Acoustical Characterization of Exploding Hydrogen-Oxygen Balloons

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ABSTRACT

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Exploding hydrogen-oxygen balloons are a popular demonstration in introductory chemistry and physical science courses. Initial research quantified potential hearing risk from exploding hydrogen-oxygen balloon demonstrations. Further time waveform and spectral analysis was conducted to characterize hydrogen-oxygen balloons as impulsive noise sources. Pure hydrogen balloons produce low levels (less than 140 dB) and inconsistent reactions. Balloons filled the stoichiometric ratio of hydrogen to oxygen produce very consistent results between trials. Hydrogen-oxygen balloons are also nearly omnidirectional, with little variation over angles. Levels for hydrogen-oxygen balloons increase as a function of balloon size and oxygen content.

Comparison is provided with other impulsive noise sources, including various firearms, other explosive chemistry demonstrations, and firecrackers. Consideration is given to characteristics such as A-duration, rise time, and peak level. It is concluded that the hydrogen-oxygen balloons are less impulsive than other sources of similar amplitude, with longer A-durations and rise times. As such, the balloons have lower characteristic frequencies than other impulsive noise sources considered.

Key words: impulse noise, chemical reaction

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Chapter 1

Introduction

1.1 Background

Impulsive noise sources have application in studying room acoustics and community noise annoyance. The impulse response function is used to predict the acoustic room response. It can be used in studying details such as reverberation time, reflections, early-to-late arriving sound ratios, and sound transmission loss through walls.[1] Potential impulsive noise sources include firecrackers[2,3], starter pistols[3], revolvers and various other guns[1,4]. Research has been previously conducted to determine the annoyance of impulsive noises such as gunfire, jackhammers, and pile driving[5].

Air-filled balloons have also been examined as impulsive noise sources.[3,6] Popped balloons are a convenient, low-cost and light weight source of impulsive noise. Deihl *et al.* [7] presents the N-wave time waveform produced by an ideal burst of a perfectly round balloon. However, balloons are not perfectly round, and rarely burst evenly. Typically the balloon tears at an arbitrary point and provides an asymmetrical noise source. Jambrosic *et al.*[3] investigated various sizes of popped balloons as impulsive sources in comparison to fireworks and an explosive acetylene mixture. It was determined that the explosive impulsive noise sources (firecrackers and acetylene mixture) provided a consistent N-pattern waveform whereas the balloon bursts were irregular and dependent on balloon size. In addition, the balloons produced a much lower peak sound pressure level. Patynen *et al.*[6]determined that the sound radiation from popped balloons is not omnidirectional.

This paper presents results for exploding hydrogen-oxygen balloons as an impulsive noise source. These balloons are a popular demonstration in introductory chemistry courses[8-11]. Because of the high-amplitude impulsive noise produced, exploding hydrogen-oxgyen balloons present a potential auditory hazard. According to OSHA and MIL standards, exposure to impulsive noises with peak sound pressures above 140 dB poses risk of hearing damage[12,13]. Early experiments to quantify peak levels of these demonstrations were performed by Battino *et al.* [14] Battino provided a summary of peak levels with consideration to variables such as balloon size, gas mixture, material of the balloon, volume of the room, and distance from the source. However, there is some question as to the validity of the results due to the instrumentation used and the misuse of acoustics terminology[15]. There was a need to revisit this problem with equipment better suited for impulsive noise measurements. Initial efforts were made to quantify hearing risks associated with these demonstrations. Peak levels of various hydrogen-oxygen balloons were published by Gee *et al.* in the Journal of Chemical Education[15].

This thesis provides a discussion of peak levels as a characterization as well as an assessment of potential auditory hazard. Further analysis provides a thorough characterization of hydrogen-oxygen balloons as an impulsive noise source. Time waveform and spectral analysis will be provided, with attention given to details including peak levels, A-durations, and repeatability of the trials. Some consideration is given to guidelines established by ISO3382 to determine potential suitability as an impulsive noise source in room acoustics. This paper will also include comparison with other impulsive noise sources.

Chapter 2

Summary of Experiment

2.1 Experimental Set Up

Measurements were taken in the large anechoic chamber at BYU. The anechoic chamber is qualified from 80Hz to 20kHz. GRAS 6.35-mm 40BH microphones were placed 3 feet from the source. GRAS 6.35-mm 40BD microphones were placed at distances of 6 and 12 feet. Figure 1 indicates location of microphones relative to the source.

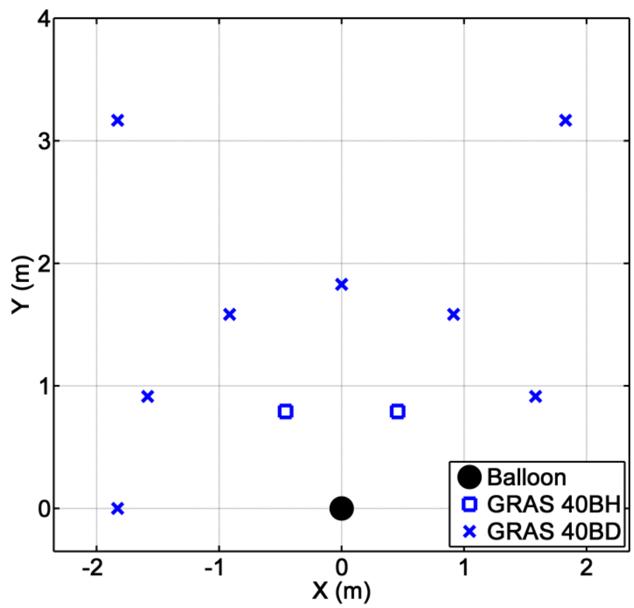

Figure 1 Set up in anechoic chamber. Microphones were placed at distances of 3, 6, and 12 feet from the source. Microphones placed at angles between 30 and 180 degrees from the X axis.30 degrees between each microphone at six feet.

Microphones were placed at grazing incidence on the ends of 0.25-in diameter wooden dowels that were attached to tripods. Data were recorded with National Instruments PXI 4462 cards at a sampling frequency of 192 kHz. Balloons were attached to a metal clamp and ignited by hand. Figure 2 includes photographs from the test.

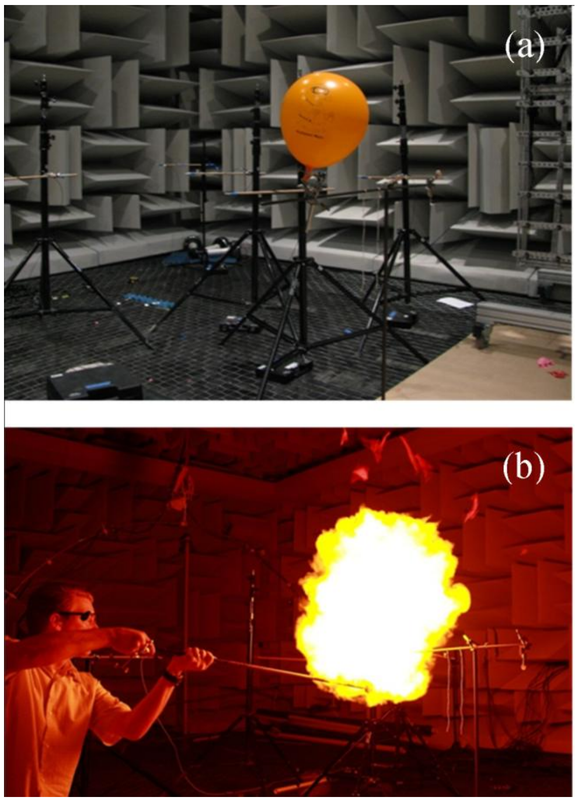

Figure 2 a) Photograph of experimental set up b)Balloons were lit with a torch, generally on the underside of the balloon. Exact location varied.

2.2 Types of balloons

Measurements were made on twelve different types of balloons. For a stoichiometric mixture of hydrogen and oxygen, the chemical reaction that produced light and heat and the resulting pressure impulse was $2\ H_2\ (g) + O_2\ (g) \rightarrow 2\ H_2O\ (g)$. Various sizes of balloons were filled with three different ratios of hydrogen and oxygen. Gas mixtures included pure hydrogen, half the stoichiometric ratio of hydrogen and oxygen (meaning a 4:1 ratio of hydrogen to oxygen), and the full stoichiometric ratio of hydrogen and oxygen (a 2:1 ratio of hydrogen to oxygen). The balloons are identified with a two letter code, the first letter indicating the amount of hydrogen in the balloon, and the second letter indicating the ratio of oxygen added. Table 1 provides the sizes, amounts of gas, and the two letter identification given to each of the 12 types of balloons.

ID	Moles H_2	Moles O_2	Total Volume (L)	Diameter (cm)	Trials
AA	0.070	0	1.98	15.58	4
AB	0.070	0.018	2.48	16.78	4
AC	0.070	0.035	2.97	17.84	3
BA	0.220	0	6.23	22.82	3
BB	0.220	0.055	7.78	24.29	3
BC	0.220	0.110	9.34	26.12	3
CA	0.370	0	10.47	27.14	4
CB	0.370	0.930	13.09	29.24	4
CC	0.370	0.185	15.71	31.08	3
DA	0.520	0	14.72	30.40	5
DB	0.520	0.130	18.40	32.76	3
DC	0.520	0.260	22.08	34.80	3

Table 1 Various types of balloons tested. The first letter of the ID indicates the amount of hydrogen in the balloon, and the second letter indicates the Trials per balloon type ranged from 3 to 5.

Chapter 3

Results

3.1 Peak Sound Pressure Levels

Peak levels are a primary consideration when determining potential hearing risk from an impulsive noise source[12,13]. Peak sound pressure levels were averaged over angle and trial. These average peak levels, rounded to the nearest decibel, are presented in Table 2.

	A	B	C	D
A	126 dB	133 dB	131 dB	134 dB
B	145 dB	150 dB	155 dB	158 dB
C	144 dB	152 dB	158 dB	161 dB

Table 2 Average peak sound pressure levels for each of the twelve types of balloons measured. Levels are averaged over trial and angle. Columns represent each size of balloon, and rows represent the different ratios of hyrogen to oxygen.

As seen from the levels presented in the top row of Table 2, pure hydrogen balloons at all sizes are well within the 140 dB limit for safe exposure. The peak level does not increase substantially with size, so large balloons can be used without posing an auditory risk for audience members. However, hydrogen-oxygen balloons of all four sizes are well above the 140 dB limit. As the balloons increase in size and oxygen concentration, the levels generally increase. An exception to this is the AB and AC balloons, which is likely due to the balloons being hand-filled and too much oxygen being added. Figure 3 provides a graphical representation of the results in Table 2. Two sets of error bars are provided at each data point.

The tighter error bars represent the variation over angle. More variation over trial resulted in the larger set of error bars. As seen from the decreasing size of error bars, adding oxygen to the balloons provided more consistent results. Note the large variation for the AB balloons, which is probably due to the small number of trials and inconsistency in filling. Further discussion on the consistency of the various balloons will be provided in the following sections.

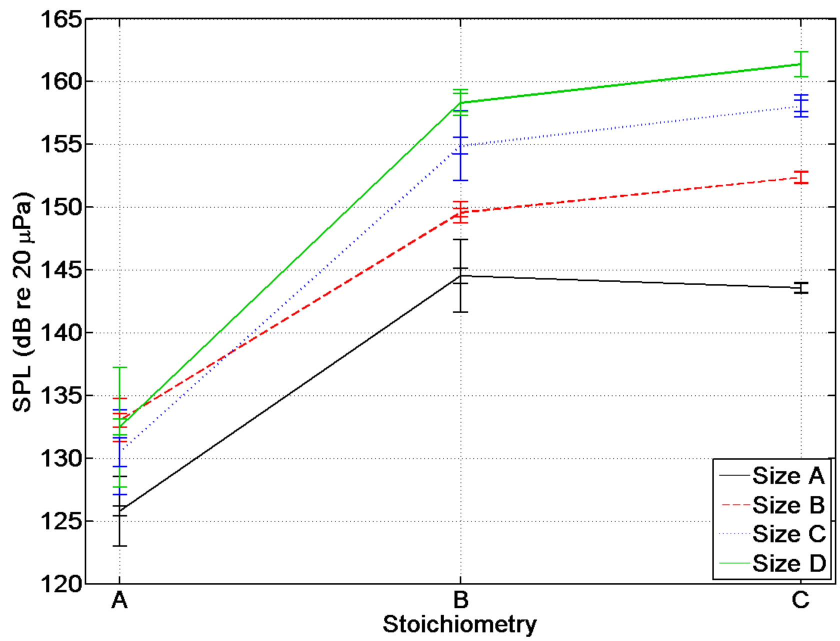

Figure 3 Average peak levels for balloons as a function of size and stoichiometry. Error bars represent variation over angle and trial. Tighter error bars represent angle.

3.2 Pure Hydrogen Balloons

The following section discusses results for large, hydrogen-filled balloons. Analysis is provided on the "CA" balloons, with a diameter of 27.14 cm.

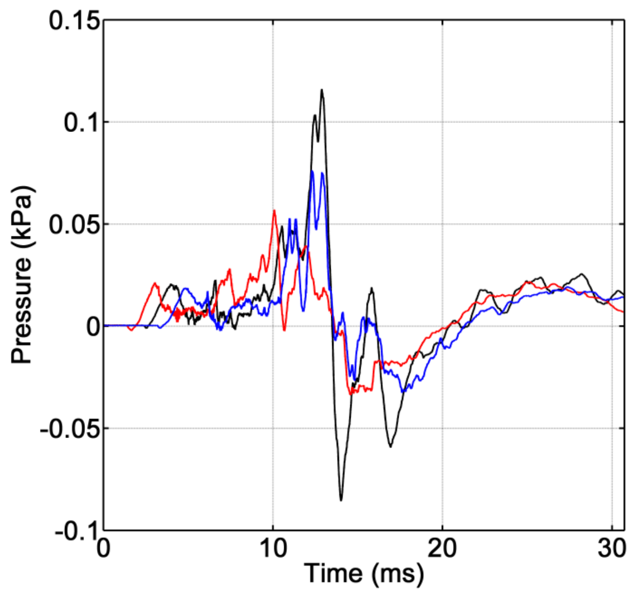

Figure 4 Time waveforms of three separate large hydrogen CA balloons

Displayed in Figure 4 are time waveforms of three large hydrogen "CA" balloons. The combustion follows a general trend for each of the hydrogen balloons; however there is significant variation in the details of the reaction. There is variation in level as well as length of the reaction. Because the balloons only contain hydrogen, oxygen from the air is required for the reaction to take place. The result is a highly variable explosion as pockets of hydrogen gas mix with the air and combust. The hydrogen balloons produce low-amplitude peak sound pressure levels, averaging around 130 dB. High-speed video analysis[16] shows that the balloon completely unwraps before the explosion begins. The time waveform indicates the balloon pops (or unwraps) prior to the explosion as well. Considering only the initial peaks, seen in Figure 4 at times of 2-4 milliseconds, rise times (1.8 ms) and levels (about 120 dB) are somewhat consistent with the results presented by Paytnen et al.[6] for popped balloons. For a similarly sized balloon (24 cm diameter) at a distance of 6.8 feet, Paytnen reported an average rise time of 1.8 ms.

3.3 Hydrogen-Oxygen Balloons

Hydrogen-oxygen balloons combust far more predictably than the pure hydrogen balloons. This section examines data from the CC (31.08 cm diameter, full stoichiometric ratio of hydrogen to oxygen) balloons.

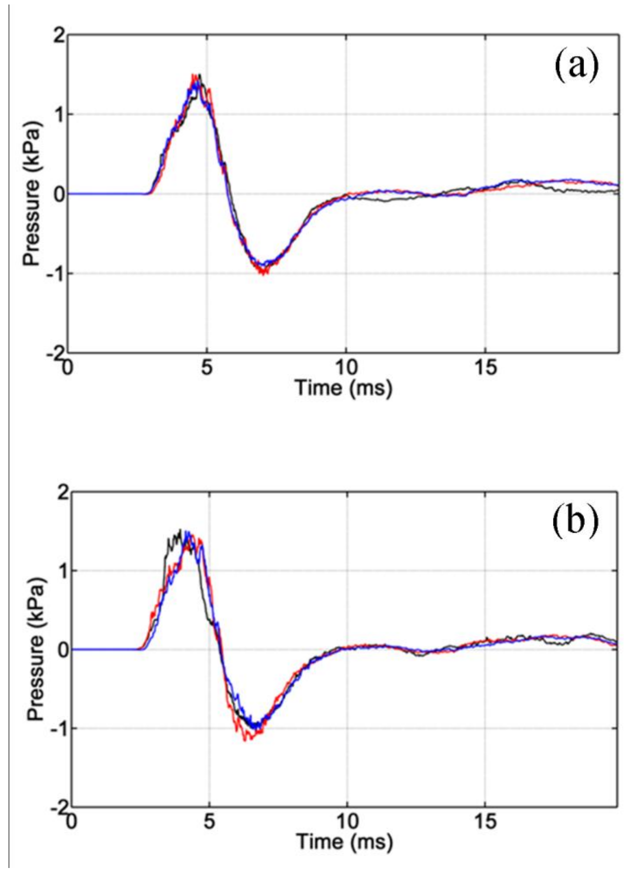

Figure 5 a)Time waveform of a single CC balloon at angles of 60, 90, and 180 degrees off the X axis at six feet from the source. b)Time waveform of three CC balloons at a single microphone six feet from the source, 120 degrees off the x-axis.

Figure 5 depicts time waveforms of CC balloons. Figure 5a shows the time waveforms of a single CC balloon at three different locations six feet from the source, including 60, 90 and

180 degrees off of relative to the horizontal axis in Figure 1. Figure 5b depicts the time waveform of three separate trials at the same microphone six feet from the source at 120 degrees relative to the horizontal axis in Figure 1. As seen from Figure 5 and Figure 3, the CC balloons are a very repeatable source. The peak sound pressure level has less than 1 dB variation from the mean at each microphone between each trial. Hydrogen-oxygen balloons are a consistent impulsive noise source.

Although analysis presented is primarily focused on data collected at a distance of six feet from the source, data collected at three and twelve feet provided two significant results, including evidence of spherical spreading and nonlinear propagation effects in the pre-shock regime. Peak sound pressure levels measured at three, six and twelve feet demonstrated that the balloons follow spherical spreading. As the distance doubles, the sound pressure levels decrease by approximately 6 dB. As the distance is decreased by a factor of two, the sound pressure levels increase by approximately 6 dB. Figure 6 provides a comparison of measured data with ideal spherical spreading. Because the data follows this trend, it is possible to predict the peak sound pressure levels at other distances, neglecting possible effects of room reflections.

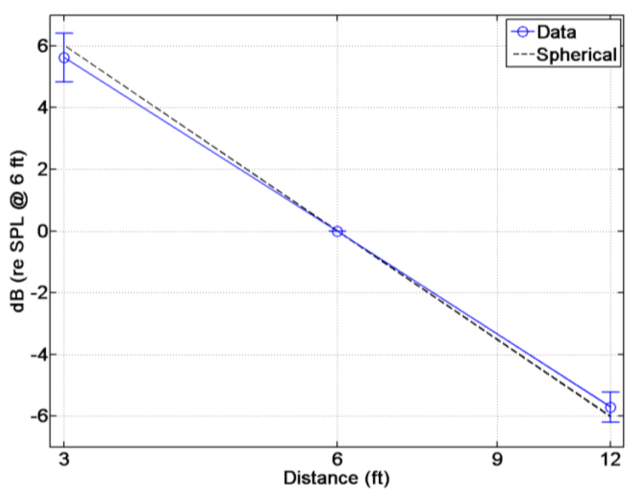

Figure 6 A comparison of measured data with spherical spreading. Depicts change in sound pressure level relative to that at six feet from the source.

Figure 7 is a color map of sound pressure levels as a function of size and stoichiometry, developed using the prediction capabilities provided by spherical spreading. The contour curves represent the conditions needed for levels of 140 dB, 146 dB, and 152 dB at six feet away. This means that by using a mixture to the left of the 146 dB line, audience members would be exposed to levels no greater than 140 dB at twelve feet away. Similarly, following the 152 dB contour, audience members are exposed to safe levels at twenty-four feet away.

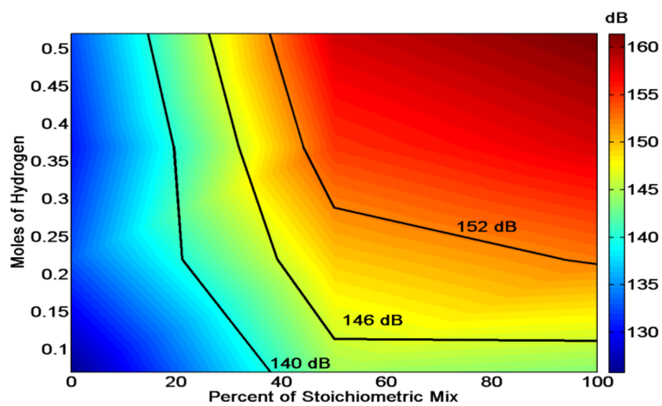

Figure 7 Peak sound pressure levels as a function of size of balloon and percent of stoichiometric mixture, six feet from the source. Due to spherical spreading, balloons types lying along the 146 dB and 152 dB contour lines will fit within 140 dB limit provided the audience is no less than twelve or twenty-four feet from the source, respectively.

Predictability due to spherical spreading is particularly relevant when creating a model for chemistry educators, because it provides an accurate prediction of peak sound pressure levels at varying distances from the source in a classroom setting. It allows chemistry educators to know how loud the demonstration is, and avoid potential hearing risk for audience members.

Examination of the 3, 6, and 12 ft data also showed appreciable evidence nonlinear propagation effects[16]. However, although the waveform steepens as it propagates, the pressure wave does not form a weak shock over the range and balloon sizes studied in this experiment.

Chapter 4

Analysis and Conclusions

4.1. Time Waveform Analysis

A comparison of the varying ratios of hydrogen to oxygen provides insight into how characteristics of the chemical reaction are related to the details found in the time waveforms.

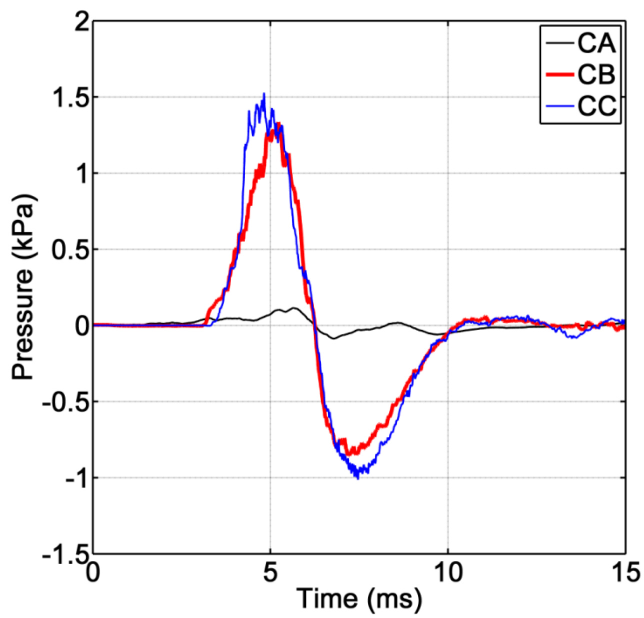

Figure 8 Time waveforms of large balloons with three different ratios of hydrogen to oxygen. CA balloon is pure hydrogen, CC balloon has the full stoichiometric ratio of hydrogen to oxygen needed for the combustion reaction

Figure 8 shows a comparison in time waveforms for varying ratios of hydrogen to oxygen. The "C" size balloon is considered for this analysis, meaning each balloon was filled with 0.370 moles of hydrogen before adding the appropriate amount of oxygen. Comparatively, AC balloon has much lower levels and a longer A-duration. Because the AC balloon is pure hydrogen, all the oxygen needed for the combustion reaction is drawn in from the air, which results in a much longer reaction time. However, the CC balloon is filled with the stoichiometric ratio of hydrogen to oxygen, and so already contains all the oxygen necessary for the reaction to take place. As such, the CC balloon has a shorter A-duration and rise time. The CB balloon has a slightly longer rise time and A-duration because some oxygen needs to be drawn in from the air in order for the combustion reaction to take place. The average peak sound pressure level is 3 dB lower than that of the CC balloon.

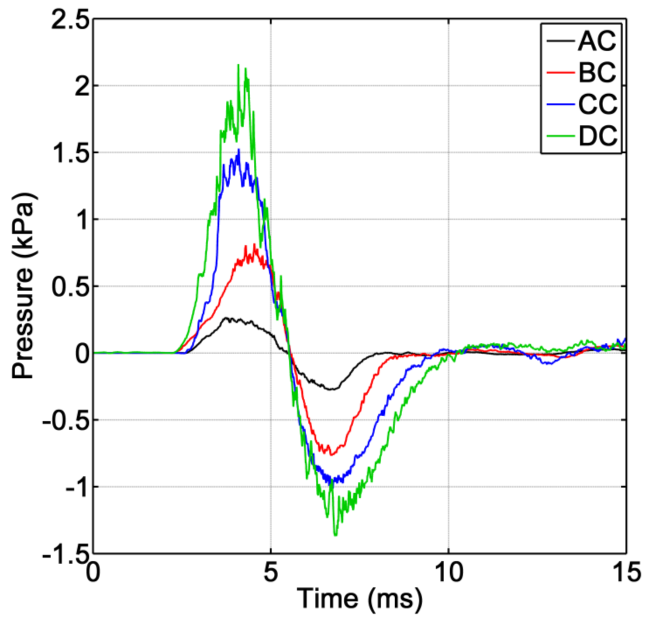

Figure 9 A single trial of each size of balloon filled with the stoichiometric ratio of hydrogen to oxygen. Measurements were taken at six feet.

Figure 9 depicts the time waveforms for four different sizes of balloons filled with the stoichiometric ratio of hydrogen to oxygen. As shown in Table 1, the volume of the AC balloon is 2.97 liters whereas the volume of the DC balloon is 22.08 liters. However, the A-duration of all four balloons is consistent within 0.2 ms. Despite having vastly different volumes of gas, the reaction occurred at approximately the same rate for all balloons.

While the chemical reaction takes the same length of time for each of the sizes of balloons, the time required for the air to relax is volume-dependant. Larger balloons have a longer period of negative pressure following the impulse. The larger volume of air pushed away during the reaction takes more time to return to equilibrium.

4.2 Spectral Analysis

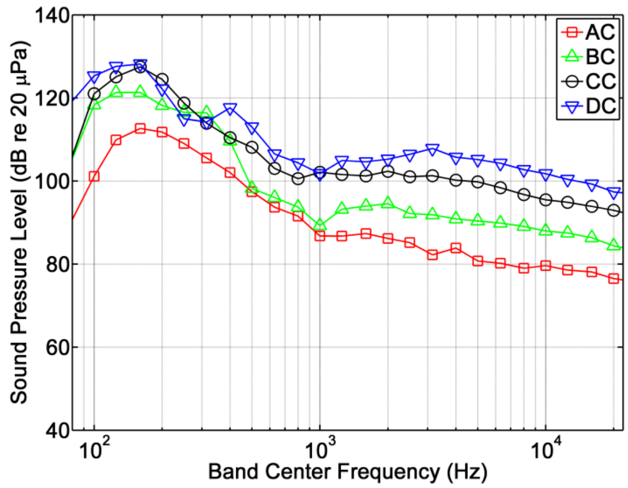

Figure 10 Third octave band levels for each size of balloon with stoichiometric ratio of hydrogen to oxygen.

Figure 10 provides the one-third octave band spectrum of each size of balloon with the stoichiometric ratio of hydrogen to oxygen. Exploding hydrogen-oxygen balloons produce primarily low-frequency content, with characteristic frequencies on the order of 100 Hz. While the characteristic frequency shifts slightly upwards with decreasing balloon size (consistent with the A-duration in Fig. 9), there is no significant change. This result is contrary to results found by Patynen *et al.*[6], who describe a more significant correlation between volume of balloon and the fundamental frequencies of popped balloons.   They provide a model loosely related to the equation for a Helmholtz resonator.

Consideration is also given to octave band levels. The standard ISO3382 provides a table of maximum deviation of directivity of a source used for room acoustics. Brief consideration was given to the possibility of the hydrogen-oxygen balloons meeting this standard. ISO3382 requires that measurements be either averaged over gliding 30 degree arcs or averaged over measurements taken in five degree increments. Tests performed did not meet the resolution required, as measurements were only taken every 30 degrees.   However, results are presented for the data available.   Figure 11 indicates the maximum deviation from the mean in decibels for each octave band. Each trial was considered individually, finding the average over the angles for a particular trial. Maximum deviation from the mean over angles was determined for each trial. Maximum deviations were then averaged and plotted below. A comparison is also provided with the maximum allowable deviations in ISO3382.

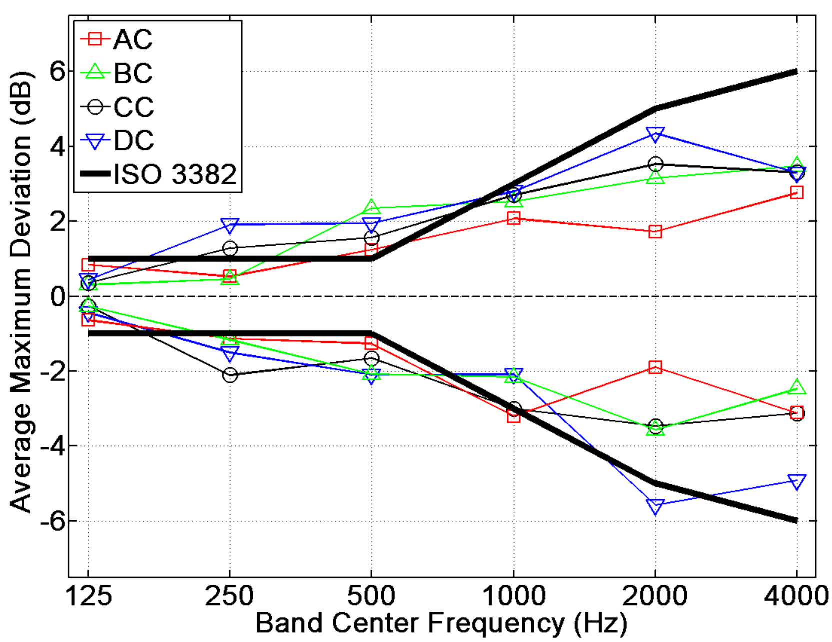

Figure 11 Octave band directivity of balloons. Maximum angle-dependent deviation from the mean sound pressure level was averaged over three trials. Point measurements were taken in 30 degree increments at six feet from the

source. Note that ISO3382 requires gliding measurements over 30 degree angles or point measurements at 5 degree increments, averaged over a 30 degree span.

Figure 11 indicates that hydrogen-oxygen balloons are close to omnidirectional, with very little angle-dependent deviation from the mean. The maximum deviations fit within the range required by ISO3382 at the high frequencies, and nearly fit within the range at the low frequencies. Further measurements taken as indicated in ISO3382 would provide a closer fit. Results averaged over thirty degree increments will have less variability over angle than point measurements. These additional measurements will more accurately determine the balloons' suitability as an impulsive noise source.

Analyses on the balloons with half the stoichiometric ratio of oxygen to hydrogen (AB, BB, CB, and DB) yield similar results to those presented in Figure 11.   We can conclude that the ratio of hydrogen to oxygen does not need to be precise when considering the ISO3382 standard.

4.3 Comparative Analysis

In addition to a discussion about details of the balloons, a comparison with other impulsive noise sources provides for a more thorough characterization. Sources discussed will include other explosive chemistry demonstrations, firearms and other weapons, and firecrackers.

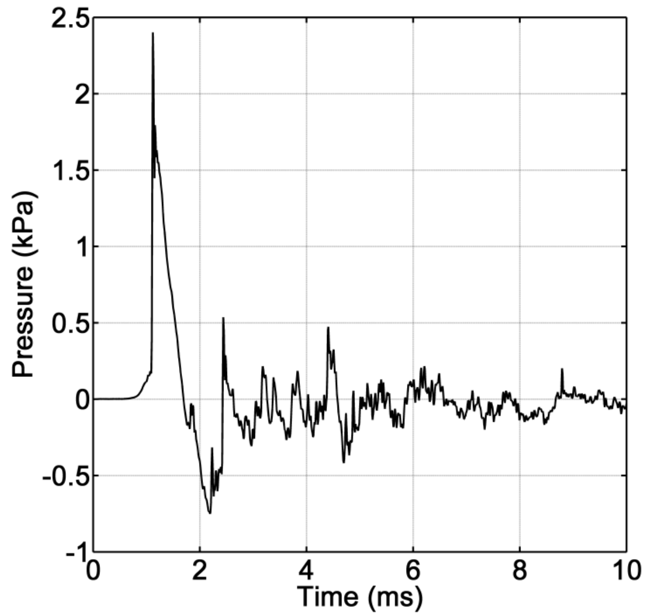

Figure 12 Time waveform of a chemistry demonstration involving a 1 liter bottle filled with hydrogen and oxygen. Reaction was started with a palladium on carbon catalyst.

Figure 12 depicts a 1-liter bottle filled with the stoichiometric ratio of hydrogen to oxygen. The palladium catalyst causes the reaction to happen much more quickly than with the balloons. The peak sound pressure level is slightly higher than the largest stoichiometric hydrogen-oxygen balloon (DC). The DC balloon is 22.08 liters, opposed to the 1 liter in the bottle. Despite having twenty times more fuel, the largest hydrogen-oxygen balloon produces lower peak sound pressure levels than the bottle. The waveform depicts the impulsive nature of the explosion. The initial upward slope is due to the bottle expanding before the reaction takes place.

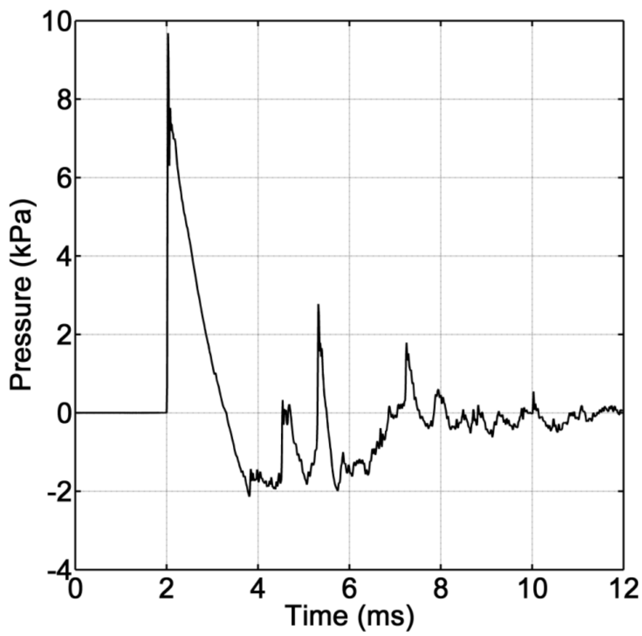

Figure 13 Time waveform of an acetylene-oxygen balloon, measured at six feet from the source

Figure 13 depicts a time waveform of an acetylene-oxygen balloon measured at six feet from the source. Despite being a somewhat small balloon (volume of 5.66 L with a diameter of 22.12 cm), the peak pressure is significantly higher than that of the hydrogen-oxygen balloons measured. Acetylene-oxygen balloons produce a loud explosion with more high frequency content than the hydrogen-oxygen balloons.

Comparison can be made to other types of impulsive noise sources. Measurements were taken by Shaw *et al.*[17] of a Gatling gun.

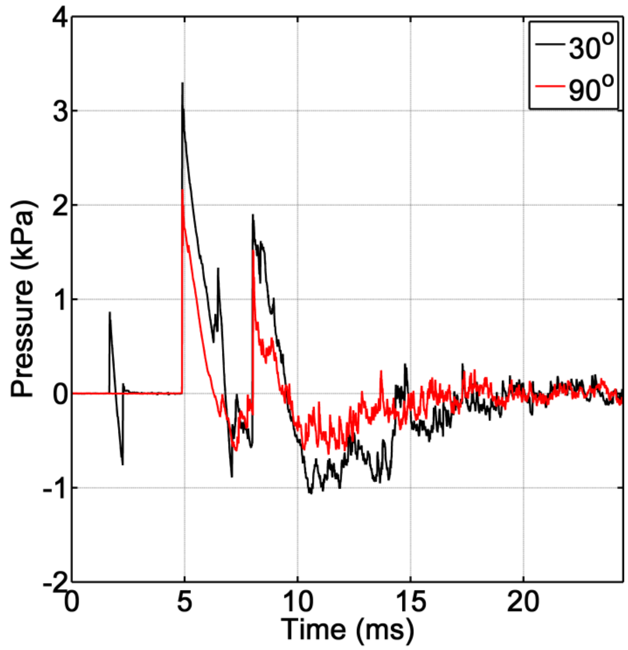

Figure 14 Time waveform of a Gatling gun at 30 degrees and 90 degrees from the source at 30 feet**.**

At 30 feet from the source and at a 90 degree angle, the Gatling gun produces similar levels to the large hydrogen-oxygen balloons. The balloon and the Gatling gun have similar A-durations, but the Gatling gun is more shock-like, with a much shorter rise time. A 120 mm tank gun, measured by Downing *et al*.[18] 50 feet away at a 90 degree angle, produced levels of 176 dB with a 5.6 ms A-duration. This is an example of a high-amplitude impulsive noise source with a long A-duration. The peak sound pressure levels are much higher than those associated with the exploding hydrogen-oxygen balloons.

Smaller sources produce levels more consistent with a typical chemistry demonstration. A study performed by Ylikoski *et al.*[19] provides characteristics of various types of small firearms. A 9 mm pistol, measured at shooter position, produces levels of 154 dB with an A-duration of 0.3 ms. A 7.62 mm assault rifle, produces peak sound pressure levels of 155 dB at shooter position. The A-duration is also 0.3 ms. These characteristics are similar to those of large hydrogen-oxygen balloons, but the characteristic frequencies vary significantly—1 kHz for the pistol and 1.2 kHz for the rifle.

Firecrackers are another commonly studied impulsive noise source. Flamme *et al.*[20] provides a detailed study of the characteristics of various types of firecrackers. It is noted that firecrackers generally follow the Freidlander waveform shape. As an example, the M70 firework produces a level of 158 dB at 6.6 feet away with a 0.38 A-duration. Firecrackers produce peak sound pressure levels and A-durations similar to those of hydrogen-oxygen balloons. However, as is the case with other impulsive noise sources considered, the rise time is much shorter.

4.4 Conclusions

Pure hydrogen exploding balloons produce low levels and a variable reaction. However hydrogen-oxygen balloons are a moderate size impulsive noise source and are consistent between trials. Hydrogen-oxygen balloons are also nearly omnidirectional. As such, further research may determine that these balloons fit the source qualifications in architectural acoustics.

In comparison to other impulsive noise sources, hydrogen-oxygen balloons produce moderate peak sound pressure levels. However the time-waveform produced is much less shock-like than sources of similar amplitudes, meaning longer rise times and A-durations. Because of this, the balloons have a lower characteristic frequency.

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