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October 2017 Codes & Standards Tech Team Update:
Building Knowledge of Cryogenic Hydrogen Behavior

Ethan S. Hecht

Sandia National Laboratories, Livermore, CA, USA

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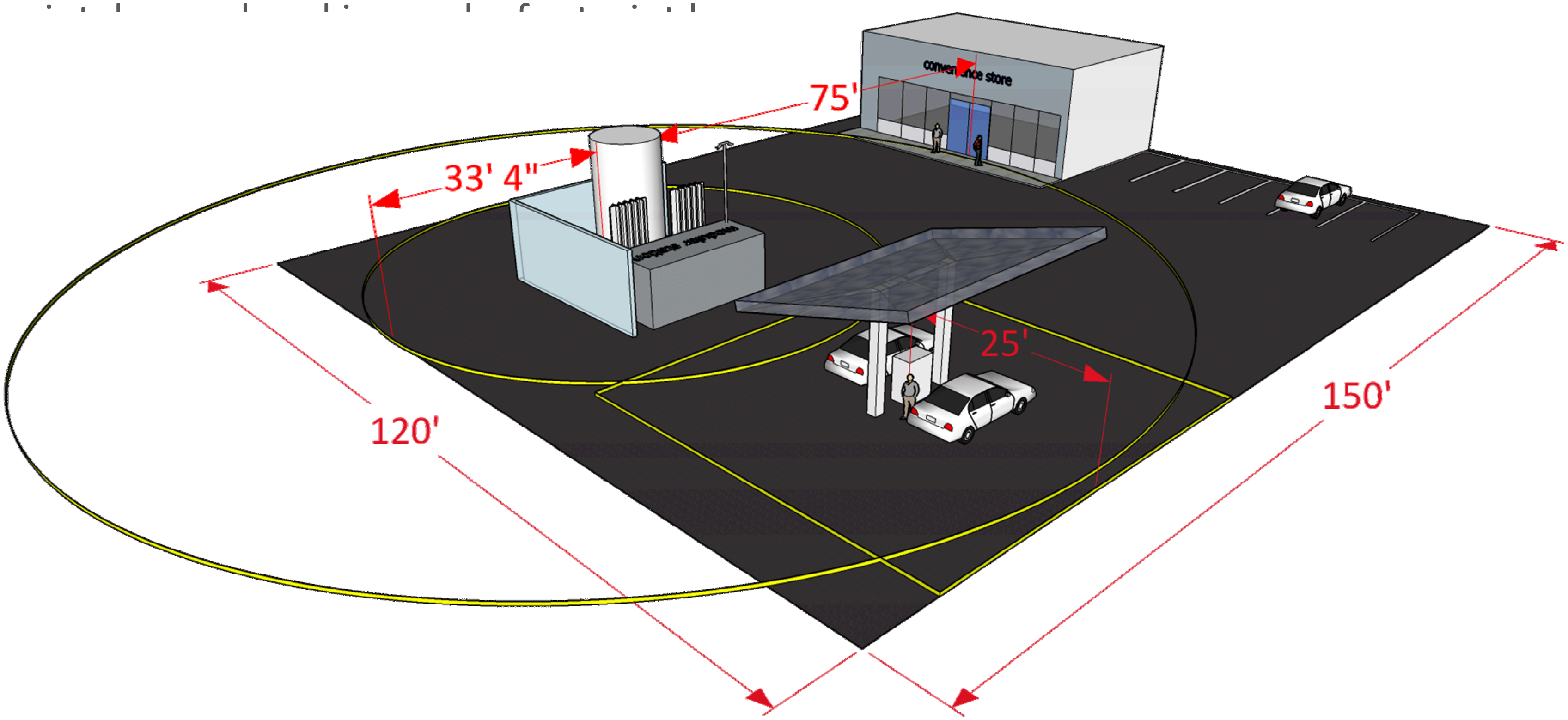
Current separation distances in NFPA 2 for liquid hydrogen are based on consensus, not science

- 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. offset to building



Complementary work under H2FIRST will help identify how this work can have impact

- Reference Stations for Urban Sites project is evaluating various engineering solutions for siting large capacity liquid stations in urban areas
- One focus area is developing an understanding of NFPA 2 and the footprint of a fully compliant station, which has identified some challenges/concerns:
  - Liquid H_2 separation distances are based on volume of the LH_2 storage, while gaseous separation distances are based on pressure and pipe size
    - System is all equipment before the “source valve” (compressor and high pressure gas storage for a station with LH_2 are subject to LH_2 separation distances)
  - Gaseous separation distances protect against a leak (3% of pipe area) and a jet fire, yet the performance based design requires consideration of many scenarios including a pressure vessel burst
    - What risks are the separation distances protecting against?
  - Understanding quantity/geometry of walls allowed, and separation distance reduction
  - Why do design philosophies seem to be different (performance based design vs. prescriptive, and LH_2 vs. gaseous)?

NFPA 2 code committee has identified high priority scenarios that impact separation distances

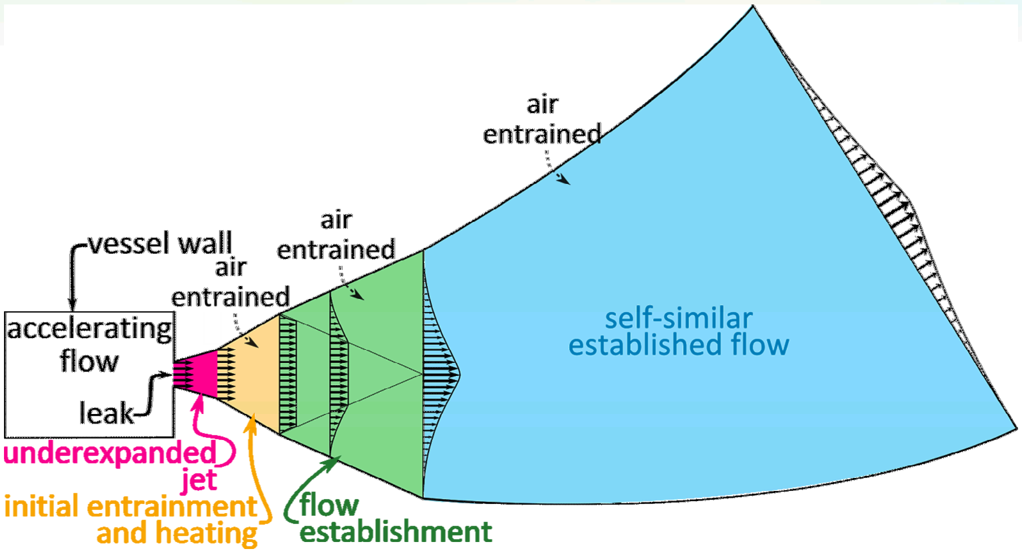
- ✓ Flow from vent of ultra-cold hydrogen (e.g. trailer venting excess pressure after normal LH_2 delivery or burst disk rupture)
  - Are vent stacks appropriately designed?
  - Separation distance from air intakes and overhead utilities
  - Vertical discharge, 3” diameter pipe, 20-140 psig
- ❑ Release from pipe containing liquid H_2 (e.g. leading from tank to vaporizer or vaporizer itself - caused by thermal cycles or ice falling from vaporizers)
  - Requires ability to model flashing, pooling and evaporation from pools
  - Need to model concentration plume and heat flux from a subsequent fire
  - Horizontal discharge, ¾”-2” diameter pipe, 20-140 psig

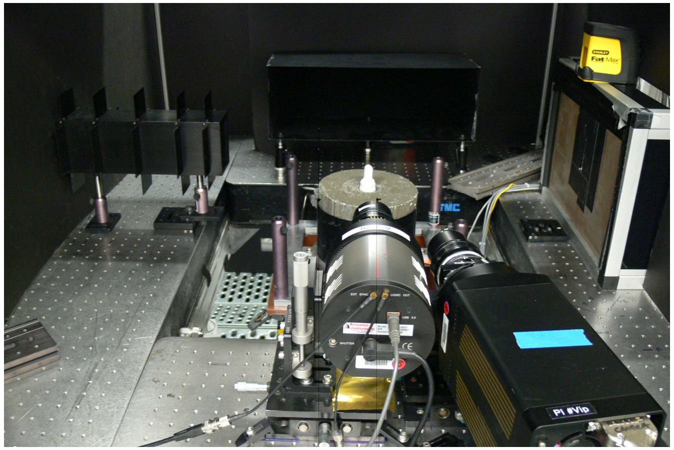
Venting cryogenic hydrogen is a regular occurrence, so we must be able to model the dispersion

- Even a liquid leak vaporizes rapidly, forming a cold gas
- Pressure relief if tank underutilized
- Trailer venting excess pressure after normal LH_2 delivery
- Burst disk rupture

Photo source: https://www.flickr.com/photos/cafcpmr/15219083519/in/album-72157647807992787/

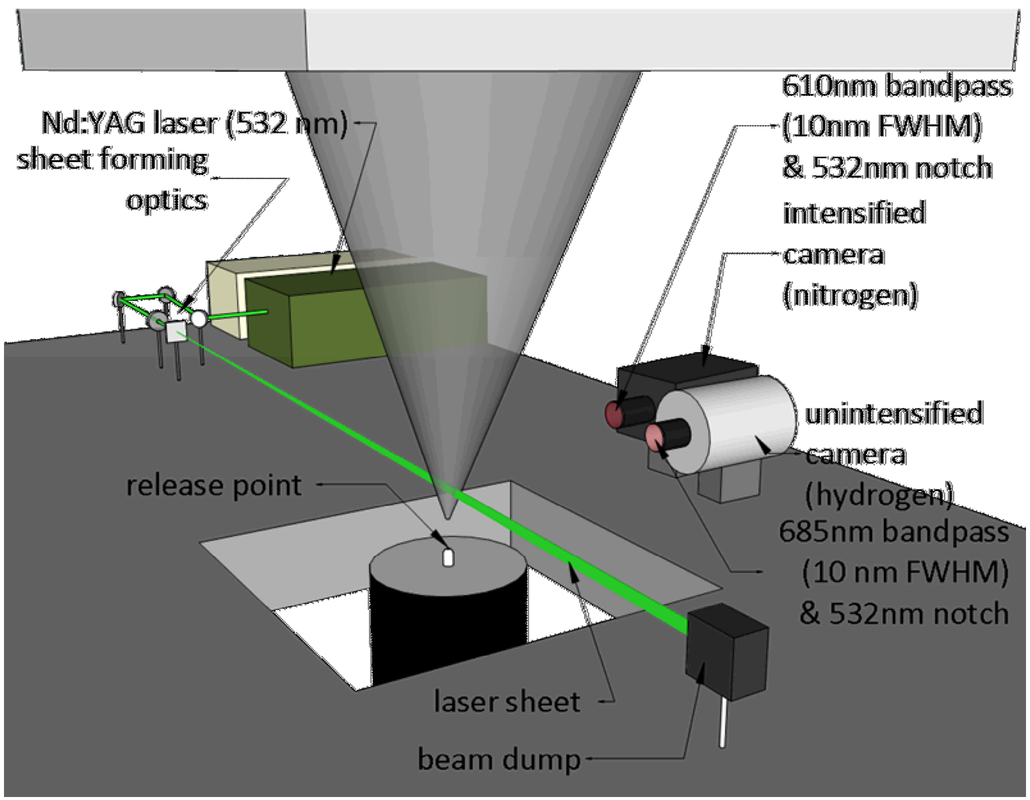
In current work, we focus on validating a model for cryogenic hydrogen dispersion





- Previously developed model requires validation data
  - Several model parameters based on empirical data
  - Data only from warm hydrogen or other warm gases
  - Are more physics required?
- Use experimental platform commissioned in 2016 to generate cryogenic hydrogen releases

We developed and implemented a Raman imaging technique to measure cryogenic plumes



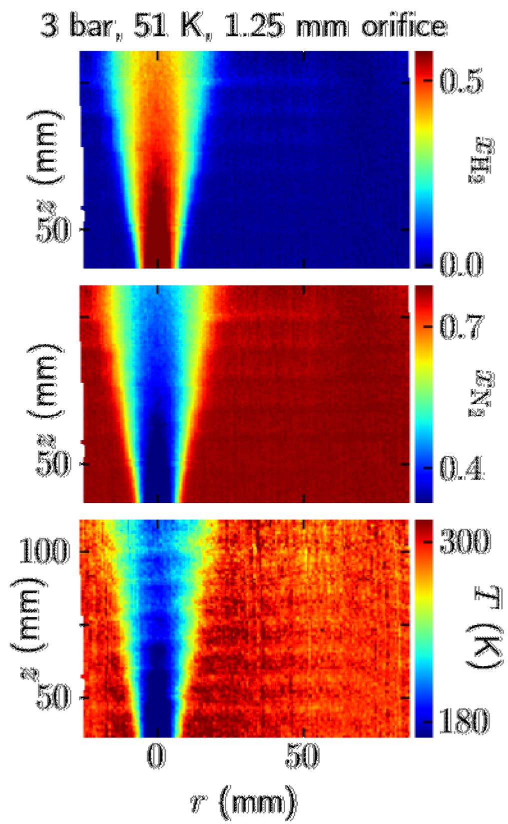
- Conventional Rayleigh signal overwhelmed by Mie scattering off of condensed water vapor in jet
- Filtered Rayleigh had insufficient Mie scattering light suppression (OD≈3)
- Raman scattering enables higher optical density filters
  - 10 nm FWHM bandpass filters at wavelengths of interest
  - OD of 12 @ all wavelengths
  - OD of 18 @ 532 nm

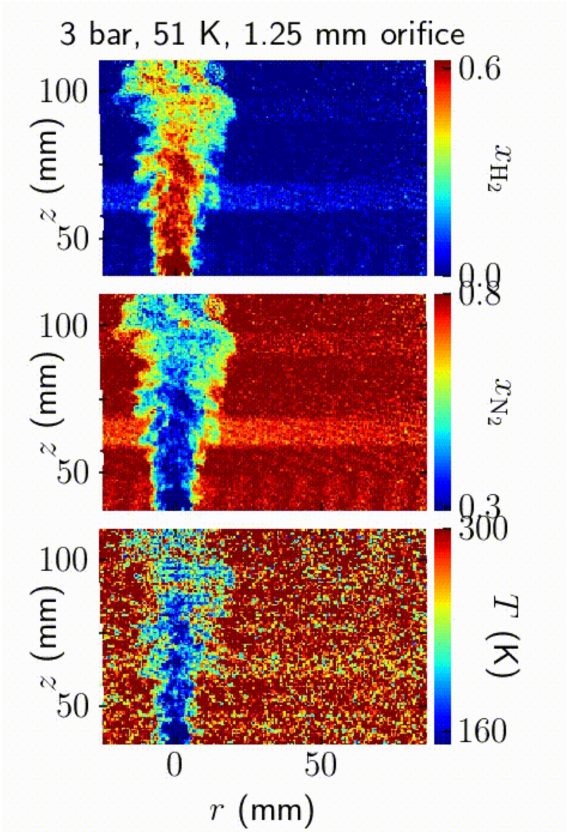
➤ Enables simultaneous measurement of concentration and temperature in 2D

Several experimental campaigns have had variations in temperature, pressure, and nozzle size

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

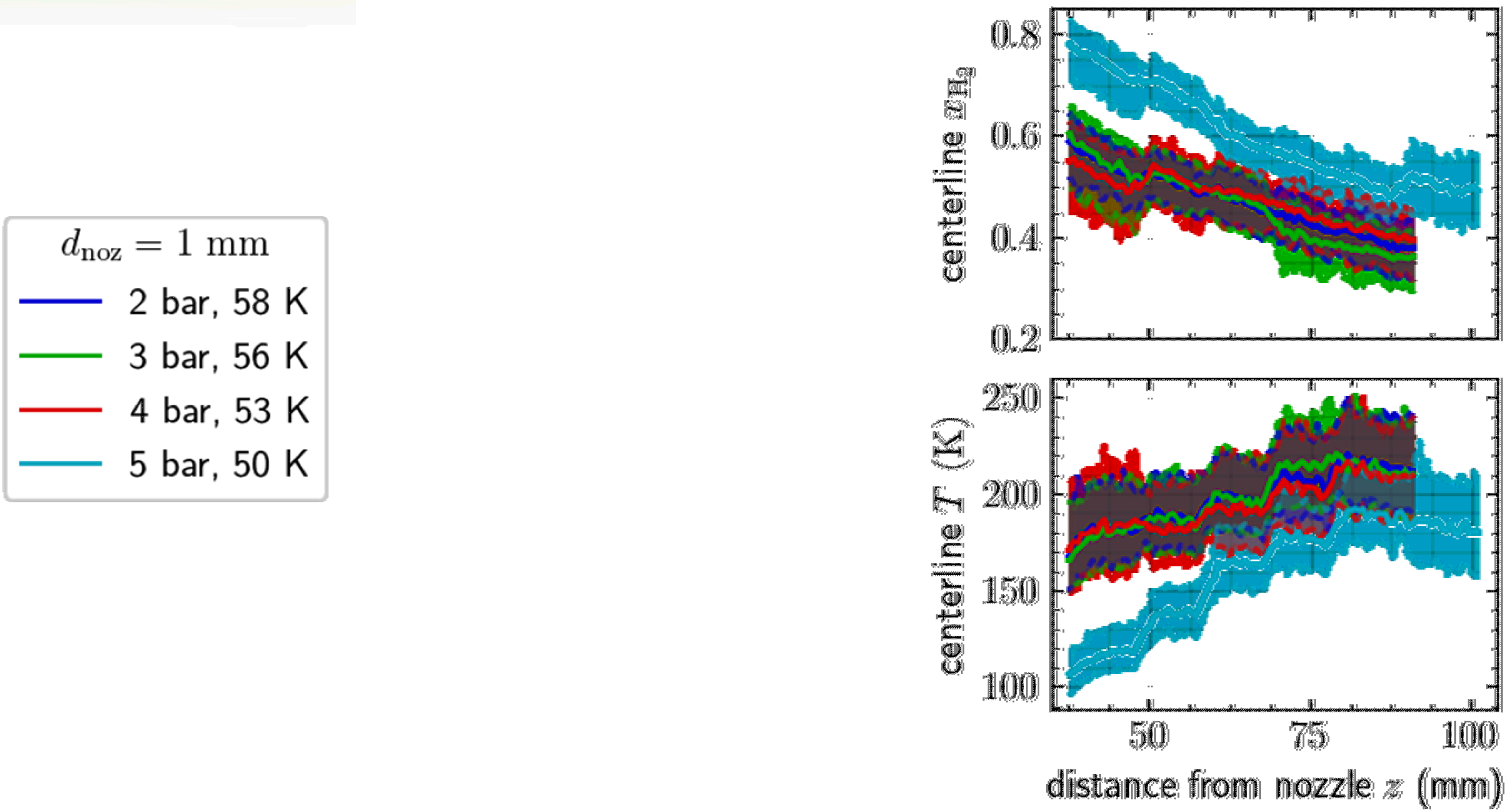
With PIV





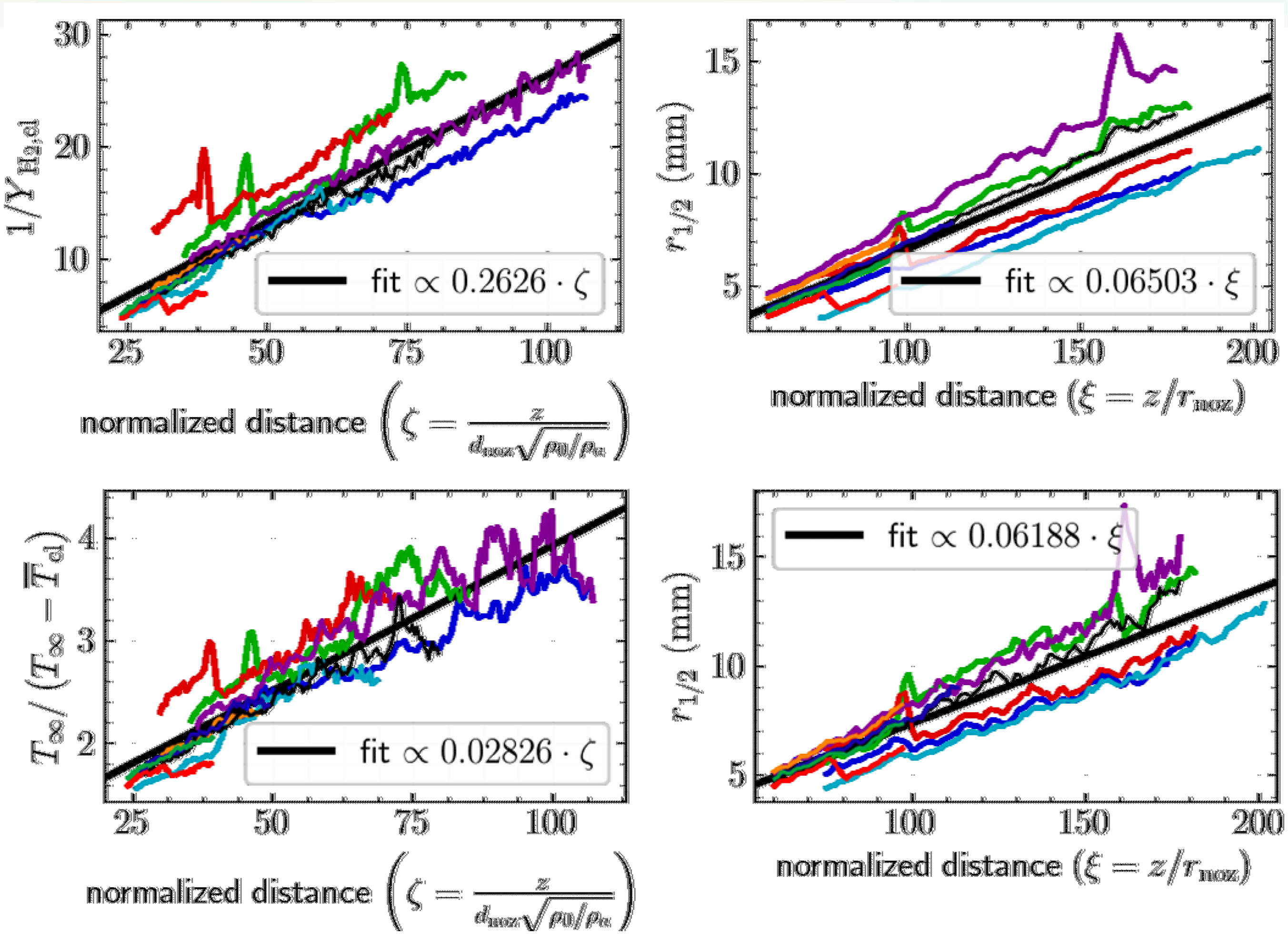
- Two-dimensional images are superior to centerline only measurements for model validation

Control of pressure, and measurement of temperature at nozzle needed for model validation



➢ Centerline mole fractions decrease and temperatures increase, as expected

When normalized properly, centerline and half-width decay rates scale linearly with distance

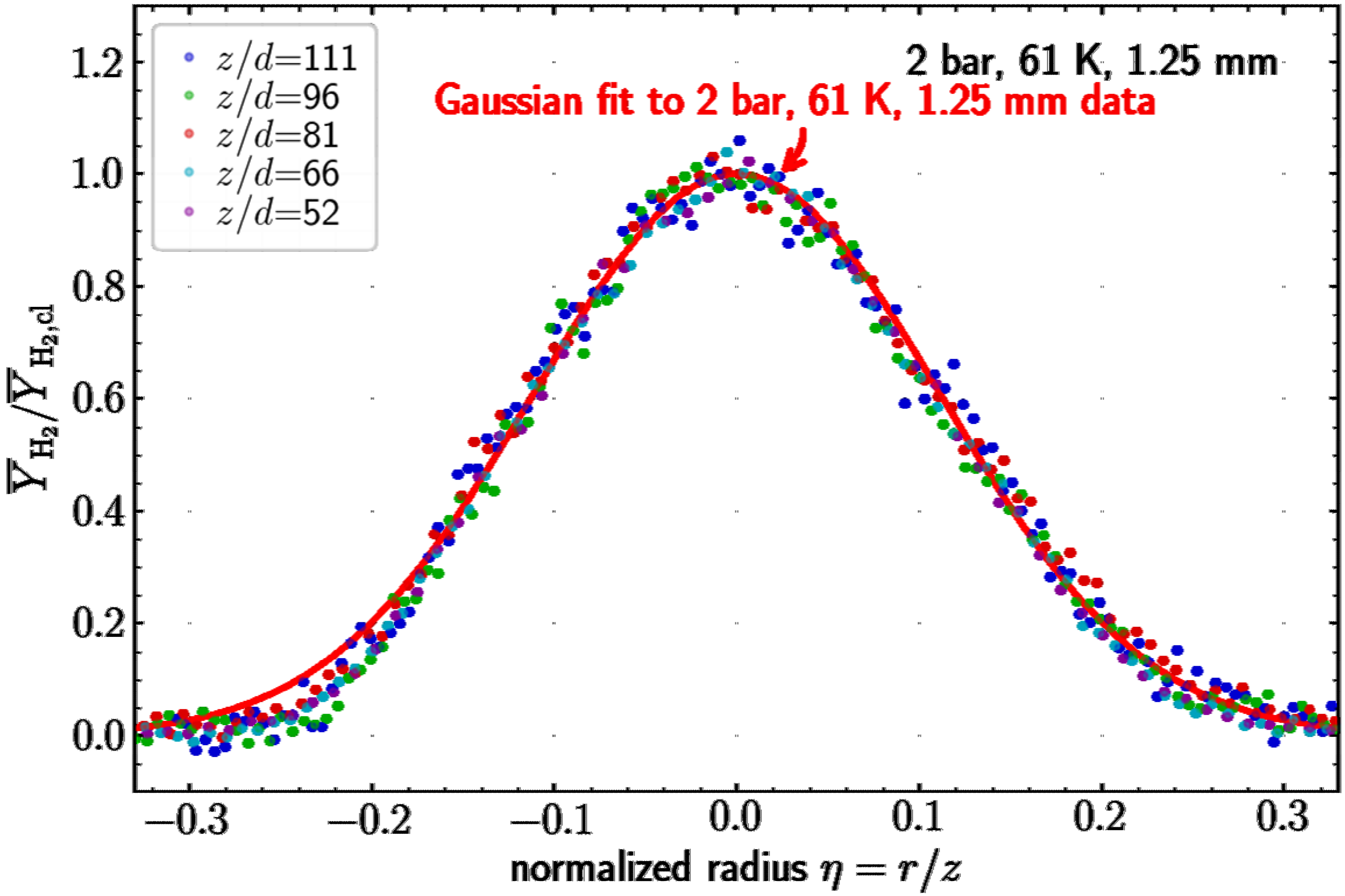


- Literature inverse mass-fraction decay rate: 0.21–0.271
- Literature mass-fraction half-width spreading rate: 0.1–0.11 mm

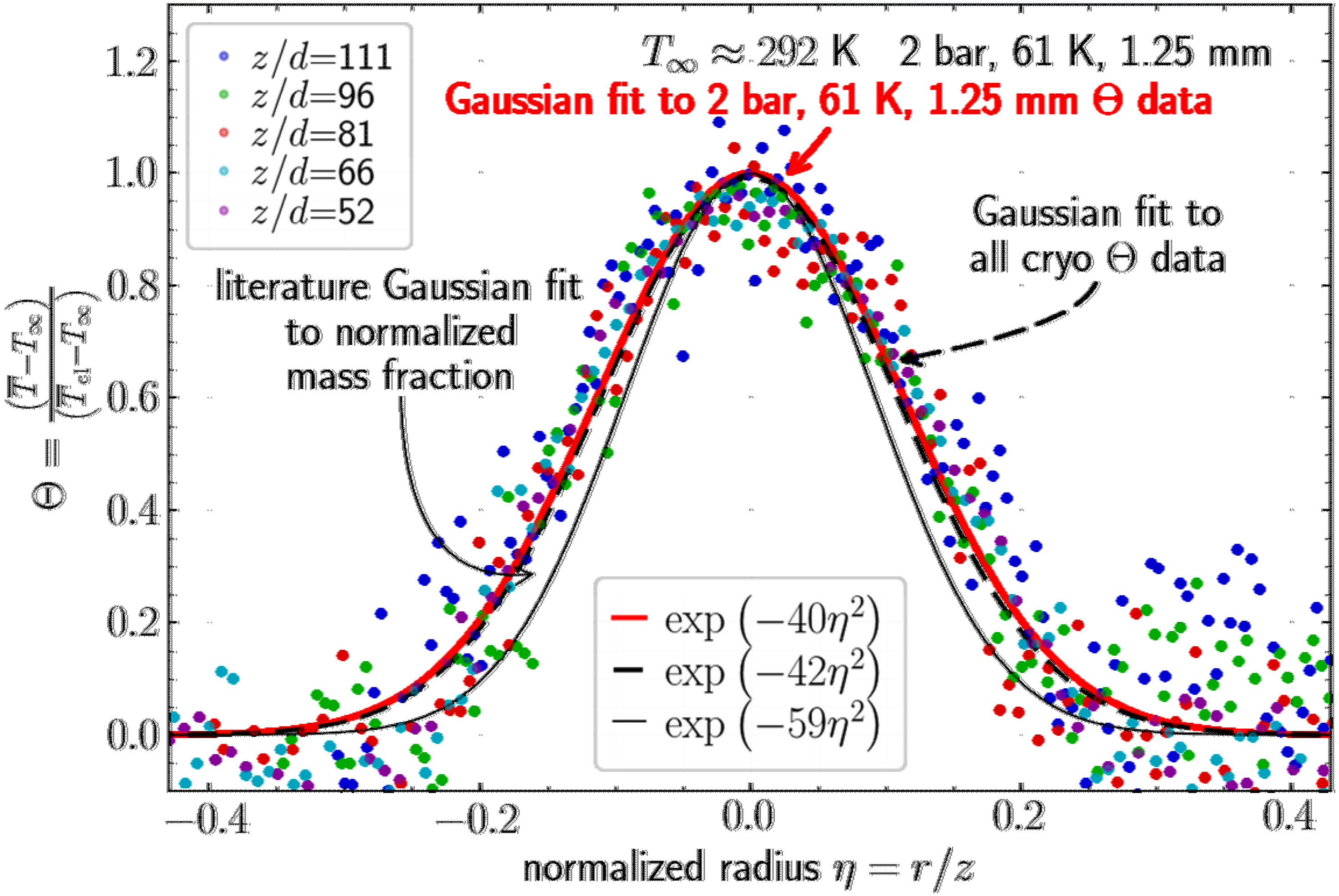
2 bar, 58 K, 1.00 mm
3 bar, 56 K, 1.00 mm
4 bar, 53 K, 1.00 mm
5 bar, 50 K, 1.00 mm
2 bar, 61 K, 1.25 mm
2.5 bar, 51 K, 1.25 mm
3 bar, 51 K, 1.25 mm
3.5 bar, 55 K, 1.25 mm
4 bar, 54 K, 1.25 mm
4 bar, 45 K, 1.25 mm

➢ First ever measurements of temperature needed for model energy balance

Radial profiles are self-similar, but wider than literature data of warm releases

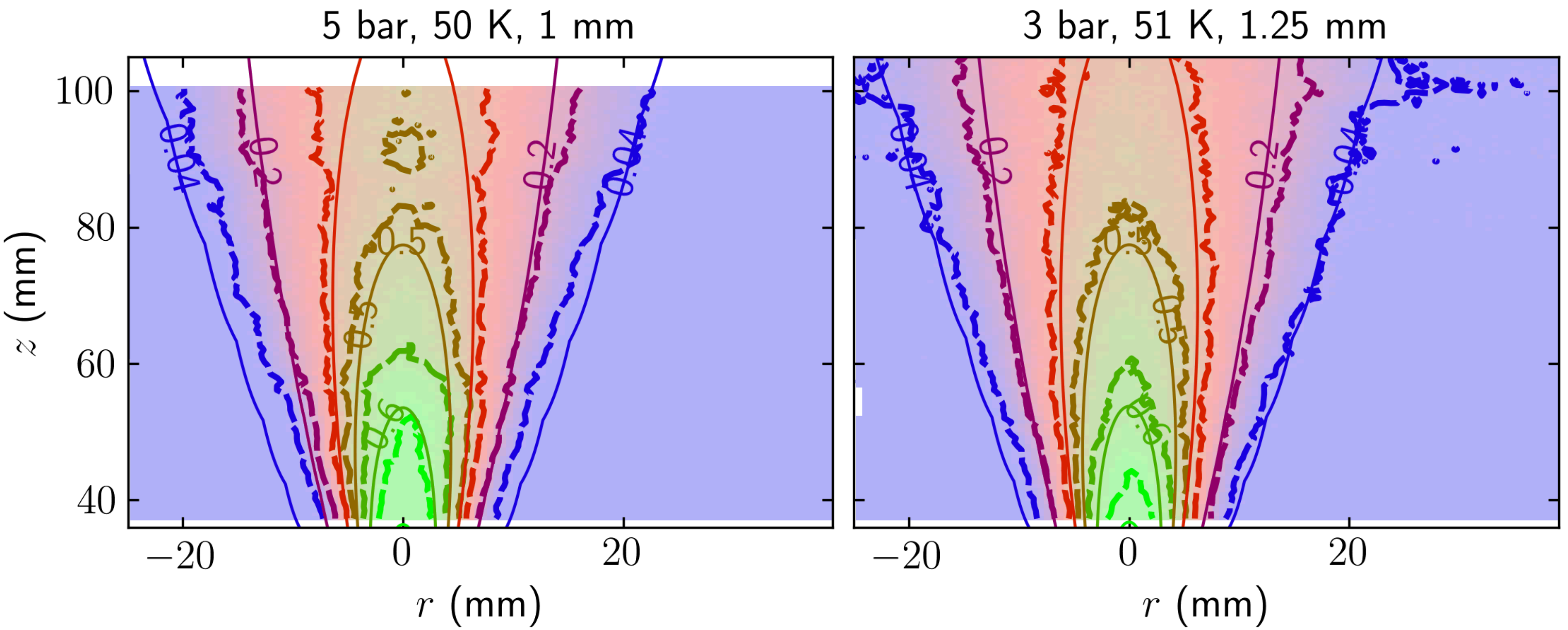


Radial profiles of temperature are also self-similar, and wider than mass fraction



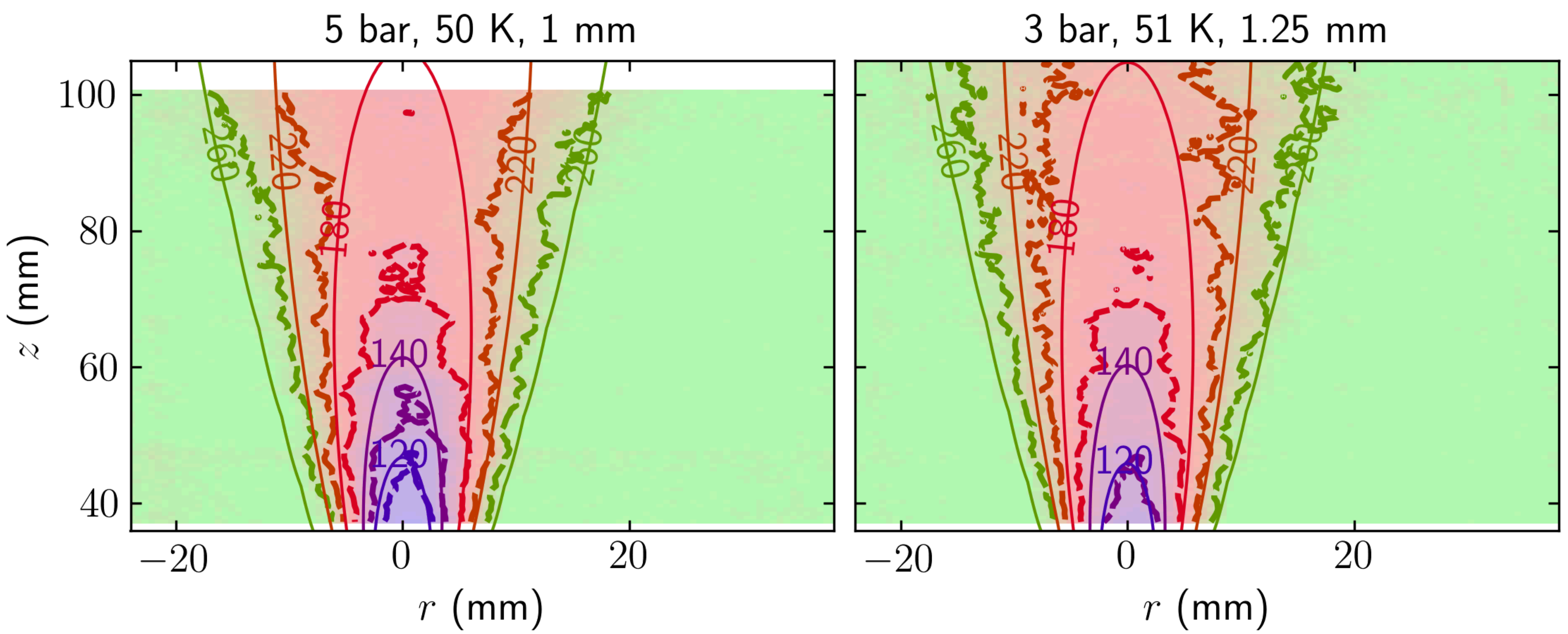
- Data can be used to validate relative spreading ratio in model

Initial comparisons to model show slightly slower centerline mole-fraction decay rate than predictions



- Expansion model and/or entrainment rate may need to be adjusted

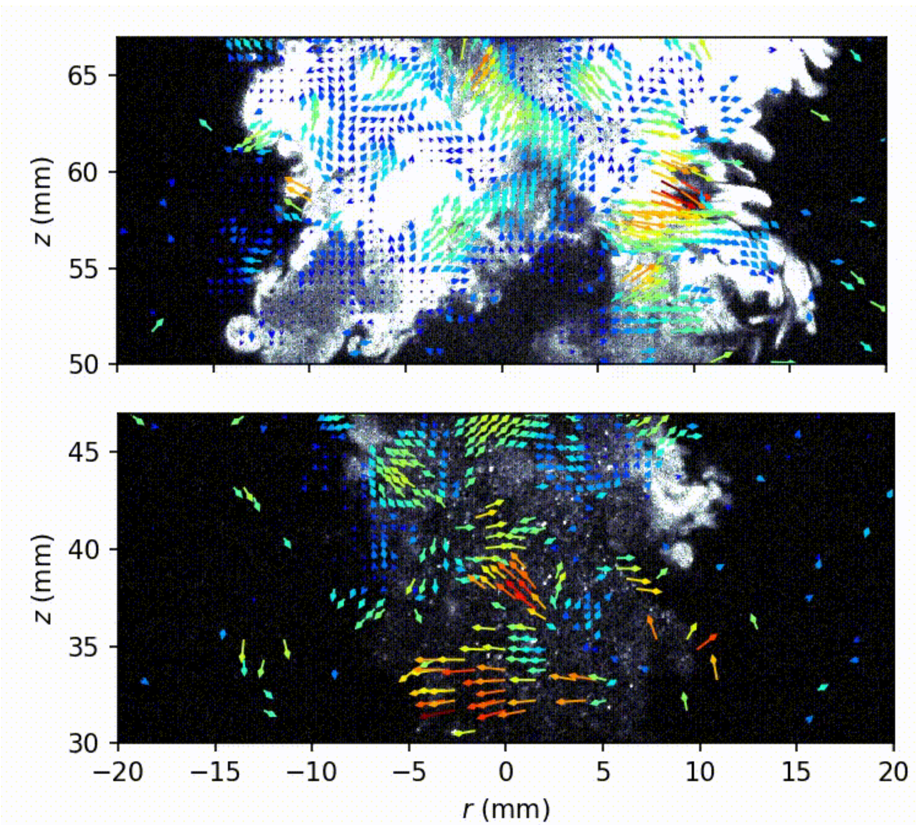
Initial comparisons to model also have minor differences in terms of temperature



- Temperature measurements are noisier than mole fraction

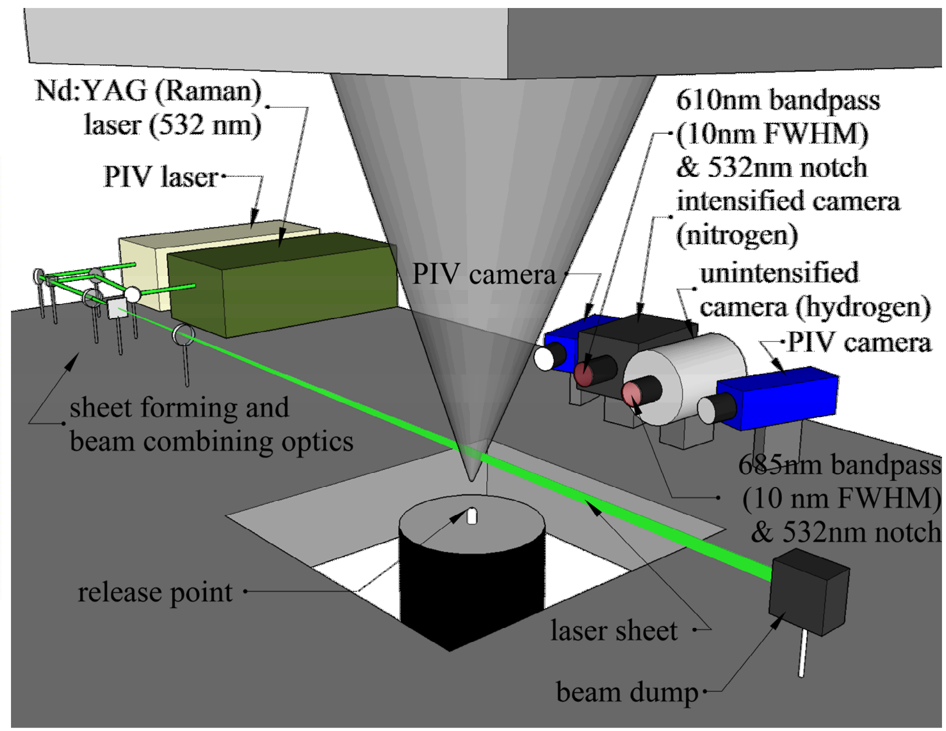
We have recently used particle imaging velocimetry to measure the velocity field of cryogenic hydrogen

2 bar, 55K, 1mm orifice



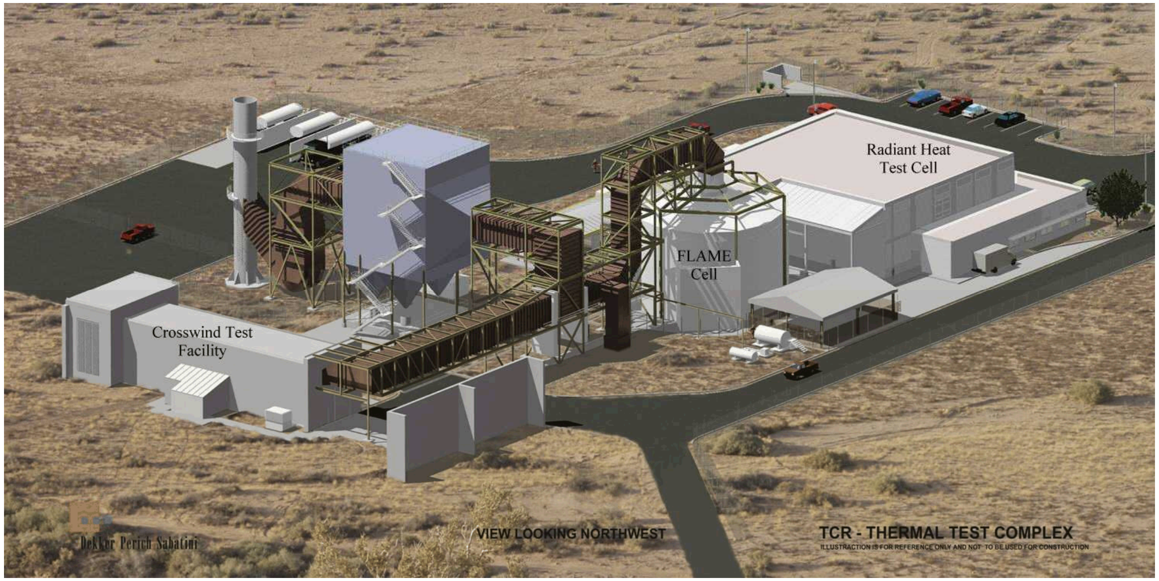
Independent model parameters:

- ✓ T - temperature
- ✓ x - mole fraction
- ✓ v - velocity
- ✓ B - halfwidth (velocity, concentration, temperature)



Future work: Characterize phenomena from large-scale releases

- Need experiments to characterize:
  - Interactions with ambient (i.e. wind)
  - Pooling
  - Evaporation from LH_2 pools
- Planning underway to develop (2 or 3-dimensional) imaging diagnostic for outdoor and large-scale experiments
- Can apply diagnostic to normally occurring outdoor releases (e.g., venting after LH2 fill) and validation experiments at well-controlled facilities



Summary

- Used advanced imaging diagnostics (planar laser Raman imaging, PIV) to measure cryogenic hydrogen mixing with air and warming
- Centerline mass fraction decay rate for cryogenic hydrogen similar to warm hydrogen
- Centerline temperature also increases linearly against normalized distance
- Mass-fraction (and temperature) profiles are self-similar, Gaussian, and slightly wider than for ambient temperature hydrogen
- Without modification, model is doing a reasonable job of predicting mole fraction and temperature, although improvements are possible (we have yet to compare velocity)
- **Future work**:
  - Complete validation and modification (if necessary) of ColdPLUME model using the data
  - Implement ColdPLUME into HyRAM (risk assessment toolkit)
  - Develop diagnostic for outdoor and large-scale experiments
  - Perform large-scale experiments and develop models for pooling and evaporation
  - Use models to advise NFPA 2 code committee on hazards and harm for high priority scenarios (to inform 2022 edition of NFPA 2)

Acknowledgements

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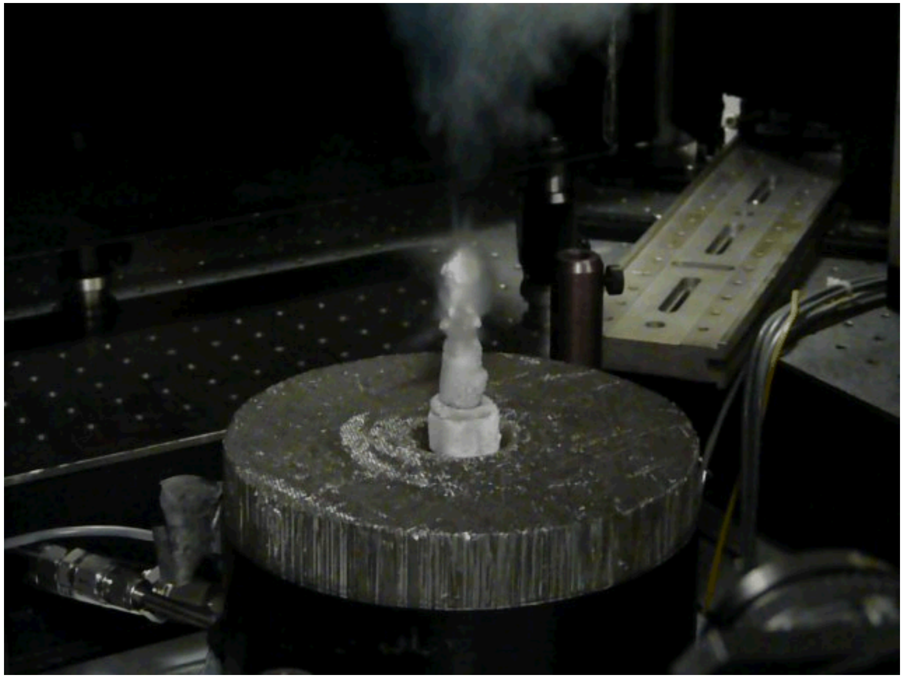
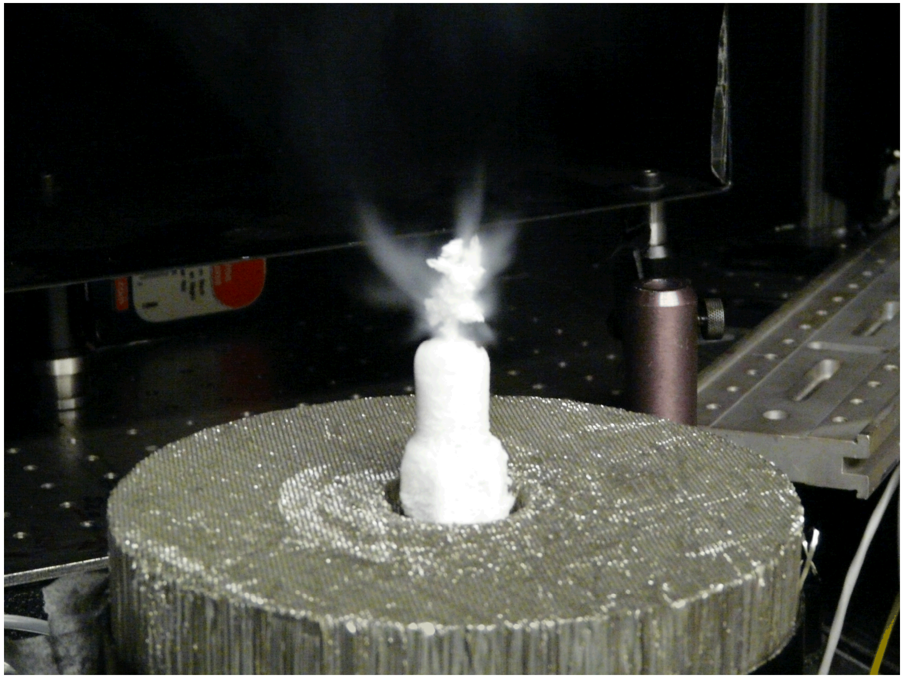
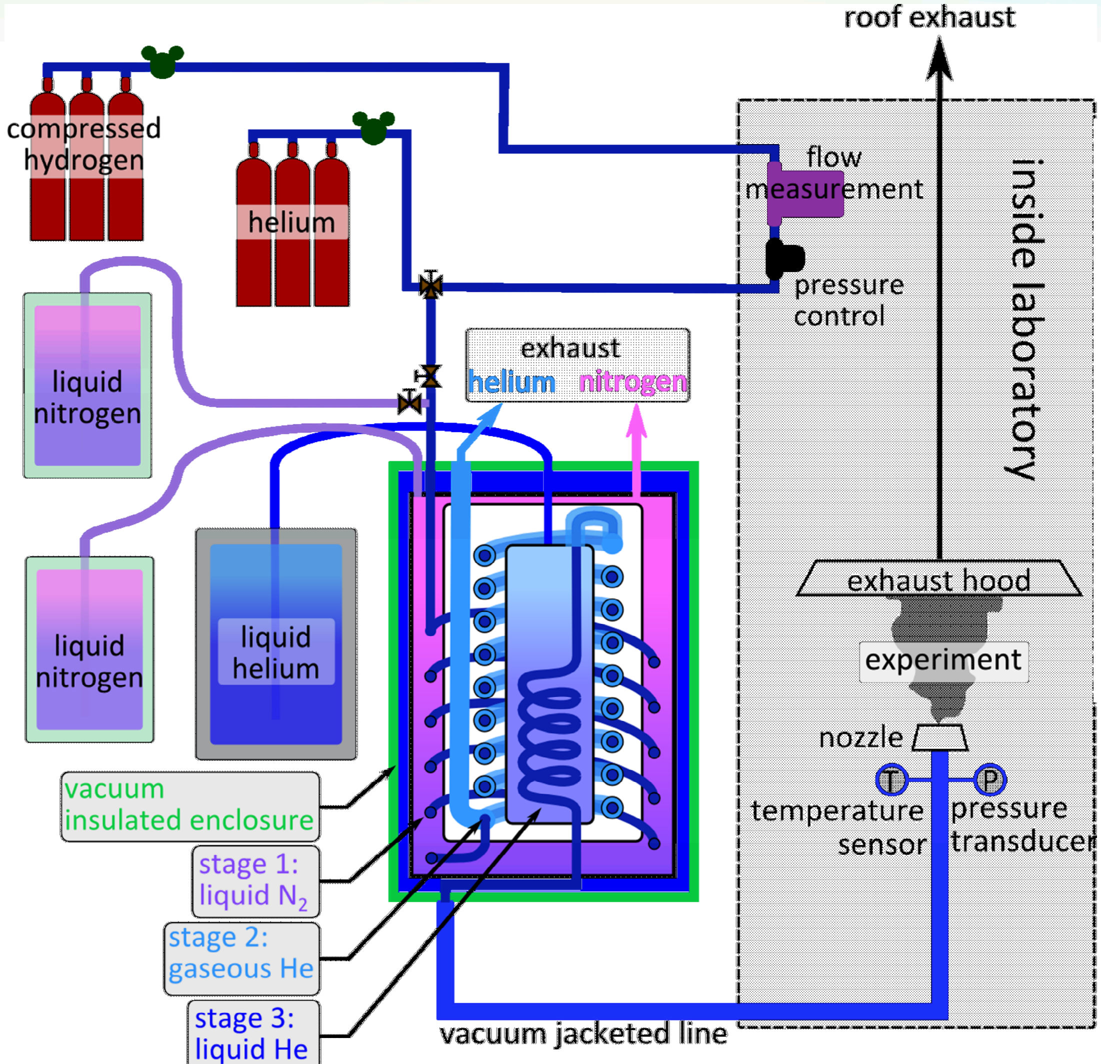
- Team members:
  - Bikram Roy Chowdhury (behaviors), Anthony McDaniel (behaviors), Rad Bozinoski (modeling), Myra Blaylock (CFD), Jon Zimmerman (H2 program manager), Chris San Marchi (materials/metal interactions with H2), Chris LaFleur (Risk, Codes & Standards), John Reynolds (HyRAM), Nalini Menon (polymer interactions with H2), Alice Muna (Risk)
  - Previous researchers including: Katrina Groth, Isaac Ekoto, Adam Ruggles, Bob Schefer, Bill Houf, Greg Evans, Bill Winters

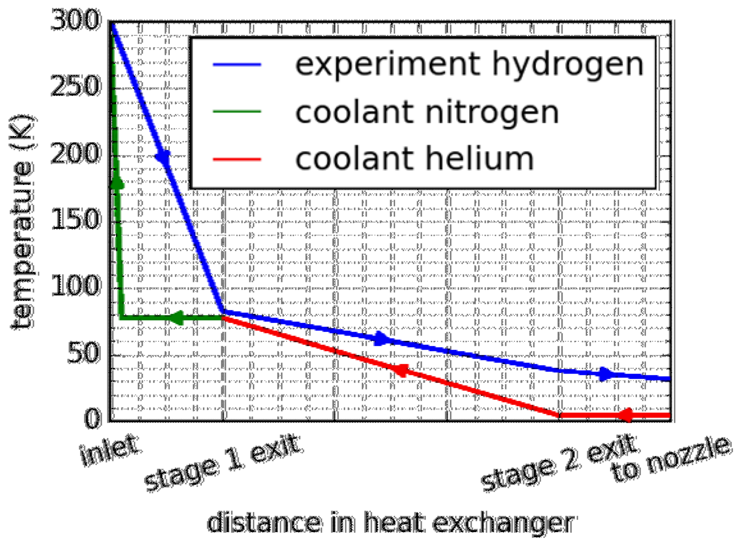
(Air) icing at the nozzle likely improves mixing for temperatures < 50K





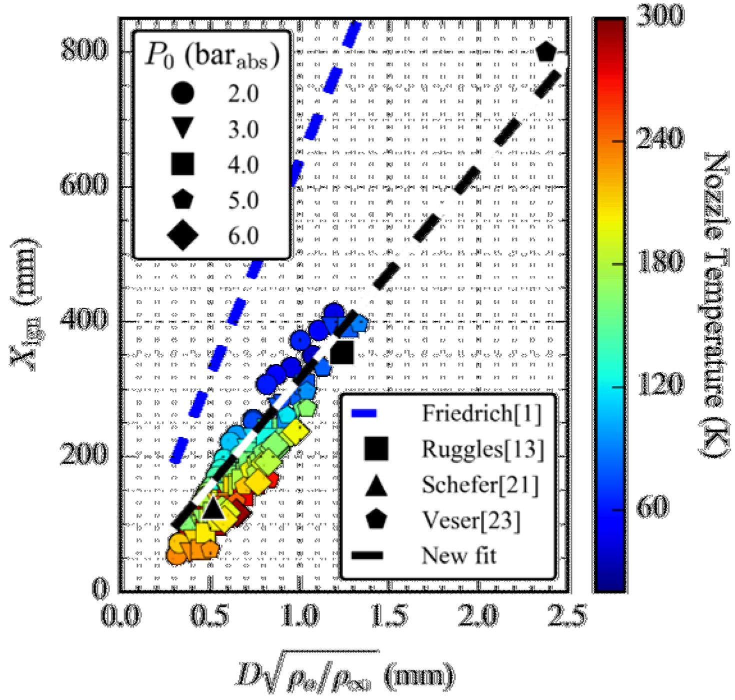
We are running an experiment, releasing ultra-cold hydrogen in the laboratory

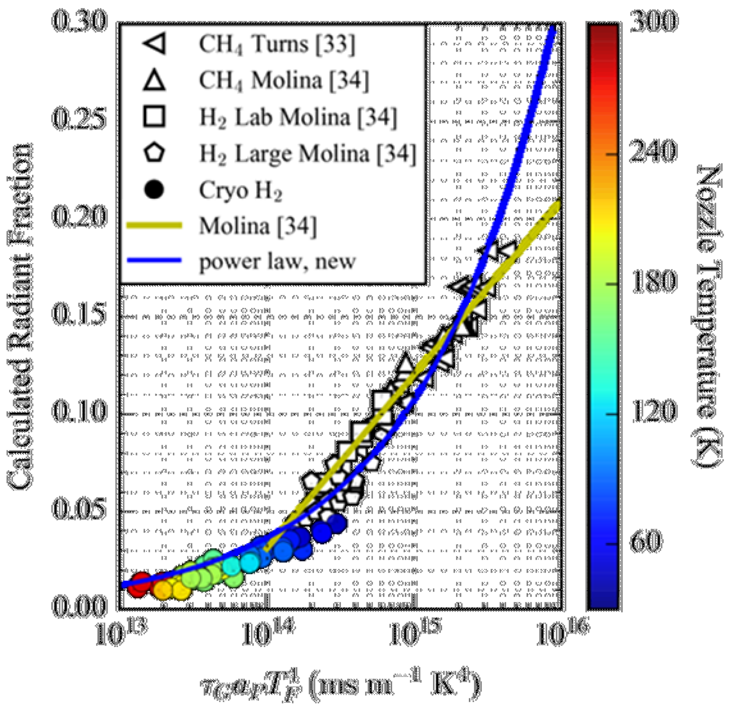




- Accurate control/measurement of boundary conditions

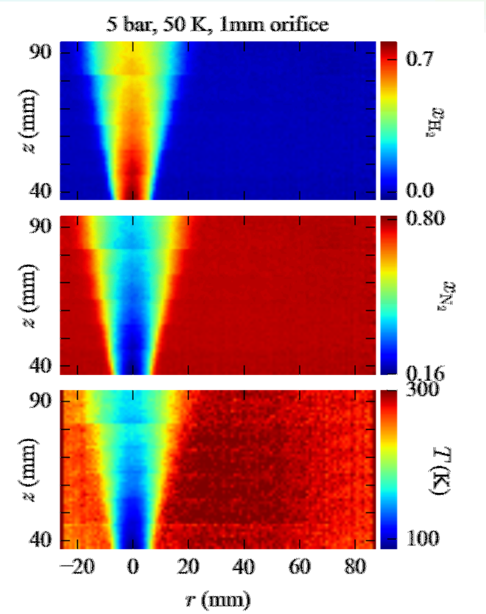
Ignition distance and radiant fraction were mapped out last FY





Sandia has 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



HYRAM
HYDROGEN RISK ASSESSMENT MODELS