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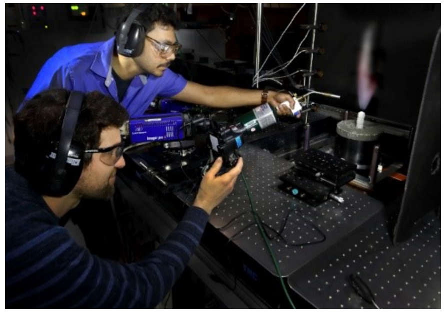
Experiments to understand liquid hydrogen pooling and dispersion in a steady cross-wind

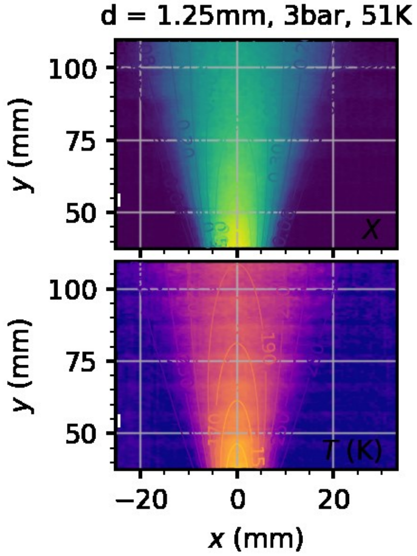
Ethan S. Hecht
Experimental Team: Victor Figueroa, Carl Fitzgerald, Shane Adee, Daniel Roybal, Seth Spitzer, Travis Fitch, Alvaro Cruz-Cabrera, Byron Demosthenous, Caleb Heine, Chris Lively, Kyle Winter
Modeling Team: Myra Blaylock, Kevin Mangala-Gitushi
SCS Team: Brian Ehrhart

ELVHYS International Stakeholders' Seminar on Safety of Liquid Hydrogen Transfer and Operations
September 30, 2024

Sandia H_2 safety codes and standards research consists of coordinated activities that facilitate deployment of hydrogen technologies



Hydrogen Behavior
Develop and validate scientific models to accurately predict hazards and harm from liquid releases, flames, etc.



problems

analysis

HyRAM+
Hydrogen Plus Other Alternative Fuels Risk Assessment Models

models

model needs

Enable Hydrogen Infrastructure through Science-based Codes and Standards
Apply QRA and behavior models to real problems in hydrogen infrastructure and emerging technology

problems

analysis

Quantitative Risk Assessment, tools R&D
Develop integrated methods and algorithms enabling consistent, traceable, and rigorous QRA (Quantitative Risk Assessment) for H_2 facilities and vehicles

There is limited data in the literature on liquid hydrogen pooling and dispersion

BAM (1994)

[https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf
https://juser.fz-juelich.de/record/860517/files/J%C3%BCl_3155_Dienhart.pdf]

HSE (2010)

[https://www.hse.gov.uk/research/rrpdf/rr986.pdf
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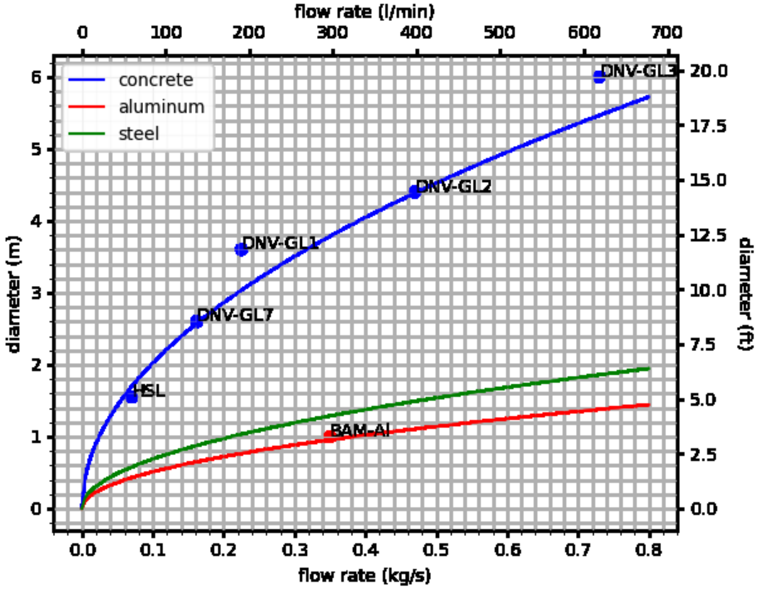
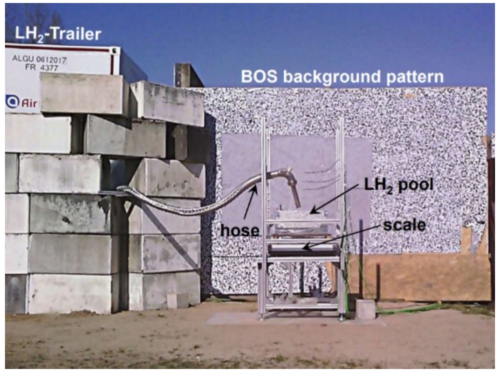




DNV-GL (2020)

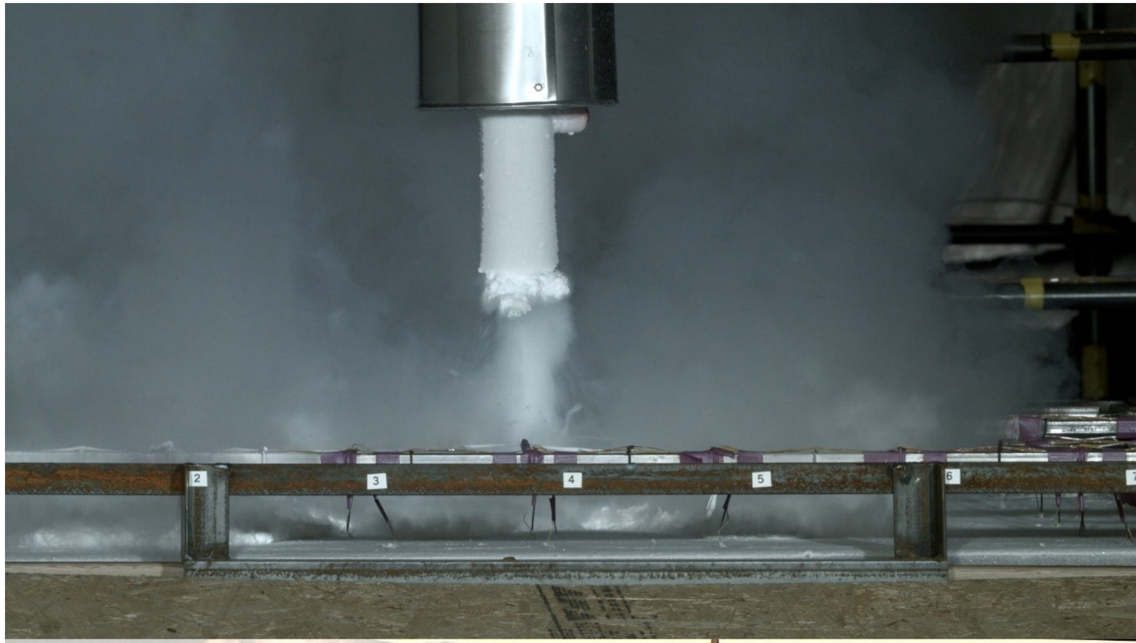
[Huescar et al. Liquid hydrogen safety data report: Outdoor leakage studies. DNV-GL. Report 853182, Rev. 2, 2020]

PreSLHy (2020)

[https://hysafe.info/wp-content/uploads/sites/3/2021/08/20210802-PRESLHY_D3_3_ReleaseMixingExperiments_V1p0.pdf]

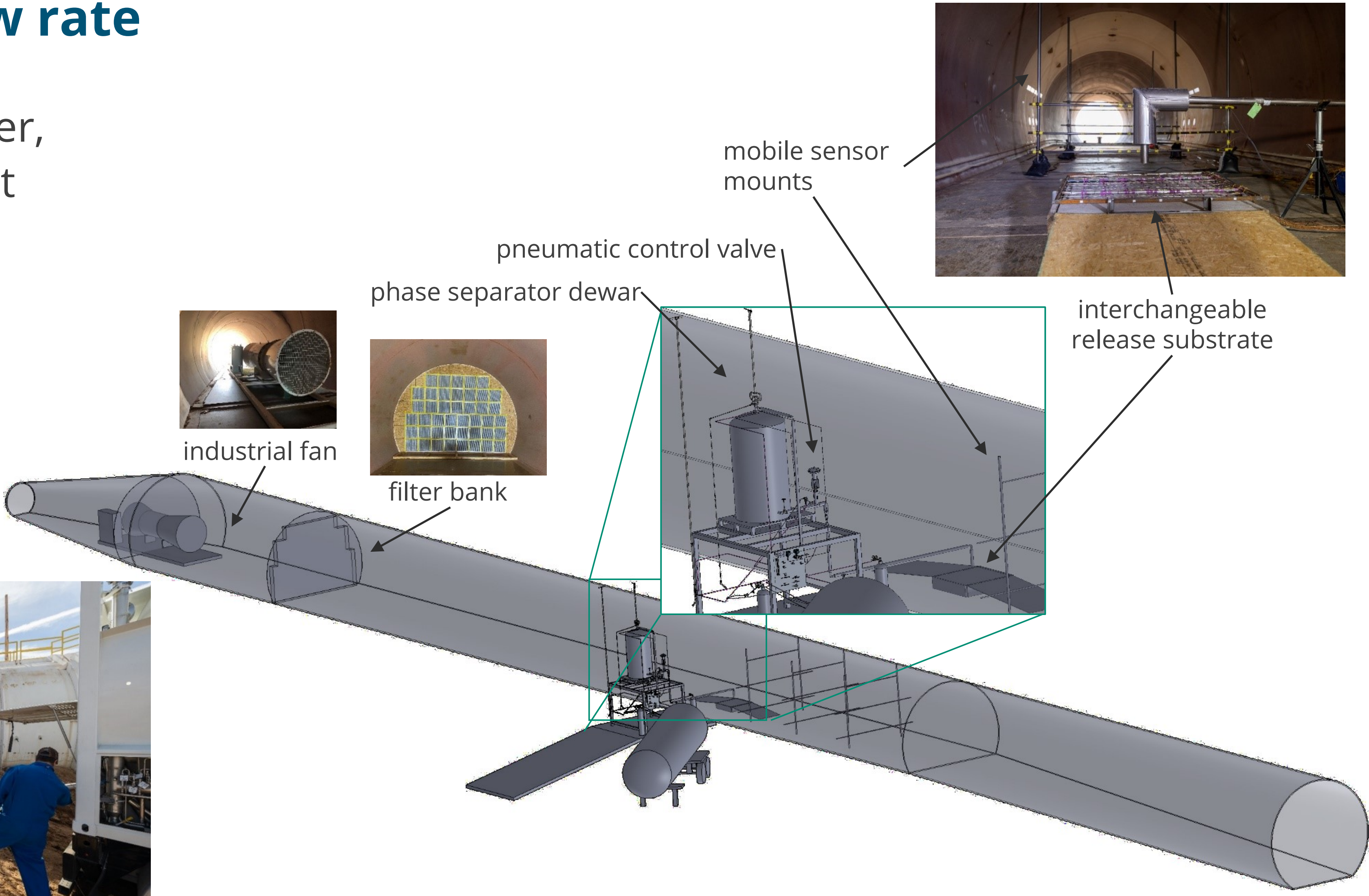
Objective: generate LH_2 pooling and dispersion data for model validation

- Predictive models that can be used to assess liquid hydrogen system risk are needed
- Experiments were designed for steady-state conditions with variation in:
  - Cross-wind speed
  - Substrate for spill
  - LH_2 release rate



The experimental setup enabled a steady cross-wind and liquid hydrogen flow rate

- Experiments in 19 ft diameter, 300 ft long blast tube to limit variations in wind
- 150 HP fan used to control cross-wind speed
- Dewar and control valve allowed for steady liquid hydrogen spill rates



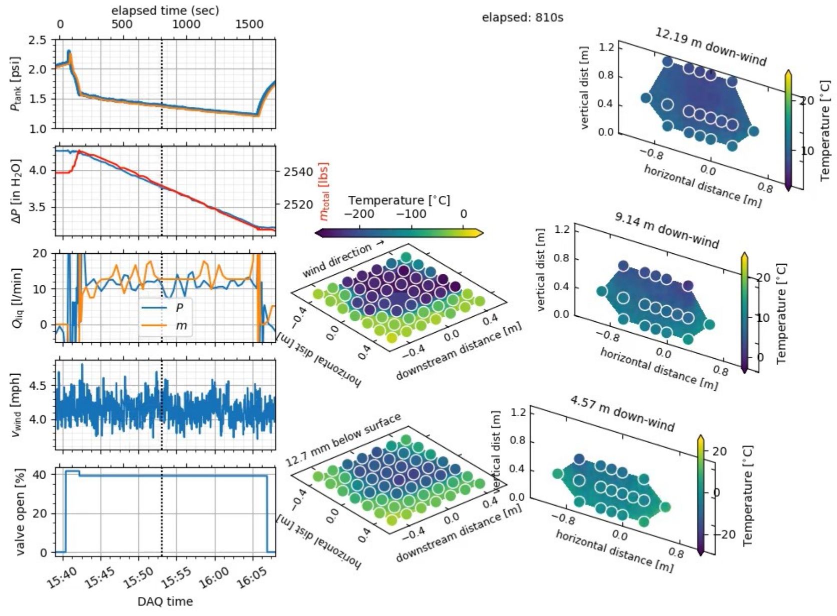
Steady-conditions generated idealized data for pooling and dispersion model validation

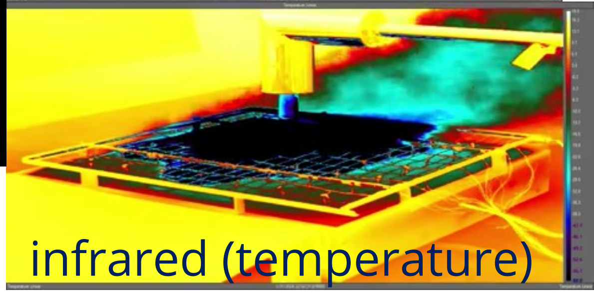
16 test runs were completed over 4 days

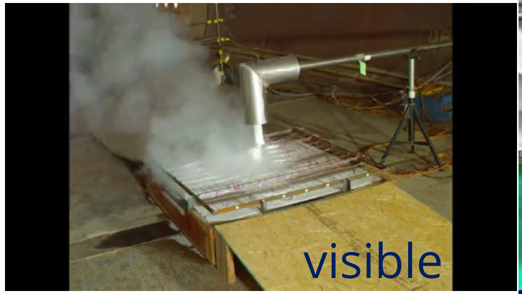
Date	Substrate	Wind speed (mph)	Spill rate (lpm)
Tuesday, 01/30/2024	concrete	3	10
	concrete	3	10
Wednesday, 1/31/2024	Instrumented concrete	3	10
	Instrumented concrete	3	50
	Instrumented concrete	**4**	**10**
	Instrumented concrete	4	50
Thursday, 2/1/2024	Instrumented concrete	2	10
	Instrumented concrete	2	10
	Instrumented concrete	2	50
	Steel	2	10
	Steel	2	50
Friday, 2/2/2024	Steel	4	10
	Steel	4	50
	Steel	4	10
	concrete	3	10
	concrete	3	100(initial)-40(final)

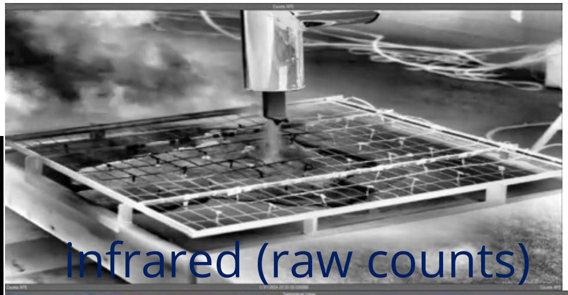
Details for this test in upcoming slides

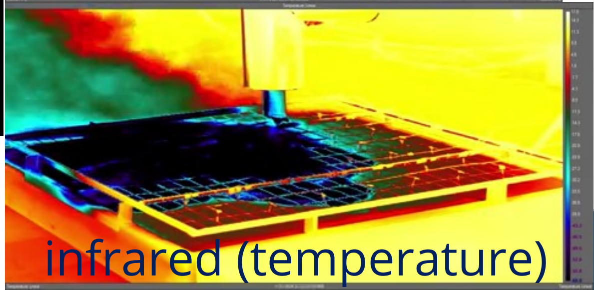
We have a rich archive of data that is being processed





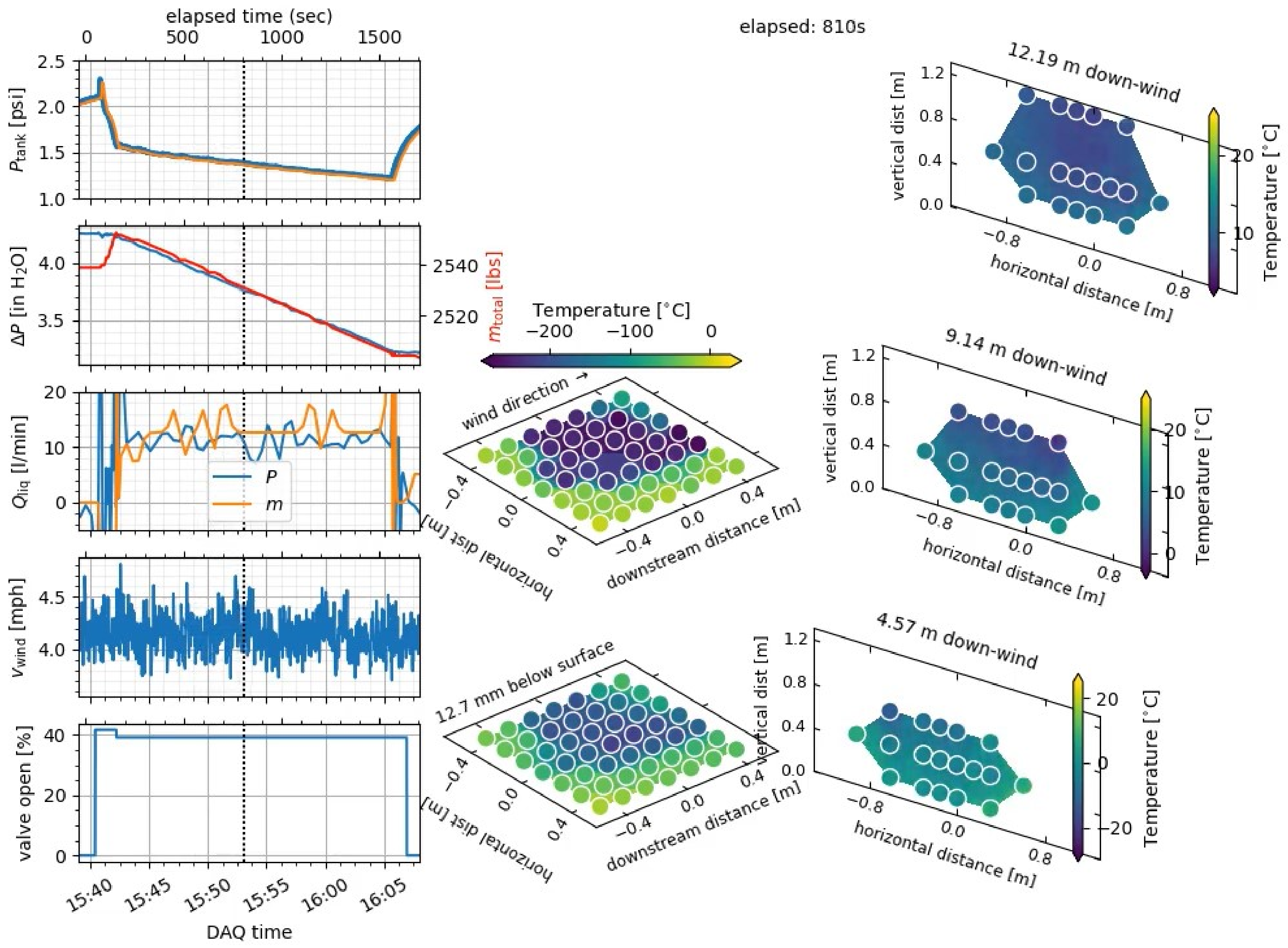






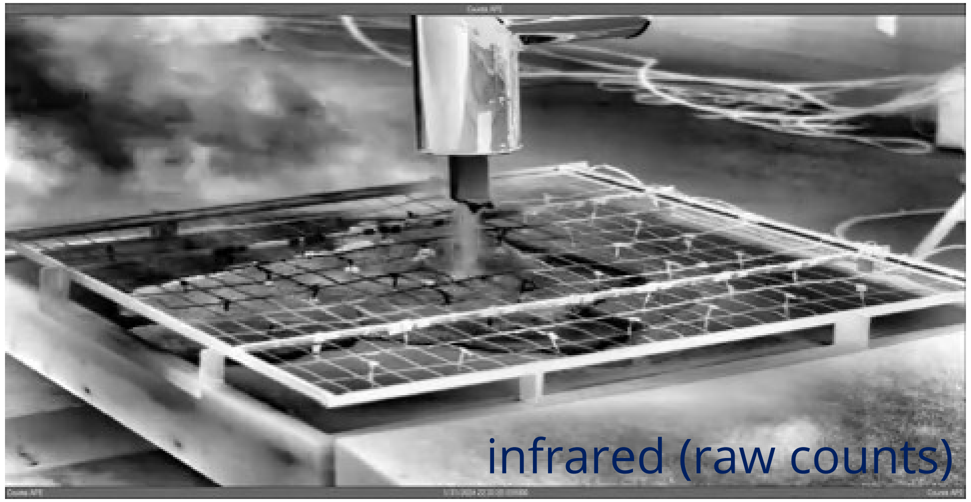
Steady-state conditions were achieved over an extended period of time

- Change in pressure and scale resulted in same flowrate calculation
- Wind speed measurement was steady (+/- 10%)
- Pool size grows rapidly for first five minutes and then more slowly
- Embedded thermocouples show same shaped pool as surface, but have higher temperatures
- Downwind temperatures unsteady due to turbulence but clearly detect cold gasses



Imaging with microbolometer (infrared) shows more details than visible imaging

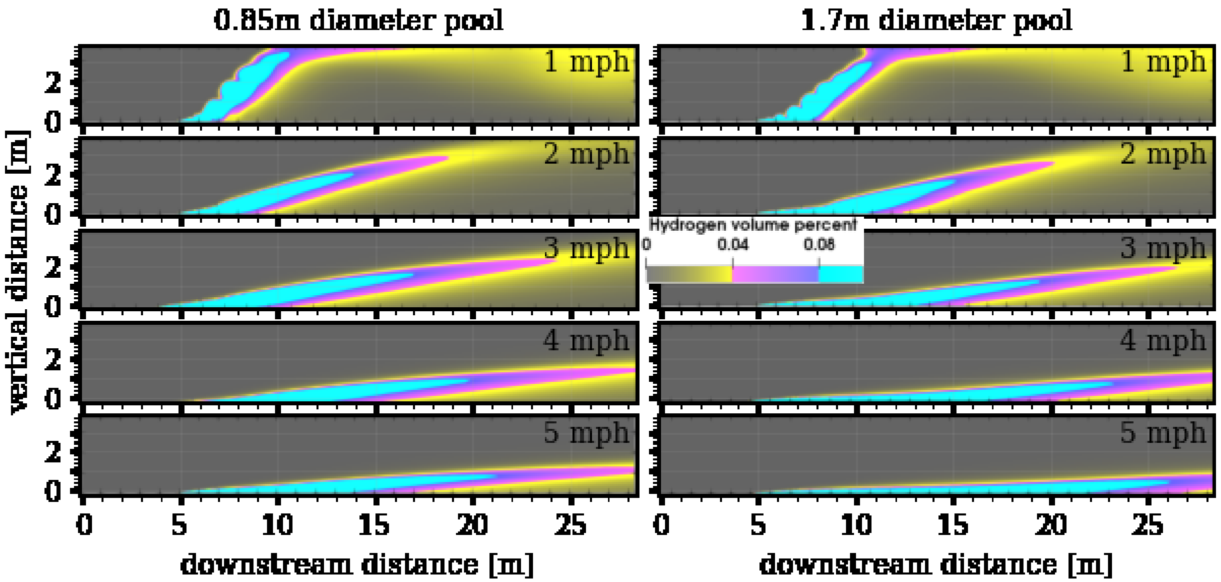
- Fog is less dense in IR images
- Liquid stream is clearly discernable
- Pool edges have sharp contrast



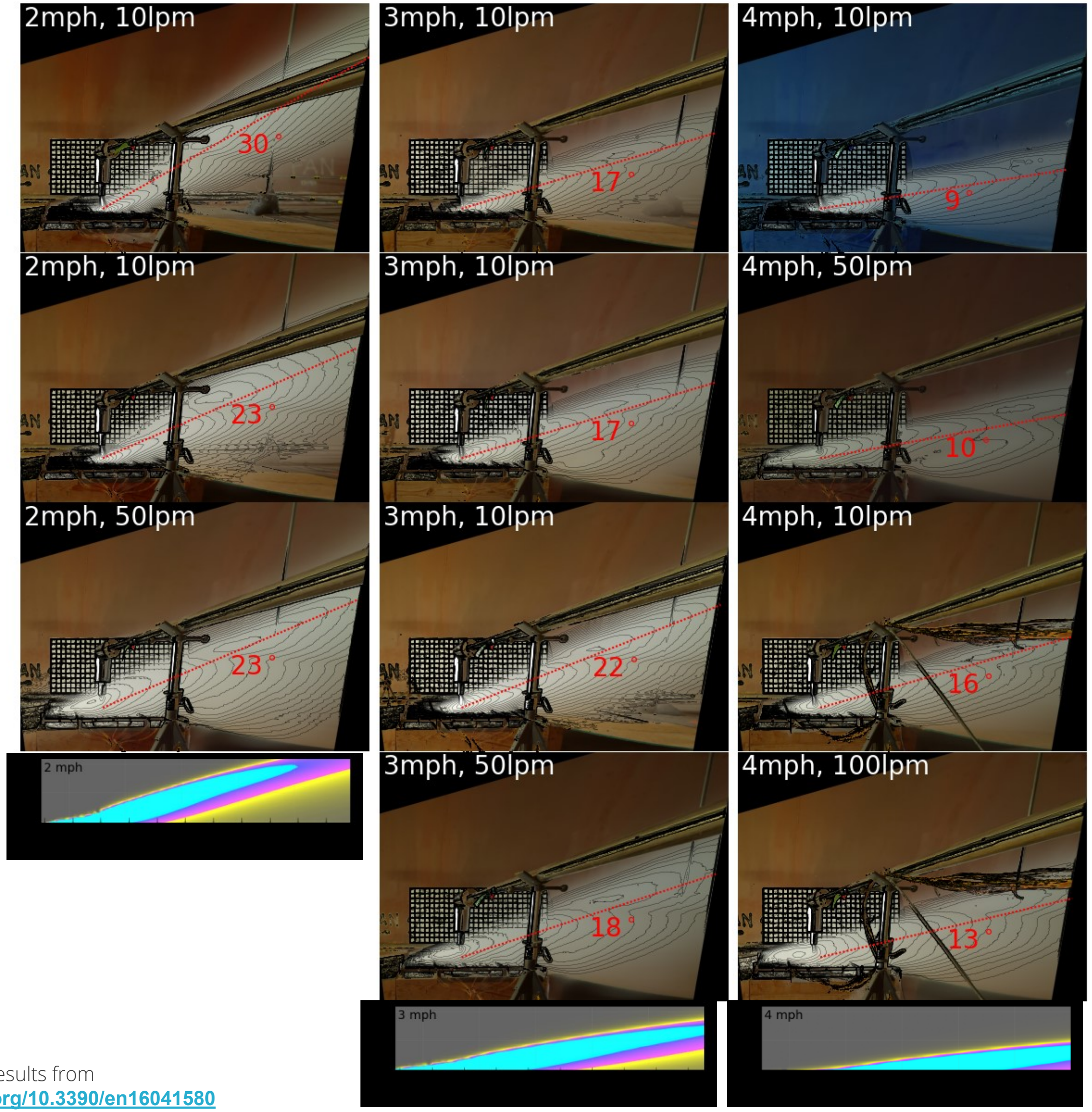
Before the experiments, the expected plume trajectory was calculated to inform experimental conditions and sensor placement

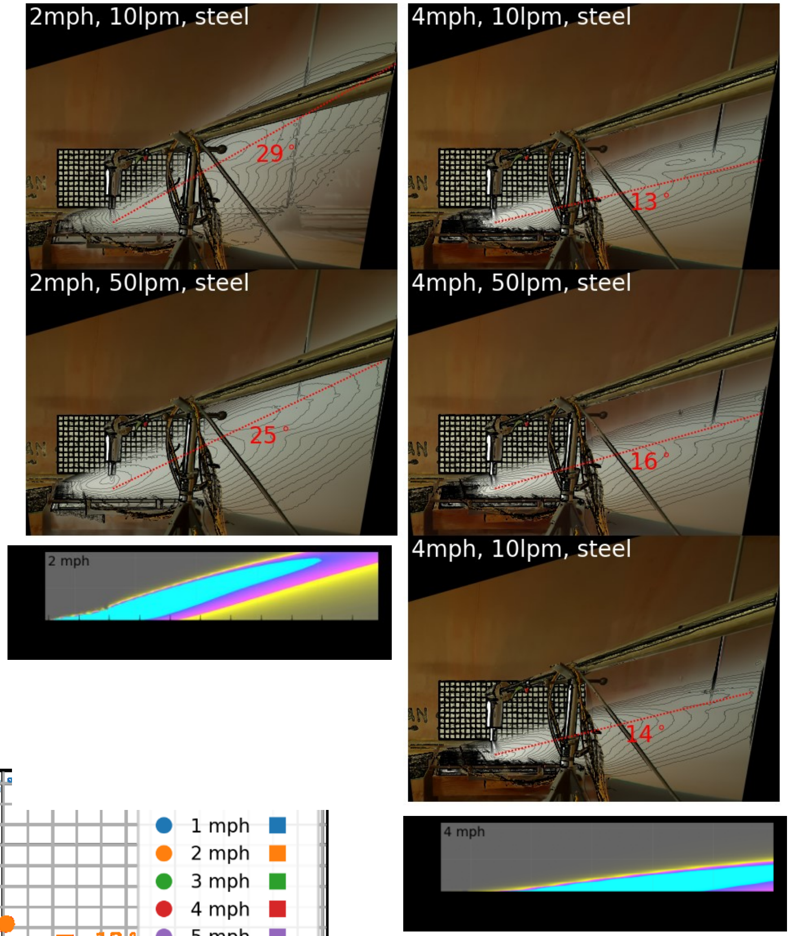
- Computational Fluid Dynamics (CFD) simulations using Fuego from Sierra Suite
- RANS simulations with two-equation k-ε turbulent closure
- Only modeled gas dispersion, ignoring pooling and phase-change

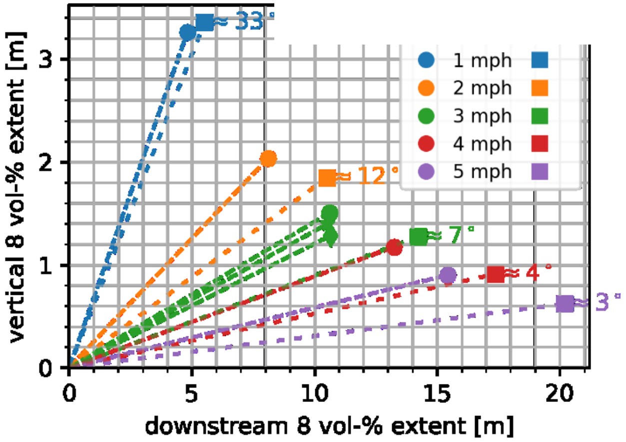
- Plume will interact with ceiling at low cross-wind speed
- Pool size (uncertain) has minor effect on plume dispersion
- Wind speed has large effect on plume dispersion
- Sensor locations were varied with wind speed



Plume angle varies with wind speed, but seems more buoyant than expected by previous simulations

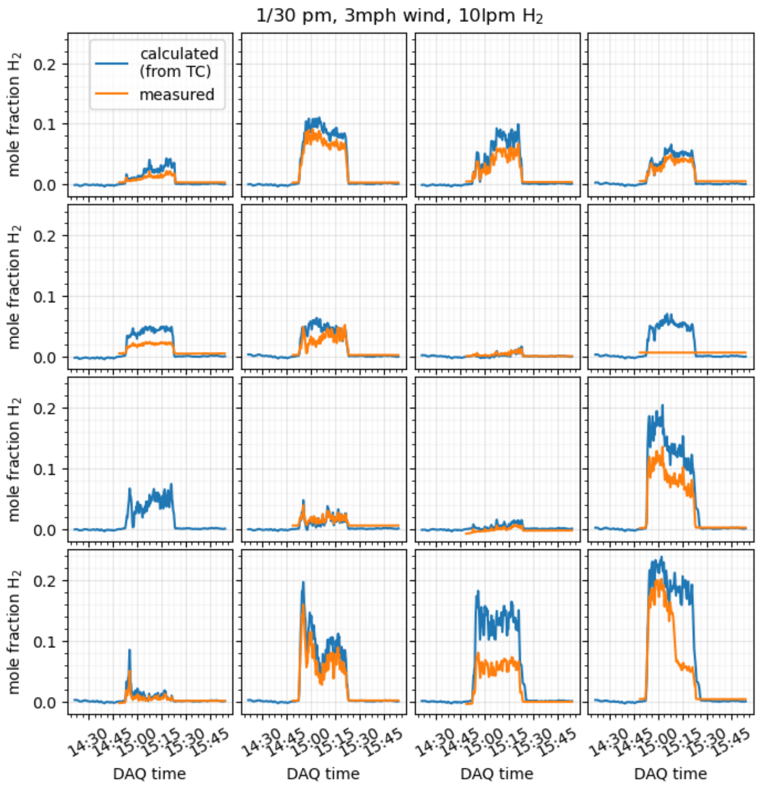


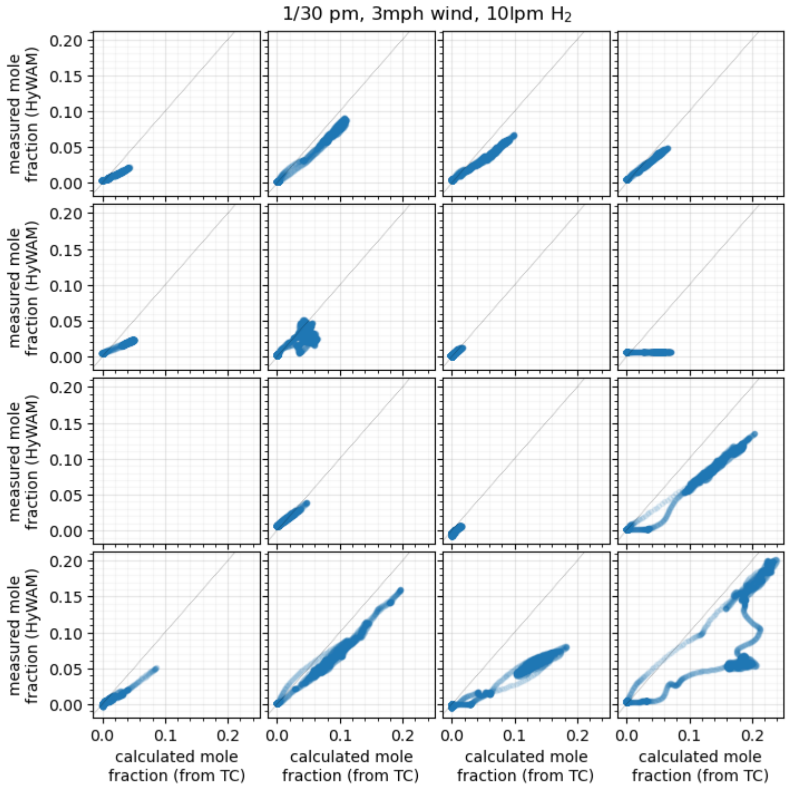


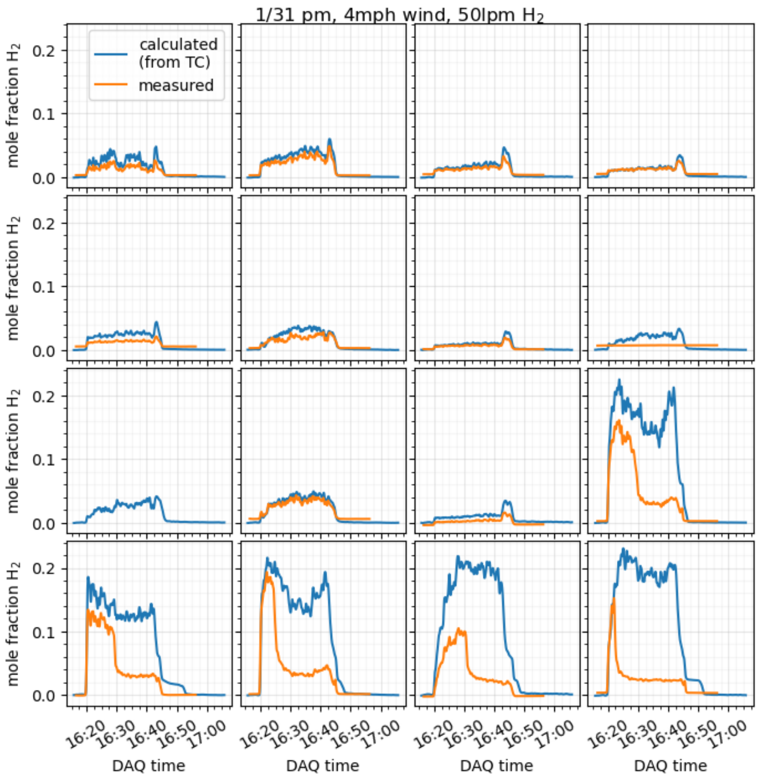


Simulation results from https://doi.org/10.3390/en16041580

Adiabatic mixing assumption results in good agreement between concentration and temperature data

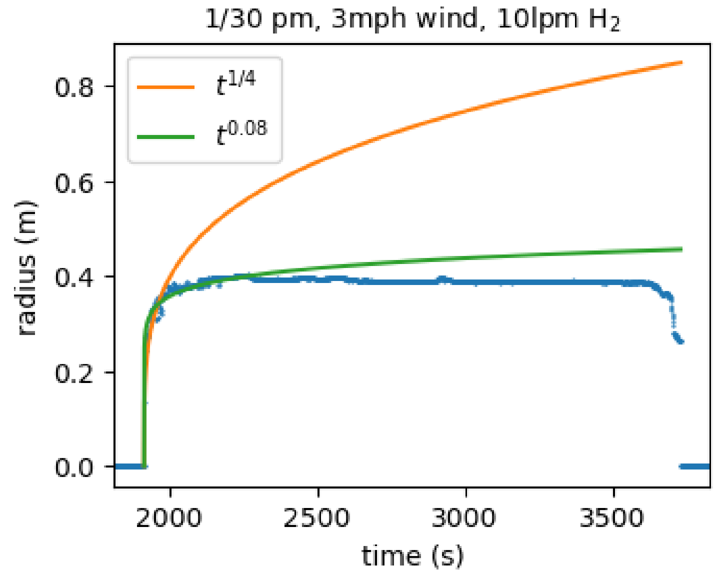


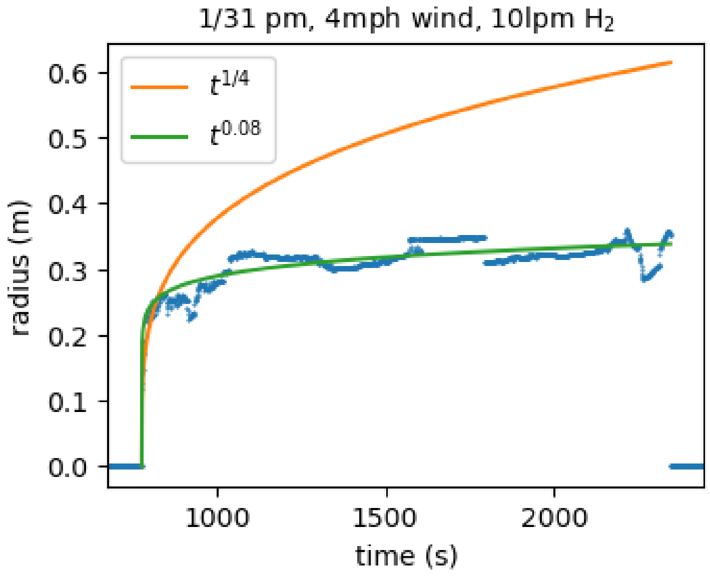


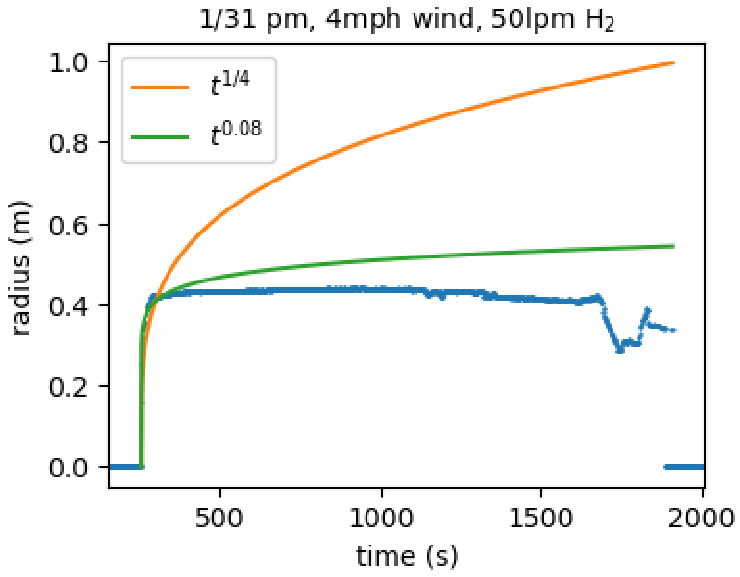


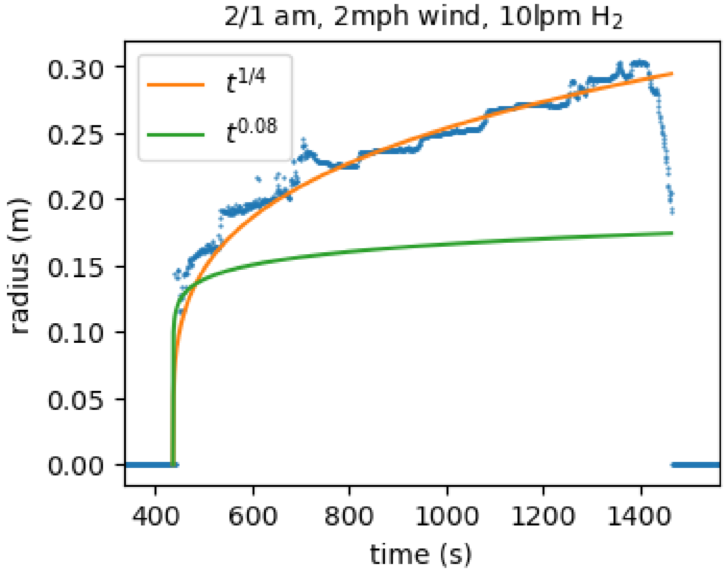
- Even small spikes of low concentration are observed by both thermocouples and HyWAM
- Temporal alignment of small concentrations very good
- Some channels seem to have small, systematic offset
- Possible hardware issues causes HyWAM measured high concentrations to drop after some time

Currently investigating whether pool growth follows a $t^{1/4}$ dependency









- Pools initially grow rapidly, then growth slows
- Measurements only out to about 0.5m radius
- Fluid flows over edge of substrate, complicating analysis
- For semi-infinite medium, would expect $t^{1/4}$ dependence

Summary

- Steady-state, well controlled liquid hydrogen pooling and vaporization experiments were completed
- Liquid level changes (as measured by pressure differential) correlated well with mass loss changes
- IR cameras show more details of liquid hydrogen behavior than visible cameras
- Variations in wind caused variations in dispersion angle
- Dispersion angle for steel and concrete are similar
- Previous simulations predicted less buoyancy than was observed
- Downwind thermocouples observed cold gasses
- Downwind temperatures correlate well with concentration
- Pools grew rapidly initially after start of release, then more slowly

Future work

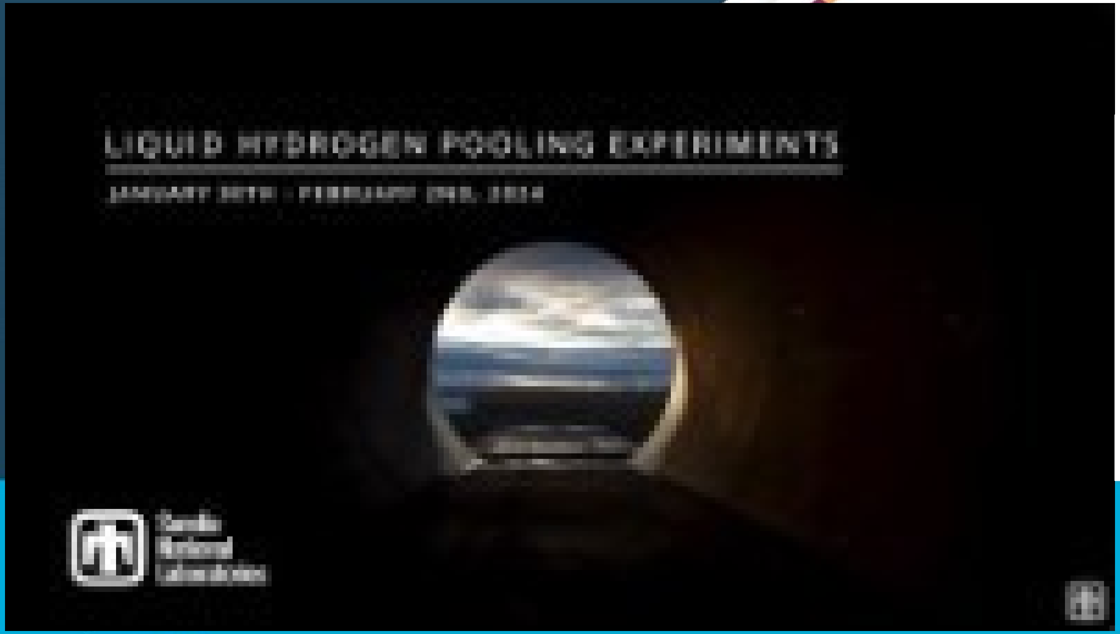
- Finalize quantification of pool growth, size, and analyze heat flux to LH_2
- Map out downwind dispersion from temperature measurements and compare to visible plume
- Finalize analyses quantifying pool and plume behavior
- Develop simplified model for inclusion in HyRAM+
- Use models to update and impact future safety codes & standards for LH_2 systems

hyram.sandia.gov

This work is supported by the U.S. DOE Office of Energy Efficiency and Renewable Energy (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO) Safety Codes and Standards (SCS) sub-program under the direction of Laura Hill

Thank you!
Questions?

Contact:
ehecht@sandia.gov

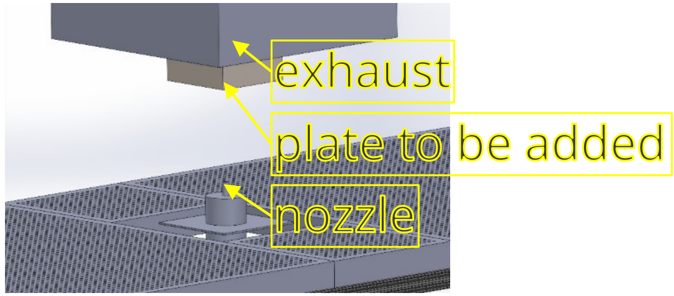


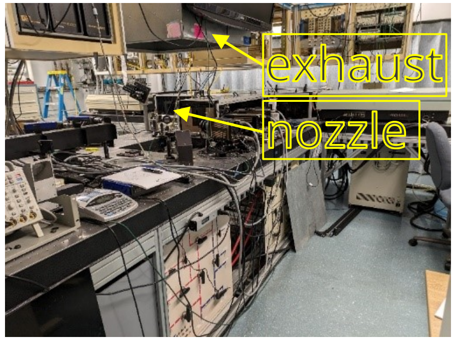
https://youtu.be/L7UmfvOwhgI

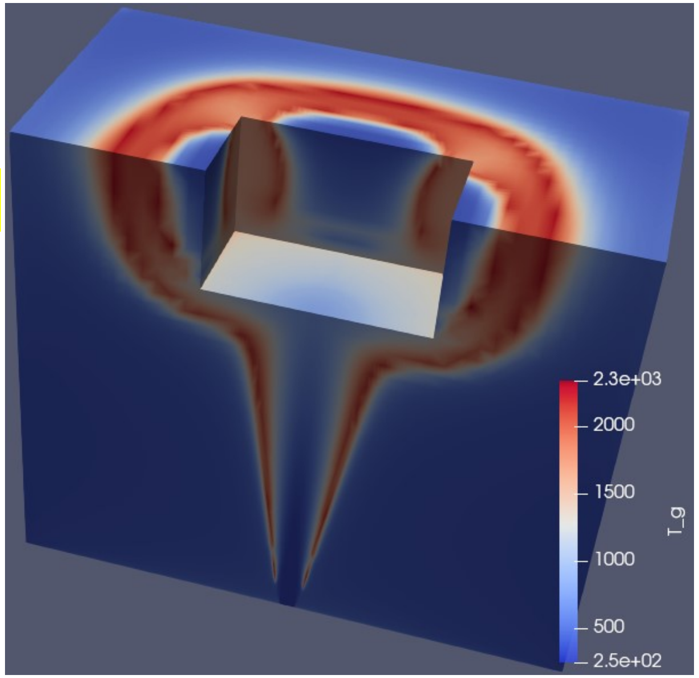
Location: Thunder Range

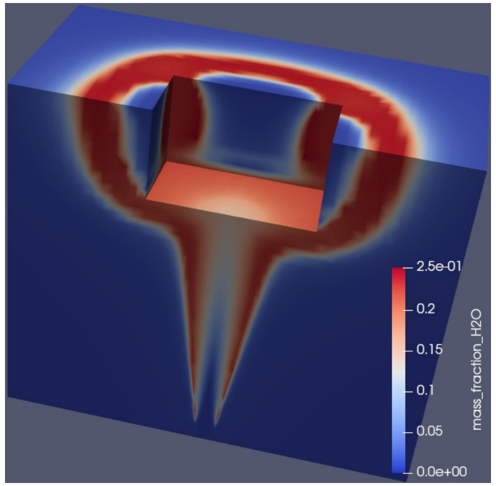
Other future work: understand heat transfer from impinging diffusion flame

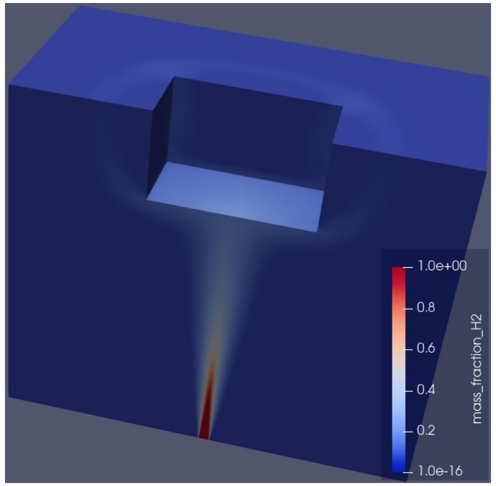
- Modeling is a part of the safety analysis and planning for laboratory experiments
  - Appropriate surface size
  - Ensure all products go out ventilation hood
  - Necessary ventilation rate
  - Estimate of heat flux for surface design
- CFD model will be revised after performing experiments
- Data will also be used to develop reduced order model for HyRAM+







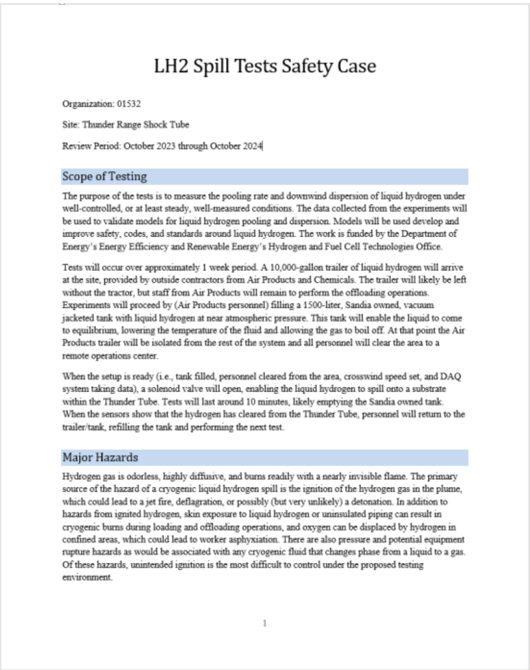




Experiments will enable predictions of overall heat flux (convective and radiative) for impinging jet flames

Safety Planning

- Extensive safety planning
  - Operational procedures reviewed by internal (e.g., Environmental Safety and Health staff) and external (Air Products, Chart Industries) stakeholders
    - Purging with helium before filling tank with LH_2
    - Maintenance of positive pressure to prevent cryo-pumping of air into tank
  - Engineering and administrative controls to prevent hydrogen from flowing when personnel needed to access blast tube
  - Avoided ignition of the hydrogen, but were prepared if ignition occurred:
    - Personnel in blast rated bunker when spills took place
    - Administrative controls to ensure personnel all accounted for and in acceptable location when spills took place



LH2 Spill Tests Safety Case

Organization: 01532

Site: Thunder Range Shock Tube

Review Period: October 2023 through October 2024

Scope of Testing

The purpose of the tests is to measure the pooling rate and downwind dispersion of liquid hydrogen under well-controlled, or at least steady, well-measured conditions. The data collected from the experiments will be used to validate models for liquid hydrogen pooling and dispersion. Models will be used develop and improve safety, codes, and standards around liquid hydrogen. The work is funded by the Department of Energy's Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office.

Tests will occur over approximately 1 week period. A 10,000-gallon trailer of liquid hydrogen will arrive at the site, provided by outside contractors from Air Products and Chemicals. The trailer will likely be left without the tractor, but staff from Air Products will remain to perform the offloading operations. Experiments will proceed by (Air Products personnel) filling a 1500-liter, Sandia owned, vacuum jacketed tank with liquid hydrogen at near atmospheric pressure. This tank will enable the liquid to come to equilibrium, lowering the temperature of the fluid and allowing the gas to boil off. At that point the Air Products trailer will be isolated from the rest of the system and all personnel will clear the area to a remote operations center.

When the setup is ready (i.e., tank filled, personnel cleared from the area, crosswind speed set, and DAQ system taking data), a solenoid valve will open, enabling the liquid hydrogen to spill onto a substrate within the Thunder Tube. Tests will last around 10 minutes, likely emptying the Sandia owned tank. When the sensors show that the hydrogen has cleared from the Thunder Tube, personnel will return to the trailer/tank, refilling the tank and performing the next test.

Major Hazards

Hydrogen gas is odorless, highly diffusive, and burns readily with a nearly invisible flame. The primary source of the hazard of a cryogenic liquid hydrogen spill is the ignition of the hydrogen gas in the plume, which could lead to a jet fire, deflagration, or possibly (but very unlikely) a detonation. In addition to hazards from ignited hydrogen, skin exposure to liquid hydrogen or uninsulated piping can result in cryogenic burns during loading and offloading operations, and oxygen can be displaced by hydrogen in confined areas, which could lead to worker asphyxiation. There are also pressure and potential equipment rupture hazards as would be associated with any cryogenic fluid that changes phase from a liquid to a gas. Of these hazards, unintended ignition is the most difficult to control under the proposed testing environment.

1