Validation data for models of cryogenic hydrogen releases and flames

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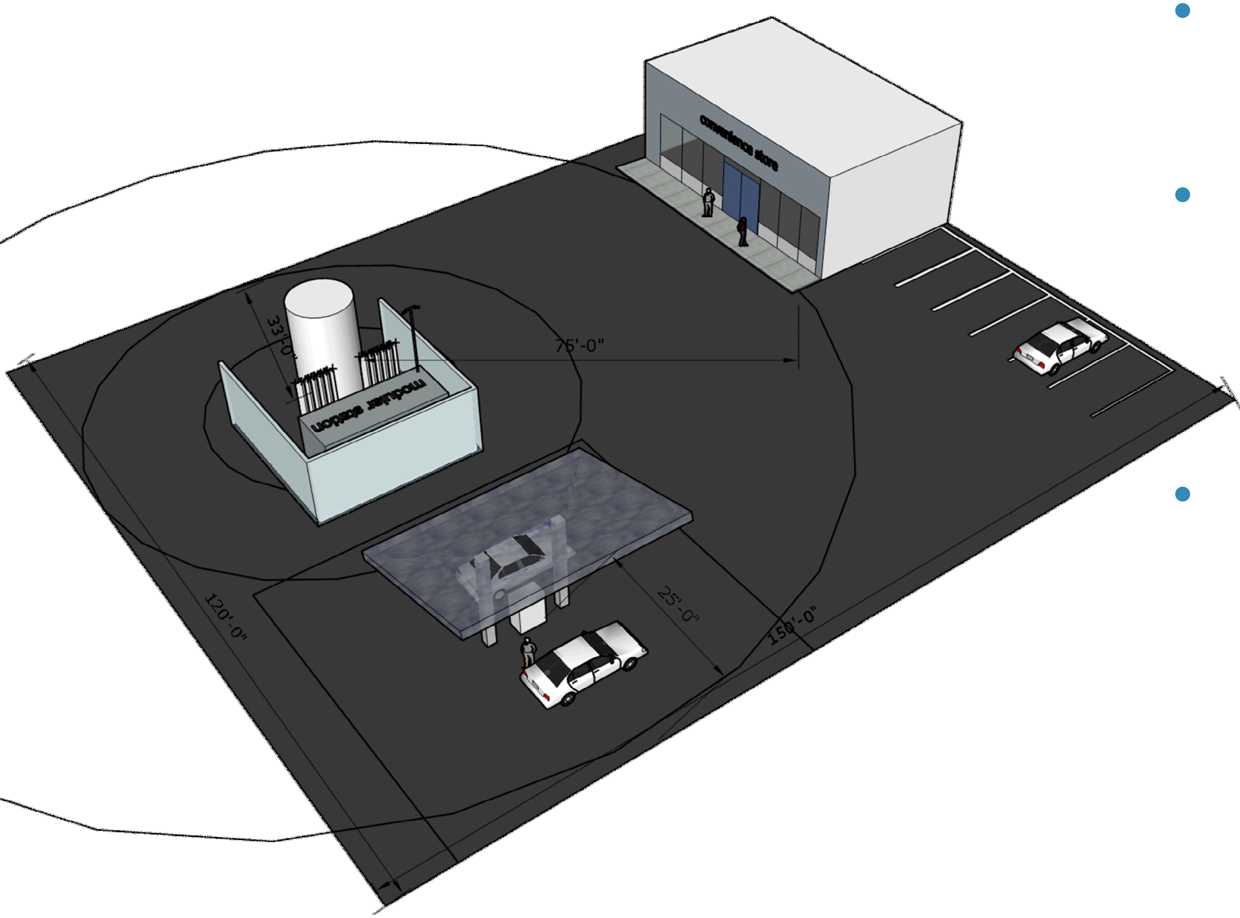
We are trying to provide a scientific basis for liquid hydrogen separation distances



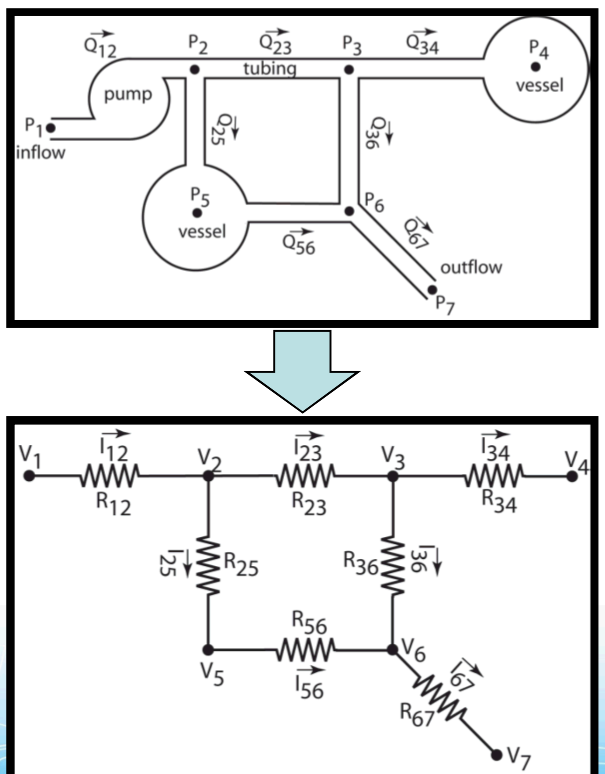
- Previous work by this group led to science-based, reduced, gaseous H_2 separation distances
- Higher energy density of liquid hydrogen over compressed H_2 makes it more economically favorable for larger fueling stations
- Even with credits for insulation and fire-rated barrier wall 75 ft (22.9 m) offset to building intakes and parking make footprint large

Two high priority scenarios identified by the NFPA 2 code committee are initially targeted for modeling

- ✓ Flow from trailer venting excess pressure after normal LH_2 delivery
  - Modeling results will be used to calculate separation distance from air intakes and overhead utilities
  - Vertical discharge, 3” diameter pipe, 20-140 psig
- ❑ Release from pipe leading from tank to vaporizer or vaporizer itself caused by thermal cycles or ice falling from vaporizers
  - Modeling results of hydrogen concentration plume and heat flux from a subsequent fire will be used for all other separation distance exposures because this is the highest risk priority
  - Horizontal discharge, ¾”-2” diameter pipe, 20-140 psig

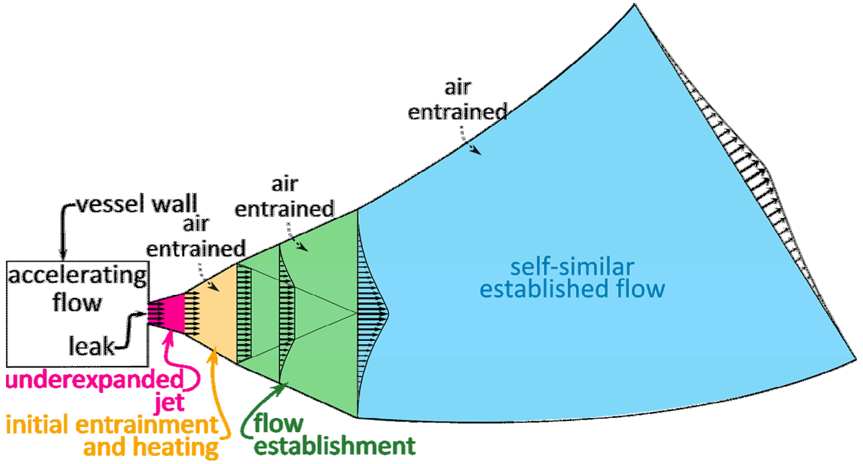
An internal flow model is used to predict the conditions at the vent stack

- Temperature in the tank is NOT the temperature at the vent stack
- Valves, piping, and other components represented as an electrical network
- Data needed for vent layouts and heat transfer from components in vent stack

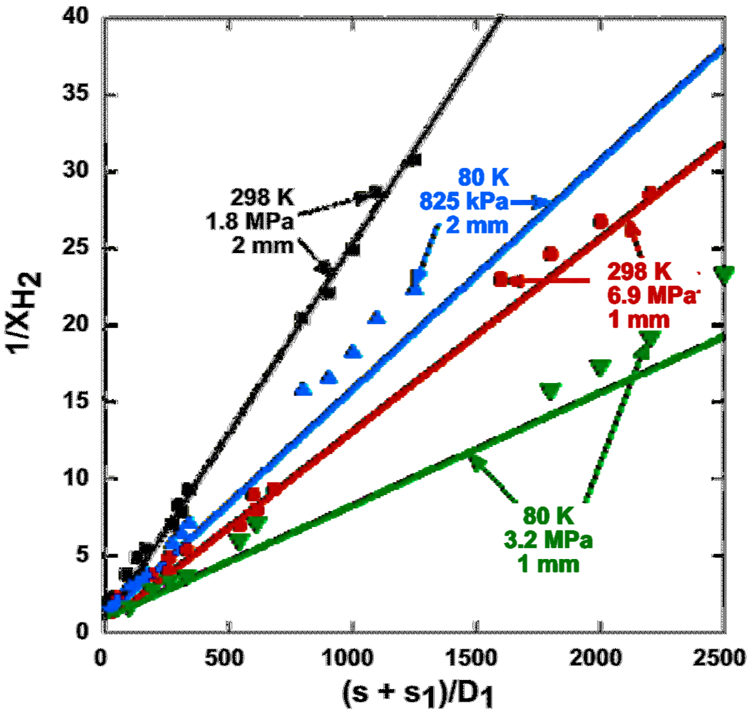


Liquid hydrogen storage tank

1-dimensional model (with buoyancy) needs validation data

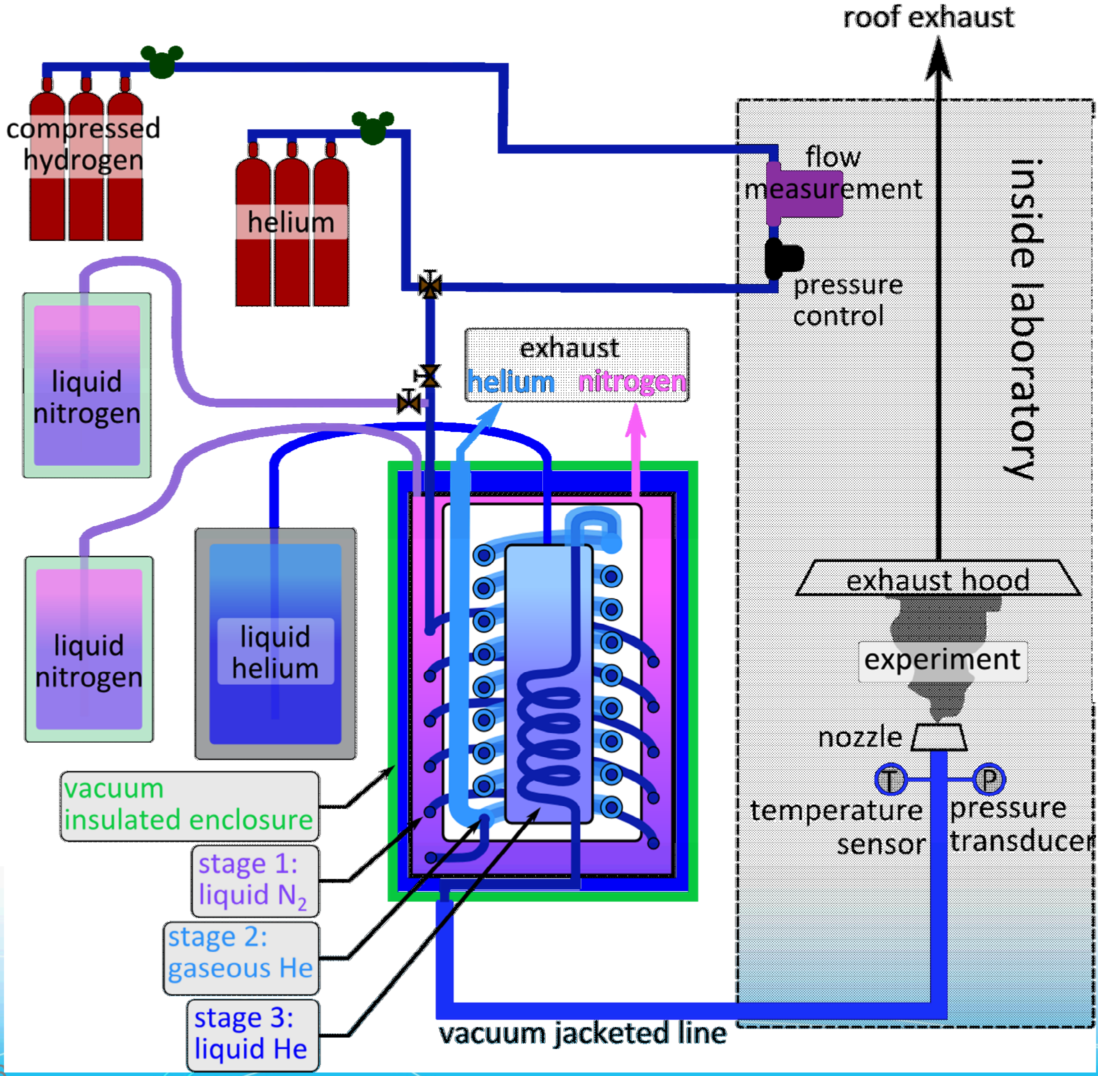


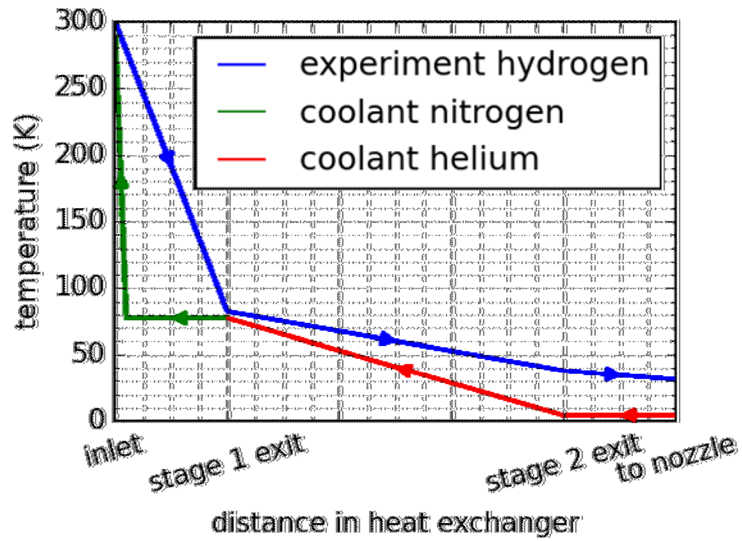
- No air or moisture condensation considered
- Over-predicts centerline concentration for 80 K release



Xiao et al, IJHE, 2011
Houf & Winters, IJHE, 2013

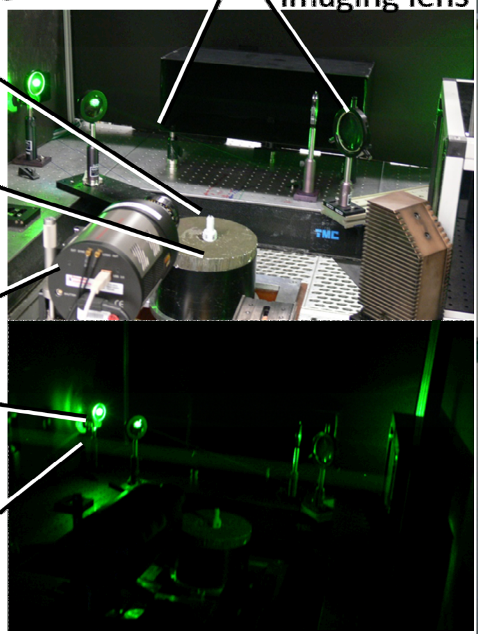
We are running an experiment, releasing ultra-cold hydrogen in the laboratory

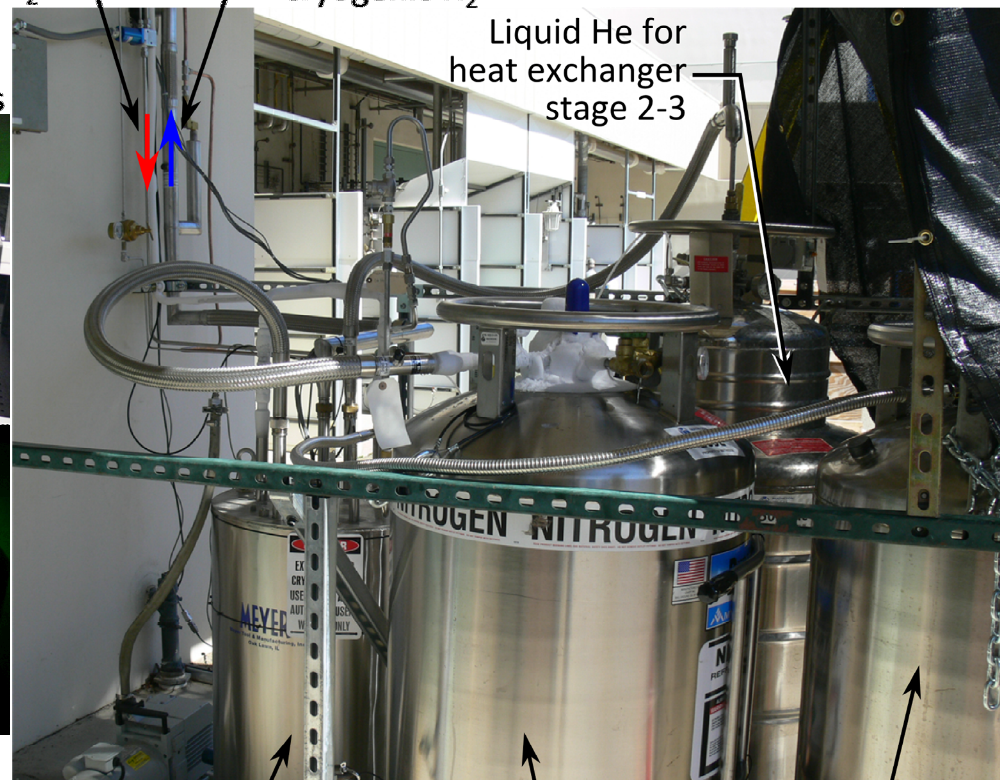




- Accurate control/measurement of boundary conditions

We have applied Schlieren imaging and used a laser spark to ignite ultra-cold releases

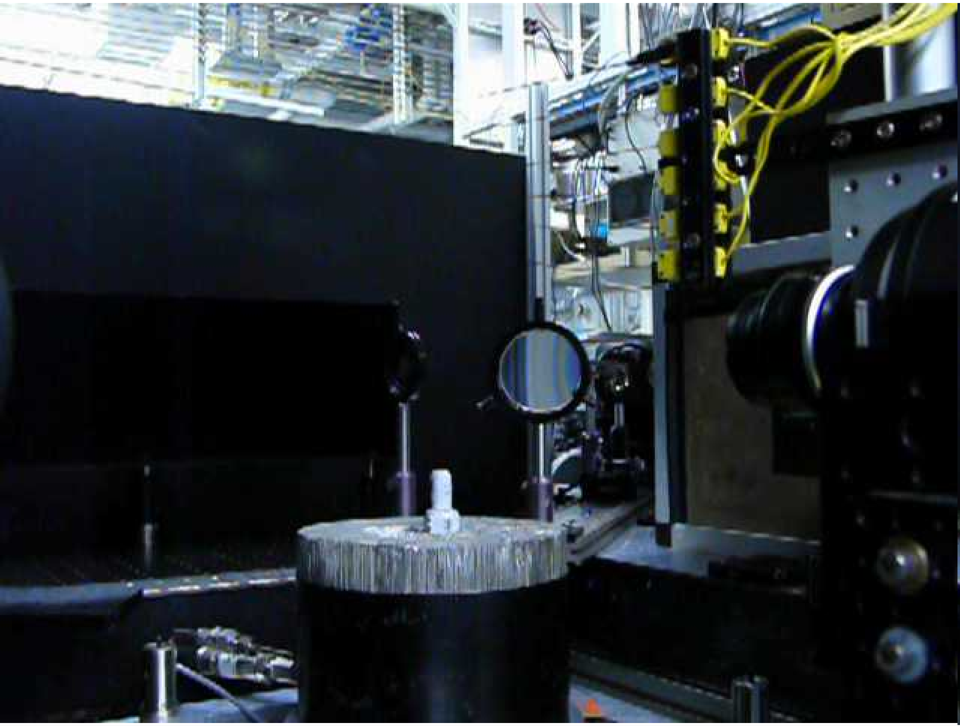




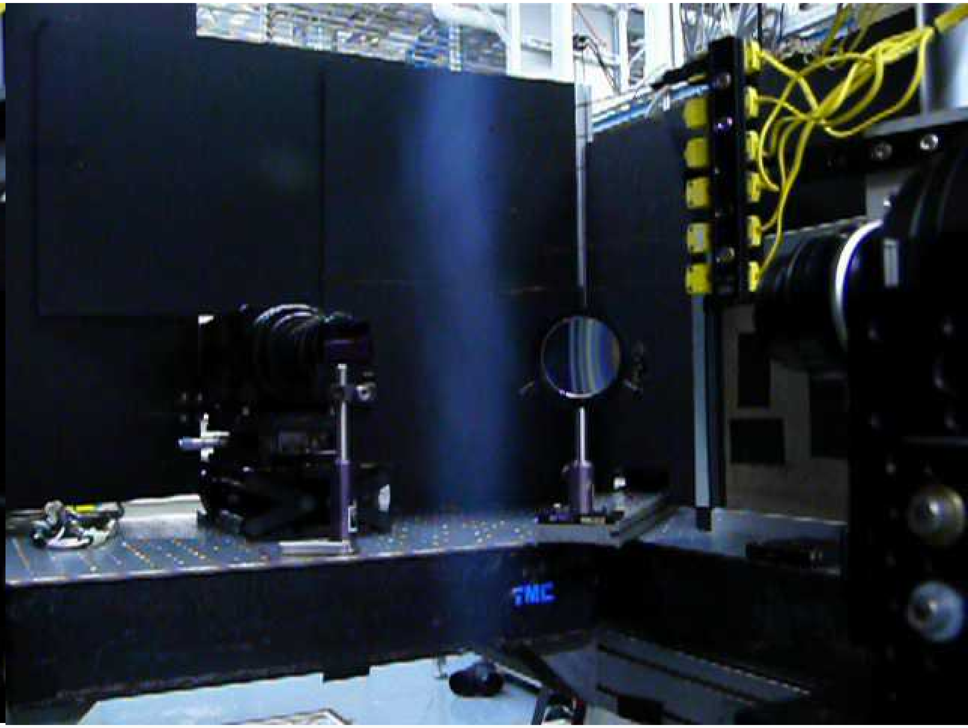
- Multiple diagnostics are used to precisely characterize releases

The first study looked at the ignition distance using a laser spark to ignite the flows

P = 1 bar, T = 290 K, distance = 85 mm

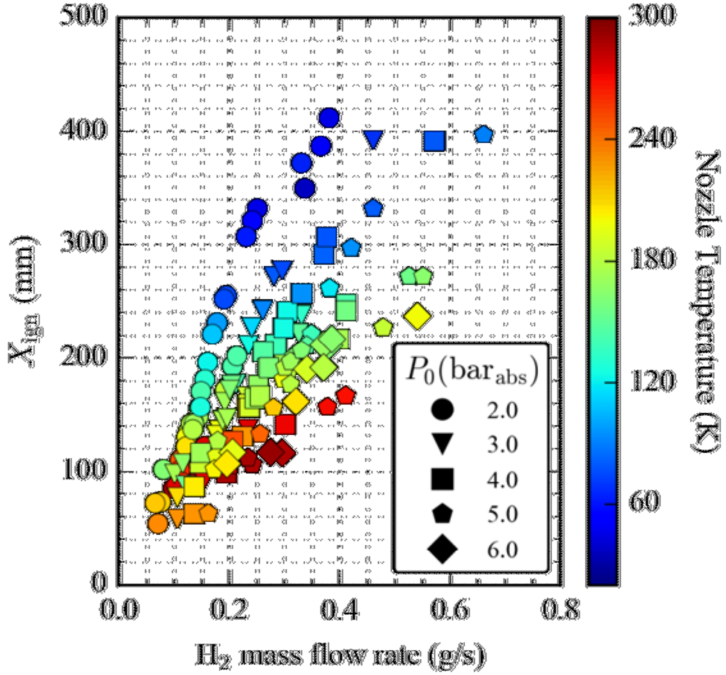


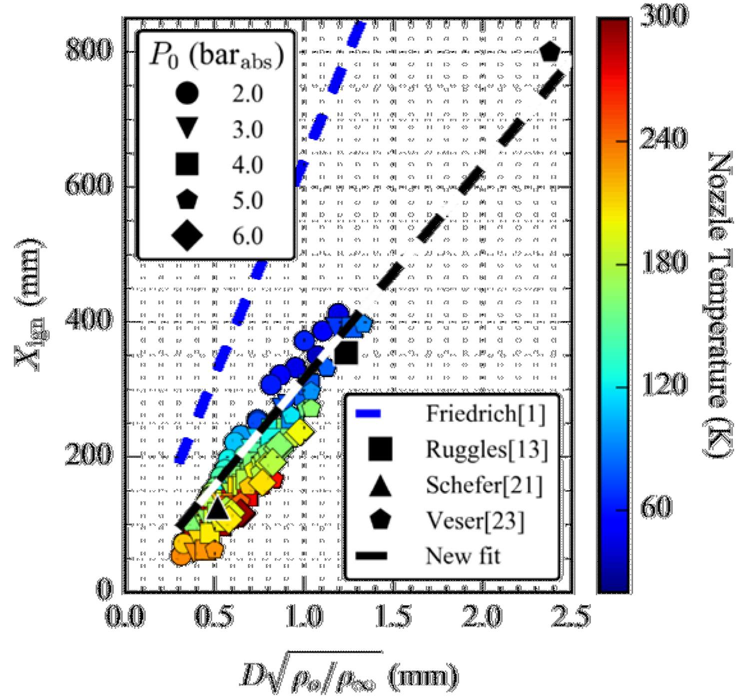
P = 1 bar, T = 37 K, distance = 325 mm



- Entrained moisture (and possibly air) condenses in the cold flow

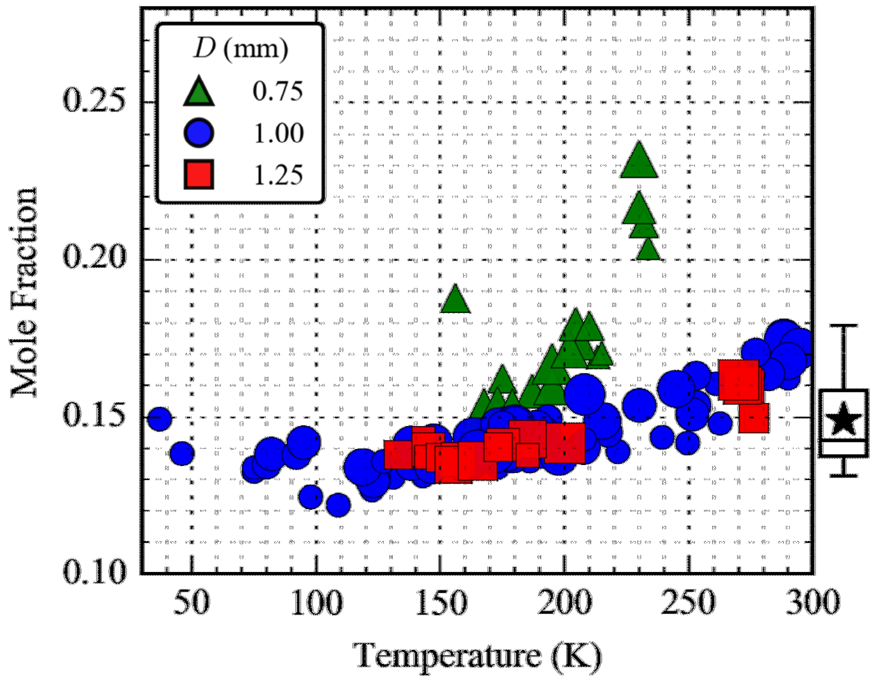
The maximum ignition distance scales with the effective diameter





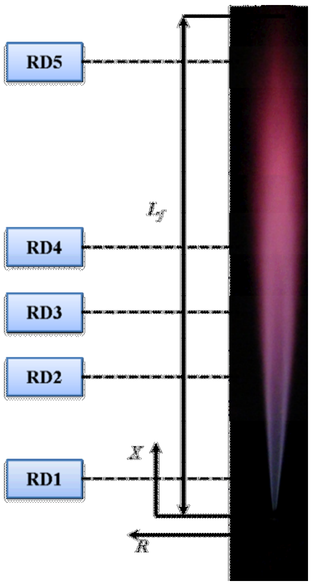
- for a given mass flow, ignition of cold H_2 occurs much further from the release point
- temperature affects ignition distance much more than pressure
- a maximum ignition height is achieved at a lower mass flow rate of hydrogen for the colder jets
- Maximum ignition distance linearly varies as a function of effective diameter (same as room temperature releases)

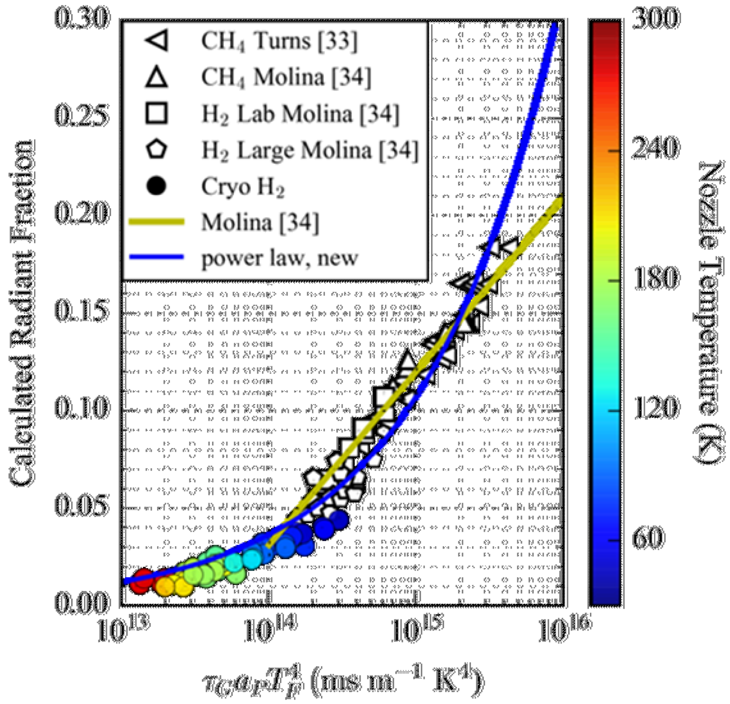
Simulations (using the unvalidated model) predict the mole fraction at the ignition point



- Simulated jet mean hydrogen mole fraction at each ignition point using COLDPLUME developed by Houf and Winters
- No significant trend observed in terms of temperature or pressure
- 90 % of the data lies within 0.13 - 0.18 mole fraction
- mole fraction at the point of ignition is much greater than the 4% LFL

Radiant fraction for cryogenic hydrogen jet flames scales the same as room temperature jet flames

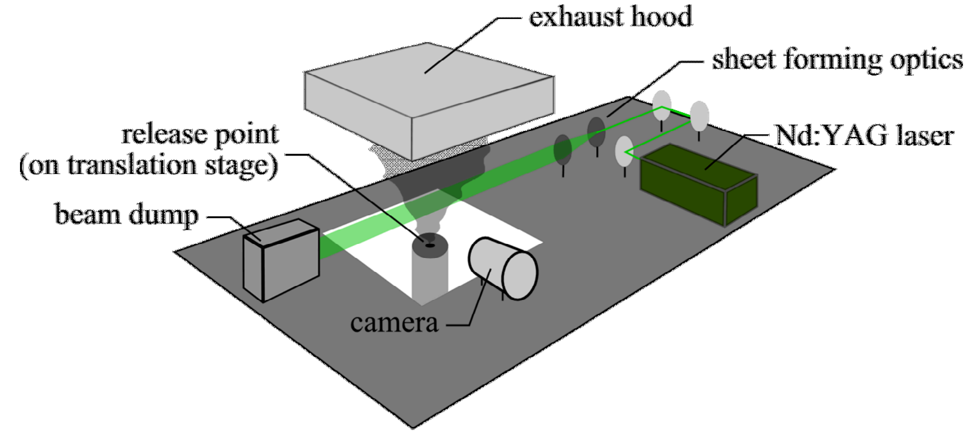




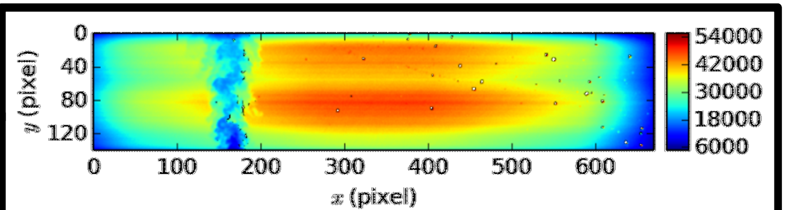
- Radiometers placed at 5 axial locations along the flame length to measure radiative heat flux
- Hydrogen flames have lower radiant heat flux compared to methane or syngas flames
- An increase in radiant fraction is observed for the colder H_2 jets due to longer flame residence time

Planar laser Rayleigh scattering has historically been used to measure concentration fields in the lab

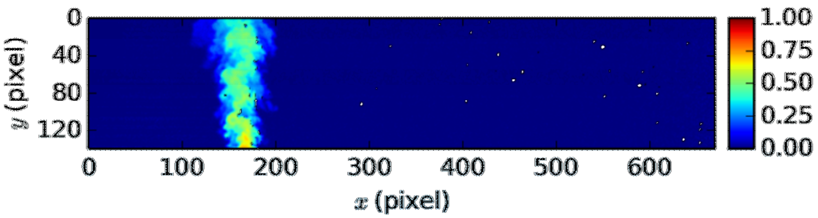
- R: Raw image
- B_G: Background luminosity
- p_F: Laser power fluctuation
- O_R: Camera/lens optical response
- S_B: Background scatter
- S_t: Laser sheet profile variation
- I: Corrected intensity



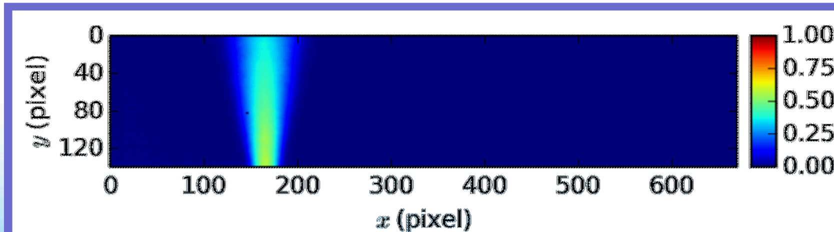
$$R = O_R \cdot (I \cdot S_t + S_B \cdot p_F) + B_G$$



Mole Fraction $(\chi_{H2}) \propto I$



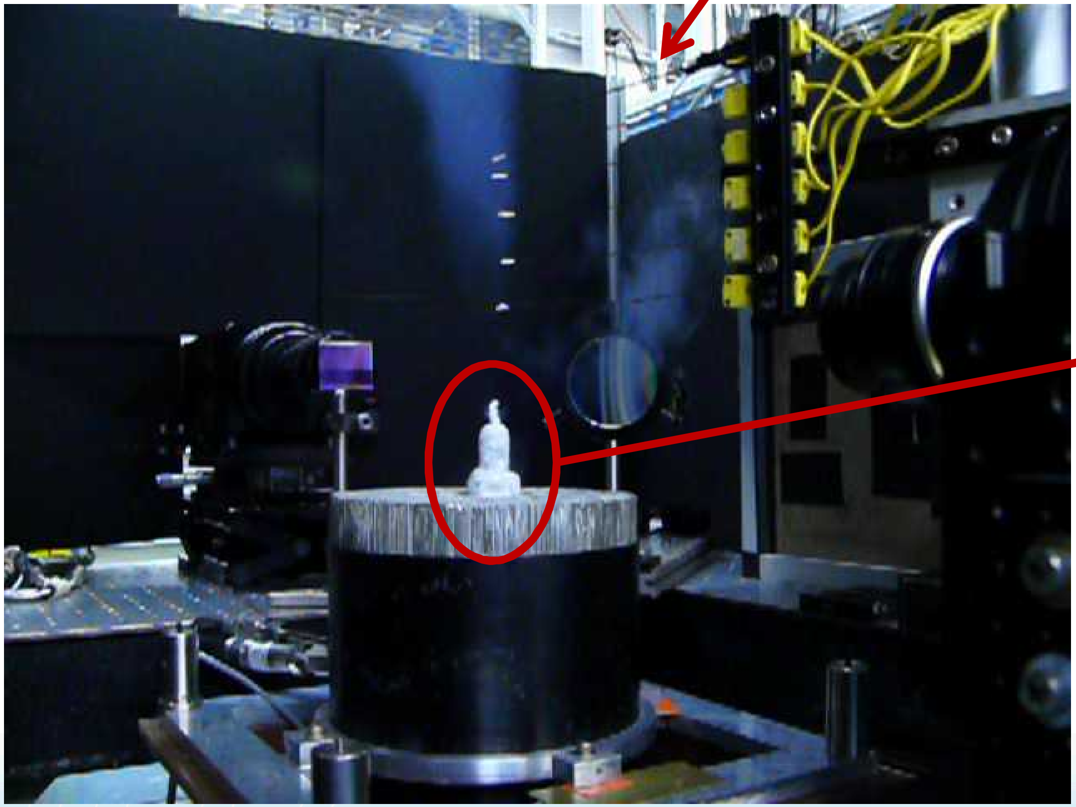
Instantaneous

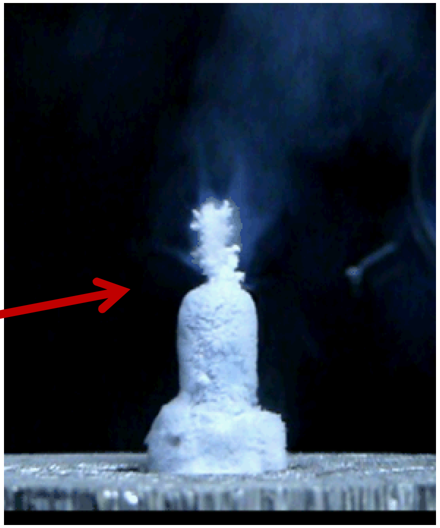


Mean

Icing observed at the nozzle during cryogenic H_2 release, and cold jet condenses moisture

Array of thermocouples measuring the plume temperature

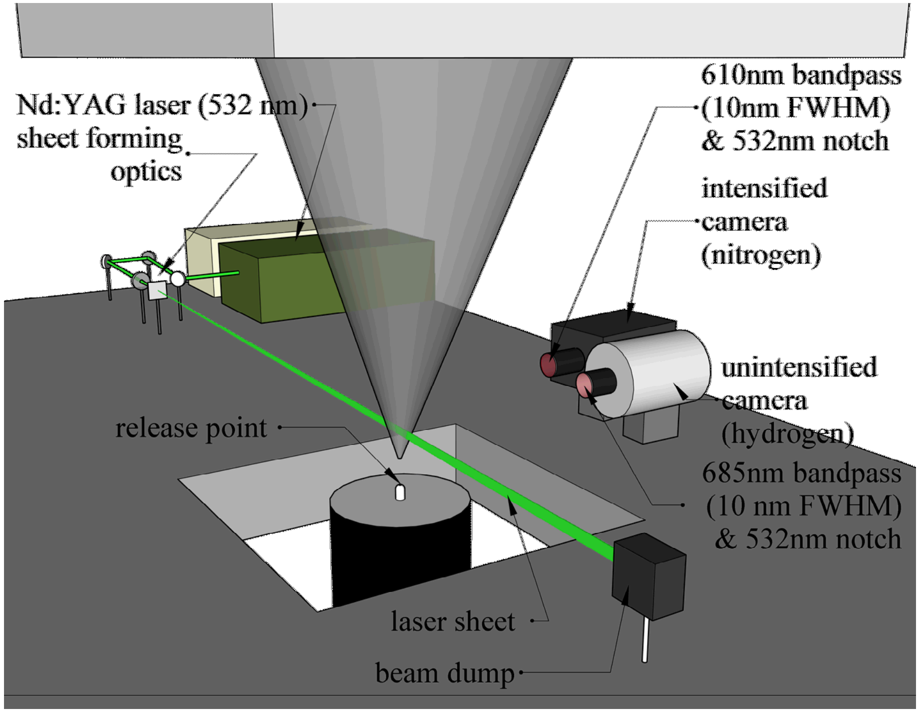


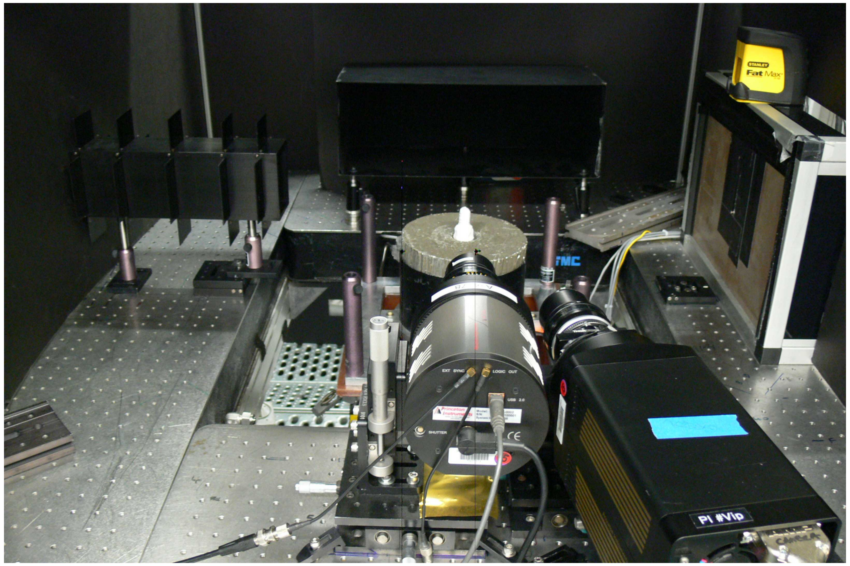


(air, moisture?) icing around liq. H_2 jet column ($T < 50K$)

- Challenging to provide sufficiently dried air while maintaining experimental integrity

We have had success using Raman imaging to extract concentration fields of the flows

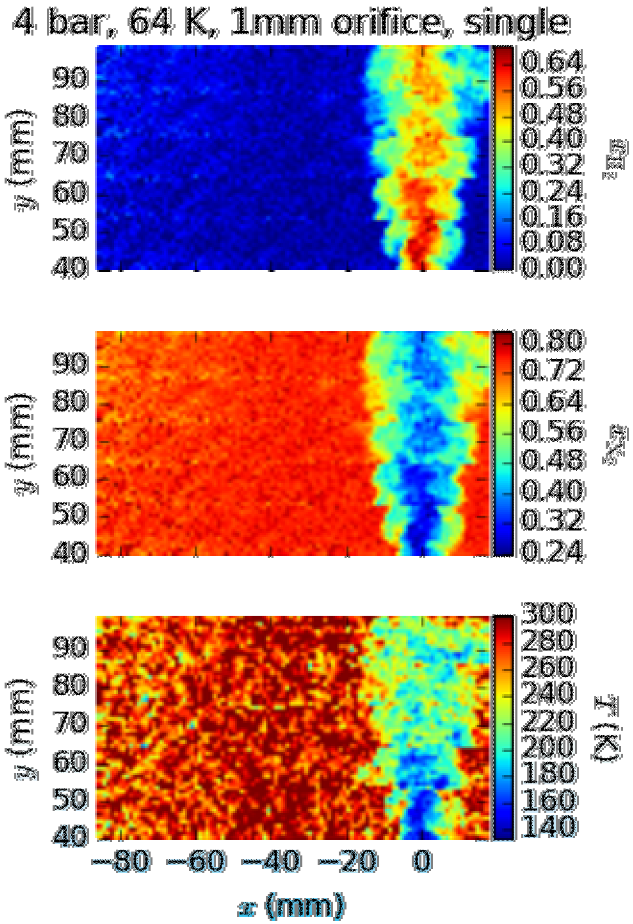




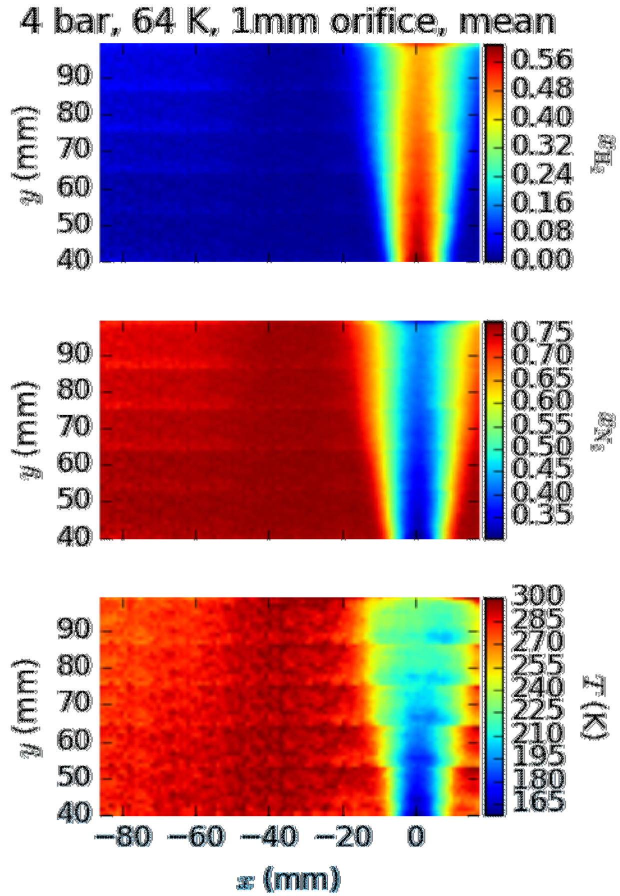
- At temperature below 200 K H_2 plume entrains humid air and condenses water vapor
- Mie scattering from condensed water vapor saturates the camera sensors for Rayleigh scattering
- Raman scattering has significant wavelength shift from laser line

We have begun to map out the concentration of cryogenic hydrogen jets

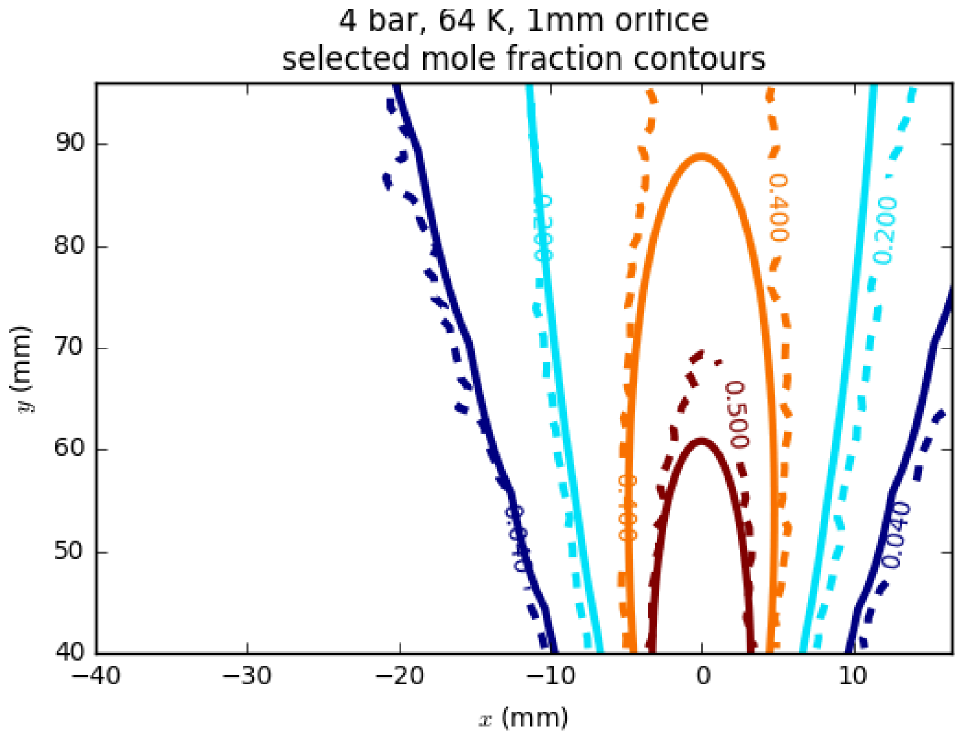
instantaneous information



mean information

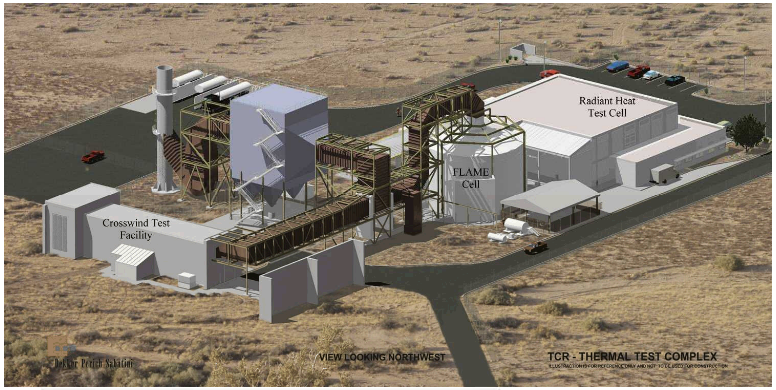


Initial results agree well with the model



- Without tuning empirical model parameters, accurately predicting 4% boundary
- Concentration decay of model is slightly faster than experiment
- Range of pressures and initial temperatures have been measured – data analysis underway

We are planning experiments to answer other scientific questions



Larger releases that involve

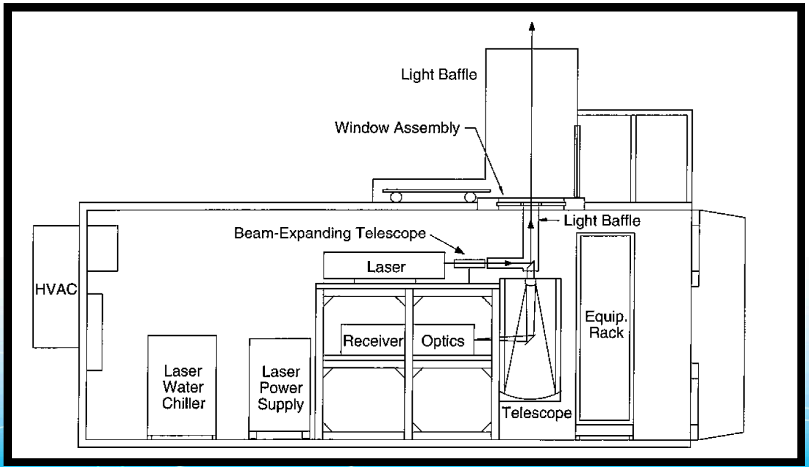
- Pooling
- Evaporation from LH2 pools

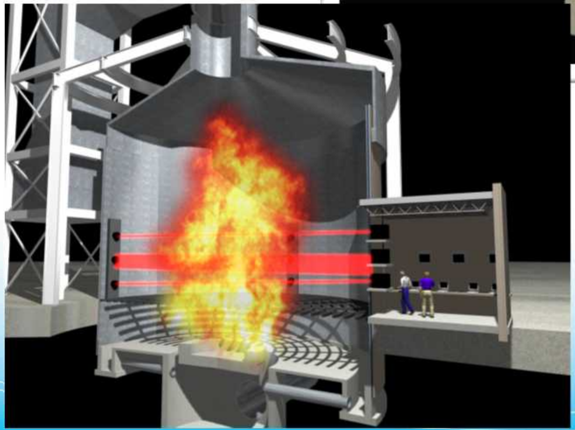
Using Sandia (Albuquerque) facilities

- Thermal test complex
  - Flame cell
    - Up to 3m diameter pool
    - 18.3 m dia. x 12.2 m high
    - Well characterized conditions for model validation
  - Crosswind test facility
    - Dispersion in controlled crosswind
    - Single-direction flow
    - Well-characterized ambient conditions
- Severe Accident Phenomena/Analysis (Surtsey)
  - 100 m^3 pressure vessel with 6 levels of instrumentation ports

Additional diagnostics that have been used by Sandia experts are being considered

- Coherent Anti-Stokes Raman Scattering (CARS)
  - Quantitative species and temperature information
- Particle Imaging Velocimetry (PIV)
  - Quantitative velocity field imaging
- Raman LIDAR
  - Quantitative species, temperature and range





Summary

- Cryogenic hydrogen release laboratory has been used to understand cryogenic hydrogen ignition and flame radiation
  - Ignition distance, flame length, and radiant fraction scale with the same flow variables as for room temperature hydrogen releases
  - Article published: Panda, P, Hecht, E.S. Ignition and flame characteristics of cryogenic hydrogen releases. International Journal of Hydrogen Energy, 42 (2017), pp 775-785. http://dx.doi.org/10.1016/j.ijhydene.2016.08.051
- Raman imaging being used at low temperatures
  - Quantitative mole fraction and temperature imaging
  - Data analysis for a range of pressures and temperatures underway
  - To be written up initially in conference article (International Conference on Hydrogen Safety)
- Initial comparisons of model to experiments shows decent agreement
- Internal flow model available to generate hydrogen conditions where needed (e.g. at the vent stack)
- Planning new, larger scale experiments in the coming years
  - Study pooling and evaporation
  - Effect of cross-winds and humidity
  - Making decisions on diagnostics needed and facilities to be used

Acknowledgements

- United States Department of Energy, Energy Efficiency & Renewable Energy, Fuel Cell Technologies Office, Safety, Codes, and Standards subprogram managed by Will James
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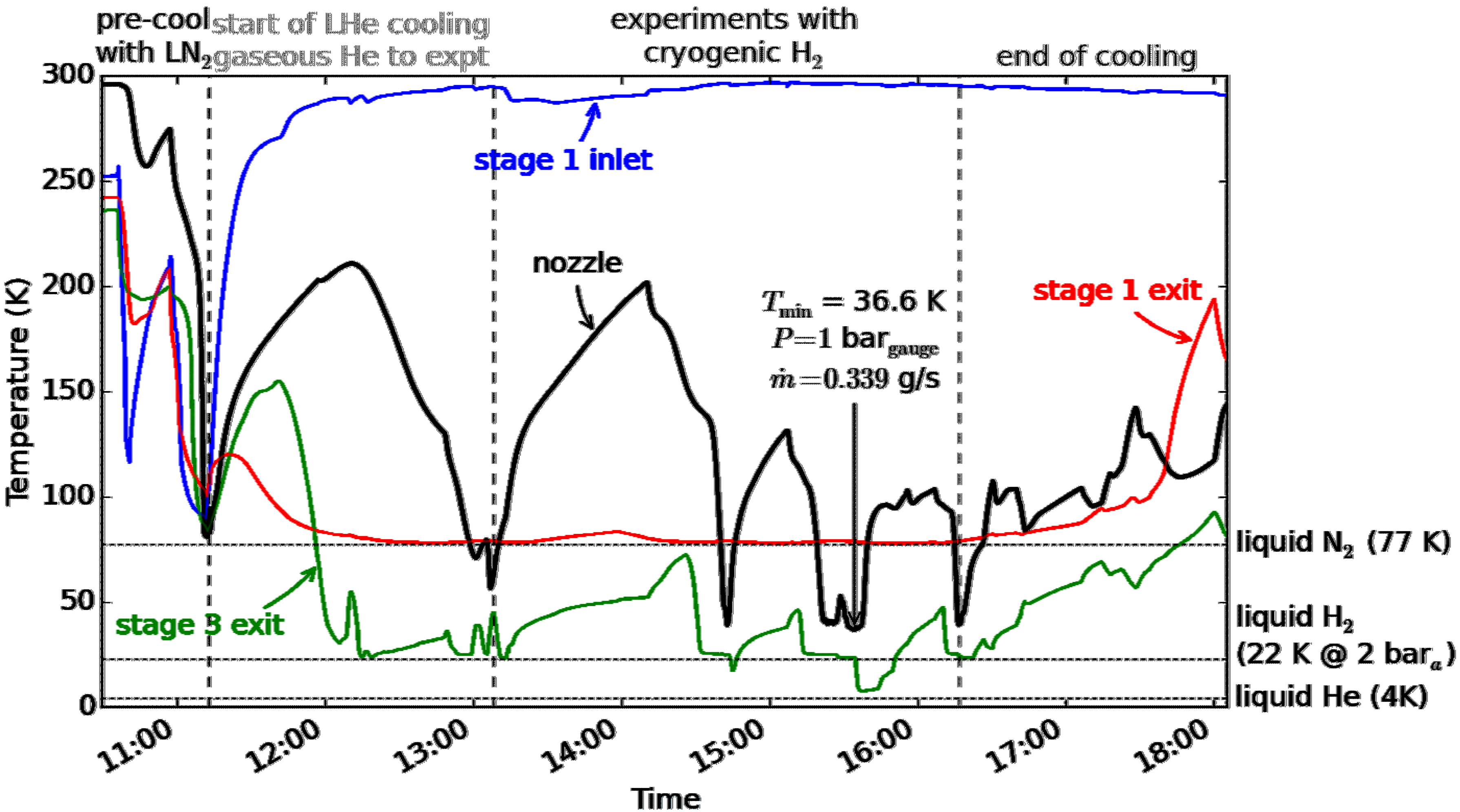
- Previous researchers: Pratikash Panda, Isaac Ekoto, Adam Ruggles, Bob Schefer, Bill Houf, Greg Evans, Bill Winters
- Team Members: Myra Blaylock (CFD), Jon Zimmerman (H_2 program manager), Chris San Marchi (materials/metal interactions with H_2), Chris LaFleur (Risk, Codes & Standards), Katrina Groth (QRA), John Reynolds (HyRAM), Nalini Menon (polymer interactions with H_2), Rad Bozinoski (Modeling), Alice Muna (Risk), Tony McDaniel (Behaviors)

Hydrogen was cooled to a liquid and released in the laboratory



- Experimental challenges include avoidance of freezing air and hydrogen

(Air) icing at the nozzle for temperatures < 50K