Hydrogen: Past and Future Test Programs

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Relevant BakerRisk Testing

- 2008 Lean Hydrogen VCE Tests
- 2010 LBV of Hydrogen–Hydrocarbon Mixtures
- 2012 Hydrogen-Hydrocarbon Mixture Burning Velocity Testing
- 2014 Effect of Inert Species on LBV of H_2 and C_2H_4
- 2018 Vented Hydrogen DDTs
- 2020 Hydrogen Ignition Testing
- 2022 VCE Testing of Very Lean Hydrogen-Air Mixtures
- 2022 Vented Hydrogen-Syngas Deflagration Testing
- 2023 Hydrogen-Methane VCE Testing

Given the expected push for the expansion of hydrogen-related infrastructure, it is critical that industry leaders, regulators, and safety professionals understand the hydrogen-related hazards. The goal of this paper is to review the publicly available hydrogen test programs that have been performed by BakerRisk, our clients, and the Explosion Research Cooperative (ERC).

ERC Test Programs

The ERC is a BakerRisk-organized joint industry program (JIP) founded in 1993. JIPs like the ERC are a great way to leverage research dollars to address industry concerns. ERC-funded research is highlighted yellow in the sidebar to the left. The ERC-funded research is proprietary to the ERC and is summarized via the publicly available prospectus documents as well as relevant photographs and still frames. Below are summaries of those four ERC-funded research projects, followed by descriptions of additional hydrogen-related testing efforts conducted by BakerRisk in collaboration with other groups and clients.

Laminar Burning Velocity of Hydrogen/Hydrocarbon Mixtures (2010)

Laminar Burning Velocity (LBV) is used as the reactivity index for the Baker-Strehlow-Tang (BST) vapor cloud explosion (VCE) blast load prediction method. This study used a bench-top scale test apparatus, shown in Figure 1, to establish limits of the applicability of Le Chatelier's rule for the LBV of hydrogen-hydrocarbon mixtures (e.g., hydrocracker fuel streams) and provided a compilation of hydrogen-hydrocarbon LBV data. This data is useful for determining which fuel reactivity class should be used for a given hydrogen-hydrocarbon mixture.

Laminar Burning Velocity of Hydrogen/Hydrocarbon Mixtures (2012)

This study measured the LBV of hydrogen/hexane and hydrogen/octane fuel mixtures. The measurements provided LBV data that could be compared to LBV estimates that had been made using Le Chatelier's rule, as well as other methods for calculating the LBV of fuel mixtures. A total of 63 tests were performed.

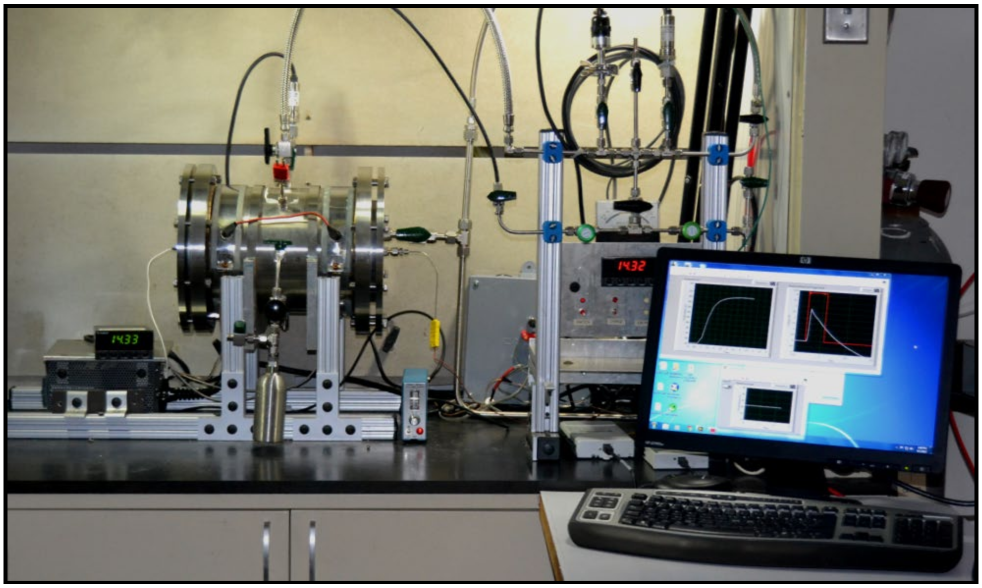

Figure 1. BakerRisk LBV test apparatus

Vented Hydrogen/Syngas Deflagration Testing (2022)

Due to a ramped up demand for hydrogen production and consumption, additional research is required to characterize the consequences of containerized hydrogen and hydrogen-rich syngas VCEs. This study explored the characteristics of vented deflagrations involving hydrogen-rich syngas and pure hydrogen inside a 20-ft long Conex container, applying a variety of congestion, confinement, and duration of fuel release options.

Still frames from a syngas test are provided in Figure 2. The results of this program allowed BakerRisk and the ERC member companies to explore the applicability of NFPA 68 to these types of vented deflagrations.

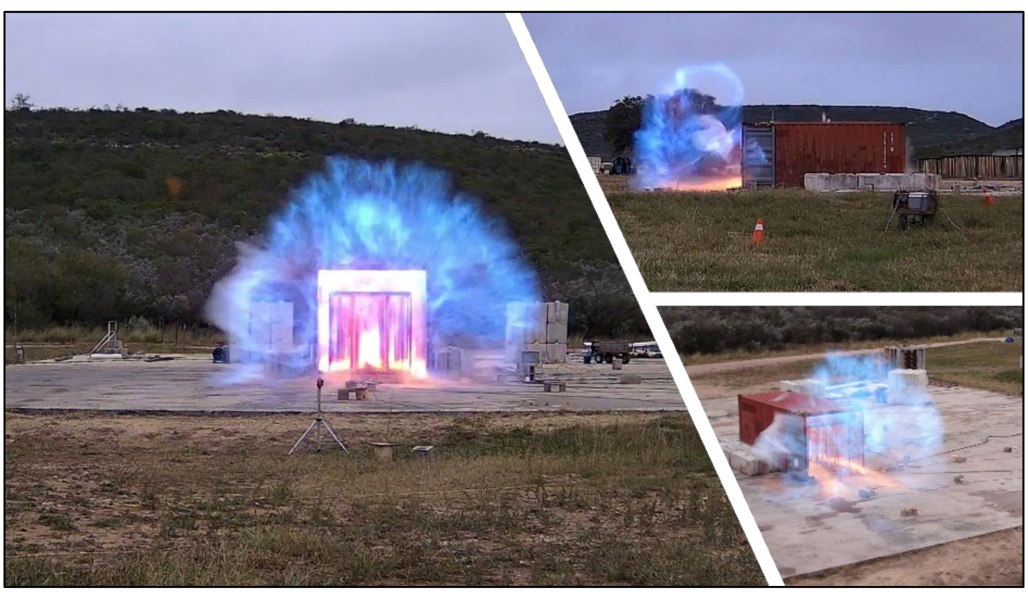

Figure 2. High definition still frames recorded during a syngas test

Hydrogen/Methane VCE Testing (2023)

Some proposed hydrogen transportation schemes involve blending hydrogen into the existing natural gas transportation system. A consequence of this proposed hydrogen/natural gas blending, however, is a substantial increase in the LBV, and subsequent VCE severity, for a given release scenario. This study investigated the consequences of confined hydrogen/natural gas (methane) deflagrations using BakerRisk's unique Deflagration Load Generator (DLG) rig. The DLG rig with a test in process is shown in the still frame image provided in Figure 3.

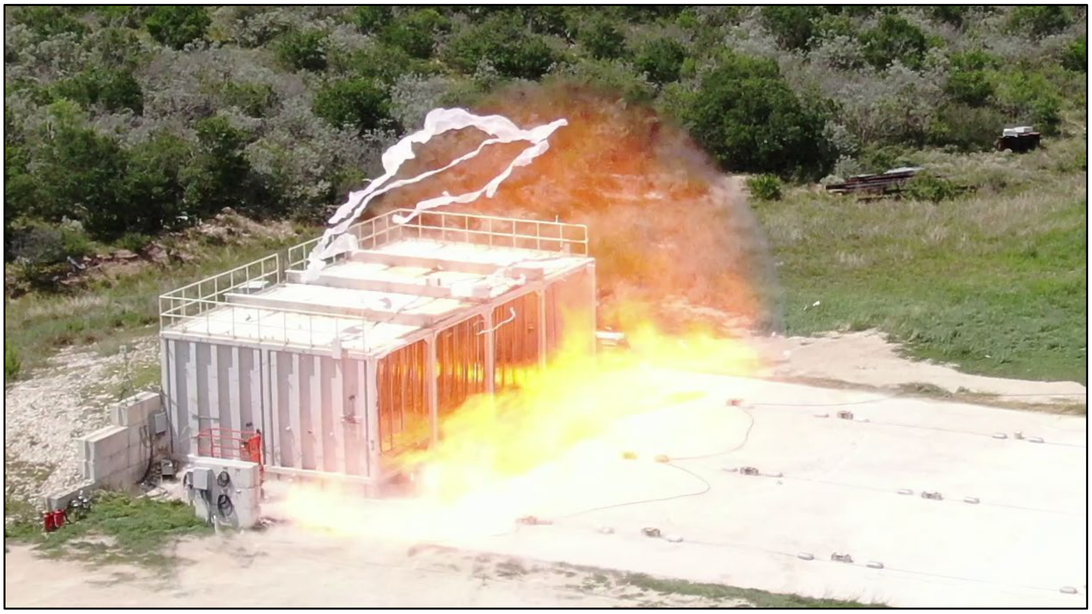

Figure 3. Still frame of a vented hydrogen/methane VCE from BakerRisk's Deflagration Load Generator

In addition to ERC-supported testing, BakerRisk has also supported client-specific test programs. All client research is held in confidence unless express permission is provided to share the information and potential lessons learned with the larger industry, in the form of a joint publication. The next section summarizes a client-funded project that was shared publicly.

Vented Hydrogen DDTs

This test program was funded by Daewoo Engineering & Construction Co. Ltd. (Daewoo). The purpose of the test program was to perform vented (i.e., partially-confined) VCE tests in order to support validation of a computational fluid dynamics (CFD) code [1].

Two tests with lean hydrogen mixtures were performed. The first test was performed using a 20% hydrogen mix and resulted in an average internal peak overpressure of 8.6 psig (0.6 barg). The hydrogen concentration was increased to 22.5% in the second test, and a deflagration-to-detonation transition (DDT) occurred as the flame front exited near the central portion of the open face of the rig. The average internal peak overpressure with the DDT was approximately 89 psig (6.1 barg). The external peak pressures were also measured for both test series. High speed video recordings were made of all tests. Still frame images of the observed onset of DDT from the second test is provided in Figure 4.

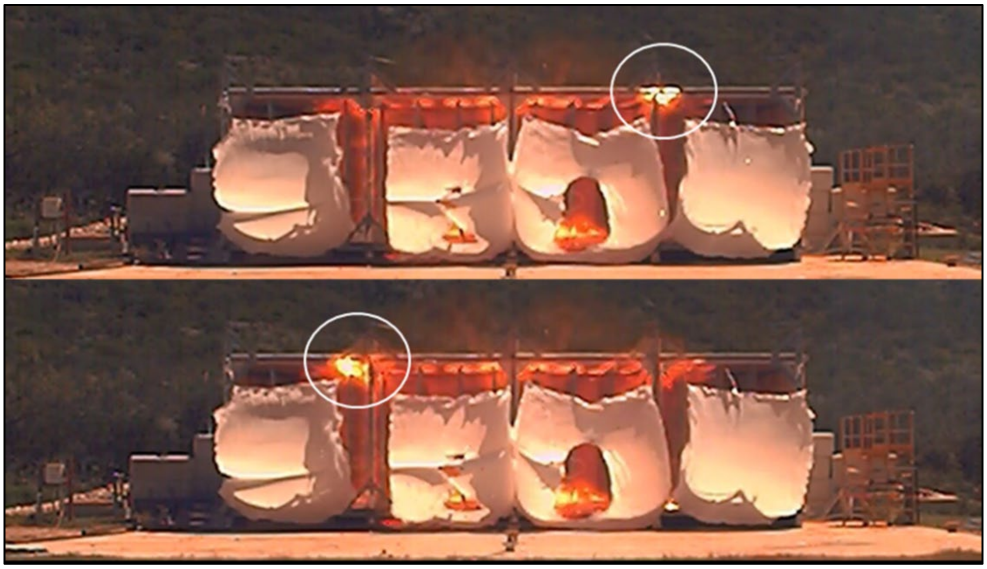

Figure 4. Still frames of the observed detonation kernels during the 22.5% hydrogen test

BakerRisk Internal Research

For over 15 years, BakerRisk has funded internal research programs to help advance industry knowledge of hydrogen-related hazards. The first test program was completed in 2008 and published in 2010. BakerRisk continues to invest in scientific research to better support our clients and the safety industry.

Lean Hydrogen VCE Tests

This test program was performed to provide benchmark data for predicting the occurrence of DDTs with unconfined, lean hydrogen-air clouds.[2] The test setup included a congested region that was 48 feet long by 12 ft wide by 6 ft high. Tests were performed with hydrogen-air mixtures from 16-22% hydrogen. A DDT was observed near the end of the test rig during the test with 22% hydrogen in air.

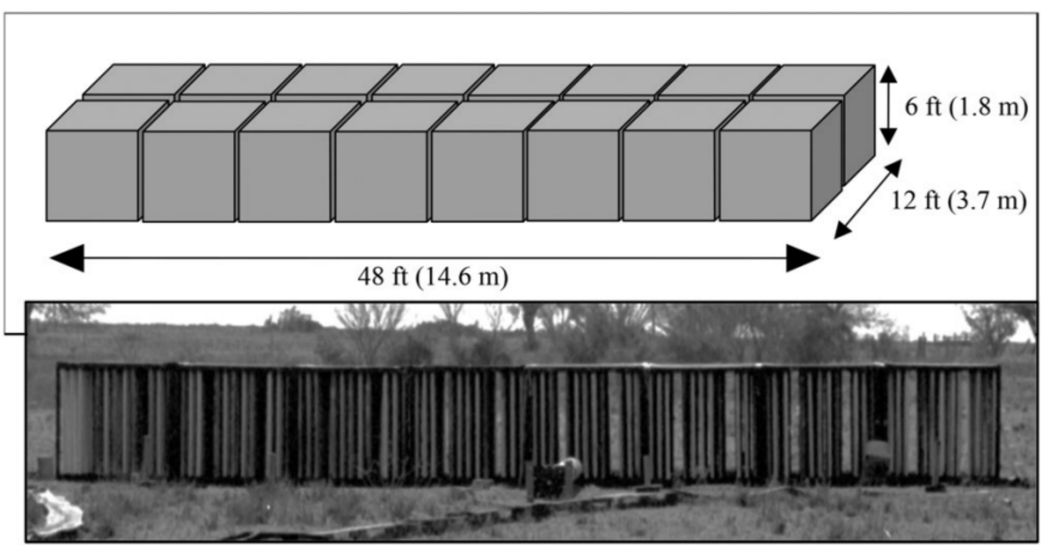

Figure 5. Schematic (top) and photograph (bottom) of the lean hydrogen VCE test rig

Effect of Inert Species on LBV of Hydrogen (H_2) and Ethylene (C_2H_4)

As previously stated, LBV is one of the inputs required to calculate the severity of a postulated VCE when using a simplified blast prediction method such as TNO/GAMES, BST, or the Congestion Assessment Method (CAM). This internal research program measured LBV of H_2/inert and C_2H_4/inert mixtures using both nitrogen and carbon dioxide as inert species.[3] The measured LBV values were compared against simplified LBV predictions (e.g., Le Chatelier and Spalding).

Hydrogen Ignition Tests

Ignition probability is one of the key inputs to quantitative risk assessments (QRAs). Unfortunately, one of the common misconceptions/myths about hydrogen is that it will always ignite (i.e., hydrogen ignition probability = 1). Numerous literature reviews have demonstrated that this simply is not the case [4].

BakerRisk used this internal research program as a first step towards better understanding hydrogen ignition probabilities. A series of < ½-inch releases was performed to generate a set of data that could be used to estimate ignition frequencies for small releases. BakerRisk did not observe any "spontaneous" ignitions during the execution of this test program. However, as shown in Figure 6, BakerRisk was able to observe ignition when a competent ignition source, such as a power tool, was present during the release. Note also, due to the desire to create a more robust data set, this research is still ongoing/has not been officially published at the time of this whitepaper.

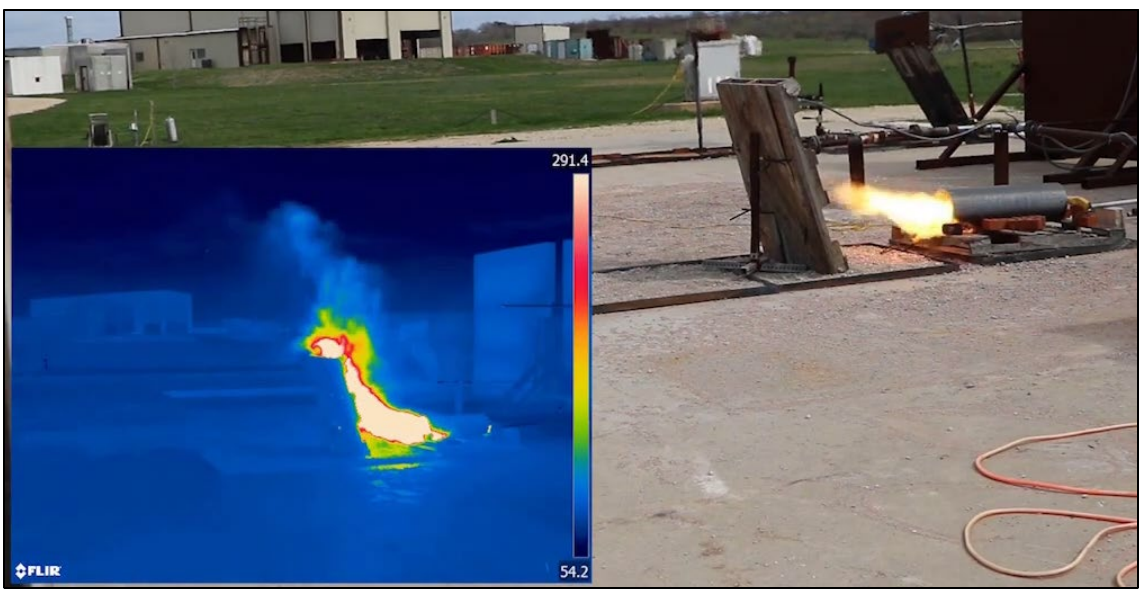

Figure 6. Video and infrared still frames from a ½-inch hydrogen release ignited by a power drill

VCE Testing of Very Lean Hydrogen-Air Mixtures

The specific purpose of this research was to explore the lower concentration limit at which hydrogen-air mixtures could be expected to produce damaging blast loads in an unconfined environment.[5] This research expanded on the prior work performed by BakerRisk for studying lean hydrogen VCEs. As shown in Figure 7, this test program used a long test rig (96 ft) to explore the lower bound concentration at which hydrogen-air clouds would not produce damaging blast loads.

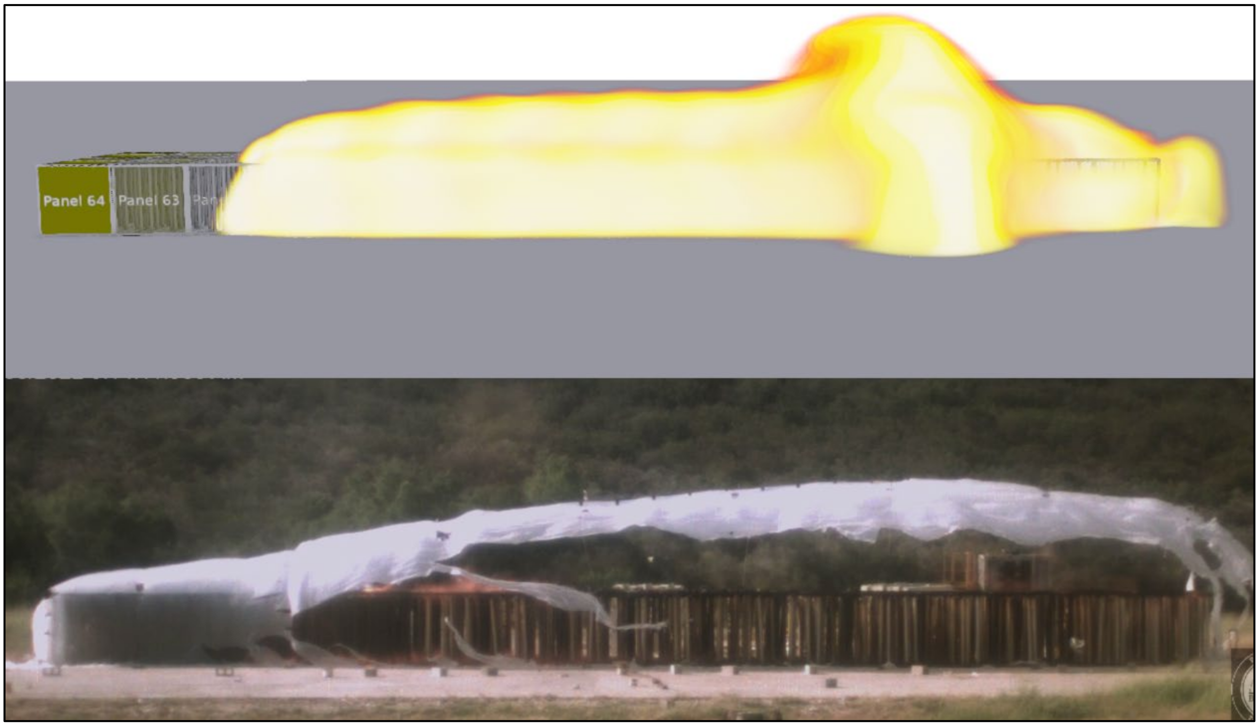

Figure 7. Still frame images from FLACS [top] and video of the representative test [bottom]

The key findings from this research were:

- Lean H2-air mixtures may result in a DDT with congested volumes representative of industrial facilities at concentrations down to about 16% H_2. The likelihood of DDT decreases as this concentration value is approached.
- Very lean H_2-air mixtures (<12% H_2) will not contribute to the blast loads generated by a VCE with congested volumes representative of industrial facilities.
- To ensure conservatism BakerRisk proposed the use of a lower explosion limit (LEL) of 10% H_2 when performing VCE blast load analysis.

Summary and Future

Test programs, such as those discussed above, have provided significant validation of the current methodologies used to analyze hydrogen hazards. Despite the enormous amount of work done by BakerRisk, the ERC, and others to understand the hazards associated with hydrogen, there is still more work to be done. Potential future test programs include the following:

- VCE testing to demonstrate detonation wave failure in very lean (<12%) H_2-air mixtures.
- Additional testing of vented deflagrations within containerized/modular enclosures.
- Ignition testing of large scale (>1 kg/s) hydrogen dispersions.
- VCE testing of hydrogen/methane blends.

The next paper will discuss the current industry outlook on hydrogen and highlight existing challenges for deployment in various end user industry sectors.

References

[1] B.-H. Bang, et al., *Theoretical, numerical, and experimental investigation of pressure rise due to deflagration in confined spaces*, International Journal of Thermal Sciences (2017), http://dx.doi.org/10.1016/j.ijthermalsci.2017.05.019

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[3] Lowry, W.B., Thomas, J.K., *Effects of Inert Species on the Laminar Burning Velocity of Hydrogen and Ethylene.* Paper presented at the Mary Kay O'Connor Process Safety Center's 17th Annual International Symposium, October 28-30, 2014, College Station, TX, USA

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[5] Malik D.R., Lowry, W.B., Vivanco, E., and Thomas, J.K., *Very lean hydrogen vapor cloud explosion testing*, Process Saf Prog. 2023;42(2):242-251. doi:10.1002/prs.12459