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Liquid Hydrogen Behavior Studies June 27, 2016

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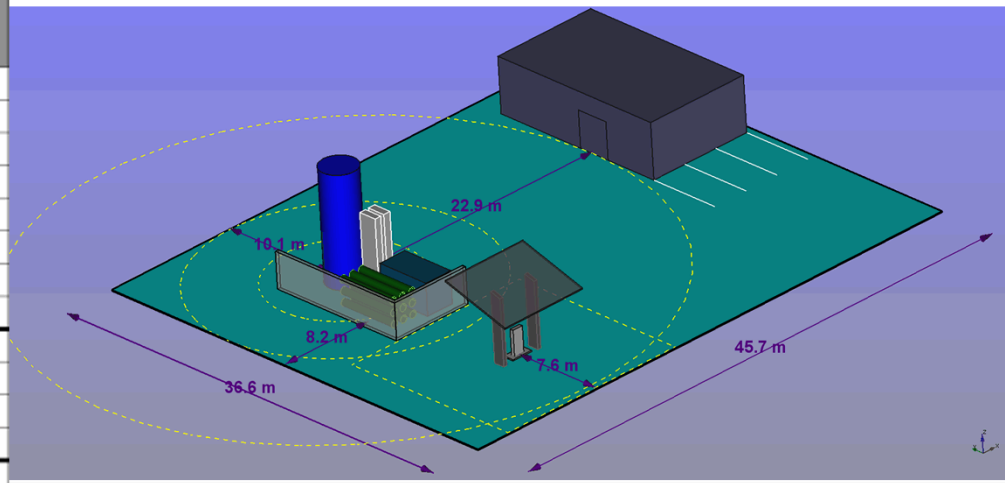
Current separation distances for liquid hydrogen are not science-based

- 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 reduced gaseous H_2 separation distances

Separation Distances (NFPA 2-2011) **and Areas required for two station concepts**
(critical distances and areas emphasized)

Fueling System Description GH2: 12,500psi storage, 100kg, 0.4"ID tubing with a barrier wall LH2: 3500-15000 gallon (910-1300kg) with barrier wall and insulation	GH2	LH2
Lot lines (ft)	**24**	**33**
Public Streets, Alleys (ft)	24	33
Parking (public assembly) (ft)	13	**75**
Buildings (sprinkled, fire rated) (ft)	10	5
Building Openings or air intakes (ft)	**24**	**75**
Flammable and Combustible liquid storage, vents or fill ports (ft)	10	50
Parking from fill connections on bulk storage (ft)	13	25
Class 1 Div. 2 area diameter (ft)	15	15
Max Bulk Storage Dimensions with Sep. Distances (ft)	78	123
Min Bulk Storage Dimension with Sep. Distances (ft)	68	123
Max Bulk Storage Equipment Dimension with lot lines (ft)	54	40
Min Bulk Storage Equipment Dimension with lot lines (ft)	49	40
Reference Bulk Storage Equipment Area with lot lines (sqft)	2646	1600
Reference Storage Area with Sep. Distances (sqft)	**5304**	**15129**
Note: Add 5 feet for vehicle protection on vehicle facing sides of equipment		



Harris, SAND-2014-3416

Of 70 stations surveyed (out of 343), none met the NFPA 2 Ch. 6 separation distance requirements.

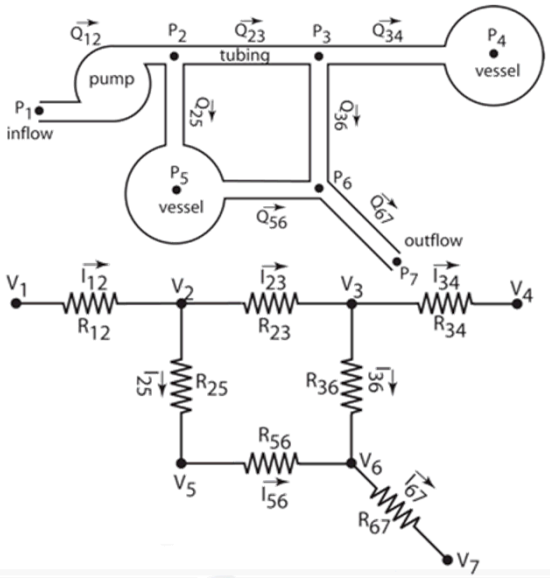
High priority scenarios have been identified by the NFPA 2 code committee

- Release from pipe leading from tank to vaporizer or vaporizer itself caused by thermal cycles or ice falling from vaporizers
  - Modeling results of hydrogen concentration plume and heat flux from a subsequent fire will be used for all other separation distance exposures because this is the highest risk priority
  - Horizontal discharge, ¾”-2” diameter pipe, 20-140 psig
- Flow from trailer venting excess pressure after normal LH_2 delivery
  - Modeling results will be used to calculate separation distance from air intakes and overhead utilities
  - Vertical discharge, 3” diameter pipe, 20-140 psig

Scenarios require internal flow model and validated jet/plume model

Internal flow model

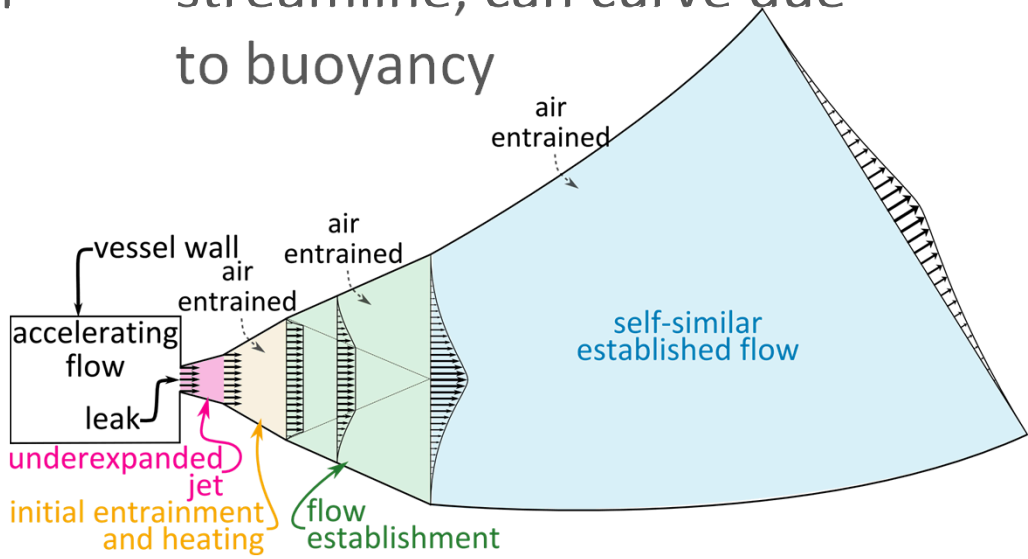
- Electronic network representation of flow path



- Being updated to handle 2-phase flows

Jet/plume model

- 1-dimensional along streamline, can curve due to buoyancy



- Lab data for validation

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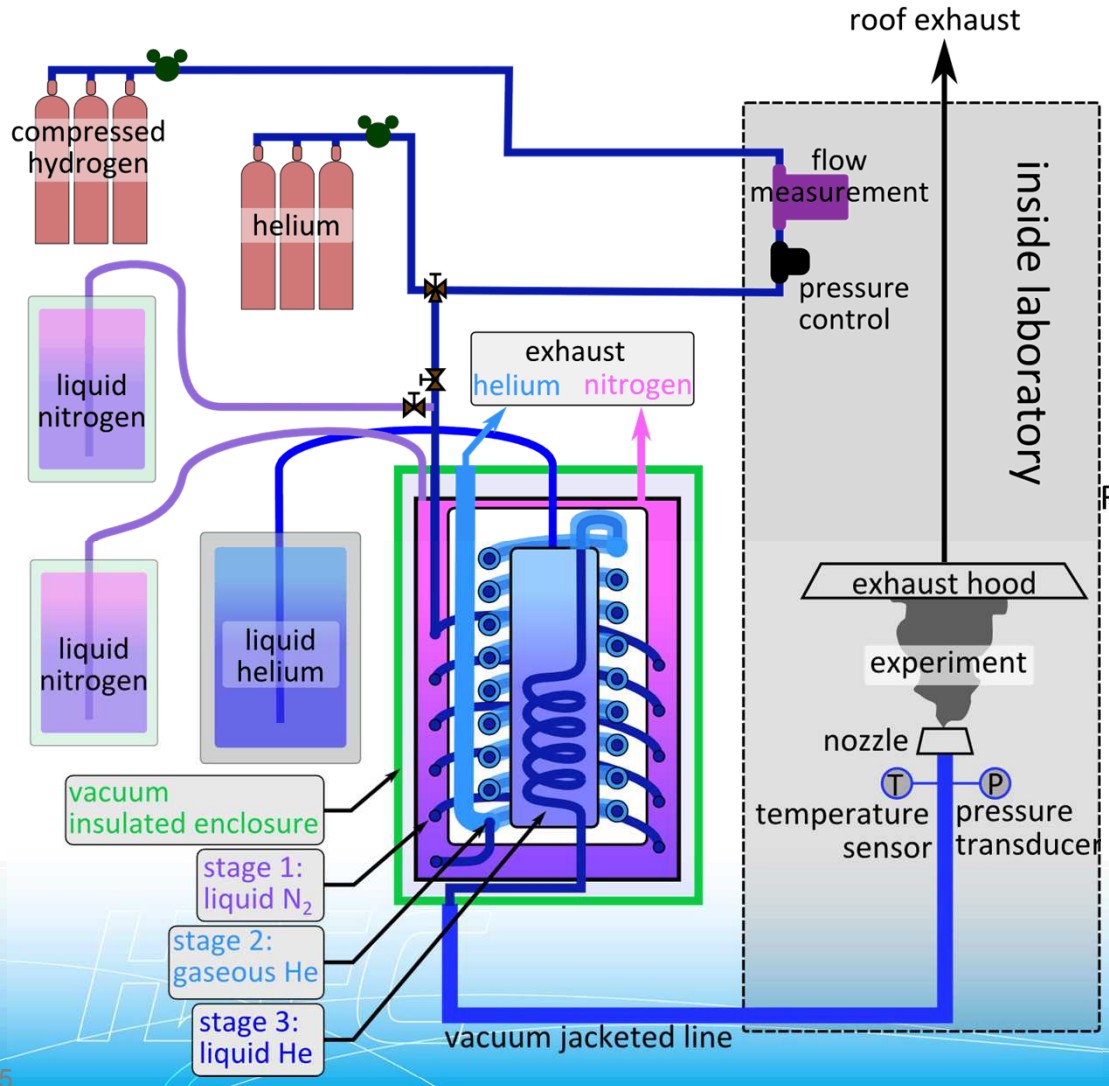
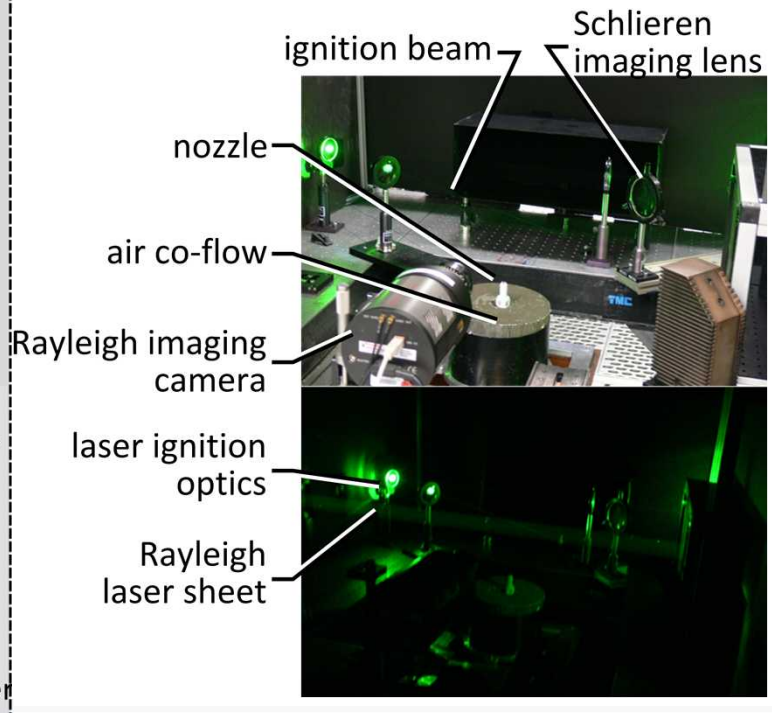
The cryogenic hydrogen release laboratory is in use

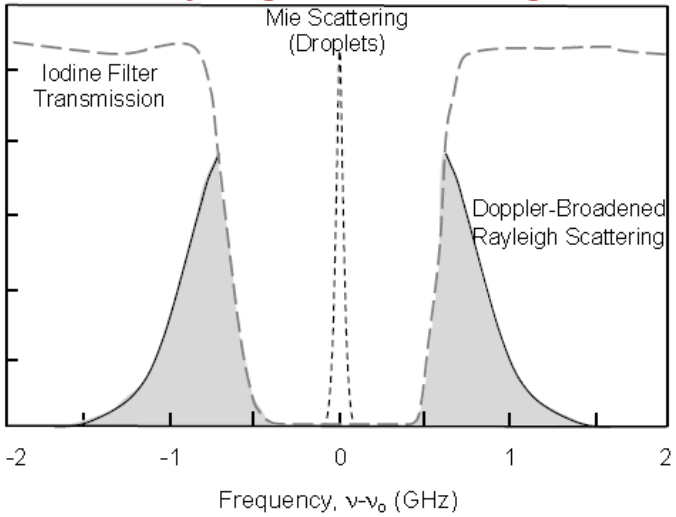




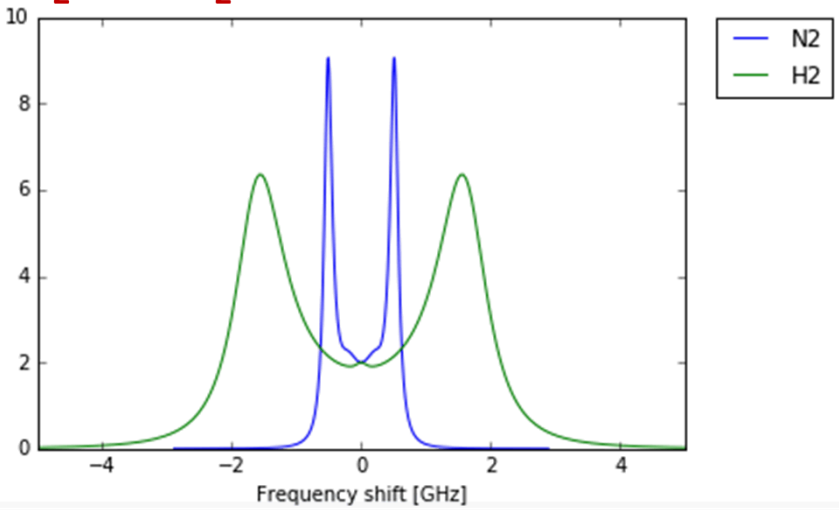
Laser nearly ready to perform filtered Rayleigh imaging for concentration (& temp) measurements

- At temperature below 200 K, water vapor from entrained air condenses
- Mie scattering from condensed water overwhelms Rayleigh signal
  - Filtered Rayleigh takes advantage of Rayleigh scattering line broadening

Filtered Rayleigh Scattering Concept



Rayleigh Scattering Spectra for H_2 and N_2 at T = 80 K

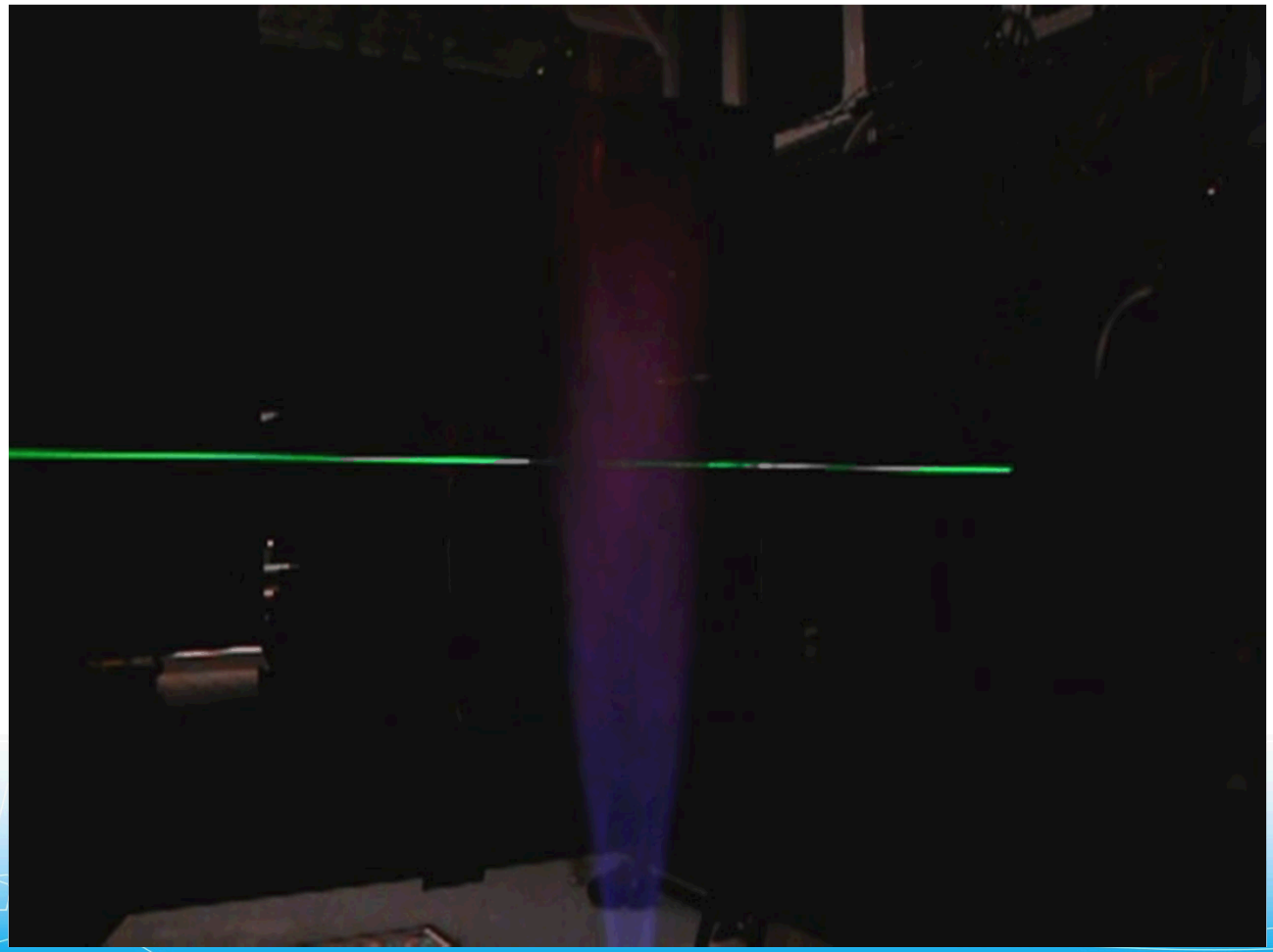


Using a narrow band-width (Δν < 0.003 cm-1) laser and a molecular I_2 filter tuned to center wavelength of the laser beam, it possible to filter out the Mie scatted light

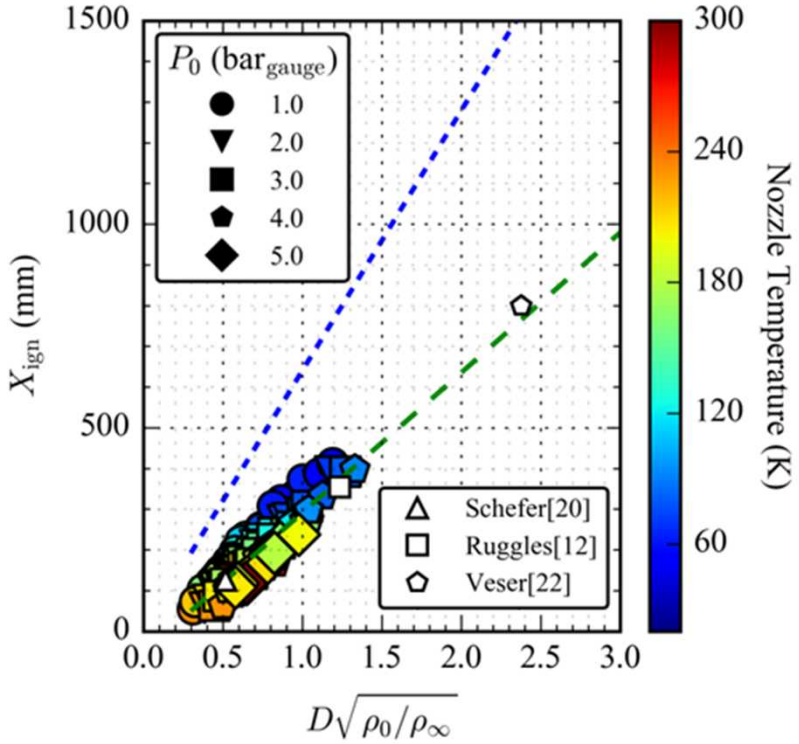
Doppler broadened H_2 spectra is promising for filtered Rayleigh scattering measurements

Laser-spark ignition and flame radiation experimental campaign has been completed

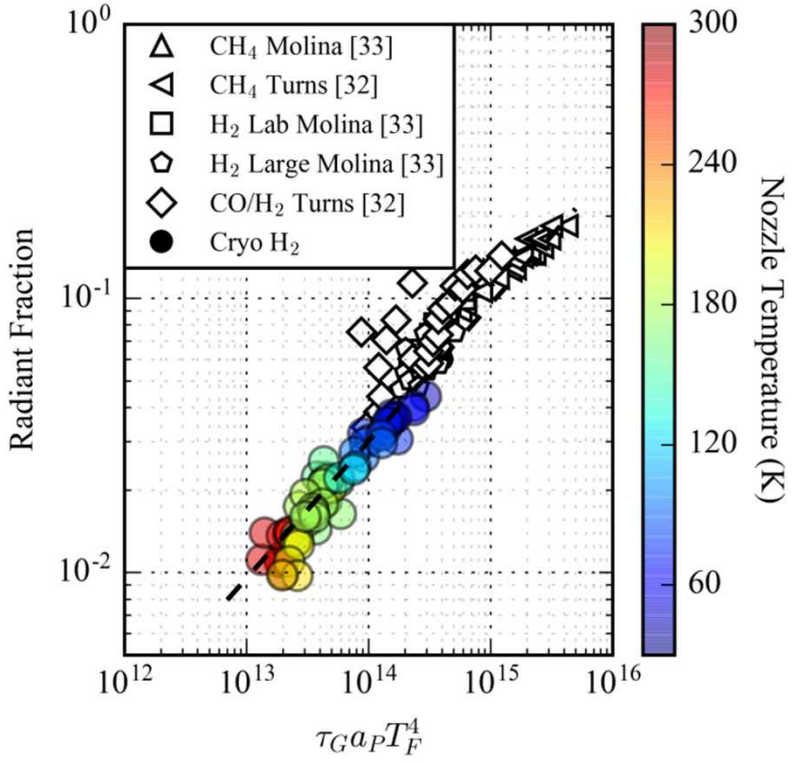
P = 1 bar, T = 37 K, Max. Ignition Distance = 325 mm



Ignition distance and heat-flux has been mapped out



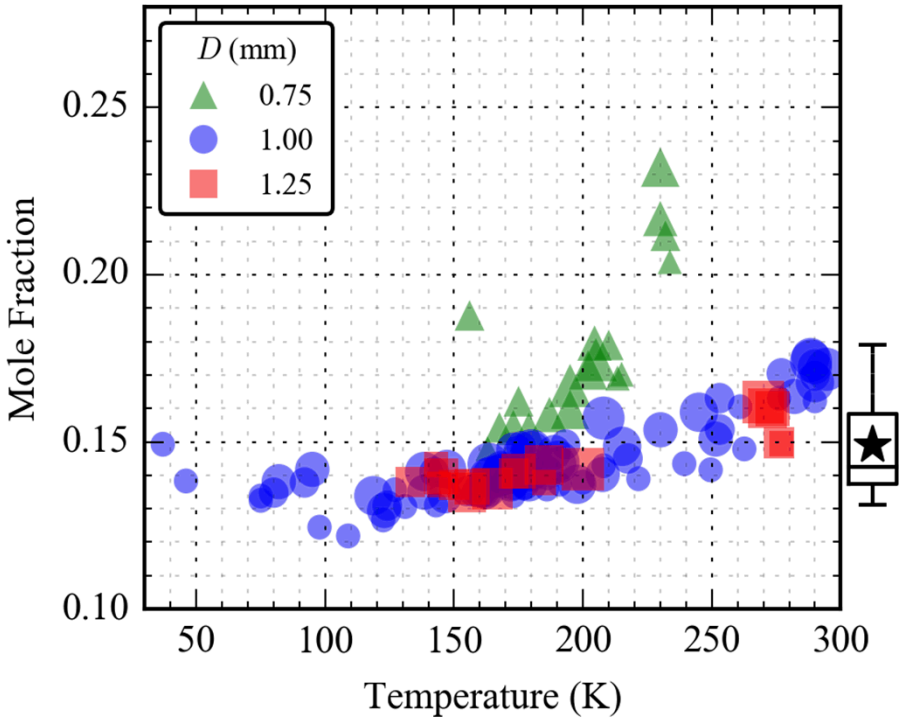
- Scales by the effective diameter



- Scales by the flame residence time

The preliminary mean mole-fraction at ignition has been calculated with the cold-plume model

Unvalidated model simulations



- Model predicts little dependence on temperature
- All predicted mole fractions > 0.12 (>> 0.04)
- Entrainment model may not be correct

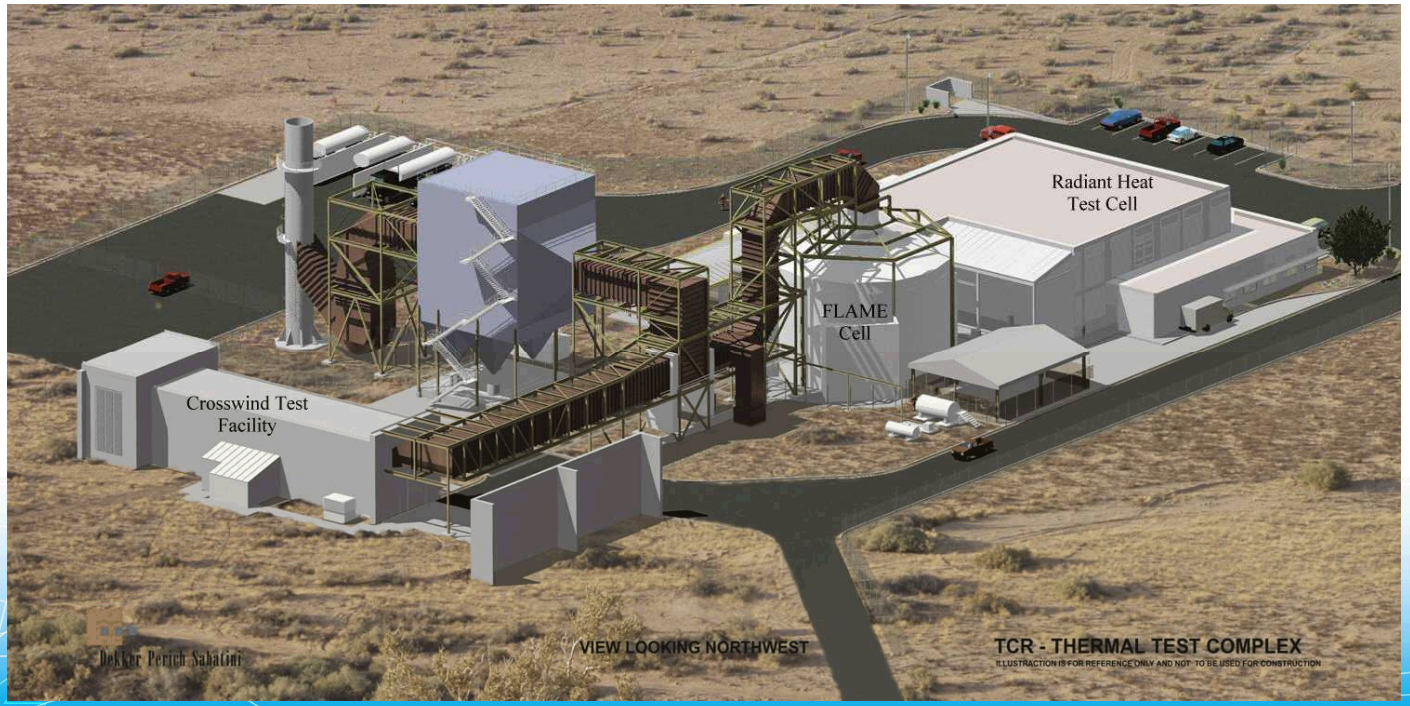
Validation data generated by lab scale experiment should be sufficient for high priority scenario simulations

- Current test plan:
  1. Continue to map out ignition distance (complete)
     - more data points between 20-80 K
     - additional nozzle diameters
     - higher pressures (up to 10 bar)
  2. Repair laser to allow for filtered Rayleigh imaging (May-June)
  3. Make concentration measurements of cold releases (June-November)
  4. Modify/validate models (Sept 2016-Jan 2017)
  5. Use model to simulate high priority scenarios (Jan 2017-March 2017)
  6. Design laboratory experiment with vertical walls (Jan 2017 – June 2017)
  7. Laboratory experiments with vertical walls (June 2017 – Dec. 2017)
  8. Wall interaction model development (Sept. 2017 – March 2018)
  9. Use wall interaction model to simulate other scenarios (March 2018-May 2018)

Additional data/models are needed for some scenarios

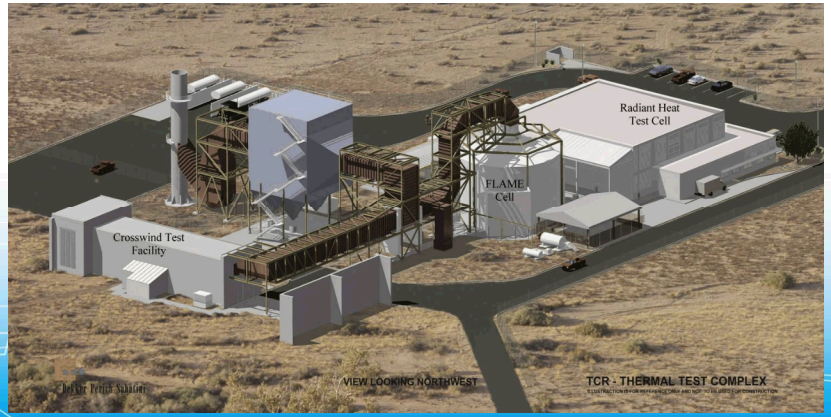
- Additional scenarios will require models for
  - internal flows (work underway)
  - wall/ground interactions (lab scale vertical tests planned, large scale tests with alternate configurations are likely necessary)
  - Pooling, pool vaporization, air-condensation/interaction with pools, modeling and experiments ($750k)
  - Bulk storage behavior in an exposure fire ($500k)
- Large scale plume and flame experiments to justify model scaling ($600k)

The thermal test complex at Sandia Albuquerque could be used for pooling/evaporation experiments



Larger-scale phenomena can be studied at the thermal test complex

- Flame cell
  - Up to 3m diameter pool
  - 50 ft tall
  - Validated flow models have been developed (air circulation)
  - Well-characterized ambient conditions (humidity, water-cooled walls)
- Crosswind test facility
  - Dispersion in controlled crosswind
  - Single-direction flow
  - Well-characterized ambient conditions (humidity, flow rate)



Storage tank behavior in an exposure fire could be studied at the SNL Albuquerque burn site

Summary

- 3-stage heat exchanger cooling gaseous hydrogen with liquid nitrogen, cold gaseous helium, and liquid helium
- Ignition and radiation characteristics have been mapped out
  - Ignition distance scales with the effective diameter
  - Heat flux scales with the residence time
  - Unvalidated model suggests mean mole-fraction at ignition of > 0.12
  - Article to be submitted this week
- Need for filtered Rayleigh scattering for quantitative concentration measurements (laser repair to be completed this week)
- Data will be used to used to validate and guide development of first-order model
- Internal flow model with 2-phase flows under development
- Models will first be used for high priority scenarios (preliminary results in January 2017)

Acknowledgements

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