AN EXPERIMENTAL STUDY OF UNCONFINED HYDROGEN / OXYGEN AND HYDROGEN /AIR EXPLOSIONS

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ABSTRACT

Development tests are being conducted to characterize unconfined Hydrogen/air and Hydrogen/Oxygen blast characteristics. Most of the existing experiments for these types of explosions address contained explosions, like shock tubes. Therefore, the Hydrogen Unconfined Combustion Test Apparatus (HUCTA) has been developed as a gaseous combustion test device for determining the relationship between overpressure, impulse, and flame speed at various mixture ratios for unconfined reactions of hydrogen/oxygen and hydrogen/air. The system consists of a central platform plumbed to inject and mix component gasses into an attached translucent bag or balloon while monitoring hydrogen concentration. All tests are ignited with a spark with plans to introduce higher energy ignition sources in the future. Surrounding the platform are 9 blast pressure “Pencil” probes. Two high-speed cameras are used to observe flame speed within the combustion zone. The entire system is raised ~6 feet off the ground to remove any ground reflection from the measurements. As of this writing greater than 175 tests have been performed and include Design of Experiments test sets. Many of these early tests have used bags or balloons between ~340L and ~1850L to quantify the effect of gaseous mixture ratio on the properties of interest. All data acquisition is synchronized between the high-speed cameras, the probes, and the ignition system to observe flame and shock propagation. Successful attempts have been made to couple the pressure profile with the progress of the flame front within the combustion zone by placing a probe within the bag. Overpressure and impulse data obtained from these tests are used to anchor engineering analysis tools, CFD models and in the development of blast and fragment acceleration models.

INTRODUCTION

Hydrogen’s high combustion energy per unit mass makes it an attractive and therefore commonly used liquid propellant (LP) in the space industry. The tradeoff for having any high specific energy fuel is the danger associated with its accidental release and ignition, potentially creating a blast wave that is a risk to crew, cargo, ground personnel, pad structure, and the public. The blast potential of a LP system is historically calculated using a TNT equivalence method based on the total mass of propellants in the system [1]. This method generates an approximation of the overpressure and impulse and does not accurately capture the physics of LP explosions or account for the differences in LP explosions. High explosives are point-source supersonic combustion events (detonations) which produce very high pressures in the near field, whereas LP explosions are large volumes of gas with subsonic combustion (deflagrations) [2–3]. Data from 13 launch vehicle accidents and 2 full scale tests is shown in Figure 1 along with the TNT equivalence model used by NASA during Project Constellation to predict the explosive potential of Ares I [3–14]. The TNT model over predicts the blast wave by a significant margin over the entire range. Of particular interest to crew safety are the overpressures at 100 ft, the approximate distance a crew capsule sits relative to a first stage explosion; the TNT model predicts an overpressure which may not be survivable but all empirical data indicates a survivable overpressure around 10 psi. Note that the accident and experimental data has not been corrected for ground reflection or any sensor alignment issues so measured overpressures are likely artificially elevated due to these effects.

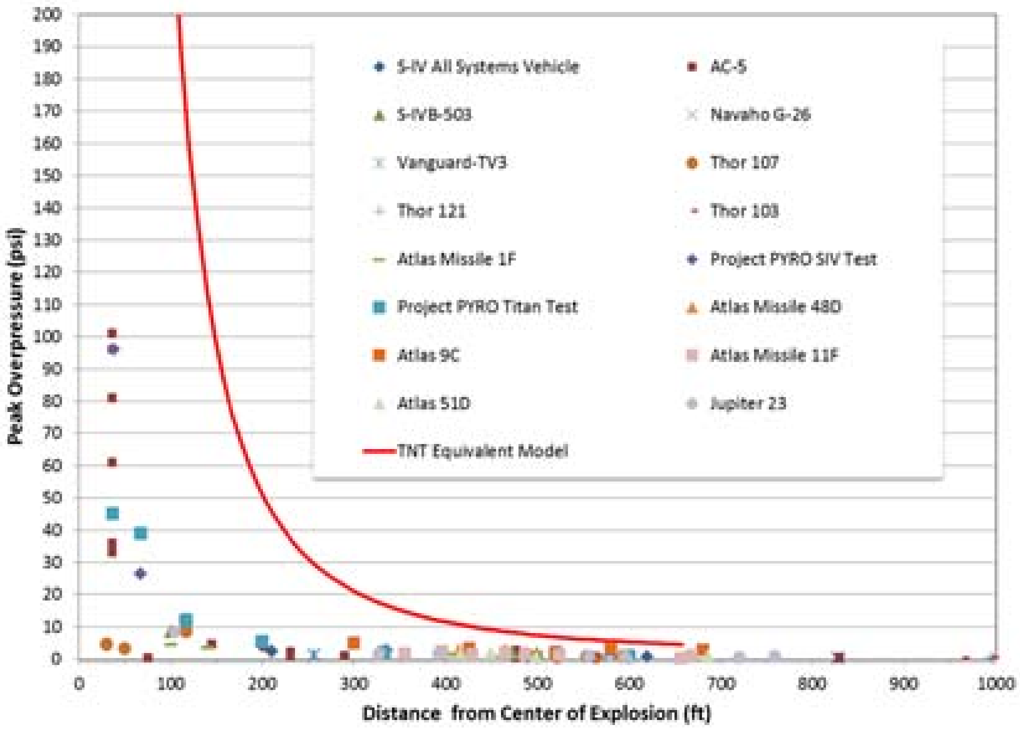

Figure 1: Measured Overpressure from Launch Vehicle Explosions and Full Scale Tests

Unfortunately, data for well-defined reaction volumes of H_2/air and H_2/O_2 unconfined explosions is scarce, and the actual reacting volumes in the previously discussed data cannot be known. A literature review turned up a handful of unconfined H_2/air explosion experiments performed in Japan and Germany [15–18]. Sizes ranged from 9.4 m^3 to 2094 m^3 with both spark and high explosive ignition sources. Additionally, several large scale test programs have been conducted with liquid H_2/O_2 propellant mixtures such as projects HOVI, LSHOE, and PYRO; however none of these test programs were able to quantify the actual amount of propellant which participated in the resulting explosion [1, 2, 19–21]. In many cases, two systems with identical amounts of propellant would produce significantly different results under the same test conditions For example; the HOVI 9 and HOVI 10 tests each had nearly identical amounts of propellant and similar test configurations, but HOVI 9 produced peak overpressure on the order of 300 psi while HOVI 10 produced peak overpressures of less than 10 psi.

The HUCTA system has been developed to quantify the peak impulse/overpressure, rate of impulse/overpressure decay, and the flame speed associated with unconfined gaseous explosions from well-defined volumes H_2/O_2 and H_2/Air as a function of mixture ratio. Nearly 200 tests have been performed at small volumes ranging from ~340 Liters to ~1850 Liters utilizing a spark igniter.

RESULTS AND DISCUSSION

EXPERIMENTAL SETUP

Explosive tests were performed with Oxygen mixed with Hydrogen at concentrations between 25% and 85% hydrogen by volume and varied in 5% increments. Some additional experiments were performed near stoichiometric H_2/Air mixtures, 29.7% Hydrogen by volume. Hydrogen and Oxygen were introduced from compressed gas cylinders into a translucent plastic bag (approximately 1 mil thick and ~340 L) or a 5 ft diameter clear latex balloon (~1840 L). Experiments with air did not use additional Oxygen from a compressed gas cylinder; instead the air was pumped into the bag from the surrounding atmosphere. In each system an explosion proof pump was used to recirculate the mixture and a hydrogen sensor was used to continuously monitor the hydrogen concentration. Early testing with multiple hydrogen sensors located throughout the bag indicated that the mixture became homogenous in less than 30 seconds after ceasing to inject new gas. Additionally, with the pump turned off, the gas stayed well mixed for at least 30 minutes, significantly longer than the usual waiting period to fire. The mixtures were ignited in approximately the center of the bag with an electric spark igniter from a commercial gas grill. Two high speed cameras were positioned ~20 ft from the Center of Explosion(COE) to capture the flame propagation within the bag. A diagram of the HUCTA system can be seen in Figure 2.

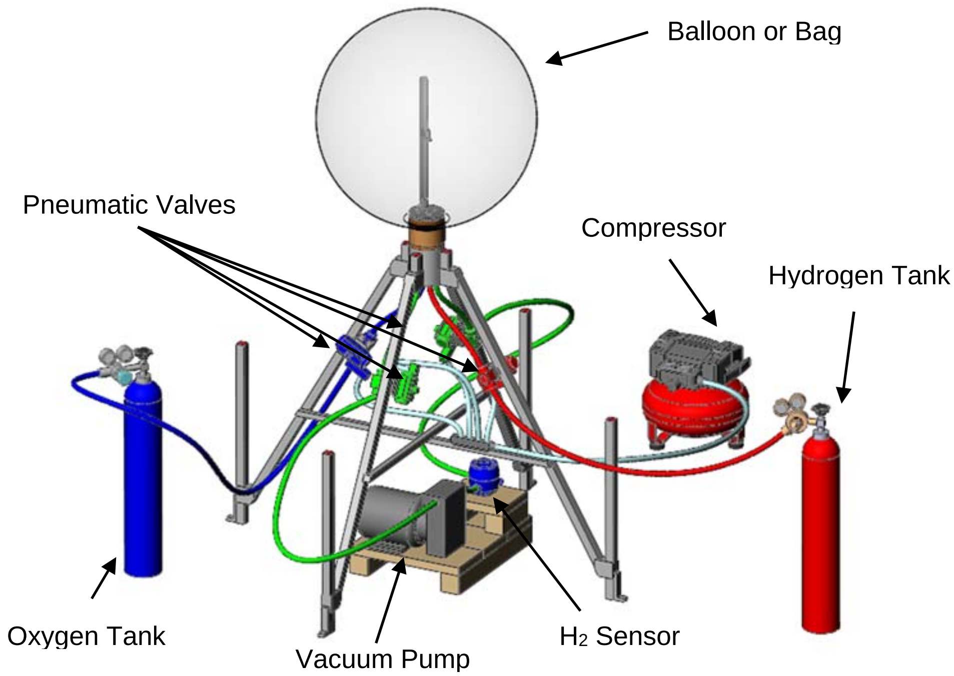

Figure 2: HUCTA System

Blast wave pressure was measured using PCB Piezotronics Quartz ICP Blast Pressure Pencil Probes, 137B23B, capable of measuring between 0 and 50 psi incident overpressure. Output signals from the sensors were converted to a voltage output by a PCB Piezotronics Signal Conditioner, 483C05, and passed to the National Instruments 9222 Digitizer operating at 100 kHz per channel. Sensors were typically arranged on three lines radially outward from the COE at 120° apart. For most experiments the first set of sensors was placed as close as possible to the COE, between 30 – 60 inches away, the second set between 80 – 120 inches, and the final set between 120 – 200 inches (Figure 3) depending on balloon geometry and test objectives. The sensors were most often placed at the same height as the ignition system at approximately 6 ft from the ground. Placement of the sensors and igniter well above the ground prevented any blast waves reflected from the ground from affecting the initial blast wave within the area of measurement. Placing the sensors well above the shock reflection was based on lessons learned from data analyzed in other test programs. Project PYRO, for example, had sensors mounted on metal plates just a few inches above the ground and placed perpendicular to the flow. The perpendicular metal plates caused a shock reflection that, at a minimum, doubled the observed overpressure. Additionally, it is very likely that the sensors were experiencing another reflection due to their proximity to the ground, again multiplying the observed overpressure. At the time of the experiment, these effects were unknown and the data was not corrected for these reflections, resulting in extremely high apparent overpressures, some greater than 5000 psi. In the LSHOE and HOVI experiments, these effects were known and well understood therefore the sensors were placed parallel to the blast wave in concrete pads on the ground, ensuring that each sensor would be parallel to the passing wave. High speed video was used to determine the height of burst and back out a correction factor for the ground reflection at each sensor. The raised sensor stands used with HUCTA avoid the need for a correction factor by placing the sensor out of the ground reflection long enough for the primary wave to reach the sensor first.

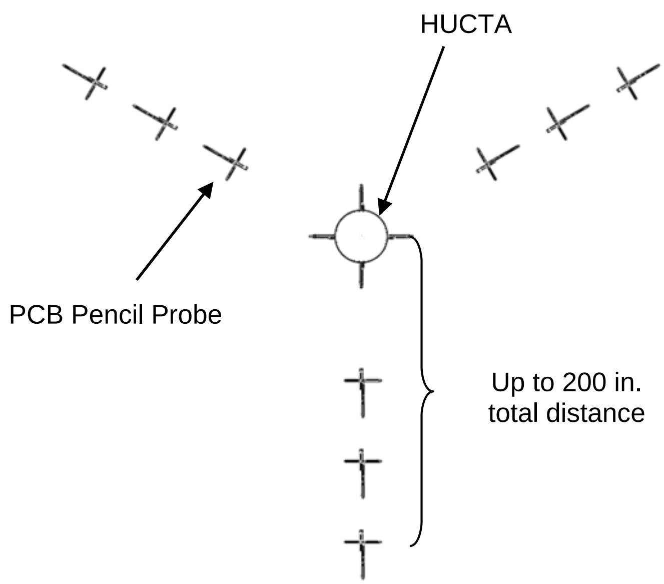

Figure 3: HUCTA with Sensor Configuration

Explosion phenomena were recorded with two Photron SA1.1 cameras operating at 10,000 or 20,000 frames per second. For best results an infrared cut filter (IR-695) was added to the camera which removed the bright burning associated with the ignition wires that washed out the light from the hydrogen flame. The cameras were triggered off the same firing command and used a TTL output trigger signal to synchronize camera frames with overpressure data. The entire system initiated recording upon reception of the fire command.

EXPERIMENTAL RESULTS

H_2/O_2 explosions between 30% and 80% Hydrogen by volume were visible on high speed video. At 10,000 fps about 6 – 8 frames were captured with the 340L small bag before the camera optics were overwhelmed by the explosion (Figure 4). Approximately 15 frames were captured on the 1840L latex balloon, Figure 5 shows 6 of 15 representative frames of flame propagation from initial spark thru to contact with the balloon. As the combustion front propagated outwards bright emissions appeared ahead of the front; this appears to be the ignition of the foreign material within the combustion zone such as tape, wire insulation, and sealants as a result of radiation from the oncoming fireball. This did create a small amount of localized flame acceleration but did not result in any measurable difference in the overpressure and impulse decay. H_2/Air explosions could not be visualized with the high speed camera, even when at stoichiometric mixture ratio.

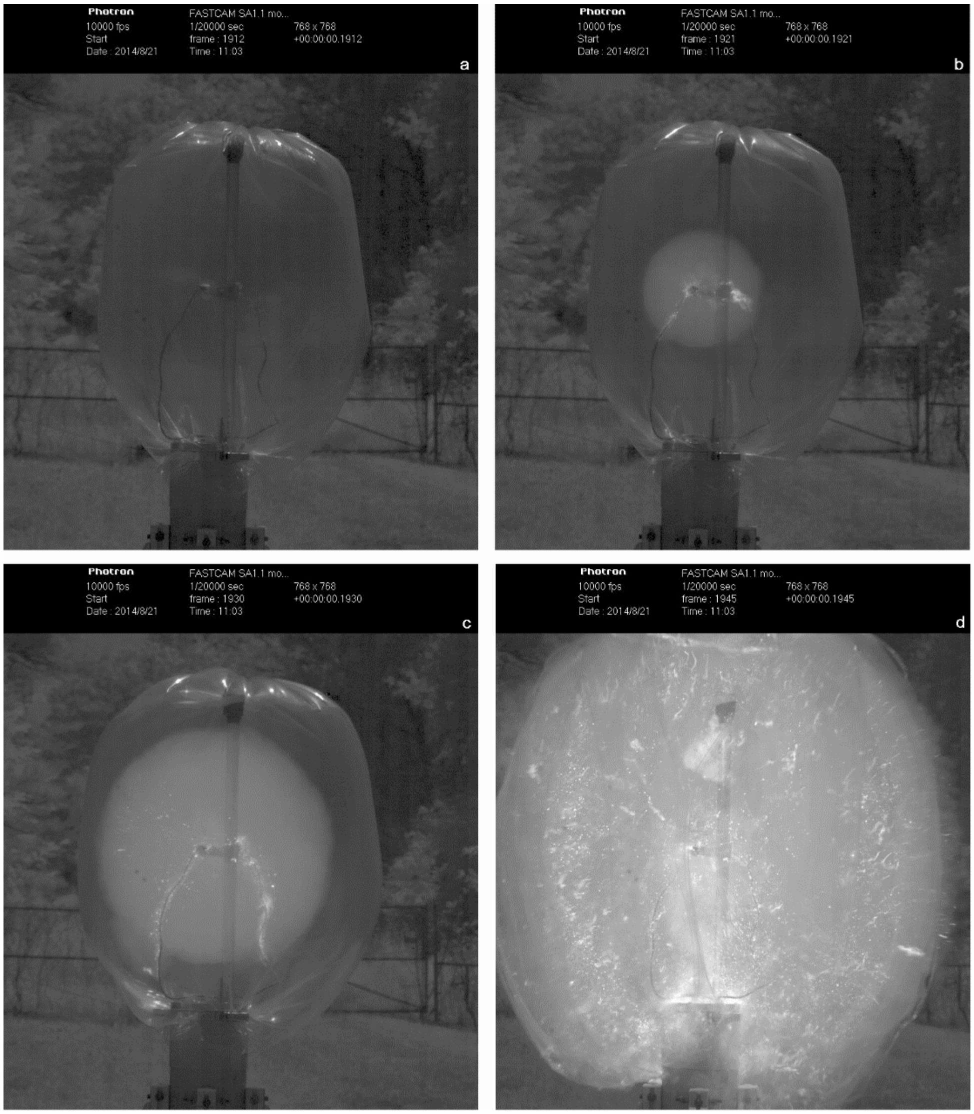

Figure 4: Typical results of high speed video for small bag combustion at 67.5% hydrogen by volume (a) t = 0, (b) t = 9ms, (c) t = 18 ms, (d) t = 33 ms after ignition by spark.

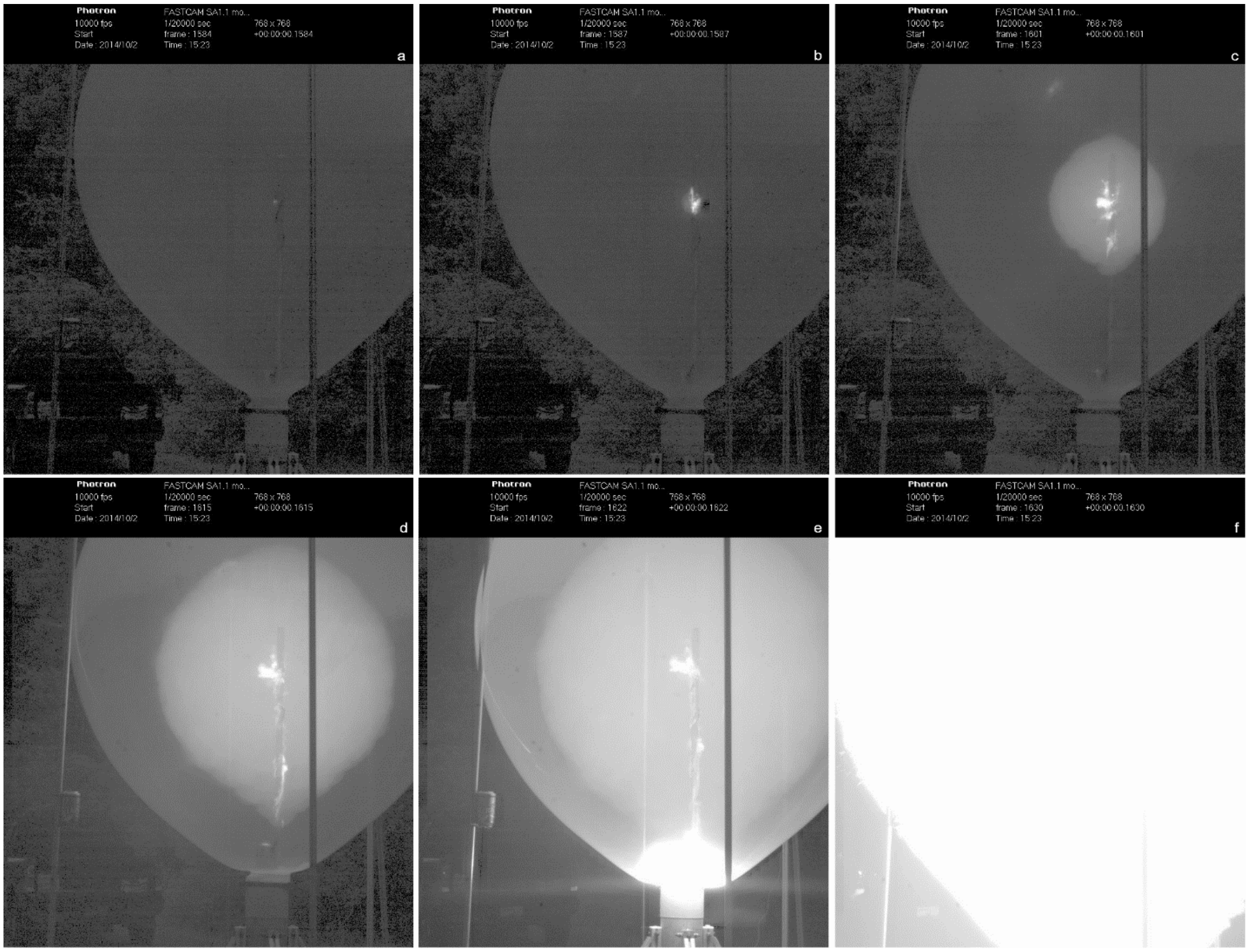

Figure 5: Typical results of high speed video for balloon combustion at 64% hydrogen by volume (a) t = 0, (b) t = 3ms, (c) t = 17 ms, (d) t = 31 ms, (e) t = 38 ms, (f) t = 46 ms after ignition by spark.

For the small bag combustion velocity varied as a function of mixture ratio (Figure 6). The flame front was not visible on tests below 30% and above 80% Hydrogen. Balloon test data is currently limited to only stoichiometric mixture ratios; combustion velocity is approximately the same as the stoichiometric small bag tests, an average of 375 ft/s. Currently, no flame acceleration has been observed due to the increased combustion distance available in the balloon however this does not rule out flame acceleration with further increases in combustion zone length. The additional width of the balloon produced more measurement points as plotted in Figure 7. This increased certainty on the flame propagation velocity. No bag or balloon has produced a combustion wave which exceeds the speed of sound in the mixture and this indicates that only deflagrations have been produced with the existing ignition system.

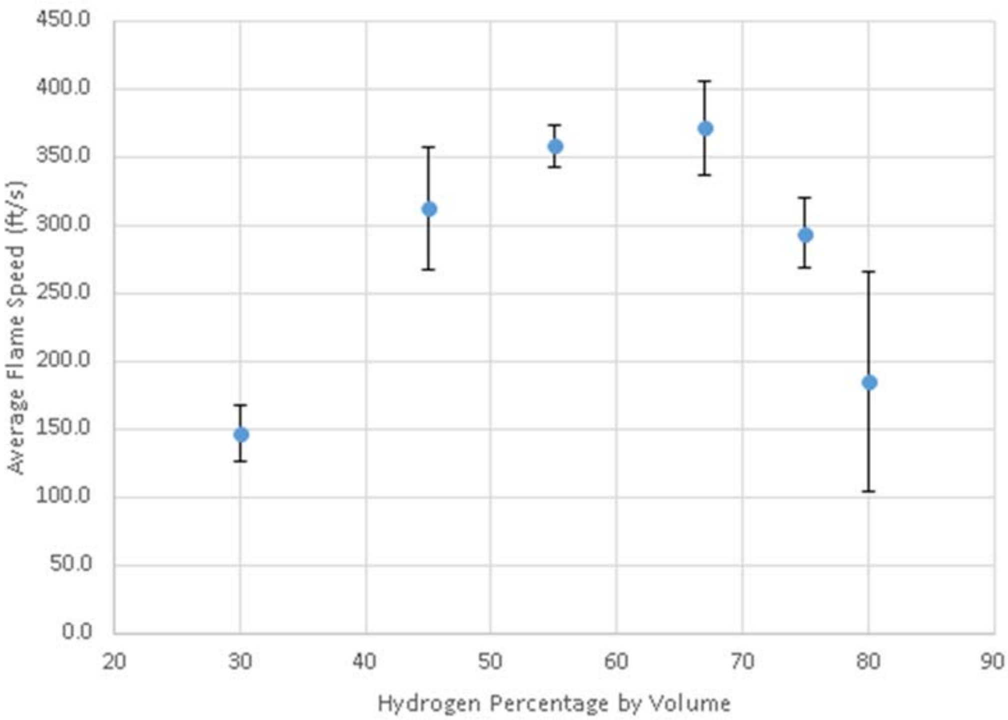

Figure 6: Small Bag Flame Average Flame Speed vs. Hydrogen Concentration

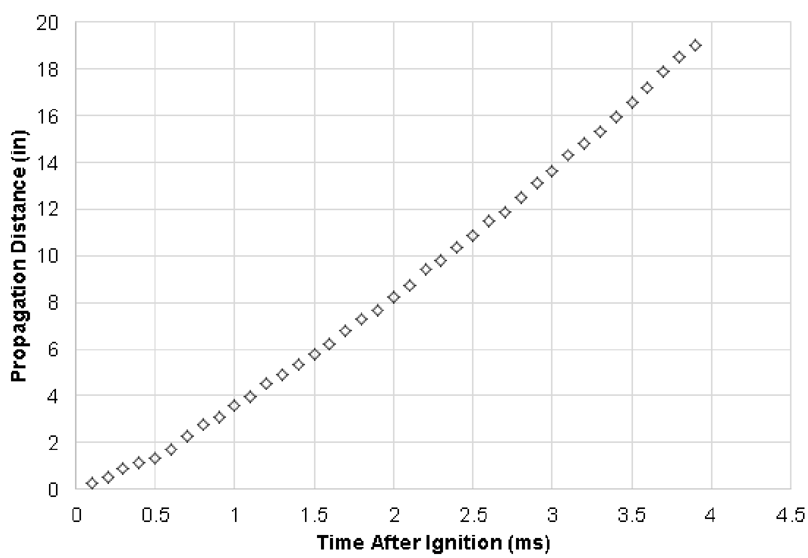

Figure 7: Large Balloon Flame Propagation vs. Time for Stoichiometric H_2/O_2

Figure 8 and Figure 9 show blast wave histories from 3 sensors for the small bags near stoichiometric concentrations of H_2/O_2 and H_2/Air with the sensors located at identical distances from the COE in each test; 46 inches, 110 inches and 202 inches. Time zero is the initiation trigger signal for the igniter and camera, gas ignition could take place as much as 150 milliseconds after the output signal due to igniter charging time. The H_2/O_2 mixtures exhibited a slow initial pressure rise which transitioned to a discontinuity consistent with the formation of a shockwave outside the bag starting in the first sensor and becoming more pronounced, although of lower magnitude, through the second and third sensor. This discontinuity was observed in H_2/O_2 concentrations between 60% and 75% H_2 by volume although the peak overpressure was declined and the discontinuity took longer to fully develop as concentration diverged from stoichiometric. The H_2/Air mixtures were very low magnitude and displayed no discontinuities. Off stoichiometric mixture ratios were difficult to detect with H_2/Air due to the resulting very low overpressure and therefore high signal-to-noise ratio. Additionally, the slow burn rate combined with wind gusts would sometimes blow hot gasses over the closest sensors. The crystal in the pencil probe will experience a voltage drop as it expands due to the applied heat load, resulting in the appearance of a steep negative transient as seen in Figure 9.

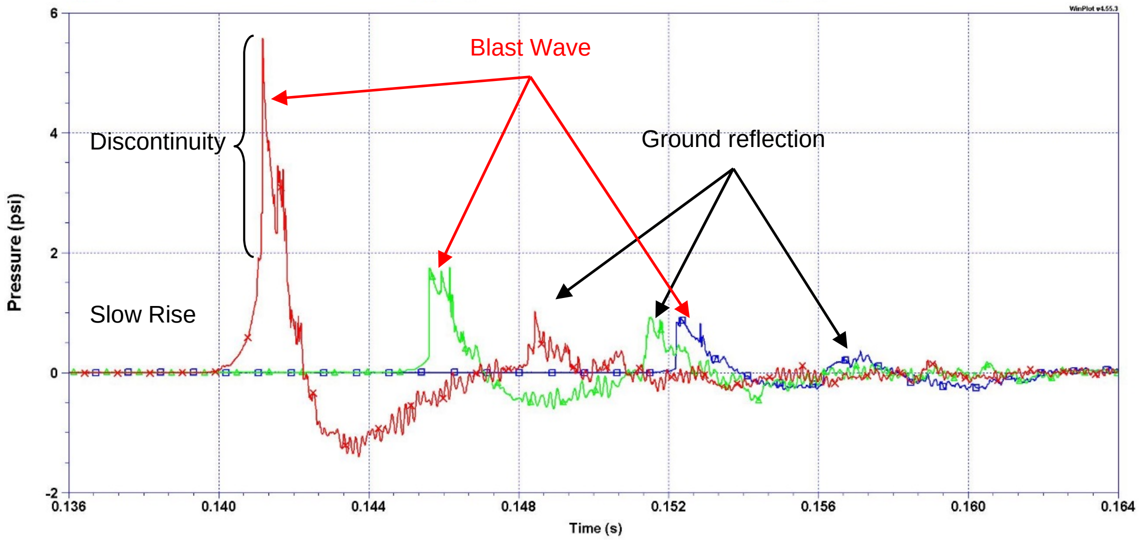

Figure 8: HUCTA 101, Bag at 65.4% H_2 by Volume with O_2

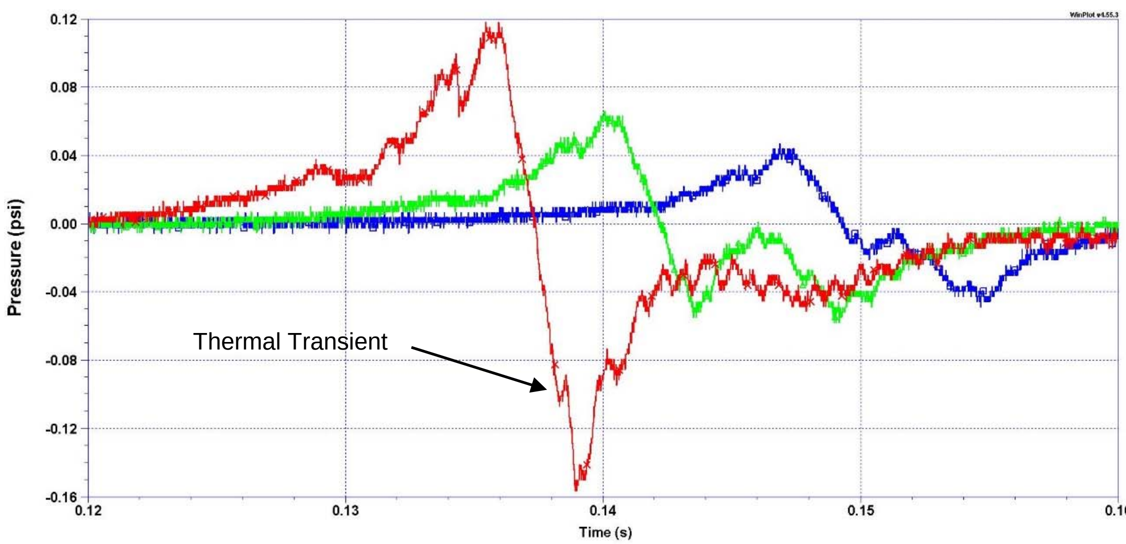

Figure 9: HUCTA 125, Bag at 30.1% H_2 by Volume with Air

The latex balloon experiments near stoichiometric H_2/O_2 concentration indicated similar behavior to the small bag experiment although at a significantly higher overpressure; the sensors closest within 4 ft of the COE observe a slow increase in pressure, transition to a discontinuity, and then a quick decay to a negative pressure. The slow pressure rise was almost entirely dissipated in sensors further out as the discontinuity was propagating faster than the slow initial pressure rise. In the smaller bags the slow pressure rise was observable until the final sensor as far out as 200 in. Another phenomenon was observed in all the experiments to date with the latex balloon, a second higher peak shock was observed at the closest sensor about ½ ms after the first shock, the cause of this second peak is uncertain at this time. Figure 10 illustrates the blast wave history from a 5 ft latex balloon at stoichiometric H_2/O_2 mixture ratio; sensors are located at 51, 100.5, and 172.5 inches from the COE.

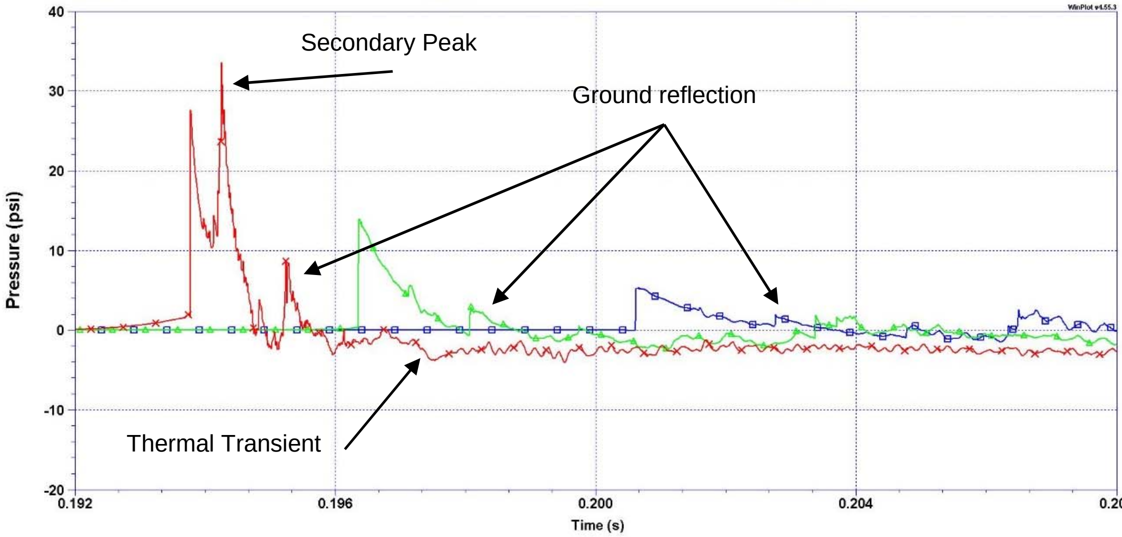

Figure 10: HUCTA 177, Balloon at 67% H_2 by Volume with O_2

Two tests have been conducted with a sensor inside the combustion zone located 7 inches from the COE to observe the correlation of the combustion wave and the overpressure. A row of sensors external to the bag started as close as possible to the bag at 27.25 inches, 50.75 inches, and 77 inches. Although the bag was near stoichiometric, clear discontinuities are not visible within the resulting data (Figure 11). Geometry issues prevented additional sensors from being utilized inside the combustion zone. Figure 12 through Figure 14 show the rise in pressure which occurs as the combustion wave is approaching the sensing element, peaking well after the combustion wave has moved past the probe and is beginning to interact with the bag.

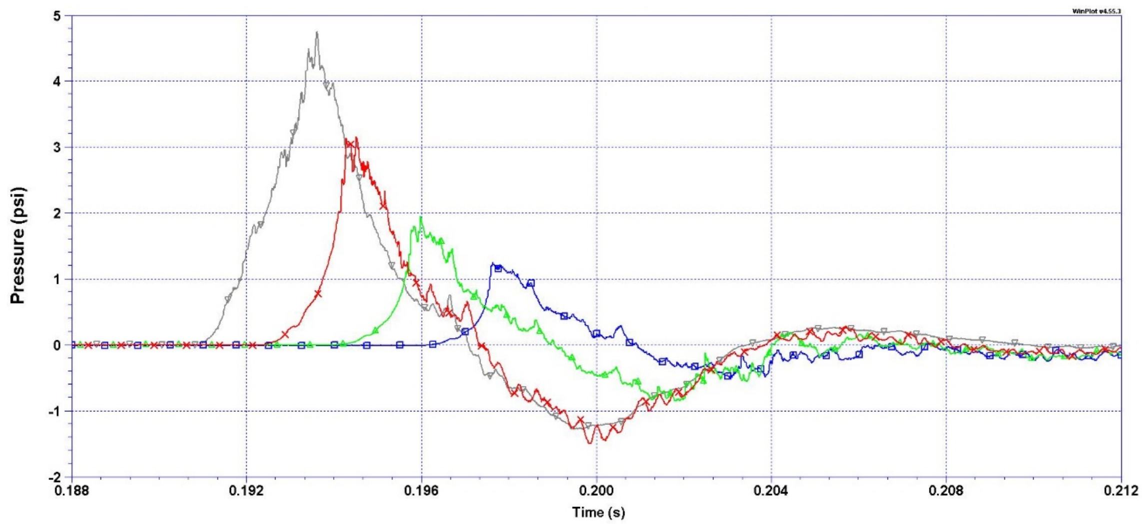

Figure 11: HUCTA 133, Bag at 68.6% H_2 by Volume with O_2 and Internal Sensor

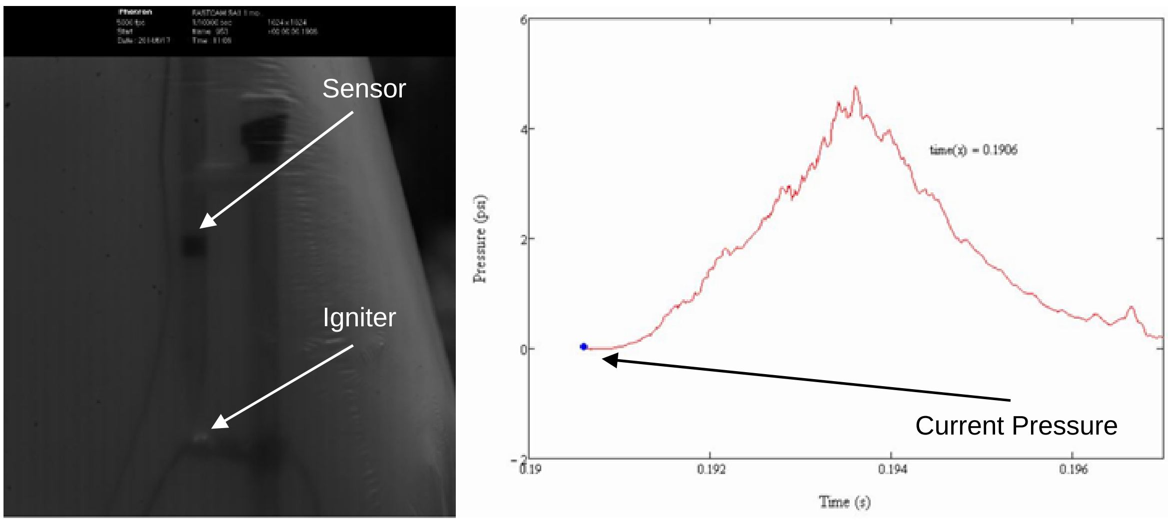

Figure 12: HUCTA 133, Bag at 68.6% H_2 by Volume with O_2 and Internal Sensor, t = .1906s

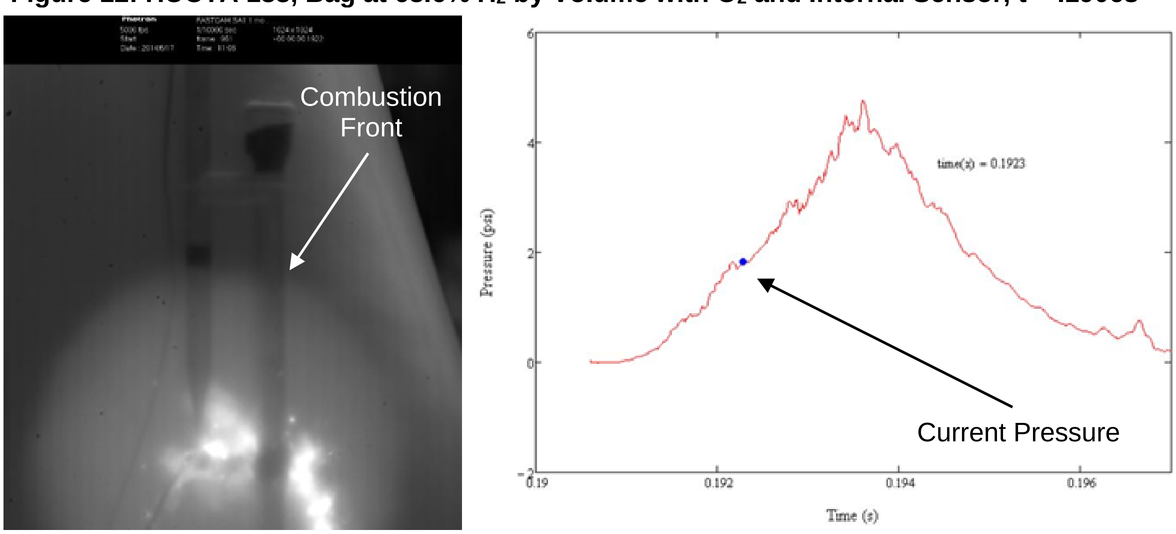

Figure 13: HUCTA , Bag at 68.6% H_2 by Volume with O_2 and Internal Sensor, t = .1923s

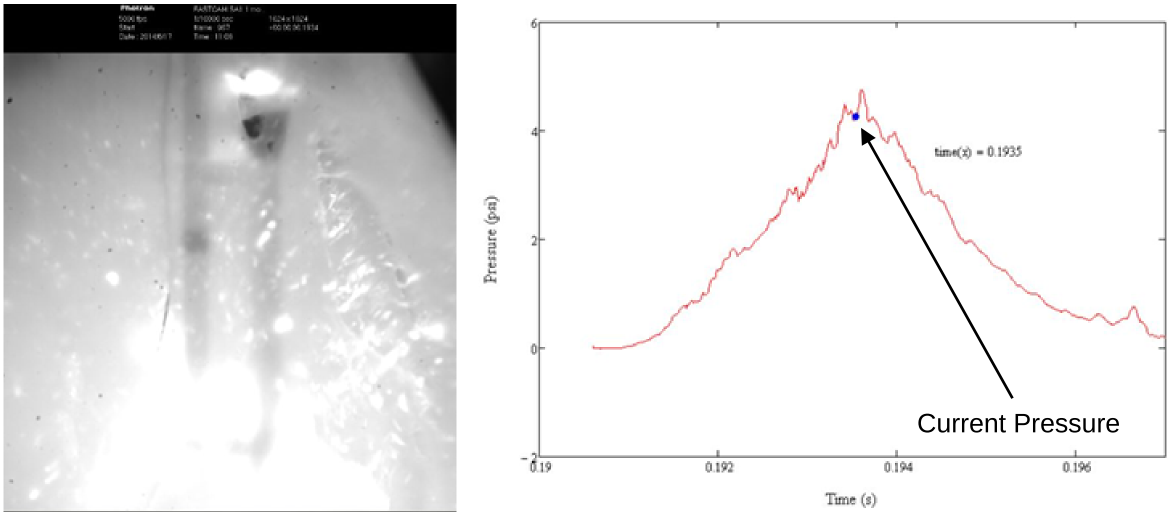

Figure 14: HUCTA 133, Bag at 68.6% H_2 by Volume with O_2 and Internal Sensor, t = 0.1935s

Peak overpressures often show some variation along each radial line, typically showing higher peaks along one row of sensors such as 1, 2, and 3 in Figure 15. At first glance this implies that the explosion is not uniform, suggesting the energy is directed preferentially in one direction. However, the high peaks that indicate these results are low impulse, possibly a result of interaction with the test apparatus, interaction with the bag, or reflections off the apparatus/sensor. Looking at the equivalent impulse curve for the same data shows that very little energy is contained within those peaks (Figure 16). This illustrates the importance of measuring not only peak overpressure but also the entire pressure/time wave to obtain an accurate impulse.

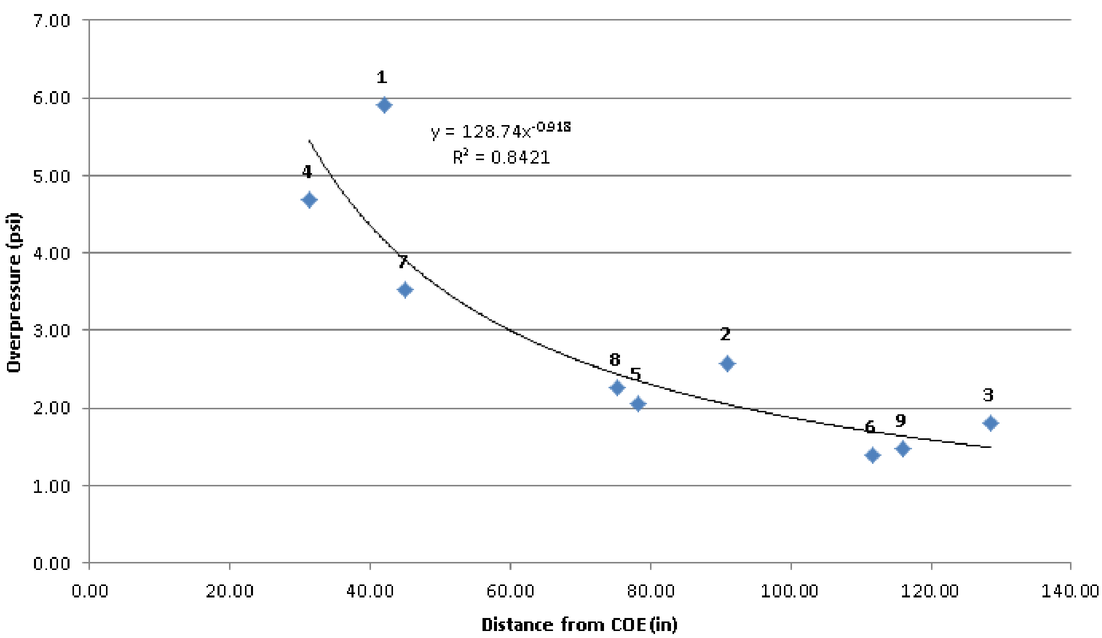

Figure 15: HUCTA 50, Bag at 60.8% H_2 by volume with O_2, Peak Overpressure vs. Radial Distance from COE

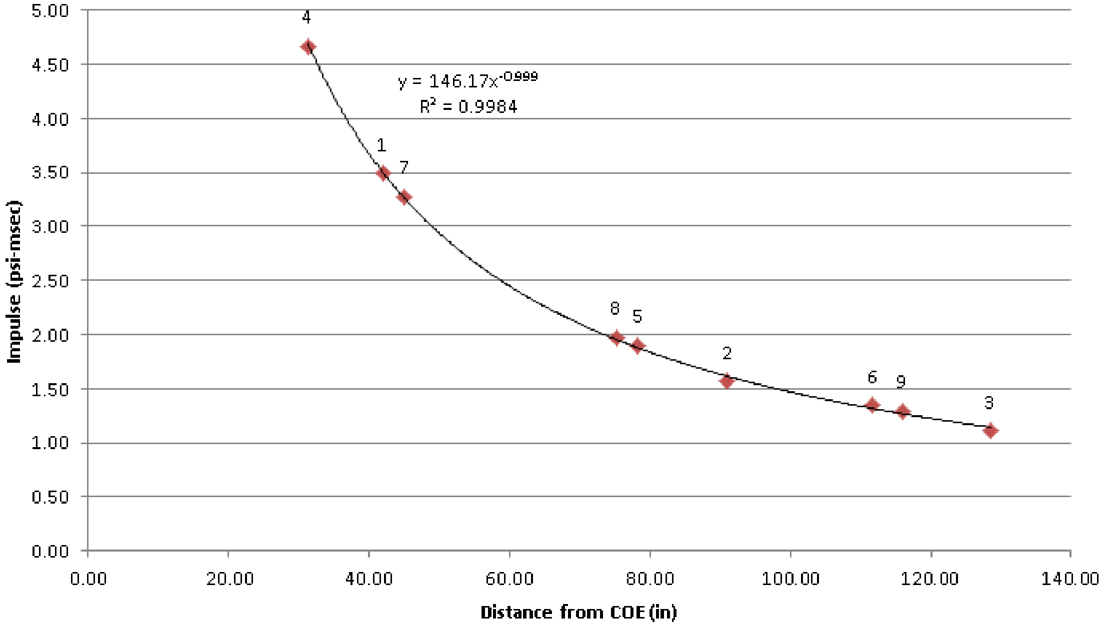

Figure 16: HUCTA 50, Bag at 60.8% H_2 by volume with O_2, Impulse vs. Radial Distance from COE

A series of tests was performed using the small bag to determine the change in peak overpressure and impulse as a function of mixture ratio between 25% and 85% hydrogen by volume. Usually 3 tests were performed at each interval, although only a single test was performed at 25% and at 85% due to the low magnitude of impulse and overpressure. Figure 17 and Figure 18 illustrate the results of these experiments. As expected there is an increase overpressure as hydrogen concentration is increased to a peak at stoichiometric followed by a steep decline in the fuel rich region. Variations from the extraneous peaks found in the individual sensors increased measurement uncertainty for the overpressure, as before this effect was smoothed out when observing the impulse component. The high signal-to-noise ratio prevented an accurate determination for impulse at concentrations of 25% and 85% and these are not included in Figure 18.

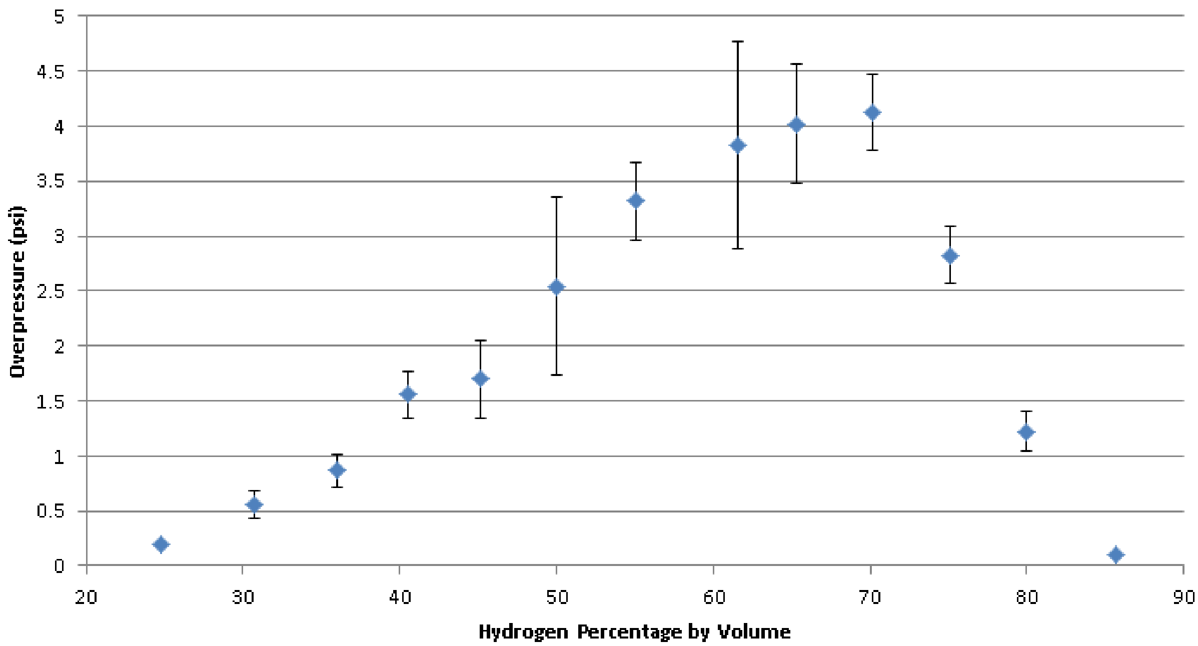

Figure 17: Average Overpressure vs. Concentration for small bags of H_2/O_2 at 42" from the Center of Explosion

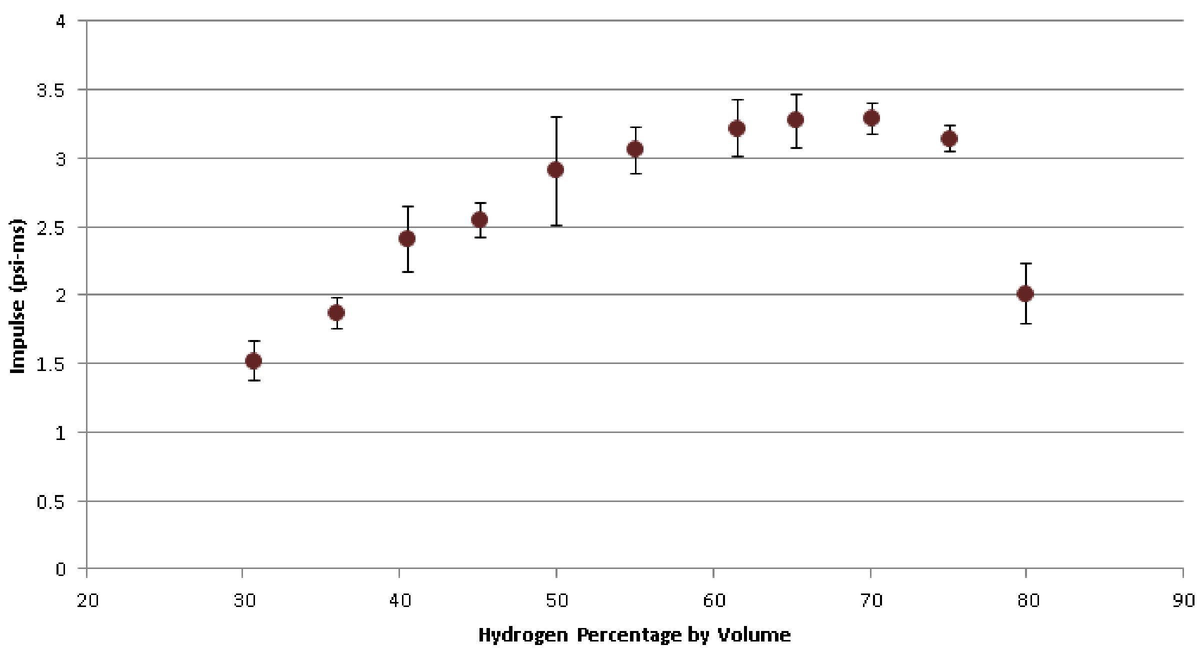

Figure 18: Average Impulse vs. Concentration for small bags of H_2/O_2 at 42" from the Center of Explosion

SUMMARY AND CONCLUSIONS

To date 178 tests have been conducted with HUCTA. Overpressure data and high speed video have shown the relationship between overpressure, flame speed, and impulse at various mixture ratios of hydrogen and oxygen. As of this writing, no mixture showed any evidence of detonating. All flame speeds showed slower-than-sound velocities and have been therefore classified as deflagrations. This data is further supported by a small number of tests performed with sensors within the combustion zone showing the initial pressure wave preceding the slower-than-sound combustion wave followed by the peak pressure well after the combustion wave has moved past the sensor.

FUTURE WORK

The data collected within the combustion zone is limited to a single point taken during only two tests. Currently an apparatus is being developed to introduce an array of sensors within a large balloon which can be position horizontally once the balloon is inflated. This series of sensors will allow for a more accurate accounting of the development of the combustion wave and it’s coupling to the pressure wave in a deflagration. This would also lead to an understanding of the relationship of the peak combustion zone overpressures to the overpressure and impulse decay rates.

As of this writing only deflagrations have been produced in the test system. The introduction of a high explosive initiator should drive a supersonic combustion and provide the ability to make direct comparisons between gaseous detonations and high explosive detonations.

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