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Research on gaseous and cryogenic hydrogen physics with applications to safety codes and standards

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Sandia National Laboratories

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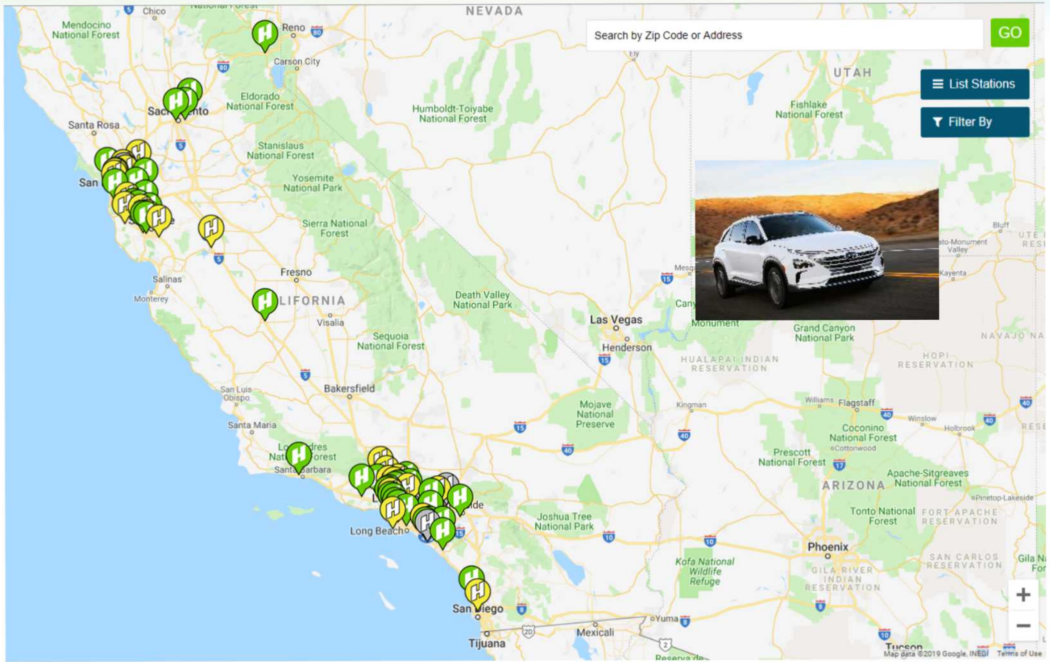
Hydrogen fuel cell vehicles are on the road today

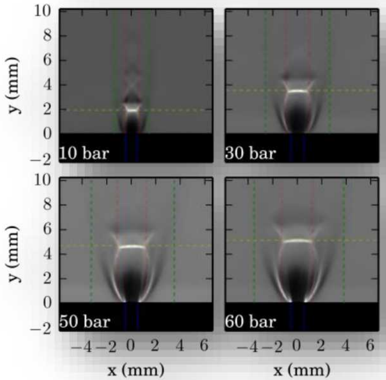


Current station map (40 open stations, 23 under development)
Map from CaFCP.org

2030 station density (1000 stations could support 1 million vehicles)

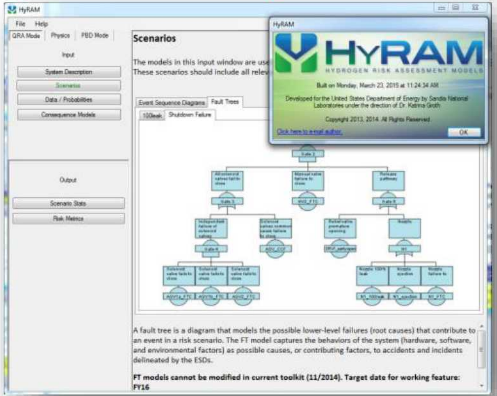
The hydrogen safety codes and standards team studies scientific fundamentals to generate models that can be used to quantify risk

H_2 behavior R&D



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

QRA methods, tools R&D



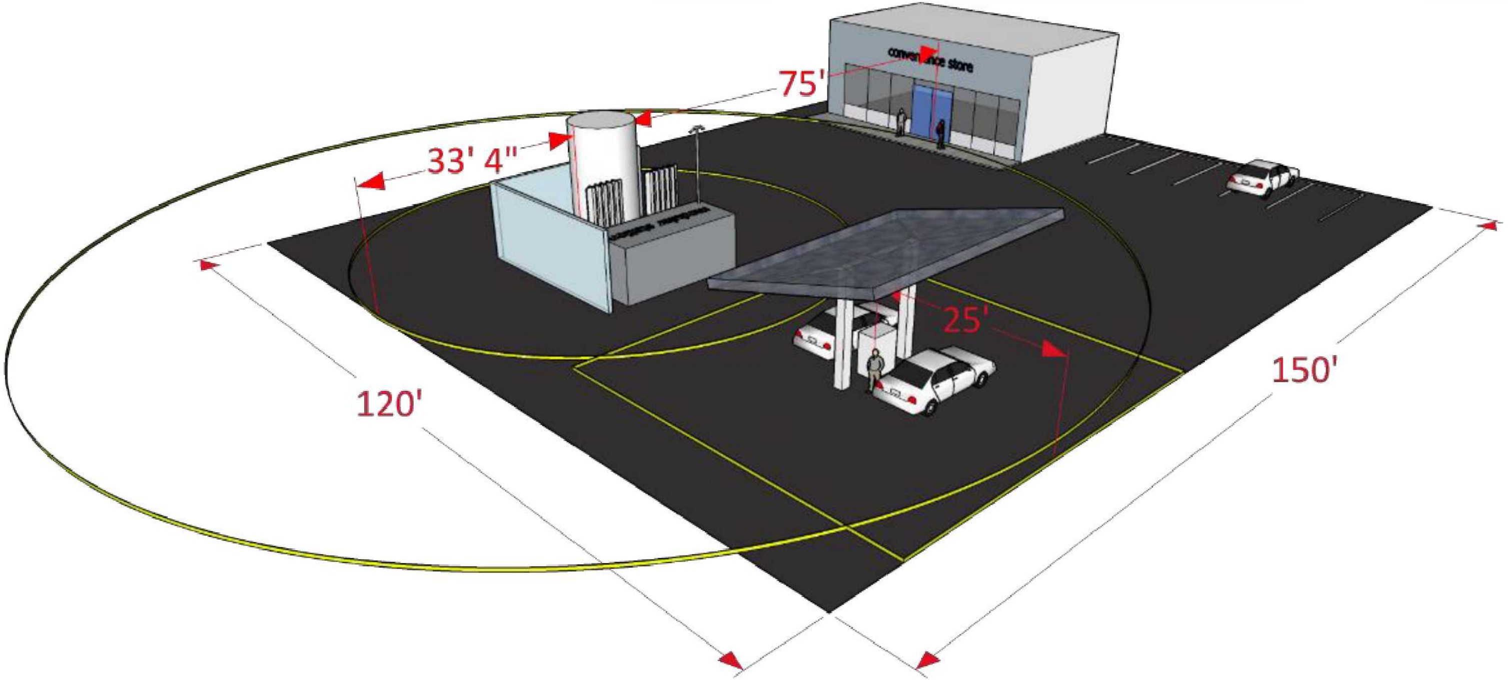
Develop integrated algorithms for conducting QRA (Quantitative Risk Assessment) for H_2 facilities and vehicles

Apply R&D in RCS

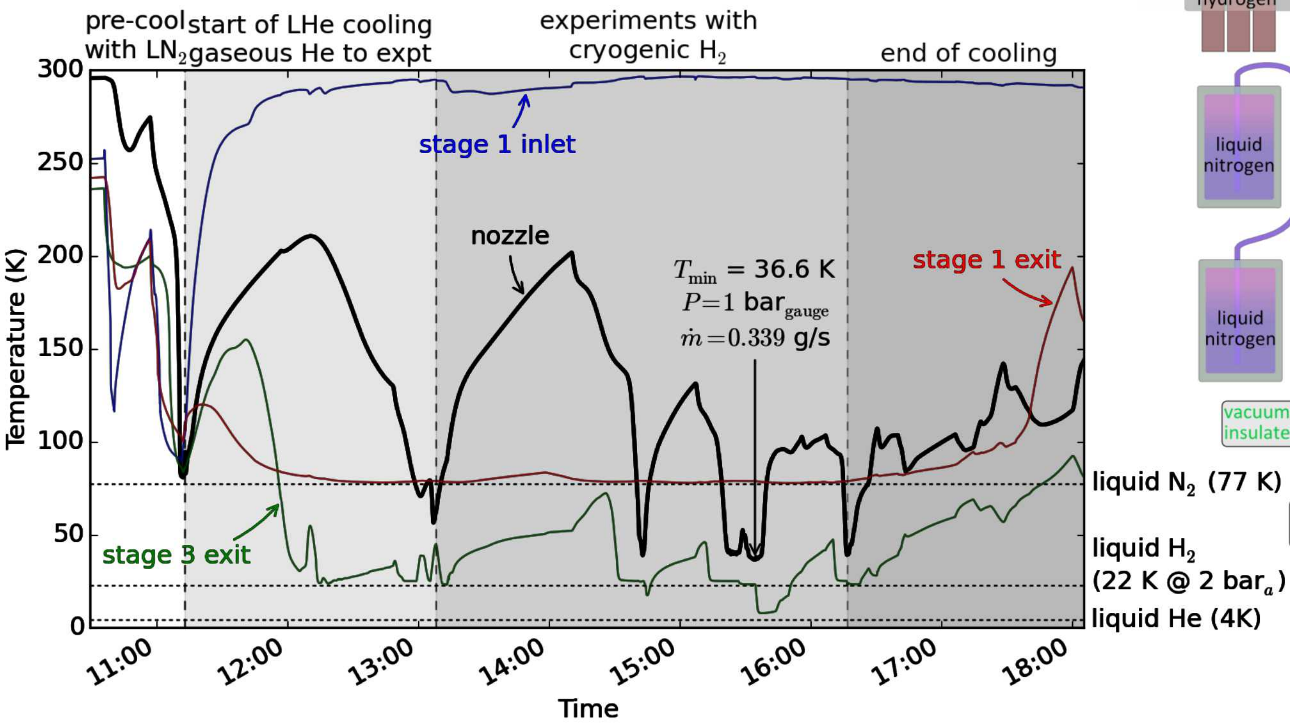
Apply risk assessment techniques in step-out hydrogen technologies

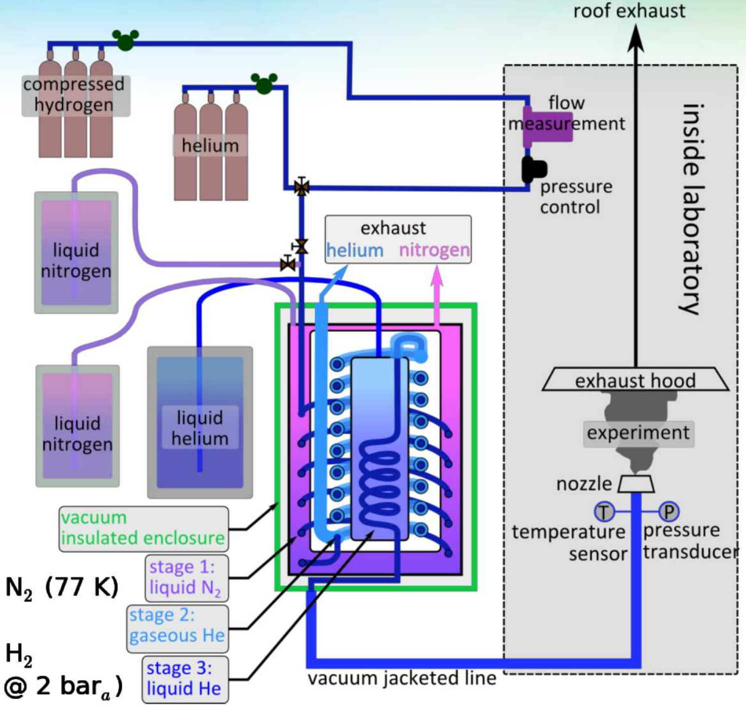
Enabling methods, data, tools for H_2 safety & RCS community

Current experiments are focused on understanding cryogenic hydrogen systems to provide a scientific basis for setback distances

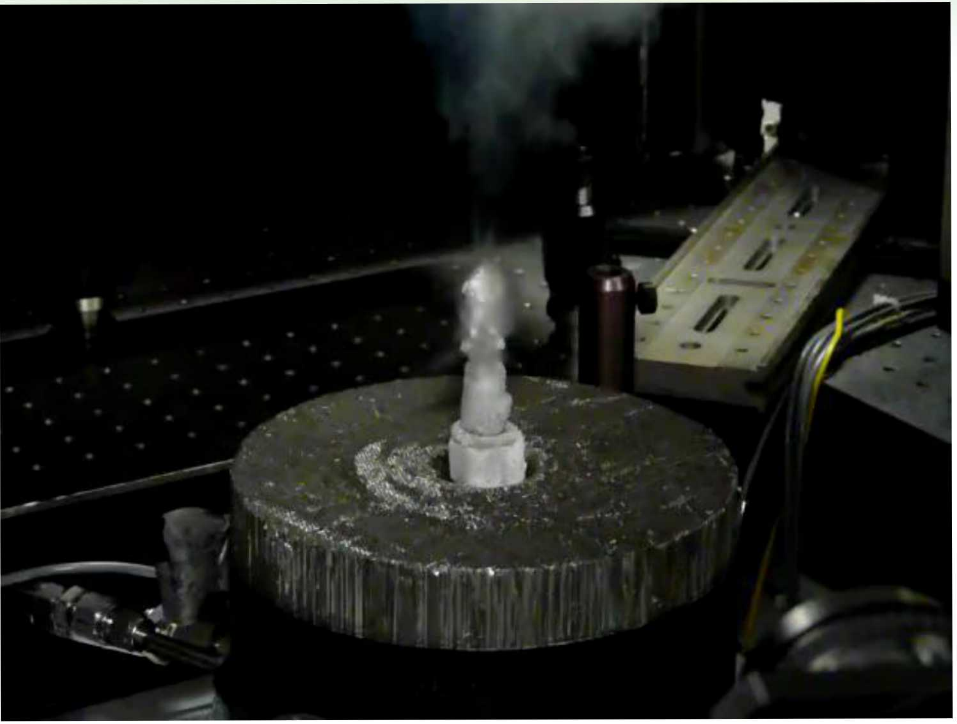


We are releasing cryogenic hydrogen in this laboratory to study its dispersion and flame properties



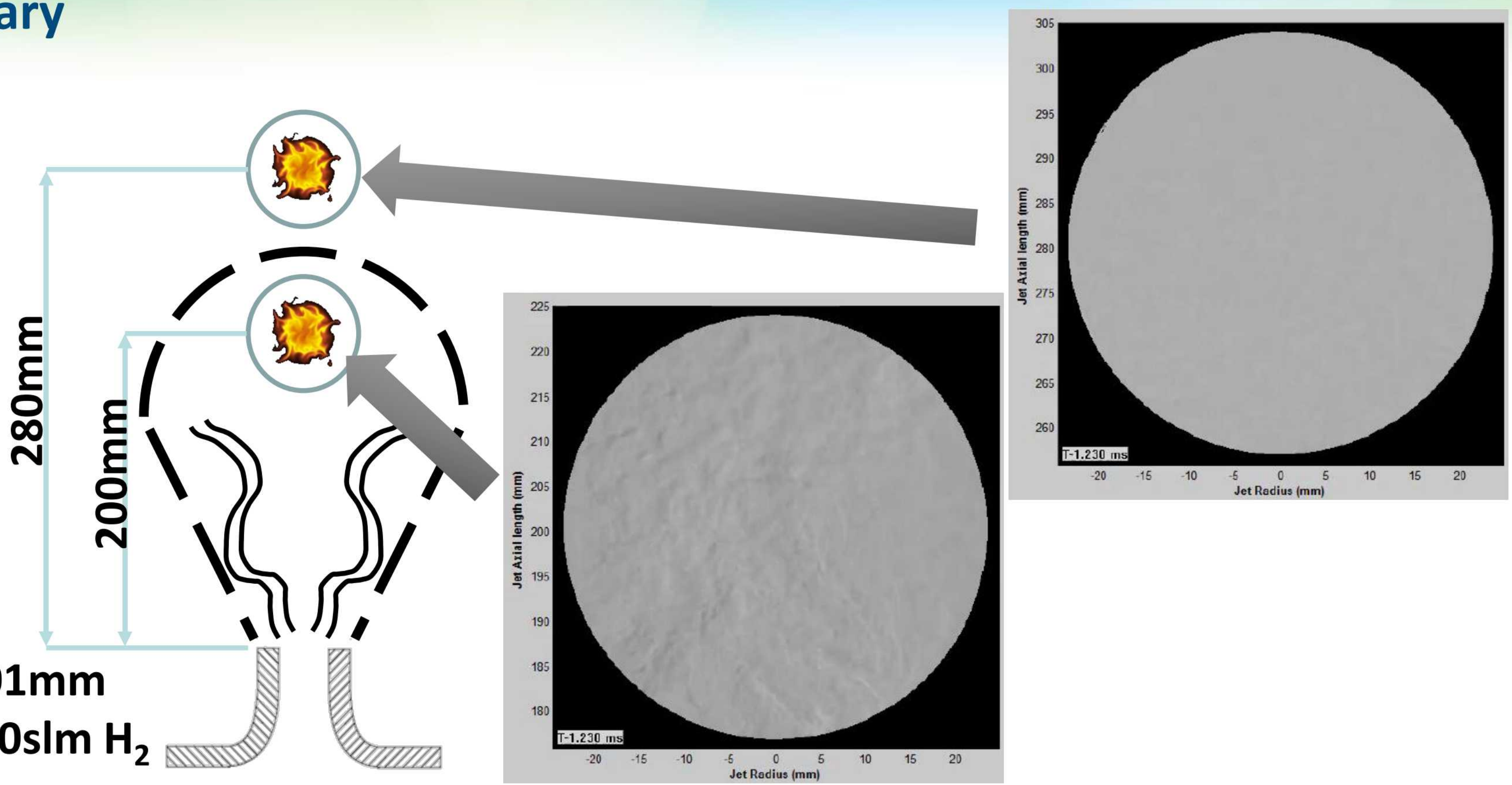


Moisture and air freeze on the nozzle as the temperature drops



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

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

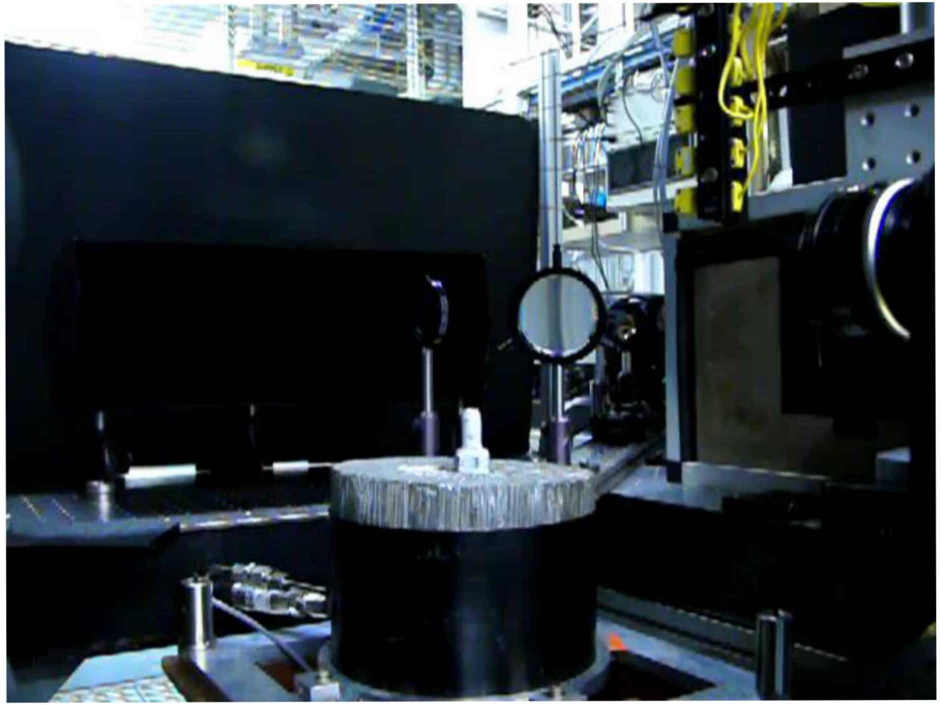


D = Ø1.901mm

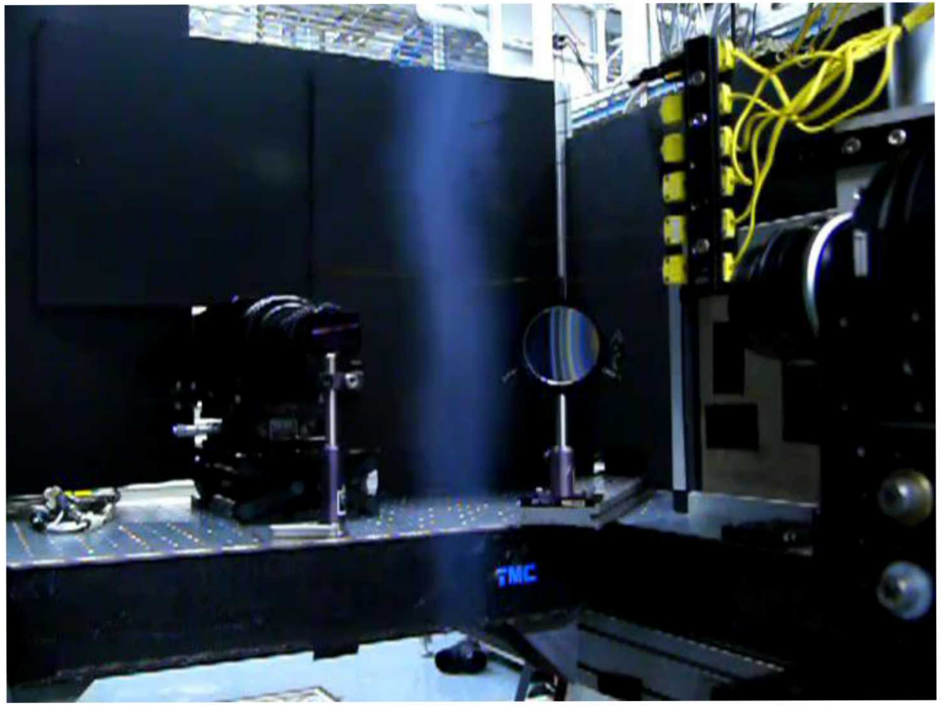
Flow = 100slm H_2

We have measured the ignition distance of cryogenic hydrogen, and mapped out the radiative properties of cryogenic flames

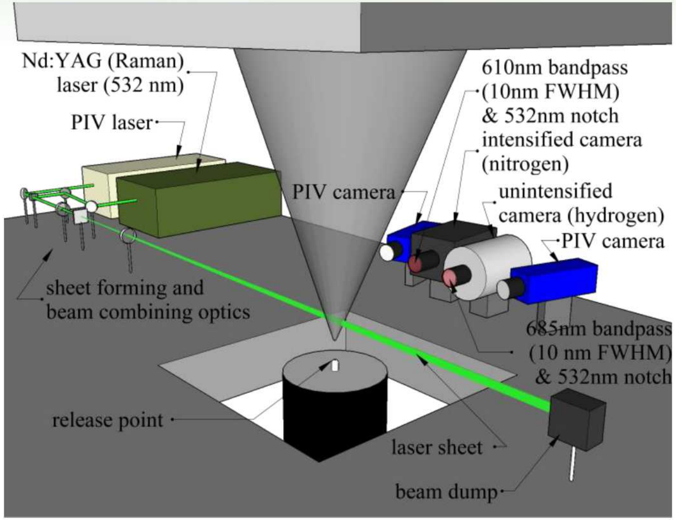
P = 1 bar, T = 290 K, distance = 85 mm

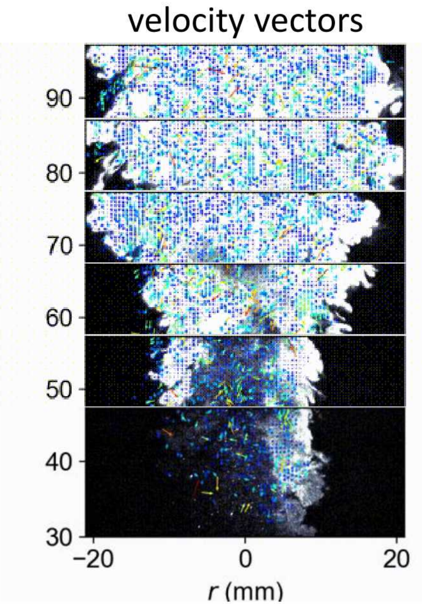


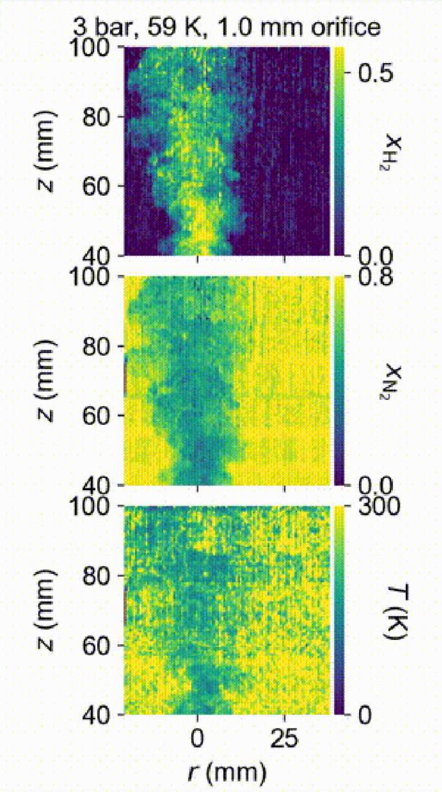
P = 1 bar, T = 37 K, distance = 325 mm



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



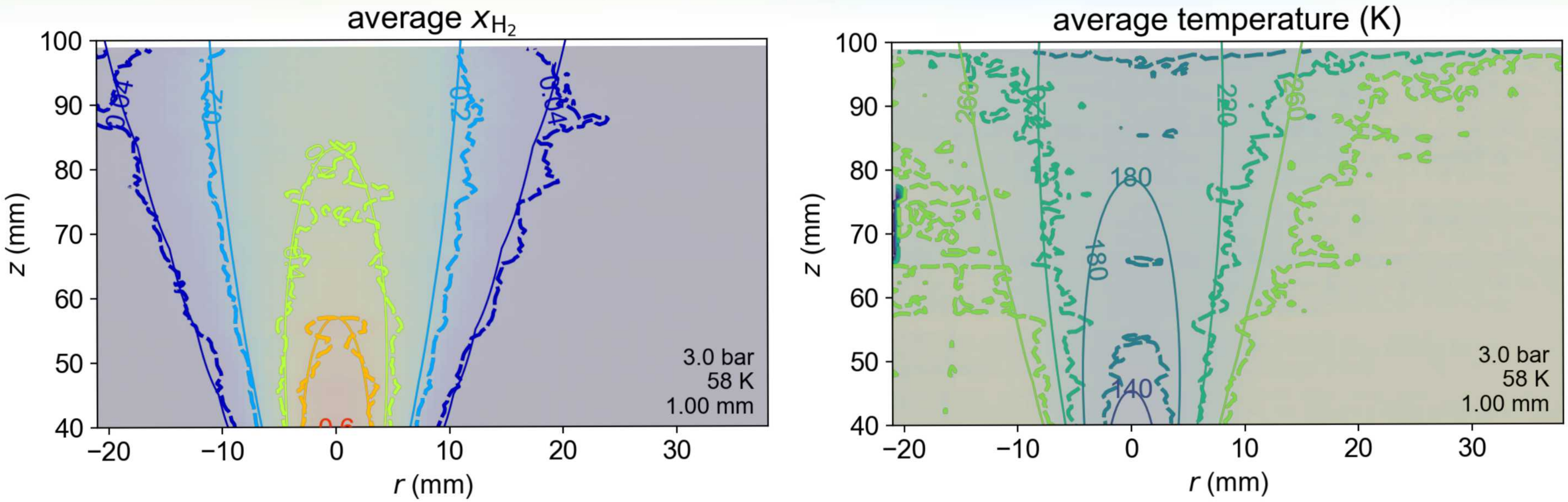




Independent model parameters:

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

We use our measurements to validate the models

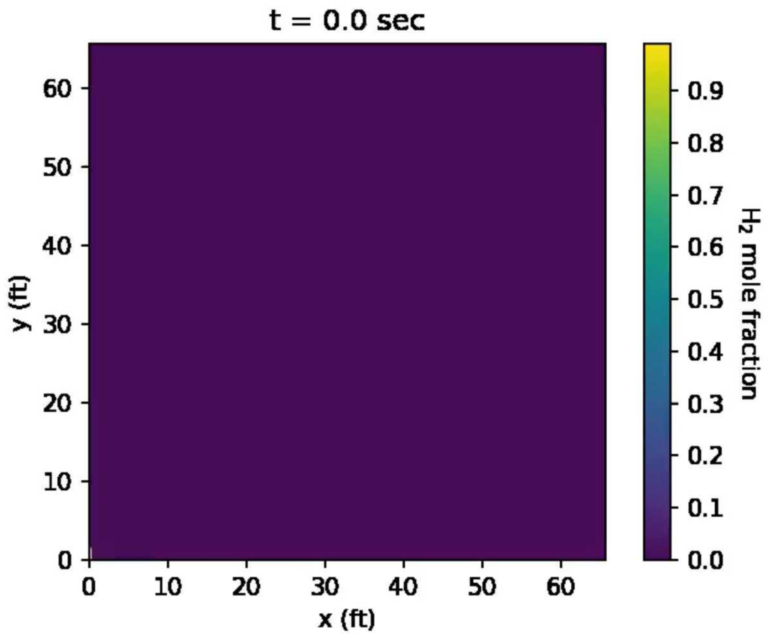


- Experiment: thick, dashed lines and shading
- Model: think, solid lines

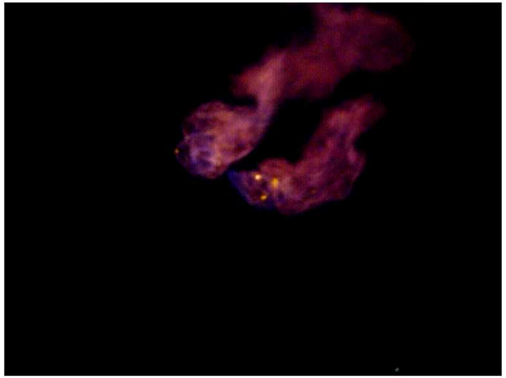
Fast-running, first order models are used in HyRAM to predict hydrogen trajectory and concentration contours (and flames)

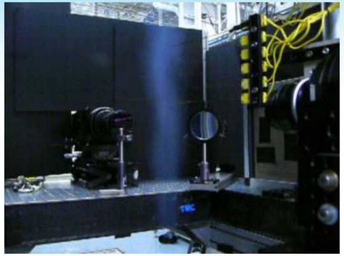
- Captures buoyancy effects without full CFD
- Makes it possible to rapidly run many scenarios
- Physical plume/jet (and flame) model coupled to probability of component failure and ignition models to ***quantify*** risk

HyRAM
HYDROGEN RISK ASSESSMENT MODELS



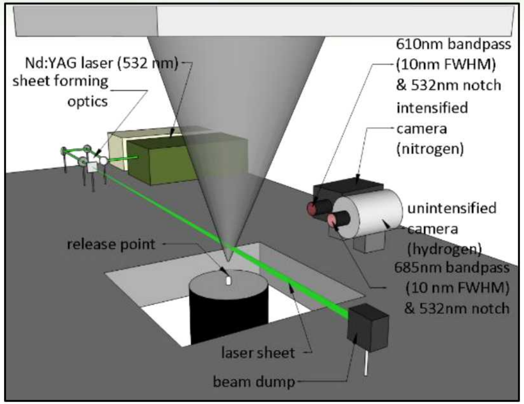
This fiscal year, we are planning larger outdoor experiments

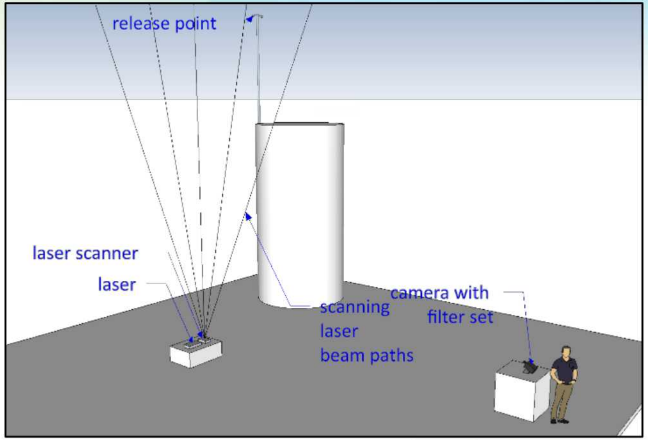


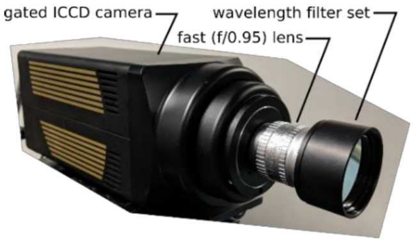


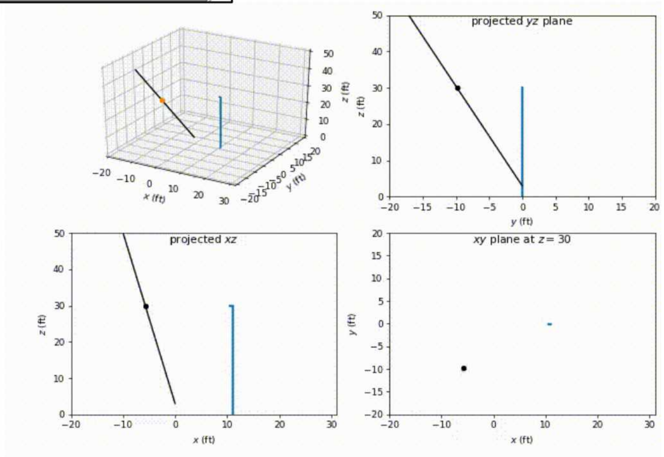
- Supporting the CGA G-5.5 testing task force measurements of LH_2 vent stack flames
- Working with coleagues at LLNL to measure dispersion from LH_2 vent stacks

We are currently developing a diagnostic to apply to large-scale and outdoor releases









We are also planning other large-scale experiments to study pooling, vaporization and pool-fires

LNG fires on water at Sandia Albuquerque

Large scale indoor facilities at Sandia Albuquerque

SRI Corral Hollow remote test site (near Livermore)

- Opportunities for collaborations

Collaborations enable this research and expand impact

- CRADA with BKi to fund experiments ($175k received from CaFCP Auto OEM Group, Linde, Shell)
  - Data exchange with contributing members
- H2@Scale CRADA with Air Liquide signed ($150 k from Air Liquide and partners, $150 k from DOE)
- NFPA 2 Technical Code Committee
  - Regular attendance with expert advisory role
- Fuel Cells and Hydrogen Joint Undertaking (FCH-JU, European Union)
  - Advisory board member for Prenormative Research for Safe Use of Liquid Hydrogen (PreSLHy) project
- Shandong University (China)
  - Hosted visiting professor with expertise on hydrogen behavior
- CGA G-5.5 testing task force
  - Providing hardware for and analysis support of measurements of LH_2 vent stack flames

We are leveraging multiple sponsors to enable this work and have a strong team

- Funding support from:
  - United States Department of Energy, Energy Efficiency &Renewable Energy, Fuel Cell Technologies Office, Safety, Codes, and Standards subprogram managed by Will James
  - Industry support including the OEM Group at the California Fuel Cell Partnership, Linde, and Shell
  - Industry support from Air Liquide
- Team members:
  - Ethan Hecht (behaviors), Tony McDaniel (behaviors), Bikram Roy Chowdhury (behaviors), 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) , Myra Blaylock (CFD), Rad Bozinoski (Modeling), Alice Muna (Risk), Brian Ehrhart (Risk)
  - Previous researchers including: Katrina Groth, Pratikash Panda, Isaac Ekoto, Adam Ruggles, Bob Schefer, Bill Houf, Greg Evans, Bill Winters

Larger scale experiments have been performed in collaboration with SRI International

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

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

Walls can be an effective mitigation strategy

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

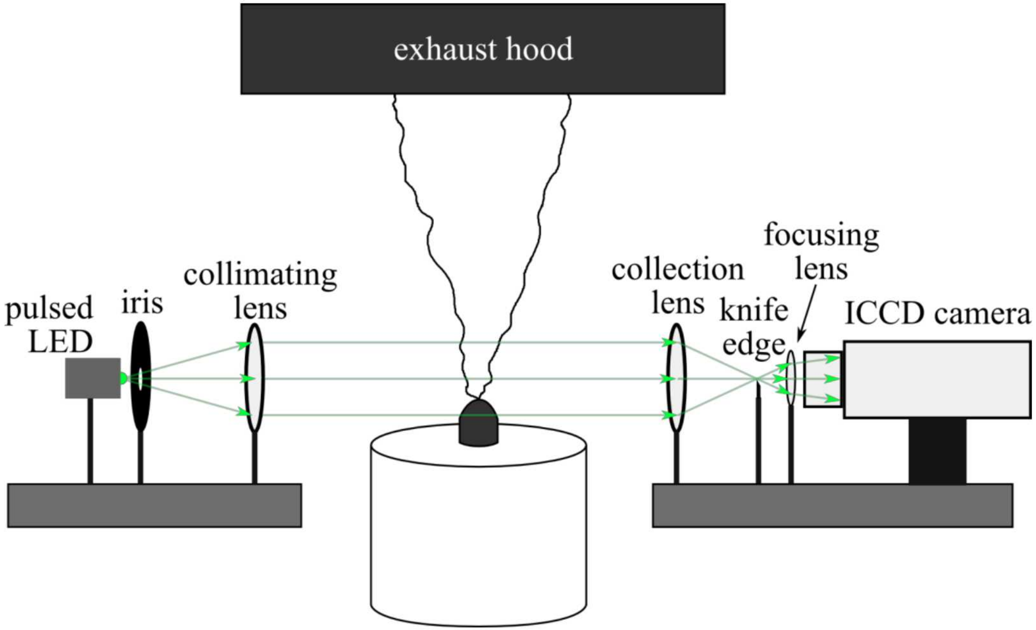
Risk requires a release and a hazard to cause harm (e.g., ignition leading to a jet flame that radiates heat to a person)

$$Risk \propto \sum_{i,j,k} P(\mathrm{Release}_i)P(\mathrm{Ignition}_j)P(\mathrm{Hazard}_k)P(\mathrm{Harm})$$

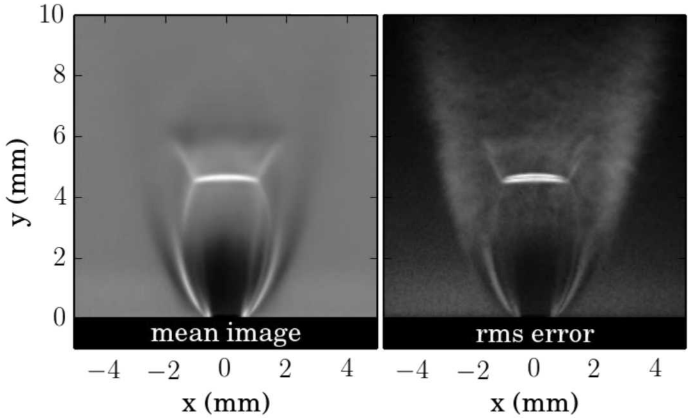
Goals:

- Understand releases from high-pressure and cryogenic fuel sources
  - release characteristics (e.g., shocks)
  - dispersion, mixing, heat transfer with air
  - ignition
- Validate fast-running engineering models that can be coupled to probabilistic models for a range of release scenarios
- Validate models for CFD simulations of specific scenarios

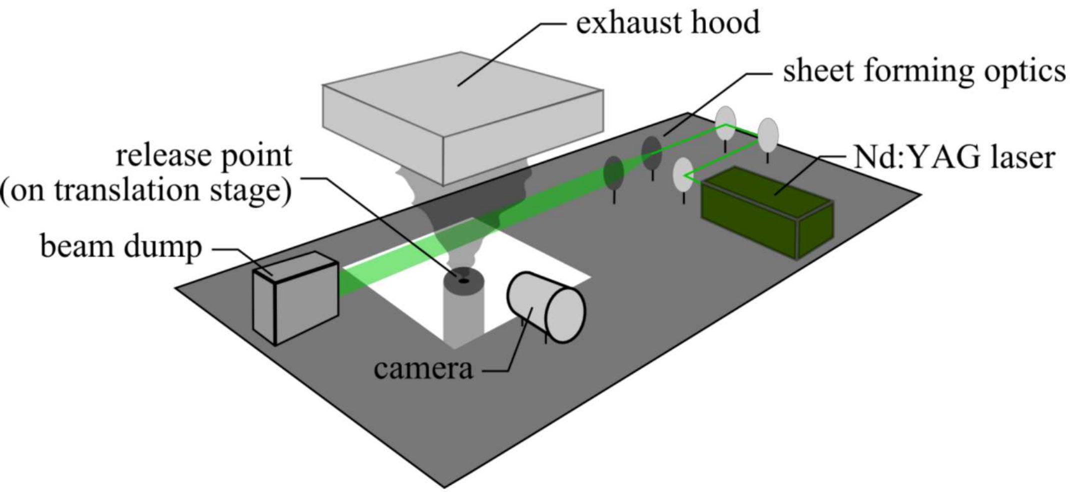
Schlieren imaging is used to characterize near-nozzle region and other regions with high density gradients



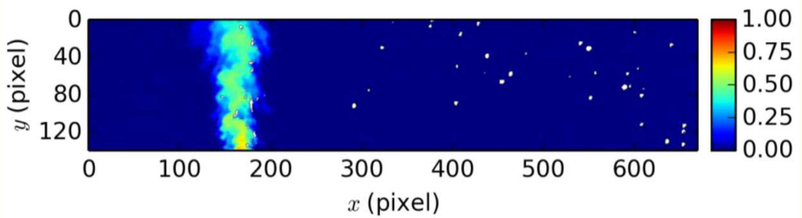
50 bar room temperature H_2 release



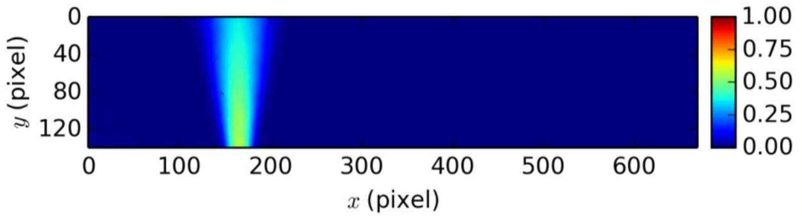
Planar laser Rayleigh scattering is used to measure concentration fields of high pressure and room temperature gases



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

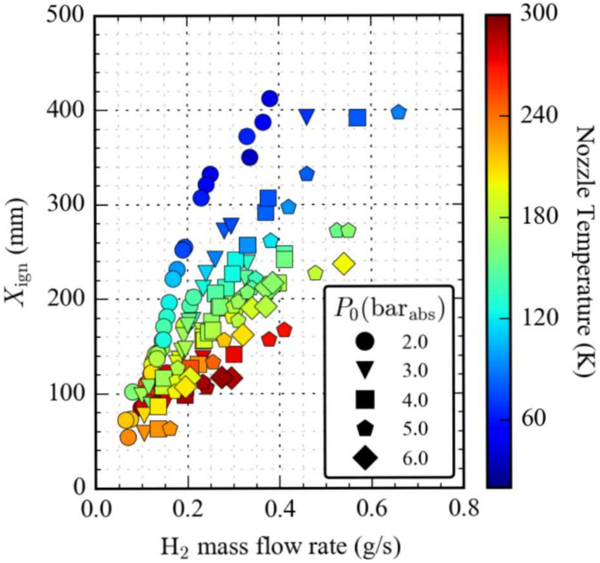


Instantaneous

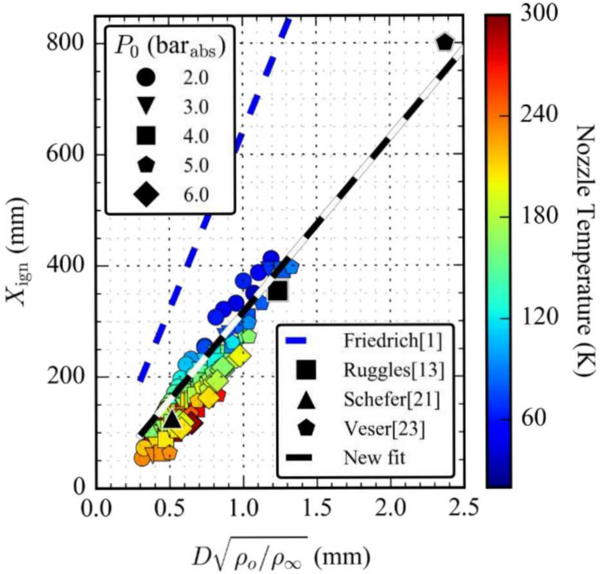


Mean

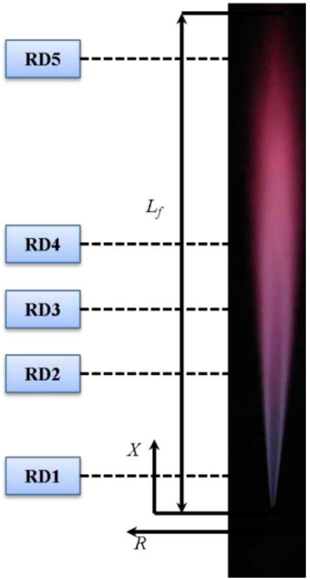
Maximum ignition distance for cryogenic hydrogen

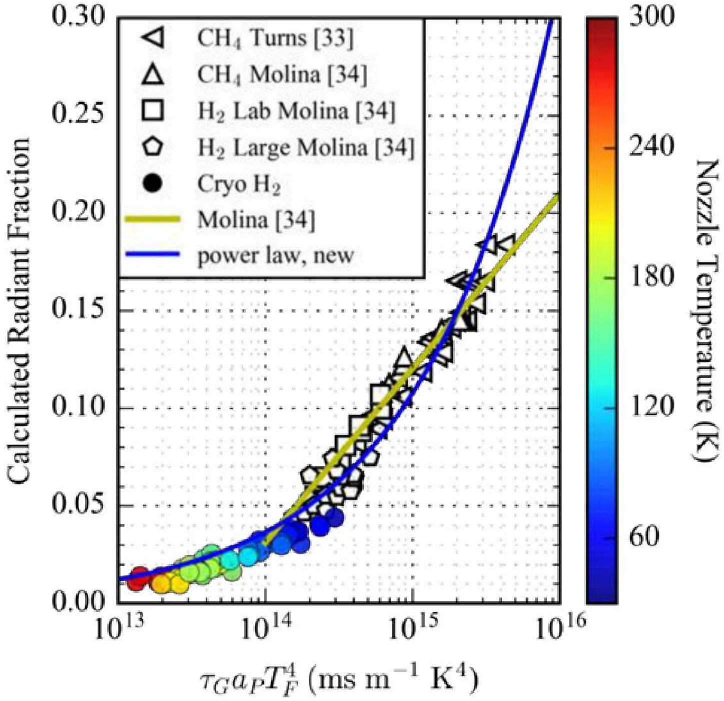


- for a given mass flow, ignition of cold H_2 occurs much further from the release point
- temperature affects ignition distance much more than pressure
- a maximum ignition height is achieved at a lower mass flow rate of hydrogen for the colder jets
- Maximum ignition distance linearly varies as a function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



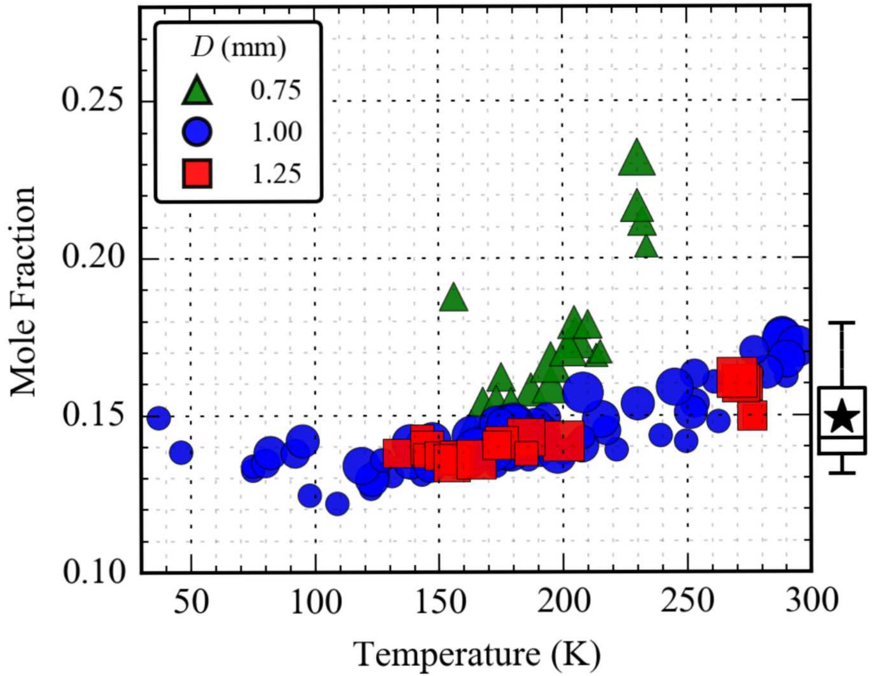
Radiant fraction for cryogenic hydrogen jet flames scales the same as room temperature jet flames





- 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

Simulated H_2 mole fraction at the point of ignition is much greater than the 4% LFL



- Simulated jet mean hydrogen mole fraction at each ignition point using ColdPLUME
- No significant trend observed in terms of temperature or pressure
- 90 % of the data lies within 0.13 -0.18 mole fraction