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Cryogenic Hydrogen Plume Behavior

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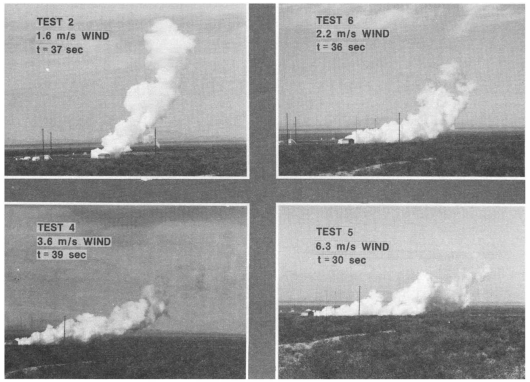
Large experiments have demonstrated condensation in plumes and ground cooling

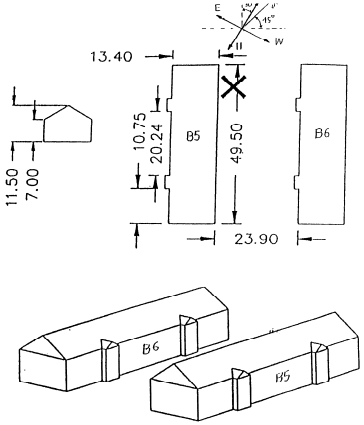
Rapid release of 1500 gal LH2 at NASA White Sands



- Quickly warms, become buoyant and mixes with air
- Prolonged spills cool ground and can travel further

Witcofski and Chirivella, IJHE, 1984

Large-scale releases (0.4 kg/s) by Battelle Ingnieurtechnik for BAM

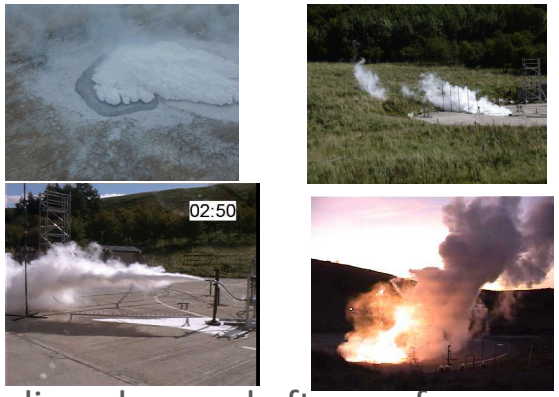


- Ignitable gas cloud significantly smaller than visible condensed water vapor cloud (in humid conditions)
- Little pooling observed
- Cooled ground significantly

Schmidtchen et al., Cryogenics, 1994

Statharas et al., J. Haz. Mat., 200

Experiments at the Health and Safety Lab (HSL) in the UK observed condensed oxygen and nitrogen



- Pooling observed after surface cooled
- Releases at sufficient height evaporate before reaching ground
- Solid deposit ignited in one test (trapped H_2 in solid O_2)

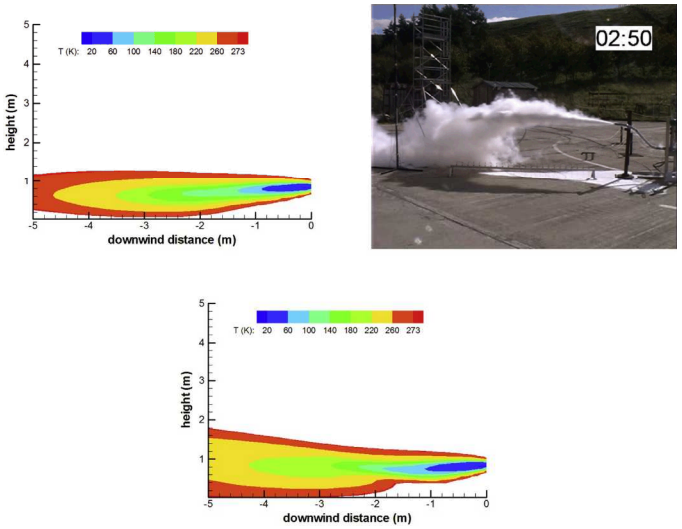
Royle and Willoughby, Proc. Safety and Env. Protection, 2011

Royle and Willoughby, Health and Safety Executive, 2014

Hall, Health and Safety Executive, 2014

Simulations have had limited success (and limited data)

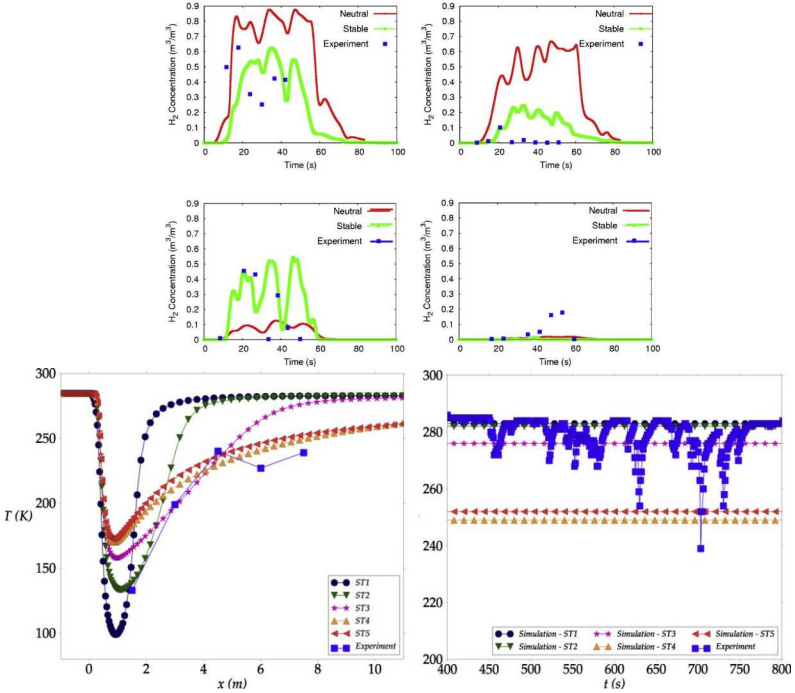
ADREA-HF has been used to simulate HSL work



- needed to account for humidity and slip between vapor and non-vapor phases

Giannissi et al. IJHE 2014

The HSL, BAM and NASA liquid hydrogen release experiments were modeled using FLACS



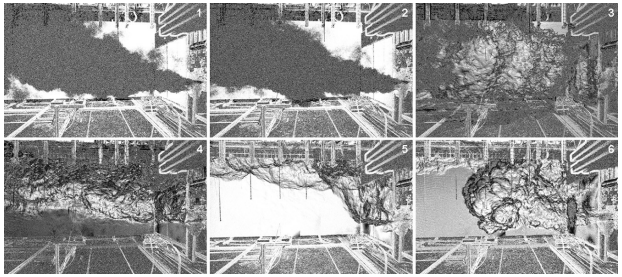
- Shallow water equations for pooling
- Assume gas/liquid phases in local thermal and kinematic equilibrium

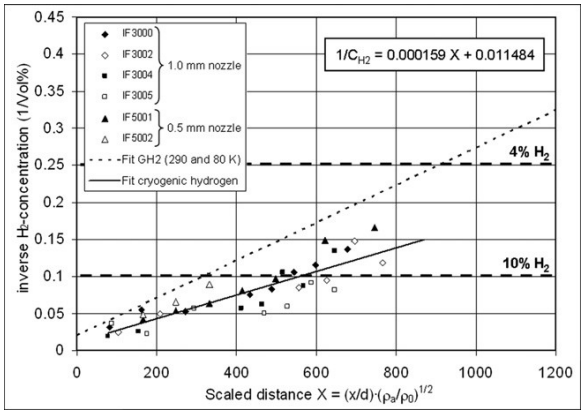
Middha, Ichard, Arntzen, IJHE 2011

Ichard et al. IJHE 2012

Smaller experiments with more boundary condition control are more appropriate for validation

Experiments at Karlsrhue Institute of Technology (KIT)



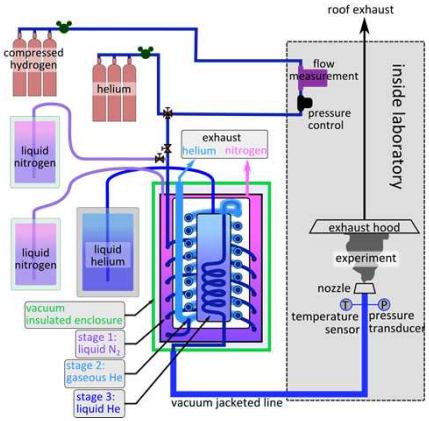


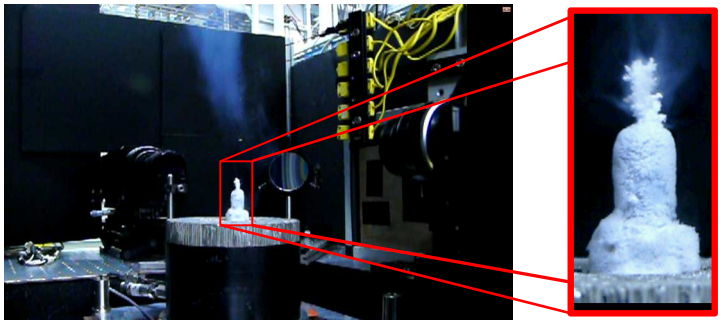
- Discrete temperature and sampling locations
- Concentration decay less rapid than for gaseous hydrogen

Friedrich et al. IJHE 2012

Xiao et al. IJHE 2011

Experiments at Sandia National Labs

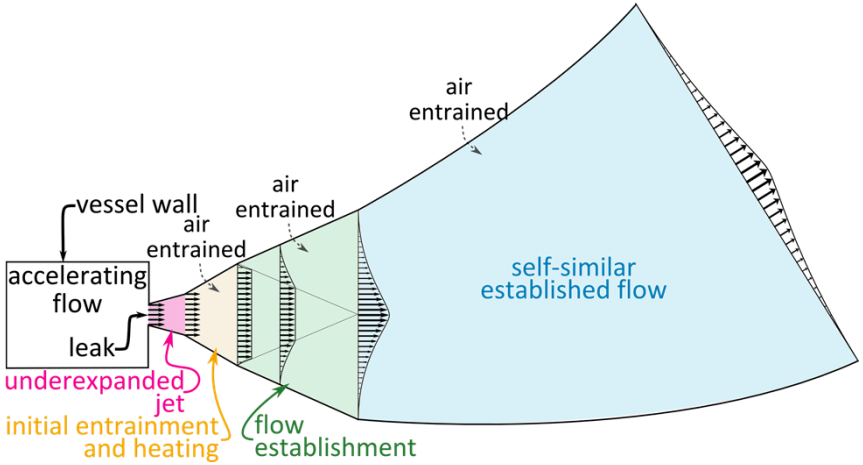


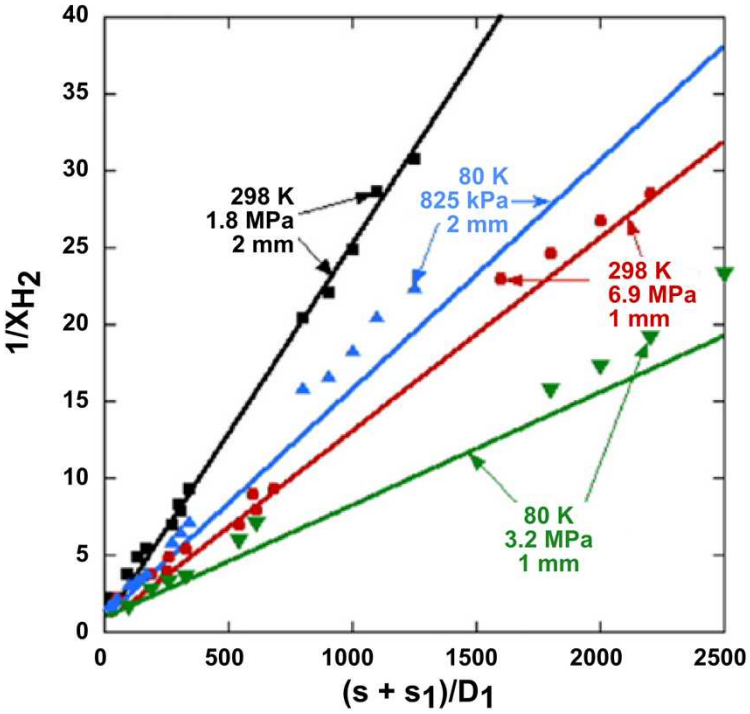


- (Air, moisture?) icing around Liq. H_2 Jet Column
- Performed ignition and radiation study on cold H2
- Working to implement filtered Rayleigh for measuring concentration field

Panda and Hecht, IJHE 2016

A cold dispersion model exists (for incorporation into HyRAM), but requires further validation data





- No air or moisture condensation considered
- Overpredicts centerline concentration for 80 K release

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

Knowledge gaps for cryogenic hydrogen plume behavior

- Internal flow modeling (flows through tubing, valves, etc. before release point)
- Higher fidelity concentration data for model validation
- Pooling, evaporation, heat transfer with ground and other surfaces
- Condensation on super-cooled surfaces (moisture AND air)
- Accurate state modeling
- Boiling Liquid Expanding Vapor Explosion events (BLEVE)