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Cryogenic hydrogen behavior

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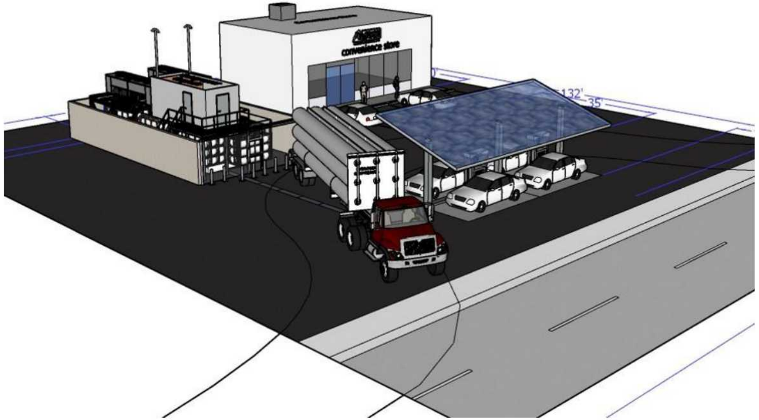
Current separation distances for liquid hydrogen systems in the U.S. are based on consensus rather than a comprehensive scientific basis

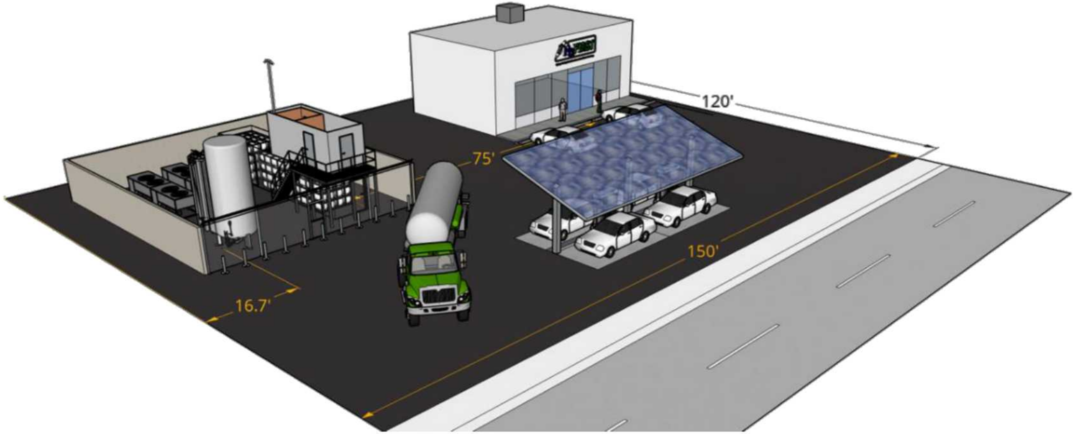
Compressed H_2 storage

- Previous work by Sandia led to science-based gaseous H_2 separation distances



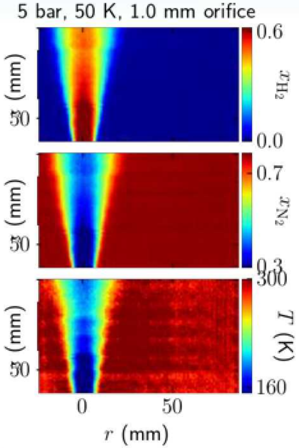
Liquid H_2 storage

- Even with credits for insulation and fire-rated barrier wall, 75 ft. offset to building intakes and parking make footprint large

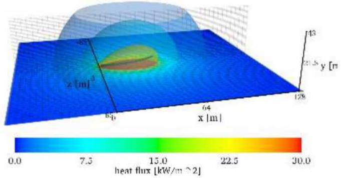


Sandia H_2 Safety Codes and Standards research includes coordinated activities that facilitate deployment of hydrogen technologies

- Hydrogen Behavior
  - **Develop and validate scientific models** to accurately predict hazards and harm from liquid releases, flames, etc.
- 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
- Enable Hydrogen Infrastructure through Science-based Codes and Standards
  - **Apply QRA and behavior models to real problems** in hydrogen infrastructure and emerging technology
  - **Facilitate updates to NFPA 2** through deep technical analyses

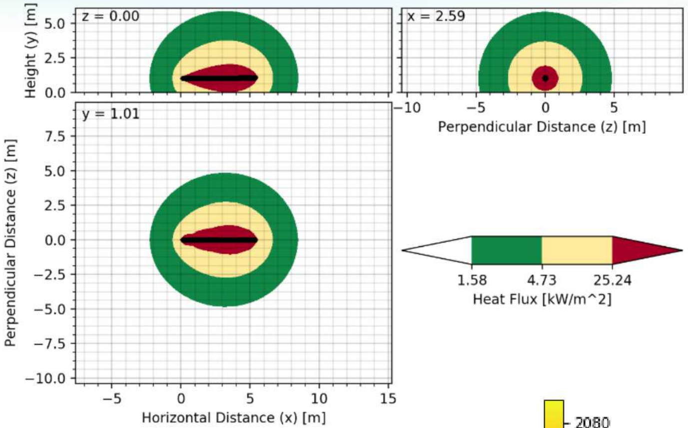


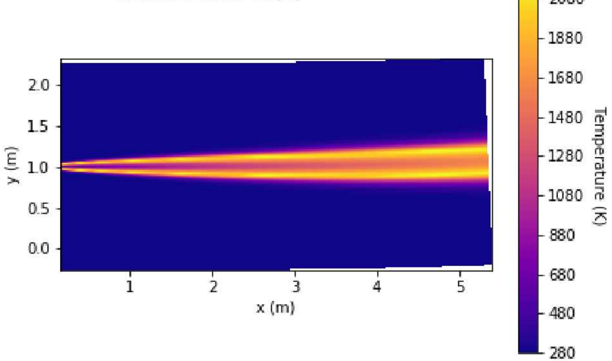
HyRAM
HYDROGEN RISK ASSESSMENT MODELS

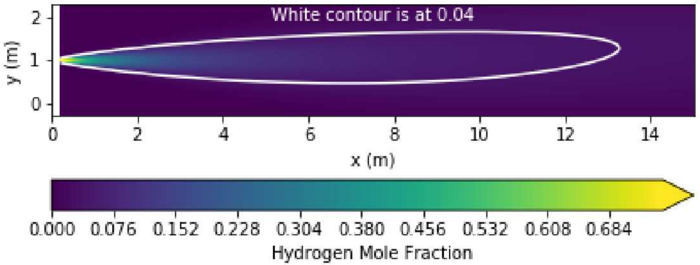


A variety of validated physical models are used in HyRAM – valid models for LH_2 are needed

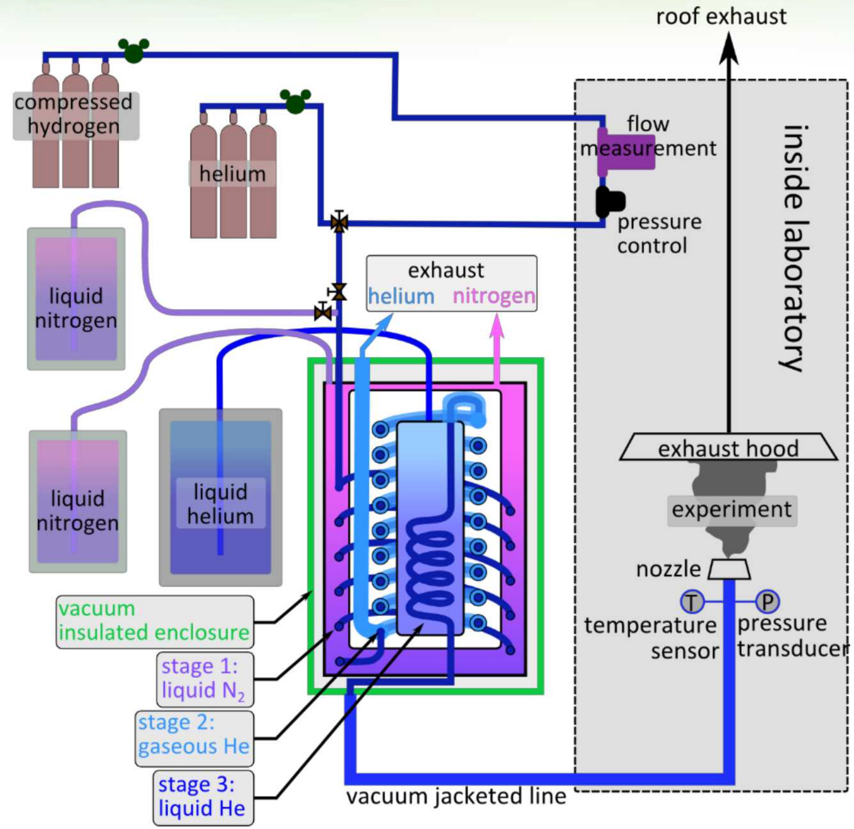
- Unignited dispersion
  - Distance to certain concentration
- Flame model
  - Temperature field
  - Heat flux field
- Overpressure for delayed ignition of indoor releases





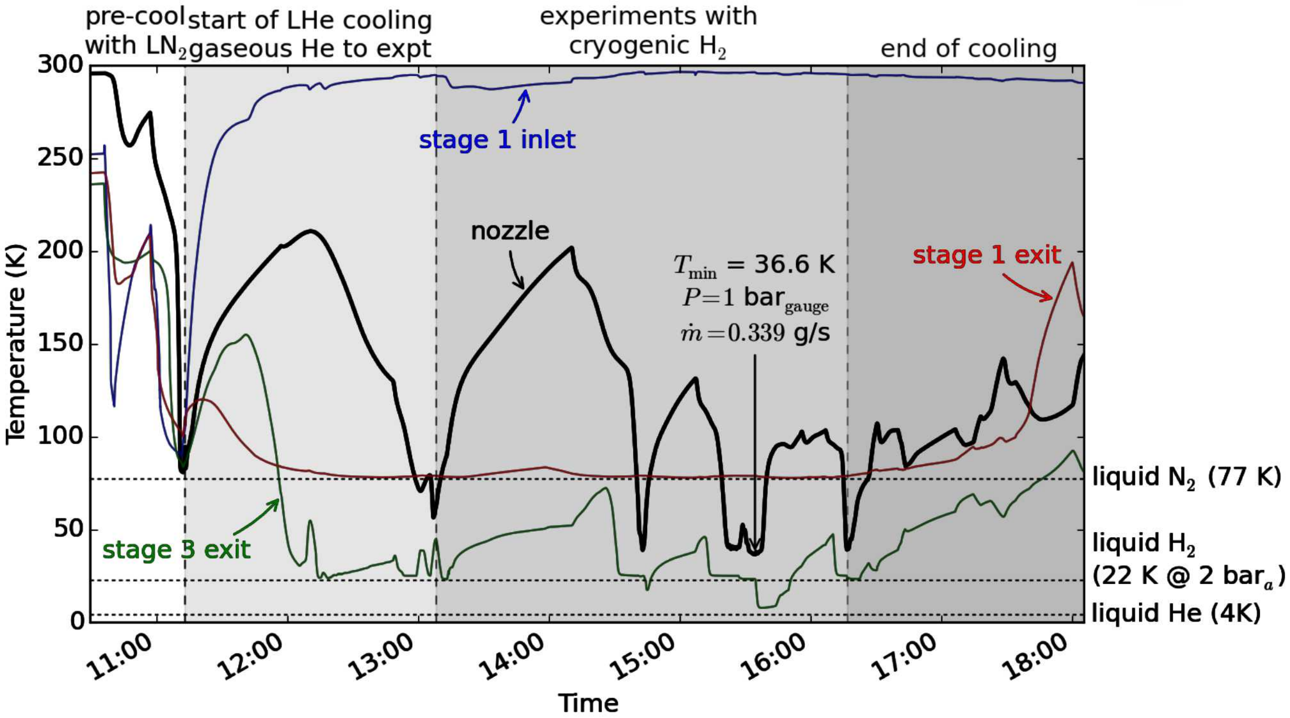


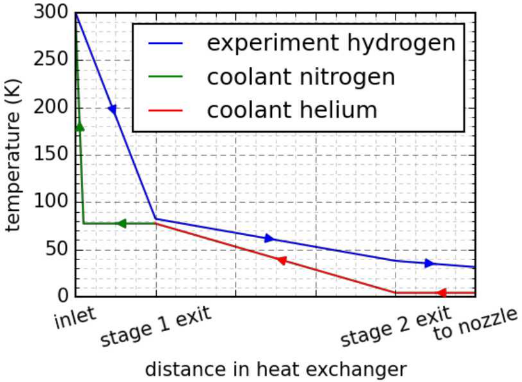
Our laboratory experiment uses a heat exchanger to liquefy hydrogen



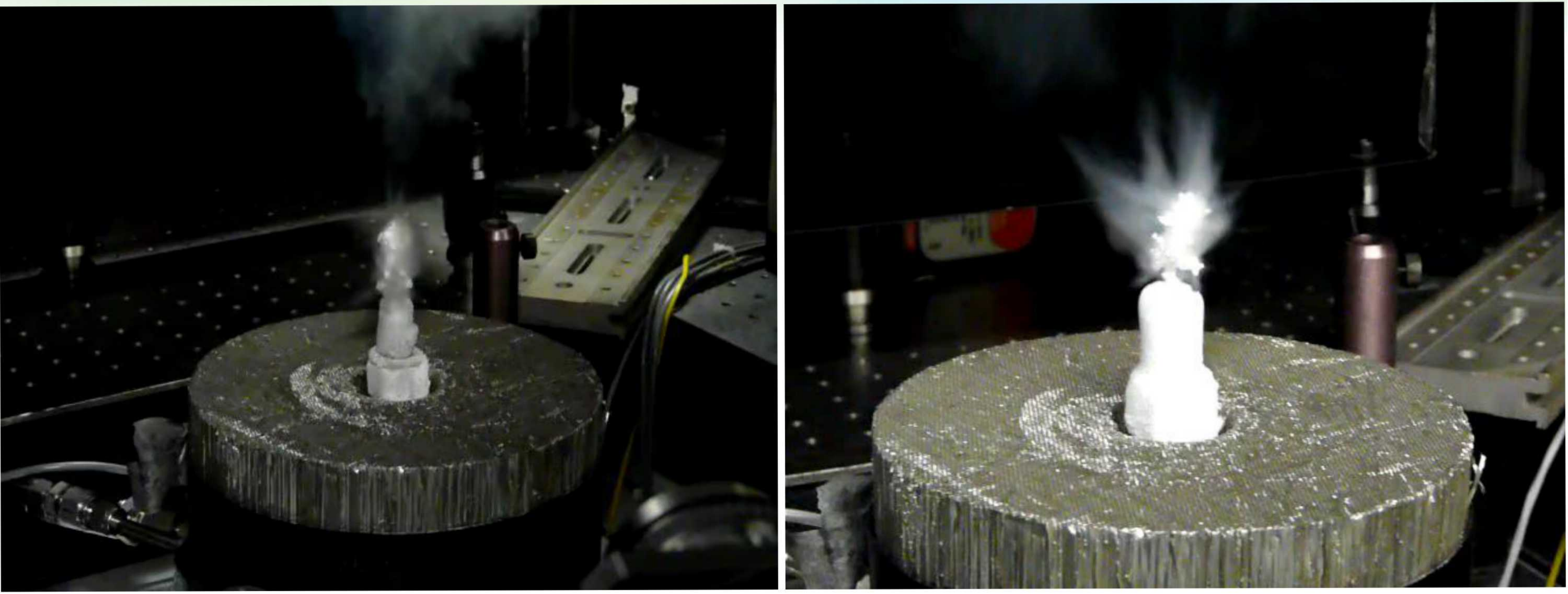
- Gaseous hydrogen is liquefied using liquid nitrogen and liquid helium
- Flow rate is measured as a gas using a thermal mass flow meter
- Nozzle pressure is controlled upstream of heat exchanger
- Silicon diode temperature sensors

We can reach nozzle temperatures below 40 K



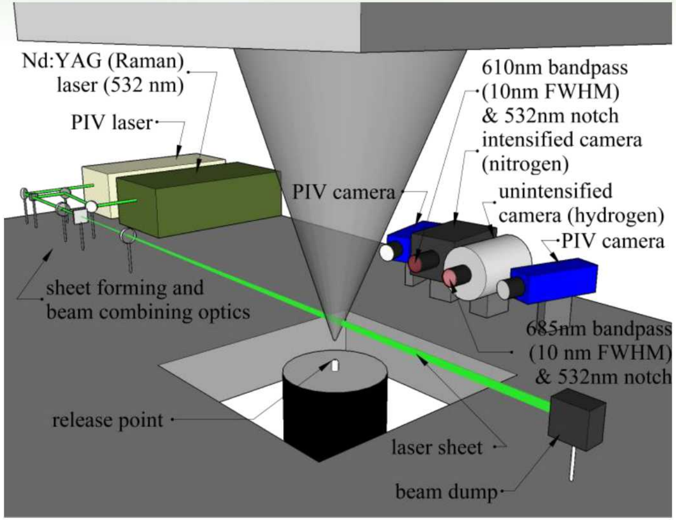


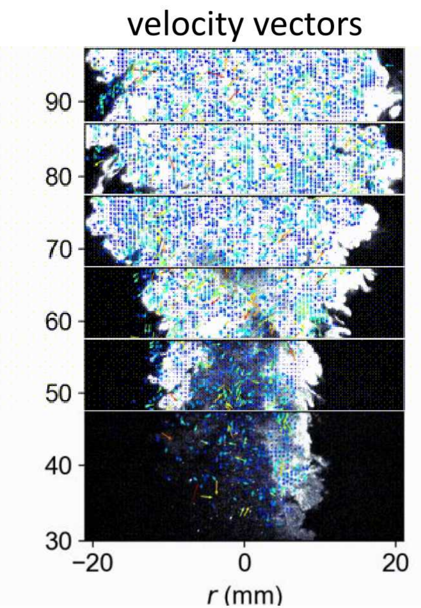
Moisture and air freeze on the nozzle as the temperature drops

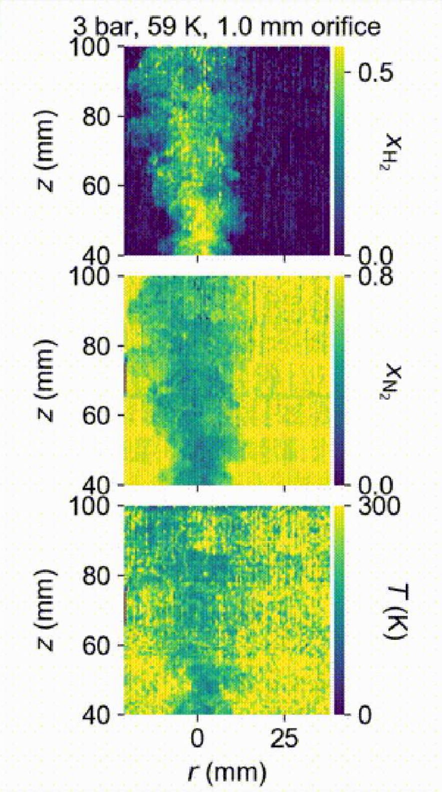


Air and moisture icing around liquid H_2 jet column – improves dispersion and reduces hazard distance

H_2-N_2 Raman imaging and particle imaging velocimetry are used to measure concentration, temperature, and velocity of cryogenic H_2

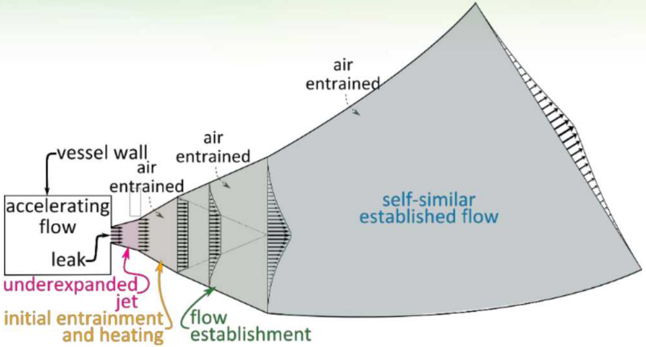


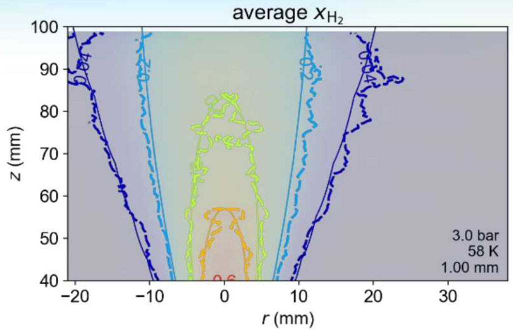


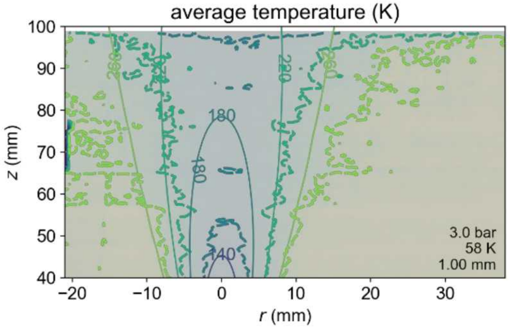


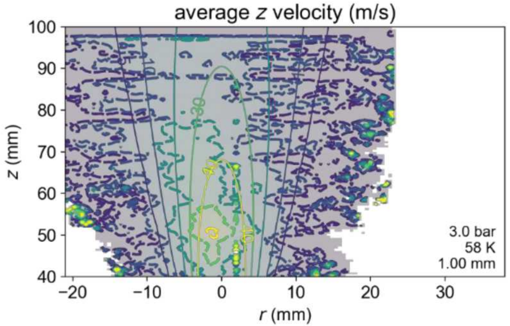
Independent model parameters:
- ✓ T - temperature
- ✓ x - mole fraction
- ✓ v - velocity
- ✓ B - halfwidth (both velocity and concentration)

The ColdPLUME model shows good agreement with the data







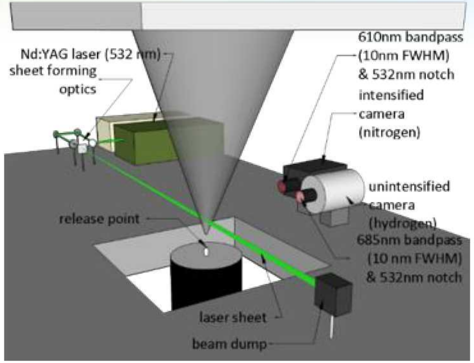


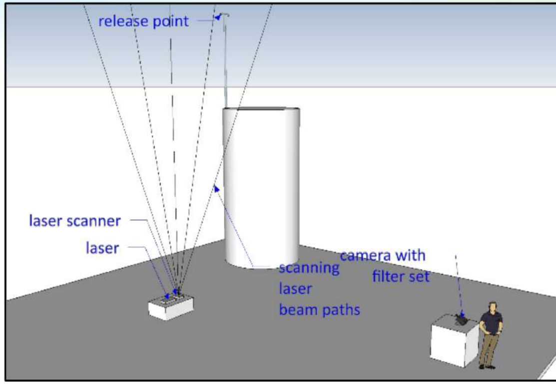
- Experimental results shown by shading and thick, dashed lines
- ColdPLUME model results are thin, solid lines

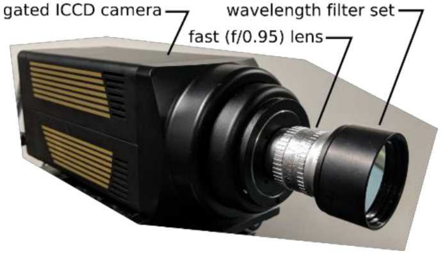
➢ Model accurately simulates mole fraction, temperature, and velocity -- can be used as a predictive tool

The diagnostic will be modified to study LH_2 vents and large-scale experiments

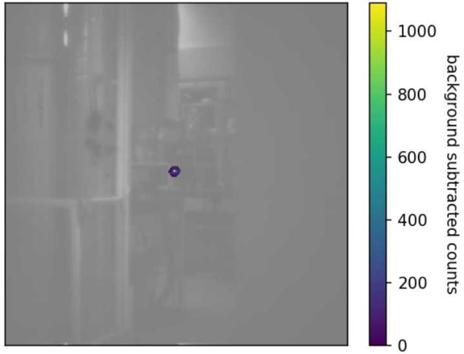
- Demonstrated acceptable signal to noise for large-scale diagnostic
- Uniquely fast optics enable collection of small Raman signal
- Imaged hydrogen from 40 foot standoff distance in the laboratory
- Observed nearly 30 degree field of view (20 ft scene from 40 ft distance)





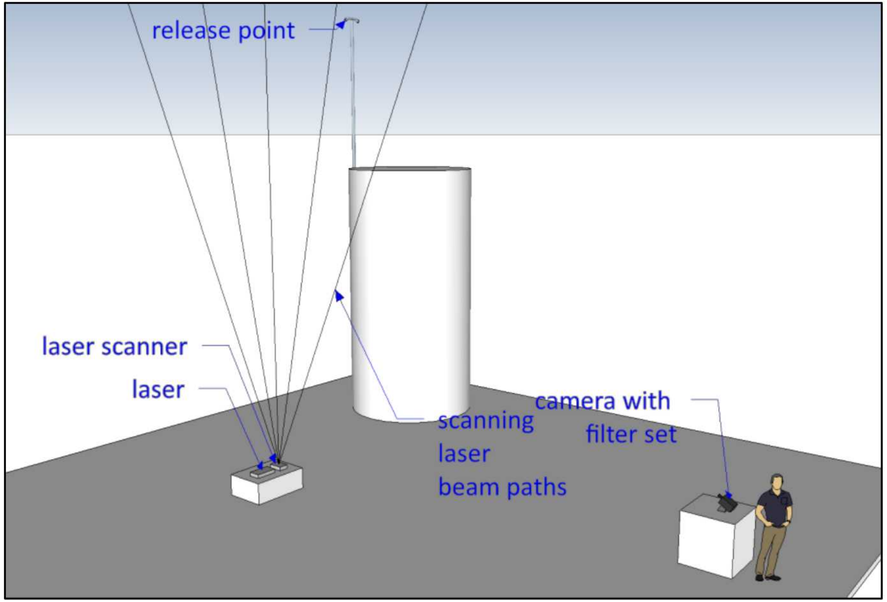


Raman signal overlaid on laboratory scene



We have strategies for illumination of large-scale scene

- On-camera accumulation will provide a complete snapshot of the plume with reasonable resolution
- Effective background light suppression is key (both sunlight and illumination source that reflects off of condensed water vapor)
  - Time gating
  - Spectral gating
- High-powered light source required to excite as many molecules as possible
  - High-power laser scanning in space
  - Concentrations measured along a series of lines
  - 1st generation: galvanometer scanning a 10 Hz laser
  - 2nd generation: high speed polygonal scanning using pulse-burst laser



We are working with our colleagues at LLNL to perform LH_2 vent stack releases

- Additional temperature sensors along vent stack to validate internal flow model
- May require additional plumbing changes
- Replacing bull-horn with single outlet to enable model comparisons
- Variations in temperature, flow-rate, and external conditions (e.g. wind) in experiments
- Comparison to NREL sensor approach for some tests
- Late summer 2019

Petitpas & Aceves, IJHE 43: 18403-18420: https://doi.org/10.1016/j.ijhydene.2018.08.097

- ➢ Heaters and pump enable a wide range of flow rates and temperatures at vent stack
- ➢ Proximity to SNL enables experiments to be run on short notice (when weather is right)

Remaining challenges: Executing outdoor experiments and planning additional large-scale experiments

Ensure safety when operating laser outdoors

- follow ANSI Z136 standard
- Non-visible (UV light) helps

Perform experiments during a range of weather conditions

- High- and low-wind conditions
- Humidity differences (potentially with precipitation)

Need experiments to characterize:

- Pooling
- Evaporation from LH_2 pools
- Interactions of plumes with ambient

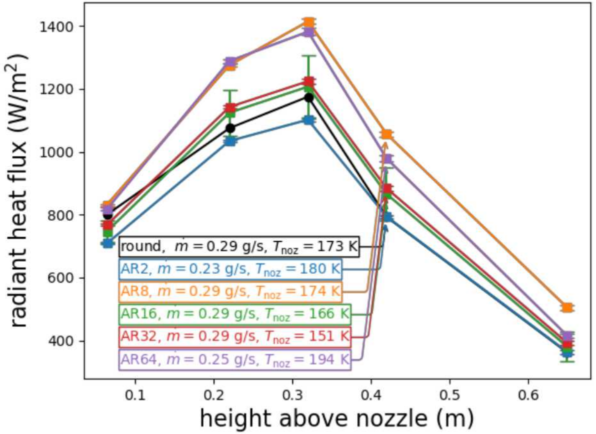
Solution:

- Well-controlled experiments at Sandia facilities
- Partner with others, applying diagnostic at remote locations (European colleagues)

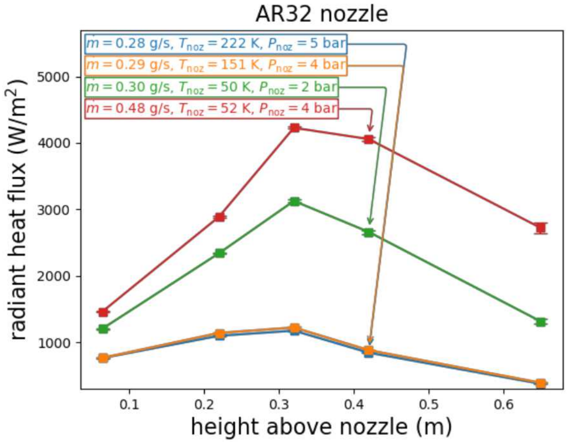
Ignited measurements (heat flux) are also important for calculating safety – we have studied round and non-round nozzles

Measuring whether the round nozzle is worst-case scenario as assumed

- Aspect Ratios: 2-64
- Nozzle pressures: 1.5-6 bar
- Nozzle temperatures: 48-295K



- For an equivalent mass flux, heat flux increases at cryogenic temperatures

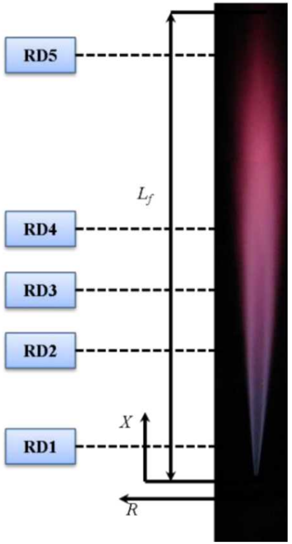


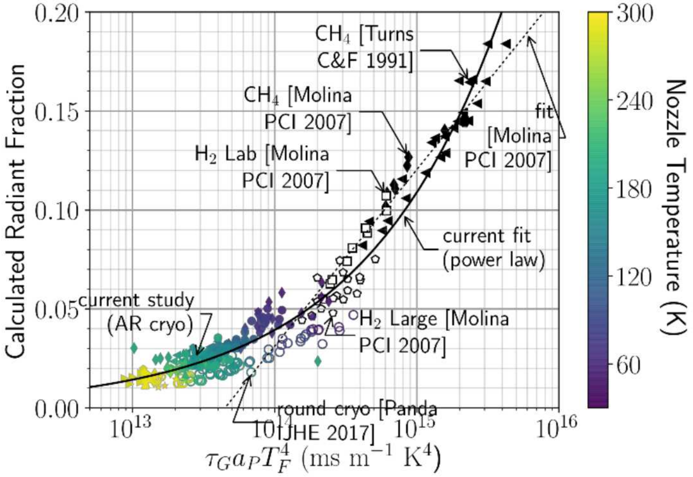
Hydrogen flames have less visible emission than other fuels

These experiments were conducted at SRI International in collaboration with Sandia National Laboratories Combustion Research Facility

The radiant fraction and heat flux from hydrogen flames is also lower than for hydrocarbons

- Lab-scale measurements of hydrogen heat flux for round and non-round nozzles
- Supporting the CGA G-5.5 testing task force measurements of LH_2 vent stack flames
  - Calculation of heat flux from vent stacks in CGA G-5.5 assumes high radiant fraction
  - Radiant fraction for hydrogen much lower than other gases (no carbon that makes soot)
  - Making measurements of vent stack flames to improve heat flux calculations

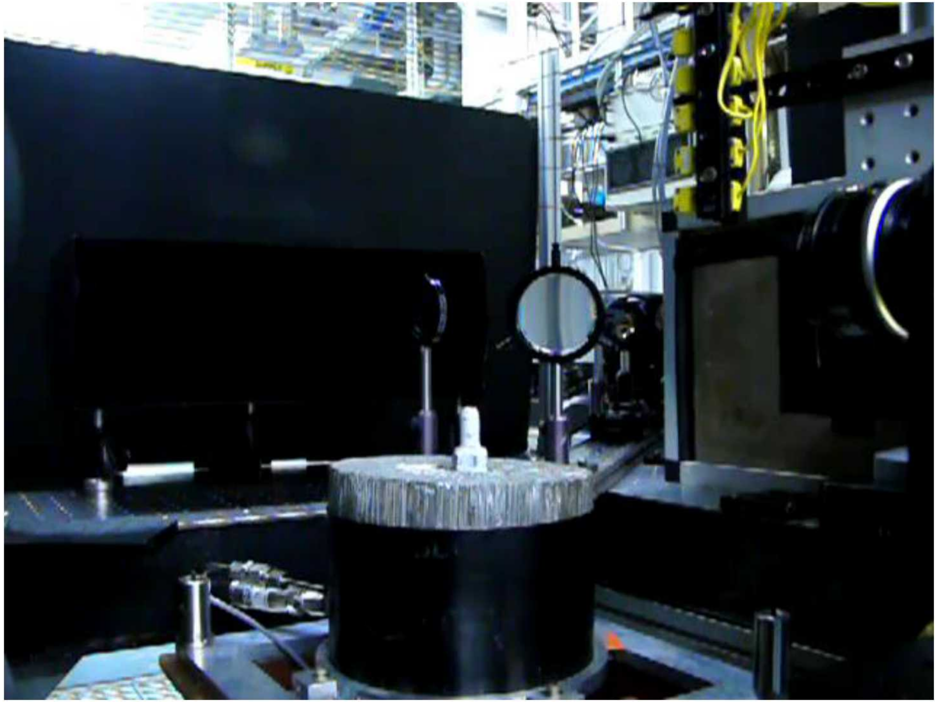




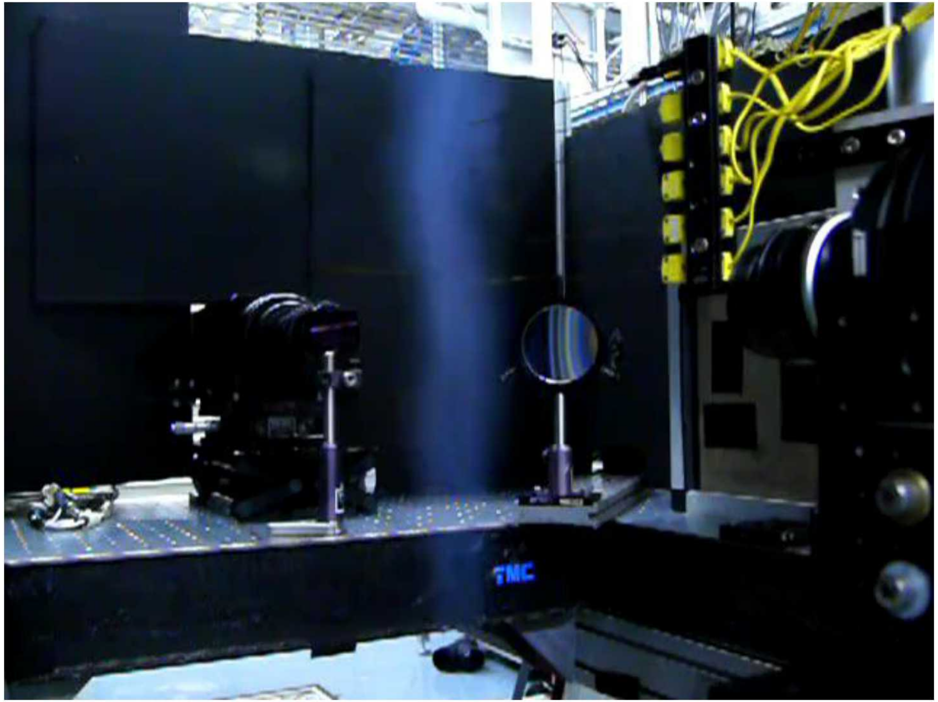
$$radiant\ heat\ flux \propto (radiant\ fraction)(mass\ flow)(heat\ of\ combustion)(transmissivity)$$

The ignition distance/light-up boundary is an important parameter for safety – need to keep ignition sources away from leaks

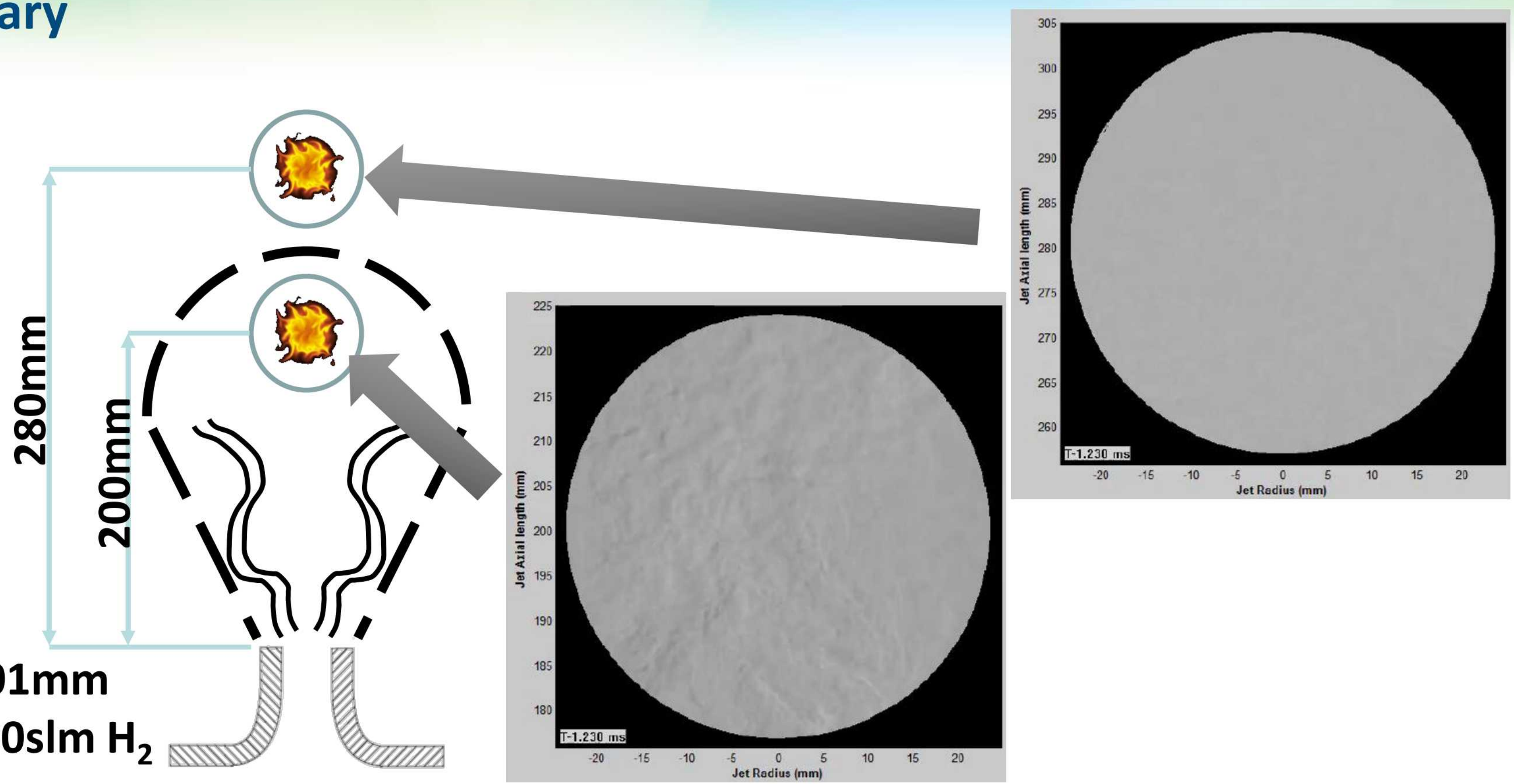
P = 1 bar, T = 290 K, distance = 85 mm



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



A laser spark ignition is used to precisely determine the light-up boundary

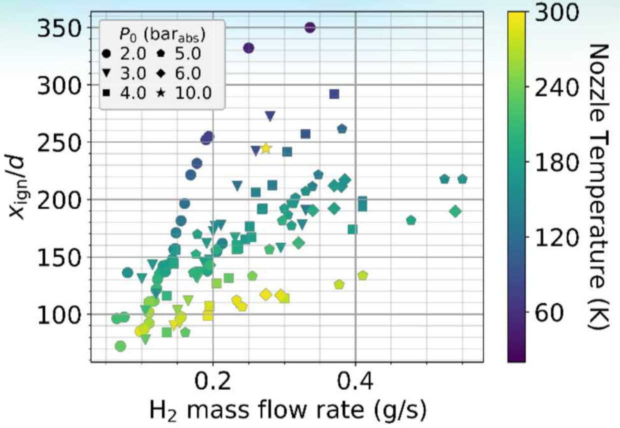


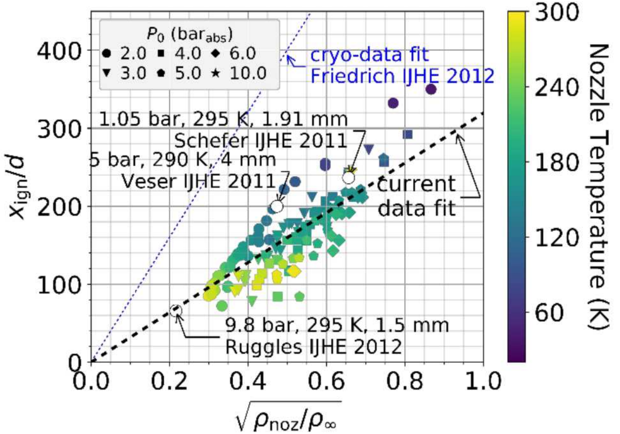
D = Ø1.901mm

Flow = 100slm H_2

The ignition distance for cryogenic hydrogen scales in the same manner as for warm hydrogen

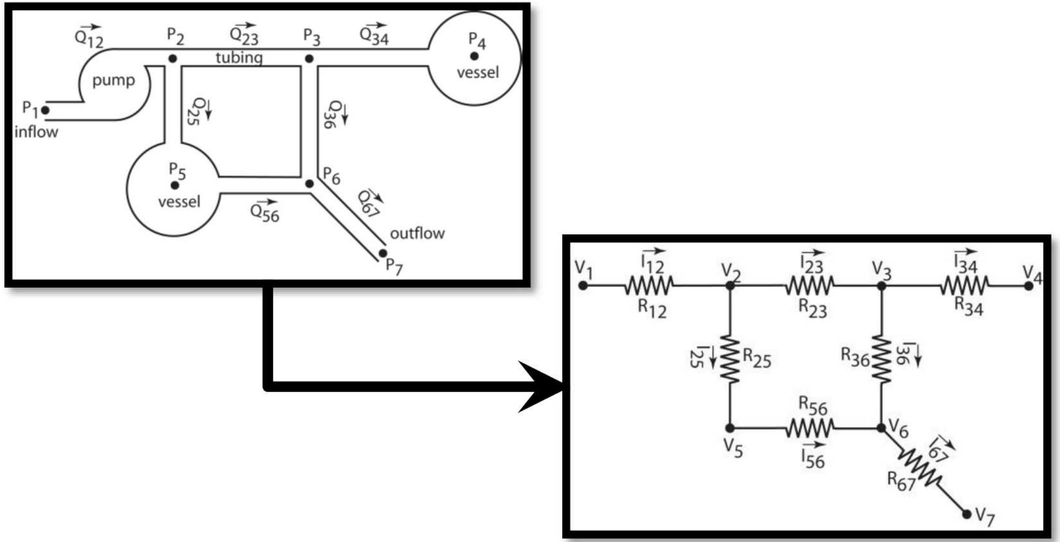
- for a given mass flow, ignition of cold H_2 occurs much further from the release point
- a larger ignition distance is observed at a lower mass flow rate of hydrogen for the colder jets
- Ignition distance linearly varies as a function of effective diameter (same as literature reported room temperature releases)





A model for internal, phase-changing flow is necessary to calculate plume/flame boundary conditions

- Flow out a vent stack is no longer at LH_2 temperature
- Valves, piping, and other components represented as an electrical network in Sandia’s MassTran model
- Need details (heat transfer rate, component orifice sizes, etc.) to accurately calculate conditions at release point



Liquid hydrogen storage tank

The validated models tie into the QRA process for LH_2 systems – some gaps remain

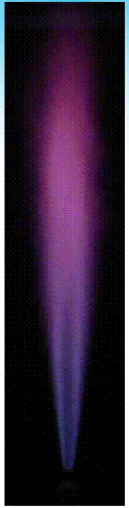
- Selection of a typical system
- Leak data for LH_2 systems
- Calculation of leak frequency (function of size)
- Models for physical behaviors and consequences:
  - Unignited dispersion
    - Pooling, vaporization
    - Interaction with the environment (e.g. wind)
  - Ignited behavior
    - Flame radiation
    - Overpressure
- Harm models (from consequence models)
- Determination of acceptable risk

- Planning pooling and vaporization experiments at well-controlled Sandia facilities
- Collaborations welcome (take diagnostics to other locations)

Summary

- Lab-scale experiment liquefies gaseous hydrogen with liquid nitrogen and liquid helium
- Cryogenic hydrogen dispersion measured using simultaneous Raman scattering and particle imaging velocimetry
- Raman diagnostic being scaled for larger experiments
  - Camera remains fixed
  - Laser illumination scanned in space to create 3-D measurements of concentration
- Measurements of reacting hydrogen also made at lab and larger scale
  - Ignition distance using laser spark
  - Radiant fraction and heat flux
    - Round and high aspect ratio nozzles at lab scale
    - Liquid hydrogen vent stacks with CGA G-5.5 testing task force
- Validating an model for calculation of internal flows (e.g. from LH_2 tank to vent stack)

QUESTIONS?



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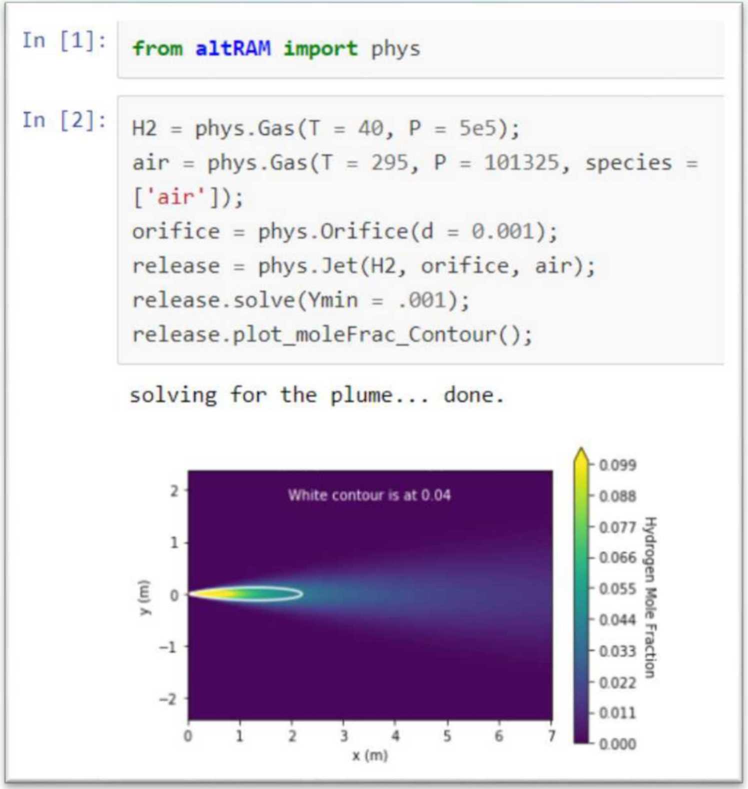
And thanks to the hydrogen research team at Sandia including:

- Jon Zimmerman (H_2 program manager), Bikram Roy Chowdhury (experiments), Chris LaFleur (Risk, Codes & Standards) , Alice Muna (Risk), Brian Ehrhart (H_2FIRST), Gaby Bran-Anleu (H_2FIRST), Scott Bisson (optics), Tony McDaniel (experiments), Rad Bozinoski (modeling), Myra Blaylock (CFD), Chris San Marchi (materials/metal interactions with H_2), Joe Ronevich(materials/metal interactions with H_2), John Reynolds (HyRAM), Nalini Menon (polymer interactions with H_2)
- Previous researchers: Pratikash Panda, Joe Pratt, Katrina Groth, Isaac Ekoto, Adam Ruggles, Bob Schefer, Bill Houf, Greg Evans, Bill Winters

Updated Python modeling packages (including ColdPLUME)

- Release of HyRAM 2.0 as open source software
- Validated version of ColdPLUME included
- Updated physics and QRA submodules
- Python package implementation with documentation



```
In [1]: from altRAM import phys
```

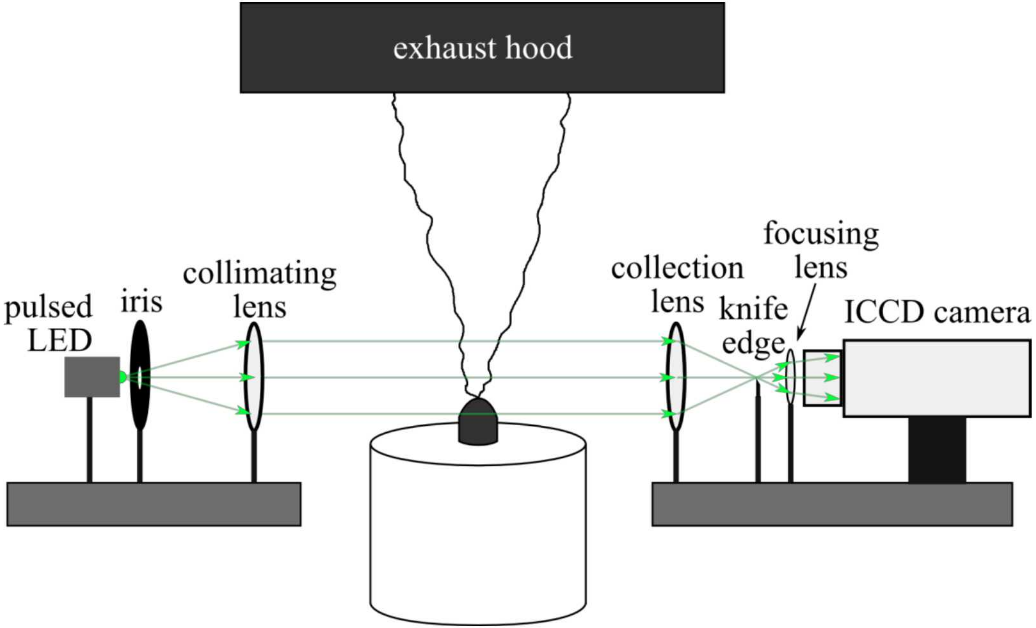
```
In [2]: H2 = phys.Gas(T = 40, P = 5e5);
        air = phys.Gas(T = 295, P = 101325, species =
        ['air']);
        orifice = phys.Orifice(d = 0.001);
        release = phys.Jet(H2, orifice, air);
        release.solve(Ymin = .001);
        release.plot_moleFrac_Contour();

solving for the plume... done.
```

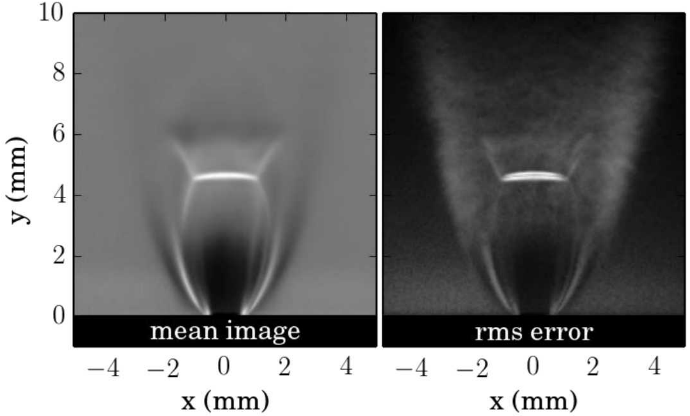
Schlieren imaging

- Measures gradients in density (1st derivative)
- For quantitative measurements:
  - Calibrated schlieren – uniform light source, light intensity quantifies refraction angles
  - Rainbow schlieren – color cutoff filter in place of knife edge, color quantifies refraction angles
  - Diverging light background oriented schlieren (BOS) – pixel offset from original position determines refraction angle
- BOS (using sunlight) possible for H_2, however:
  - Need semi-ordered background
  - Density gradients caused by both temperature and composition
  - Line-integrated, total refraction measured, extremely complex to quantify, even with tomography
  - No symmetries for an open plume

Schlieren imaging is used to characterize near-nozzle region and other regions with high density gradients



50 bar room temperature H_2 release

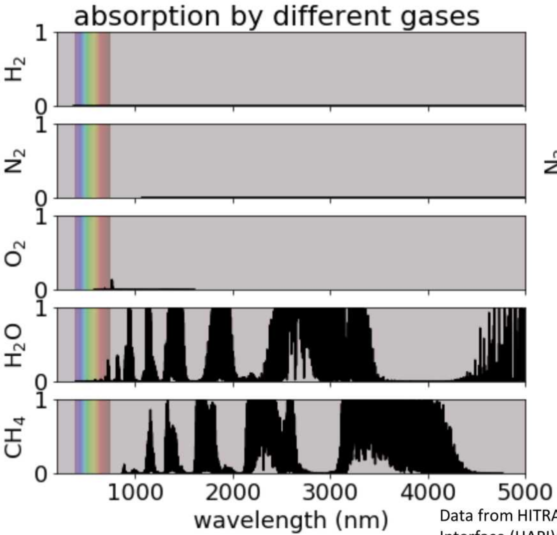


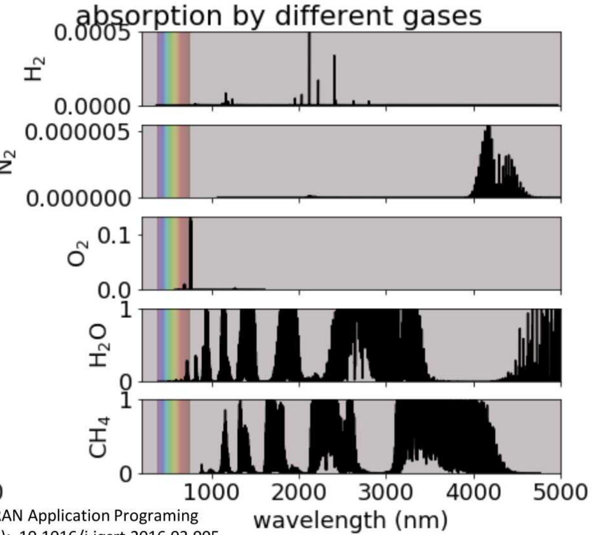
Fluorescence

- OH fluorescence possible, but only for flames, not unignited H_2
- Unignited concentration measurement would require seeding hydrogen with fluorescent tracer material (aliphatic ketones like acetone or 3-pentanone often used)
  - For cryogenic H_2, no gaseous or liquid options at LH_2 temperatures
  - Very challenging to get solid particles dispersed in liquid, and get them to follow gas flow during phase change

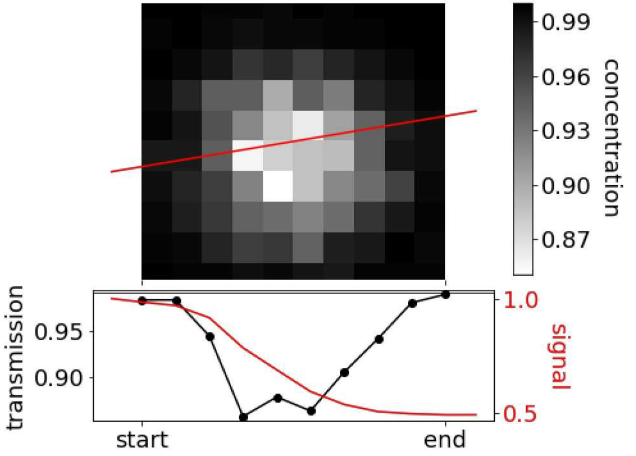
Absorption

- H_2 lacks strong absorption features (unlike CH_4)
- Would require illumination and light collection on opposite sides of plume (or mirror to reflect light)
- Line-integrated absorption, to quantify, requires multiple angles, tomography





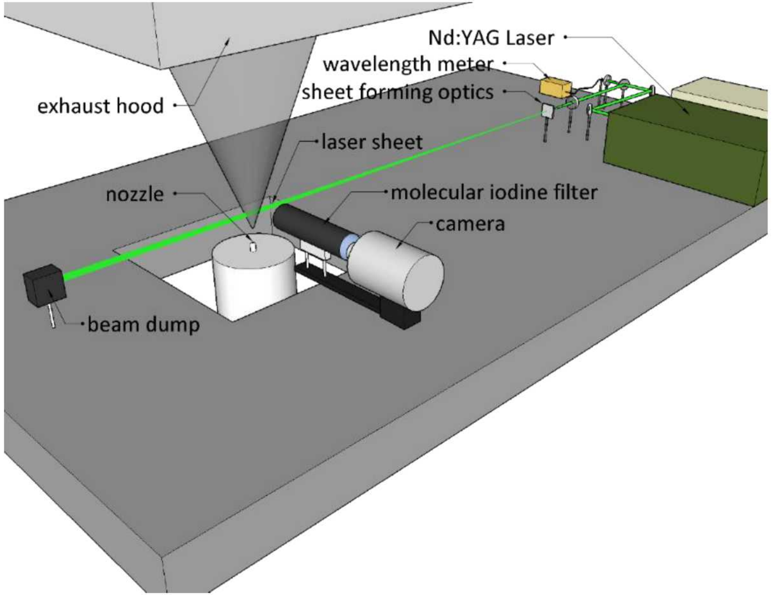
Data from HITRAN Application Programing Interface (HAPI): 10.1016/j.jqsrt.2016.03.005



Rayleigh scattering

H_2 Rayleigh cross-section ≈ 10^{-27} cm^2

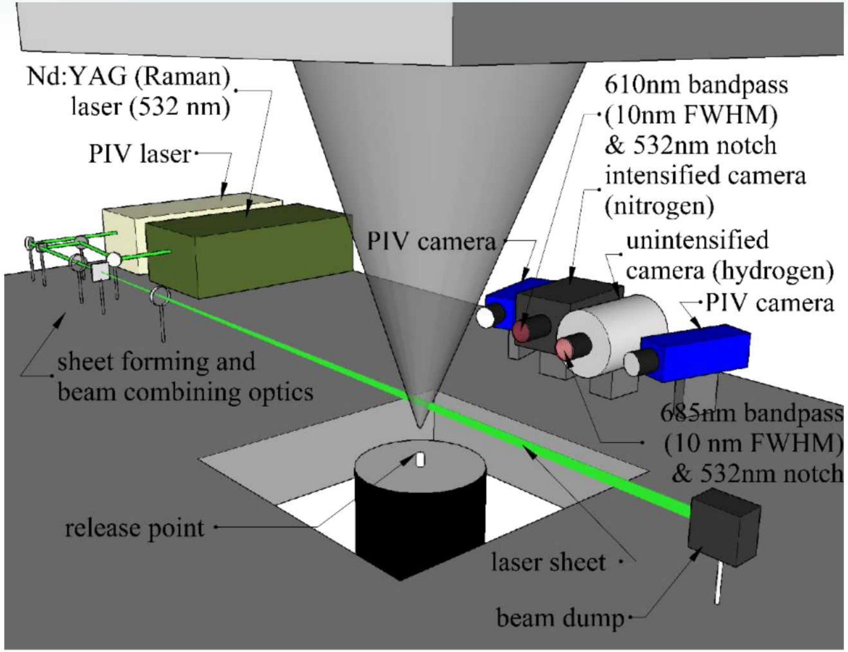
- Planar laser Rayleigh scattering used at Sandia for atmospheric temperature hydrogen releases
- Scatter proportional to number density; variations are caused by both composition and temperature
- For warm releases, always measured in atmospheric temperature region to eliminate this variable and enable composition quantification
- Not feasible to wait until cryogenic plume has warmed back to atmospheric temperature
- Rayleigh imaging will have signal overwhelmed by Mie scattering off of condensed entrained moisture in cryogenic plume
- Filtered Rayleigh has insufficient Mie scattering (condensed, entrained moisture) light suppression (OD≈3)



Planar Raman imaging works in a lab setting

H_2 Raman cross-section ≈ 10^{-30} cm^2

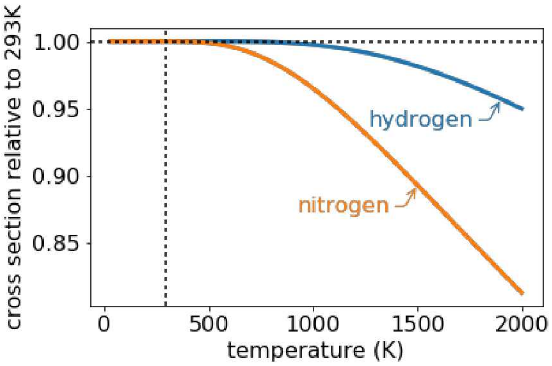
- Signals are low
  - High powered light source required (~700 mJ/pulse @ 532nm, 12mm tall sheet)
  - Fast optics for collection (F/1.2)
- Large Raman shift enables higher optical density filters to remove unwanted Mie scatter
  - 10 nm FWHM bandpass filters at wavelengths of interest
  - OD of 12 @ all wavelengths
  - OD of 18 @ 532 nm
- Signals for other Raman lines (rotational, etc.) low at cryogenic temperatures



H_2: shift of 4161 cm^{-1} (532nm → 683 nm, 355nm → 416 nm)
N_2: shift of 2331 cm^{-1} (532nm → 607 nm, 355nm → 387 nm)

Quantification of Raman signals

- Signal is proportional to number density of molecules
- We use the ideal gas law to relate temperature and mole fraction to number density
    - $\frac{n_{total}\Sigma x}{V} = \frac{P_{total}\Sigma x}{RT}$
    - other equation of state could be used but may not have analytical solution
- Cross-section dependence matters for high-T (flames), but not low-T (cryogenic)



Eq. 1: $\frac{I_{H_2}}{I_0} = k_{H_2}\frac{x_{H_2}}{T}$ ← unknown 1 ← unknown 2

measured values

calibration constants

Eq. 2: $\frac{I_{N_2}}{I_0} = k_{N_2}\frac{x_{N_2}}{T}$ ← unknown 3

based on the composition of air

Eq. 3: $1 = x_{H_2} + 1.28x_{N_2}$

$$\begin{cases} x_{H_2} = \dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}\left(\dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}} + \dfrac{1.28\mathrm{I}_{\mathrm{N}_2}}{k_{N_2}}\right)} \\ x_{N_2} = \dfrac{\mathrm{I}_{\mathrm{N}_2}/\mathrm{I}_0}{k_{N_2}\left(\dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}} + \dfrac{1.28\mathrm{I}_{\mathrm{N}_2}}{k_{N_2}}\right)} \\ T = \dfrac{1}{\dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}} + \dfrac{1.28\mathrm{I}_{\mathrm{N}_2}}{k_{N_2}}} \end{cases}$$

Raman has been used in a lab-scale campaign to measure releases from ≈1 mm orifices

T_{noz} [K]	P_{noz} [bar_{abs}]	d [mm]	T_{throat} [K]	n_{hts}
58	2	1	43.5	4
56	3	1	41.9	4
53	4	1	39.6	4
50	5	1	37.4	5
61	2	1.25	45.7	6
51	2.5	1.25	38.2	2
51	3	1.25	38.2	6
55	3.5	1.25	41.2	3
54	4	1.25	40.4	2
43	4	1	32.1	2
59	3	1	44.2	6
56	3.5	1	41.9	1
80	3	1	60.3	5

With PIV