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Validation data for cryogenic hydrogen releases and flames

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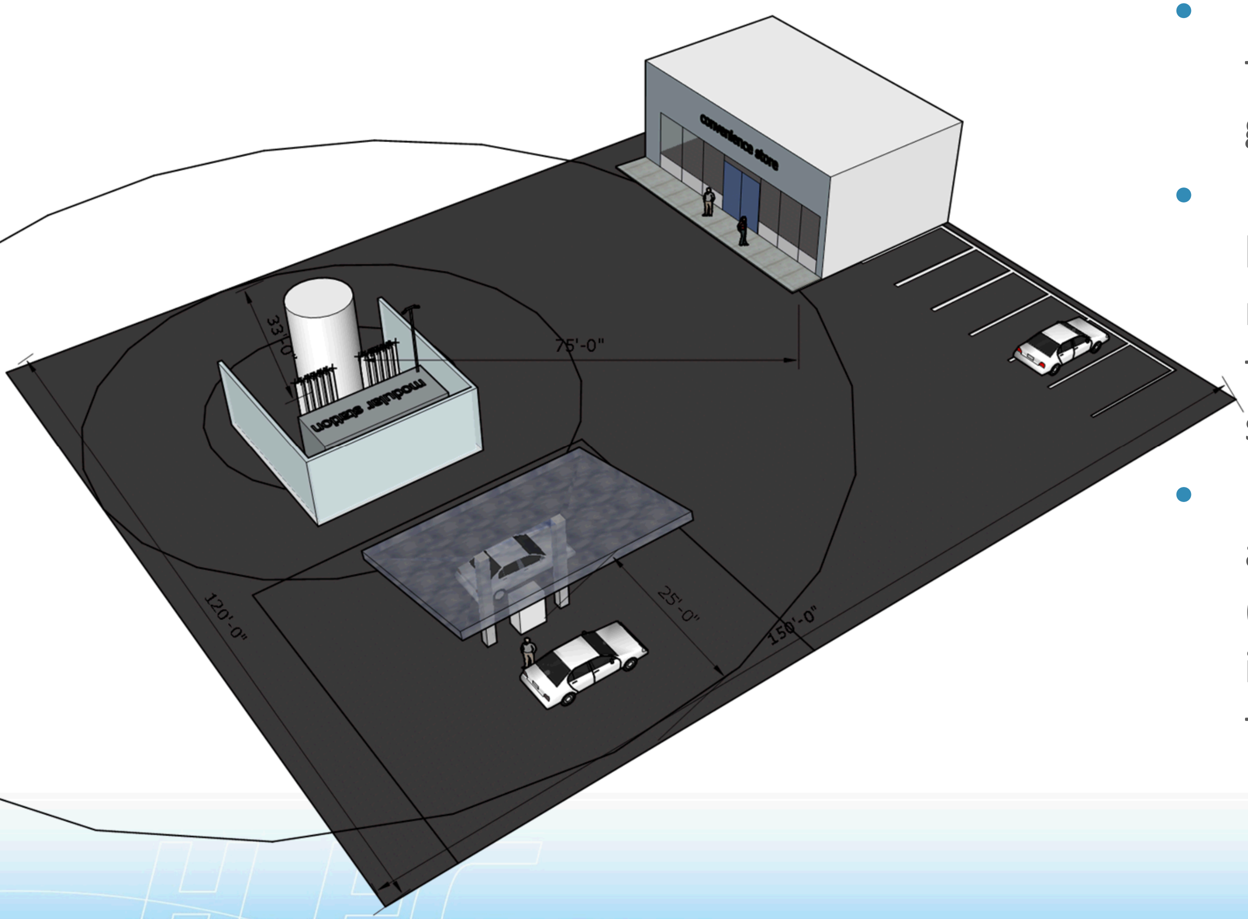
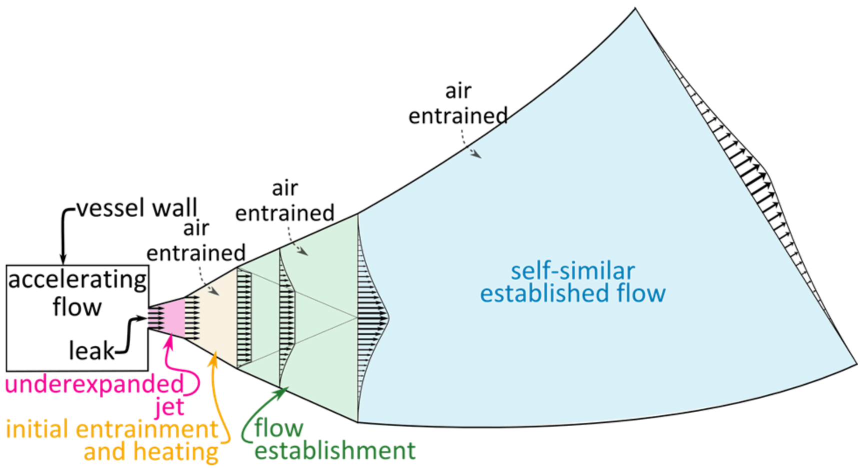
We are trying to provide a scientific basis for liquid hydrogen separation distances

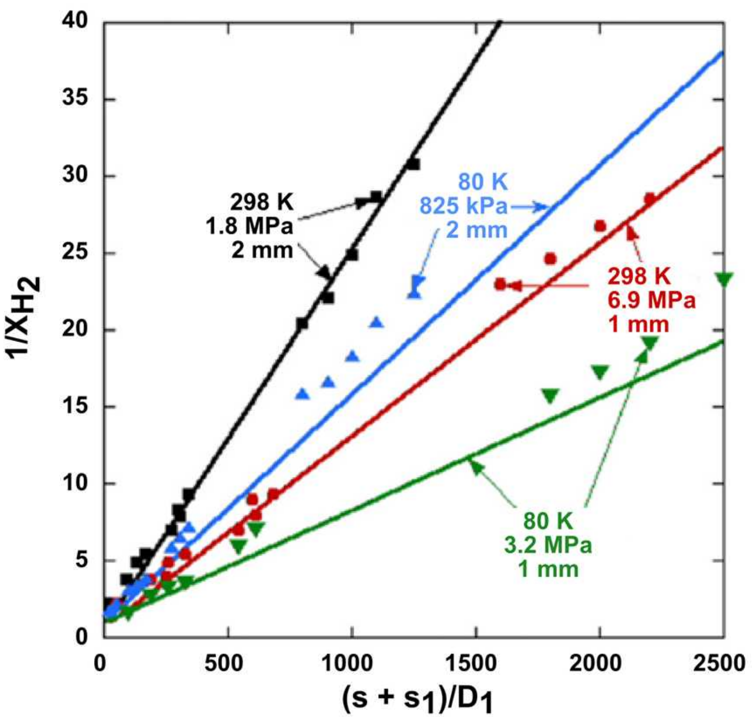


- Previous work by this group led to science-based, reduced, gaseous H_2 separation distances
- Higher energy density of liquid hydrogen over compressed H_2 makes it more economically favorable for larger fueling stations
- Even with credits for insulation and fire-rated barrier wall 75 ft (22.9 m) offset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

1-dimensional model (with buoyancy) needs validation data



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

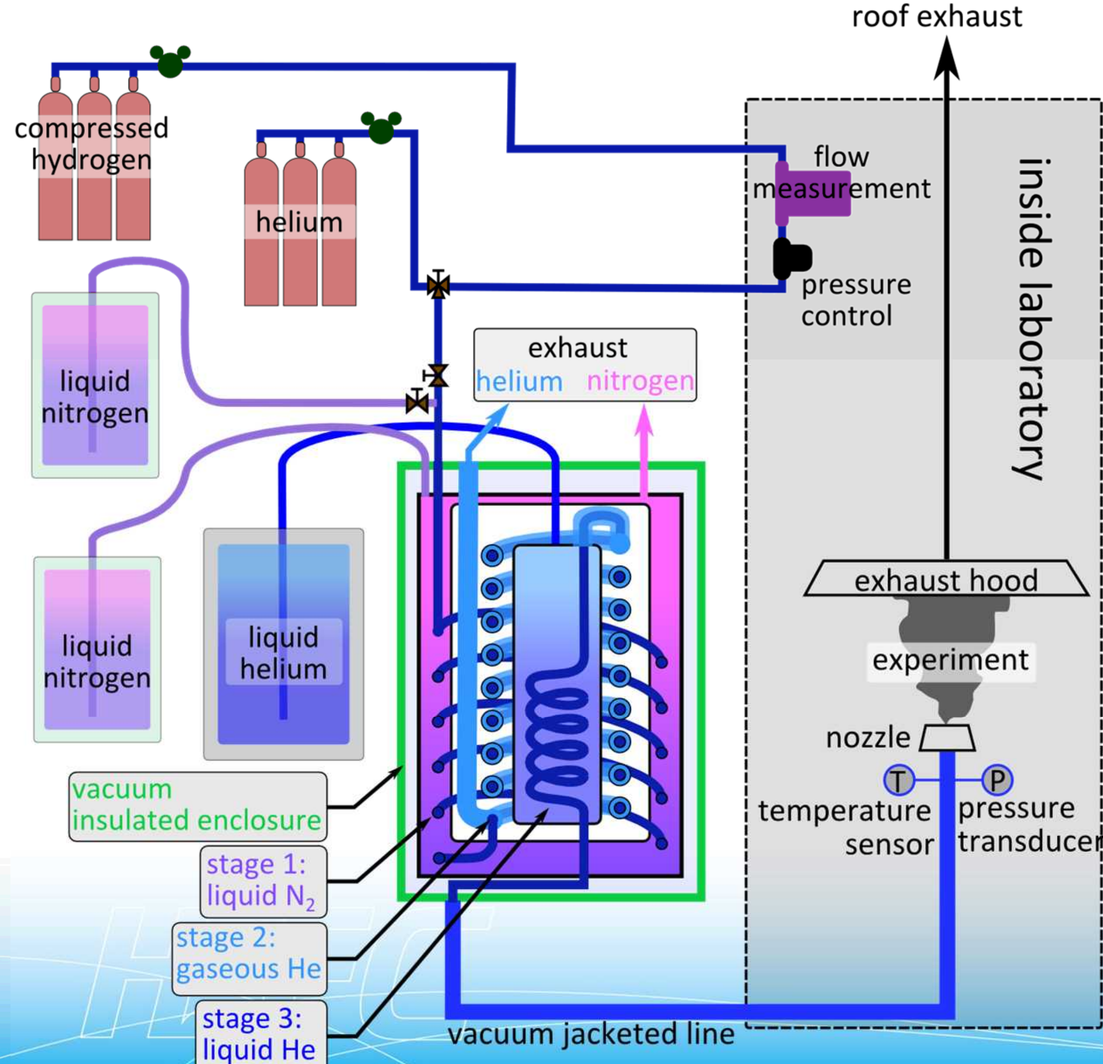


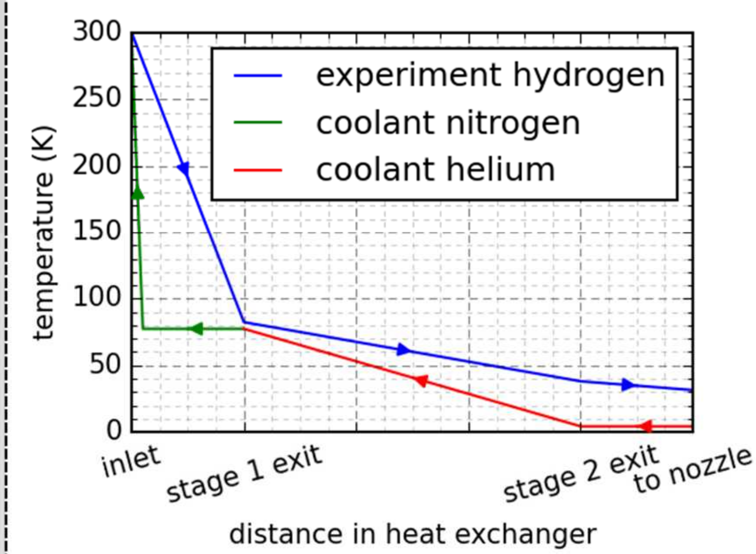
Xiao et al, IJHE, 2011
Houf & Winters, IJHE, 2013

Model will be exercised for some high priority scenarios identified by the NFPA 2 code committee

- ❑ 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
- ✓ 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

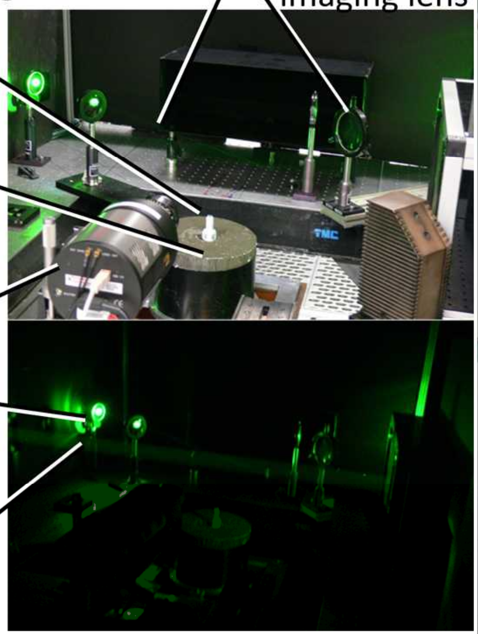
We are running an experiment, releasing ultra-cold hydrogen in the laboratory

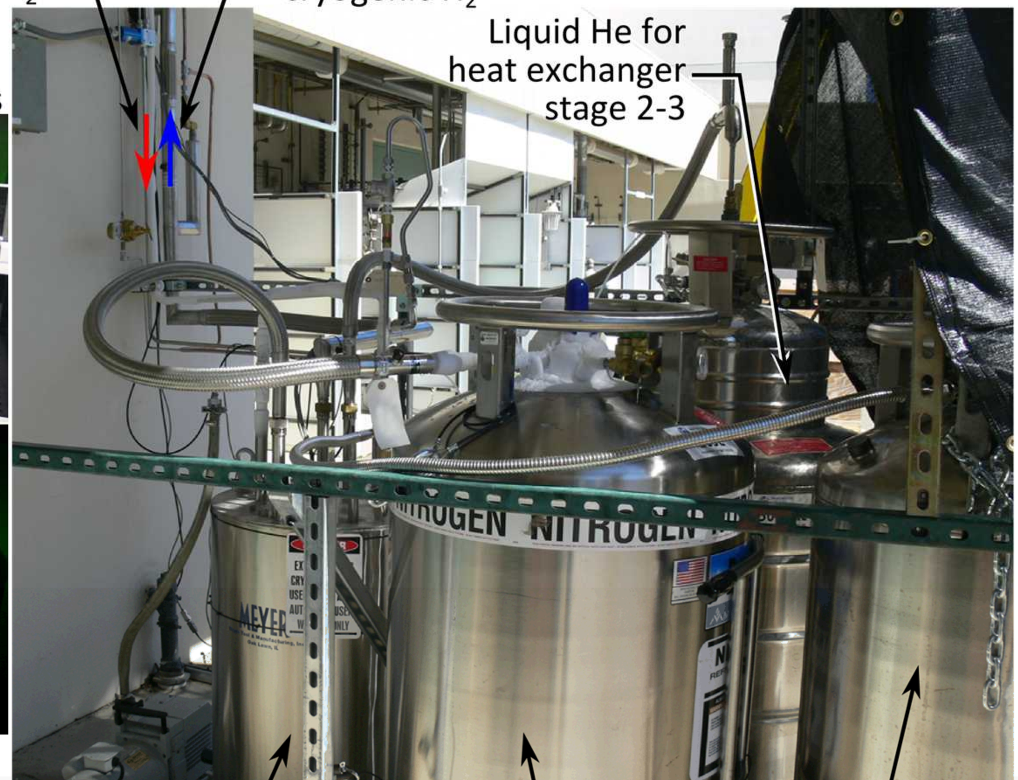




- Accurate control/measurement of boundary conditions

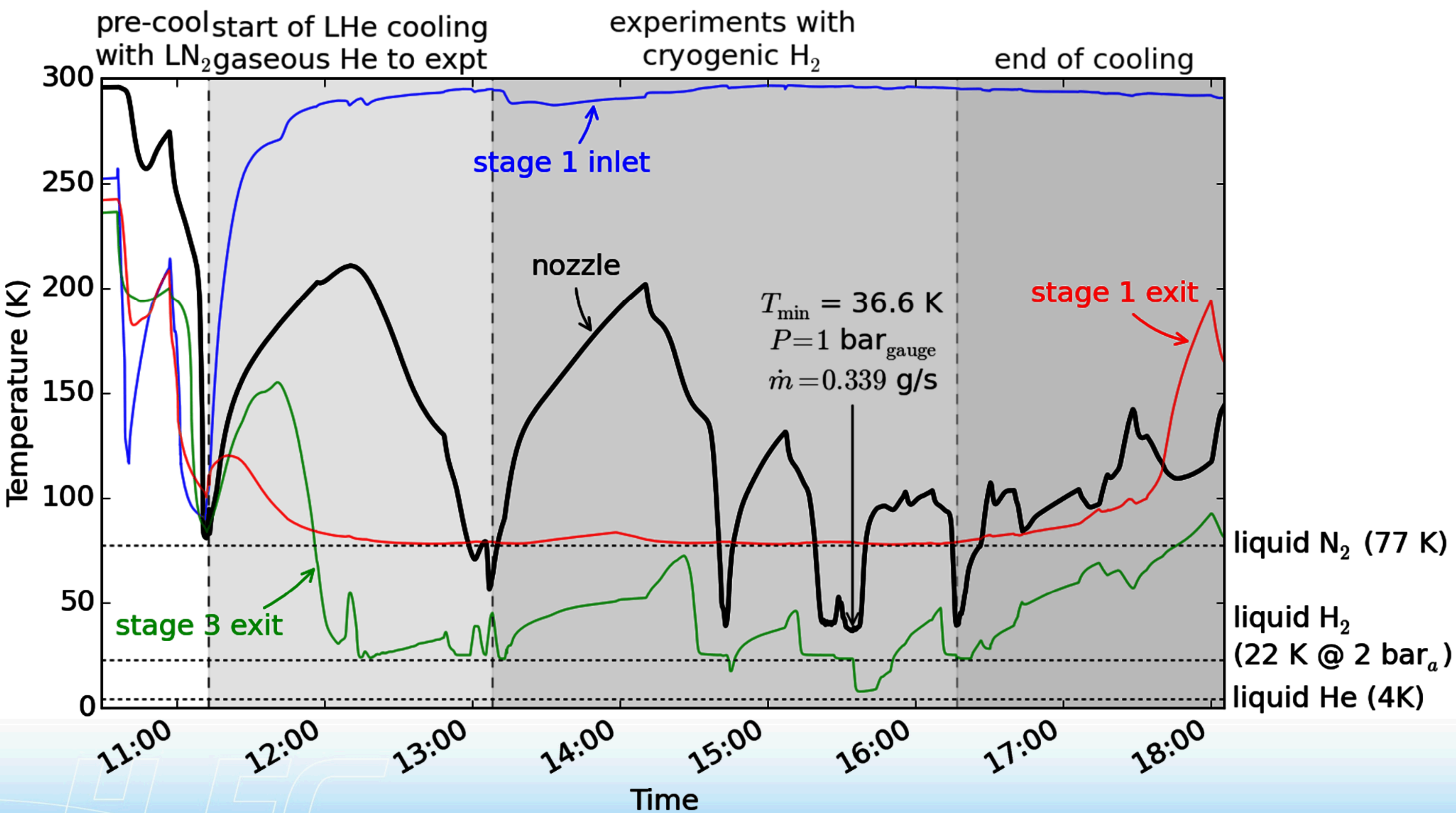
We have applied Schlieren imaging and used a laser spark to ignite ultra-cold releases





- Multiple diagnostics are used to precisely characterize releases

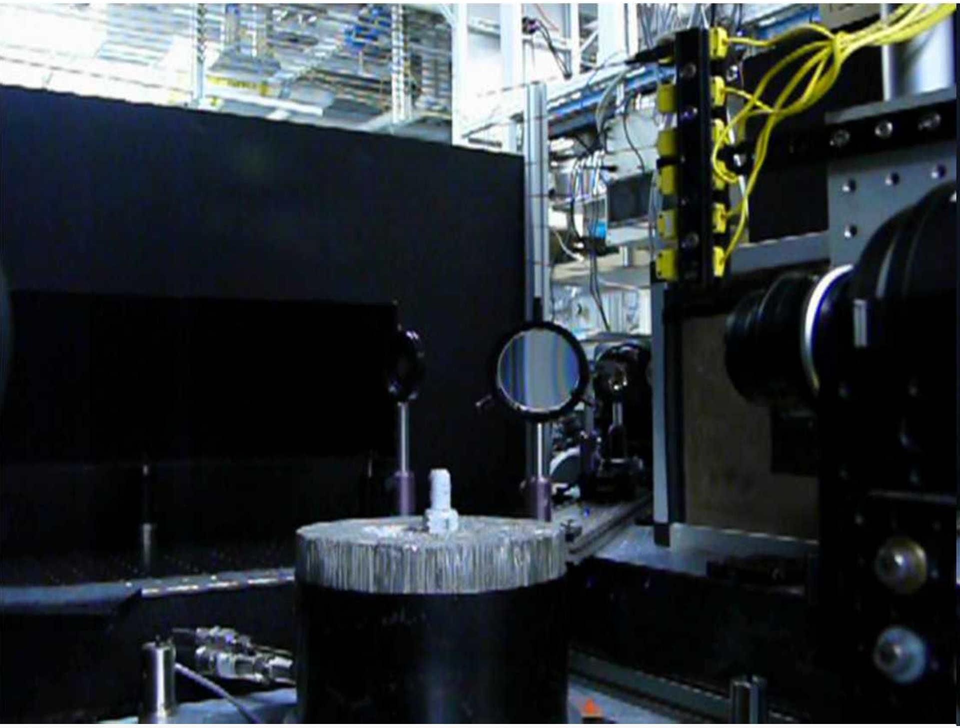
Hydrogen was cooled to a liquid and released in the laboratory



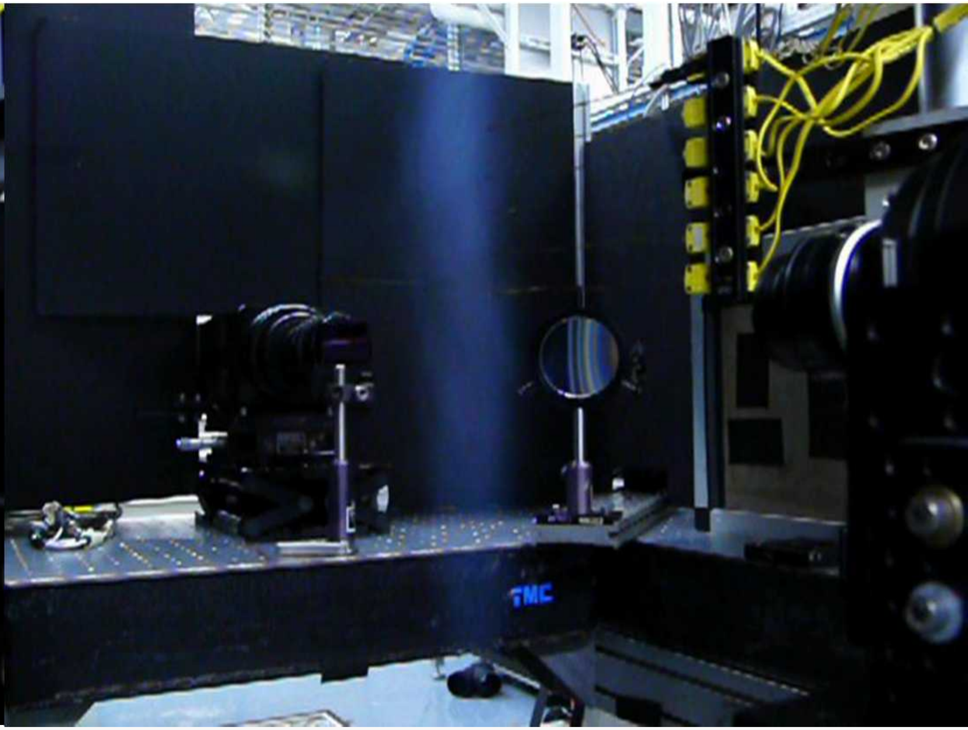
- Experimental challenges include avoidance of freezing air and hydrogen

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

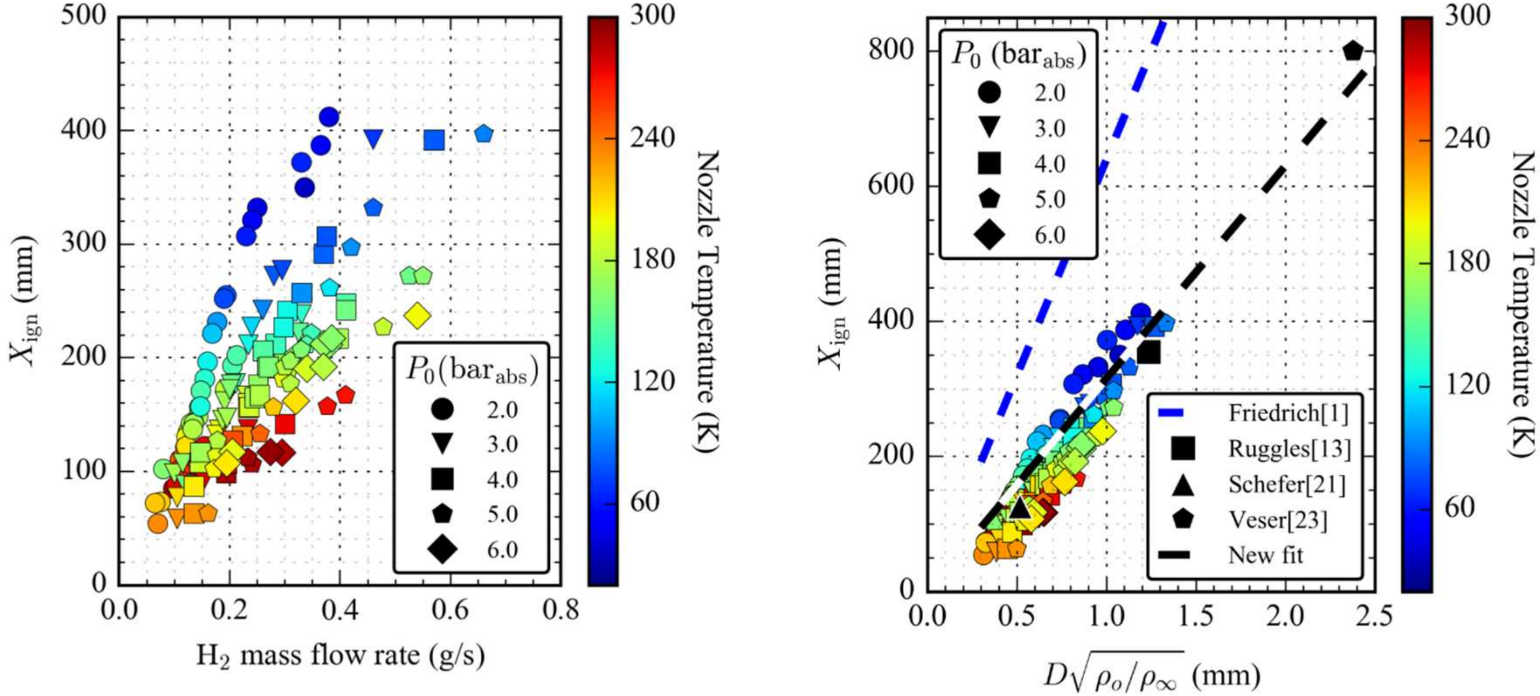


P = 1 bar, T = 37 K, distance = 325 mm



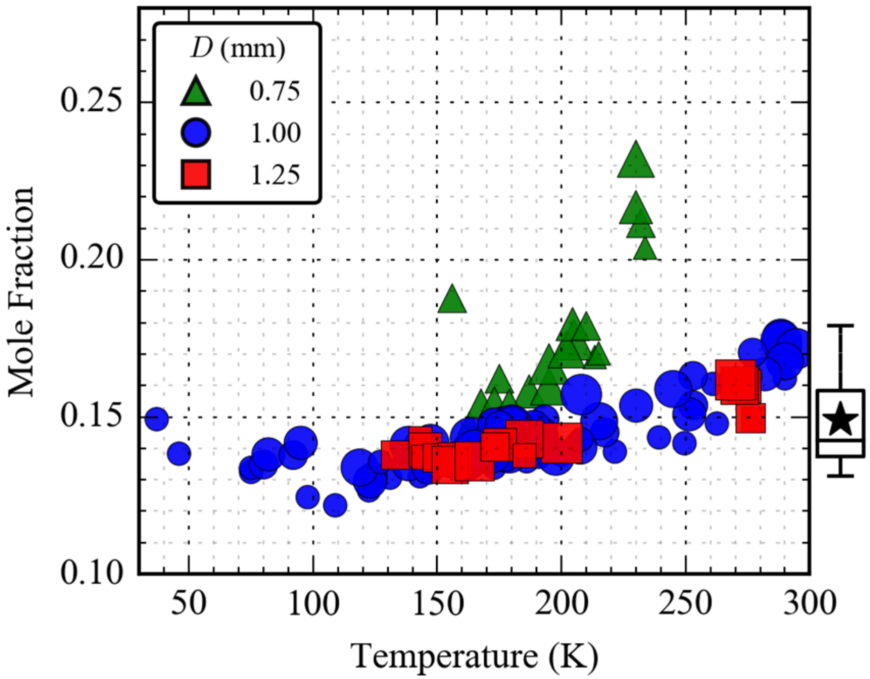
- Entrained moisture (and possibly air) condenses in the cold flow

The maximum ignition distance scales with the effective diameter



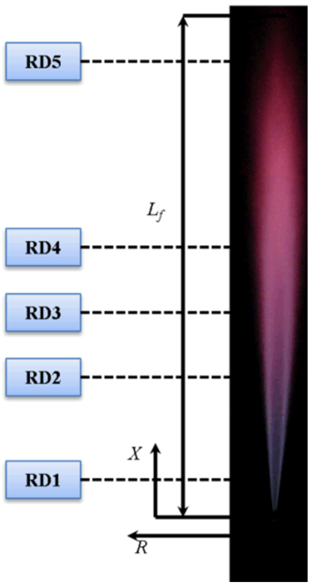
- for a given mass flow, ignition of cold H_2 occurs much further from the release point
- temperature affects ignition distance much more than pressure
- a maximum ignition height is achieved at a lower mass flow rate of hydrogen for the colder jets
- Maximum ignition distance linearly varies as a function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

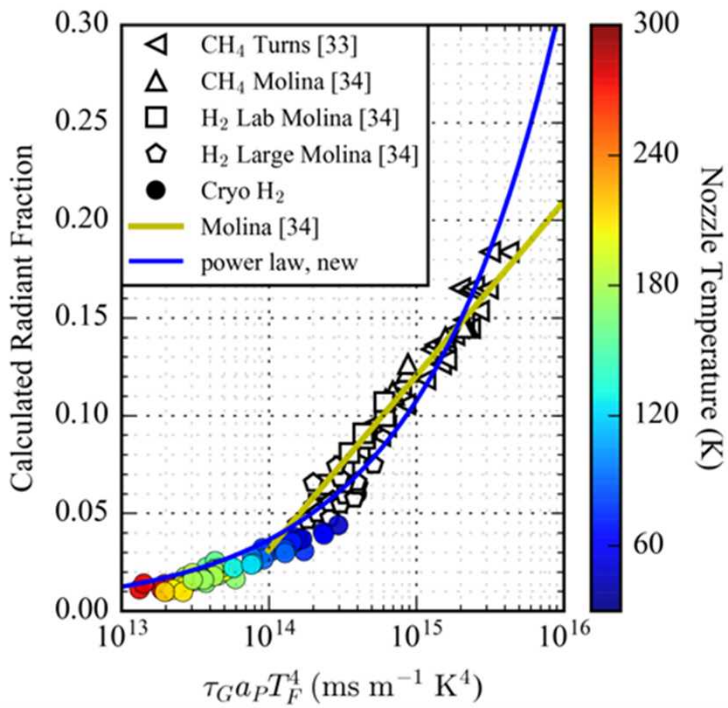
Simulations (using the unvalidated model) predict the mole fraction at the ignition point



- 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



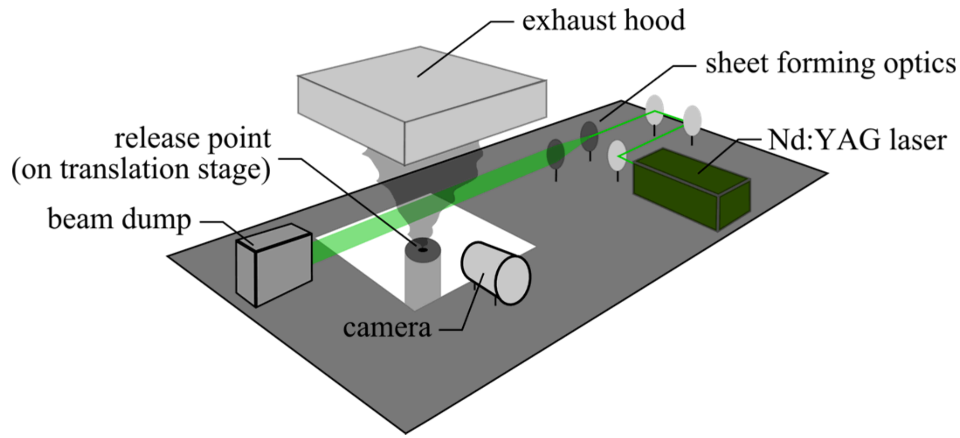


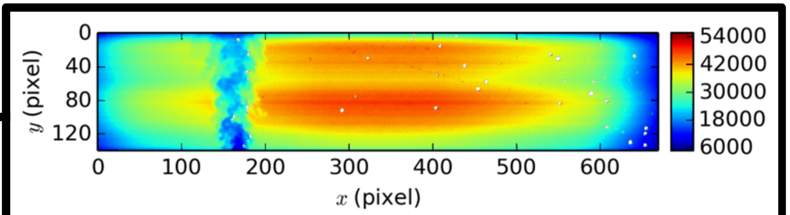
- Radiometers placed at 5 axial locations along the flame length to measure radiative heat flux
- Hydrogen flames have lower radiant heat flux compared to methane or syngas flames
- An increase in radiant fraction is observed for the colder H_2 jets due to longer flame residence time

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

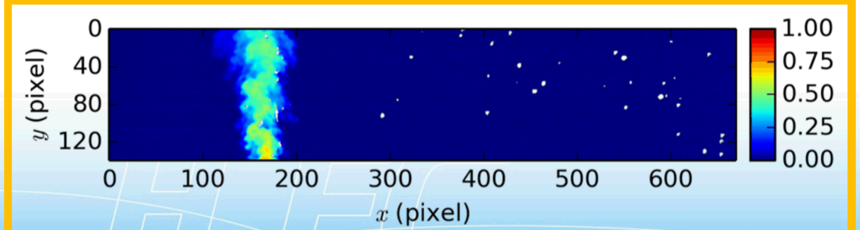
R:	Raw image
B_G:	Background luminosity
p_F:	Laser power fluctuation
O_R:	Camera/lens optical response
S_B:	Background scatter
S_t:	Laser sheet profile variation
I:	Corrected intensity

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

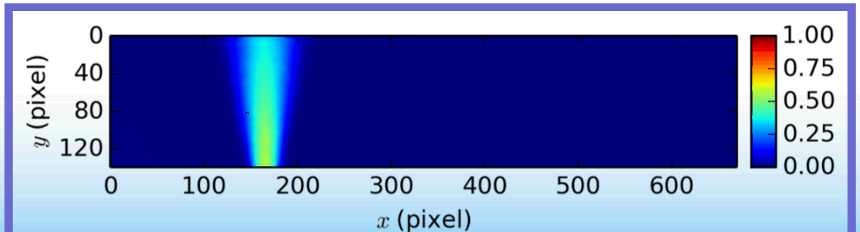




Mole Fraction $(\chi_{H2}) \propto I$



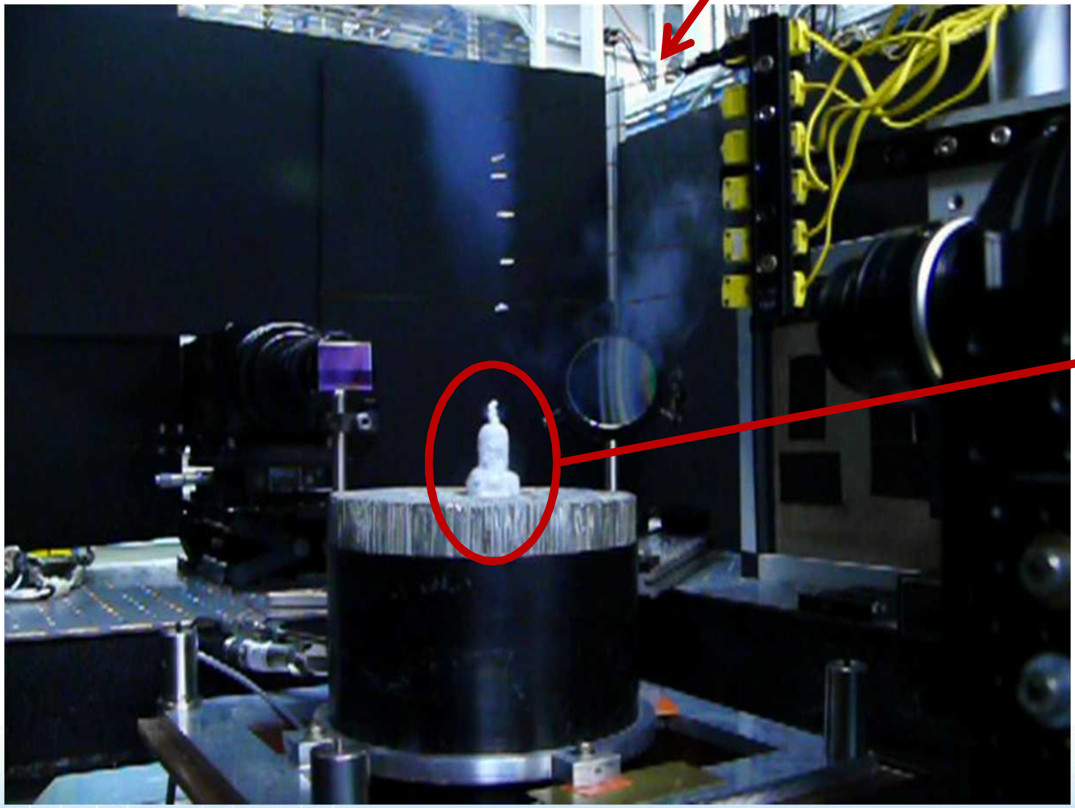
Instantaneous

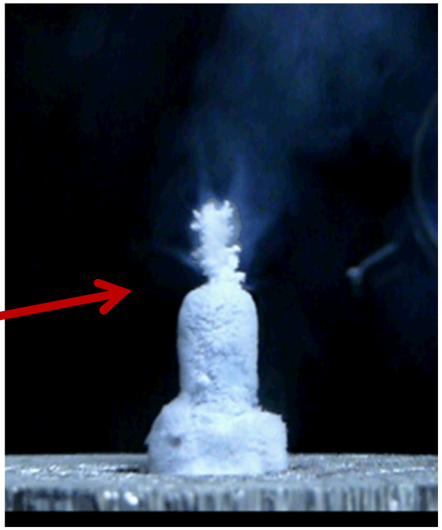


Mean

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

Array of thermocouples measuring the plume temperature

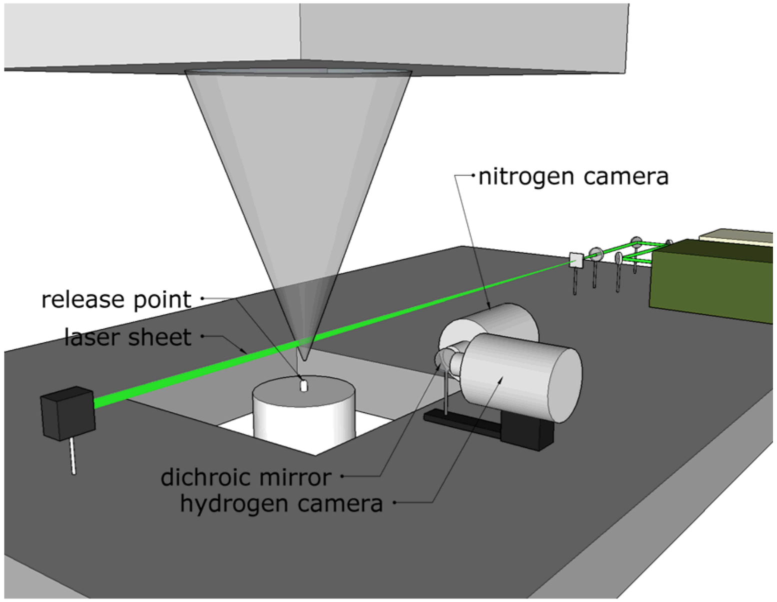




(air, moisture?) icing around liq. H_2 jet column

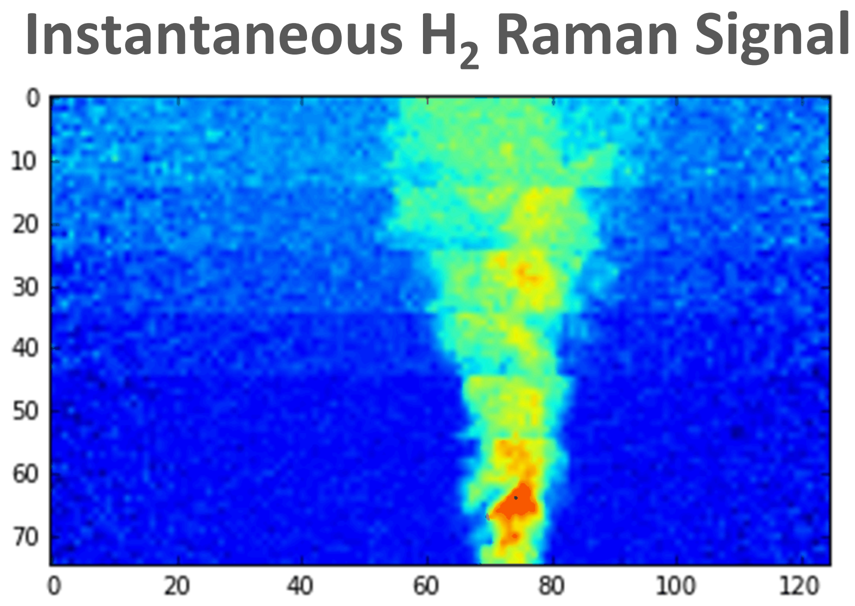
- Challenging to provide sufficiently dried air while maintaining experimental integrity

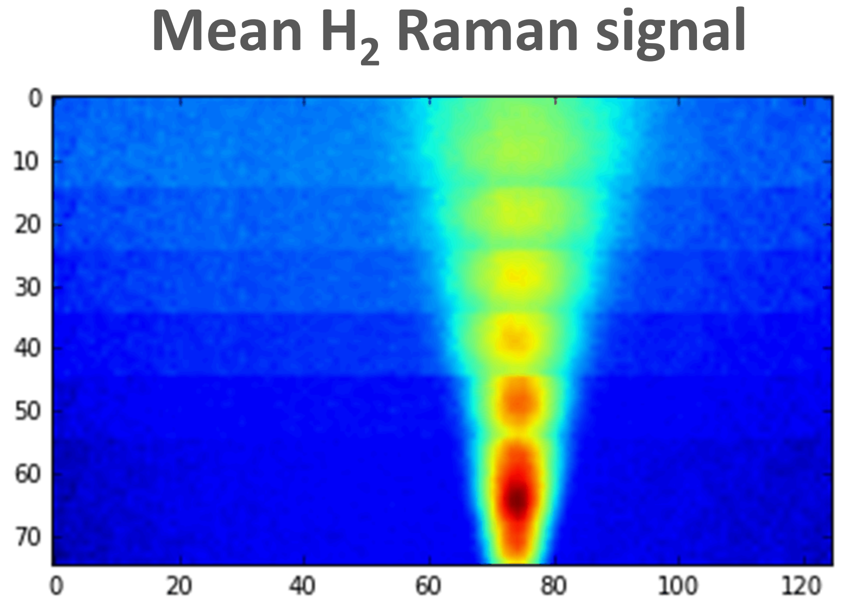
Currently implementing Raman scattering to measure concentration field



- 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

Initial Raman data has good signal, even at low temperatures with significant condensation



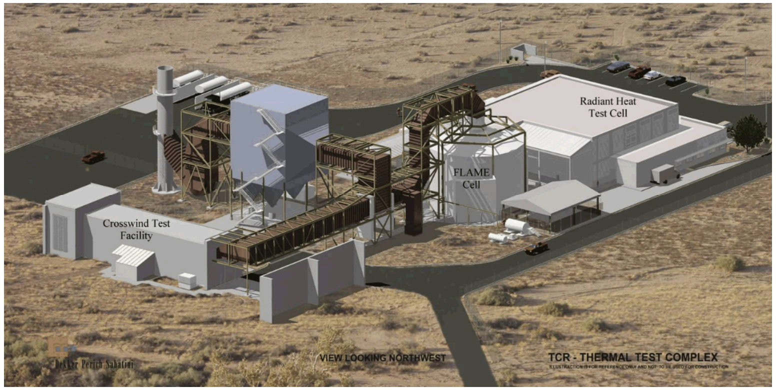


Temperatures from 140K (-133 °C, -208 °F) -176K (-97 °C, -143 °F)

Planning begins this fiscal year for new experiments in the coming years

Large scale releases will be used to study other phenomena needed for NFPA 2 high-priority scenarios

- Thermal test complex at Sandia Albuquerque
  - Flame cell
    - Up to 3m diameter pool
    - 50 ft. tall indoor cell
    - Well characterized ambient conditions
      - Humidity
      - Water-cooled walls
  - Crosswind test facility
    - Dispersion in controlled crosswind
    - Single-direction flow
    - Well-characterized ambient conditions



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 in press: Panda, P, Hecht, E.S. Ignition and flame characteristics of cryogenic hydrogen releases. International Journal of Hydrogen Energy, 2016. http://dx.doi.org/10.1016/j.ijhydene.2016.08.051.
- Trying to make concentration measurements (ideally optically in 2D)
  - Raman imaging (lower signal, will require averaging, lower experimental exactness)
  - If unsuccessful, extractive probe (can affect flow field, point measurement, average concentration only)
- Concentration measurements will be used to validate/further develop model
- Developing internal flow model to understand phase transitions and heat transfer in tubes
- Planning new, larger scale experiments in the coming years
  - Study pooling and evaporation
  - Effect of cross-winds and humidity

Acknowledgements

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