

Hydrogen Explosion Hazards

Unv. of Houston Hydrogen Symposium

J. Kelly Thomas, Ph.D.

Vice President

Blast Effects Section Manager



OUTLINE

- Purpose
- Background
- Accidental Unconfined H₂ VCEs
- H₂ VCE Tests
 - Unconfined
 - Jet Release
 - Vented
- H₂ VCE Blast Load Prediction
- Conclusions

Purpose

- Provide broad overview of explosion hazards associated with a release of hydrogen in an industrial setting:
 - Unconfined vapor cloud explosion (VCE)
 - Establish that an unconfined hydrogen VCE is credible
 - Vented explosion (i.e., within an enclosure)
 - Blast load prediction approaches

Background (1 of 2)

- Hydrogen poses a fire and explosion hazard
- Not unique, and other commonly encountered fuel sources also pose fire and explosion hazards
 - Natural gas & propane (home, LNG, BBQ grills, etc.)
 - Gasoline
- Important to recognize the hazard and properly manage the risk
 - This presentation limited to hydrogen explosion hazard
- Hydrogen guidance available:
 - NFPA codes & standards (NFPA 2, NFPA 68 & 69, etc.)
 - Hydrogen Safety Panel

Background (2 of 2)

- Papers and conference presentations upon which this presentation is primarily based:
 - 1) Malik, D.R., W.B. Lowry, E. Vivanco and J.K. Thomas (2023) “Very-Lean Hydrogen Vapor Cloud Explosion Testing,” Process Safety Progress (AIChE GCPS, Houston, TX, March 12-16, 2023).
 - 2) Jallais, S., E. Vyazmina, D. Miller and J.K. Thomas (2018) “Hydrogen Jet Vapor Cloud Explosion: A Model for Predicting Blast Size and Application to Risk Assessment,” Process Safety Progress, 37(3): 397-410.
 - 3) Thomas, J.K., J. Geng, O.A. Rodriguez, et al. (2018) “Potential for Hydrogen DDT with Ambient Vaporizers,” Mary Kay O’Connor Process Safety International Symposium, College Station, TX, October 2018.
 - 4) Horn, B.J., O.A. Rodriguez, D.R. Malik and J.K. Thomas (2018) “Deflagration-to-Detonation Transition (DDT) in a Vented Hydrogen Explosion,” AIChE GCPS, Orlando, FL, April 22-25, 2018.
 - 5) Thomas, J.K. and D.R. Malik (2017) “Ammonia and Hydrogen Vapor Cloud Explosion Testing (A Tale of Two Gases),” 62nd Annual Safety in Ammonia Plants and Related Facilities Symposium, New York, September 10-14, 2017.
 - 6) Thomas, J.K., C.D. Eastwood and M.L. Goodrich (2015) “Are Unconfined Hydrogen Vapor Cloud Explosions Credible?” Process Safety Progress, 34(1): 36-43.
 - 7) Miller, D., C.D. Eastwood and J.K. Thomas (2015) “Hydrogen Jet Vapor Cloud Explosion: Test Data and Comparison with Predictions,” AIChE GCPS, Austin, TX, April 26-30, 2015
 - 8) Thomas, J.K., M.L. Goodrich and R.J. Duran (2013) “Propagation of a Vapor Cloud Detonation from a Congested Area into an Uncongested Area: Demonstration Test and Impact on Blast Load Prediction,” Process Safety Progress, 32(2): 199-206.
 - 9) Thomas, J.K., R.J. Duran and M.L. Goodrich (2010) “Deflagration to Detonation Transition in a Lean Hydrogen-Air Unconfined Vapor Cloud Explosion,” Mary Kay O’Connor Process Safety International Symposium,” College Station, TX, October 27, 2010,

- Accidental Unconfined H₂ VCEs



Accidental H₂ VCEs (1 of 8)

- Focus on accident history is on unconfined H₂ VCEs:
 - Some doubts expressed in this regards due to
 - Hydrogen being light (buoyant) – “doesn’t it just float away?”
 - High likelihood of immediate ignition – “doesn’t it just form a jet fire?”
- Many not reported (as with all explosions)
- Listing in 2015 paper remains a good summary, but incidents have continued to occur
 - Thomas, J.K., C.D. Eastwood and M.L. Goodrich (2015) “Are Unconfined Hydrogen Vapor Cloud Explosions Credible?” Process Safety Progress, 34(1): 36-43

Accidental H₂ VCEs (2 of 8)

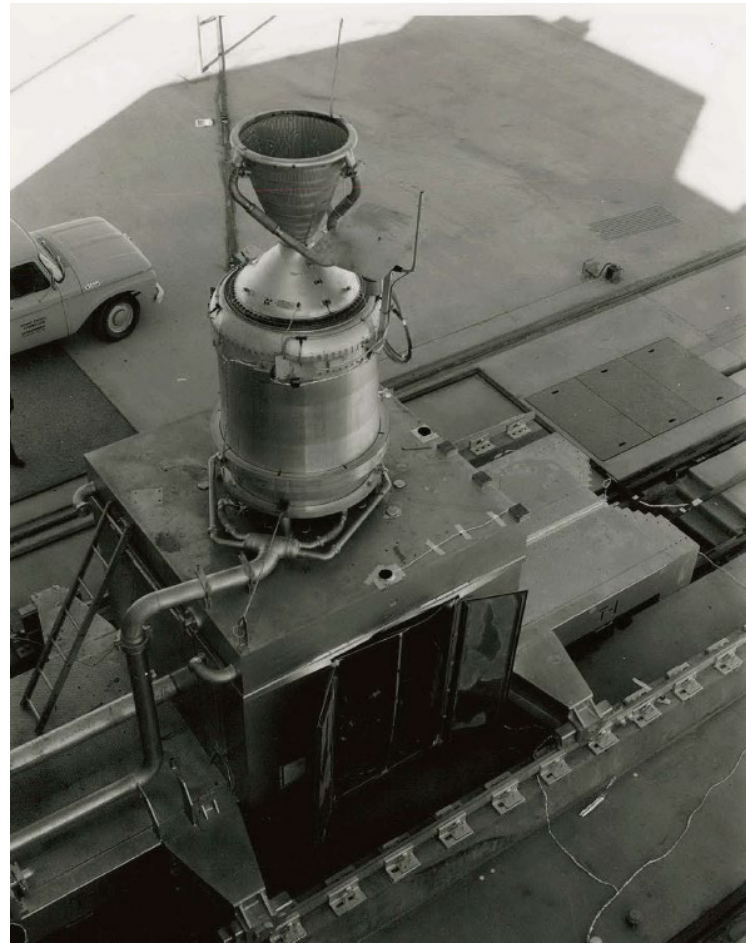
- Ordin (1974):
 - Reviewed incidents from NASA operations
 - 62% of releases to environment ignited (i.e., 38% did not)
 - At least 9 unconfined H₂ VCEs due to releases through vent stacks & failed components
 - Some reported to be detonations, up to 20 lb_m (9.1 kg) of TNT-equivalent
- Zalosh and Short (1978):
 - Reviewed > 400 H₂ accidents (1965 – 1977)
 - Slightly > ½ of incidents were explosions
 - 3/4 of incidents involved H₂ gas

Accidental H₂ VCEs (3 of 8)

- Other reviews & data collections:
 - H₂ Safety Panel “H₂ Incident Examples” report
 - H₂ Incidents database (2014 paper data review)
 - 7 events clearly unconfined H₂ VCEs
 - Sarnia and another similar incident
 - Several similar to Muskingum River Plant incident
- Selected reported unconfined H₂ VCEs:
 - Jackass Flats, NV, 1964
 - Polysar, Sarnia, Ontario, 1984
 - Muskingum River Plant, Beverly, OH, 2007
 - Air Products, Santa Clara, CA, 2019

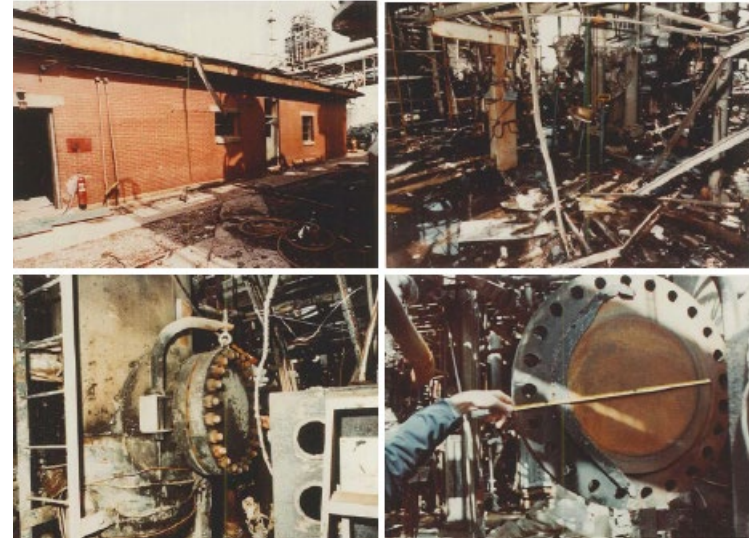
Accidental H₂ VCEs (4 of 8)

- Jackass Flats (Jackass Flats, NV, 1964):
 - Reider, Otway & Knight, 1965
 - Rocket motor test program
 - H₂ test run without ignition (by design)
 - Release from 3,400 psi (23.6 MPa) upward through convergent-divergent nozzle
- Flowed 13 sec. before unintentional ignition
- Estimated 200 lb_m (90 kg) of H₂ (10% of that released) involved in VCE
- VCE determined to be deflagration
 - Flame acceleration due to jet turbulence



Accidental H₂ VCEs (5 of 8)

- Polysar petrochemical complex (Sarnia, Canada, 1984):
 - MacDiarmid & North, 1989
 - Release of H₂ from partially failed gasket on compressor in open-sided shed (i.e., not completely unconfined)
 - 700 psi (48 bar), 10 to 15 sec before ignition, released 30 kg of H₂
 - Building damage at 500 ft (150 m) consistent with 1.1 psi (0.076 bar) overpressure
 - Consistent with detonation of 26 kg of H₂ (BST); high fraction of estimated release



used with permission

Accidental H₂ VCEs (6 of 8)

- Muskingum River Plant (Beverly, Ohio, 2007):
 - Rupture disc failure on outdoor hydrogen storage tank vent line during tank filling operations
 - Tank pressure at roughly 2000 psi
 - Release continued for roughly 10 sec. before ignition
 - WHA estimated 18 kg H₂ released
 - Killed driver, heavily damaged adjacent buildings



Accidental H₂ VCEs (7 of 8)

- Air Products (Santa Clara, CA, 2019):
 - H2 Safety Panel Report (June 2021)
 - Filling H2 trailer (gaseous), gas cylinders loaded to 7,200 psi
 - Did not involve liquid H₂
 - Attempt to repair leaking valve results in release from open pipe
 - Explosion within seconds, followed by jet fire; other cylinders to release through PRDs and contribute to fire
 - Window failure at 125 feet



Accidental H₂ VCEs (8 of 8)

- Based on review of accidental unconfined H₂ VCE information:
 - They have happened regularly in the past,
 - They have happened recently, and
 - It is therefore reasonable to expect will happen in the future.

- Unconfined H_2 VCE Tests

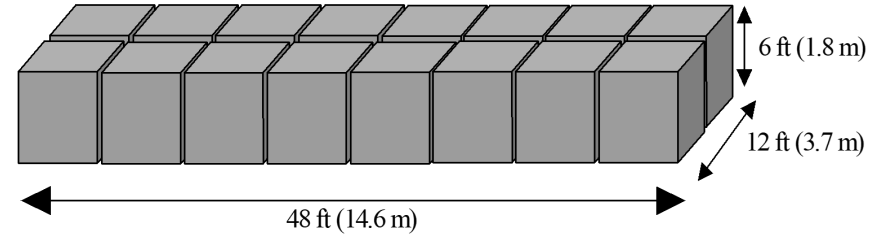


Unconfined H₂ VCE Tests

- Numerous unconfined H₂ VCE tests by multiple organizations have been performed
- Unconfined H₂ VCE testing has shown the potential consequences of H₂ release into unconfined area with delayed ignition:
 - Can produce significant blast loads from unconfined H₂ VCE,
 - Can achieve deflagration-to-detonation transition (DDT) at moderate congestion levels
- Selected BakerRisk test programs illustrated on following slides

Unconfined Lean H₂ VCE Testing

- Congested volume consisted of a regular array of vertical circular tubes:
 - 2.375-in (60 mm) tube dia.
 - 45 per 6-foot cube (+ corner supports)
 - “Medium” congestion level
- Center ignition (near grade)



Schematic of VCE Test Rig



Photograph of VCE Test Rig

18% Hydrogen (ER = 0.52)



20% Hydrogen (ER = 0.60)

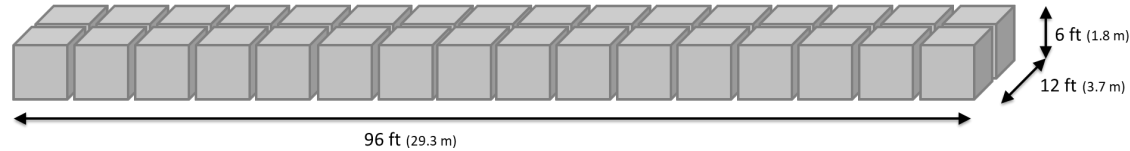


22% Hydrogen (ER = 0.67)



Unconfined Very Lean H₂ VCE Testing

- Double rig length & volume
- Congestion provided by regular array of vertical circular tubes:
 - 3.5-in (89 mm) tube dia.
 - 42 per 6-foot cube (+ corner supports)
 - “High” congestion level
- Ignition at 24 ft from end
 - 3x the run-up distance
 - 72 ft. vs. 24 ft.



Schematic of VCE Test Rig



Photograph of VCE Test Rig

12% Hydrogen (ER = 0.33)



14% Hydrogen (ER = 0.39)



Unconfined H₂ VCE Tests

- Hydrogen concentrations less than 10%H₂ will not contribute to a VCE
 - Conservative value as testing demonstrated 12%H₂
 - Makes a significant difference in VCE blast load prediction, as much of the flammable cloud is at concentrations below 10%.
- Should consider potential for DDT at hydrogen concentrations above approximately 18%
 - Likelihood will depend on extent of congestion and confinement as well as size of flammable cloud interacting with congested/confined area

- Jet Release H₂ VCE Tests



H₂ Jet Release Explosion Tests

- Jet release tests generally into open (unobstructed) environment
- Jet release tests with H₂ have shown the potential consequences of hydrogen jet release:
 - Can produce significant blast loads
 - Unlikely to be governing scenario for blast loading on buildings at an industrial site
 - May provide governing scenario in vicinity of release
- Large-scale test program carried out by Air Products illustrated on following slides (BakerRisk involved in evaluating test data)

H₂ Jet Release Air Products Test (1 of 2)

- Test conditions:
 - Horizontal release from 3.25 m elevation
 - 60 bar source pressure
 - ¾-inch and 2-inch release sizes
 - Initial release rates of ≈ 1 and 8 kg/s
 - Ignition ≈ 2 seconds after release initiated
- Load for 2-inch release (off centerline):
 - 10 meters: 0.43 barg (6.2 psig) 15 ms
 - 20 meters: 0.21 barg (3.0 psig) 13 ms



H₂ Jet Release Test Video (2" release)



- Vented H_2 Explosion Tests

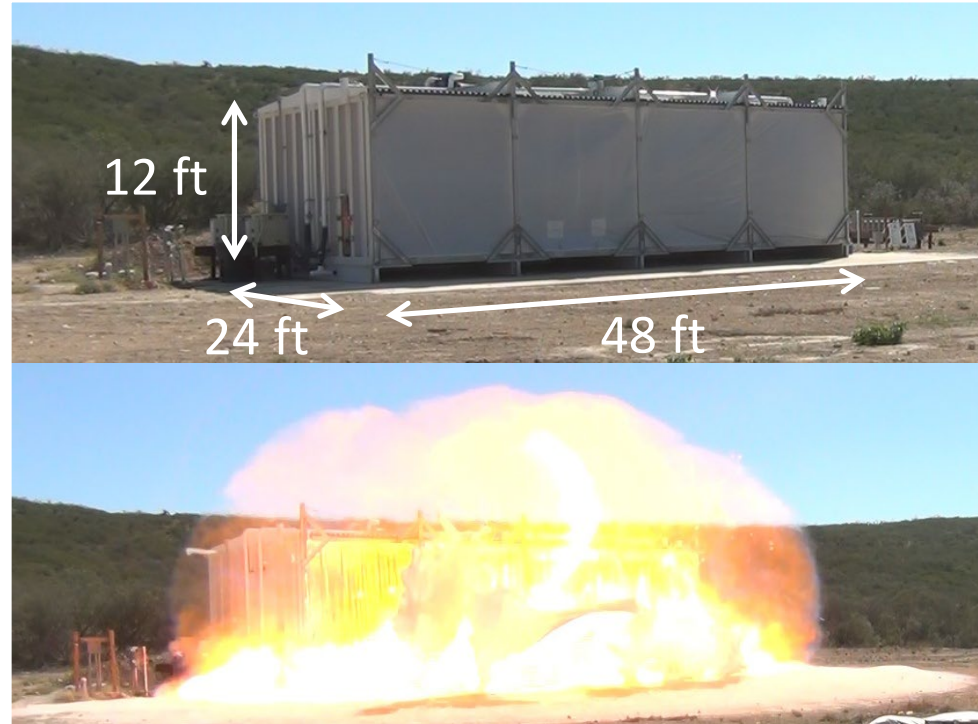


Vented H₂ Explosion Tests

- Numerous vented H₂ explosion tests by multiple organizations have been performed
- Vented H₂ explosion shown the potential consequences of H₂ release into enclosure with delayed ignition:
 - Can produce significant blast loads from vented H₂ explosions,
 - Can achieve deflagration-to-detonation transition (DDT) at low congestion levels
- Single large-scale BakerRisk test program illustrated on following slides

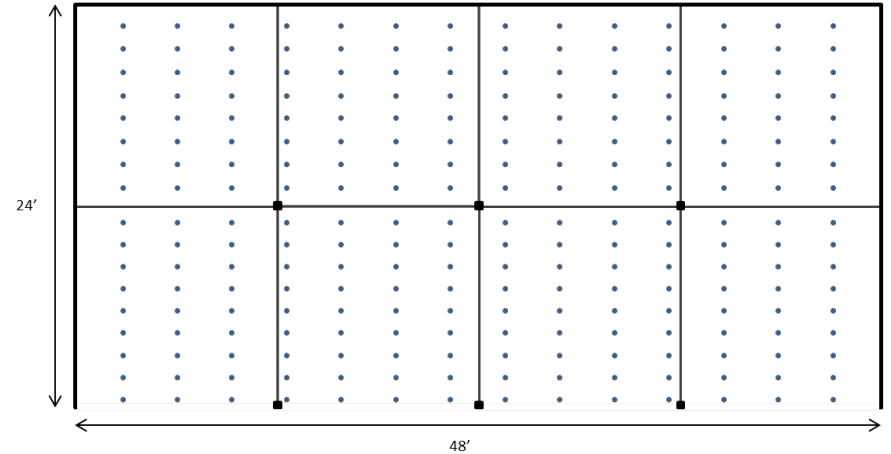
Lean H₂ Vented Explosion Testing (1 of 2)

- Deflagration Load Generator (DLG)
 - 48 × 24 × 12 ft (14.6 × 7.3 × 3.7 m)
 - Enclosed volume of 13,800 ft³ (392 m³)
 - One open side sealed with plastic
- Test rig used by BakerRisk both to:
 - Produce blast loads to test structural response of full-scale structures
 - Investigate vented deflagration hazards



Lean H₂ Vented Explosion Testing (2 of 2)

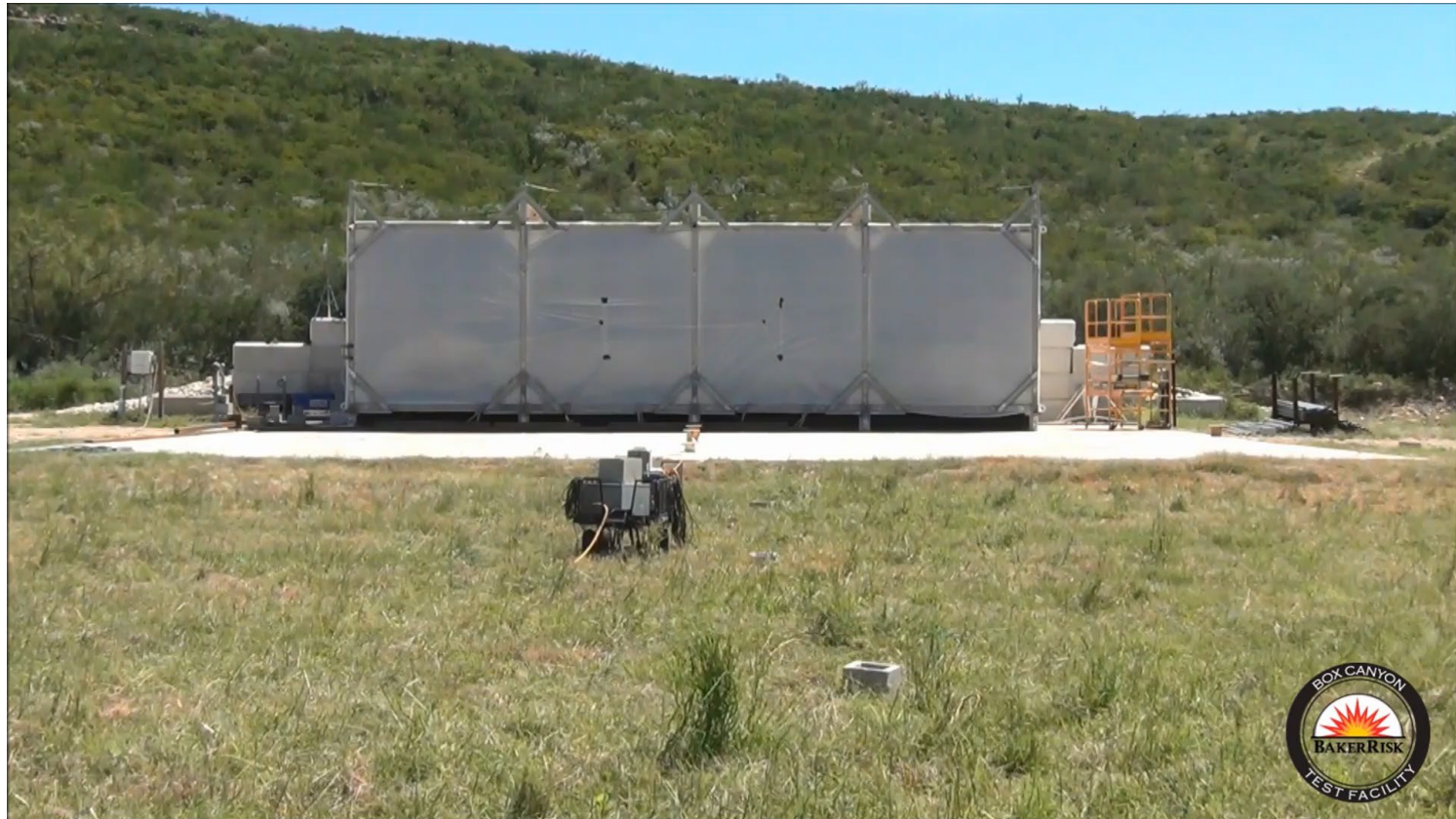
- Very low congestion array of vertical circular tubes (next slide):
 - 2.0 and 2.375-in (60 mm) tube dia.
 - Pitch to diameter = 8.5
 - Area and vol. blockage ratios of 5% and 0.5%, respectively
- Center rear-wall ignition



20% Hydrogen (ER = 0.60)



22.5% Hydrogen (ER = 0.69) – normal video



22.5% Hydrogen (ER = 0.69) – high-speed video

00 Shutter : OPEN NAC HSMegaSC



• H2 VCE Blast Load Prediction



VCE Blast Load Predictions (not H₂ specific)

- VCE blast load prediction methods:
 - TNT Equivalent (explicitly recommend not using)
 - Blast curve methods
 - Baker-Strehlow-Tang (BST)
 - TNO Multi-Energy Method (TNO MEM)
 - Computational fluid dynamic (CFD) methods
 - FLACS (GexCon)
 - Others are available
- VCE blast load function of:
 - Explosion energy (how much energy is released)
 - Flame speed (how fast this energy is released)
 - Standoff (how far away you are from the energy released)

Unconfined H₂ VCE Blast Loads

- Have seen that:
 - Accidental releases with significant flow rates can generate large flammable clouds,
 - Delayed ignition can occur with such clouds, and
 - VCE if such clouds engulf an unconfined congested volume (+ delayed ignition)
- What type of blast loads can result?
- Hydrogen flame speeds:
 - High compared to typical hydrocarbons at near-stoichiometric concentrations
 - Too low to produce blast load at < 10% H₂
 - DDT expected for concentrations approaching stoichiometric in moderate levels of congestion (even with no confinement)
 - DDT observed at 22% in BakerRisk's testing (vs. 30% stoichiometric) & predicted at 18% for larger test rig configuration

- Conclusions



Closing Thoughts

1

H₂ poses unconfined VCE hazard

Can form a large flammable gas cloud near grade level and can have delayed ignition.

2

Accidental H₂ VCEs are not rare

Incident history clearly illustrates this is a credible scenario

3

H₂ mixtures are subject to DDT

Observed in both unconfined and confined VCE testing.


4

Blast loads from H₂ VCEs can be large

Should account for potential loads in facility siting.

CONTACT US

Kelly Thomas, Ph.D.

 3330 Oakwell Court, Suite 100
San Antonio, Texas 78218-3024

 +1.210.824.5960

 KThomas@bakerrisk.com





QUESTIONS?

[BakerRisk.com](https://www.BakerRisk.com)



WE HAVE ANSWERS

SERVICES

Better Risk Management Starts Here



Accident
Investigation



Functional and
Electrical Safety



Fire Protection and
Insurance Risk



Consequence and
Risk Modeling



Qualitative Hazard
Identification and
Risk Assessment



Protective
Structures



Testing



Low Carbon Energy

BAKERRISK LEARNING CENTER



BAKERRISK
LEARNING CENTER

LOCATIONS



San Antonio

Houston

Chicago

Los Angeles

Canada

United Kingdom



BAKERRISK