Vented Hydrogen DDTs

Deflagration-to-Detonation Transition (DDT) in a Vented Hydrogen Explosion

B. Horn, O. Rodriguez, D. Malik, P.E., and J.K. Thomas, Ph.D.
Baker Engineering & Risk Consultants, Inc. (BakerRisk®)
3330 Oakwell Court, Suite 100
San Antonio, TX 78218-3024
(210) 824-5960
BHorn@BakerRisk.com

B. Bang, Y. Kim and M. Lee
Technology Development Team,
Daewoo Institute of Construction Technology
60, Songjuk-dong, Jangan-gu, 440-210, Suwon, Korea

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Abstract

Baker Engineering and Risk Consultants, Inc. (BakerRisk®) and Daewoo Engineering and Construction Co. Ltd. (Daewoo) performed vented (i.e., partially-confined) vapor cloud explosion (VCE) tests with both propane and lean hydrogen mixtures. BakerRisk's Deflagration Load Generator (DLG) test rig was used to perform the tests. The DLG test rig was designed primarily to produce centrally-peaked blast waves that are representative of VCEs suitable for blast loading test articles, but has also been used for vented deflagration testing. The DLG test rig is a steel box with one open side, measuring 48 ft. long by 24 ft. deep by 12 ft. high (14.6 m by 7.3 m by 3.7 m). The DLG test rig is outfitted with congestion, filled with the desired fuel-air mixture, and then ignited near the center of the rear wall.

Two test series were performed. The first series of tests used a uniform, very-low congestion pattern with a near-stoichiometric propane-air mixture (4.33% propane). The average internal peak overpressure was 5.9 psig (0.4 bar). The second test series used the same congestion pattern with lean hydrogen mixtures at increasing hydrogen concentrations. The first test was performed at 20% hydrogen and resulted in an average internal peak overpressure of 8.6 psig (0.6 bar). 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 bar). The external peak pressures were also measured for both test series. High speed video recordings were made of all tests.

This paper describes the tests performed and discusses the implications with regards to predicting the blast loads resulting from vented VCEs.

1 INTRODUCTION

Baker Engineering and Risk Consultants, Inc. (BakerRisk®) was contracted by Daewoo Engineering & Construction Co. Ltd. (Daewoo) to perform vented (i.e., partially-confined) vapor cloud explosion (VCE) tests. BakerRisk utilized the Deflagration Load Generator (DLG) test rig for this purpose. The DLG rig is located at the Box Canyon Test Facility (BCTF), located approximately two hours west of San Antonio, Texas. The purpose of these tests was to provide data to support validation of a computational fluid dynamics (CFD) code [1].

The test matrix is provided in Table 1. A uniform internal congestion array was installed in the DLG to induce turbulence and increase flame speed in order to produce a peak internal overpressure in the range of 5 to 10 psig (0.3 to 0.7 bar) with a propane/air mixture at a near-stoichiometric propane concentration. Two propane/air tests were performed to establish the repeatability of the resulting VCE blast loads.

Following the propane tests, the test matrix called for a series of three tests using hydrogen as the fuel, with the hydrogen concentration being incrementally increased to reduce the potential for explosion loads which could damage the DLG. An initial hydrogen concentration of 20% was tested. The hydrogen concentration would then be increased towards the stoichiometric concentration (30% H_2) in subsequent tests, depending on the loads observed in the initial test.

Table 1. Test Matrix

Test	Fuel	Proposed Test Concentration	Actual Goal Concentration
A01	Propane	4.33	4.33
A02			
B01	Hydrogen	20	20
B02		25	22.5
B03		30	Not Performed

The test setup is discussed in Section 2. The test results are discussed in Section 3. A discussion of the results is presented in Section 4.

2 TEST SETUP

Four vented (i.e., partially-confined) VCE tests were conducted using the DLG test rig. The DLG test rig, instrumentation layout, and congestion pattern are discussed in the following sections.

2.1 DEFLAGRATION LOAD GENERATOR

The DLG test rig was designed by BakerRisk to produce both long duration centrally-peaked pressure waves typical of a VCE, as well as shorter duration shock waves with an instantaneous rise to peak pressure that are typical of high explosives. The shocked-up loads range from 2 to 12 psig (13.8 to 82.7 kPa) at external locations with effective durations of 20 to 40 ms. Centrally-peaked loads range from 0.5 to 5 psig (3.4 to 34.5 kPa) at external locations with effective durations of 30 to 60 ms. Effective durations are calculated by dividing twice the impulse by the peak pressure. Increased durations can be achieved with alternative ignition source configurations. Higher loads are achieved internal to the DLG. Large test articles (e.g., buildings, tents, trailers, etc.) can be placed in front of the DLG while smaller test articles (e.g., drums, electrical enclosures, etc.) can be placed either internal or external to the DLG.

The DLG is essentially a reinforced steel box with one open side and dimensions of 48 feet long × 24 feet deep × 12 feet high (14.6 m × 7.3 m × 3.7 m) with a total flammable volume of 13,824 ft^3 (391.5 m^3). The DLG is outfitted with congestion (i.e., vertical steel pipes) that induces turbulence to increase flame speed and produce the target blast load. The one open side is temporarily sealed with 6 mil (0.15 mm) thick plastic sheeting to contain the fuel-air mixture. The fuel gas was introduced into the rear-center of the DLG and mixed to generate a uniform fuel/air mixture via four large internal fans. The DLG fuel/air concentration is sampled with a distributed array of sample points and analyzed using oxygen analyzers. Once the target fuel concentration was obtained, the fans were shut off for a period of four minutes to allow the mixture to become quiescent and minimize pre-ignition turbulence.

The flammable cloud was ignited with a low energy (~50 joules) exploding fuse wire at the back wall in order to produce a VCE. The partially-confined VCE vents out through the open side producing external blast loads, and in close proximity, fire exposure as the flame escapes the open side and expelled gas continues to burn. The congestion, fuel concentration, and standoff distance of the target can be varied to produce a blast wave with the desired characteristics.

2.2 INSTRUMENTATION LAYOUT

Pressure (100 kHz), high speed video (3000 frames per second, fps), and high definition (HD) video (30 fps) were recorded for all tests. A total of 43 dynamic pressure gauges were deployed to capture the pressure history within and external to the DLG test rig. All pressure data, except for Test B02, was smoothed with a running average of N=100 to yield an effective sampling rate of 1 kHz. Test B02 pressure data exhibited a near instantaneous pressure rise which would be distorted if smoothed; the data from this test therefore was not post-processed.

2.3 DLG Internal Congestion

The DLG congestion pattern was a uniform distribution, chosen to produce internal pressures in the range of 5 to 10 psig (0.3 to 0.7 bar) with a propane/air mixture at a near-stoichiometric propane concentration. The congestion pattern is shown below in Figure 1 and Figure 2. The bulk of the congestion is a standard 2.0-inch outer diameter (5.08 cm) pipe with a thickness of 0.065 inches (1.65 mm), while the front two rows are a thicker pipe with outer diameter of 2.375 inches (6.03 cm) and thickness of 0.1875 inches (4.76 mm).

The congestion pattern used has an area blockage ratio (ABR) of 4.9%, a volume blockage ratio of 0.5%, and a pitch to diameter ratio (P/D) of 8.5. These congestion characteristics are well below those utilized in tests to define "Low" congestion flame speeds for the Baker-Strehlow-Tang (BST) VCE blast load prediction methodology [2, 3].

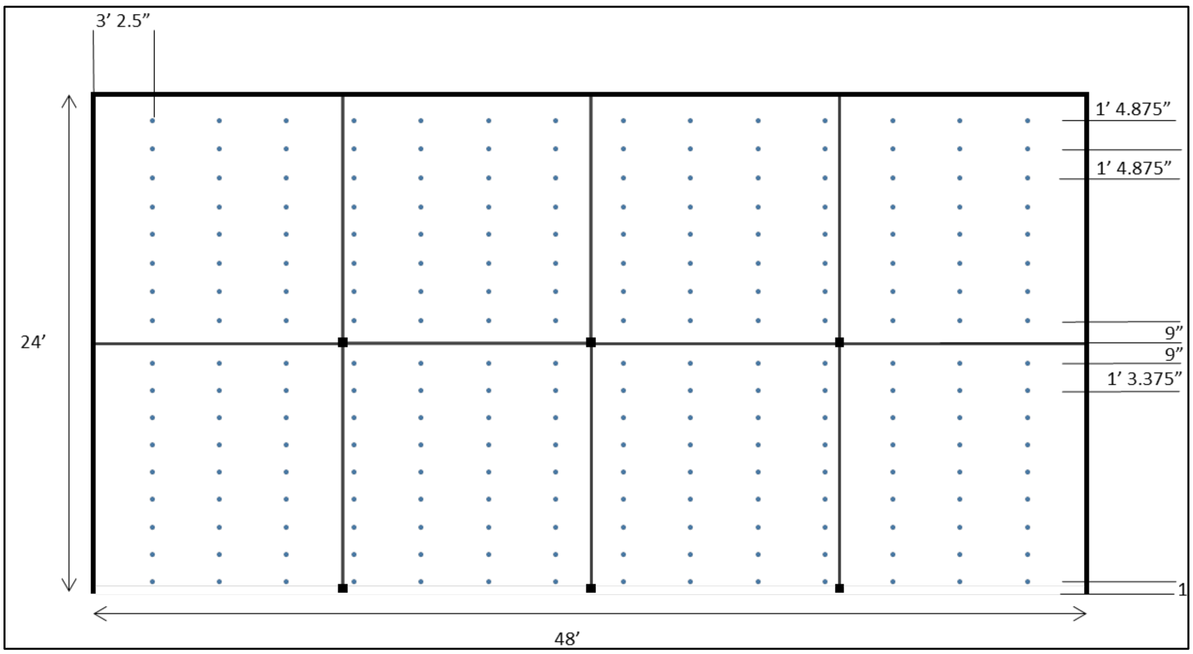

Figure 1. DLG Internal Congestion

Figure 2. Photo of DLG and Internal Congestion

3 TEST RESULTS

BakerRisk conducted four VCE tests. The first two tests (A01 and A02) were performed using a propane fuel/air mixture with a slightly hyper-stoichiometric target concentration of 4.33% propane; the repeat shot was performed to demonstrate repeatability. Test B01 and B02 utilized hydrogen gas for the fuel/air mixture with target concentrations of 20.0% and 22.5% hydrogen, respectively. The test results are discussed in the following sections. The average internal peak overpressure (*P*, psig), total positive phase impulse (integration of pressure with respect to time, *i*, psi-ms), effective duration ($2i/P$, t_d, ms) and fuel concentration for each test are summarized in Table 2. The actual concentration is the average of all sample points just prior to ignition.

Table 2. Average Internal Blast Loads and Fuel Concentrations

Test	Fuel	Peak Overpressure (psig)	Impulse (psi-ms)	Effective Duration (ms)	Fuel Concentration (molar, %)		
					Actual	Target	Acceptance Range
A01	C_3H_8	5.9	210	73	4.34	4.33	4.16 - 4.44
A02	C_3H_8	5.9	227	77	4.36	4.33	4.16 - 4.44
B01	H_2	8.6	230	56	20.06	20.00	19.85 - 20.15
B02	H_2	89	413	10	22.47	22.50	22.35 - 22.65

3.1 PROPANE RESULTS

The average overpressure for all internal gauges was 5.9 psig (40.7 kPa) for Tests A01 and A02. The average impulse was 210 and 227 psi-ms (1450 and 1570 kPa-ms), and the average effective duration was 73 and 77 ms, for Tests A01 and A02, respectively. A frame from the HD video for Test A02 is shown in Figure 3. Figure 4 shows the pressure-time histories from selected gauges for Test A02, both internal and external to the DLG test rig; the pressure histories for the internal gauges were shifted forward in time by 0.25 seconds for clarity.

3.2 TEST B01 RESULTS

The average overpressure of all internal gauges for Test B01 was 8.6 psig (59.0 kPa) with an impulse of 230 psi-ms (1590 kPa-ms) and effective duration of 56 ms. A frame from the HD video is shown in Figure 5. The average concentration prior to ignition was 20.06% H_2. Figure 6 shows the pressure-time histories for selected gauges, both internal and external to the DLG test rig; the pressure histories for the internal gauges were shifted forward in time by 0.20 seconds for clarity.

3.3 TEST B02 RESULTS

The average overpressure of all internal gauges for Test B02 was 89 psig (612 kPa) with an impulse of 413 psi-ms (2850 kPa-ms) and effective duration of 10 ms. Sequential frames from the HD video (30 fps) are shown in Figure 7 and Figure 8. The average concentration prior to ignition was 22.47% H_2. Figure 9 shows the pressure-time histories for selected gauges, both internal and external to the DLG test rig; the pressure histories for the internal gauges were shifted forward in time by 0.15 seconds for clarity.

Figure 3. Test A02 - Still Image from 45º HD Video

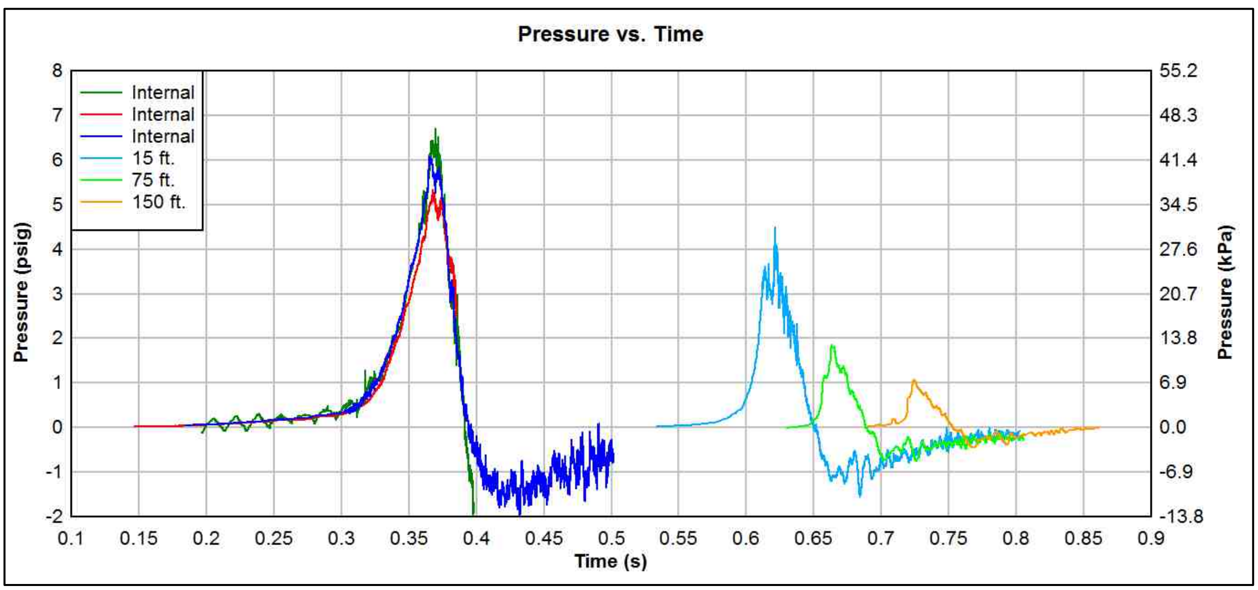

Figure 4. Test A02 – Pressure-Time History for Select Gauges

Figure 5. Test B01 - Still Image from Front HD Video

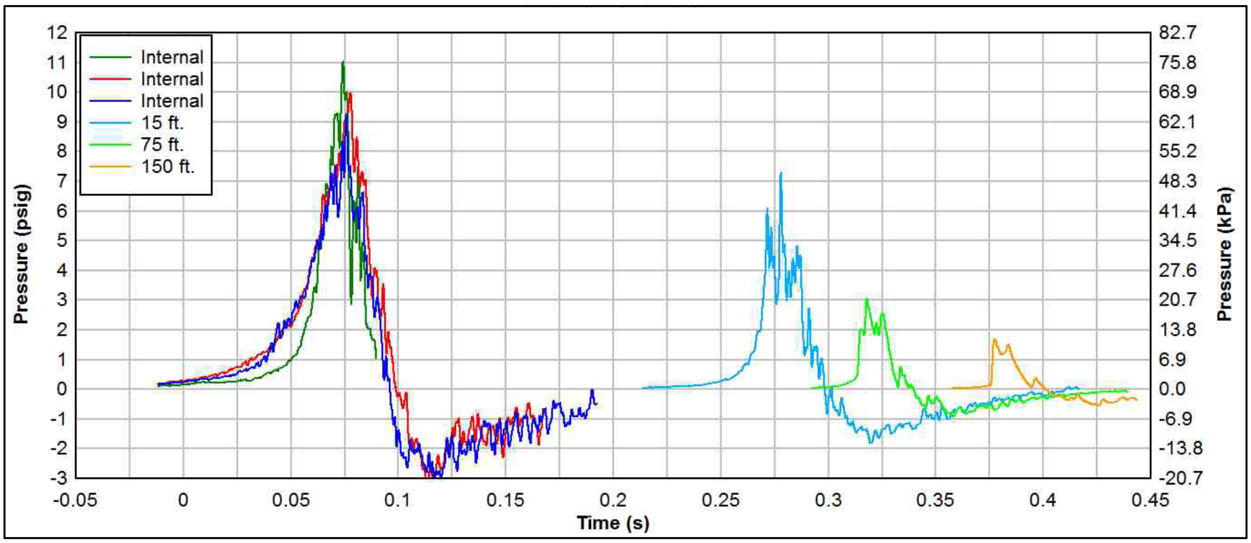

Figure 6. Test B01 – Pressure-Time History for Select Gauges

Figure 7. Test B02 - Still Image from 45º HD Video – Frame 1

Figure 8. Test B02 - Still Image from 45º HD Video – Frame 2

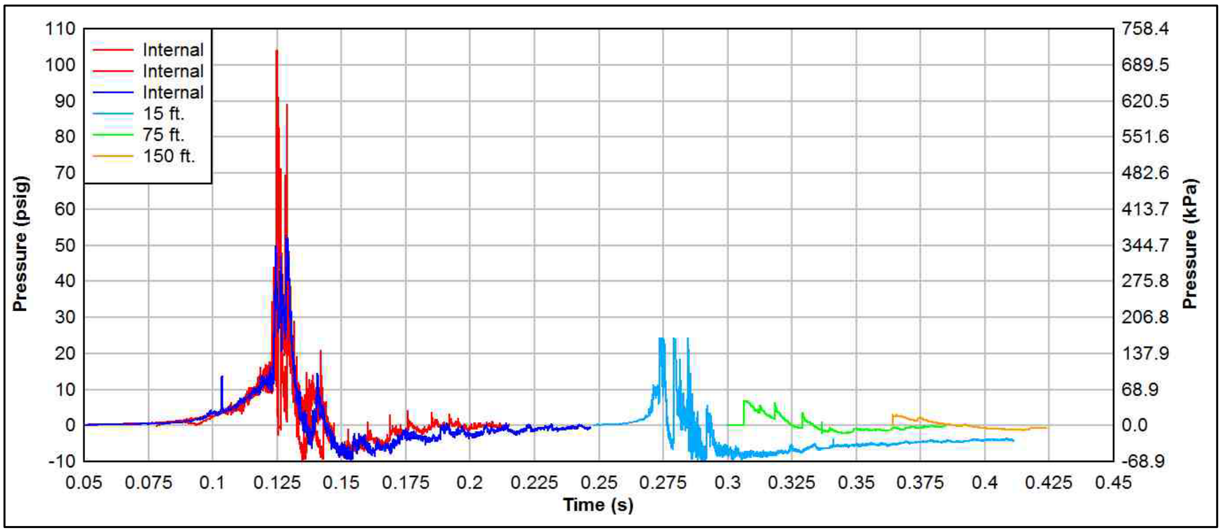

Figure 9. Test B02 – Pressure-Time History for Select Gauges

4 DISCUSSION OF RESULTS

This study provided large scale vented (i.e., partially-confined) VCE test data for the purpose of CFD model validation. Tests A01 and A02 showed very good repeatability with average internal DLG pressures of 5.85 and 5.91 psig (40.3 and 40.7 kPa), respectively. Average propane concentrations for these tests were within 0.03% of the 4.33% target concentration.

Following the propane shots, the first hydrogen Test (B01) was performed at 20.1% H_2. The average internal DLG pressure was 8.6 psig (59.3 kPa). Since the pressure was slightly higher than expected, Test B02 was performed at 22.5% H_2 (i.e., rather than 25%). Two DDTs occurred near the tops of the east and west support columns in Test B02 as the flame exited around the column gusset plates; the two DDTs were separated in time by approximately 0.7 ms. Figure 10 and Figure 11 provide still frames showing the two DDT locations (circled in white) from the high speed video (3000 fps). By tracking the detonation front in sequential frames, the flame speed was estimated to be roughly 5,700 ft/s (1,700 m/s, Mach 5.1).

Once a DDT has occurred, the detonation front will generally consume any remaining portion of the flammable cloud as a detonation [4]. In Test B02, the detonation wave travelled back into the DLG along the sides, consuming the remaining fuel and resulting in an average internal pressure of 89 psi (610 kPa). Although the impulse associated with this pressure was relatively small, the applied load damaged the internal congestion (i.e., pipes), slightly deformed the DLG, and severely damaged congestion support systems. The approximate pipe deflection directions and magnitudes are shown in Figure 12, and listed in Table 3, respectively. A photo showing the deflection of the pipes near the DLG side wall is provided in Figure 13.

5 Conclusions

5.1 Blast Load Prediction Methodologies and DDTs

The results demonstrate the potential for a DDT with hydrogen in an enclosure at low levels of congestion. The current BST flame speed table [2] gives a flame speed of Mach 0.59 for low congestion, 2D confinement, and high reactivity fuel (e.g., hydrogen). A medium level of congestion is required for a DDT prediction using the BST method, in either 2-D confinement or in the absence of confinement (i.e., 3D). Previous BakerRisk tests demonstrated that lean hydrogen mixtures can undergo a DDT without confinement at a medium congestion level [5, 6]. While these tests were more confined than 2D (i.e., three side walls as well as a roof), the results demonstrate that DDTs can occur even at very low levels of congestion in such arrangements. Within the context of the BST method, it may be appropriate to assign a medium level of congestion in such cases to capture the potential for a DDT. Other blast load prediction methodologies (e.g., TNT, TNO) may need to be adjusted for such cases as well.

5.2 Implications on Facility Siting

Differentiating between a high-speed deflagration and a DDT can be important with respect to VCE blast load predictions [4]. The loads from a high-speed deflagration and a detonation do not differ significantly at moderate to large standoffs if the flammable cloud is smaller than the congested volume of interest. However, the blast loads from these two cases can be very different if the flammable cloud extends well beyond the congested volume (i.e., for a release scenario with a large release rate). This difference arises since a detonation wave, once initiated by a DDT, will generally consume any remaining portion of the flammable cloud as a detonation (i.e., including that portion of the flammable cloud outside the congested volume). Conversely, the flame speed associated with a deflagration will decrease to values associated with flash fires once the flame exits the congested volume. The detonation of a cloud larger than the congested volume can therefore produce significantly higher blast loads at occupied buildings, or other targets of interest, due both to increased explosion energy and reduced stand-off distance. If the assumption of a DDT produces an unacceptably high blast load or explosion risk, then more detailed consequence models (i.e., CFD codes) can be used to further analyze the scenarios of interest.

A post-test FLACS analysis was performed for both the 20% and 22.5% H_2 tests. Both tests were analyzed to determine the likelihood of a DDT occurring using FLACS along with the published DDT criterion based on the dimensionless pressure gradient parameter (i.e., DPDX) [7]. The results show that a DDT would be predicted to be "Possible" for the 20% H_2 Test B01 and "Likely" for the 22.5% H_2 Test B02. Based on the DDT criteria developed by BakerRisk, a DDT was not predicted at 20% H_2 and was predicted at 22.5% H_2, in agreement with the test results. These results demonstrate the utility of CFD-based DDT analyses if required.

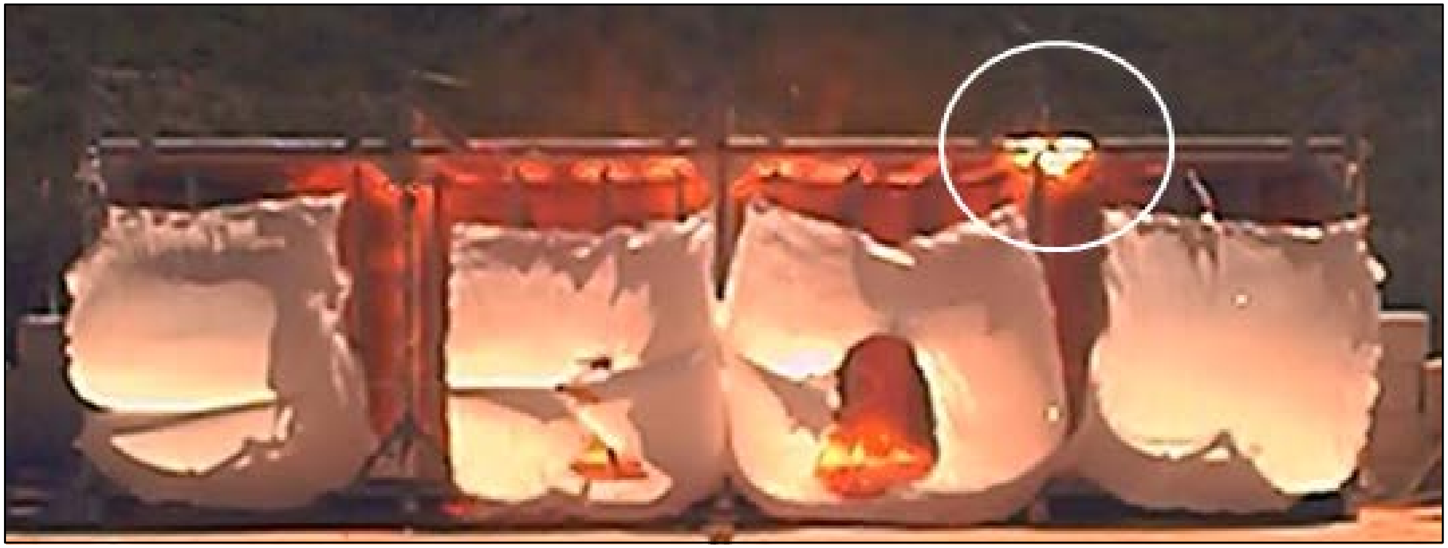

Figure 10. Test B02 – HS Video – Right Side DDT Location

Figure 11. Test B02 – HS Video – Left Side DDT Location (0.66 ms after Figure 10)

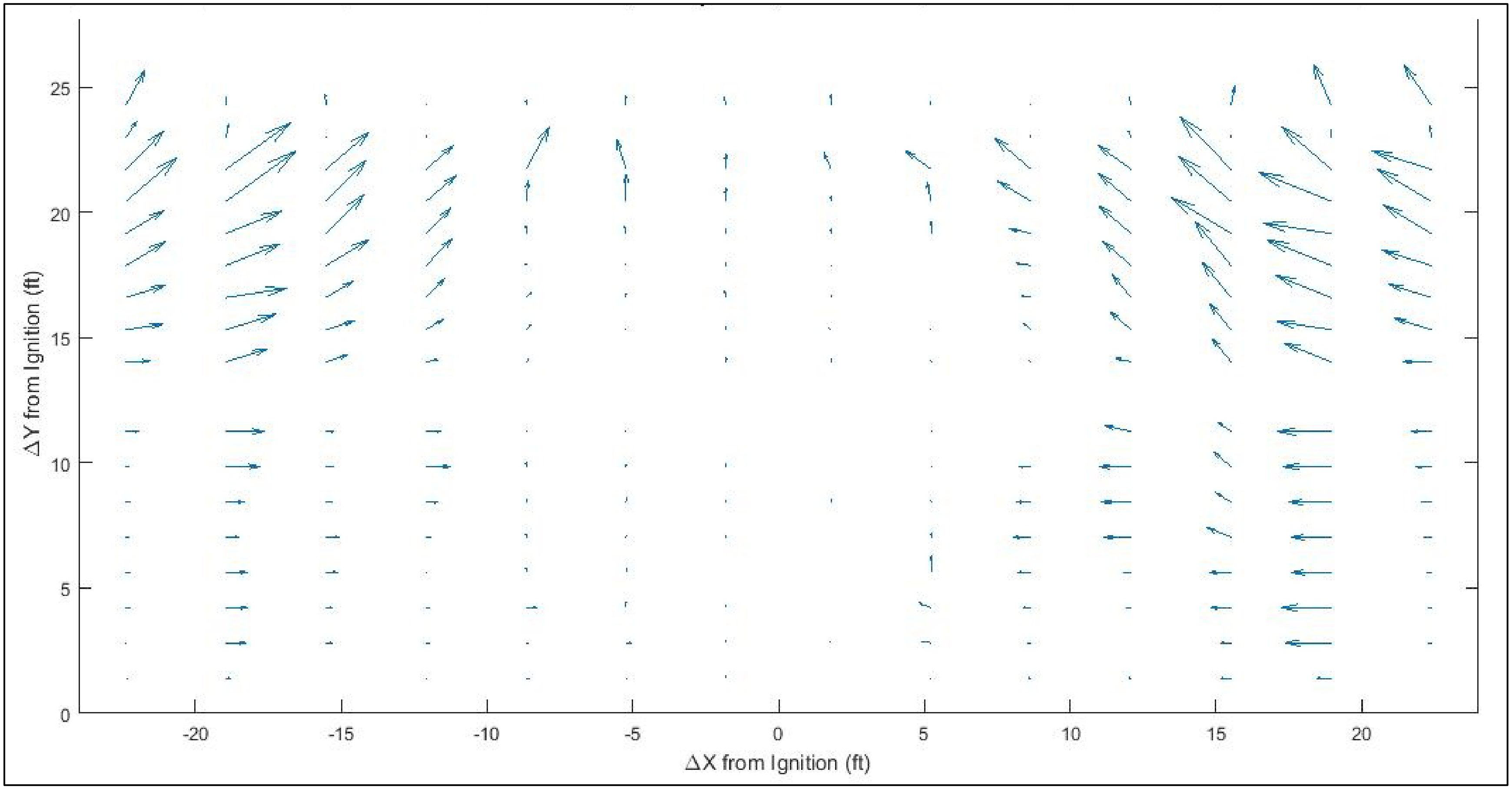

Figure 12. Test B02 – Pipe Deformations – Vector Plot

Table 3. Test B02 – Congestion Deflection – Measurements (inches)

R X C	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.7	1.2	0.0	0.3	1.1	0.5	0.8	0.0	0.6	0.8	0.7	3.0	4.2	0.0
2	0.3	5.8	1.7	0.9	0.9	1.6	1.0	0.7	2.9	1.2	0.0	2.9	13.3	1.1
3	1.2	6.3	1.9	1.0	3.3	2.0	0.8	0.5	3.9	2.4	1.4	6.0	14.4	0.7
4	1.2	6.1	3.2	0.6	1.5	1.3	0.0	0.0	5.7	4.1	2.3	6.3	11.5	1.3
5	0.9	3.9	3.9	1.4	1.3	0.6	0.6	0.0	1.4	5.3	7.8	7.7	11.6	2.1
6	1.2	5.1	1.8	3.5	0.9	1.7	0.6	1.1	0.6	4.1	8.5	5.5	12.2	2.8
7	0.8	9.8	2.3	7.3	1.6	0.7	1.1	0.0	0.5	3.6	9.3	7.2	13.8	4.3
8	3.7	11.1	2.3	4.3	0.4	0.3	0.0	0.0	0.1	0.3	7.9	4.8	15.4	5.7
9	6.9	12.9	6.6	3.7	1.0	0.0	1.3	0.9	0.7	0.8	4.7	9.6	15.1	8.2
10	10.8	15.3	8.6	5.9	2.1	0.2	1.1	1.3	0.8	2.9	8.6	10.9	16.0	11.3
11	12.1	17.8	9.8	8.3	2.4	1.4	2.3	0.8	0.0	3.0	9.4	14.6	17.5	13.0
12	13.8	17.3	14.9	11.8	0.6	0.4	1.0	0.5	0.3	4.6	11.5	18.3	20.6	14.9
13	13.6	17.8	17.0	11.1	2.7	2.6	1.7	1.6	4.0	6.5	13.1	20.8	19.9	16.6
14	20.8	26.3	18.1	12.4	6.9	9.2	4.6	1.8	6.6	11.8	13.3	21.3	23.2	19.1
15	16.8	24.2	17.6	11.1	15.8	10.4	5.1	5.9	9.8	15.0	12.5	22.9	20.0	18.1
16	6.1	4.4	0.6	0.5	0.0	0.0	0.0	0.0	0.0	0.5	2.2	0.8	2.5	3.9
17	12.9	2.6	3.5	0.6	1.6	3.0	2.6	3.6	1.1	0.8	2.6	6.4	14.8	15.4

Figure 13. Photo of Pipe Deformation following Test B02 DDT

6 ACKNOWLEDGEMENTS

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