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Comparison of Hydrogen and Hydrocarbon Fuels Hazards, and Practical Risk Management Strategies

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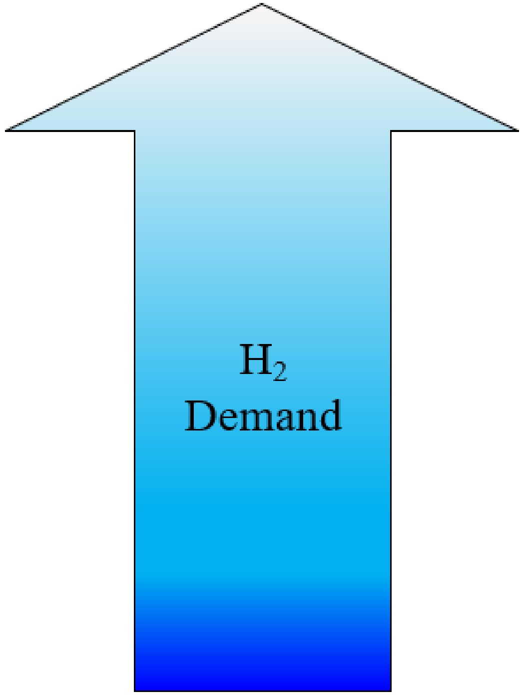
Presentation Overview

- Context
- Hydrogen Hazard Overview
  - Flammable dispersion
  - Jet Fires
  - Pool fires
  - Vapor Cloud Explosions (VCEs)
- Consequence comparison of hydrogen and common hydrocarbon fuels
- Incident Review
- Key Findings
- Questions

Context

- Amid a global focus on sustainability, governments and companies are searching for alternative fuel and energy sources to reduce green house gas emissions and minimize carbon footprints
- In 2022 at the United Nations Climate Change Conference, the US and 18 other countries committed to reaching a goal of net-zero emissions from government by 2050
- Quantity and demand of Hydrogen (H_2) is expected to increase as its usage as a fuel and energy carrier increases globally
- Hazards of hydrogen and hydrogen equipment are less commonly understood by those who may be planning to use hydrogen as a fuel



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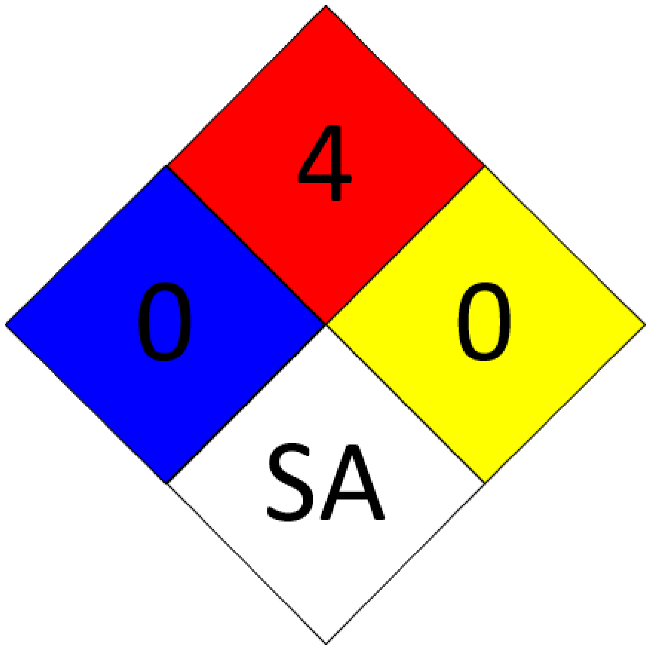
Study Objective

- Summarize flammable hazards associated with hydrogen
- Compare hydrogen hazards with hazards of common hydrocarbon fuels through consequence modeling
- Provide current industry risk practitioners with useful guidance to understand the hazards associated with hydrogen
- Provide overview of select hydrogen release incidents



NFPA 704 Fire Diamond for Hydrogen

Hazard: Flammable Dispersion

Property	Hydrogen	Methane	Propane	Butane
Flammable Range	4% to 75%	4% to 16%	2% to 10%	2% to 9%
Minimum Ignition Energy	0.019 mJ	~0.1 mJ	~0.1 mJ	~0.1 mJ
Dispersion characteristics	Gaseous H_2: buoyant Liquefied H_2 (LH2): Initially dense vapor after release, buoyant after vapor warms	Buoyant, but initially dense vapor for high-pressure and liquefied-gas releases, buoyant after vapor warms	Dense vapor generated from vaporization of liquid propane release	Dense vapor generated from vaporization of liquid butane release

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Hazard: Jet Fire

- H_2 jet fires burn with a very pale blue flame
  - H_2 flames are almost completely invisible in daylight and very difficult to see with the naked eye
  - Before modern IR scanning technology, a rudimentary detection method known as the “broom method” was even used to find hydrogen leaks
- Hydrogen jets will generally be choked at sonic velocity due to the high storage pressures typically used for hydrogen fuel applications (7000 psig)
- Lower density and molecular weight of hydrogen results in a shorter flame length than an equivalent natural gas release
- Hydrogen produces less thermal radiation than methane upon combustion

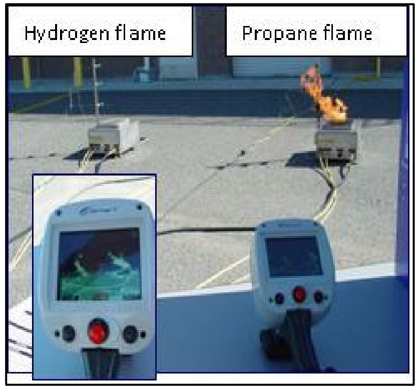

Image source: D. Bjerketvedt and A. Mjaavatten, "A Hydrogen-Air Explosion in a Process Plant: A Case Study," Faculty of Technology, Telemark University College, 2005.

Image source: https://spinoff.nasa.gov/spinoff1997/ps1.html

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Hazard: Pool Fire

- LH2 must be refrigerated below -253°C (20 K) and is generally stored near atmospheric pressure.
- Experimental releases of LH2 have observed air both condensing and freezing near the surface of LH2 releases, resulting in a buildup of solid air near the surface.
- Potential to ignite if exposed directly to an ignition source.
- Like LPG and LNG, LH2 vaporizes rapidly upon release and is capable of generating large flammable vapor clouds

Image source: P. Hooker, D. B. Willoughby, J. Hall and M. Royle, "Experimental Releases of Liquid Hydrogen," Crown Copyright, 2012.

Hazard: Vapor Cloud Explosion

- H_2 flame speed much higher than other common hydrocarbon fuels
- H_2 flame speed 286 cm/s versus methane flame speed of 37 cm/s
- H_2 has higher propensity for deflagration to detonation transition (DDT) than other common hydrocarbon fuels
- H_2 gas becomes very buoyant and may disperse more quickly than other hydrocarbon fuels in open environments
- These effects can result in hydrogen leaving congested regions before ignition, reducing the flammable mass of the cloud, and limiting downwind dispersion prior to potential ignition

Modeling Comparison Scenarios Evaluated

Scenario Number	Material	Temperature (°C)	Pressure (barg)	Phase	Release Orientation [2]	Volume (gal)	Bund Area (m^2) [3]
1	H_2	25	350	Vapor	Horizontal	10,000	N/A
2	LH2	-255	0	Liquid	Downward	6,000	100
3	Methane (CH_4)	25	350	Vapor	Horizontal	8,000	N/A
4	LNG (Refrigerated)	-163	0	Liquid	Downward	8,000	100
5	LNG (Pressurized)	-109.7	17.2	Liquid	Horizontal	10,000	100
6	LPG [1]	25	8.5	Liquid	Downward	10,000	100
7	LPG [1]	25	8.5	Liquid	Horizontal	10,000	100

[1] LPG conservatively modeled as pure propane
[2] Releases were modeled at 1m elevation
[3] Liquid release scenarios were modeled as "bunded" and "unbunded"; vapor release scenarios marked as "N/A"
All scenarios modeled using Phast v8.71, see full paper for additional modeling details

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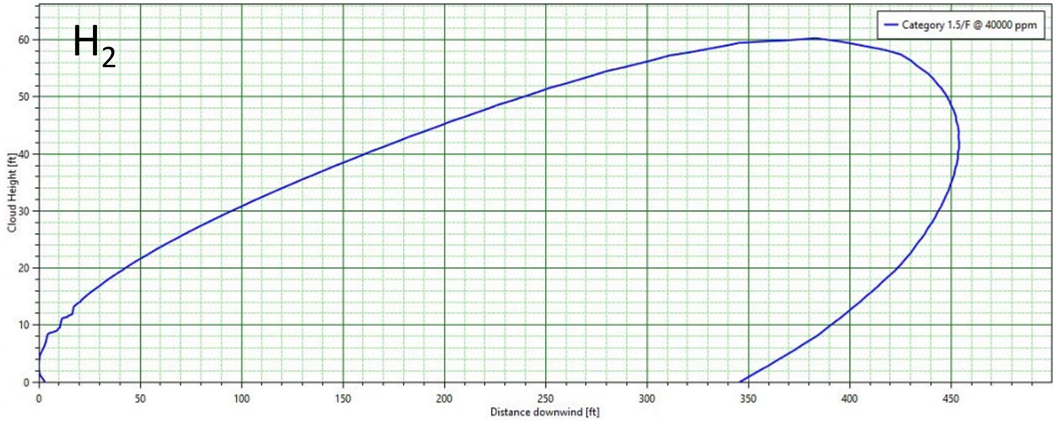
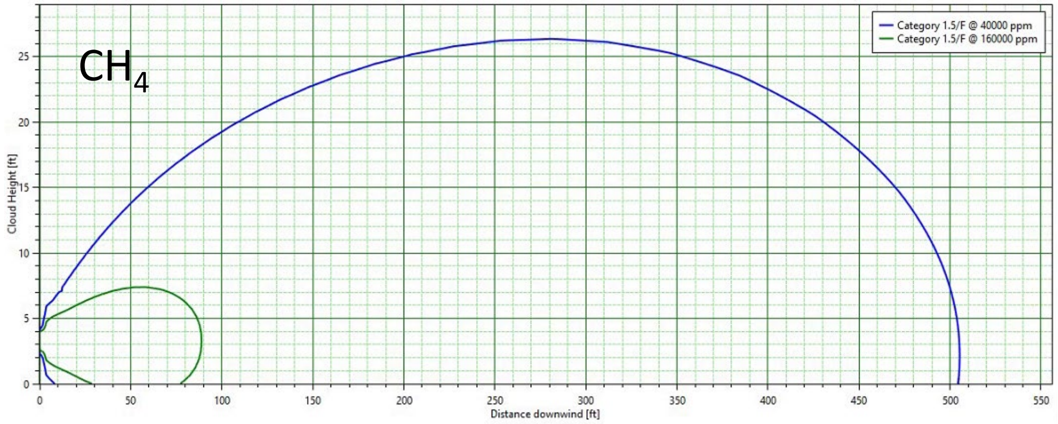
Flammable Dispersion Modeling Comparison

Flammable dispersion of hydrogen is characterized by:

- Buoyancy-driven lift off in far field from compressed gas releases
  - Near field dispersion is momentum driven
- Dense clouds from LH2 pools, which translate into buoyant clouds
- Wide flammable limits (4% - 75%)
  - Comparatively, Methane's is 4% to 16%





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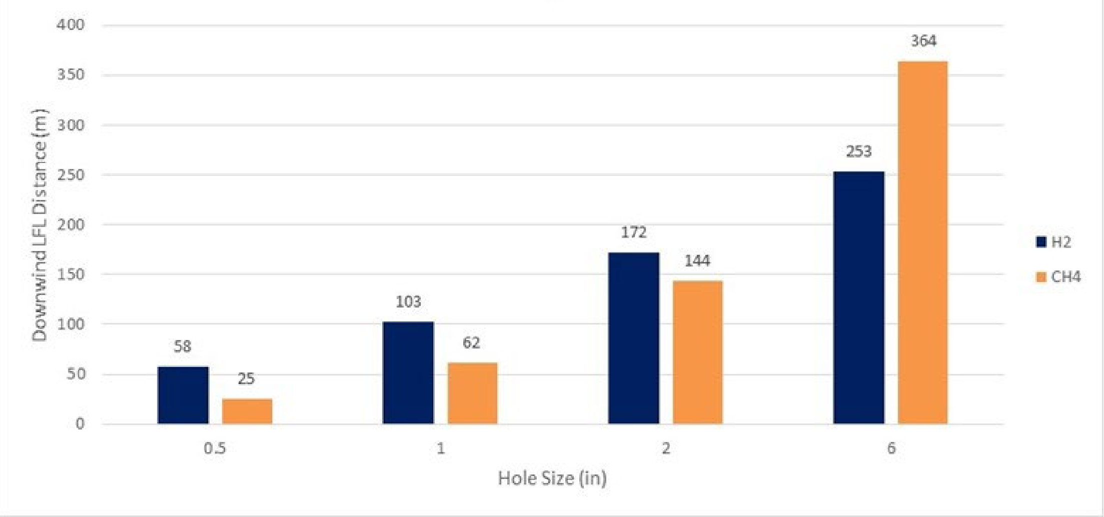
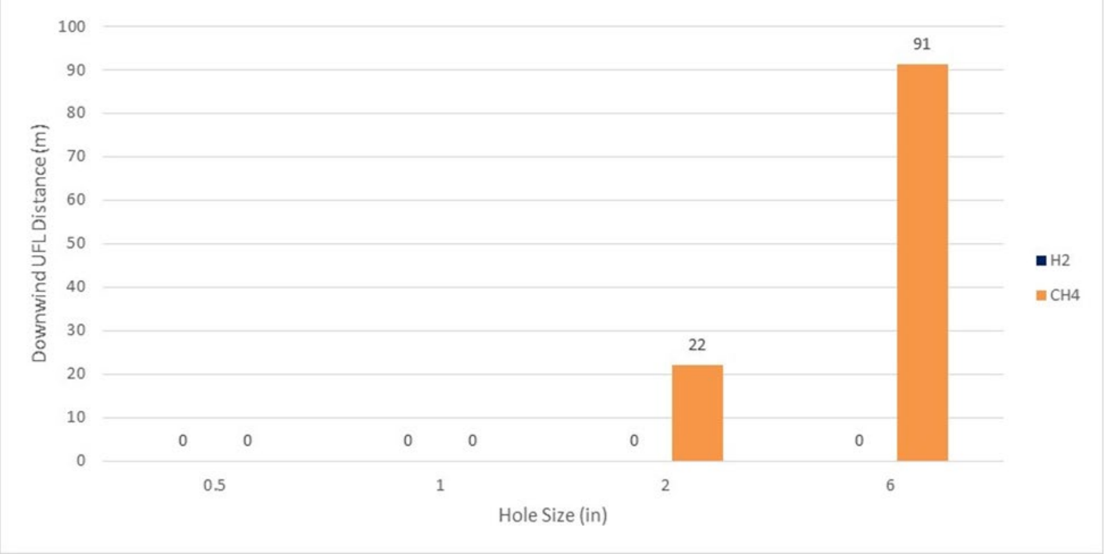
Flammable Dispersion Modeling Comparison



Downwind LFL Distance (m) vs Hole Size for Gas Releases at Storage Conditions (at ground level)



Downwind UFL Distance (m) vs Hole Size for Gas Releases at Storage Conditions (at ground level)

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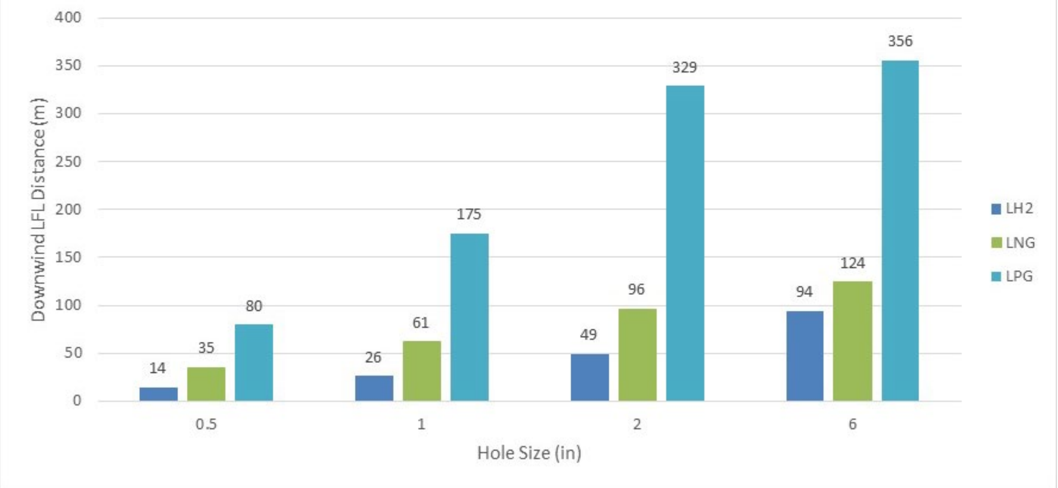
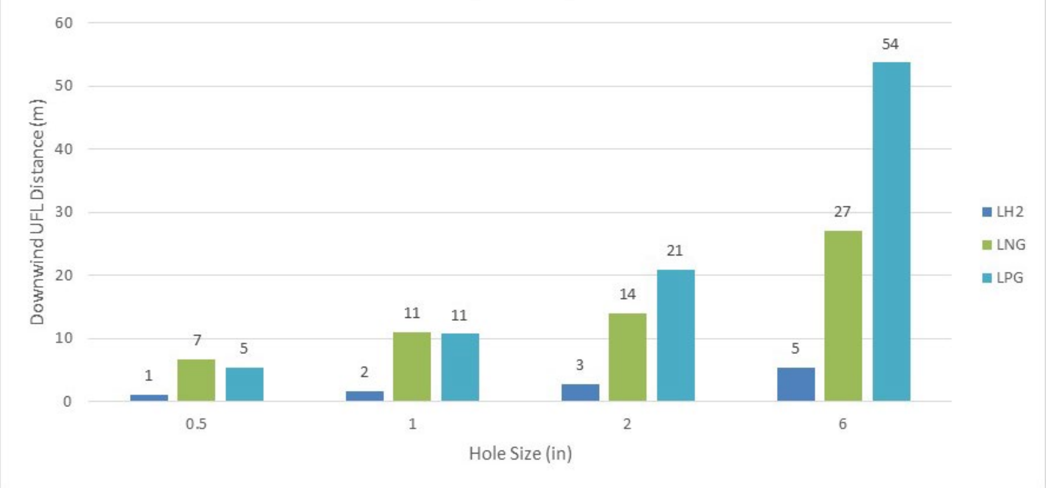
Flammable Dispersion Modeling Comparison



Downwind LFL Distance (m) vs Hole Size for Liquid Releases at Storage Conditions (Unbunded)



Downwind UFL Distance (m) vs Hole Size for Liquid Releases at Storage Conditions (Bunded)

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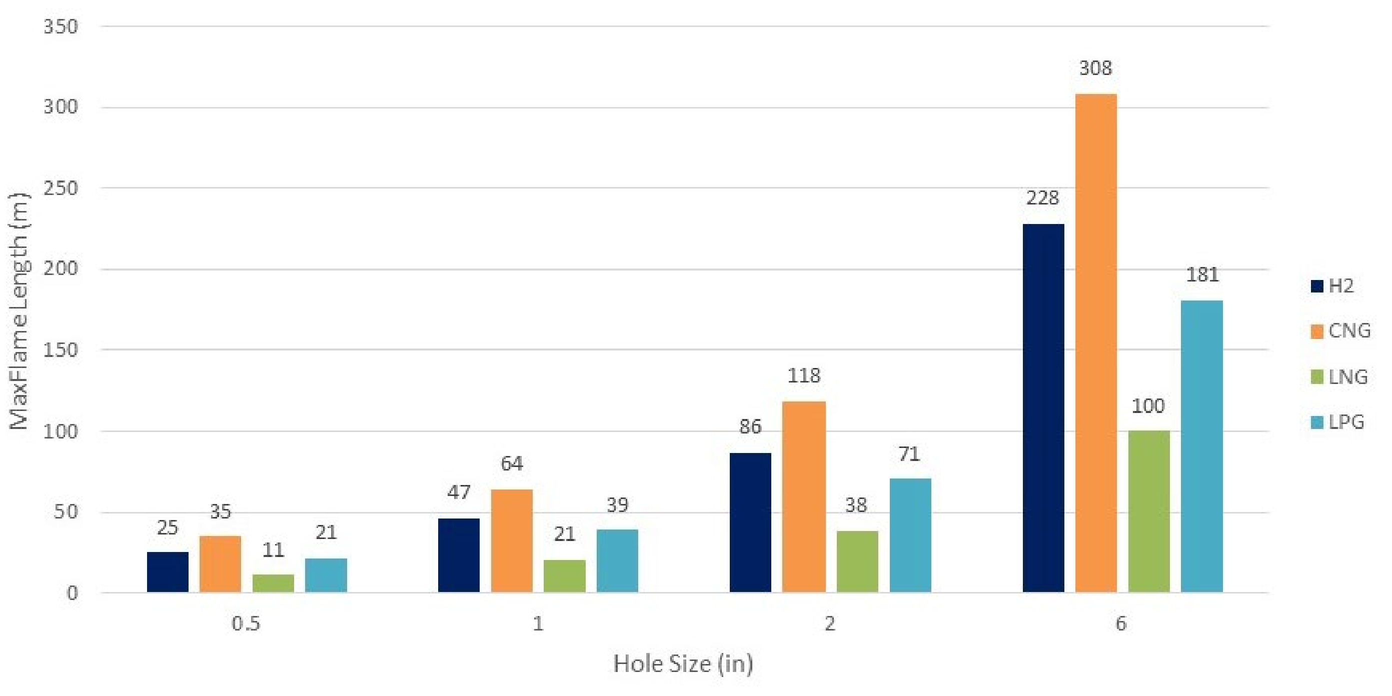
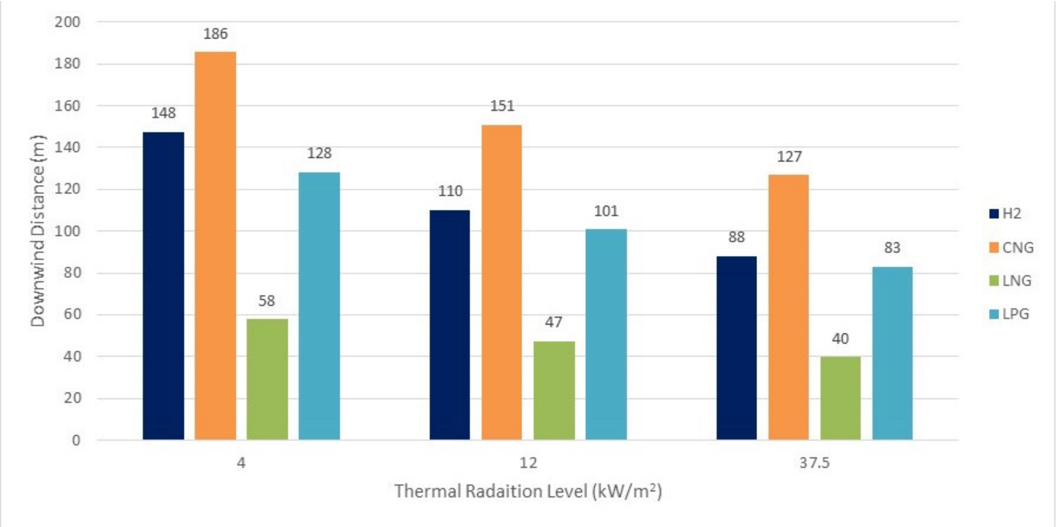
Jet Fire Modeling Comparison

- Jet fire consequences for the hydrocarbon and hydrogen fuels were modeled at typical storage conditions
  - Hydrogen jet fires were modeled using the “Miller” model within Phast
  - Hydrogen jet fires consequences were more similar to LPG fires than compressed natural gas (CNG)

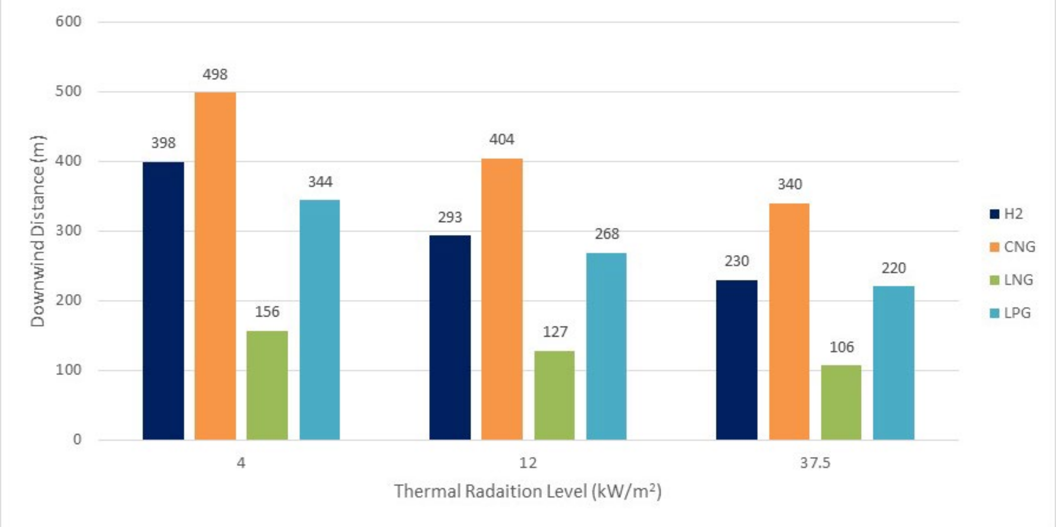


Jet Fire Flame Length for Fuels at Storage Conditions vs Release Size

Jet Fire Modeling Comparison



Jet Fire Thermal Footprint for 2" Releases



Jet Fire Thermal Footprint for 6" Releases

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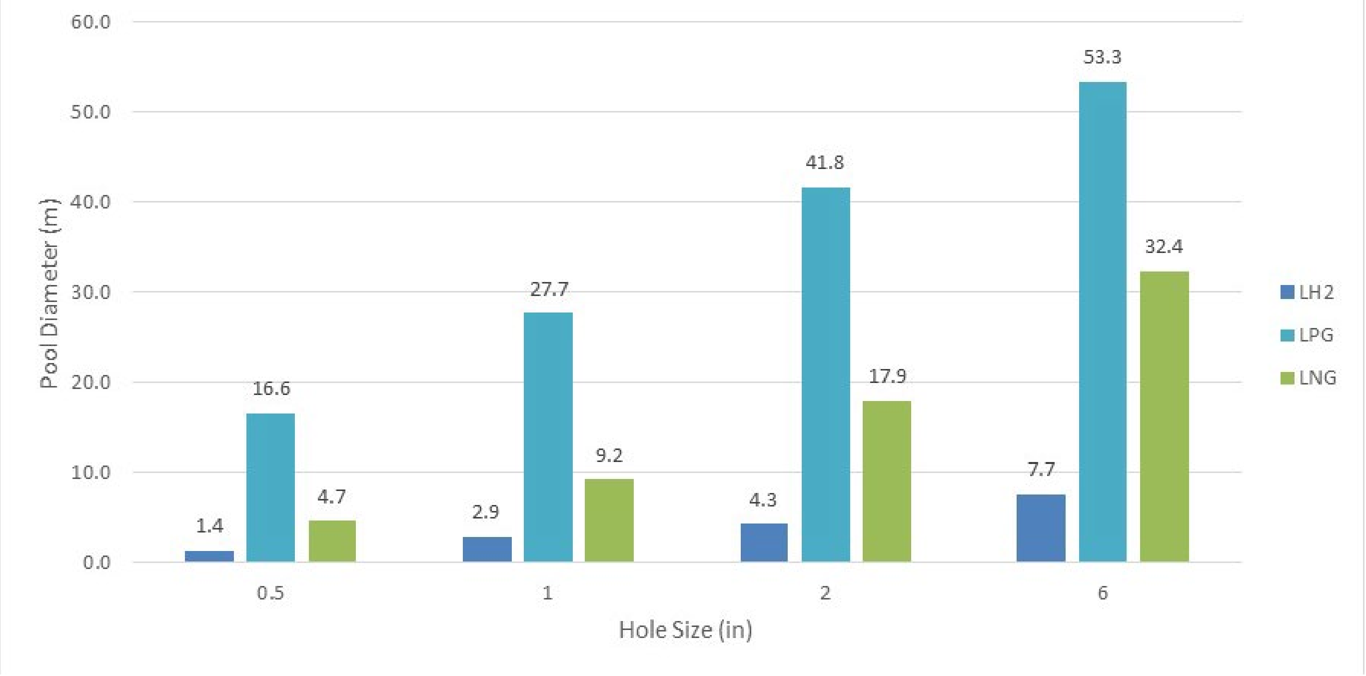
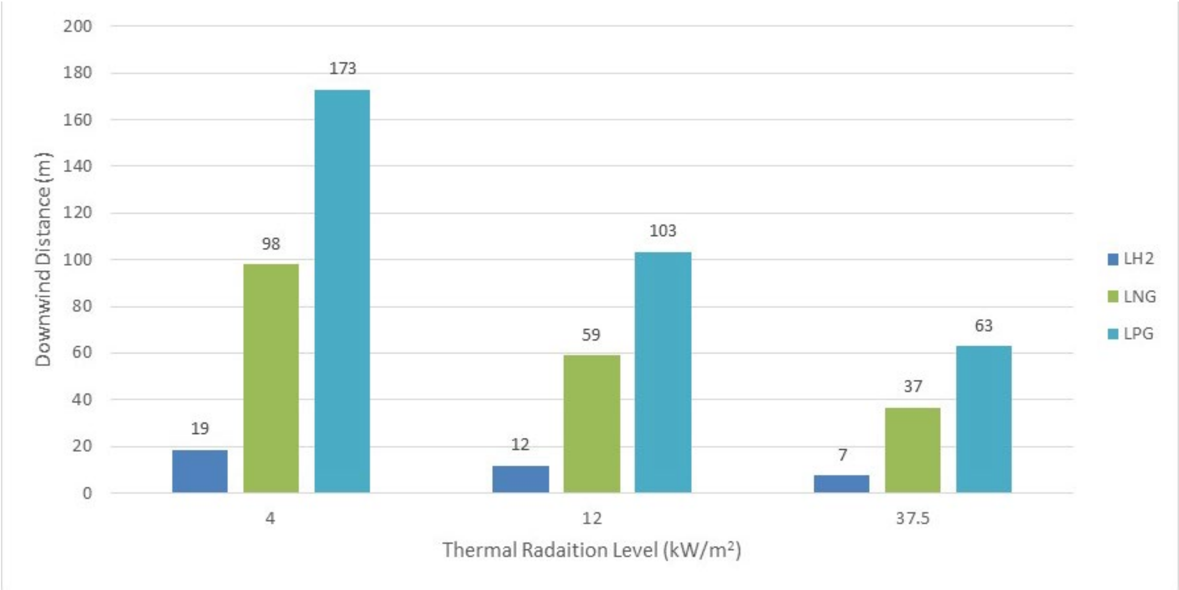
Pool Fire Modeling Comparison

- Pool fires were modeled for LNG, LH2, and LPG
  - Scenarios were modeled as both free pools and pools limited to a bund of $100m^2$
  - LH2's higher vaporization rate limited the pool to less than the bund area
  - LH2's lower thermal output compared to HC fuels limits the thermal footprint

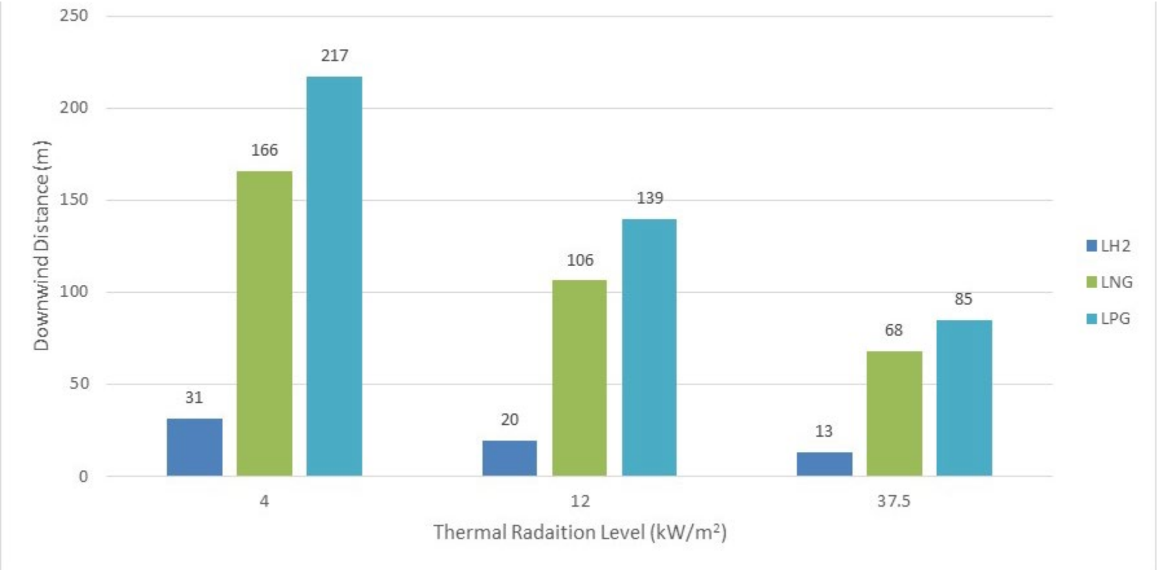


Pool Diameter for Unbunded Liquid Releases

Pool Fire Modeling Comparison: Unbunded Liquid Release



Thermal Footprint for Unbunded 2” Liquid Releases



Thermal Footprint for Unbunded 6” Liquid Releases

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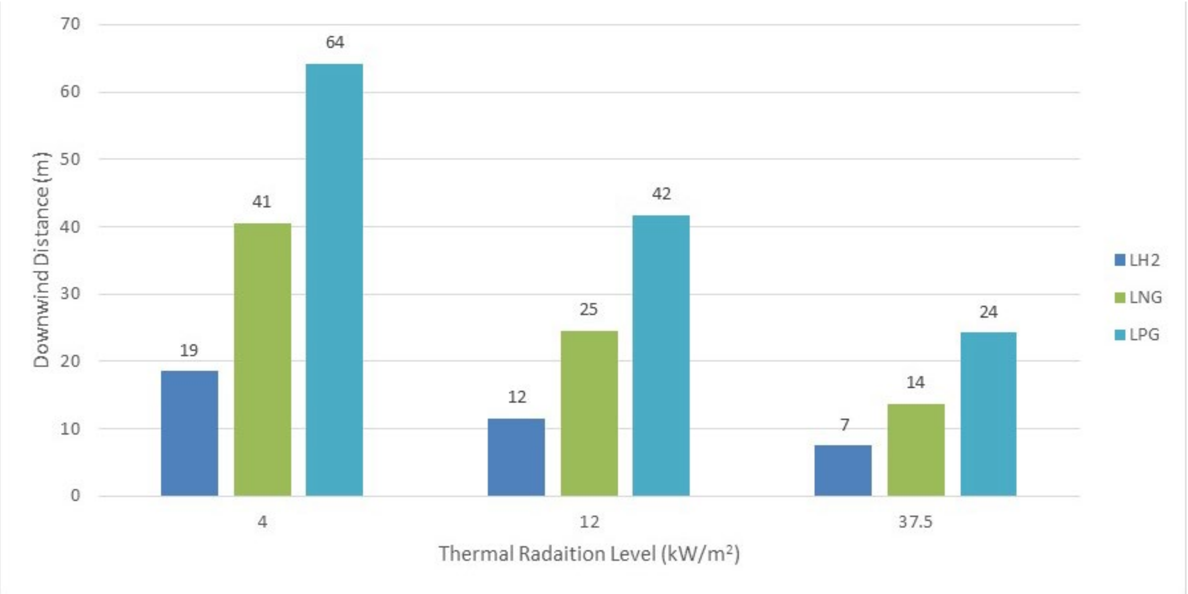
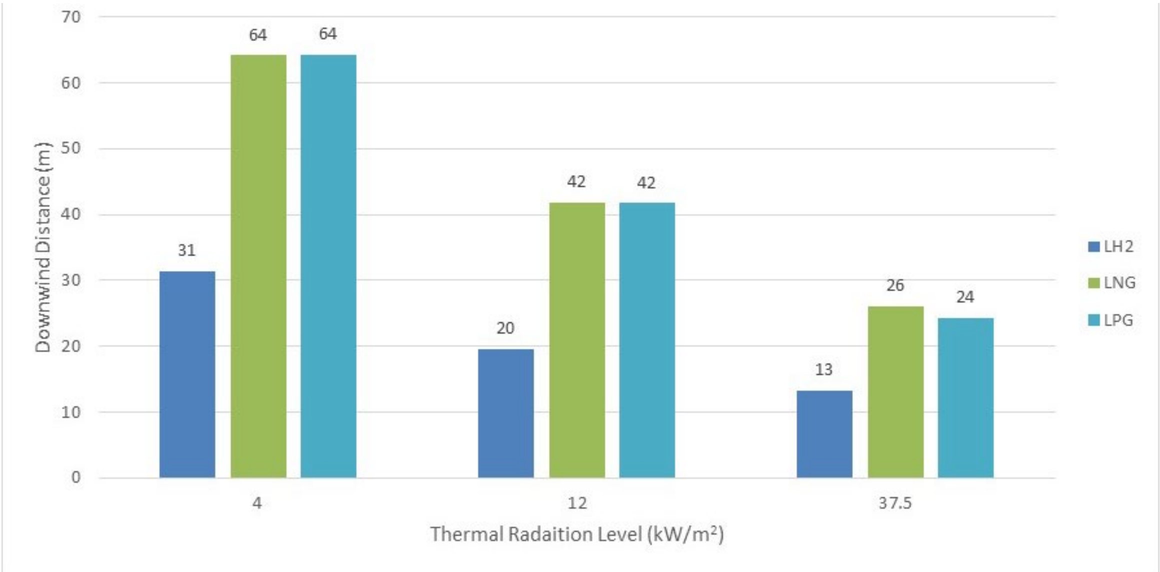
Pool Fire Modeling Comparison: Bunded Liquid Release



Thermal Footprint for Bunded 2" Liquid Releases



Thermal Footprint for Bunded 6" Liquid Releases

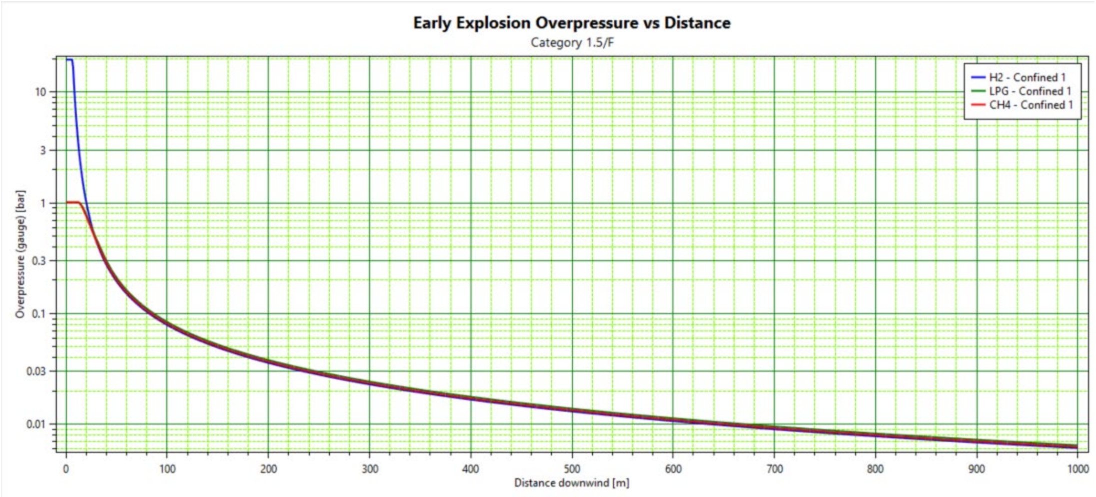
Vapor Cloud Explosion Modeling Comparison

Explosion modeling included the following three configurations:

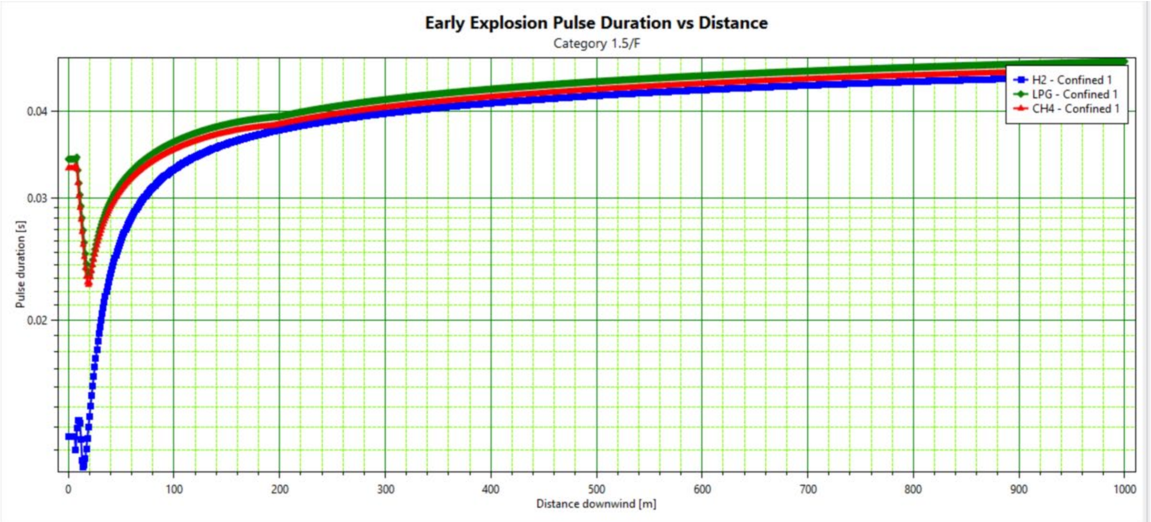
1. **Configuration 1 TNO**: 849.5 m^3 (30,000 ft^3) being filled with stoichiometric amounts of each fuel before igniting. TNO source strength of 10 for H_2 (DDT) and 7 for hydrocarbon fuels (strong deflagration).
   a. 152 kgs (335 lbs) H_2
   b. 333 kgs (734 lbs) LPG
   c. 303 kgs (668 lbs) CH_4
2. **Configuration 2 BST**: 25 kgs of H_2, CH_4, and LPG in medium congestion with 2D expansion
3. **Configuration 3:** Releases from H_2, CH_4, and LPG at storage conditions dispersing into a 20m x 20m x 20 x congested region. TNO source strength of 10 for H_2 (DDT) and 7 for hydrocarbon fuels (strong deflagration).

Vapor Cloud Explosion Modeling Comparison

Configuration 1: Stoichiometric amounts of each fuel filling 30,000 cubic feet. Modeled using TNO methodology



Overpressure vs Distance (m)



Pulse Duration vs Distance (m)

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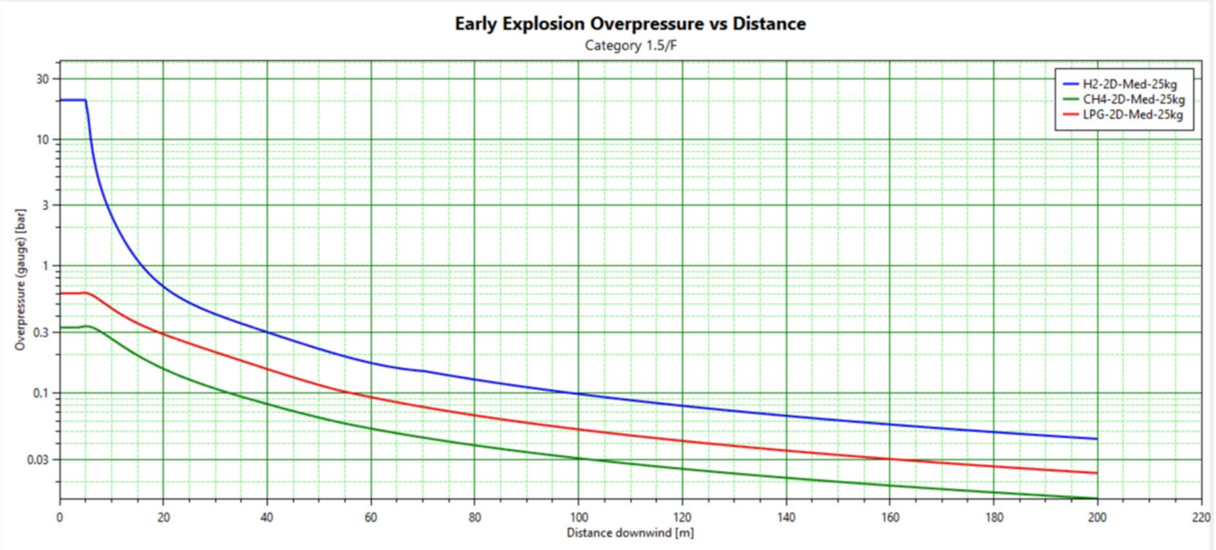
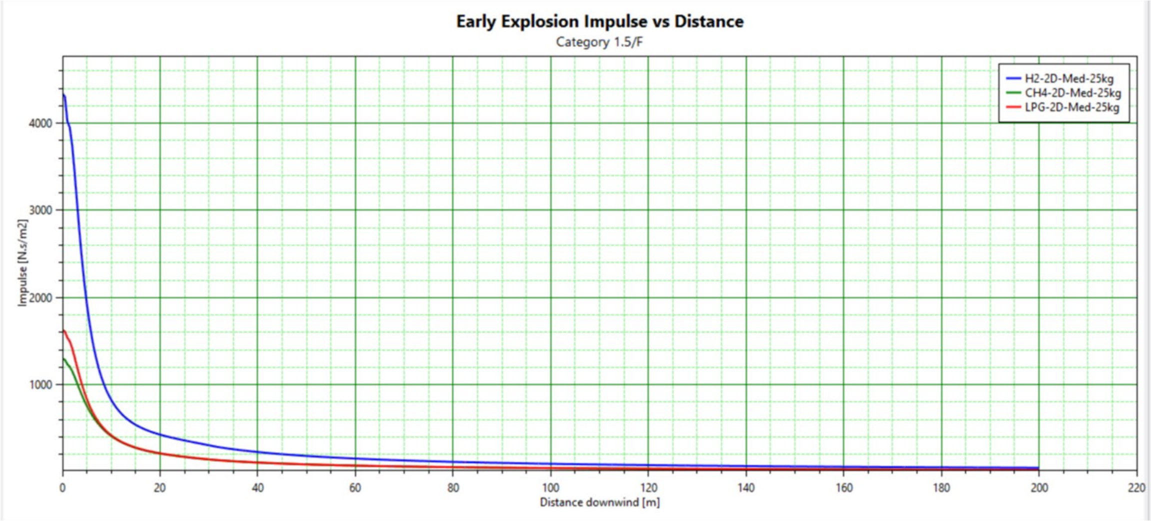
Vapor Cloud Explosion Modeling Comparison

Configuration 2: 25 kgs of each fuel modeled using BST methodology – 2D expansion in medium congestion.



Overpressure vs Distance (m)



Pulse Duration vs Distance (m)

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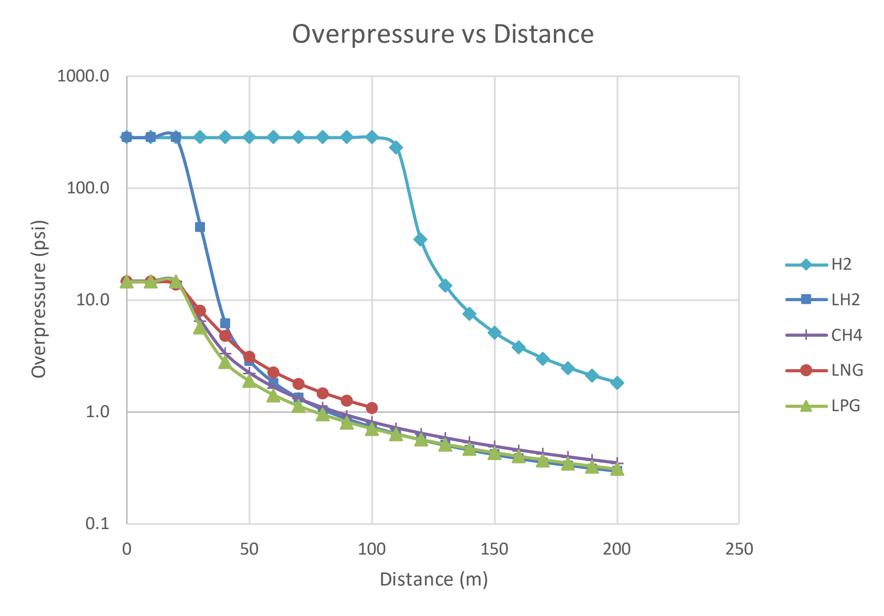
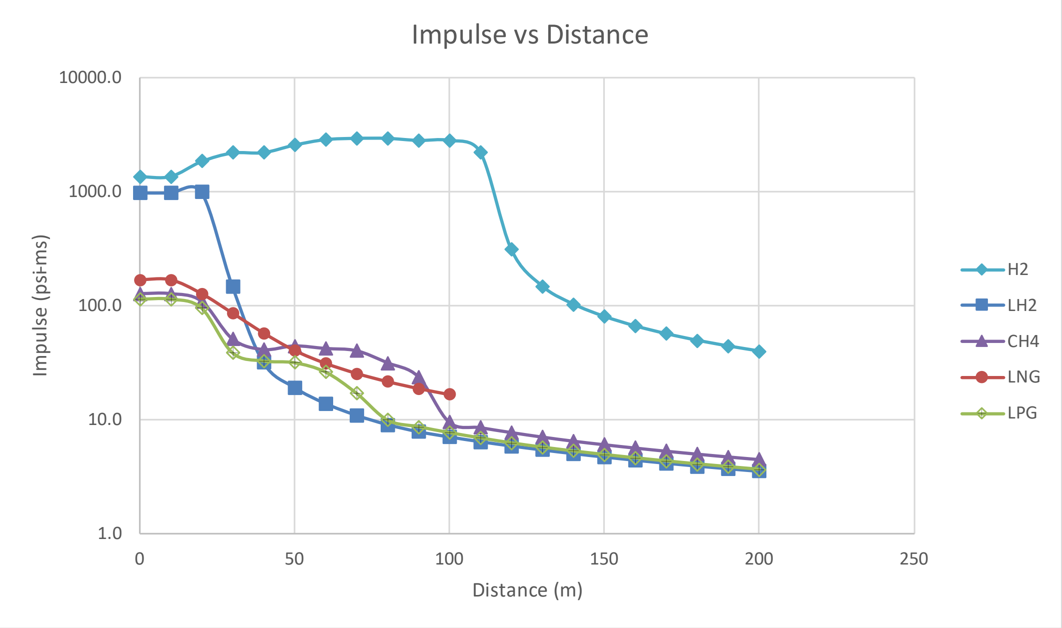
Vapor Cloud Explosion Modeling Comparison

Configuration 3: Releases of each fuel dispersing into a 20m x 20m x 20m confined region – modeled using TNO methodology



Overpressure vs Distance (m)



Pulse Duration vs Distance (m)

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Vapor Cloud Explosion Modeling Comparison

- Each configuration illustrated that if DDT is taken into consideration, hydrogen explosions yield large, but short-lived overpressures
- Literature has shown that hydrogen detonation typically requires confinement and a high concentrations of H_2
- Facility incidents where hydrogen detonation, rather than deflagration, may have occurred appear to be limited to incidents with confinement, such as in-building releases

Select Incident Review

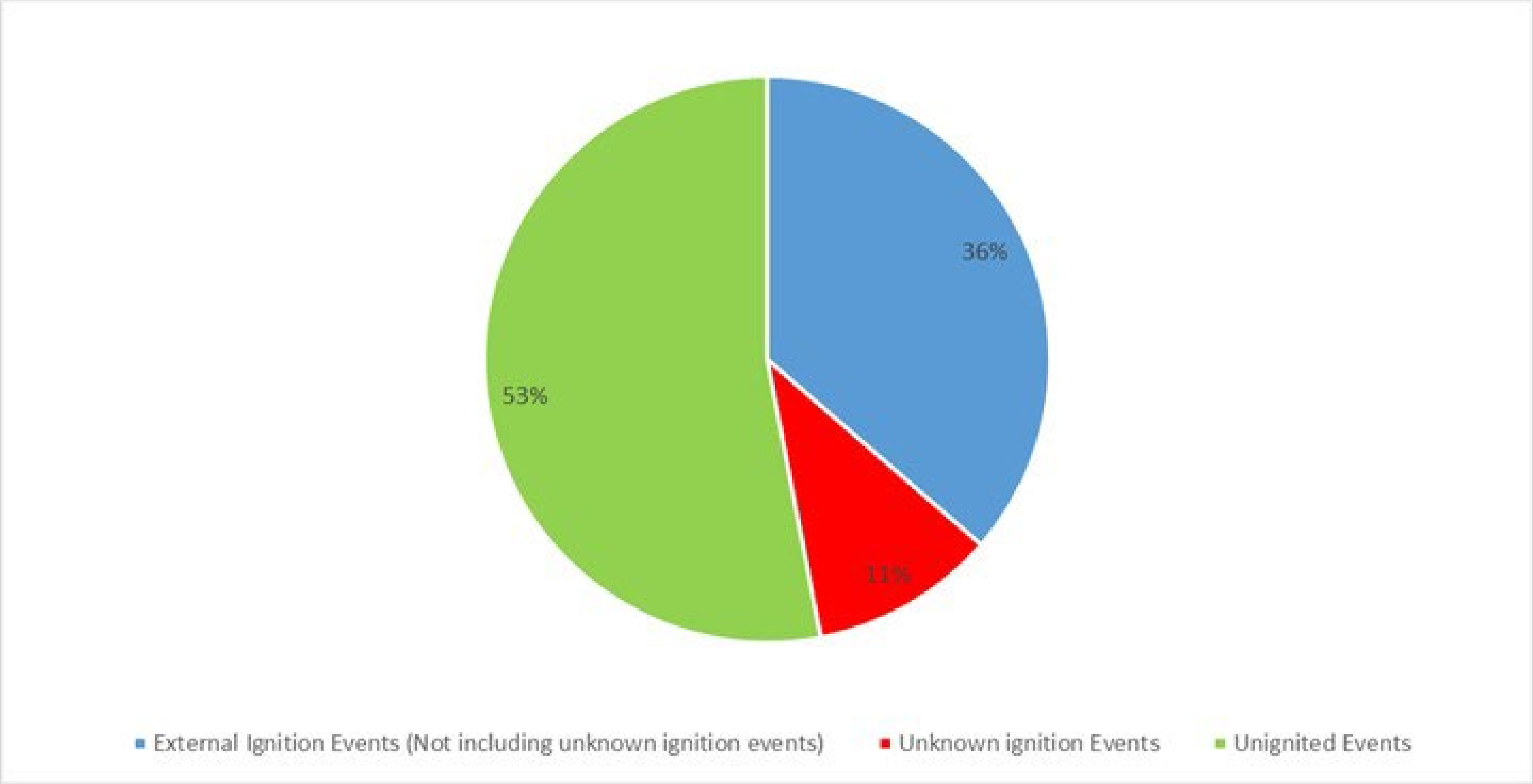
Incident summaries of 66 H_2 release events published by the Hydrogen Safety Panel were reviewed to understand relative prevalence of potential outcomes. The hydrogen release events within this summary were organized into the following categories:

- Fueling Station Incidents
- Hydrogen Instrument Incidents
- System Design, Operator, and Maintenance Incidents
- Pressure Relief Device Incidents
- Hydrogen Cylinder Incidents
- Industrial Truck Incidents
- Laboratory Incidents
- Liquid Hydrogen Incidents
- Piping Incidents
- Hydrogen Compressor Incidents

Image source: https://currentaffairs.adda247.com/ohmium-launches-indias-first-green-hydrogen-electrolyzer-gigafactory/

Select Incident Review

Summary of events by Ignition Source



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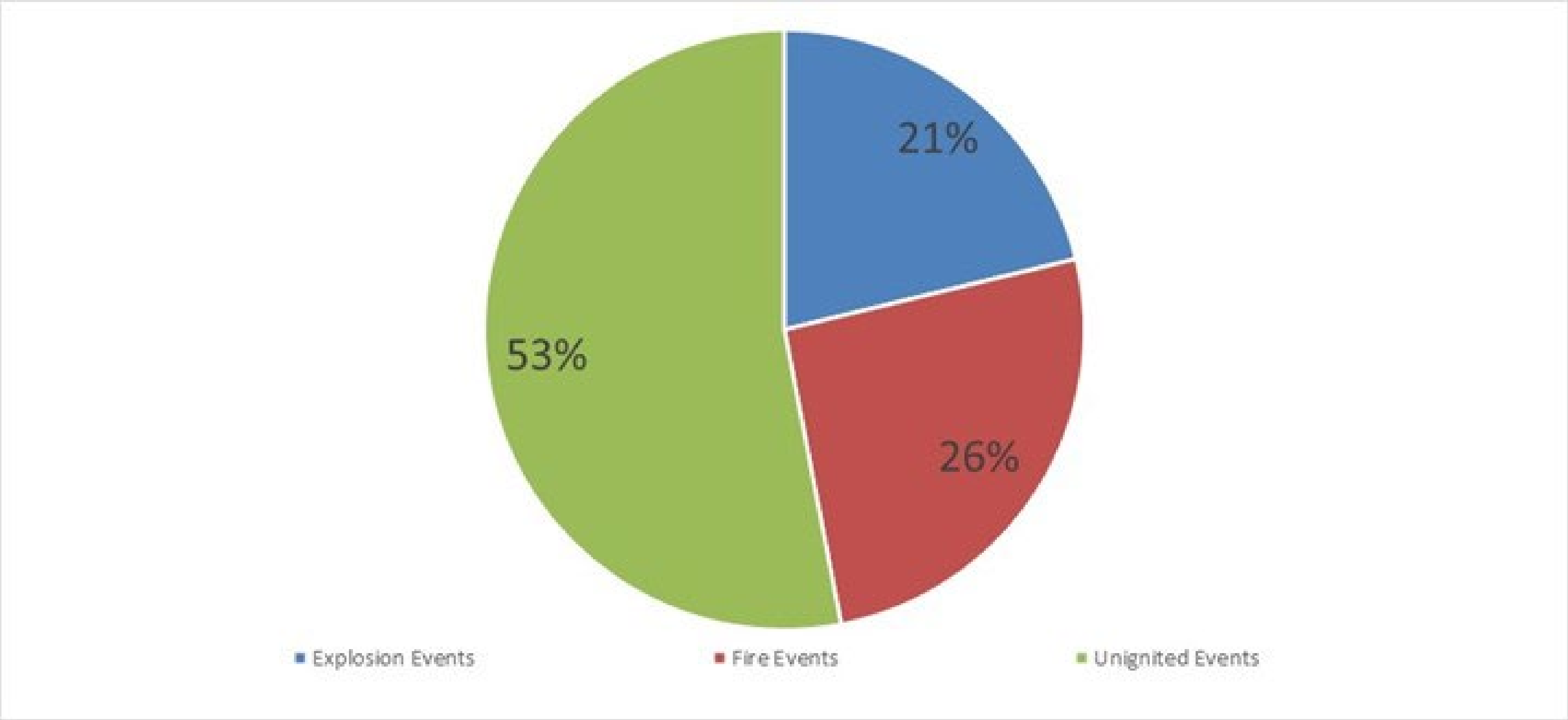
Select Incident Review

Summary of events by Consequence Type



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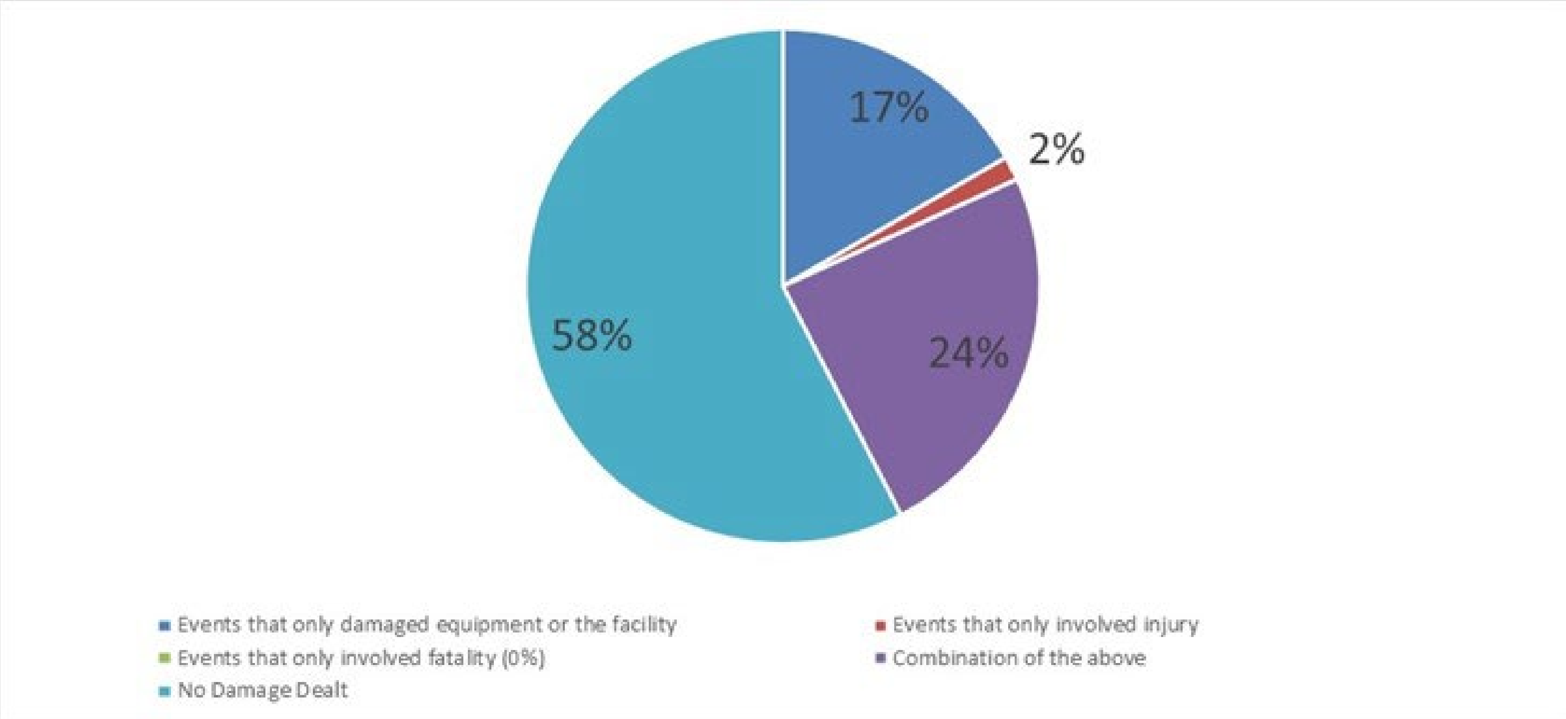
Select Incident Review

Summary of events by Damage Type



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Select Incident Review

- Probabilities of specific outcomes from these summaries were calculated to understand the relative occurrences of the potential outcomes
- This dataset shows that a variety of potential outcomes could occur following a hydrogen release

Probability*	Value
Total Ignition probability given hydrogen release Known Ignition probability given hydrogen release Unknown Ignition probability given hydrogen release	47% 36% 11%
Probability of non-ignition given hydrogen release	53%
Explosion Probability given ignition	45%
Fatality given ignition	6%
Damage to equipment or facility given ignition	39%
* Probabilities are based on a limited incident dataset, and therefore, are representative only of the reported incidents evaluated.	

Key Findings

1. At equivalent pressures and temperatures, large releases (2” and greater) of gaseous H_2 are predicted not to disperse as far as natural gas, considering distances to the lower flammability limit. However, for small releases (1” and smaller), the wide flammability range of H_2 results in larger dispersion distances to the lower flammability limit than natural gas.
2. Flammable vapor from LH2 releases are predicted not to disperse as far as equivalent flammable vapor from LNG and LPG releases across all release sizes in the study, considering distances to the lower flammability limit.
3. At equivalent pressures and temperatures, jet fires from a gaseous hydrogen release have shorter flame lengths and have lower thermal output than natural gas releases.
4. H_2 flame speeds are significantly higher than those of hydrocarbon fuels, such as natural gas/LNG and LPG. Considering the potential for H_2 DDT for VCE originating within obstructed regions, hydrogen blasts produce higher overpressures and larger blast radii than deflagrations of hydrocarbon fuels. Further evaluation of the hazard potential of unconfined hydrogen vapor cloud explosions should be considered to support sound hydrogen-specific spacing requirements.
5. LH2 pool fires stored at typical process conditions are typically less severe than hydrocarbon pool fires at their respective storage conditions.

Thank you!

Questions?

- Special thanks to CCPS and CHS Peer Reviewers!

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