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Updated Justification for LH_2 Exposure Distance Proposal

Ethan S. Hecht and Brian D. Ehrhart

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How were the exposure distances in the public input calculated?

- Leak scenario
  - 1% of flow area
  - Multiple pipe sizes and relief pressures
- Distance criteria: grouped the same as for bulk gaseous
  - Group 1: greater of the distances to 8% concentration or 1.577 kW/m^2 heat flux
  - Group 2: distance to a heat flux of 4.732 kW/m^2
  - Group 3: distance to visible flame length or heat flux of 20 kW/m^2
- Safety factor: 2 (1.5 for gaseous)

- Similar assumptions as for bulk gaseous setbacks
  - Does not mean that full quantitative risk assessment has been done for LH_2
  - Does not mean that all LH_2 HAZOP scenarios have been modeled quantitatively

What was the resulting public input?

- Tables with distances based on pipe size and relief pressure - much like the gaseous exposure distance tables:

Table 8.3.2.3.1.6(A)(a) Minimum Distance from Outdoor Bulk Liquefied Hydrogen [LH_2] Systems to Exposures — Typical Maximum Pipe Size (1.5 in [38.1 mm])

Relief Pressure (gauge)	< 30 psig < 210 kPa		30 to 75 psig 210 to 520 kPa		75 to 120 psig 520 to 830 kPa		120 to 165 psig 0.83 to 1.14 Mpa		165 to 210 psig 1.14 to 1.45 MPa		210 to 255 psig 1.45 to 1.76 MPa		255 to 300 psig 1.76 to 2.07 MPa	
Exposures Group 1	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft
Lot lines Air intakes (HVAC, compressors, other) Operable openings in buildings and structures Ignition sources such as open flames and welding	7	23.1	9.2	30.3	11.2	36.7	13	42.5	14.5	47.5	16.7	54.7	19.3	63.2
Exposures Group 2	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft
Exposed Persons other than those servicing the system Parked Cars	5	17	7	23	8	27	10	31	10	33	12	38	13	43
Exposures Group 3	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft
Buildings of non-combustible non-fire-rated construction Buildings of combustible construction Flammable gas storage systems above or below ground Hazardous materials storage systems above or below ground Heavy timber, coal, or other slow-burning combustible solids Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation otherh than that found in maintained landscaped areas Unopenable openings in buildings and structures Encroachment by overhead utilities (horizontal	4	13	5	18	6	21	7	23	7	23	8	26	9	29

Table 8.3.2.3.1.6(A)(b) Minimum Distance from Outdoor Bulk Liquefied Hydrogen [LH_2] Systems to Exposures by Maximum Pipe Size

Relief Pressure (gauge)		< 30 psig < 210 kPa				30 to 75 psig 210 to 520 kPa				75 to 120 psig 520 to 830 kPa			
Exposures		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3	
Internal Pipe Diameter													
in	mm	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft
0.1	2.5	0.5	1.7	0.4	1.5	0.5	1.5	0.7	2.2	0.6	1.9	0.6	2
0.25	6.4	1.3	4.1	1.1	3.5	1	3.4	1.7	5.6	1.4	4.7	1.4	4.5
0.5	12.7	2.5	8.1	2	6.7	1.8	5.9	3.4	11	2.7	9	2.4	7.8
0.75	19	3.7	12	2.9	9.7	2.5	8.1	5	17	4	13	3.3	11
1	25.4	4.7	15	3.6	12	3	9.7	6.3	21	4.9	16	3.9	13
1.25	31.8	5.9	19	4.4	14	3.5	12	7.8	26	5.9	20	4.7	15
1.5	**38.1**	**7**	**23**	**5.1**	**17**	**4.1**	**13**	**9.2**	**30**	**7**	**23**	**5.4**	**18**
1.75	44.4	8.2	27	5.9	19	4.6	15	11	35	8	26	6.1	20
2	50.8	9.4	31	6.6	22	5.1	17	12	40	9	30	6.9	23
2.25	57.2	11	35	7.3	24	5.6	18	14	45	10	33	7.5	25
2.5	63.5	12	39	8	26	6.1	20	15	49	11	36	8.2	27
2.75	69.8	13	42	8.7	29	6.5	22	17	54	12	39	8.8	29
3	76.2	14	46	9.4	31	7	23	18	59	13	43	9.5	31

Relief Pressure (gauge)		75 to 120 psig 520 to 830 kPa					
Exposures		Group 1		Group 2		Group 3	
Internal Pipe Diameter							
in	mm	m	ft	m	ft	m	ft
0.1	2.5	0.8	2.7	0.7	2.4	0.7	2.4
0.25	6.4	2.1	6.8	1.7	5.7	1.6	5.3
0.5	12.7	4.1	14	3.3	11	2.8	9
0.75	19	5.8	19	4.5	15	3.7	12
1	25.4	7.6	25	5.8	19	4.6	15
1.25	31.8	9.4	31	7.1	23	5.5	18
1.5	**38.1**	**11**	**37**	**8.4**	**27**	**6.4**	**21**
1.75	44.4	13	43	9.6	32	7.2	24
2	50.8	15	48	11	36	8	26
2.25	57.2	17	54	12	39	8.8	29
2.5	63.5	18	60	13	43	9.6	32
2.75	69.8	20	66	14	47	10	34
3	76.2	22	71	16	51	11	37

Feedback from the committee

- The committee believes in the intent of the PI but would like the public to have adequate time to review these changes prior to being incorporated. Additionally, the committee would like additional time to ensure that changes have the following attributes:
  1. methodology used is well documented
  2. retrievable - ex: SAND reports
  3. repeatable - ex: someone else (independent) can be reasonably expected to have the same separation results
  4. revisable - ex: all input assumptions are clearly defined and revisable at a later date
  5. Independent verification of the model and method used
  6. Sandia to complete testing and verify dispersion model

Paper submitted to International Conference on Hydrogen Safety

- Papers are peer-reviewed (currently underway)
- Published in conference proceedings (September, 2021)
- Converted to International Journal of Hydrogen Energy paper in special issue (peer-reviewed a second time before publication – Special Issue likely in 2022)
- Provided to Dave Farese for review by task group – note: not publically available or in final form yet



ANALYSIS TO SUPPORT REVISED DISTANCES BETWEEN BULK LIQUID HYDROGEN SYSTEMS AND EXPOSURES

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ABSTRACT

The minimum distances between exposures and bulk liquid hydrogen listed in the National Fire Protection Agency's Hydrogen Technology Code, NFPA 2, are based on historical consensus without a documented scientific analysis. This work follows a similar analysis as the scientific justification provided in NFPA 2 for exposure distances from bulk gaseous hydrogen storage systems, but for liquid hydrogen. Validated physical models from Sandia's HyRAM software are used to calculate distances to a flammable concentration for an unignited release, the distance to critical heat flux values and the visible flame length for an ignited release, and the overpressure that would occur for a delayed ignition of a liquid hydrogen leak. Revised exposure distances for bulk liquid hydrogen systems are calculated. These distances are related to the burst disc pressure protection on the tank and the line size as compared to the current exposure distance calculations, which are based on system volume. This analysis is being refined as additional information on leak frequencies is incorporated and changes have been proposed to the 2023 version of NFPA 2.

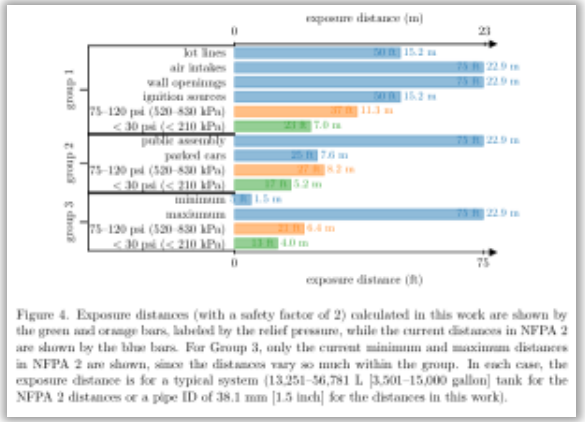
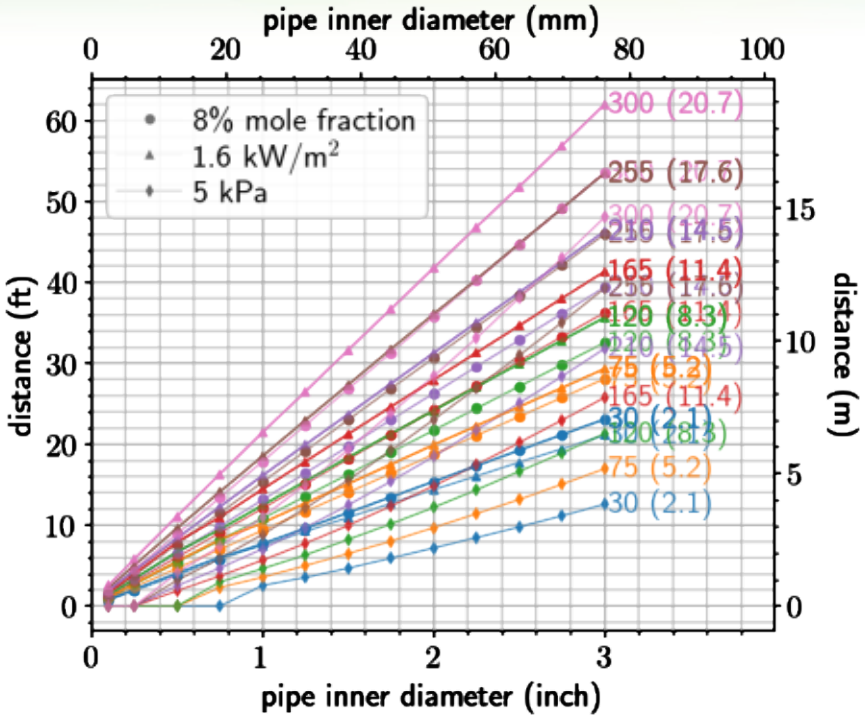


Figure 4. Exposure distances (with a safety factor of 2) calculated in this work are shown by the green and orange bars, labeled by the relief pressure, while the current distances in NFPA 2 are shown by the blue bars. For Group 3, only the current minimum and maximum distances in NFPA 2 are shown, since the distances vary so much within the group. In each case, the exposure distance is for a typical system (13,251–56,781 L [3,501–15,000 gallon] tank for the NFPA 2 distances or a pipe ID of 38.1 mm [1.5 inch] for the distances in this work).

Since the public input, we added unconfined overpressure as a hazardous criteria



Line labels denote system pressure in psi (bar)

- Example: Group 1, largest of:
  - Mole fraction of 8%
  - Heat flux of 1.6 kW/m2
  - Overpressure of 5 kPa
- Heat flux highest for all but 30psi system pressure
- 8% mole fraction highest for 30psi system pressure

➢ Even at maximum system pressure and diameter, distance (62 ft) is less than current air intake/parking distance (75 ft)

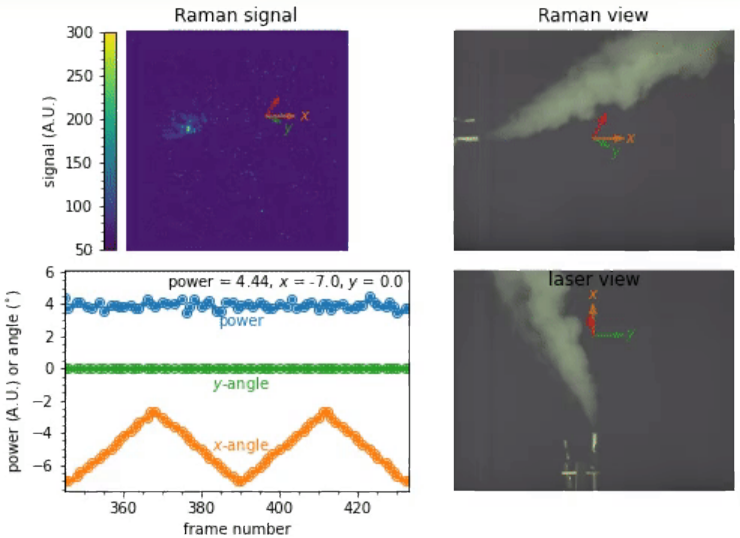
- ➢ Most systems have smaller pipes (≤ 1.5”) and lower relief pressures (≤ 75 psi)
- ➢ Safety factor increases for actual exposure distance

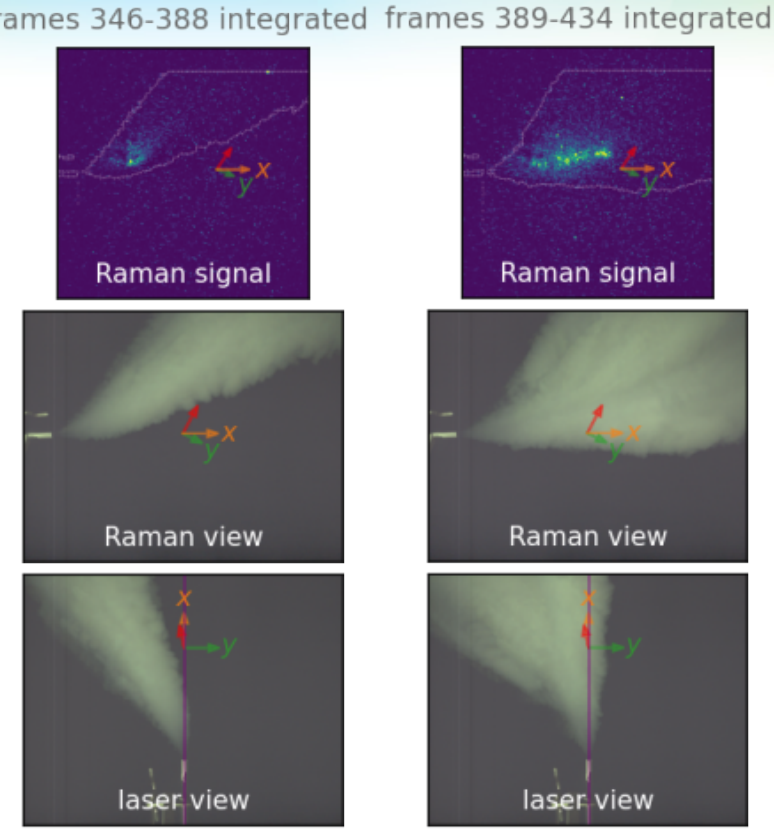
How does the distance change for a 3% leak area vs a 1% leak area?

Group	Criteria	Distance increase
1	8% mole fraction	1.7 times
1	1.6 kW/m^2	1.7 times
1	0.7 psi overpressure	2.5-3.3 times
2	4.7 kW/m^2	1.7 times
2	2.3 psi overpressure	2.5-3.3 times
3	20 kW/m^2	1.6 times
3	Visible flame length	1.4-1.6 times
3	10.2 psi overpressure	2.5-3.3 times

- Safety factor of 2 on 1% leak area is equivalent to safety factor of 0.15 on 3% leak area
- As calculated distances are conservative for 1% or 3% leak area

Experimental validation for larger flowrates and with wind has also progressed

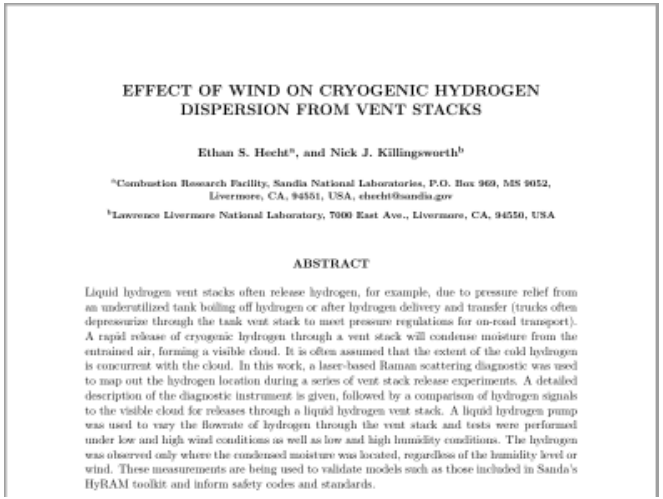




- As wind blows the visible plume off, then back on of the laser-line, the Raman signal disappears, then increases

Second paper submitted to International Conference on Hydrogen Safety

- Papers are peer-reviewed (currently underway)
- Published in conference proceedings (September, 2021)
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EFFECT OF WIND ON CRYOGENIC HYDROGEN DISPERSION FROM VENT STACKS

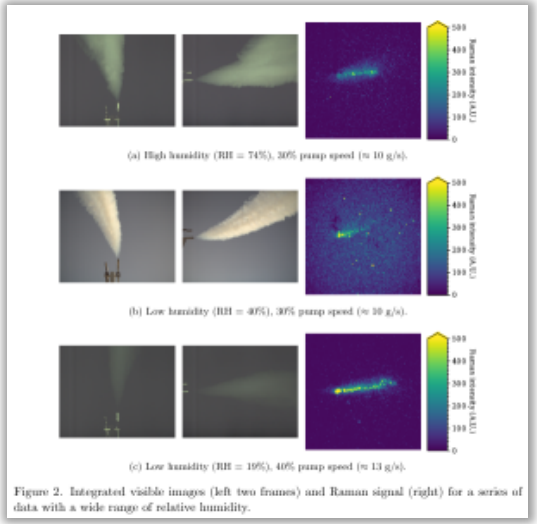
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ABSTRACT

Liquid hydrogen vent stacks often release hydrogen, for example, due to pressure relief from an underutilized tank boiling off hydrogen or after hydrogen delivery and transfer (trucks often depressurize through the tank vent stack to meet pressure regulations for on-road transport). A rapid release of cryogenic hydrogen through a vent stack will condense moisture from the entrained air, forming a visible cloud. It is often assumed that the extent of the cold hydrogen is concurrent with the cloud. In this work, a laser-based Raman scattering diagnostic was used to map out the hydrogen location during a series of vent stack release experiments. A detailed description of the diagnostic instrument is given, followed by a comparison of hydrogen signals to the visible cloud for releases through a liquid hydrogen vent stack. A liquid hydrogen pump was used to vary the flowrate of hydrogen through the vent stack and tests were performed under low and high wind conditions as well as low and high humidity conditions. The hydrogen was observed only where the condensed moisture was located, regardless of the humidity level or wind. These measurements are being used to validate models such as those included in Sandia's HyRAM toolkit and inform safety codes and standards.



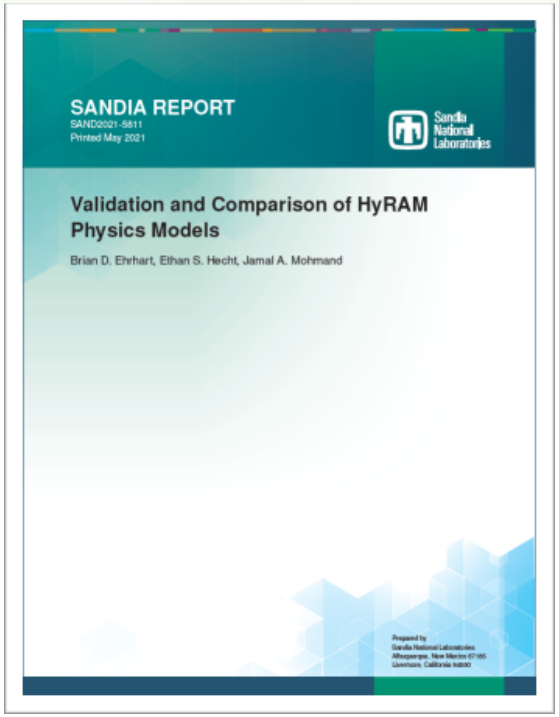
(a) High humidity (RH = 74%), 30% pump speed (≈ 10 g/s).

(b) Low humidity (RH = 40%), 30% pump speed (≈ 10 g/s).

(c) Low humidity (RH = 19%), 40% pump speed (≈ 13 g/s).

Figure 2. Integrated visible images (left two frames) and Raman signal (right) for a series of data with a wide range of relative humidity.

Verification of HyRAM models against lab-scale and literature data has been completed and published



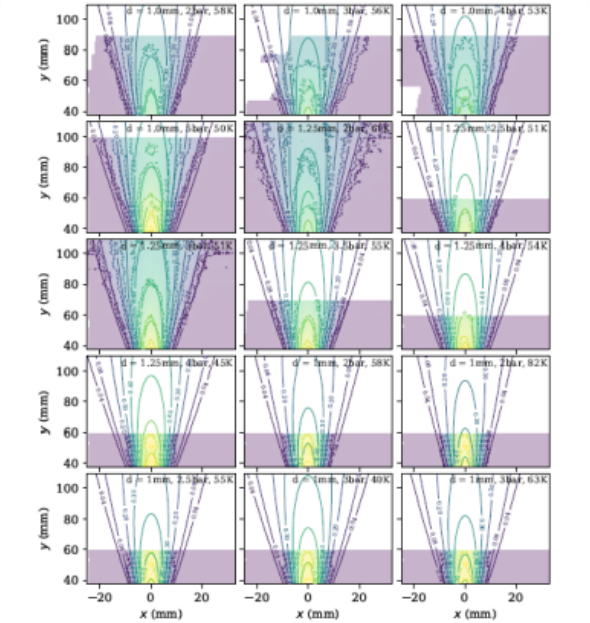


Figure 3-26 Comparison of mole fraction calculated by HyRAM 3.1 (thin, solid lines) to cryogenic hydrogen dispersion data reported by Hecht and Panda [13] (shading and thick, dashed lines) as well as some previously unreported data

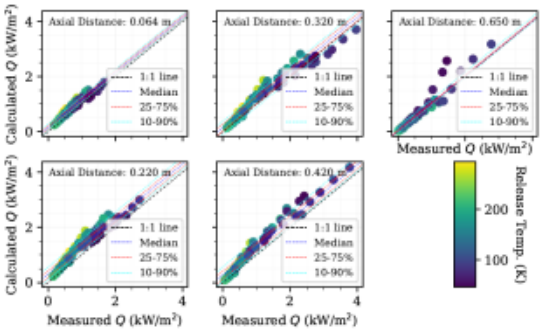


Figure 3-32 Comparison of heat flux ($\dot{Q}$) calculated by HyRAM 3.1 to those measured by Panda and Hecht [12]

- Distance calculations locked to a specific (3.1), retrievable version of the models

Recent experiments under PreSLHy project show that rainout/pooling unlikely except for vertically downward releases near ground level

- Releases through ¼" – 1" orifices, 0.5m – 1.5m from ground, 1 and 5 bar_g
  - Rainout/pooling only observed for vertically downward releases through ½" pipe 0.5m from ground (105/265 g/s)



Figure 3-18. Visible cloud during dispersion and rainout tests at HSE facility.

Rainout did not occur during the established flow of these releases, but there was evidence of rainout soon after valve closure (probably liquid air). Further to this, condensed components of air formed around the release point and on impingements for releases from the 6 and 12 mm nozzles. Pools were only formed with low, vertically downward releases. These pools potentially comprised of LH_2, condensed components of air, or a mixture of the two.

https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf
https://hysafe.info/wp-content/uploads/sites/3/2020/08/exp_workshop_260620_WP3_v2.pdf

➢ Pooling is a credible, but unlikely scenario

Summary

- Public input created but rejected for first draft
- Work underway to bolster support for the proposal
  - Distances recalculated
    - Included unconfined overpressure criteria (not limiting for any of the groups)
    - Using well documented version of HyRAM models (3.1)
      - Validation report for this version of the models
    - Paper submitted for peer-review with approach and results (could be included in annex)
  - Experiments with larger releases have been performed, providing additional validation for model
    - Paper submitted for peer-review with approach and results (could be included in annex)
  - Pooling and vaporization not included in modeling
    - Evidence suggest that pooling is unlikely
  - Leak frequencies are being compiled and documented
- Public comment to be submitted for second draft outlining these steps to support the proposal



QUESTIONS

COMMENTS

DISCUSSION



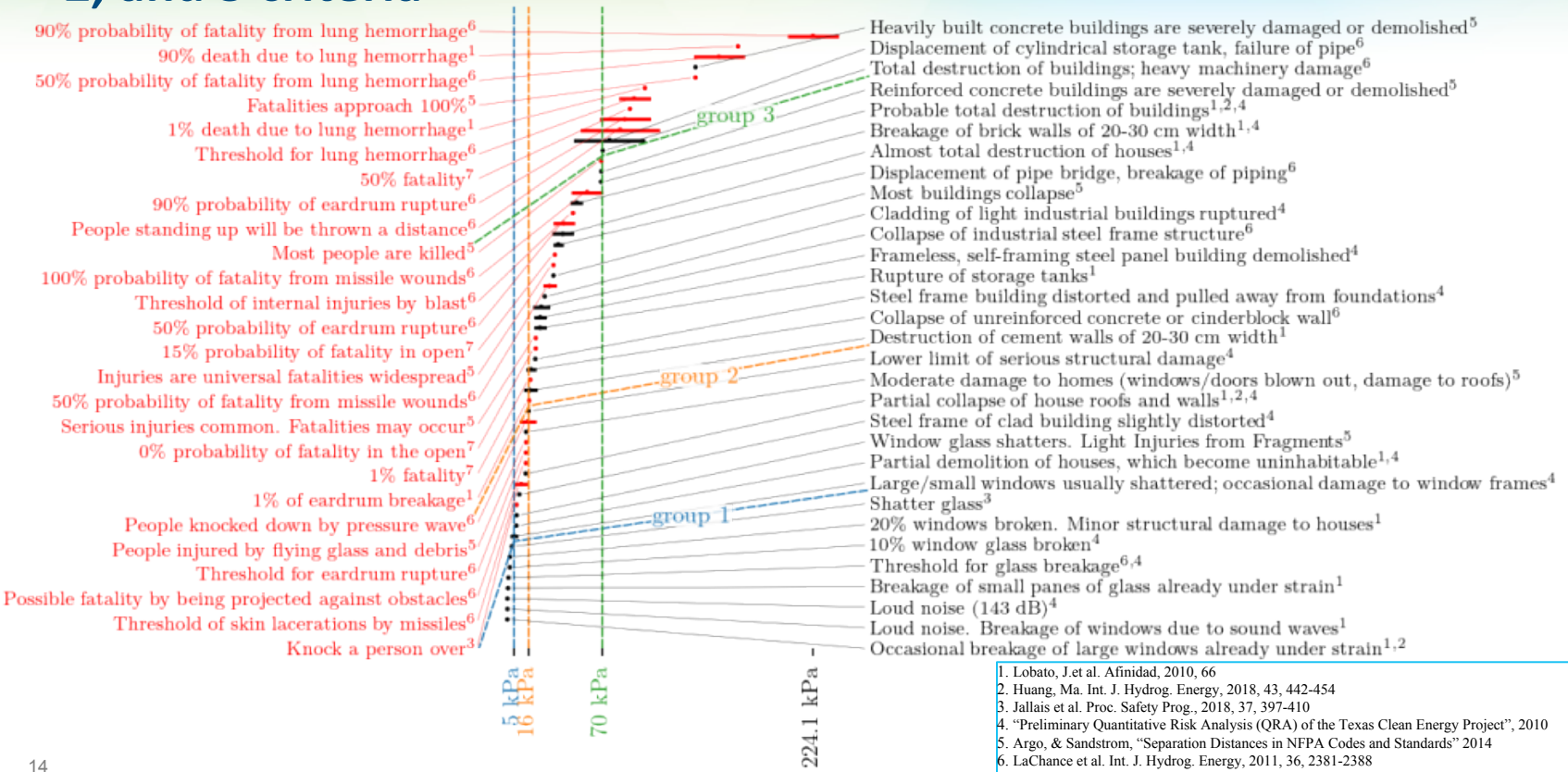
Suggestions for additional work to support the proposal?

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- United States Department of Energy, Energy Efficiency &Renewable Energy, Fuel Cell Technologies Office, Safety, Codes, and Standards subprogram managed by Laura Hill
- Industry support including the OEM Group at the California Fuel Cell Partnership, Linde, and Shell
- Air Liquide and partners

Overpressure harm criteria have reviewed, with selection of Groups 1, 2, and 3 criteria



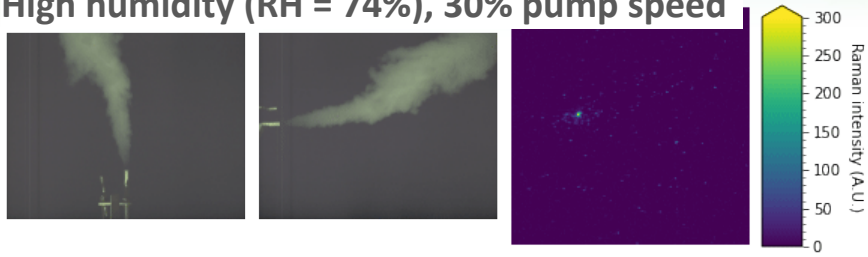
1. Lobato, J.et al. Afinidad, 2010, 66
2. Huang, Ma. Int. J. Hydrog. Energy, 2018, 43, 442-454
3. Jallais et al. Proc. Safety Prog., 2018, 37, 397-410
4. "Preliminary Quantitative Risk Analysis (QRA) of the Texas Clean Energy Project", 2010
5. Argo, & Sandstrom, "Separation Distances in NFPA Codes and Standards" 2014
6. LaChance et al. Int. J. Hydrog. Energy, 2011, 36, 2381-2388
7. "Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment." 2010

Humidity has little effect on hydrogen/visible plume trajectory

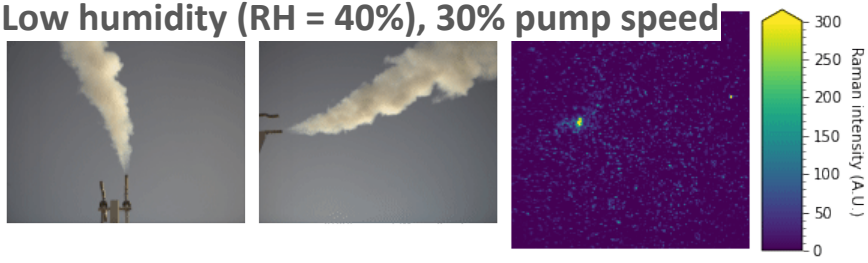
- Additional humidity does not lead to larger (wider) visible plume
- Buoyancy not affected by humidity (trajectories similar)
- Raman signal similar for all (19-74%) relative humidity

➢ Condensation of water vapor has minimal influence on dispersion

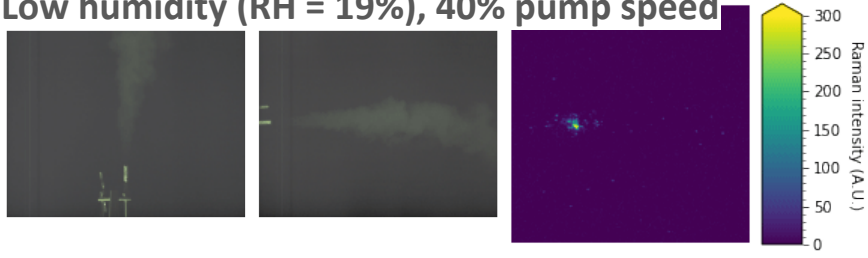
High humidity (RH = 74%), 30% pump speed



Low humidity (RH = 40%), 30% pump speed



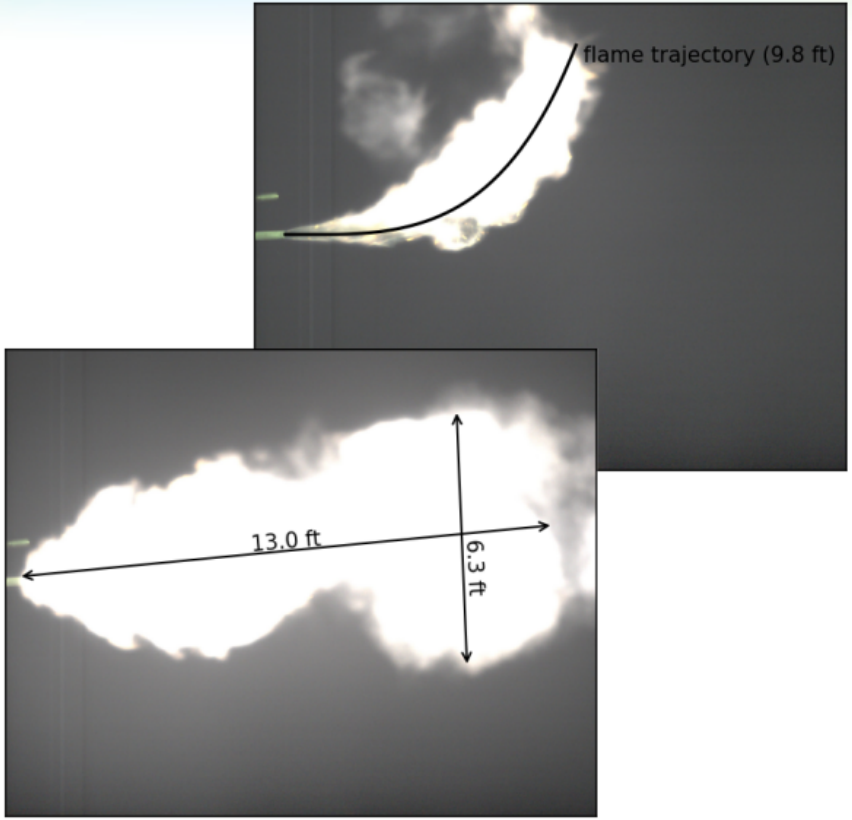
Low humidity (RH = 19%), 40% pump speed



High laser power resulted in ignition, but the flame was safely extinguished without harm (to personnel or equipment)







- Data for validation of our flame model