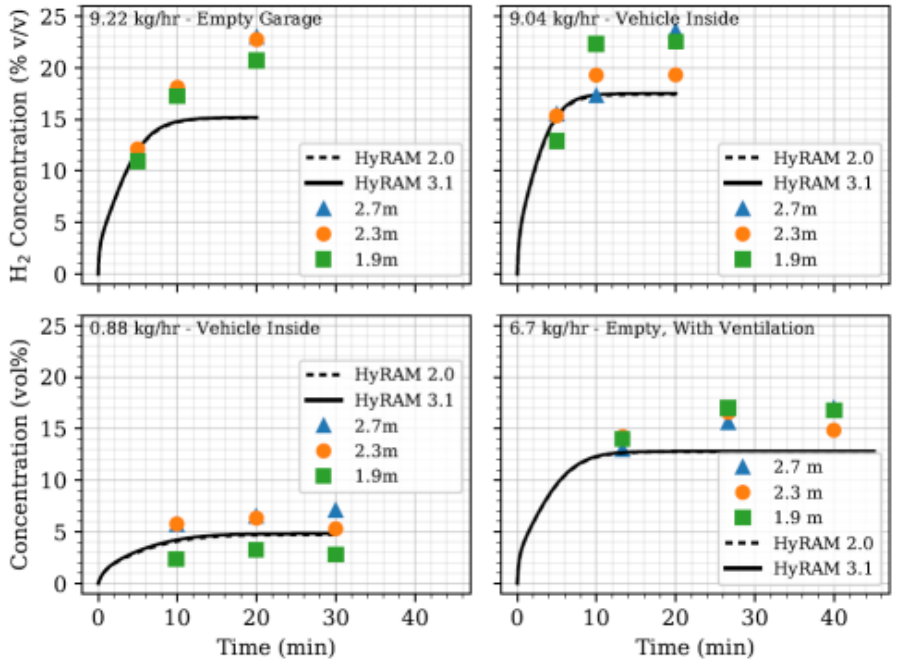


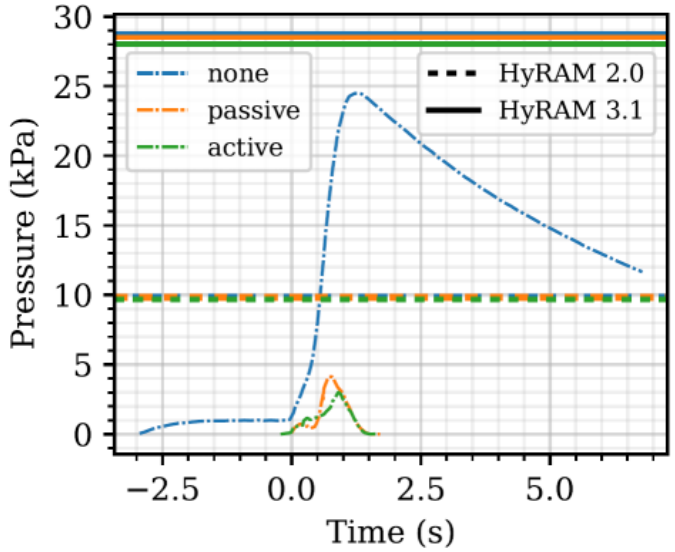


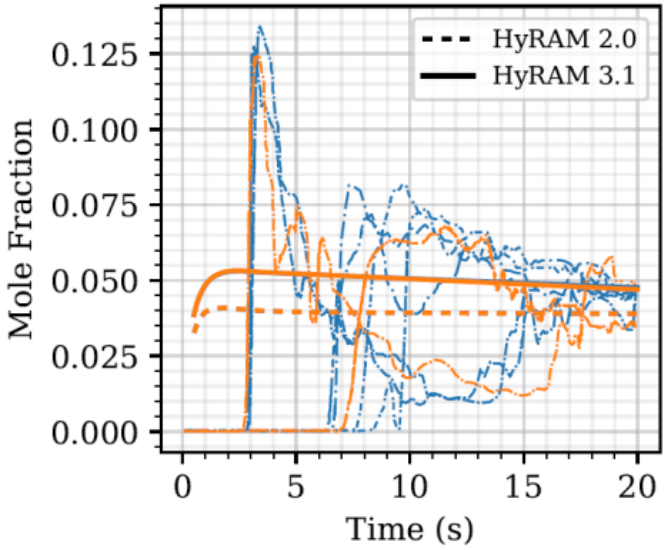


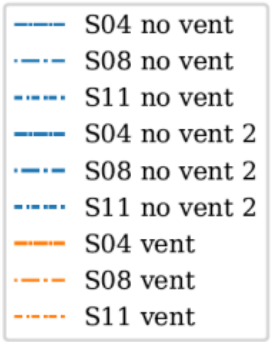
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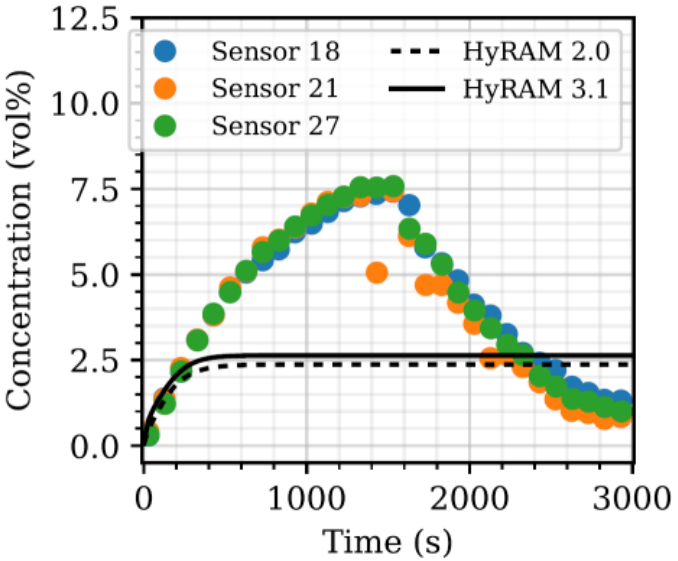
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