Vision for validating the liquid hydrogen plume model at temperatures less than 80K

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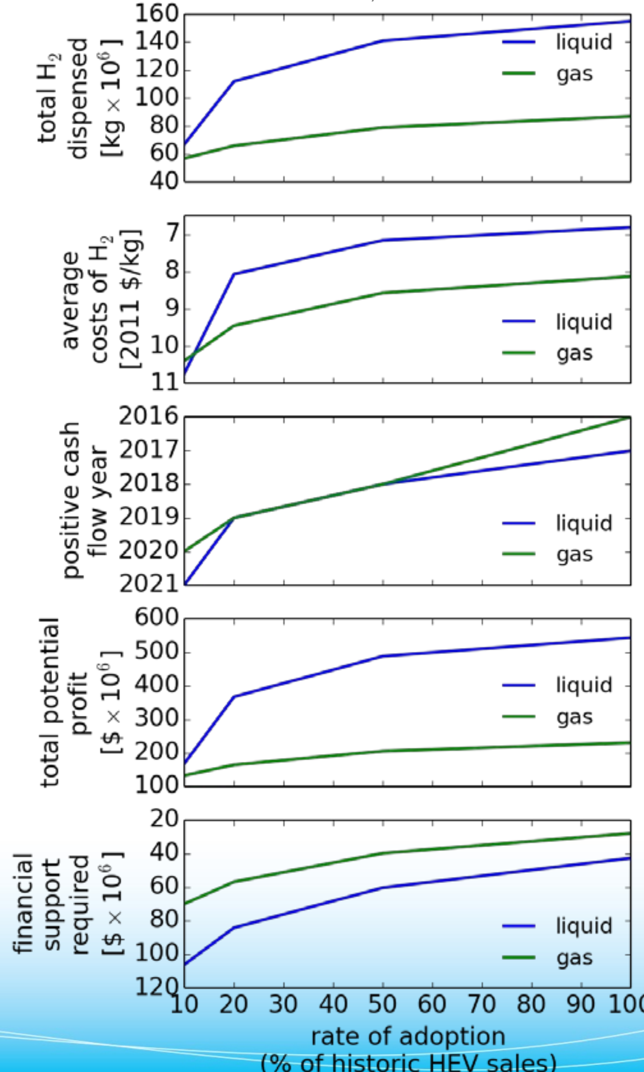
Liquid hydrogen stations have been found to be more economically favorable than gaseous stations

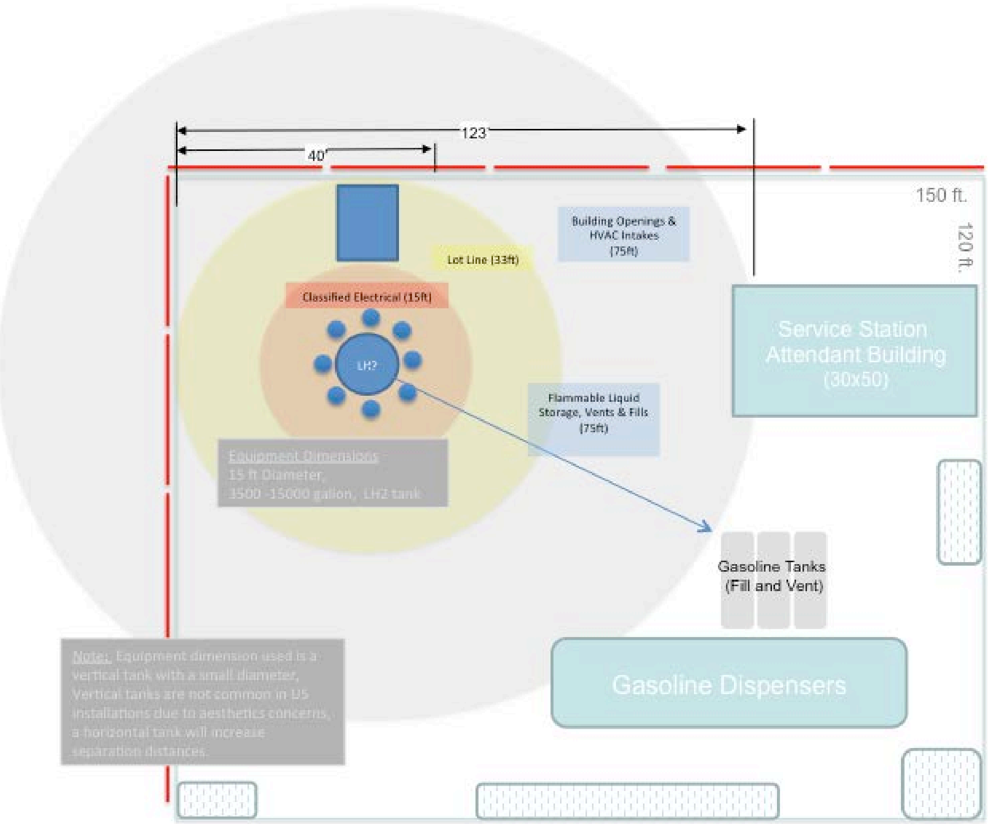
As compared to gaseous stations, liquid storage stations have:

- Larger storage capacity
- Lower costs for product
- Similar positive cash flow year
- Higher potential profit
- Larger return on investment (although more investment is required)

Brown et al., IJHE 2013

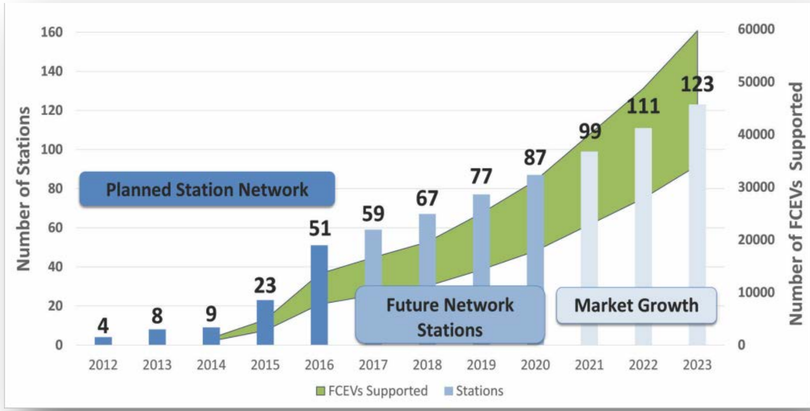


Standoff distances in NFPA 2 for liquid hydrogen stations are often prohibitively large

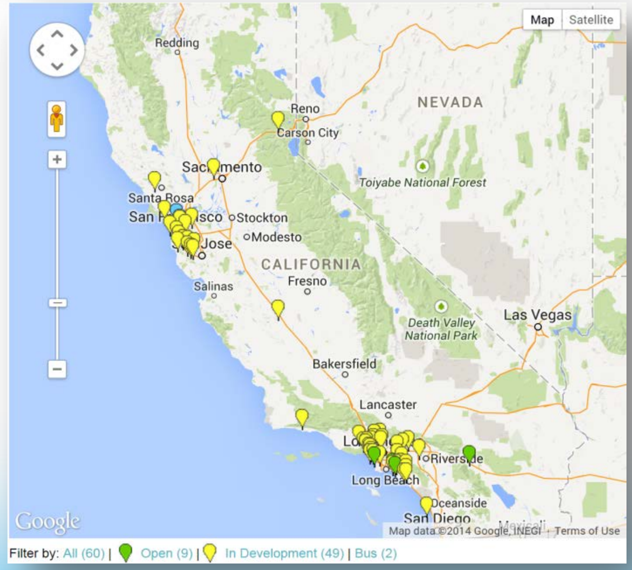


70 stations surveyed (of 343 sites), none met the NFPA 2 Ch. 6 separation distance requirements.

Harris, SAND-2014-3416

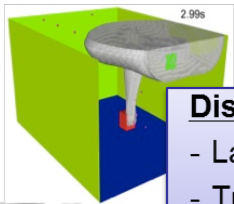


A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles, CalFCP, July 2014

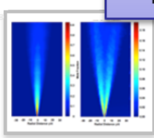


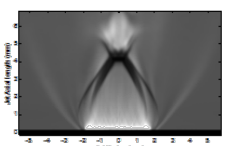
http://www.cafcp.org/stationmap

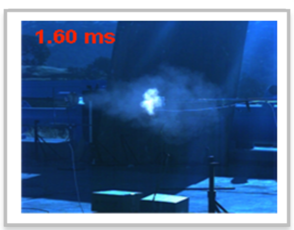
Previous modeling of releases from gaseous hydrogen storage have informed the fire code

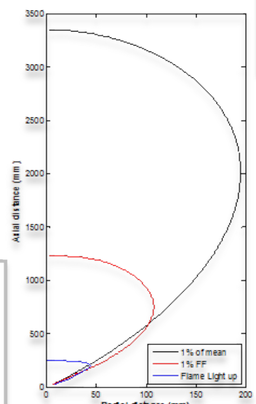


Dispersion Characteristics
- Laminar Flow
- Turbulent jet
- Volumetric rupture
- Enclosure Accumulation

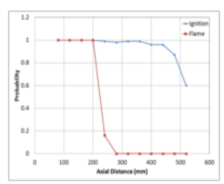




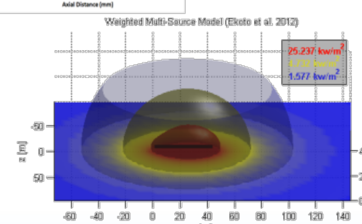




Ignition Probability
- Ignition mechanism
- Mixture ignitability
- Ignition delay/location
- Sustained light-up



Hazard Characteristics
- Flame radiation
- Overpressure (deflagration/detonation)
- O_2 dilution/depletion

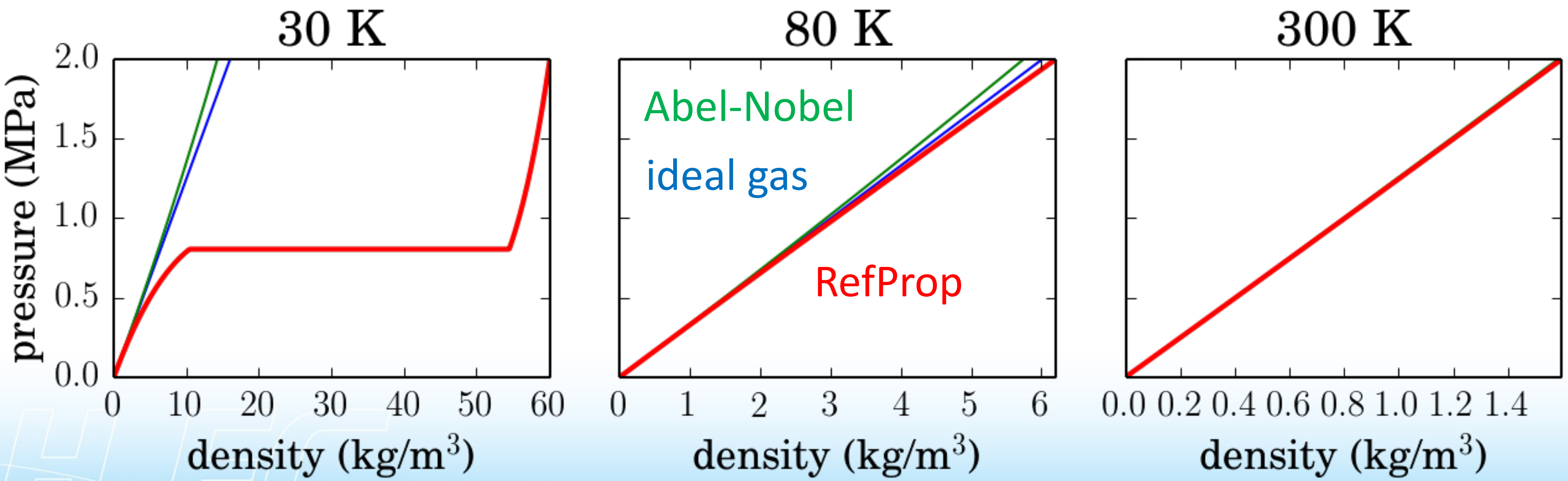


Risk requires a **Release**, then **Ignition**, forming a **Hazard**, causing **Harm**

- We ***quantify*** each of these events using models
- **Purple** events quantified with statistical models, **Red** with reduced-order behavior models

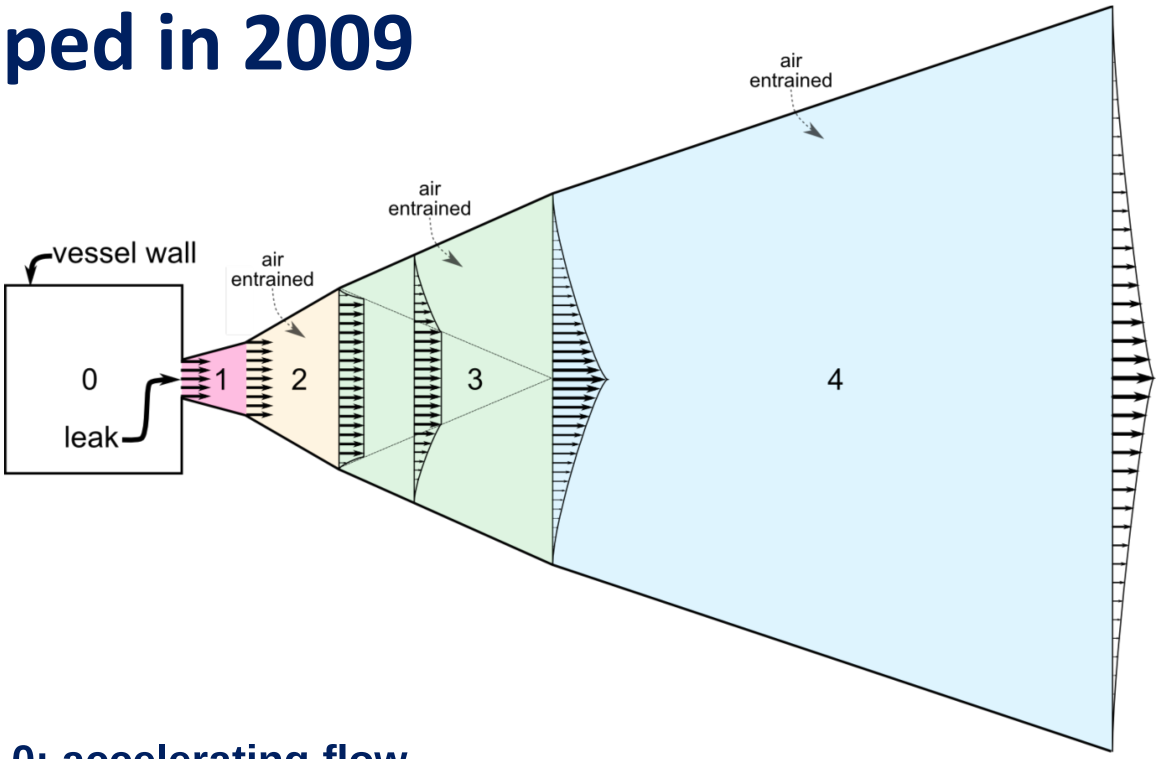
Current network flow model (NETFLOW) must be updated for use near saturation conditions

- Models 1-D flow networks (e.g. piping, valves, tanks) by solving conservation and state modeling equations with local corrections for wall friction, heat transfer, and pressure loss
- Conventional state equations invalid near saturation conditions
- Important to capture phase-change behavior
- Must model compressible and incompressible flows



A conceptual model for liquid H_2 releases was originally developed in 2009

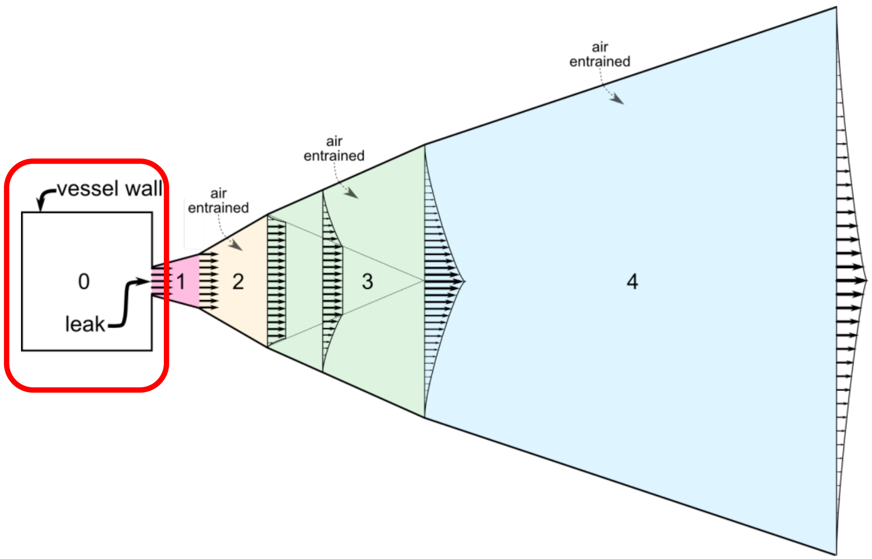
- Steady-state
- 1-dimensional (along streamline coordinate)



- Zone 0: accelerating flow
- Zone 1: underexpanded jet
- Zone 2: initial entrainment and heating
- Zone 3: flow establishment
- Zone 4: self-similar, established flow

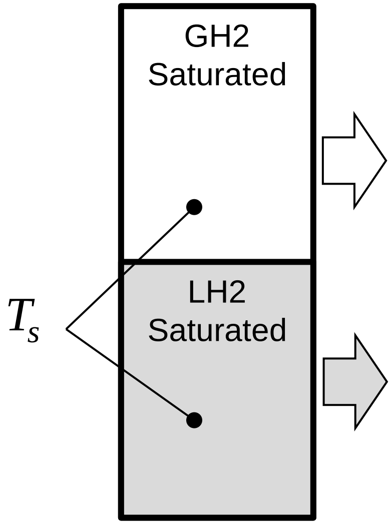
Winters, SAND Report 2009-0035
Winters & Houf, IJHE, 2011
Houf & Winters, IJHE, 2013
Ekoto et al., SAND2014-18776

Accelerating flow (leak) develops from saturated storage conditions



- conserved energy with isentropic expansion

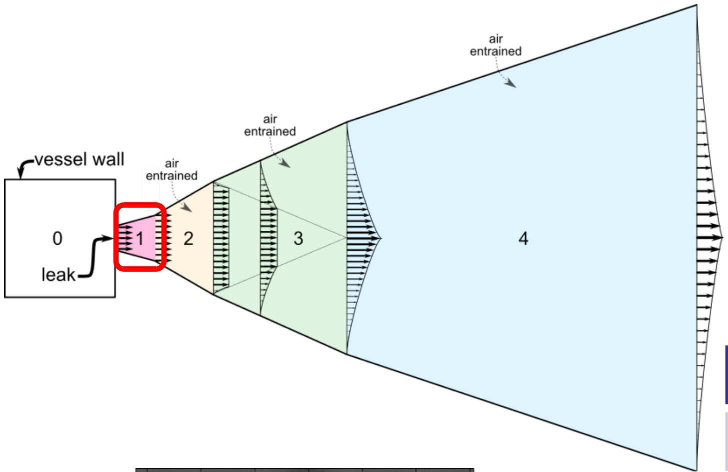
Ekoto et al., SAND2014-18776



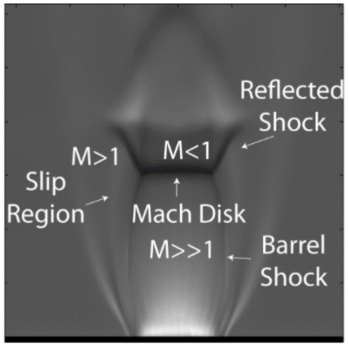
$$w_1^2 = 2(h_0 - h_1)$$
$$s_1 = s_0$$

- conditions at zone 0 capture by network flow model (requires development)
- hydrogen is stored as a pure substance
- multi-phase components have equal velocities

Pseudo source models are used to account for choked flow behavior in Zone 1 (if applicable)



Several source models have been developed to predict the mass weighted effective diameter, (i.e., the critical scaling parameter): $d^* \equiv d_{eff}\sqrt{\rho_{eff}/\rho_{amb}}$



Ruggles & Ekoto, *IJHE*, 2012

Source Model	*d** [mm]
Birch et al. (1984)	0.947
Ewan & Moodie (1986)	0.993
Birch et al. (1987)	0.790
Yuceil & Otugen (2002)	0.790
Harstad & Bellan (2006)	1.440
Molkov (2008)	0.993
SNL Data (2011)	***0.867***

***All models updated w/ Able-Noble EOS**

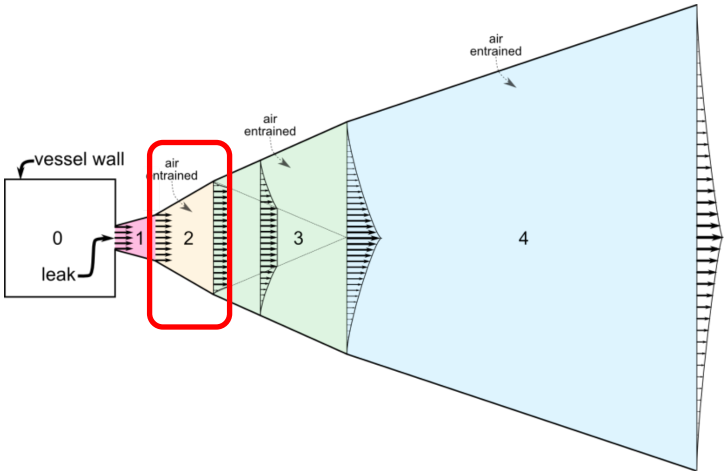
Neglects Mach Disk (i.e., fully supersonic)

All flow through Mach disk (i.e., fully subsonic)

Reality is that fluid is split between the slip and Mach disk regions

Ongoing work to develop validated two-zone source model that accounts for the fluid split ratio between the slip region & Mach disk regions

Plug flow assumption invoked for Zone 2 as the jet begins to warm



Winters, SAND Report 2009-0035

unknowns

assumed value

Mass $\dot{m}_{H_2} \rightarrow$, $\dot{m}_{air}$: $\dot{m}_3 = \dot{m}_{H_2} + \dot{m}_{air}$

Momentum $\dot{m}_{H_2} V_{H_2} \rightarrow$, 0: $\dot{m}_3 V_3 = \dot{m}_{H_2} V_{H_2}$

Energy $\dot{m}_{H_2} h_{H_2} \rightarrow$, $\dot{m}_{air} h_{amb}$: $\dot{m}_3 h_3 = \dot{m}_{H_2} h_{H_2} + \dot{m}_{air} h_{amb}$

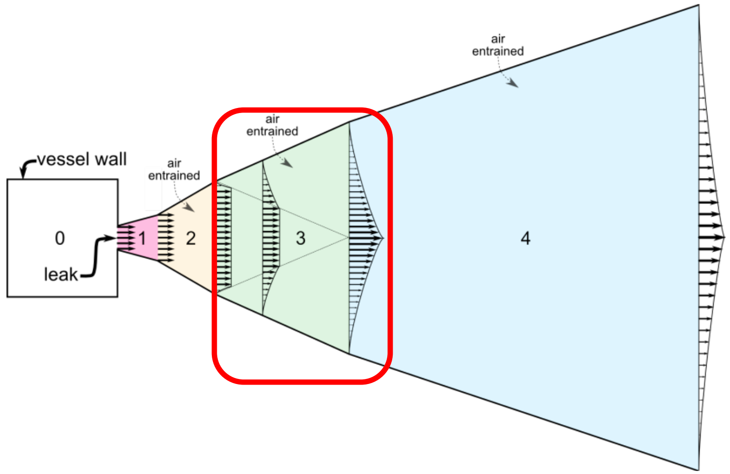
State modeling by NIST H_2 EOS: $h_3 = f(Y_{H_2,3}, p_{amb}, T_3)$

Species conservation used to close system of equations: $\dot{m}_{air} = \dot{m}_{H_2} \frac{1 - Y_{H_2,3}}{Y_{H_2,3}}$

Turbulent jet entrainment rate used to estimate zone length:

$$E_{mom} \equiv \frac{1}{\rho_{amb}} \frac{d\dot{m}}{dS} \approx \frac{1}{\rho_{amb}} \frac{\dot{m}_{air}}{S_3} \Rightarrow S_3 = \frac{\dot{m}_{air}}{E_{mom} \rho_{amb}}, \text{ where } E_{mom} = \alpha_m \left(\frac{\pi D_{H_2}^2}{4} \frac{\rho_{H_2} V_{H_2}^2}{\rho_{amb}} \right)^{\frac{1}{2}}$$

Flow develops to the assumed self-similar profile in Zone 3



Winters, SAND Report 2009-0035

unknowns
assumed value

$$V_{CL,4} = V_3$$

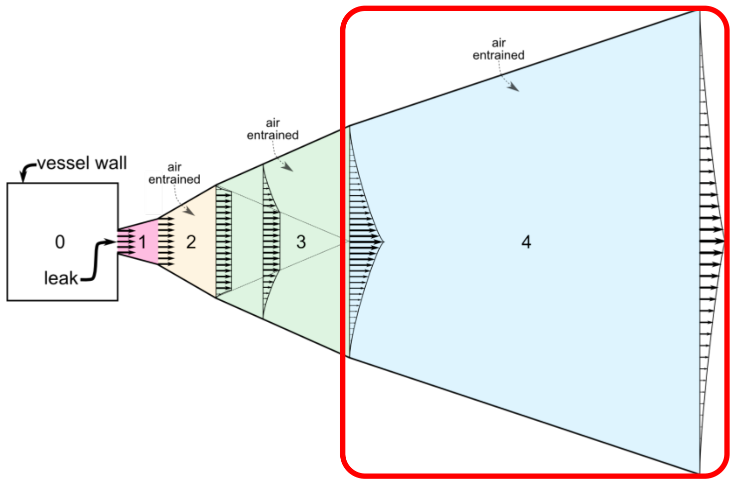
Mass

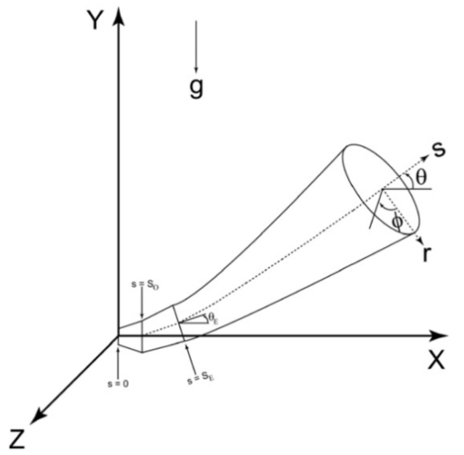
$$\rho_3 \frac{D_3^2}{4} = B_4^2 \left[\rho_{amb} - \frac{\lambda^2}{\lambda^2 + 1} \left(\rho_{amb} - \rho_{CL,4} \right) \right]$$

Momentum

$$\underbrace{(\rho_{amb} - \rho_3) \frac{D_3^2}{4}}_{S_3} = \underbrace{B_4^2 \left[\frac{\rho_{amb}}{2} - \frac{\lambda^2}{2\lambda^2 + 1} \left(\rho_{amb} - \rho_{CL,4} \right) \right]}_{S_4}$$

Zone 4 modeled with previous SNL 1D integral jet/plume models that invoke self-similarity – FY08





Entrainment due to buoyancy & momentum

F_{rL}: Jet Froude length
α_b: Buoyancy entrainment coefficient
α_m: Momentum entrainment coefficient
g: Gravity constant

$$E_{buoy} = \frac{\alpha_b}{F_{r_L}}(2\pi V_{CL} B)\sin\theta$$

$$E_{mom} = \alpha_m \left(\frac{\pi D^2}{4}\frac{\rho V^2}{\rho_{amb}}\right)^{\frac{1}{2}}$$

$$F_{r_L} = \frac{V_{\mathrm{CL}}^2 \rho_{exit}}{gB(\rho_{amb} - \rho_{CL})}$$

Mass $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V r dr d\phi = \rho_{amb} E$$

x-Mom $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \cos\theta\, r dr d\phi = 0$$

y-Mom $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \sin\theta\, r dr d\phi = \int_0^{2\pi}\int_0^{\infty}(\rho_{amb} - \rho) g r dr d\phi$$

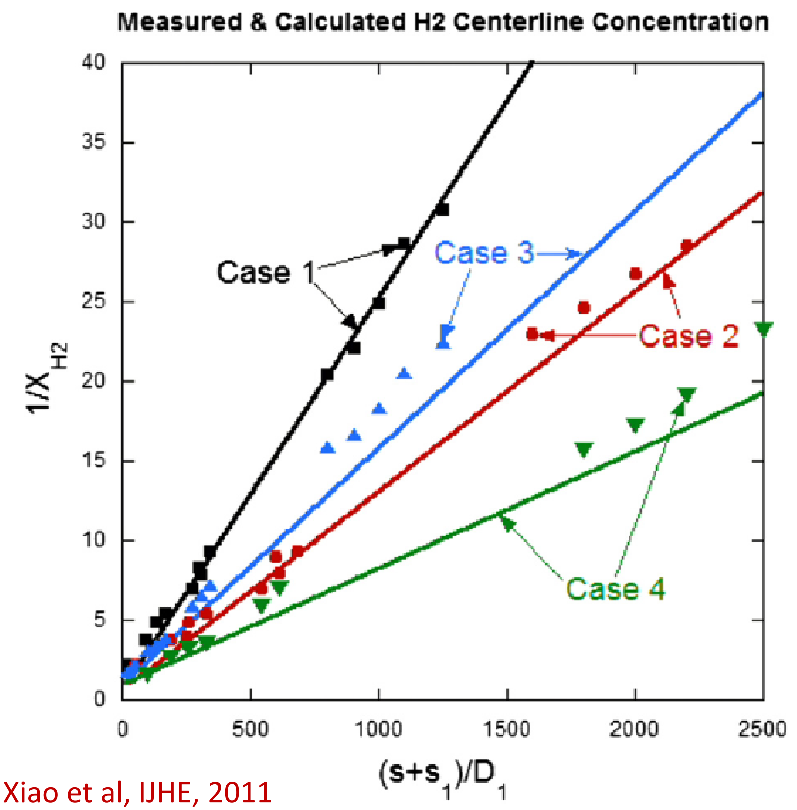
Species $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V Y r dr d\phi = 0$$

Energy $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V(h - h_{amb}) r dr d\phi = 0$$

Houf & Schefer, IJHE, 2008

Model results compare favorably to experiments from Karlsruhe Institute of Technology

Case	Reservoir pressure [MPa]	Reservoir temperature [K]	Leak diameter [mm]
1	1.7	298	2
2	6.85	298	1
3	0.825	80	2
4	3.2	80	1

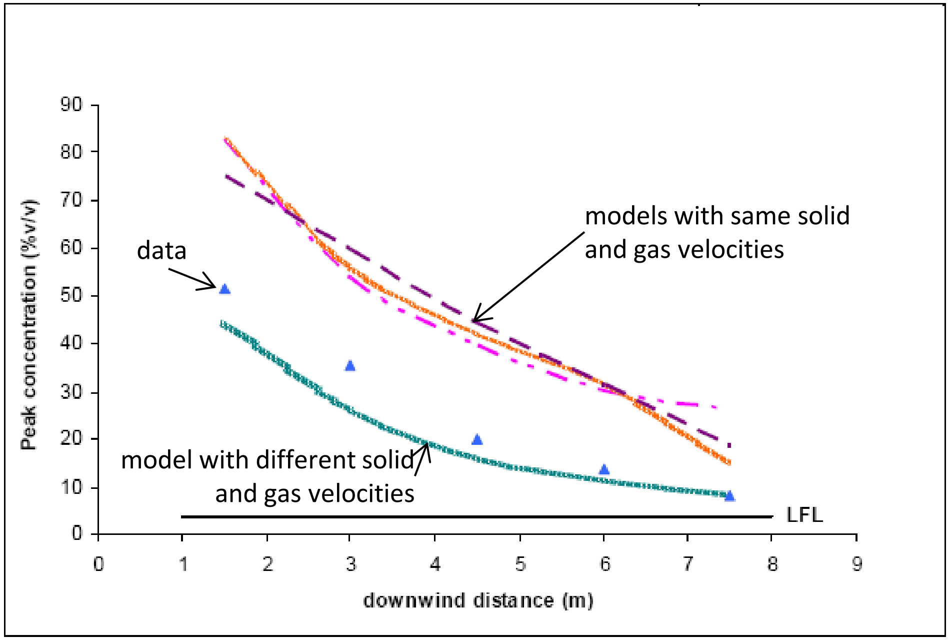


Xiao et al, IJHE, 2011
Houf & Winters, IJHE, 2013

However, no well-controlled validation data is available at lower temperatures where multi-phase flows are expected (i.e., T < 77 K)

As moisture and air condense, multi-phase flows may have droplet/particle slip

Liquid and vapor phases have different velocities due to density differences — slip models have captured these effects in CFD simulations.



HSL Measurements: Sample probes

Hooker et al, ICHS, 2011

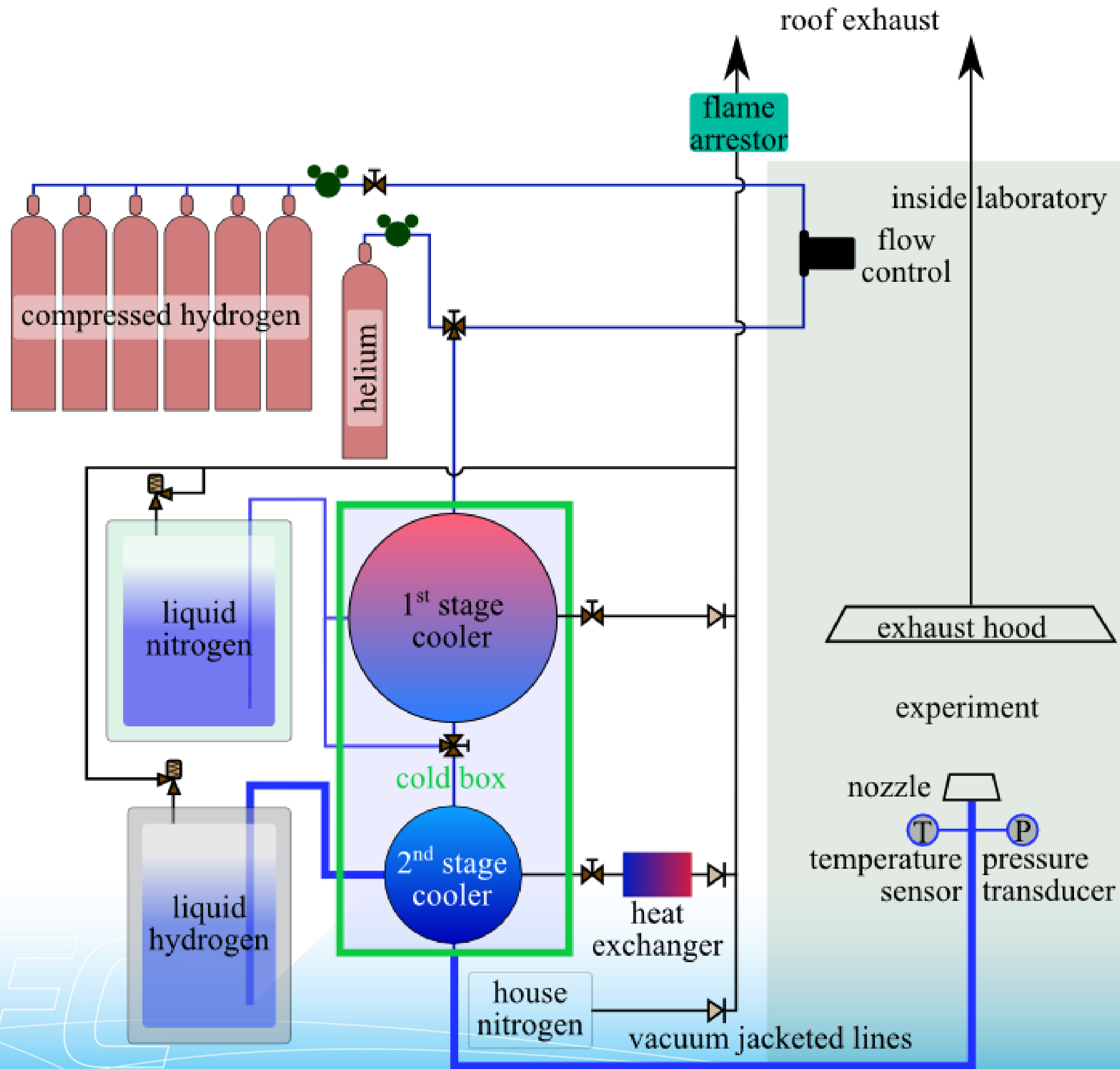
ADREA-HF CFD Simulations

Giannissi et al, ICHS, 2013

Substantial differences in model results suggest 2-phase effects cannot be neglected for LH2 releases

Experiments had poor control of release and environmental boundary conditions, which are needed for suitable benchmark data

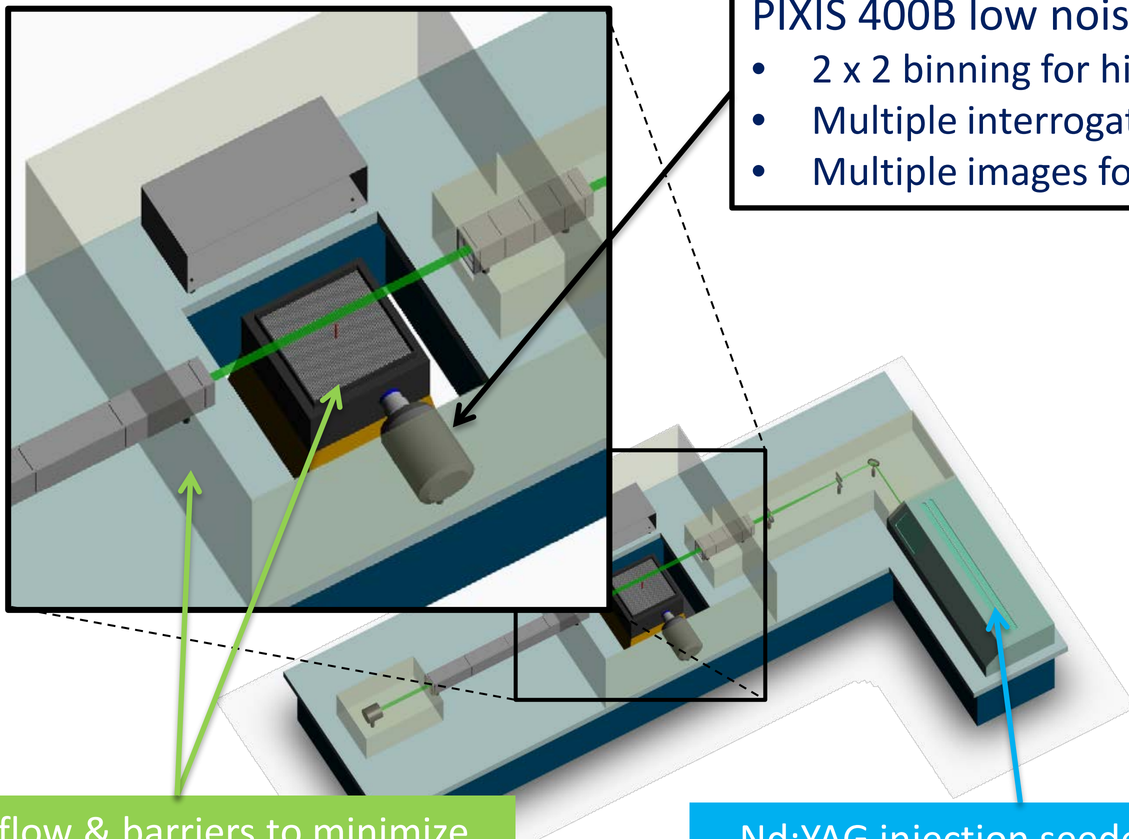
We plan to retrofit our lab to generate the necessary low temperature data for model validation



Optical diagnostics with carefully controlled boundary conditions will provide validation data

PIXIS 400B low noise CCD Camera

- 2 x 2 binning for high signal-to-noise (~400:1)
- Multiple interrogation regions to image full jet
- Multiple images for converged statistics

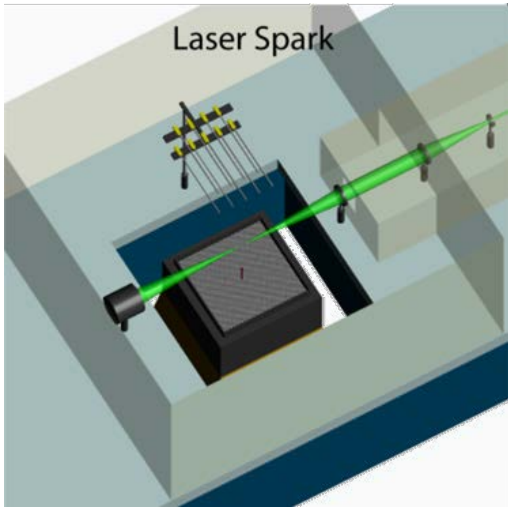


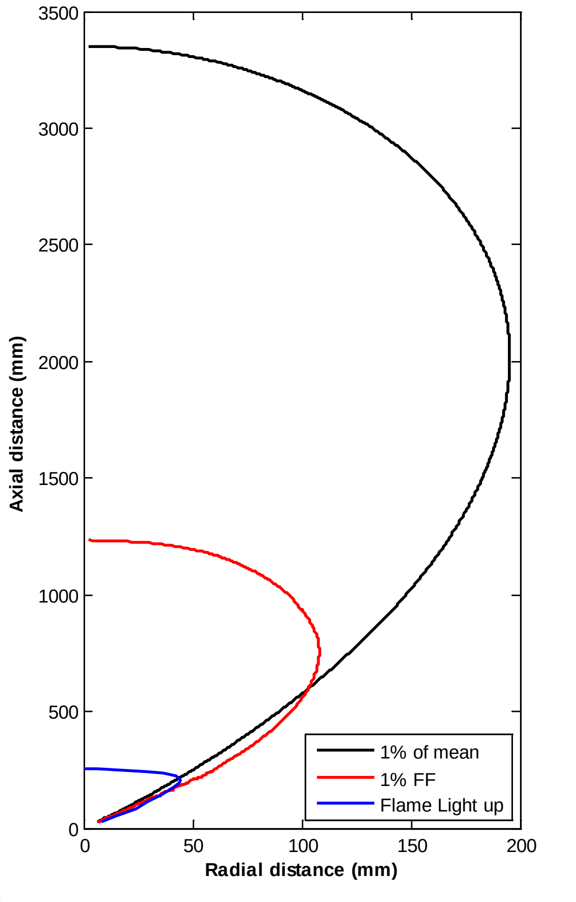
Air co-flow & barriers to minimize impact of room currents

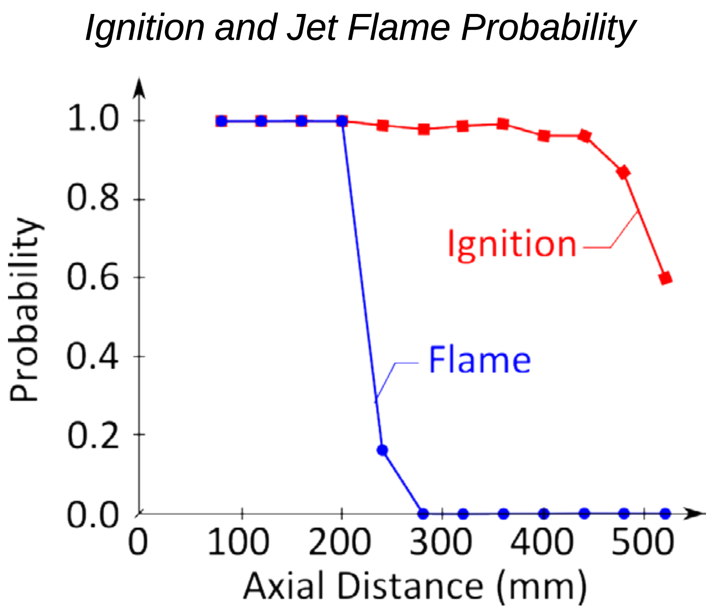
Nd:YAG injection seeded laser (1 J/pulse @ 532 nm)

Opportunity for additional upstream measurements using complementary Raman diagnostics in an adjacent lab

Future work to verify and quantify ignition boundaries







Summary and conclusions

Experimental plans:

- update network flow model
- build out laboratory system
- planar laser Rayleigh scattering to measure jet spreading
- particle imaging velocimetry to measure velocity
- model validation and updating
- ignition quantification

Challenges for liquid H_2 reduced-order modeling:

- accurate state modeling
- pool spreading and evaporation
- humidity effects
- multiphase flow models, with velocity slip
- interactions with surfaces (e.g. barriers, ground)

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