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ORIGINAL ARTICLE

Very lean hydrogen vapor cloud explosion testing

Darren R. Malik | **W. B. Lowry** | **E. Vivanco** | **J. K. Thomas**

Baker Engineering and Risk Consultants, Inc., San Antonio, Texas, USA

Correspondence
Darren R. Malik, Baker Engineering and Risk Consultants, Inc., 333- Oakwell Court, Suite 100, San Antonio TX, 78218, USA.
Email: dmalik@bakerrisk.com

Abstract

Hydrogen is a key energy carrier for modern society. The breaking of the hydrogen bonds within traditional hydrocarbon molecules has been the primary mode of energy utilization since the industrial revolution. An increased focus on "net-zero" greenhouse gas emissions, specifically carbon dioxide and methane, has resulted in a global push for lower carbon energy vectors, including pure hydrogen. Accurately modeling the dispersion, fire, and explosion hazards associated with new and existing hydrogen production, distribution and transportation networks, and consumption is a key component to the safe expansion of these networks. BakerRisk performed a series of very lean hydrogen-air vapor cloud explosion (VCE) tests as part of an internal research effort. The goal of these tests was to better understand the VCE hazards associated with very lean hydrogen-air mixtures (≲14% H_2). Flame speeds and blast loads were measured using high-speed video and an array of dynamic pressure transducers. This paper discusses the test setup and test results, including a comparison with data from prior tests. The measured flame speeds are compared to those predicted using computational fluid dynamics analysis and referenced to deflagration-to-detonation criteria. Discussion regarding the application of these test results to facility siting studies is also provided.

KEYWORDS
deflagration, detonation, hydrogen, vapor cloud explosion

1 | INTRODUCTION

Hydrogen is often discounted as a vapor cloud explosion (VCE) hazard due to the ease of igniting a flammable hydrogen-air mixture (i.e., its low, minimum ignition energy (MIE)). This suggests that a hydrogen release is likely to be ignited before a flammable hydrogen-air cloud with sufficient volume to produce significant VCE blast loads can even form. While hydrogen's low MIE does indeed mean that prompt ignition is much more likely than for typical hydrocarbon fuels, this does not imply that delayed ignition will not occur.[1] Hydrogen is also sometimes discounted as a VCE hazard due to its buoyancy, which suggests that a hydrogen release will "float away" before a flammable cloud with sufficient volume to produce significant blast loads can form. While a hydrogen-air mixture is typically buoyant, assuming the hydrogen release is not very cold, the dispersion of a high-pressure hydrogen release will not be influenced by this buoyancy during the momentum-dominated dispersion phase, which can result in a large flammable hydrogen-air cloud being formed at grade-level.[2,3] Furthermore, assertions that hydrogen cannot pose a VCE hazard are contradicted by the existence of accidental unconfined hydrogen VCEs that have produced damaging blast loads.[4]

Given the expected push for the expansion of hydrogen-related infrastructure, it is critical that industry leaders, regulators, and safety professionals understand the potential for hydrogen-air clouds to produce damaging blast loads. The specific purpose of this research effort was to explore the lower concentration limit at which hydrogen-air mixtures can be expected to produce damaging blast loads in an unconfined environment.

Section 2 of this paper describes a method by which elongated vapor clouds can be described in terms of the physical dimensions, run-up length, and distance to the free vent. This method provides a means for evaluating whether or not an unconfined VCE will undergo

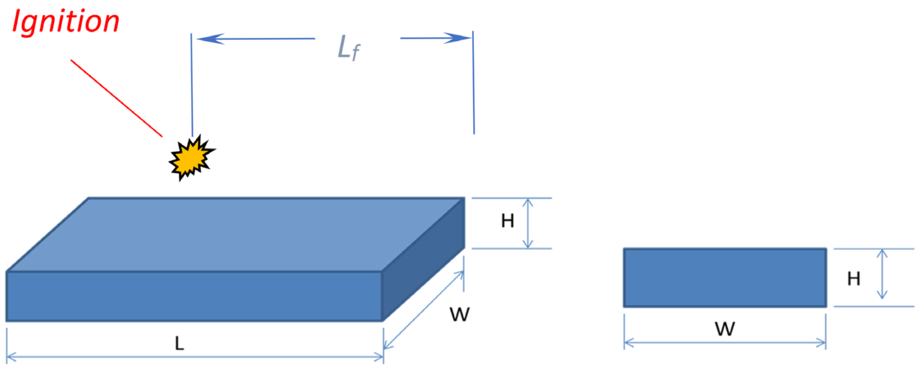

FIGURE 1 Dimensions of the elongated vapor cloud.

TABLE 1 Cloud geometry and blast field parameter definitions.

Parameter	Symbol	Definition
Free vent distance	L_{FV}	$MIN\left(H, \frac{W}{2}\right)$
Flame travel distance	L_f	n/a
Normalized flame travel distance	Ln_f	L_f/D_{FV}

a deflagration to detonation transition (DDT) or remain a deflagration. The lean hydrogen VCE tests performed as part of this work are described in Section 3, and the computational fluid dynamics (CFD) analysis results are provided in Section 4. Key findings are discussed in Section 5, and an example application of these findings to screening-level facility siting studies is provided in Section 6. Conclusions and areas for future work are provided in Section 7.

2 | DDT IN ELONGATED GEOMETRIES

Several simplified VCE blast load prediction methods consider flame travel distance within a congested volume, as well as fuel reactivity, as input parameters,[5,6] but do not explicitly consider the distance to the free vent (L_{FV}). Prior work by BakerRisk noted a correlation between normalized flame run-up length (Ln_f), distance to free vent (L_{FV}), and the propensity of a VCE to undergo a DDT within a congested volume with a uniform fuel concentration and congestion array.[7]

Figure 1 depicts an elongated flammable cloud with length L, width W, and height H. It is assumed that the entire flammable cloud occupies a congested volume with the same dimensions (i.e., that no part of the cloud occupies an uncongested space). The parameters shown in Table 1 are utilized to characterize the cloud.

For the simplified rectangular geometry shown in Figure 1, the "*Free Vent Distance*" (LFV) is the minimum of the cloud height or half the cloud width (i.e., this is the minimum flame travel distance for lateral venting). The "*Flame Travel Distance*" (Lf) is the distance from ignition to the flame front position at the specified instant in time, with a maximum value equal to the distance to the edge of the cloud; noting that the ignition source could be located at the cloud center, cloud end, or anywhere in the cloud. The "*Normalized Flame Travel Distance*" (Lnf) is the ratio of these two parameters (i.e., L_f/L_{FV}), as shown in Table 1.

Figure 2 provides an example of the observed deflagration and detonation regimes for elongated cloud geometries[7]; observed flame speeds from three different tests performed as part of the Buncefield Joint Industry Project (JIP)[8] are shown. Two of the tests enter the detonation regime within six normalized flame travel (Ln_f) distances and undergo a DDT. The third test remains below the deflagration regime threshold at $Ln_f = 6$. This test remains a deflagration and does not undergo a DDT. The testing and analyses conducted in this work are presented on a normalized flame travel distance (L_{nf}) basis.

3 | BAKERRISK—LEAN HYDROGEN TESTING

Figure 3 provides a timeline of relevant hydrogen VCE research performed by BakerRisk. The original set of unconfined lean hydrogen VCE tests, described in Section 3.1, was performed in 2009 using a rig and a medium level of congestion with a length of 48 feet, a width of 12 feet, and a height of 6 feet. The lean hydrogen mixture was ignited at grade near the rig center.[9] The next tests, described in Section 3.2, were performed in 2022 in a test rig that was twice as long as the original test rig: 96 feet long, 12 feet wide, and 6 feet tall, with a high level of congestion. The mixture was ignited at grade, 24 ft from the west edge of the test rig.

3.1 | 2010 2 × 8 lean hydrogen VCE tests

The test rig for the hydrogen VCE tests was the same as had been previously used by BakerRisk for ethylene VCE testing.[10,11] For each 6 ft (1.8 m) cube, a total of 45 vertical tubes were installed, along with the 4 cube corner supports. The congestion arrangement was made up of vertical circular tubes [2.375-inch (6 cm) diameter], giving a pitch-to-diameter ratio of 4.5 and providing area and volume blockage ratios of 22% and 4.1%, respectively. The ratio of the surface area of congestion within a cube to the surface area of a cube, and the ratio of the total surface area of congestion to the surface area available for venting from the test rig, was 0.85 and 2.3, respectively. This level of congestion corresponds to the "medium" congestion level in the Baker-Strehlow-Tang (BST) flame speed table.[12] An illustration and

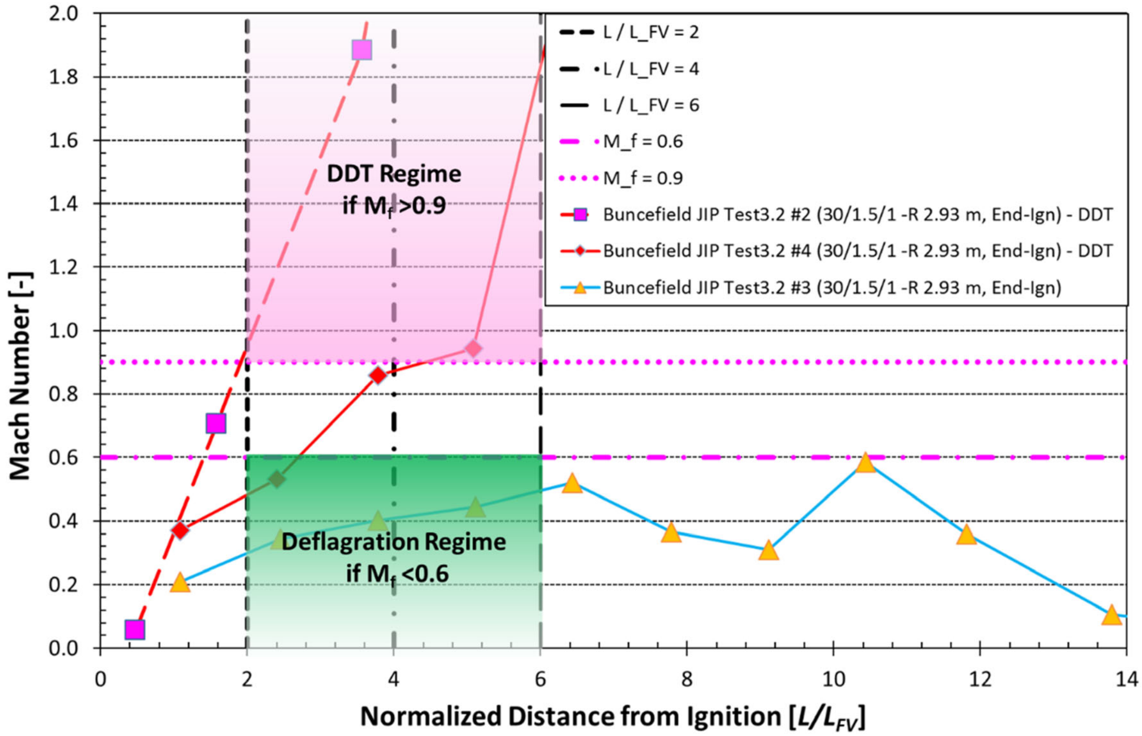

FIGURE 2 Observed deflagration and detonation behavior based on normalized flame travel distance.

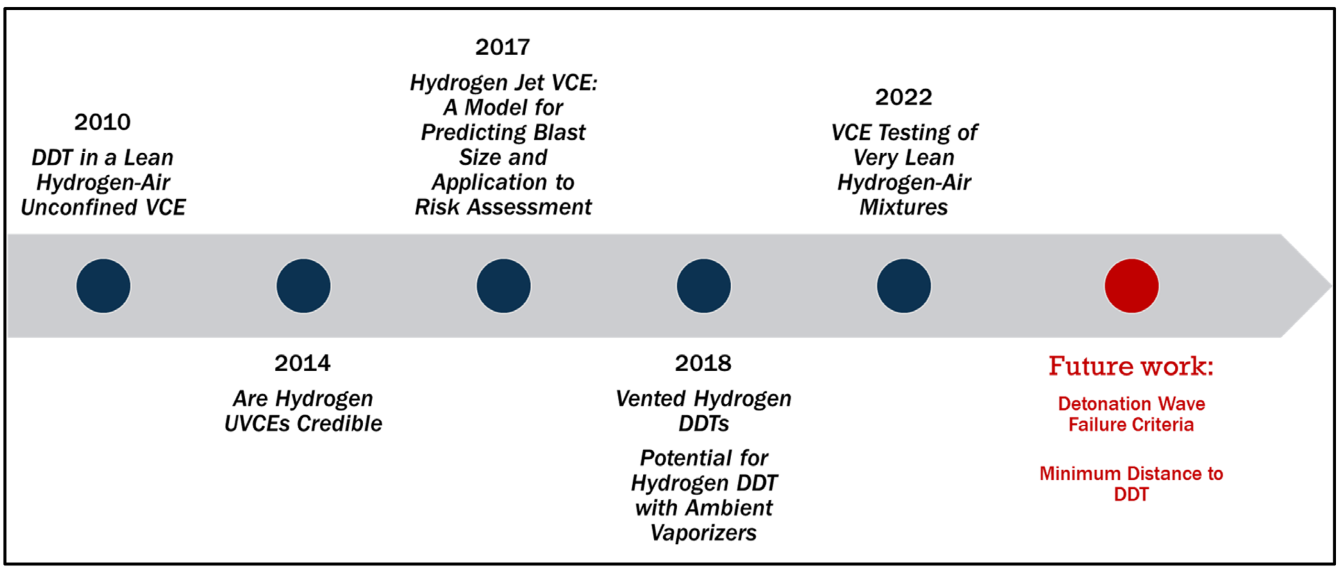

FIGURE 3 Timeline of relevant BakerRisk hydrogen VCE research.

photograph of the test rig in this configuration are shown in Figure 4. The test rig was configured without any confinement (i.e., no wall or roof sections).

The fuel-air mixture was contained within the rig using a thin plastic tent (1.5 mils thick). Six venturis deployed down the length of the rig (at mid-height) and directed downward were employed to inject the fuel, with additional mixing provided by 16 fans mounted at the top of the rig (1 per cube). The mixture was sampled from 4 different points in the rig to confirm a uniform mixture at the desired concentration prior to ignition. The fuel was injected over a period of one-half to one hour, and a quiescent period of 5–20 min was observed prior to ignition. The target hydrogen concentrations for these tests were 16%, 18%, 20%, and 22%; all of these mixtures are lean (i.e., stoichiometric concentration is 30%).

The mixture was ignited at the center of the rig near grade level using an electrochemical match, such that the maximum flame travel

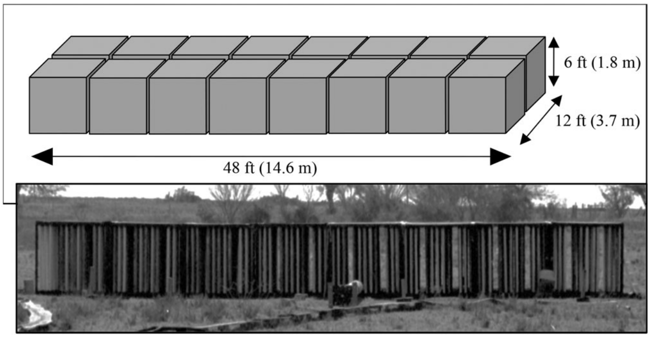

FIGURE 4 Schematic (top) and photograph (bottom) of the 2010 H_2 test rig.

distance (L_F/L_{FV}) was equal to 4. Normal-speed video, high-speed video, and dynamic pressure sensors were used to characterize the results of each test.[9]

3.1.1 | 2010 2 × 8 lean hydrogen VCE test results

The hydrogen concentrations and peak pressures measured within the test rig for all 4 hydrogen tests are summarized in Table 2. This table also provides average and peak flame speeds. The flame speeds from Tests H01 and H02 were based on thermocouple array measurements due to low flame luminosity, whereas high-speed video images could be used to calculate flame speeds for Tests H04 and H05.

Discussion of 2010 2 × 8 lean hydrogen test results

High-speed video analysis showed that a deflagration-to-detonation transition (DDT) occurred in Test H05 (22% H_2) near the ends of the rig (both ends), with a detonation wave traveling at approximately Mach 5 traversing the remainder of the hydrogen-air mixture. This is consistent with peak pressures above 100 psig being measured in the test. Conversely, a DDT was not observed in Test H04 (20% H_2), although the blast loads were still high (34 psig maximum within the rig) and a peak flame speed in excess of Mach 1.

These tests clearly demonstrated that an H_2-air mixture, if allowed to accumulate and ignite, can produce a significant VCE. In the presence of moderate congestion, even with no confinement, lean hydrogen mixtures can undergo a DDT. As indicated by the regions defined in Figure 2, the observed flame speeds in both the 18%H_2 (H02) and 20%H_2 (H04) tests indicate that a DDT would be expected in a test rig with a longer flame propagation (L_F/L_{FV}) distance.

3.2 | 2022 2 × 16 very lean hydrogen VCE tests

In 2022, BakerRisk performed a series of very-lean hydrogen-air VCE tests in a rig that was twice as long as the 2 × 8 test rig used to perform the 2010 tests (i.e., 96 ft. long rather than 48 ft.). The congestion arrangement was made up of vertical circular tubes [3.5-inch (8.9 cm) diameter]. For each 6 ft (1.8 m) cube, a total of 42 vertical tubes were installed, along with the 4 cube corner supports. The ratio of the surface area of congestion within a cube to the surface area of a cube and the ratio of the total surface area of congestion within the test rig to the surface area available for venting from the test rig were 1.1 and 3.0, respectively. This level of congestion corresponds to the "high" congestion level in the BST flame speed table.

An illustration and photograph of the test rig in this configuration are shown in Figure 5. The fuel injection, mixing, and sampling systems were essentially the same as used in the 2010 lean H_2-air VCE tests described in Section 3.1 as was the data acquisition system. The mixture was ignited 24 ft. from one end of the rig, along the rig centerline near grade, with an electrical fuse wire.

The primary goal of the very lean hydrogen tests was to determine a lower concentration limit at which an H_2-air VCE would not produce damaging overpressures (i.e., similar to the ammonia-air VCE tests described in[13]). A secondary goal was to provide additional data relevant to the DDT regime map shown in Figure 2. The first test series (A) was performed with a 12% H_2-air mixture, with the second series (B) at a 14% H_2 concentration.

3.2.1 | 2022 2 × 16 very lean hydrogen VCE test results

Unintended ignitions of the hydrogen-air clouds were observed in Test A01 and Test A02 when the rig was near the target test concentration of 12% H_2; the likely ignition source was an electrostatic discharge caused by the motion of the plastic film used to contain the fuel-air mixture. Neither pressure nor high-speed video data were collected for either of these tests. The hydrogen concentrations and peak pressures measured within the test rig for the 3 hydrogen tests in which pressure and high-speed video data were collected are summarized in Table 3.

Discussion of 2022 2 × 16 very lean hydrogen VCE test results

Flame speeds were calculated for Test A03, A04, and B01 using high-speed video. The low luminosity of the lean hydrogen flames made this analysis difficult for the initial flame propagation region (i.e., L_f/L_{FV} <6), as can be seen in Figure 6.

Figure 7 shows the observed flame speeds. Both Test A03 and A04 resulted in relatively steady state deflagrations with observed flame speeds of approximately Mach 0.1–0.2. These flame speeds correspond to a BST predicted pressure inside the cloud of 0.3–1.1 psi, which is in relatively good agreement with the values reported in Table 3.

The 2022 testing produced higher pressures at lower H2 concentrations than the 2010 testing (i.e., 19 psig at 14.7% H_2 vs. 9.9 psig at 16% H_2), but the 2022 tests employed a higher congestion level (high vs. medium) and a flame travel distance that was three times longer (i.e., 72 feet vs. 24 feet).

Test B01 (14.7% H_2) did not exceed a flame speed of Mach 0.9 at a normalized flame travel distance (L_f/L_{FV}) of 6 and continued to propagate as a deflagration throughout the test rig. However, as can be

TABLE 2 Peak pressures and flame speeds for 2 × 8 lean hydrogen tests.

				Flame speed (M_f)	
Test ID	Concentration (%)	Equivalence ratio	Peak pressure (psig)	Avg.	Avg.
H01	16.0	0.44	9.9	0.58	0.58
H02	18.1	0.51	6.6	0.67	0.67
H04	20.1	0.58	34	1.3	1.3
H05	22.2	0.66	115	2.1	2.1

FIGURE 5 Schematic (top) and photograph (bottom) of the hydrogen test rig.

TABLE 3 Peak pressures and flame speeds for 2 × 16 very lean hydrogen tests.

				Flame speed (M_f)	
Test ID	Average test concentration (%)	Equivalence ratio	Peak pressure (psig)	Avg.	Peak
A03	12.7	0.35	0.5	0.15	0.25
A04	12.0	0.32	0.2[a]	0.08	0.24
B01	14.7	0.41	19	0.48	1.3

[a]The gauge that recorded the peak pressures reported for Test A03 and Test B01 did not provide a reliable signal in Test A04.

FIGURE 6 Still frames from test A03.

seen in Figure 7, the flame speed continued to accelerate throughout the test rig. The Test B01 fuel concentration measurements did indicate that the hydrogen concentrations were slightly higher at the end of the rig away from the ignition source, roughly 14.8%H_2 at L_f/L_{FV} >8 versus 14.5%H_2 near the ignition location ($L_f/L_{FV} = 0$). This concentration gradient, albeit small, may explain the observed flame acceleration in the latter half of the rig. The plastic tent used to confine the mixture may also have some impact on the flame propagation behavior near the rig ends.

4 | FLACS ANALYSIS OF THE 2022 2 × 16 VERY LEAN HYDROGEN VCE TESTS

The Flame acceleration simulator (FLACS) CFD code was used to compare with test data and further explore the potential for lean H_2-air clouds to produce high-speed deflagrations, and therefore damaging blast loads. The flame speeds predicted by FLACS for hydrogen concentrations between 12.5%H_2 and 16.5%H_2 are provided in Figure 8.

The parametric FLACS modeling indicates a significant change in the predicted flame propagation for 16.5%H_2 (i.e., vs. 16.0%H_2), and that 16.5%H_2 may be at, or near, the concentration threshold at which a DDT would occur for this test rig geometry.

A comparison of the observed and predicted flame speeds is provided in Figure 9. There is relatively good agreement between Test A03, Test A04, and the FLACS predicted flame speeds for a 12.5%

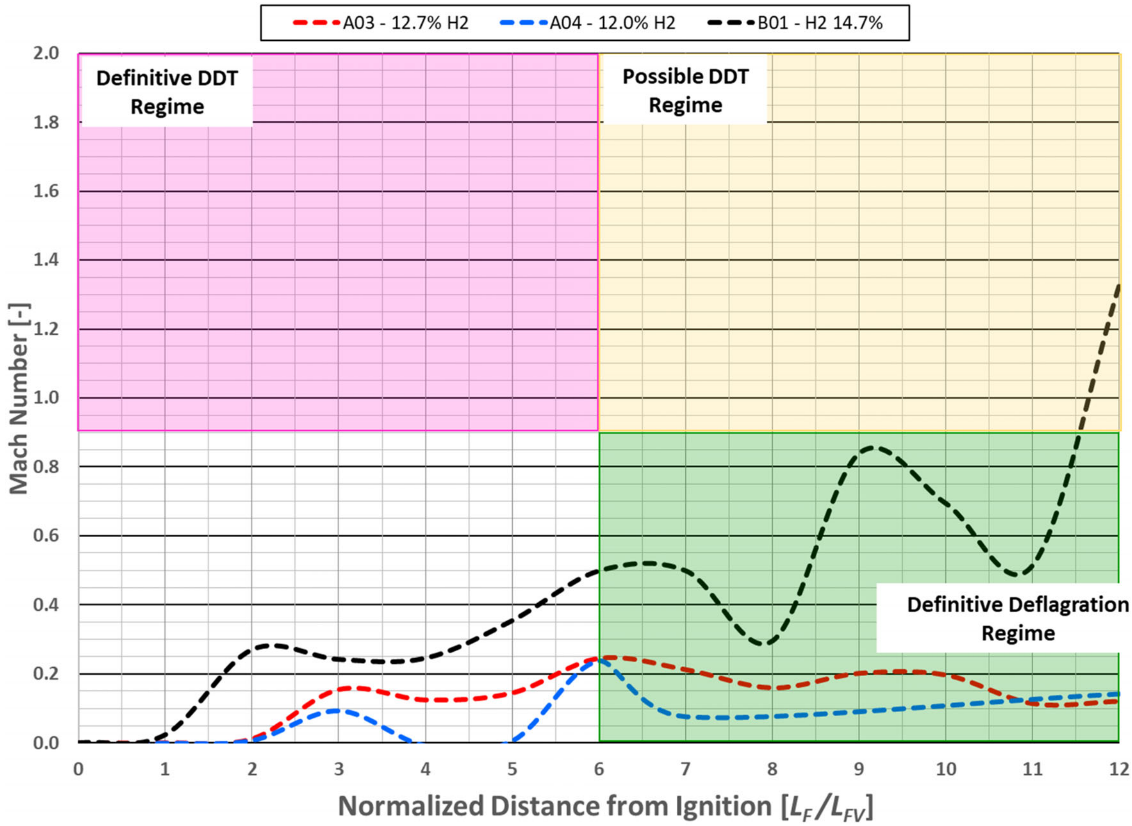

FIGURE 7 Observed flame speeds for 2 × 16 very lean hydrogen VCE tests.

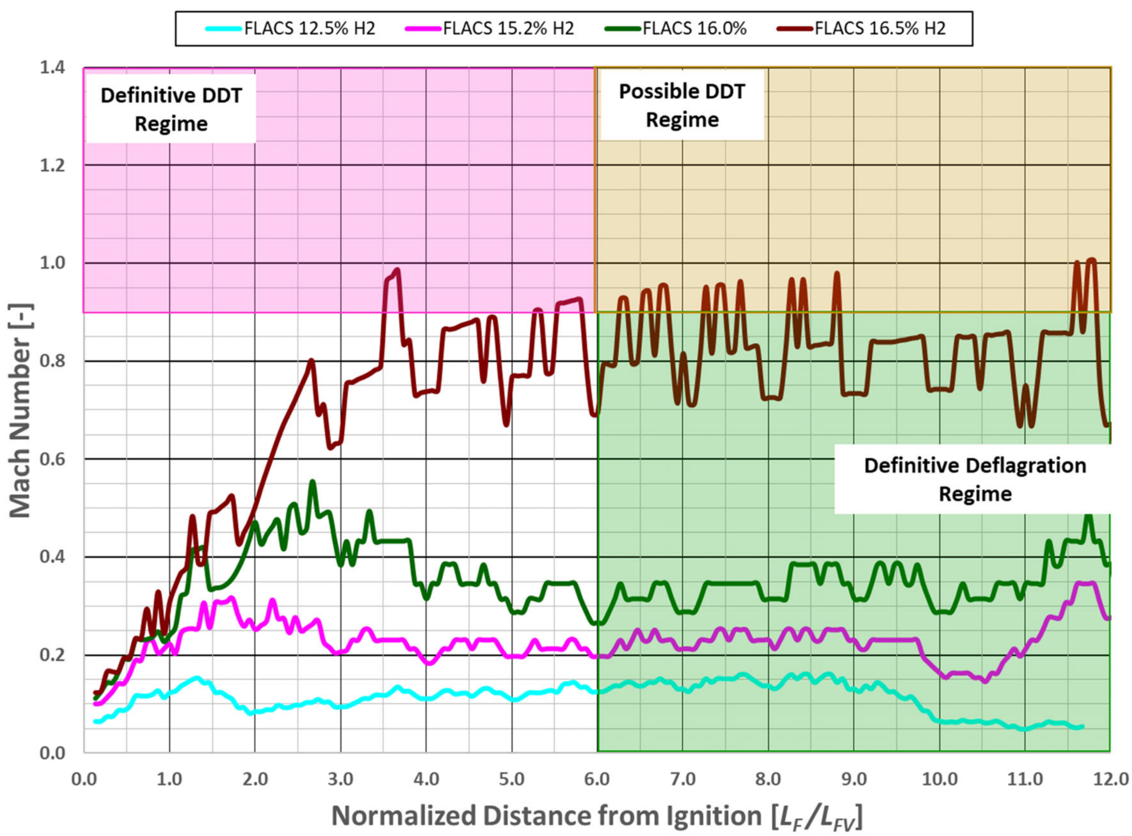

FIGURE 8 Predicted H_2-air flame speeds for the 2 × 16 tests.

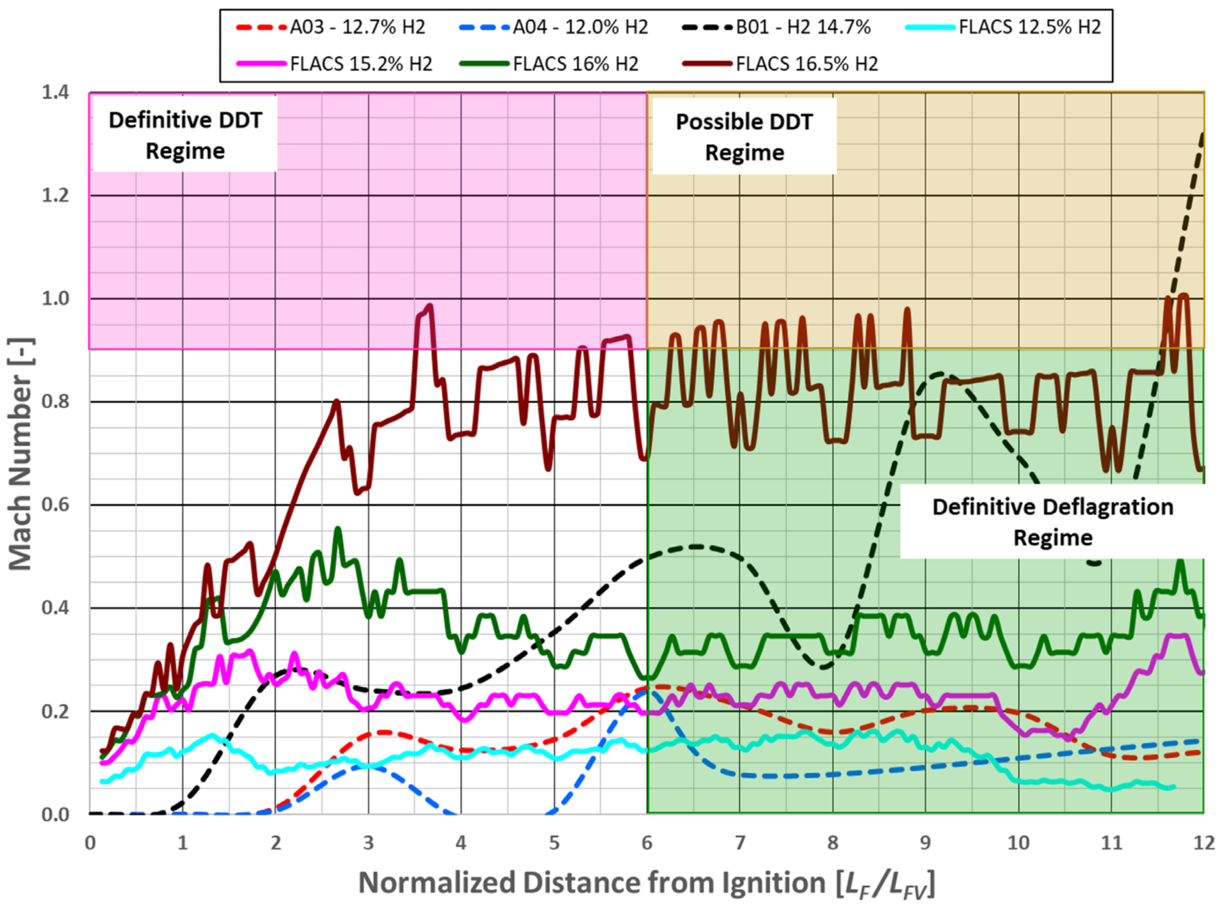

FIGURE 9 Predicted and observed H2-air flame speeds for 2 × 16 tests.

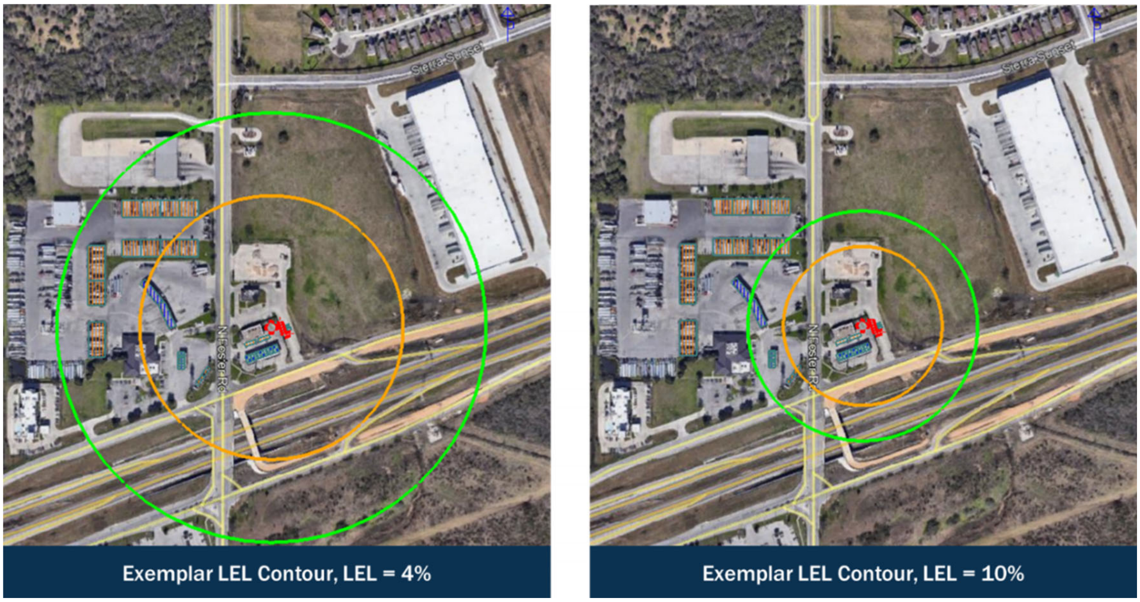

FIGURE 10 Predicted flammability contours for exemplar H_2 fueling station *(Red = UEL, Orange = LEL, Green = LEL/2).*

hydrogen-air mixture. The observed flame speed for Test B01 (14.7% H2) sits between the FLACS predicted flame speeds for a 16.0 and 16.5% hydrogen-air mixture. Given the sensitivity to small changes in fuel concentration in this regime (i.e., the doubling of FLACS predicted flame speeds across a 0.5% increase in hydrogen concentration from 16.0% to 16.5%) this appears to be an area worthy of further exploration.

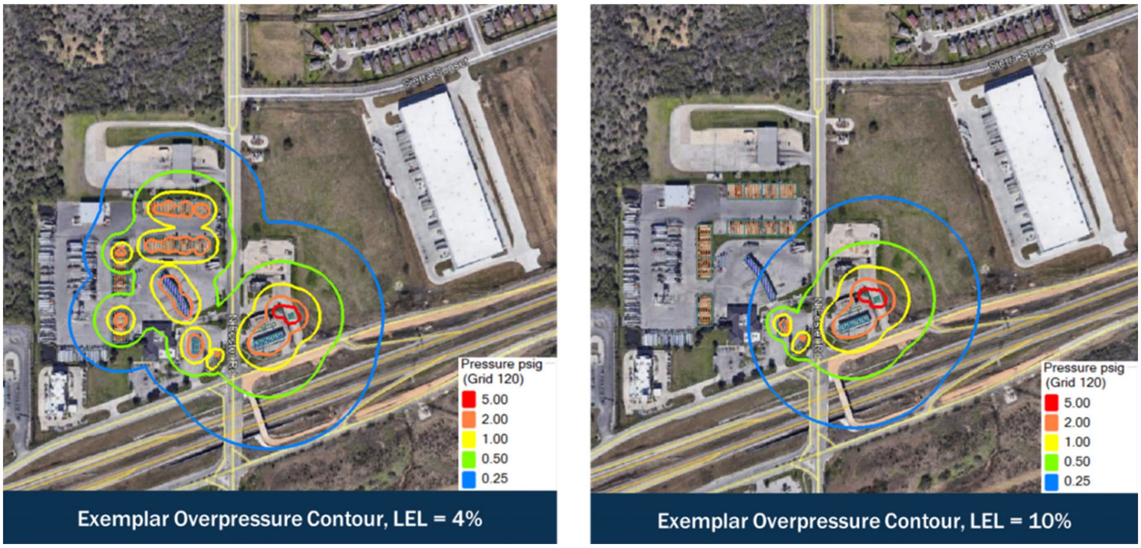

FIGURE 11 Predicted overpressure contours for exemplar H_2 fueling station.

TABLE 4 Postulated release scenarios for exemplar H_2 fueling station.

Material	Release source	Maximum hole diameter (inches)	Temperature (°F)	Pressure (psig)
Hydrogen	Truck unloading	2	−410	150
	Liquid storage tank	2	−410	90
	Cryo-pump	0.3	−400	7000
	Vaporizer	0.3	70	7000
	Dispenser	0.1	70	5100

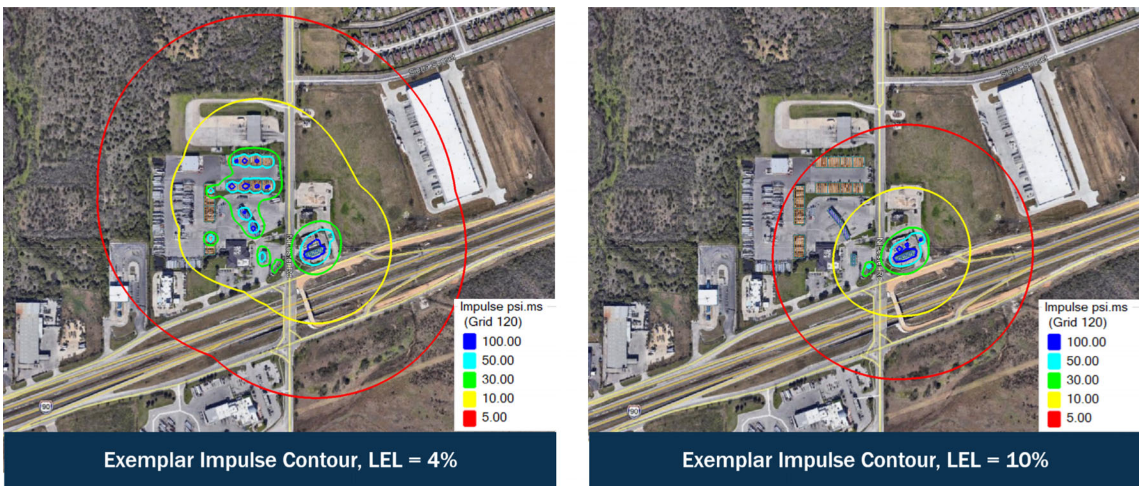

FIGURE 12 Predicted impulse contours for exemplar H_2 fueling station.

5 | KEY FINDINGS

This research brings together learnings from over a decade of ongoing work at BakerRisk on hydrogen VCE phenomena. Several key findings from this work are summarized below.

- Hydrogen VCEs are credible—experience has shown that hydrogen releases neither "float away" nor "instantly ignite."
- Lean H_2-air mixtures may result in a DDT with congested volumes representative of industrial facilities at hydrogen concentrations down to about 16%, with the likelihood of a DDT decreasing as

this concentration value is approached. Leaner mixtures (i.e., <16% H_2) would be very unlikely to DDT in actual congested volumes, albeit it is recognized test rigs could be configured to produce a DDT with leaner mixtures (e.g., a large pipe or tunnel configuration).

- Very lean H_2-air mixtures (< 12%H_2) will not contribute to the blast load generated by a VCE with congested volumes representative of industrial facilities. To ensure conservatism, and given the limited scope of the tests described in this paper, a lower explosion limit (LEL) of 10% H_2 has been adopted by BakerRisk for VCE blast load analysis; the LEL is used here to denote the concentration below which a fuel-air mixture will not burn at a velocity sufficient to produce damaging VCE blast loads.

6 | APPLICATION OF FINDINGS TO SCREENING LEVEL FACILITY SITING STUDIES

Assuming a hydrogen LEL equal to the standard lower flammable limit (LFL) for hydrogen (i.e., 4%) will produce significantly more conservative (potentially grossly so) estimates of the explosible cloud extents and blast loads for a postulated hydrogen release. To illustrate, the exemplary hydrogen fueling station shown in Figure 10 was evaluated for the postulated release cases listed in Table 4. BakerRisk's SafeSite code[14] was used to perform the release, dispersion, and VCE blast load analyses for the purposes of this illustration.

Figure 10 provides a comparison of the predicted explosible flammable cloud contours for an LEL of 4% (left) and 10% (right). Figure 11 provides a comparison of the predicted overpressure contours for these LEL values. Figure 12 provides a comparison of the predicted impulse contours; the blast response of structures (e.g., buildings) depends on both the applied blast overpressure and impulse. As can be seen in these figures, even though adopting a 10% H_2 LEL value is conservative, as noted above, increasing the LEL from 4%H_2 to 10%H_2 makes a significant difference in the predicted blast loads.

7 | CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK

The work reported here represents only a small step towards furthering our understanding of hydrogen VCE phenomena. However, it provides a technical basis for limiting VCE blast load analysis for flammable H_2-air clouds to the portions of the cloud in which the hydrogen concentration exceeds 10%. The use of a 10%H_2 LEL can significantly decrease predicted VCE blast loads, and the resulting facility siting requirements, while still ensuring a measure of conservatism. It is noted that National fire protection association (NFPA) 2 provides a basis for analyzing thermal and/or fire hazards assuming a hydrogen LFL of 8% (Annex I, Sec. 1.7), and the work reported here does not provide a basis for an alternative recommendation relative to thermal/fire hazards.

Possible considerations for future VCE testing are summarized below:

- VCE testing of ≥16% H_2-air mixtures in the 2 × 16 test rig (i.e., to establish the concentration required for a DDT).
- VCE testing of very lean (≤12%) H_2-air mixtures in test rigs with an L_{FV} >6 ft (i.e., to demonstrate that a 10%H_2 limit is sufficiently conservative under more severe conditions).
- VCE testing of very lean (≤12%) H_2-air mixtures in confined or partially confined geometries; lean H_2 mixtures testing in a vented enclosure was previously performed by BakerRisk, including the conditions required for a DDT.[14]
- VCE testing to demonstrate detonation wave failure in very lean (<12%) H_2-air mixtures.

AUTHOR CONTRIBUTIONS

Darren R. Malik: Conceptualization (lead); writing – original draft (lead). **W. B. Lowry:** Formal analysis (equal); writing – original draft (equal); writing – review and editing (equal). **E. Vivanco:** Investigation (lead). **J. K. Thomas:** Writing – review and editing (lead).

CONFLICT OF INTEREST

This work is self funded; therefore we do not believe there is a conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Darren R. Malik https://orcid.org/0000-0001-6814-2687
J. K. Thomas https://orcid.org/0000-0002-7551-8838

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