Results from Gaseous Methane/Oxygen Mixture Testing

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Liquefied natural gas (LNG) and liquid oxygen (LO_2) propulsion for launch vehicles is gaining significance in recent years. The safety standards are well-defined for LH_2/LO_2 and RP-1/LO_2 fuel-oxidizer mixtures. However similar standards are yet to be established for LNG/LO_2 mixtures. The present test program is split into three incremental blast test plans for experimental determination of the LNG/LO_2 explosive behavior. The first test phase presented in this paper involves methane-oxygen gas blast tests. Vinyl balloon of sizes 6-ft., 12-ft., 14.5-ft. and 16-ft. diameters respectively, were inflated with the gas mixture and a combustion was triggered to simulate an unconfined methane-oxygen explosion. A deflagration to detonation transition (DDT) of the combustion zone was observed in most of the tests. The primary data that was analyzed to develop empirical models were: (a)Overpressure, (b)Impulse, and (c)Acoustic data. The recorded overpressure and impulse were compared to the TNT based predictions. The initial results showed that the TNT-based overpressures over-predict the near field data when compared to the experimental data. The empirical model for impulse predicted a combined effect of a decay with scaled distance and an increase with the fuel mass. The caveat to the gas experiment based conclusion is that the test series does not exactly replicate credible accident scenarios for a vapor cloud explosion from a cryogenic fuel/oxidizer failure. However, it is believed that the gas explosions will envelope the overpressures from cryogenic propellant blasts. An attempt to characterize the decay of overpressures in the acoustic regime is made since the long-range acoustics from blast events have serious community noise and safety implications. The follow-up test series with LNG/LO_2 mixtures will a more realistic evaluation of the overpressures from a safety standpoint in the design of launch systems.

I. Nomenclature

OP	=	Overpressure (psi)
p_0	=	ambient pressure (14.7 psi)
r	=	range from the center of blast (test data at 10, 20, 30 and 50 ft.)
r_0	=	radius of the balloon (test data for 3, 6, 7.25 and 8 ft. radius balloons)
LNG	=	Liquefied Natural Gas
LO_2	=	Liquid Oxygen
LH_2	=	Liquid Hydrogen
COE	=	Center of Explosion
DoD	=	Department of Defense
RP	=	Rocket Propellent

II. Introduction

The design of launch vehicle systems requires the interpretation of safety standards set for the fuel/oxidizer propellant mixtures. This is widely adopted from the equivalent mass of trinitroluene (TNT) based methods [1]. DoD explosive standards state the energetic liquid equivalent mass of TNT to be used for RP-1/LO_2 and LH_2/LO_2 fuel-oxidizer mixtures [2]. The TNT based empirical graphs and models for overpressures versus scaled distance (range/charge weight$^{1/3}$) can then be used to find the safety distances for equipment and personnel at launch sites. However, there is scarce information on quantity-distance criteria for LNG/LO_2 propellants. The primary goal of the test program undertaken by BEi is to establish the quantity-distance relationship for LNG/LO_2 propellant mixtures. An attempt to determine the equivalent weight of TNT for these mixtures will be made.

The TNT based approach has been found to be flawed when dealing with volumetric vapor cloud explosion (VCE). The TNT empirical data is based on high energetic point source explosions and ignores aspects like confinement shape, congestion level and fuel reactivity that are associated with a VCE [3, 4]. The first phase of the test program presented in this paper, experimentally simulates the methane-oxygen volumetric gas explosions and records the overpressure from the ensuing shock waves. The gas testing helps to distinguish the impact of mixture ratio, volume of the mixing propellants, obstructions etc. on the measurements. These results are compared with the TNT based data. The results show close match between the TNT based prediction and the experimental data for overpressures at far-field distances. However, the near field results from the experiment are lower than the TNT predictions, and the discrepancy increases with increasing gas cloud size in the balloons.

The second test plan that will follow involves cryogenic liquid propellant blasts to determine ignition probability and overpressures. These results will be closer to realistically characterizing the quantity-distance criteria for LNG/LO_2 propellants.

III. Test Setup

Figure 1. (left) Central balloon tower with pressure probes installed on poles (right) CAD snapshot of central test stand with 16-foot diameter balloon

The field blast tests were performed by inflating balloons with methane-oxygen mixtures on a twenty foot tall steel structure as shown in Figure 1. This setup helped avoid any ground reflections in the overpressure data recorded from the ensuing gas blasts. This test plan will be referenced as

MUCTA (Methane-Oxygen Unconfined Combustion/Explosion Test Apparatus) throughout the paper for the methane-oxygen unconfined combustion/explosions gas tests.

A. Instrumentation

Piezoelectronic ICP blast pressure pencil probes were installed on wooden telephone poles in three legs, each 120-degree apart around the tower, with four rows of probes at 10, 20, 30 and 50 feet radial distance from the center, respectively, as shown in Figure 2.

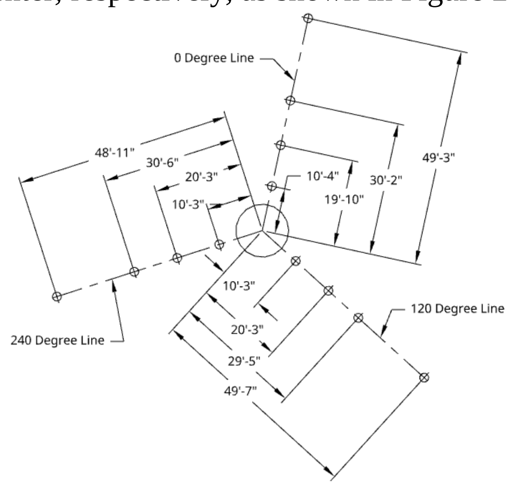


Figure 2. Schematic of MUCTA probe layout

Two high-speed video cameras, the Photron AX200 and Phantom v2512, captured the combustion zone and overall blast zone, respectively. A deflagration to detonation (DDT) transition was detected in the combustion zone inside the balloons. Long distance acoustic sensors were placed in the field. The pressure transducer and one microphone were located 861 feet from the tower, while the second microphone was located 966 feet from the tower. Other instruments included a UV spectrum analyzer directed at the combustion zone in the balloon, a coaxial calorimeter consisting of two thermocouples, both of which were fitted at the base of the balloon attachment. Additionally, a steel hollow box and a cylinder were instrumented with triaxial accelerometers and strain gauges and placed in the path of the blast. The recorded acceleration time history data was useful to quantify the shock response spectrum of the blast.

IV. Experimental Results

Methane-oxygen gas test were carried out as shown in the Table 1 below. The mixture ratios were varied as stoichiometric, $\pm5\%$, $\pm10\%$ and $\pm15\%$ by volume of methane for each of the balloon sizes. All the 6-ft. diameter balloons were tested with stoichiometric mixtures. The following section presents the overpressure and the impulse from the test series.

Table 1: Tests as conducted

Balloon sizes
6 ft.(7 tests)
12 ft.(19 tests)
14.5 ft.(5 tests)
16 ft. (15 tests)

A. Characteristics of the methane-oxygen test series

The overpressure time trace from a 12-ft. diameter methane-oxygen gas combustion event is given as an example in **Error! Reference source not found.**. The peak overpressures are used to develop a LNG/LO_2 empirical blast model for safety standards similar to the TNT equivalent methods in the literature [1]. The 10-ft., 20-ft. and 30-ft. probes at the 120-degree angle are double blast pressure pencil probes (PCB Model 137B26). This gives an added benefit of measuring the wave speed of the incident shock wave. Multiple pressure peaks are indicative of the detonations and reflections of the spherical blast wave in the combustion zone.

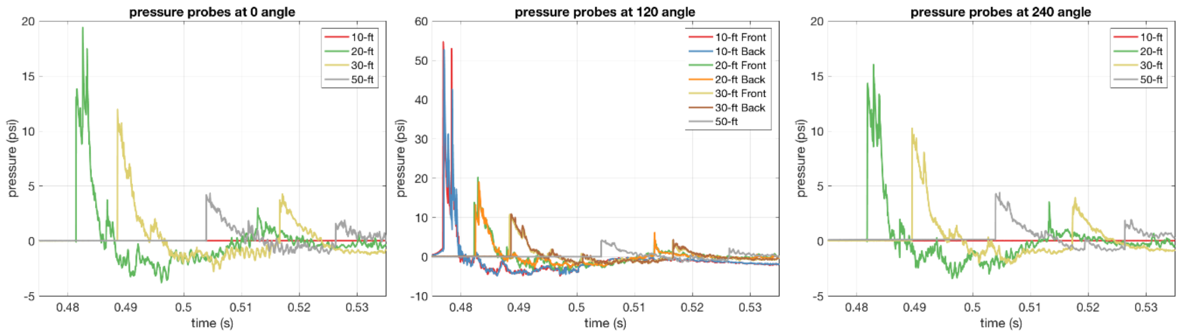


Figure 3. Typical pressure time history from a 12-ft. diameter balloon explosion

The positive phase blast wave is followed by the negative phase under-expanded region of the blast. A second trailing smaller blast pressure spike is recorded from ground reflections. Note, that the primary incident overpressures do not contain a Mach stem effect or other amplifications that might occur from coalescing of blast waves.

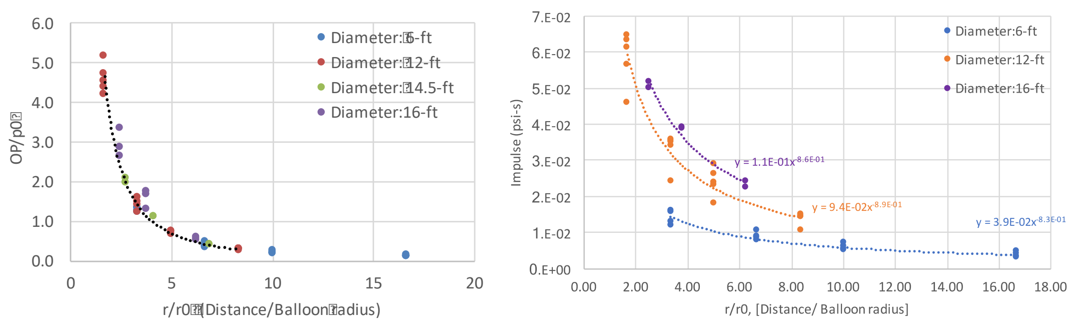


Figure 4. (left) Normalized Overpressure variation with normalized distance (right) Average impulse variation with normalized distance

The peak overpressures from the pressure history are recorded from every row of pressure probes and an average pressure is computed with distance. The overpressures are normalized with the ambient pressure. Figure 4 (left) displays the normalized peak overpressure with non-dimensional distance. The distance from the COE is normalized by the balloon mixture radius. The power curve fit of the overpressure results in the following expression shown in Equation 1 for normalized overpressure with an R^2 = 0.98:

$$OP/p_0 = 12\left(\frac{r}{r_0}\right)^{-1.748} \tag{1}$$

As the overpressure from different gas cloud sizes seem to fall on the same curve, it can be deduced that the overpressure at the edge of a methane-oxygen gas cloud ($^{r}/_{r_0}$=1) rises to a maximum of approximately 200 psi. It was observed that the methane-oxygen gas mixtures transitioned from a deflagration to a detonation in all the combustion events. This produced a repeatable shock wave energy irrespective of the size of the gas cloud. Different methods to trip the detonation early inside the balloon were tested successfully. Nonetheless, the resulting overpressures measured in air aligned with the same power decay with the normalized distance.

The theoretical Chapman-Jouguet (CJ) predicted detonation pressures for methane-oxygen mixtures, increases with equivalence ratio up to a ratio of 1.75 and drops thereafter. MUCTA tests spanned ratios between 0.78 and 1.23. The overpressure was found to be weakly dependent on equivalence ratio in this range. The curve fit was extrapolated to an equivalence ratio of 1.75 based on the CJ pressure rise, and the maximum overpressure with a 10% margin was determined to be around 220 psi.

The positive phase pressure impulse for the three balloon diameters of 6-ft., 12-ft. and 16-ft., respectively, were compared. The impulse was computed as the integrated area under the positive phase overpressure versus time plots. Figure 4 (right) displays the trend of increasing impulse with increasing gas cloud diameters. It can be inferred from the plot that a single decay curve could not accurately predict the impulse with normalized distance. While the overpressures with normalized distance exhibit the same decay regardless of the size of the gas mixture, the corresponding impulse rises with increasing propellant mass. The impulse, represented here as *J*, thus takes the form,

$$J = 38.05\ (m_{CH4})^{0.37} \left(\frac{r}{r_0}\right)^{-0.86} \text{psi} \cdot \text{ms} \tag{2}$$

The findings from the combustion zone images indicated that the detonation time in the 16-ft. balloon is higher than the 12-ft. balloon owing to the larger volume of gas mixture [5]. This converts to a higher impulse.

B. Comparison of overpressure results from experiment with TNT based data

Blast parameters depend on the amount of energy released from an explosion. It is a general practice to express the charge weight in terms equivalent mass of TNT, W_{TNT}. Blast parameters are given as a function of scaled distance, $Z = \frac{R}{{W_{TNT}}^{1/3}}$, where R is the distance from the charge. A value of 10% is recommended in a TNT based safety analysis to estimate the pressure effects corresponding to a confidence level of 97%. An explosion yield of 10% corresponds to a 5 kg TNT equivalent of 1 kg of hydrocarbon in the atmosphere [3]. Note the dependence of the TNT predictions on the proportionality factor called TNT equivalency factor, is determined from damage patterns observed in many major vapor cloud explosion incidents.

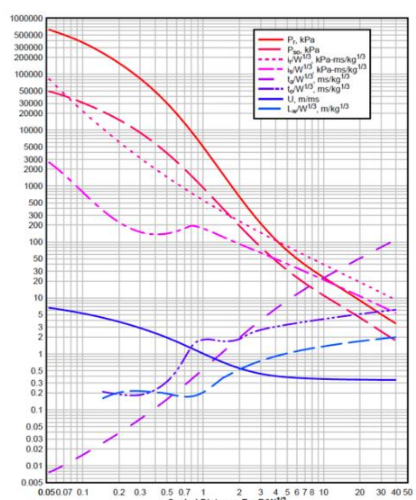


Figure 5. Parameters of positive phase of shock spherical wave of TNT charges from free-air bursts [6]

For the comparison with test data, a stoichiometric mixture of methane and oxygen gas was considered. The mass of methane for the various balloon sizes is converted to an equivalent mass of TNT following the above description. The side-on blast peak overpressure produced by a detonation of TNT charge is graphically represented in Figure 5 [6]. There are several similar charts based on TNT equivalency from various references [7, 8, 9] that estimate the side-on blast peak overpressure.

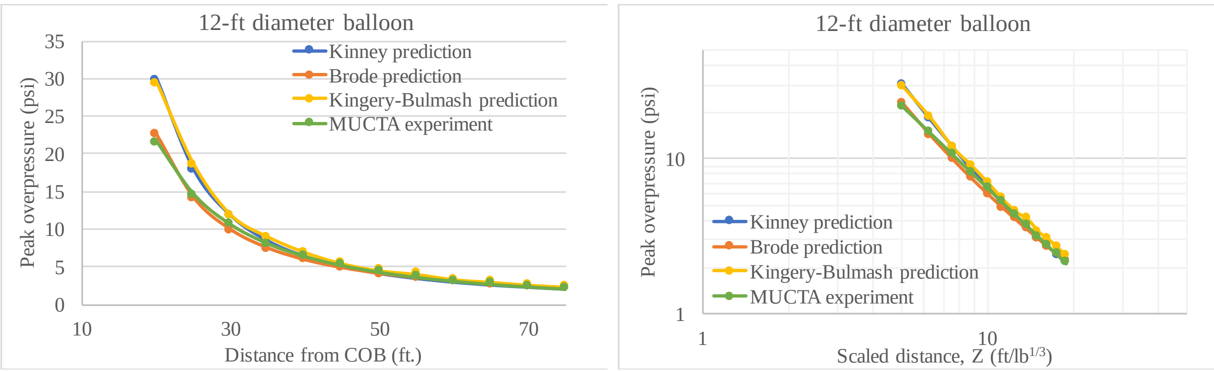


Figure 6. Comparison of experiment with TNT prediction for a 12-ft. diameter balloon gas mixture (left)Peak overpressure variation with distance (right) Log-log plot of peak overpressure variation with scaled distance

The overpressure decay with distance for a 12-ft. diameter gas mixture is shown in Figure 6 (left), while the same overpressures in terms of scaled distance is plotted on a log-log scale in Figure 6 (right). The peak overpressures recorded by MUCTA are ~40% lower than TNT predictions in the near field. However, Brode predicted overpressures are very similar to the experimental data. The far field results match the experimental findings. It must be noted that the overpressures were compared until 75 feet from the COE, after which the MUCTA overpressures decayed from a shock regime into acoustic pressure waves.

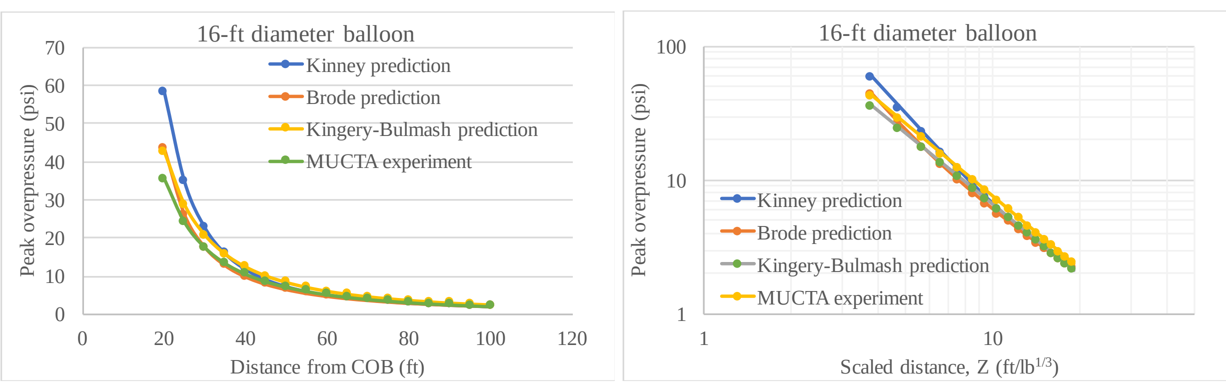


Figure 7. Comparison of experiment with TNT prediction for a 16-ft. diameter balloon gas mixture (left) Peak overpressure variation with distance (right) Log-log plot of peak overpressure variation with scaled distance

Figure 7 compares the MUCTA peak overpressures to the TNT equivalency overpressures for a 16-ft. diameter balloon gas mixture. The pressures are compared till 100 ft. away from the center of blast, beyond which the MUCTA shocks decay to acoustic pressure waves, and the empirical model does not hold. The discrepancy with the experimental data is larger as compared to the 12ft. diameter case. The near field data offset is ~20% for Kingery-Bulmash and Brode predictions. The far field data is again comparable. However, it must be noted that these comparisons are for gaseous detonations. The comparison with cryogenic explosions might reveal a larger discrepancy.

C. Comparison of Impulse results from experiment to TNT based data

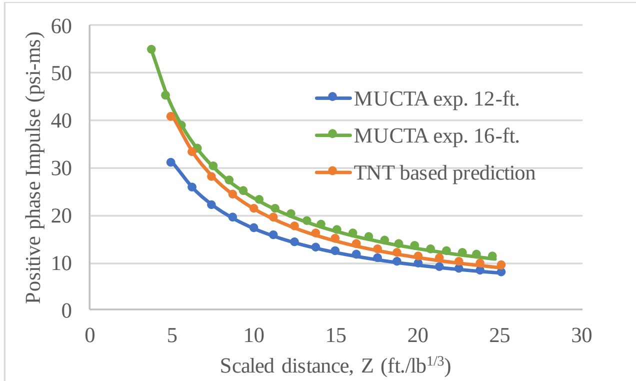


Figure 8. Comparison of impulse data from experiment with TNT predictions

Impulse variation with scaled distance is shown in

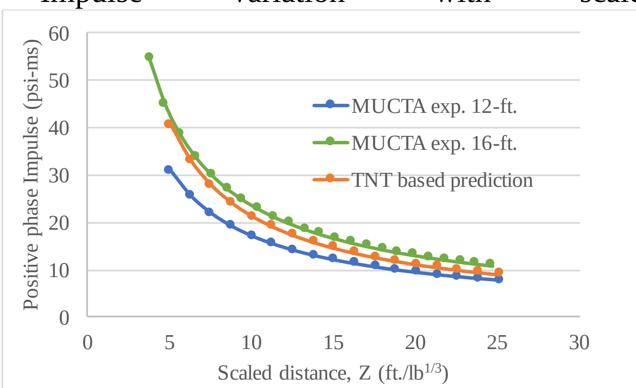


Figure 8. The decay of impulse with distance is expressed in Equation 2. The TNT based impulse is determined from the graph displayed in Figure 5. It is evident from

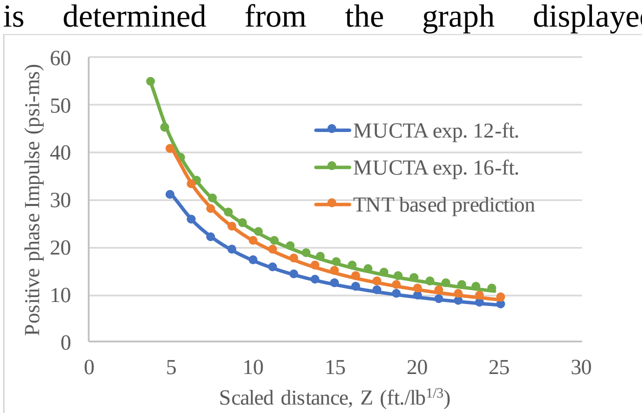
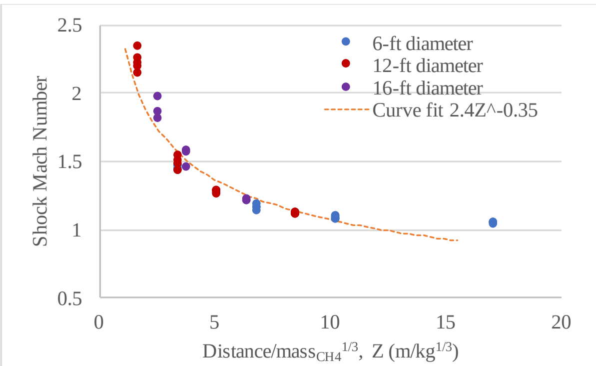


Figure 8 that the TNT predicted impulse is only dependent on the scaled distance, while the experimental model formulates a decay with scaled distance and a simultaneous rise with increasing mass of fuel involved in the explosions. The exposure time length of the overpressure increases with the propellant mass involved in accident scenarios as indicated by the rising impulse. Finally, the impulse from VCE will be limited by autoignition between the cryogenic propellants. Equation 2, which gives an expression for the impulse, will need to be modified to reflect this phenomenon.

D. Long distance acoustic results from methane-oxygen gas blasts

At long distances from the blast center, the shock waves from the explosions decay into acoustic pressure waves. Figure 9 shows the decay in the shock Mach number as calculated from the Rankine-Hugoniot relations with the given overpressure experimental data. It can be deduced that the explosions decay from shock to an acoustic wave at around 40, 72, and 96 feet, respectively for 6-foot, 12-foot and 16-foot. diameter balloon-enclosed gas mixtures. The empirical formulation for overpressure and impulse decays are no longer applicable beyond these distances. At and past these distances, the frequency content of the pressure wave has been altered due to attenuation and a theorized phase lag of certain frequencies causes the initial pressure wave to assume a form that is longer in duration than the initial near-discontinuity experienced in the shock regime.



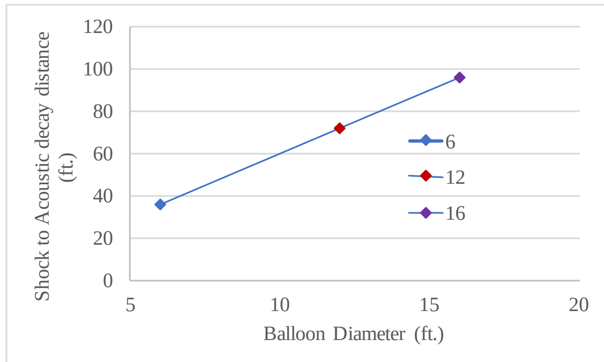


Figure 9. (left) Mach number variation with normalized distance (right) Approximate shock to acoustic decay for different balloon sizes based on the Mach number approach

The methane-oxygen gas blasts at the tests site resulted in a few formal claims of damage from the community surrounding the test range. This warranted a further study in the acoustic behavior of the explosions. A typical shock response as measured by the accelerometer at 50-ft from the center of blast spectrum is shown in Figure 10(left). This data was used to partition the pressure data into its 1/3 octave bands at the 50-foot mark from the center of the explosion, after the signal had decayed to an acoustic wave. While the higher frequencies decay rapidly with distance, the lower frequencies propagate for a longer distance. This is apparent from the graph in Figure 10 (right) that shows the reduction in the SPL at different normalized distances for the 1/3 octave bands. The SPL at lower frequency bands drops uniformly in accordance to an inverse proportion law, but the decay is faster at higher frequencies. This decay follows the ISO 9613-1:1993 formulation which supplants the inverse proportion law for sound pressure with an additional frequency-dependent damping factor that is affected by temperature, ambient pressure, and relative humidity. This formulation can be expressed in the following form:

$$P = P_0 \left(\frac{R}{R_0}\right)^{-1} 10^{-\beta(R-R_0)/20} \; where \; \beta \equiv frequency \; dependent \; damping \; factor$$

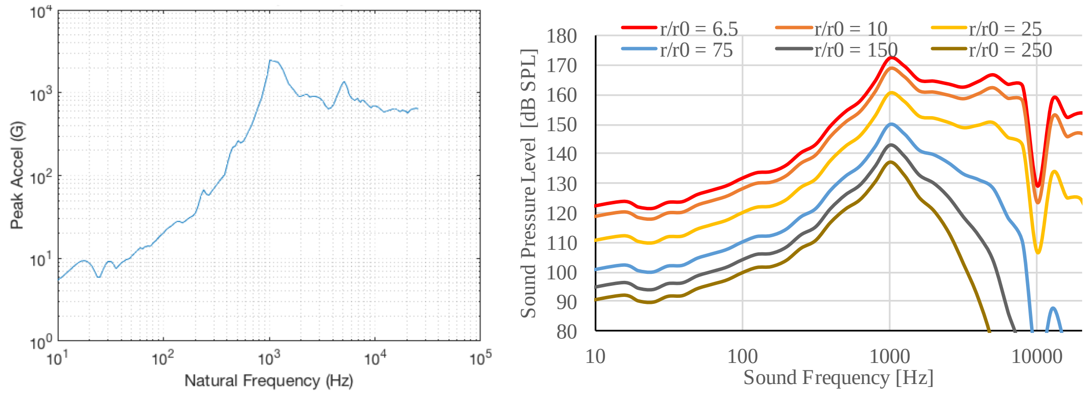


Figure 10. (left) Shock response spectrum of 16-ft diameter balloon CH4-GO2 blast event at 50 ft. from COE (right) Distribution of the frequency from the blast overpressure with distance normalized with balloon radius $\boldsymbol{R_0}$= 8 ft.

The sound pressure content of all the 1/3 octave bands are summed to give overpressure decay with distance in the acoustic zone as displayed Figure 11. The long distance acoustic pressures were measured by two microphones. The microphone placed at 861 ft. from the blast tower recorded a mean sound pressure level (SPL) of 161 dB, while the microphone at 966 ft. recorded a mean of 157.8 dB from three of the MUCTA tests. Figure 11(left) compares the acoustic model with the test data at the two distances and shows a match within 1.25% error band. Additionally, safety standards for sound level pressure (OSHA, [10]), requires hearing protection for any impulsive noise above 140 dB. This restriction will hold to about 4000-ft from the blast wave for a 16-ft diameter methane-oxygen balloon blast. Figure 11(right) represents the same acoustic model in terms of normalized pressure. Note that the decay is much slower than when the wave was modelled in the shock regime.

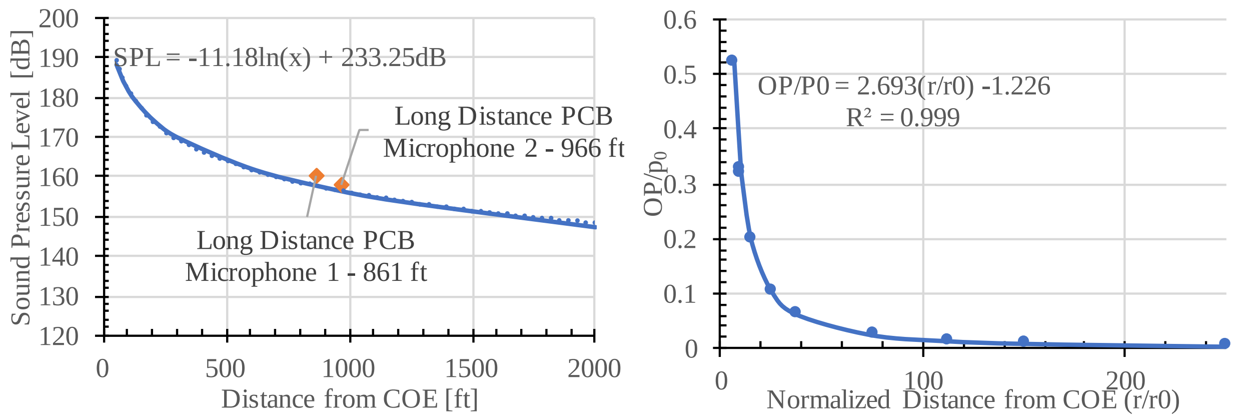


Figure 11. (left) Sound pressure level (SPL) acoustic decay model with distance indicating the measured acoustic data points. (right) Normalized overpressure decay with normalized distance in the acoustic regime

The SPL data should also be accounted for community noise and safety. The low frequency is easily transmitted inside buildings through openings. The standing waves inside the room can get amplified and cause room modes to occur that can result in building damage through a resonance phenomenon similar to the amplification of sound in a drum.

V. Conclusion

The main aspects of explosive safety for methane-oxygen gaseous explosions are addressed. An empirical model of the power law decay of the blast is observed. The overpressure data is bounded at 220 psi at the edge of the gaseous cloud irrespective of the size of the gas cloud. The TNT predicted overpressures were higher than the experimental findings in the near field and the discrepancy increased with bigger balloon sizes. It is believed that the overpressure difference with the TNT prediction will greater from an explosion arising from mixing of cryogenic propellants. The impulse also follows a power law decay with scaled distance along with an increase with an increasing mass of fuel involved in the explosions. TNT based prediction for impulse does not correct the decay of impulse with scaled distance for mass of fuel. An acoustic decay of the pressure wave is derived. This may play an important role in community noise and safety around the test range. The second part of the test program involves measurements of explosions from cryogenic LNG/LO_2 mixtures. An attempt will be made to emulate a random credible accident scenario. The hypothesis that the measurements from gas explosions envelope the cryogenic explosions will be verified.

Acknowledgments

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