

Summary of liquid H₂ research at Sandia National Laboratories

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 - Previous researchers including: Joe Pratt, Pratikash Panda, Katrina Groth, Isaac Ekoto, Adam Ruggles, Bob Schefer, Bill Houf, Greg Evans, Bill Winters

Motivation: As FCEV fueling stations serve higher capacity, liquid hydrogen delivery and on-site storage is the likely technology

- For a similar vehicle/day capacity as gasoline, liquid H₂ tankers make sense
 - Underground gasoline stations tanks hold on the order of 10,000 gallons
 - Liquid H₂ tankers can hold up to approximately 4,000 kg
 - Compressed tube trailers hold approximately 300 kg
 - Lack of hydrogen pipelines where stations are needed
- High purity hydrogen needed for FCEVs
- Cryo pump and utilization of cold make compression and dispensing efficient and fast



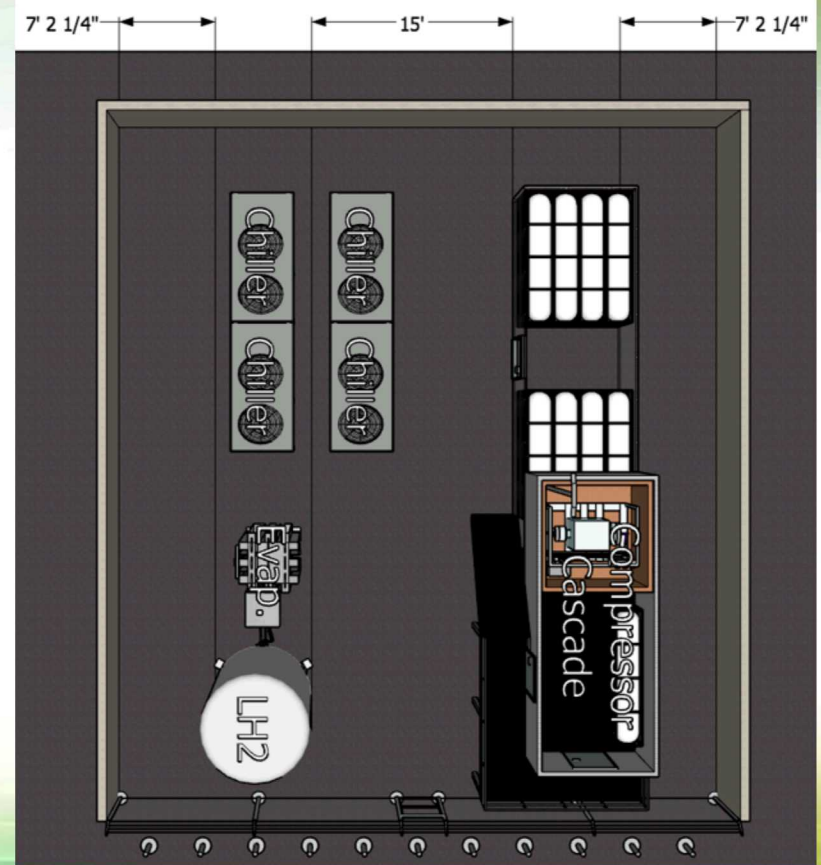
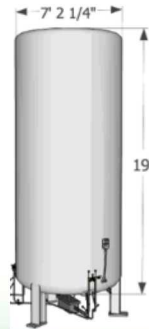
Linde's cryo pump fueling station system
<https://www.youtube.com/watch?v=Pjh639S2dek>

General NFPA 2 Requirements for Hybrid Hydrogen System



- The hybrid hydrogen system includes both liquid and compressed gas storage
 - Compressor
 - Evaporator
 - Cryogenic pump
- Liquid and gaseous portions of the combined system must be separated by at least 4.6 m (15 ft)

- Vertical tanks shall be located at a distance not less than 1 tank diameter from the enclosing walls



NFPA 2 Setback Distances for Liquid Hydrogen Bulk Systems



- Each **exposure type** has a different requirement
- Setback distances required by NFPA 2 (Chapter 8) are based only on **total amount of bulk liquified hydrogen**
 - The density of liquid hydrogen (70.8 g/L) is used to calculate a total combined hydrogen volume in the system

Table 8.3.2.3.1.6(A) Minimum Distance from Bulk Liquefied Hydrogen [LH₂] Systems to Exposures

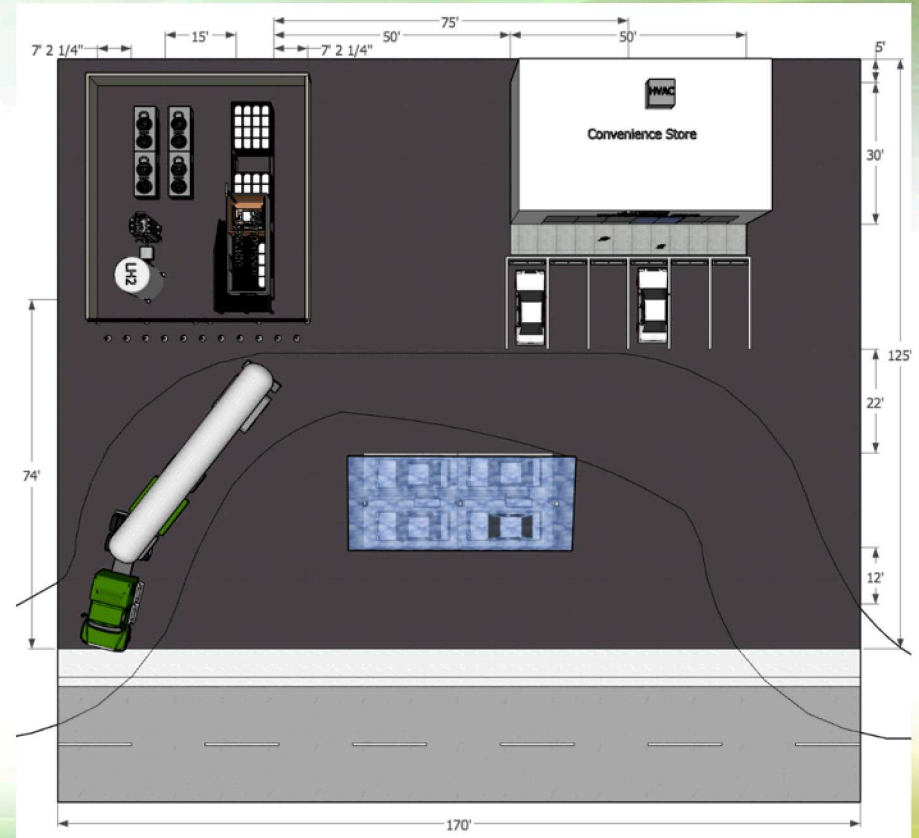
Type of Exposure	Total Bulk Liquefied Hydrogen [LH ₂] Storage											
	39.7 gal to 3500 gal		150 L to 13,250 L		3501 gal to 15,000 gal		13,251 L to 56,781 L		15,001 gal to 75,000 gal		56,782 L to 283,906 L	
	ft	m	ft	m	ft	m	ft	m	ft	m		
Group 1												
1. Lot lines	25	7.6	50	15	75	23						
2. Air intakes [heating, ventilating, or air conditioning equipment (HVAC, compressors, other)]	75	23	75	23	75	23						
3. Wall openings												
Operable openings in buildings and structures	75	23	75	23	75	23						
4. Ignition sources such as open flames and welding	50	15	50	15	50	15						
Group 2												
5. Places of public assembly	75	23	75	23	75	23						
6. Parked cars (distance shall be measured from the container fill connection)	25	7.6	25	7.6	25	7.6						
Group 3												
7. Building or structure												
(a) Buildings constructed of noncombustible or												
(c) Piping containing other hazardous materials	15	4.6	15	4.6	15	4.6						
16. Flammable gas metering and regulating stations above grade	15	4.6	15	4.6	15	4.6						

Layout for liquid hydrogen with base case assumptions



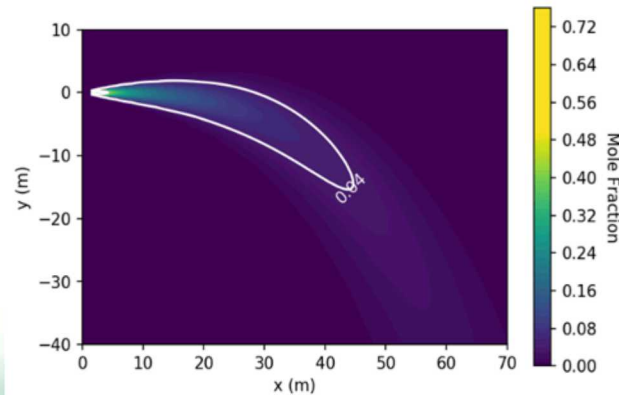
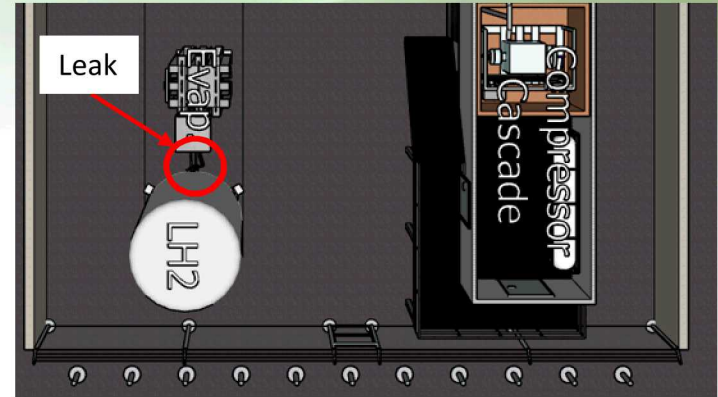
- Full Layout
 - Convenience store
 - Parking
 - Traffic flow
 - Delivery
- Total Footprint
 - 21,250 ft²

Non-hydrogen station components (e.g., delivery truck turning radius) have large effect on final station layout



Hazardous analyses and consequence assessments can enable deviations from setback distances

- A cold plume model was used to model the hydrogen concentration from the release point
- The hydrogen release was assumed to happen at the liquid storage tank
 - 25.4 mm (1 inch) OD pipe
 - At a pressure of 6 bar
 - An ID 14.27 mm (0.562 inch) leak of saturated liquid hydrogen is assumed



Outer contour shows the extent of a mean concentration at the lower flammability limit (4% hydrogen)

- Extends 45 meters from release point
- Credible leak much smaller than 100% (need data on LH2 leak frequencies)
- Turbulent jets require higher concentration (> 10%) to ignite

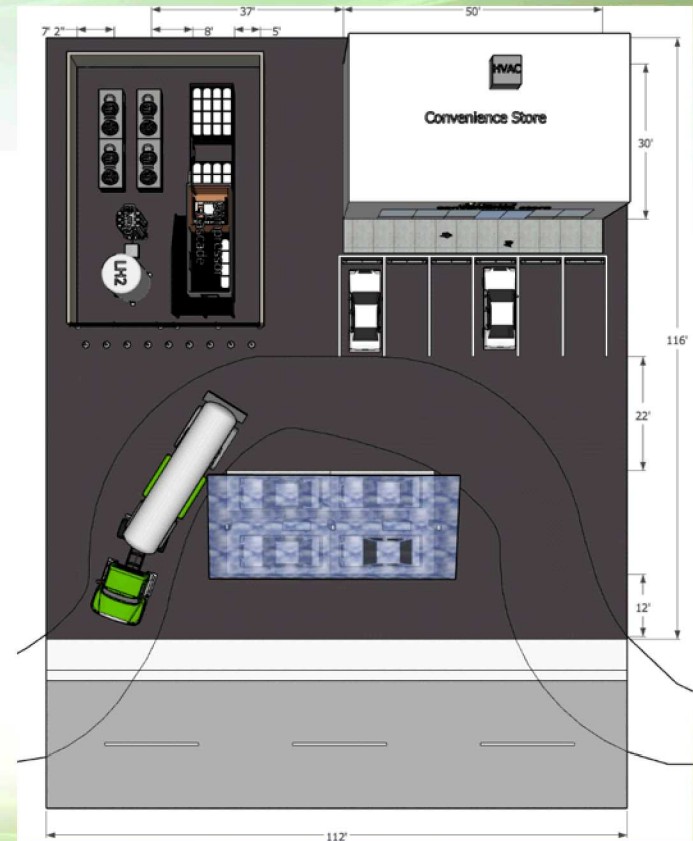
Reducing certain setbacks (23 m from building openings) can significantly reduce LH₂ footprint



- Footprint: 116 feet x 112 feet (38.9% footprint reduction from base case)
 - Lot size: 12,992 ft²
- Truck size reduced for a shorter turning radius
- Meets most setback distances, not others

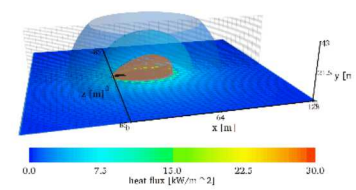
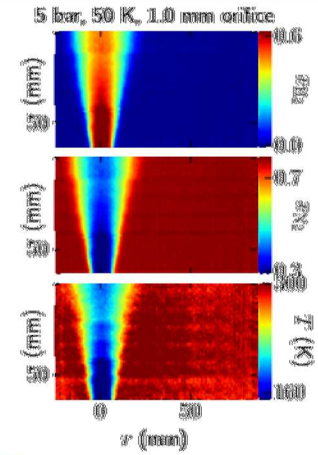
Exposure	Required	Current
1 Lot lines	*15 m (50 ft)	*3.87 m (12.2 ft)
2 Air intakes	23 m (75 ft)	18.9 m (62 ft)
3 Operable openings in buildings	23 m (75 ft)	18.9 m (62 ft)
6 Parked cars	7.6 m (25 ft)	11.3 m (37 ft)
7(a)(2)(i) Unsprinklered, without fire-rated wall	*15 m (50 ft)	*11.3 m (37 ft)

* Reducible to 0 m (0 ft)



Sandia H₂ Safety Codes and Standards research includes coordinated activities that facilitate deployment of hydrogen technologies

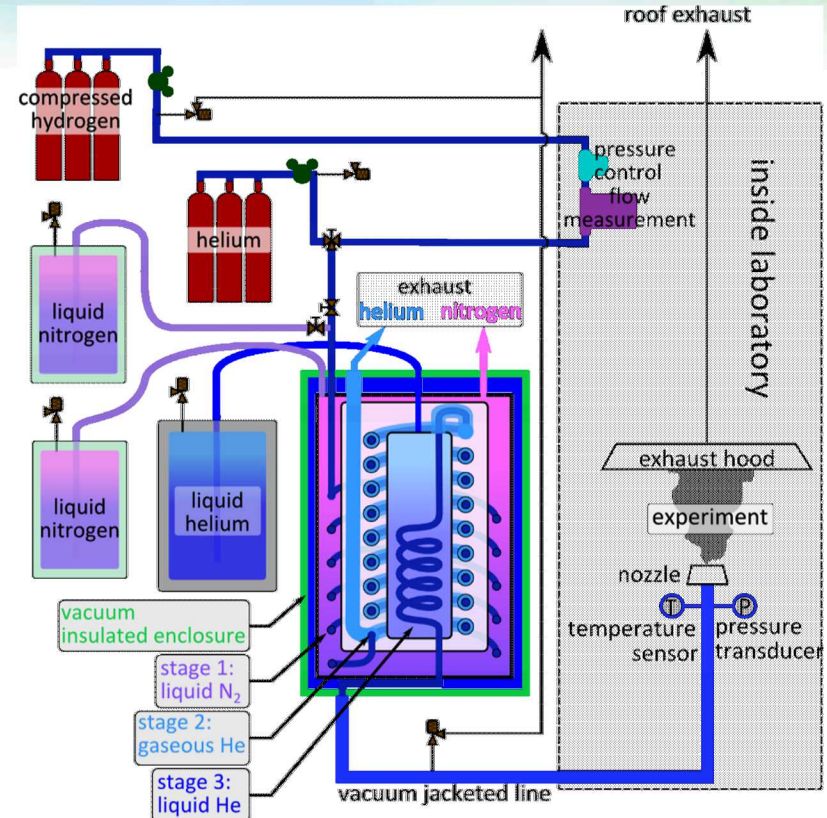
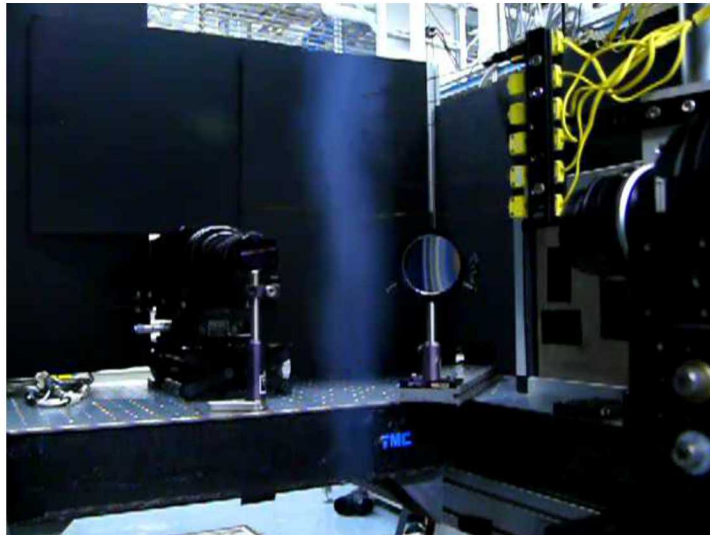
- Hydrogen Behavior
 - **Develop and validate scientific models** to accurately predict hazards and harm from liquid releases, flames, etc.
- Quantitative Risk Assessment, tools R&D
 - **Develop integrated methods and algorithms** enabling consistent, traceable, and rigorous QRA (Quantitative Risk Assessment) for H₂ 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



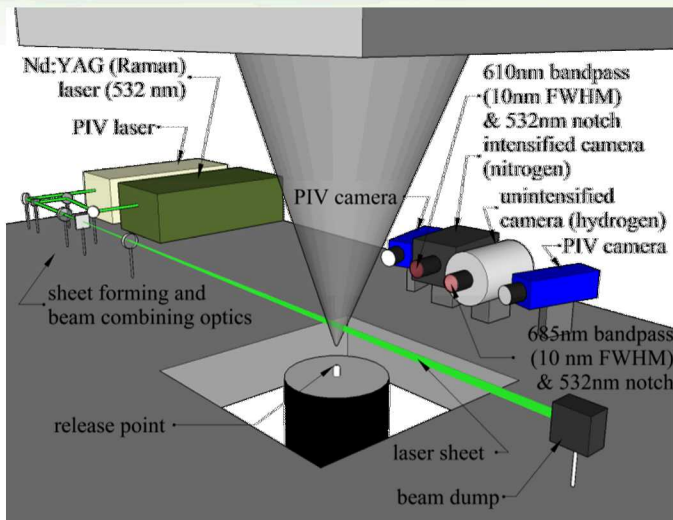
Model validation is a priority

- Experimental platform developed at Sandia to release cryogenic hydrogen through approximately 1 mm orifices at up to 10 bar
 - Research and validation for models of ignition, flames and dispersion

$P = 1 \text{ bar}$, $T = 37 \text{ K}$, ignition distance = 325 mm

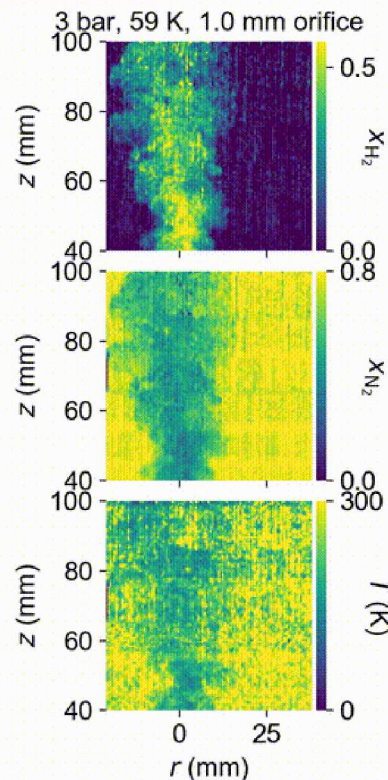
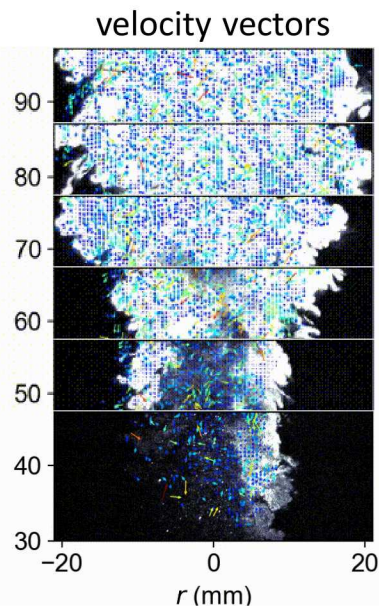


H₂-N₂ Raman imaging and particle imaging velocimetry are used to measure concentration, temperature, and velocity of cryogenic H₂

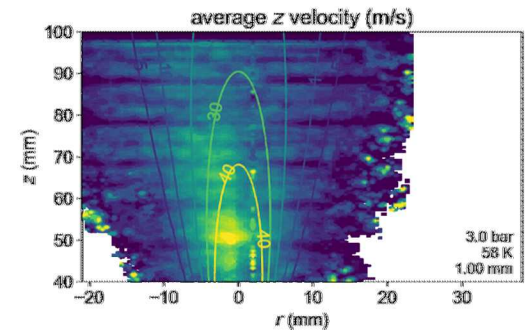
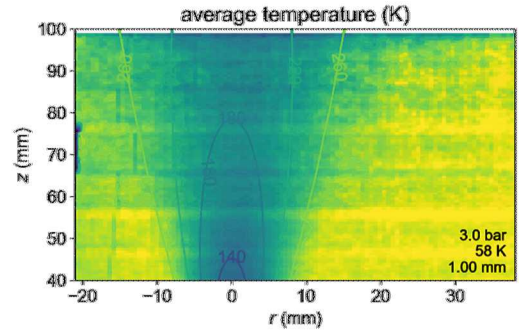
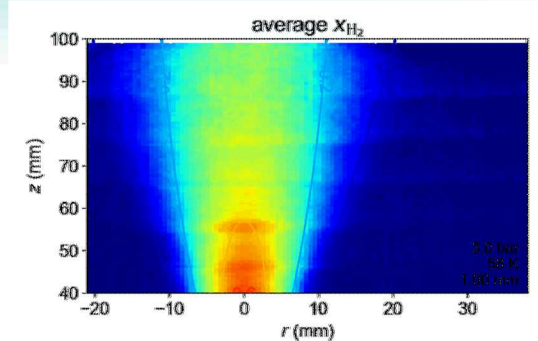
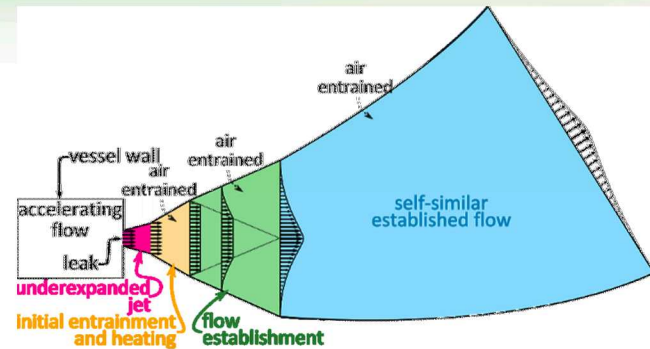


Independent model parameters:

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



ColdPLUME model shows good agreement with the data

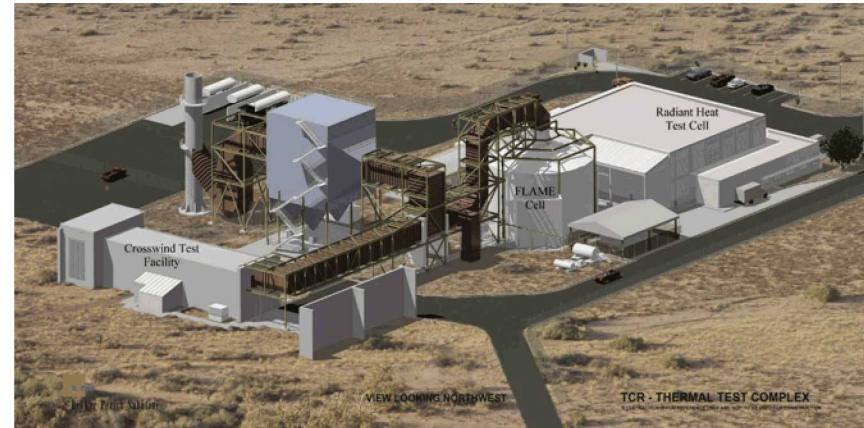
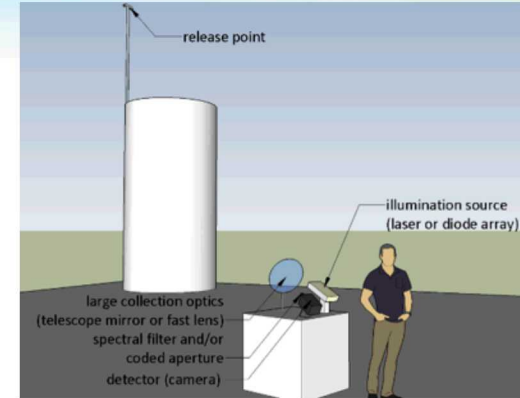
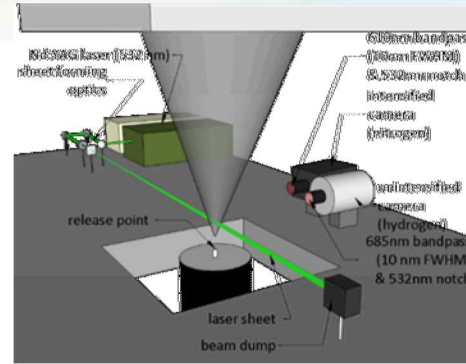


- Experimental results shown by shading and thick, dashed lines
- ColdPLUME model results are thin, solid lines

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

Lab scale data is great for model validation but we are working to scale-up our Raman imaging techniques

- **Remaining priorities for LH₂:**
 - Relate concentration data to ignition distance
 - Study non-circular orifices
 - Characterization and modeling of
 - Interactions with ambient (i.e. wind)
 - Pooling
 - Evaporation from LH₂ pools
- Currently developing an imaging diagnostic for outdoor and large-scale experiments
 - Quantitative concentration measurements
 - 2- or 3-dimensions
 - Video frame rates
 - Portable
- Will apply diagnostic to normally occurring outdoor releases (e.g., venting after LH₂ fill)
- Dedicated validation experiments (pooling, cross-wind) at well-controlled facilities next fiscal year (FY19-20)



Summary of liquid H₂ research at Sandia National Laboratories

- H₂FIRST
 - Research and development of advanced technologies to lower cost and enhance reliability of hydrogen fueling stations
 - Reference Station for Urban Sites: create compact hydrogen reference station designs appropriate for urban locations, enabled by hazard/harm mitigations, near-term technology improvements, and/or risk-informed (performance-based) layout designs
- Safety Codes and Standards
 - Coordinated research and development activities that facilitate deployment of hydrogen technologies by developing validated physical models, integrating models into HyRAM (risk assessment toolkit), applying models and analyzing real-world scenarios
 - Recently validated ColdPLUME model for cryogenic hydrogen by simultaneous Raman imaging and particle imaging velocimetry
 - Developing large-scale diagnostic for quantifying cryogenic hydrogen dispersion

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