# Propagation of a Vapor Cloud Detonation from a Congested into an Uncongested Area

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A test was conducted which demonstrates that a detonation wave, once formed due to a DDT within a congested region, will propagate as a detonation from the congested region into an uncongested region.  This is the expected behavior based on the general behavior of detonation waves and as well as other tests reported in literature.

The test rig was 16.5 m (54 feet) long with the first 9.1 m (30 feet) of the rig length comprised of a congested section 3.7 m (12 feet) in width and 1.8 m (6 feet) high.  The congestion was made up of a regular array of vertical circular tubes (6 cm (2.375-inch) diameter, pitch-to-diameter ratio of 4.1, area and volume blockage ratios of 23 % and 4.2 %, respectively).  The last 7.3 m (24 feet) of the test rig length was completely uncongested.  The test rig was configured without any confinement (i.e., no wall or roof sections).  A near-stoichiometric ethylene-air mixture completely filled both the congested and uncongested portions of the test rig.  Prior testing with a similar rig configuration had shown that this flammable mixture would undergo a DDT within the congested portion of the rig.

## 1. Introduction

The potential for a deflagration to detonation transition (DDT) to occur in an unconfined vapor cloud explosion (VCE) with high reactivity flammable gases (e.g., ethylene, hydrogen, etc.) under conditions relevant to chemical processing and petroleum refining plants has been demonstrated in multiple test programs.  While there is some uncertainty regarding the precise conditions required to trigger a DDT, the potential for a DDT if high reactivity flammable gas is released into a congested environment is widely recognized and generally accounted for in explosion consequence and risk studies.  The distinction between a high speed deflagration and a detonation may not be critical for comparatively small flammable gas clouds restricted to a congested volume (e.g., a process unit).  In either case the flammable portion of the cloud is combusted within the congested volume.  The blast loads away from the cloud are therefore similar whether the VCE occurs as a high speed deflagration or a detonation, although the loads in and near the cloud are much higher with a detonation (Pierorazio et al., 2005).

However, the distinction between a high speed deflagration and a detonation can be very important for a large flammable gas cloud extending well outside the congested volume.  If the VCE proceeds as a deflagration, then the flame front velocity will decrease rapidly outside the congested volume such that the portion of the flammable gas cloud outside the congested volume contributes little to the resulting blast load.  In contrast, a detonation wave will propagate through the portion of the flammable gas cloud outside the congested volume, increasing the explosion energy and decreasing the standoff to targets away from the congested volume.  The key difference between the two cases (i.e., high speed deflagration vs. detonation) is the behavior of the flame front external to the congested region.  The

purpose of this test program was to provide a clear demonstration of the propagation of a detonation wave formed due to a DDT from a congested region into an uncongested region.

## 2. Background

A number of test programs have shown that a DDT can occur under a variety of conditions, and that a DDT can occur with high reactivity fuels in the absence of confinement.  For example, Thomas et al. (2003) showed that a DDT would occur with a test rig geometry similar to that employed in the current test program for ethylene-air mixtures over a range of ethylene concentrations (5.9% to 9.3%). However, relatively few tests have been conducted which demonstrate the propagation of the resulting detonation wave away from a congested region into the open.

Harris and Wickens (1989) reported on a test program which explored multiple aspects of vapor cloud explosions.  Some of the tests provided observations of flame front propagation from a congested into an uncongested region.  The test rig used was 45 m (148 ft.) long and about 3 m (9.8 ft.) high.  An obstacle array with a 40 % area blockage ratio and successive obstacle rows spaced at 1.5 m (4.9 ft.) was used in the congested region between 9 m (30 ft.) and 28 m (92 ft.) along the test rig.  No obstacles were present from 28 m (92 ft.) to the end of the rig at 45 m (148 ft.).  A DDT was observed in a test with cyclohexane at about 23 m (76 ft.).  The detonation wave propagated at a speed of approximately 1700 m/s (5600 ft/s) through the remainder of the test enclosure, including the unobstructed region.  A similar test with propane also yielded a DDT with a flame front velocity of about 1800 m/s (5900 ft/s) and showed that the detonation wave propagated into the uncongested region.

## 3. Test Description

A schematic of the overall test rig is shown in Figure 1.  The test rig was composed of two sections, a congested section and an uncongested section, both of which were filled with an ethylene-air mixture. The entire test rig was 16.5 m (54 feet) long.  The first 9.1 m (30 feet) of the rig length was comprised of a congested section 3.7 m (12 feet) in width and 1.8 m (6 feet) high.  The congested section was made up of individual cubes, each cube being 1.8 m (6 feet) x 1.8 m (6 feet) x 1.8 m (6 feet).  The congestion cubes were arranged in a 2 x 5 array for this test.  A wooden "reflection" wall was placed at the rear of congested section to act as a wall of symmetry during the initial flame acceleration.  The use of the reflection wall allowed a decreased congested rig length and volume, and hence limited the resultant external blast load.  The uncongested section of the rig was 7.3 m (24 feet) long and the same height as the congestion section (1.8 m).  The uncongested section was wedge shaped, being the same width as the congested section (3.7 m) at one end and tapering to a point at the other.  A wedge shape was used for the uncongested section to limit its volume and the resultant external blast load.  The test rig was configured without any confinement (i.e., no wall or roof sections).
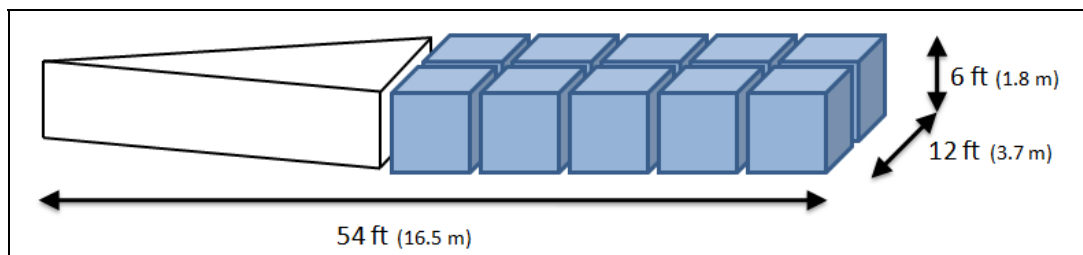


*Figure 1.  Schematic of Test Rig*

The congestion was made up of a regular array of vertical circular tubes.  The tubes were 6 cm (2.375-inch) in diameter.  The tubes were placed in a 7x7 array within each congestion cube.  The corner tubes from each 7x7 array were removed since the cube corner supports provide a roughly equivalent level of obstruction, so that 45 tubes were present within each cube.  This arrangement gives a pitch-to-diameter ratio of 4.5 and provides area and volume blockage ratios of 23 % and 4.2 %, respectively.

A photograph of the test rig showing the uncongested region with the congestion cubes in the background is given as Figure 2. Figure 3 shows a view along the side of the congested portion of the test rig.



*Figure 2.  Photograph of Test Rig (from uncongested end)*



*Figure 3.  Photograph of Test Rig (along side, looking at reflection wall)*

An ethylene concentration of 7.35 % was utilized in this test (equivalence ratio of approximately 1.1). This ethylene concentration is anticipated to yield the most reactive ethylene-air mixture.  The lower flammability limit and stoichiometric concentration of ethylene in air are 2.7 % and 6.5 %, respectively. Thomas et al. (2003) observed DDTs at ethylene concentrations ranging from 5.9 to 9.3 % with a similar test rig configuration; the Thomas et al. (2003) test rig had the same congestion pattern and cross section as the rig discussed here, but did not have an uncongested region, did not use a reflection wall, was 60 % longer and utilized center ignition.

A thin (0.001 inch, 0.025 mm) plastic tent was placed around the rig to contain the flammable mixture prior to ignition.  Ethylene was introduced into the test rig through a set of twelve venturi mixing devices

distributed along the length of the test rig to promote mixing, as illustrated in Figure 4. The venturi devices were oriented to pull air from the bottom of the rig and exhaust the gas mixture towards the top. A set of 16 small fans distributed along the length of the rig were also utilized to promote mixing. Each fan was rated at 3.1 $m^3$/min (110 $ft^3$/min) so that the combination of fans would circulate the equivalent of 60 % of the rig per minute. The fans were left on for the entirety of the test.

The fuel concentration was monitored with two separate analyzers (Liston Scientific Enviromax Model 2010 Gas Analyzer and California Analytical Model 600P Oxygen Analyzer) sampling from 8 points located along the length the rig. The combined times for a sample to reach the analyzer and for the analyzer to reach 90 % of its full reading was approximately 1 minute. The time required to reach and stabilize at the target fuel concentration was approximately 1 hour. The flammable gas mixture was ignited using an electrochemical match located along the centerline of the rig about 0.3 m in from the reflection wall and just above ground level. The plastic tent was released just before ignition.

The flame front velocity was deduced from high speed video (3000 frames per second) on the test. Blast overpressure data was not recorded during the test reported here.
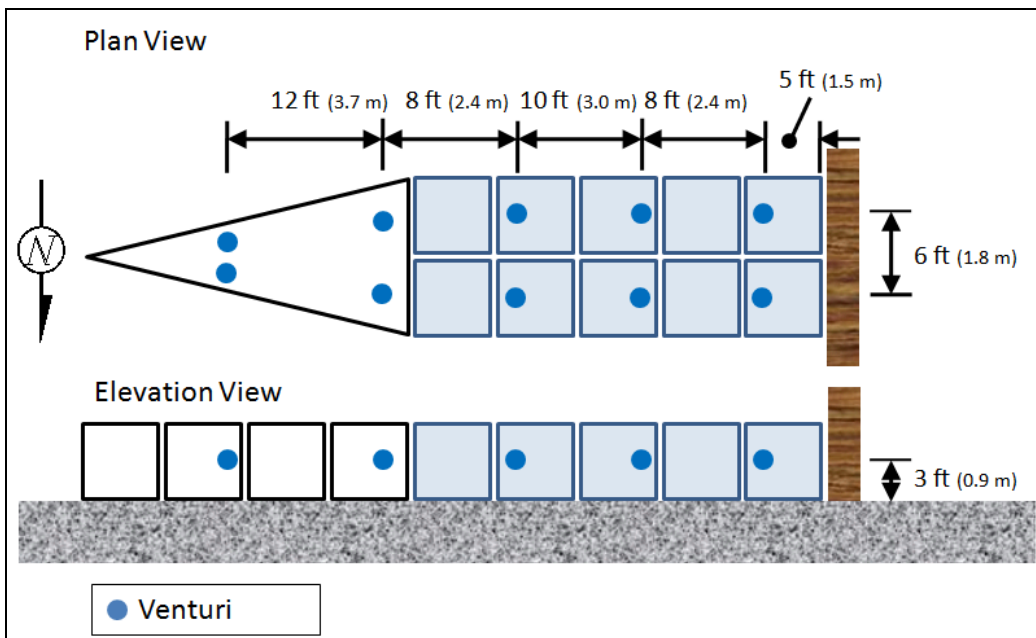


*Figure 4. Location of Fuel Injection Venturi Devices (cubes shown as blue contain congestion)*

## 4. Test Results

A DDT occurred within the congested section and the resulting detonation wave propagated into the uncongested section. Figure 5 provides a series of images from a high speed video record of the test. Ignition of the mixture is shown in Frames 1 and 2. The acceleration of the flame through the first 3 congestion cubes (3.7 m, 12 ft.) is shown in frames 4 through 5. Frame 6 captures the transition from deflagration to detonation transition (DDT), which occurs at approximately 6.1 m (20 ft.) from ignition. Frames 7 and 8 show the detonation propagating through the congested region at an average speed of approximately 1800 m/s (6,000 ft/s), which is equivalent to Mach 5.3. It is noted that the tent surface becomes illuminated ahead of the flame front. Frames 9 through 10 show the detonation continuing to propagate through the uncongested region, from 9.1 m (30 ft.) to 15.8 m (52 ft.) at an average speed of Mach 5.3.
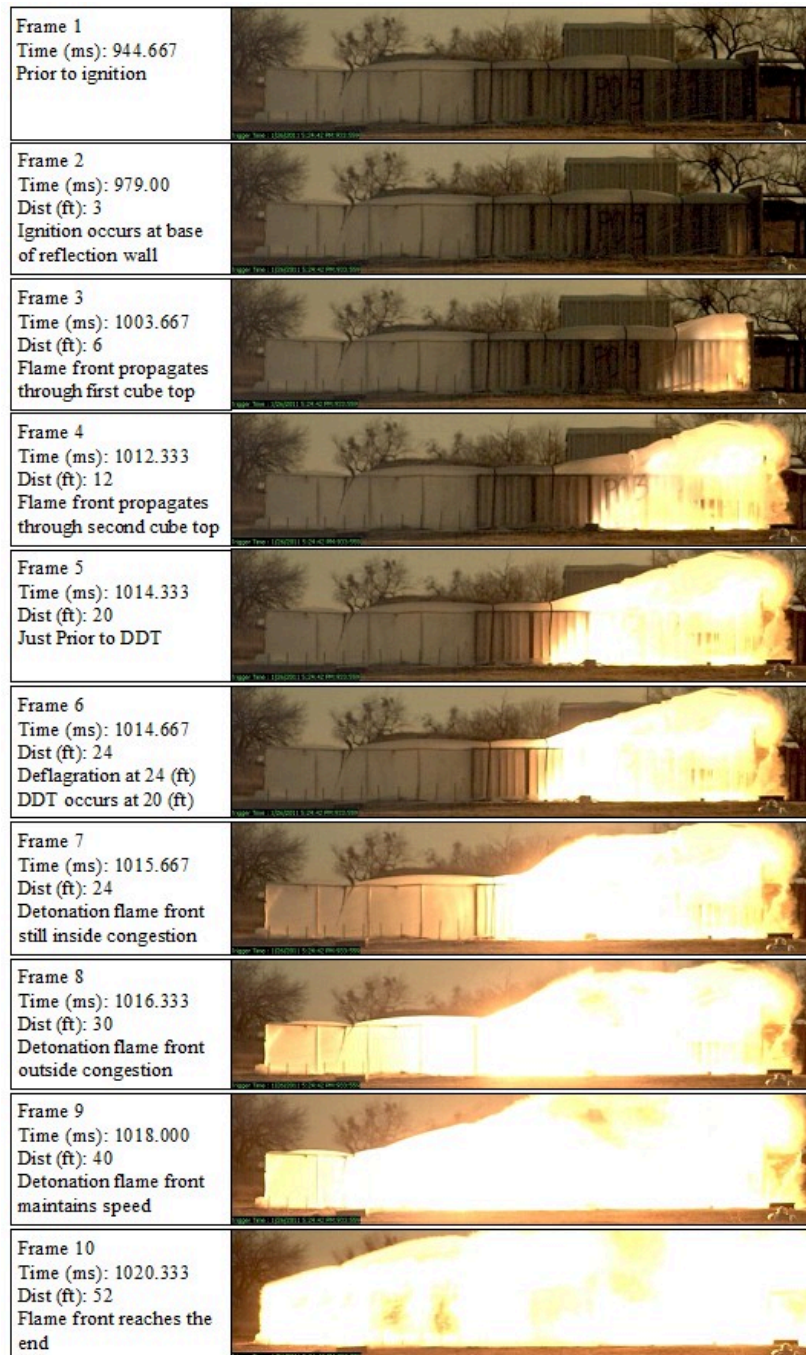
*Figure 5. Still Frames from High Speed Video Illustrating Flame Front Propagation*

## 5. Discussion

As expected, the results of this test demonstrated that a detonation wave, once formed due to a DDT within a congested region, will propagate into a flammable cloud extending into an uncongested region. This result is consistent with both the expected behavior of a detonation wave and the results of prior test programs.

Consequence and risk assessments involving high reactivity fuel VCEs should address the potential for a DDT.  If a DDT is predicted to occur for a large flammable cloud extending beyond a congested region (e.g., a process unit), then the propagation of the detonation wave into the portion of the cloud beyond the congested region should be accounted for.  Including the portion of the flammable cloud which is in the open will increase the explosion energy and may reduce the standoff distance to a target of interest (e.g., a building).  Neglecting the portion of the flammable cloud outside the congested region can result in an under-prediction of the resulting blast load.

**Acknowledgements**

**References**

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