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Hydrogen behavior R&D for Safety, Codes and Standards at Sandia National Labs

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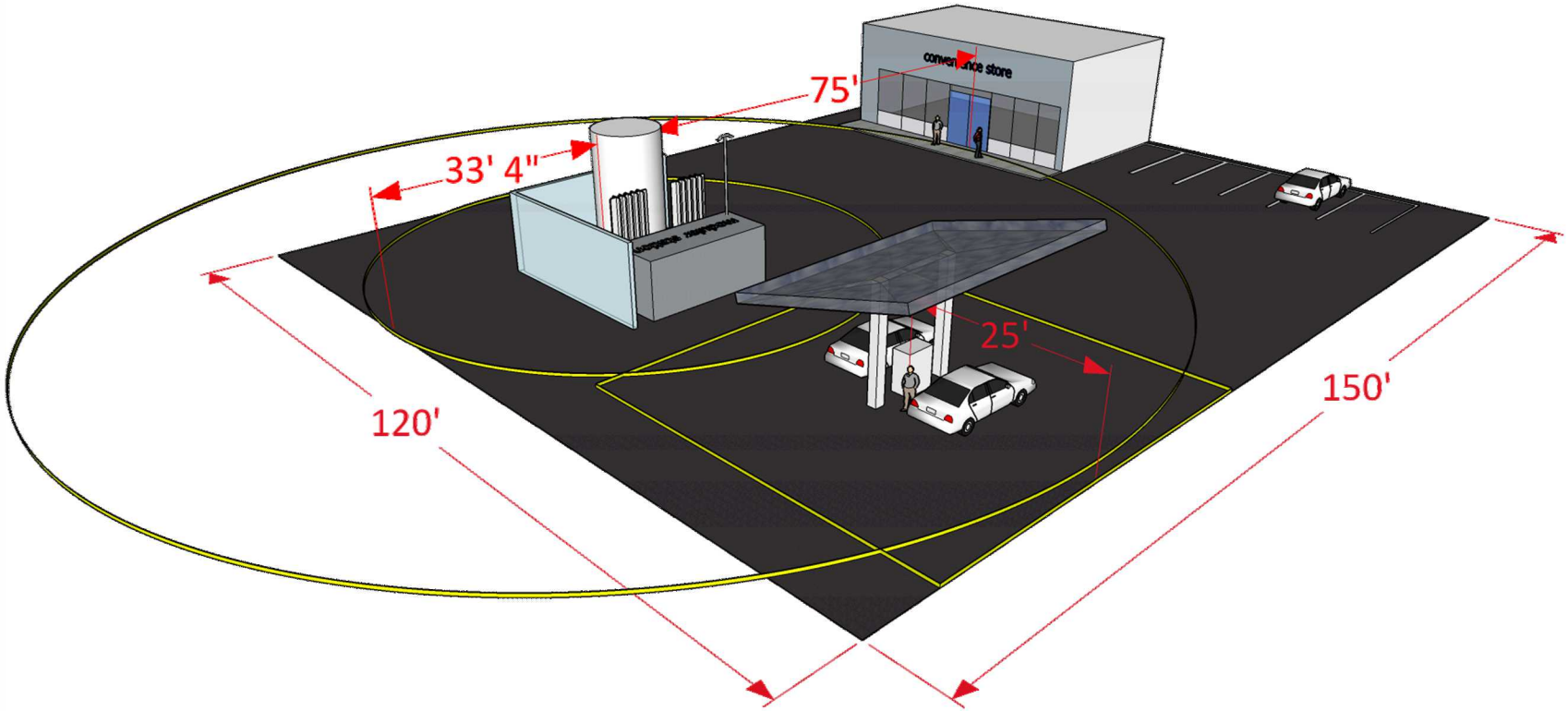
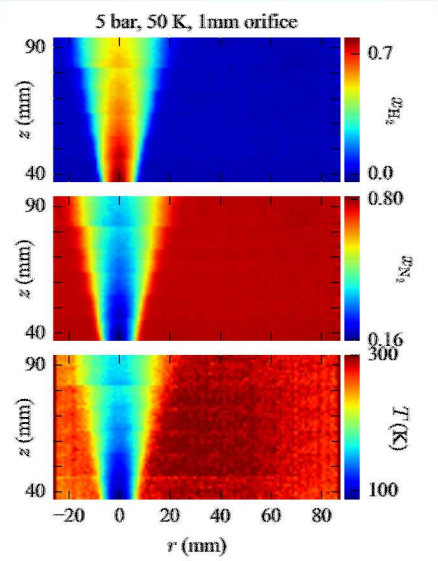
Current separation distances for liquid hydrogen are based on consensus, not science

- Higher energy density of liquid hydrogen over compressed H_2 (and lack of pipelines) make this technology viable for larger fueling stations (logistically and economically)
- Even with credits for insulation and fire-rated barrier wall 75 ft. offset to building intakes and parking make footprint large
- Previous work by our group led to science-based, reduced, gaseous H_2 separation

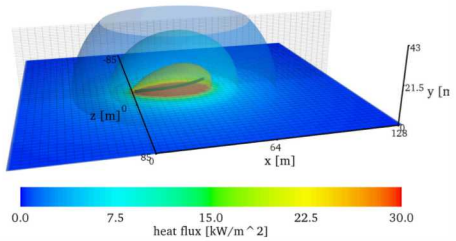


Sandia's Approach: coordinated activities that facilitate deployment of hydrogen technologies

- 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



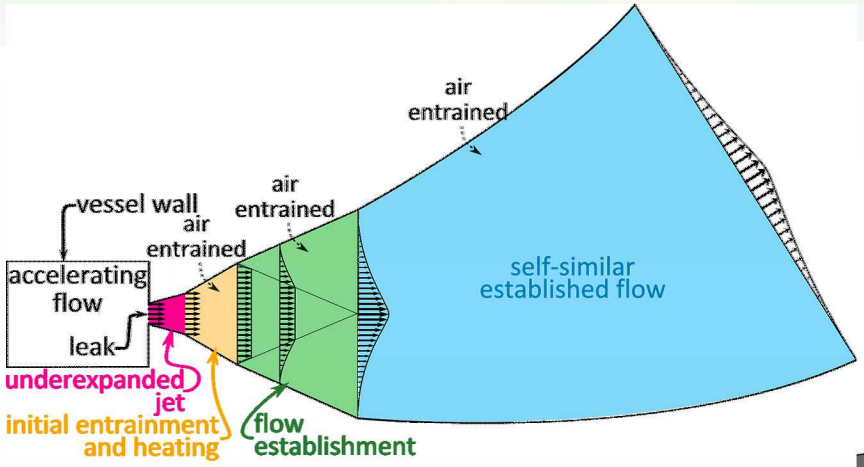
Need to enable *predictive* modeling across H_2's range of use (cryogenic models lack validation)

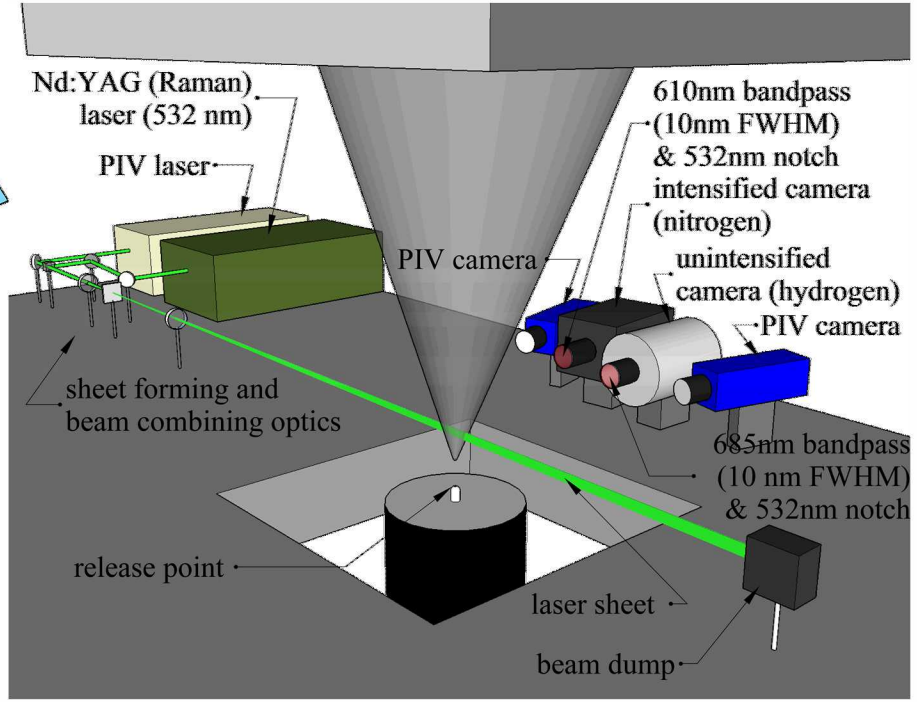
Issue: Cryogenic H_2 releases have been outdoors and/or instrumented with low fidelity sensors (space and time), with experimental uncertainty too high for model validation

- FY18 goals:
  - Complete analysis of lab-scale experimental data and validation of ColdPLUME model - complete
  - FY18 milestone: Develop a diagnostic and measure the plume from a liquid hydrogen truck depressurization in at least 2 dimensions

➢ Enable the simulation of critical scenarios and provide the science for revisions to the 2022 edition of NFPA 2

Lab-scale cryogenic hydrogen dispersion analysis and model validation





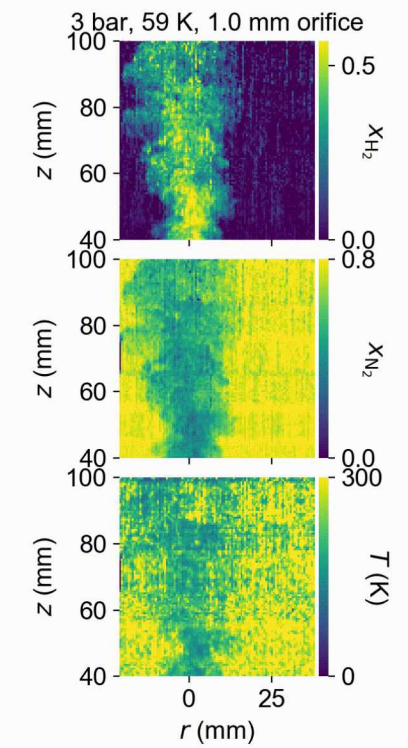
Measuring all independent model parameters:

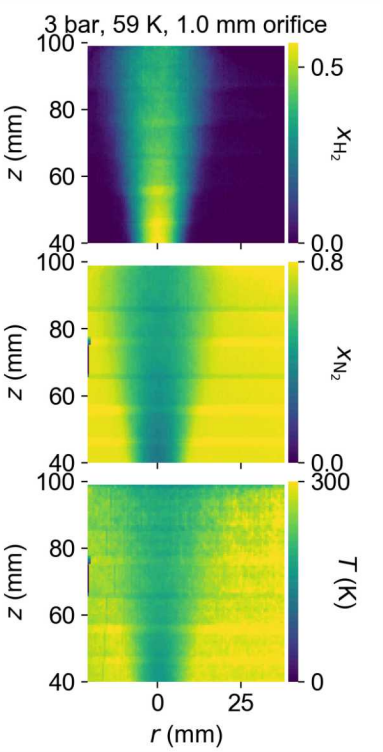
- ✓ T - temperature
- ✓ x - mole fraction
- ✓ v - velocity
- ✓ B - halfwidth (velocity, concentration, temperature)

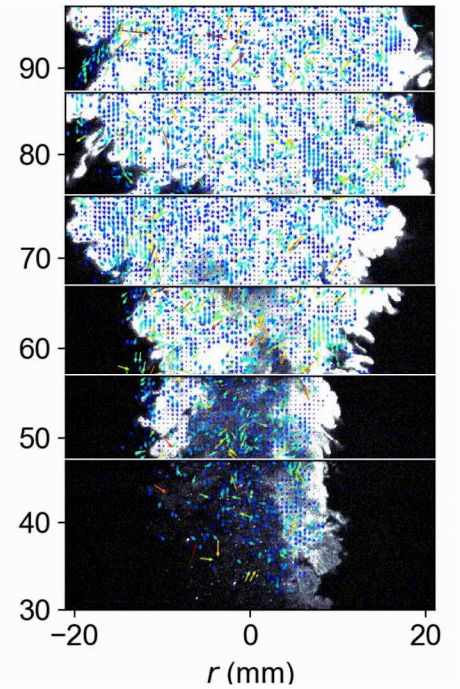
Have completed experiments with variations in temperature, pressure and nozzle size

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

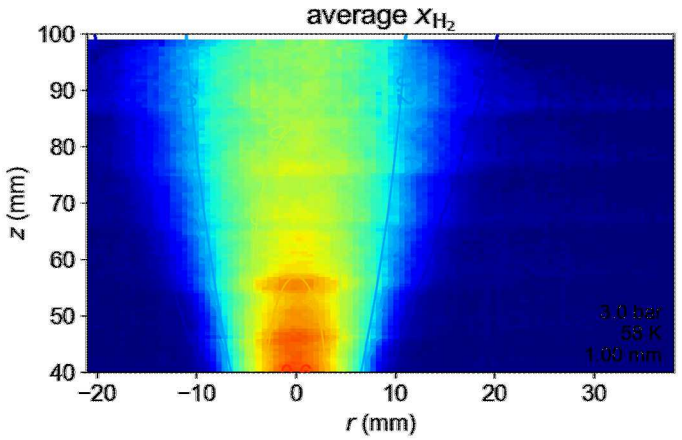


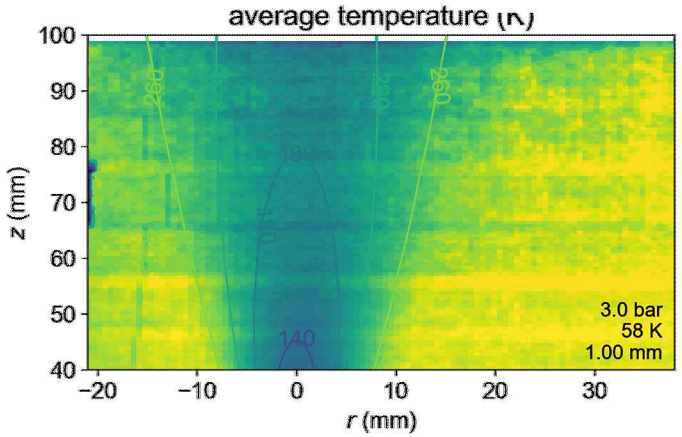


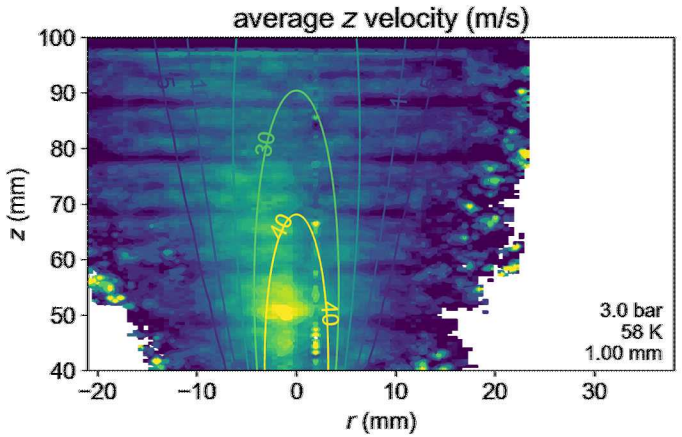


➢ Measuring dispersion in two-dimensions

The ColdPLUME model shows good agreement with the data







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

How to measure large-scale LH_2 releases (vent stacks after LH_2 delivery, evaporation from LH_2 pool, etc.)

Ideal data for model validation: quantitative concentration, velocity, temperature in 3-dimensions + time at high resolution

- Sensors
  - Can be low cost and easy to implement
  - Require gas to flow over them (placed in flow, or suction, disturbs flow)
  - Point measurements (challenging to get spatial resolution)
  - Can be affected by environmental factors (not specific to H_2)
- Optical
  - Can provide high spatial and temporal resolution
  - Non-intrusive
  - H_2 is a challenging gas to measure optically

➢ Decision: pursue optical techniques

Many optical techniques are not suitable for measuring large-scale LH_2 releases

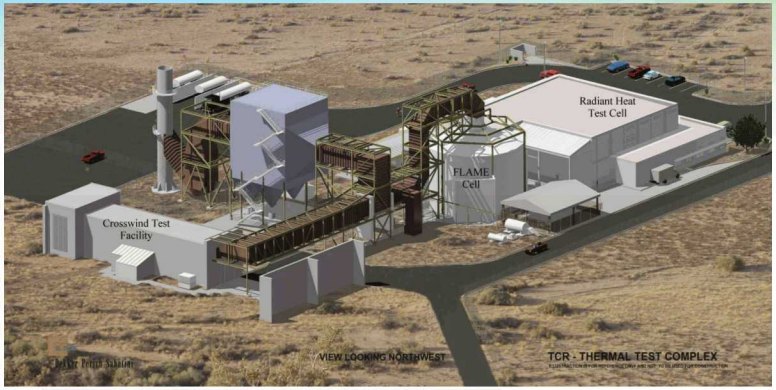
- Schlieren – cannot distinguish between temperature and concentration caused density variations (not quantitative)
- Fluorescence – no fluorescing species in the flow or species that could be seeded into the flow
- Absorption – no strong absorption features, and complex detector/illumination scheme
- Rayleigh – cannot distinguish between temperature and concentration caused density differences, entrained moisture scatters too much light
- Raman – shown to work in a laboratory setting, enables quantification of temperature and composition in multiple dimensions

➢ Challenge is how to scale-up laboratory Raman setup for larger releases

We are currently evaluating hardware to enable the large-scale diagnostic

- Need large light collection area to capture the small number of photons emitted
  - Reflective optics (large telescope mirror)
  - Refractive optics (Fresnel lens)
- High-powered light source required to excite as many molecules as possible
  - High-power laser with volumetric illumination
  - High-repetition rate laser scanned across the area quickly
  - High-power diodes
- Effective background light suppression is key (both sunlight and illumination source that reflects off of condensed water vapor)
  - Time gating
  - Spectral gating

We are also planning well-controlled large-scale release experiments



Need experiments to characterize:

- Pooling
- Evaporation from LH_2 pools

Planning underway for experiments at 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

Summary:

- **Approach**:
  - Develop and validate scientific models to accurately predict hazards and harm from liquid releases, flames, etc. Generate validation data where it is lacking.
- **Accomplishments:**
  - Measured cryogenic hydrogen dispersion (concentration, temperature, and velocity in two-dimensions) at lab-scale (≈1 mm sized orifice)
  - Validated integral model of dispersion
  - Studied ignition distance and radiative heat flux from cryogenic hydrogen flames
- **Future Work:**
  - Develop diagnostic for large scale cryogenic hydrogen dispersion experiments
  - Perform experiments on outdoor, normal LH_2 vent stack releases
  - Perform experiments on well-controlled (i.e. indoor) large LH_2 releases

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