IGNITION LIMITS OF EXPLOSIVELY DISPERSED FUEL

BY

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THESIS

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ABSTRACT

This thesis aims to explore the ignition limits of explosively dispersed fuel. Significant damage can result from the explosive dispersal and ignition of kerosene in the event of an attack on or an accident in a military facility or vessel carrying kerosene fuel tanks. As such, the work conducted approaches the ignition of explosively dispersed fuel from the context of safety in the hopes of either minimizing the amount of fuel ignited or completely eliminating fuel burn.

A test article was designed to explosively disperse and ignite kerosene fuel, using flash powder as the driving charge. These test articles were ignited in a blast chamber located at the University of Illinois at Urbana-Champaign, and the chamber pressure was recorded to determine the energy released. Some high-speed imaging was also conducted at a different facility on campus. The charge-to-fuel mass ratio was varied, while holding the fuel mass constant, to determine a relationship between the mass ratio and fuel burn fraction. A primary motivation of this study is to find a critical mass ratio at which the fuel does not burn.

It was observed that kerosene is sensitive to ignition when explosively dispersed in the test configuration. This sensitivity is suspected to result from local heating of rich regions of the fuel cloud by dispersed chunks of burning flash powder. No mass ratio was found at which fuel did not burn after being explosively dispersed. However, a different critical mass ratio was observed which marked the upper limit of fuel burn fraction. This limit was determined to be 63% fuel burn.
ACKNOWLEDGMENTS

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CHAPTER 1: INTRODUCTION

1.1. Research Motivation
Military facilities and vessels, such as arsenals, operating bases, aircraft, and ships, may house kerosene-fueled weapons or kerosene fuel tanks in general. In the event of an attack on such facilities or vessels, an explosion or a fire in close proximity may detonate the weapons or heat and pressurize the fuel tanks. The tanks containing the fuel would then rupture violently, explosively dispersing the fuel. As a result of these conditions, the fuel can vaporize, mix with the air, and ignite, causing further damage to the surroundings. The ignition of such explosively dispersed fuel is likely to produce further explosions and fires, which would result in the explosive dispersal of fuel from other nearby weapons or fuel tanks. This devastating chain reaction can severely damage or even destroy the facility or vessel. Due to the potential for significant collateral damage, it is critical to prevent the ignition of explosively dispersed fuel. This study focuses on whether kerosene will ignite and burn when explosively dispersed from a container. The limits of ignition are explored, with special emphasis placed on determining conditions that will prevent ignition.

1.2. Previous Work
The combustion of kerosene has been studied with a focus on modeling the process in engines and for safety reasons. High-pressure and low-pressure studies were conducted in which kerosene oxidation kinetics were examined; reaction intermediates were identified, and their concentrations measured over the course of the reaction [1]. Kerosene is known to be a very complex mixture of alkanes, aromatics, and napthenes. Due to the complexity of its composition, a simplified model
fuel is typically used to represent kerosene in oxidation simulations [2]. Several such models have been proposed for this purpose: 100% n-decane, n-decane-n-propylbenzene (74%/26% mol), n-decane-n-propylcyclohexane (74%/26% mol), and n-decane-n-propylbenzene-n-propylcyclohexane (74%/15%/11% mol). These various models are used in different scenarios depending on the application of the study. N-decane is acceptable if the formation of aromatics is not an issue, while the three-component model is most appropriate for jet-stirred reactor experiments. While n-decane is a suitable model under most circumstances, its oxidation yields much less aromatics than that of kerosene, necessitating more complex fuel models if it is desired to investigate the formation of aromatics, which are key compounds in the formation of soot from the oxidation of kerosene [3]. As this study is primarily experimental in nature, kerosene itself is used as opposed to any of the proposed surrogate fuels.

Experimental studies have been conducted to examine the deflagrations and detonations of kerosene. The deflagration-to-detonation transition (DDT) of kerosene has been of particular interest due to the development of air-breathing pulse detonation engines (PDEs); the low detonability of kerosene-air mixtures is a major obstacle in this regard [4]. However, this study focuses instead on safety, and DDT is not investigated as detonation is not expected in the work conducted. Rather, experiments similar to those presented by Dorofeev et al. to examine the thermal effects from the deflagration and detonation of kerosene are more relevant. In those experiments, a TNT driving charge was used to rupture a steel cylindrical vessel, from which the fuel was dispersed. The resulting rich, heterogeneous mixture of fuel and air was ignited, and relationships for various heat effects versus fuel mass were determined. [5]. This study draws strongly from such work, though on a much smaller scale. The combustion is also very lean overall,
as there exists a much larger mass of air in the facilities used compared to the mass of fuel that is loaded in the test article. However, the fuel cloud is expected to be highly heterogeneous in nature, and locally rich combustion might occur. Additionally, this study provides novel information by examining the pressure effects resulting from the ignition of explosively dispersed kerosene as opposed to thermal effects.

1.3. Limitations of the Study

The test article used in this study was designed to be simple and affordable. To this end, the materials used are easily obtainable items that were found in hardware stores and online at relatively low costs. PVC pipe and PVC pipe fittings were bought as raw material for the test articles. These were then minimally machined in-house to the desired specifications. Super glue was used to seal the test articles so that liquid fuel would not leak out. Aluminum potassium perchlorate (APP) flash powder was chosen as the driving charge since aluminum (Al) micron powder and potassium perchlorate (KClO₄) powder are commonly sold online and APP has a reasonable specific energy for the purposes of the application. These powders were then carefully mixed in-house with a stoichiometric fuel-oxidizer mass ratio. Flash powders also burn quickly and completely, producing a sharp pressure rise necessary to fragment the test article and provide consistent results. Existing laboratory facilities and equipment provided the testbed for, the execution of, and the data collection for this study.

1.4. Overview

This document is divided into several chapters related to the important aspects of this study. Chapter 2 gives the methods used in the research conducted for this study. The specifications of
the facilities and equipment used are listed, and the derivation of important parameters is detailed. An overview of the data processing is also included. Chapter 3 presents the results of the research carried out in Chapter 2. A relationship between charge-to-fuel mass ratio, lost energy fraction, and fuel burn fraction is developed. Critical points in this mass ratio are noted and video footage of a test is examined. The impact of wall effects on fuel afterburn is also studied, and a link to afterburn of fuel is proposed. Finally, repeatability of the recorded data is analyzed, and use of different sensor types is explored. Chapter 4 summarizes the findings presented in Chapter 3. Conclusions are drawn regarding the ignition limits of explosively dispersed fuel, and recommended future work is laid out. The appendices provide an overview of important equipment settings, pressure calibration data, and a copy of the code used in data processing.
2.1. Test Article

The test article used in this study comprised of four pieces. Two schedule 40 1/2” PVC unthreaded pipe end plugs served as the endcaps of the article, a 1-5/8” length of schedule 40 3/8” CPVC pipe served as the internal liner, and a schedule 40 1/2” PVC unthreaded pipe coupling served as the outer case. The end plugs were modified so that the plug depth was reduced to 1/4” and the inner diameter could accommodate a schedule 40 3/8” pipe. Additionally, a 1/8” hole was drilled in the center of the end plug that served as the upper endcap so that a wire could be passed into the test article. The pipe coupling was modified so that the outer diameter was reduced to 0.94” and the ridge inside the coupling was removed. A drawing of the test article with nominal dimensions in inches as well as an image of a partially assembled test article are shown in Figure 1. The article was held together and sealed using super glue to prevent the fuel from leaking at the seams. Super Glue was chosen over PVC pipe cement due to its quick drying characteristic.
2.2. Charge Preparation

Both 3 μm German H-Super Al flake and 99% KClO₄ from Alpha Aesar were used to prepare the stoichiometric APP flash powder that served as the driving charge. The stoichiometric mass ratio of KClO₄ to Al is 1.93:1. This can be determined by balancing the chemical reaction, multiplying the moles of each reactant by their molar masses, and taking the ratio of the result. The process is that below.

\[
\begin{align*}
8 \text{Al} + 3 \text{KClO}_4 & \rightarrow 4 \text{Al}_2\text{O}_3 + 3 \text{KCl} \\
\frac{3 \text{mol KClO}_4 \cdot 138.55}{8 \text{mol Al} \cdot 26.98} \frac{g}{\text{mol KClO}_4} &= \frac{1.93}{1}
\end{align*}
\]
Once the correct amounts for each powder were massed on a four digit gram scale, both powders were ultrasonically mixed in a hexane base for 10 minutes to ensure uniformity. The ultrasonic processor that was used is shown in Figure 2. The mixture was then decanted and placed in a vacuum oven overnight at -25 inHg and room temperature for drying. The pressure in the vacuum oven was decreased gradually so as to avoid significant bubbling in the mixture, which aerosolizes some of the powder. The vacuum oven and vacuum pump setup is shown in Figure 3. Wearing a face mask and safety glasses is recommended at all times when handling these powders.

Figure 2: Ultrasonic processor.
It is also possible to calculate the specific energy of APP knowing the enthalpies of formation of the reactants and products in the reaction. This is done by multiplying the moles of each reactant and product by their enthalpies of formation, subtracting the sum of these values for the products from the sum of these values for the reactants, and dividing the result by the total mass of the reactants. The process is demonstrated below.
\[
\begin{align*}
\left( 8 \text{ mol } Al \times 0 \, \frac{kJ}{\text{mol } Al} \right) &+ \left( 3 \text{ mol } KClO_4 \times -430.12 \, \frac{kJ}{\text{mol } KClO_4} \right) \\
&= -1,290.36 \, kJ
\end{align*}
\] (3)

\[
\begin{align*}
\left( 4 \text{ mol } Al_2O_3 \times -1,669.80 \, \frac{kJ}{\text{mol } Al_2O_3} \right) &+ \left( 3 \text{ mol } KCl \times -436.68 \, \frac{kJ}{\text{mol } KCl} \right) \\
&= -7,989.24 \, kJ
\end{align*}
\] (4)

\[
\begin{align*}
\left( 8 \text{ mol } Al \times 26.98 \, \frac{g}{\text{mol } Al} \right) &+ \left( 3 \text{ mol } KClO_4 \times 138.55 \, \frac{g}{\text{mol } KClO_4} \right) \\
&= 631.50 \, g
\end{align*}
\] (5)

\[
\begin{align*}
\frac{-1,290.36 \, kJ + 7,989.24 \, kJ}{631.50 \, g} &= 10.61 \, \frac{kJ}{g}
\end{align*}
\] (6)

2.3. Flash Powder Safety

Flash powders can be dangerous if accidentally ignited when confined, so it is recommended to store these powders in a non-rigid container such as a plastic zipper bag. Flash powders are relatively sensitive, so it is recommended for the user to wear a grounding strap when handling such powders to prevent an electrostatic discharge which will ignite the powder. Care should also be taken to avoid heating or suddenly impacting flash powders, as these conditions will also ignite the powder.

2.4. Test Article Preparation

Each test article was partially assembled, leaving the top endcap off. The test article was then placed on a scale so that the desired masses of charge and fuel could be loaded into the article. The central core of the article was filled with APP charge. While loading the charge, the powder was occasionally packed with a plunger so as to allow for a denser filling of the core. The plunger was operated by hand, and not with a table vice or press. The goal was to remove excess air so that more powder could be loaded into the core, and not to create a pressed pellet. The packing was done periodically as a large excess of air in the core would cause a puff of powder to escape when the plunger is inserted. Once the core was filled with the charge, fuel was loaded into annulus of
the article using a syringe. Kerosene fuel was used in this study as kerosene fuels are commonly used in missiles. The lower heating value of kerosene, 43.1 kJ/g, was taken as the specific energy since any water formed from the high temperature combustion of the fuel would be in vapor state.

Once the test article was completely loaded with charge and fuel, the top endcap was secured in place. A section of twin-lead solid-core wire approximately twice the height of the test article in length was cut, and a very short length was stripped at one end. The stripped portion was sufficiently short such that the wires remained close together but could not bend far enough to contact each other, allowing for a spark to occur across the gap between the wires. This end of the wire was inserted through the 1/8” hole in the top endcap and the exposed wires seated deep in the charge. The other end of the wire was then split to separate the two wires and each wire was stripped, ready to be connected to a firing system.

2.5. Instrumentation and Data Collection

A 4’x4’x4’ steel blast chamber was used for the majority of this study. A larger blast chamber would yield smaller pressure readings and a worse signal-to-noise ratio, while a smaller blast chamber would not withstand the energy release expected in the study. The blast chamber was set up with two vertical, spring-loaded columns positioned such that the article would be in the center of the chamber. The article was placed between two steel anvils that screwed into these columns, providing confinement in the axial direction so that breakout would occur in the radial direction instead. The free end of the twin-lead wire was passed through the upper anvil so that it could be connected to a longer wire leading out of the chamber and to the firing system used in this study. The blast chamber was also equipped with two Kulite XTEL-190A piezoresistive pressure
transducers located 21” radially from the center of the blast. These transducers were set up in a “lollypop” style configuration, in which a knife edge points radially towards the center of the blast. This knife edge cleanly slices the blast wave\(^1\) as it travels across the face of the transducer housing, allowing for the measurement of transient pressure, quasi-static pressure (QSP), and static pressure in the blast chamber. Figure 4 depicts this lollypop configuration and Figure 5 shows the setup of the blast chamber.

Figure 4: Lollypop configuration pressure transducer.

\(^{1}\) The blast wave is almost spherical, and emanates from the point of ignition.
A very large 8’x8’x10’ blast chamber, pictured in Figure 6, located in Quonset Hut A on the Engineering campus was also used for a few tests in this study. This blast chamber is 10 times larger in volume than the 4’x4’x4’ blast chamber and has large windows for imaging from the outside. Some videos were recorded in that large blast chamber using a high-speed CMOS camera positioned just outside the imaging window. The large blast chamber was also equipped with two Kulite XTEL-190A piezoresistive pressure transducers, much like those in the smaller blast chamber. Two steel plates held together by two bolts were used to provide axial confinement. The large blast chamber was ultimately not used for most of this study since, as expected, its large volume resulted in significantly lower recorded pressures. The smaller signal-to-noise ratio made resolving differences in energy release very difficult.
Figure 6: Large blast chamber.
A Teledyne RISI FS-43 firing system, Quantum Composers 9520 series pulse generator, and Picoscope 4424 PC oscilloscope were used in this study. The firing system generates a 4 kV potential, creating a spark across the gap between the two wires buried in the charge. The electrical arc ignites the charge, which produces a sharp pressure and temperature increase. This bursts the test article, disperses the liquid fuel into the air, and ignites the fuel cloud. The raw outputs of the pressure transducers were passed through an Endevco 136 DC amplifier, and the resulting signals were fed into the oscilloscope. The settings of the DC amplifier are listed in Appendix A. The oscilloscope was set to record 4 million samples per channel over a period of 200 ms with a 10% pre-trigger, for a 2 MHz sample rate per channel. A pressure calibration was done to convert the voltage readings to pressure readings. The data used for the calibration is recorded in Appendix B.

The firing system and oscilloscope were simultaneously triggered by the pulse generator, which was set to output a 10 μs, 5 V pulse. A Phantom v5.2 high-speed digital camera with a Tamron M12VM412 fisheye CCTV lens was used for imaging in the large blast chamber. The image resolution of the camera was set to 752 pixels x 752 pixels, with an exposure of 2 μs and a framerate of 1702 fps. The camera was also triggered by the pulse generator, with the same settings, when used. The aforementioned instruments are pictured in Figures 7-9.
Figure 7: Endevco 136 DC amplifier and Picoscope 4424 PC oscilloscope.

Figure 8: Teledyne RISI FS-43 firing system and Quantum Composers 9520 series pulse generator.
Figure 9: Phantom v5.2 high-speed digital camera and Tamron M12VN412 fisheye CCTV lens.

2.6. Data Reduction

A MATLAB graphical user interface (GUI) was developed to process the pressure data recorded in this study. The code for the GUI can be found in Appendix C. The GUI could import data saved from the oscilloscope. With some user input, the blast wave could then be characterized by important parameters such as time of arrival, rise time, peak overpressure, and impulse. A modified Friedlander equation could also be fit to the blast wave [6]. For this study, the GUI was mainly used to determine the QSP of each data set.
2.6.1. Quasi-Static Pressure (QSP)

QSP is defined as the static pressure resulting from an adiabatic and isochoric process. That is to say, no heat transfer occurs into or out of the system, and the system volume remains the same throughout. Such a process does not actually occur in reality, as some heat always departs the system through the blast chamber walls. Additionally, it is difficult to perfectly seal and maintain such a seal over repeated use in a blast chamber with so much surface area, so a slow leak of gases will inevitably occur. For these reasons, the QSP cannot simply be determined as the time average of pressure over a period of time after reflected waves die down and before significant heat loss occurs through the blast chamber walls. As all of the aforementioned effects act to reduce the pressure in the blast chamber, a line is instead fit to the decaying pressure over the period of time after reflected waves die down and extrapolated back to the time of arrival of the blast wave. Since the leak rate in the blast chamber is relatively slow, pressure along the line at the time of arrival of the blast wave is taken to be the QSP [7, 8]. This fitting method is visualized in Figure 10.

![Blast wave and QSP fit](image)

Figure 10: Blast wave and QSP fit. Figure taken from [8].
2.6.2. Energy Release

QSP can be correlated to energy release by analyzing some fundamental thermodynamic relations. This relationship is derived below, where the air in the blast chamber is the control volume and air is taken as an ideal gas.

Combine Mayer’s relation and the definition of the adiabatic index to get Equation (9).

\[ C_p - C_v = nR \]  
\[ \gamma = \frac{C_p}{C_v} \]  
\[ C_v = \frac{nR}{\gamma - 1} \]  

Then, take the ideal gas law and differentiate to obtain Equation (11).

\[ PV = nRT \]  
\[ PdV + VdP = nRdT \]  

Since the process is isochoric, \( dV = 0 \) and Equation (11) can be rewritten as Equation (12).

\[ dT = \frac{V}{nR} dP \]  

With the definition of heat capacity and with Equations (9) and (12), one obtains Equation (14).

\[ C_v = \frac{\left( \frac{dU}{dT} \right)_v}{V} \]  
\[ dU = \frac{V}{\gamma - 1} dP \]  

Recognize that the change in internal energy of the air in the blast chamber is equal to the energy released by the combustion process in this closed system to obtain Equation (15).

\[ \Delta E = \frac{V}{\gamma - 1} \Delta P \]
The system volume is known to be about 64 cubic feet (1.81 m$^3$) and $\gamma = 1.4$ for air taken as an ideal gas, so the energy release can be directly calculated from the QSP. An example of such a calculation with the blast chamber pressurized to 1 psi is shown below.

$$
\left( \frac{1.81 \text{ m}^3}{1.4 - 1} \right) \left( \frac{1 \text{ lb/ft}^2}{\text{in}^2} \right) \left( \frac{39.4 \text{ in}}{\text{m}} \right)^2 \left( \frac{4.45 \text{ N}}{\text{lb}} \right) \left( \frac{J}{Nm} \right) \left( \frac{kJ}{10^3 J} \right) = 31.3 \text{ kJ}
$$

(16)

2.6.3. Fuel Burn Fraction

A baseline with water serving as an inert fuel was made for each test in this study. The baseline characterizes the fraction of energy released by the driving charge that is lost to bursting the test article and dispersing the fuel. This quantity is referred to as lost energy, $E_{\text{lost}}$, and was added to the measured energy release in each test to accurately determine the fuel burn fraction. Knowing the lost energy for a known charge mass, the fuel burn fraction can be calculated using Equation (17), where $e_{\text{charge}}$ and $e_{\text{fuel}}$ are the specific energies of the charge and the fuel.

$$
\% \text{ Fuel Burn} = \left[ \frac{\Delta E + E_{\text{lost}} - (m_{\text{charge}} \times e_{\text{charge}})}{m_{\text{fuel}} \times e_{\text{fuel}}} \right] \times 100\%
$$

(17)

2.7. Searching Methods

In order to fill the central core and annulus of the test article completely, 5 g of charge and 3 g of fuel were used in the first tests of this study. The mass of fuel was held constant throughout the study, while the mass of charge was varied to explore the impact of charge-to-fuel mass ratio on the fuel burn fraction. The mass of charge used would gradually be decreased in an effort to find a mass ratio at which the fuel would not burn.
2.7.1. Lost Energy Hypothesis

It was initially hypothesized that the energy lost to bursting the test article and dispersing the fuel would remain constant. This hypothesis was made on the basis that the lost energy depends on the mechanical properties of the test article and the transport properties of the fuel. Since the materials used in the test article and the composition of the fuel did not vary within this study, the lost energy was expected to remain the same. Based on this hypothesis, it was assumed that the fuel would not burn if the energy released by the charge is less than or equal to the lost energy determined from the baseline tests with water. Almost all energy released would go into bursting the test article and dispersing the fuel, and little to no energy would go into igniting the fuel. Using the lost energy determined from the baselines and the specific energy of APP, a target charge mass of 2.84 g was determined for the next tests in the study.

Data from the following tests ultimately revealed that the hypothesis driving this searching method was flawed. The fuel still burned even if the energy released by the charge matched the lost energy determined by the baselines of the previous tests. Analysis of the debris field in the blast chamber provided an explanation for the failure of the hypothesis. As the charge mass decreased, the test article burst into fewer, and larger fragments. This decrease in surface area-to-volume ratio of the test article fragments resulted in less energy lost to bursting the test article. For solids, dividing the bulk of the material into pieces disrupts its bonds. This process consumes energy, which scales directly with the number of divisions made [9]. As such, dividing a material into more pieces, which increases the surface-area-to-volume ratio, increases the energy lost to the process. In general, it was observed that the lost energy decreases as the charge mass decreases. Additionally, it was found that the ratio of lost energy to charge energy, hereafter referred to as the lost energy
fraction, is not a constant. The variation in lost energy and lost energy fraction affirmed the need to conduct baselines with water for each test to accurately determine the fuel burn fraction.

The work required to accelerate the test article fragments was not considered in the analysis as the change in total kinetic energy of the system of fragments is expected to be approximately the same in all cases. A smaller charge produces fewer but more massive fragments that move at slower speeds, while a larger charge produces more but less massive fragments that move at faster speeds. As the change in total kinetic energy of the fragments is related to the work done on the fragments, the work required to accelerate the fragments is approximated as the same for all charge masses.

2.7.2. Bisection Method

Following the failure of the lost energy hypothesis, the bisection method was chosen to guide the study. According to this searching method, the mass ratio would be repeatedly halved until a critical point at which no fuel burns is observed. Once an interval over which this critical point exists is established, the interval would be bisected and the subinterval in which the critical point exists would be chosen to continue the search.
CHAPTER 3: RESULTS AND DISCUSSION

3.1. Ignition Limits

The results of this study are summarized in Figure 11, and Table 1 details the baseline tests with water while Table 2 details the tests with kerosene fuel. It is observed that the upper limit of fuel burn fraction in the test configuration is 63%. Increasing the mass ratio does not appear to have any effect on the fuel burn fraction above a critical point between 0.24 and 0.47. It is also observed that the lost energy fraction likely reaches a maximum at the same critical mass ratio. Following the correlation between charge mass and test article fragment size outlined before, this observation suggests that there may be a lower limit on the average fragment size in the test configuration. In other words, the average fragment size does not continue to decrease indefinitely as the mass ratio increases above the critical point. As the test articles are completely filled in the tests with mass ratio of 1.67, a hypothetical second critical point above which the lost energy levels off is not observed in this study. A larger test article with room for greater charge masses would have to be created, or a second test matrix in which the charge mass is held constant while fuel mass is decreased would have to be conducted.
Figure 11: Fuel burn fraction and lost energy fraction vs. mass ratio.

Table 1: Water baseline tests.

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<td>53.00</td>
<td>22.84</td>
<td>30.17</td>
<td>57%</td>
</tr>
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<td>0.95</td>
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<td>1.91</td>
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<td>1.40</td>
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Table 2: Kerosene fuel tests.

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<td>1.67</td>
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<td>104.38</td>
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<td>3.82</td>
<td>129.30</td>
<td>35.42</td>
<td>34.81</td>
<td>27%</td>
</tr>
<tr>
<td>0.09</td>
<td>2.86</td>
<td>129.30</td>
<td>12.38</td>
<td>11.69</td>
<td>9%</td>
</tr>
<tr>
<td>0.06</td>
<td>1.91</td>
<td>129.30</td>
<td>2.81</td>
<td>2.29</td>
<td>2%</td>
</tr>
</tbody>
</table>

While one of the primary motivations of this study is to find a critical mass ratio at which the fuel does not burn, no clear conclusion can be drawn regarding such a critical point. Following the bisection method, the mass ratio was repeatedly halved in order to find a point at which no fuel burns. However, the fuel appeared to continue burning even down to a mass ratio of 0.06, at which point the test article did not burst. Images of the unburst test article are provided in Figure 12. Since the test article did not burst, the fuel burn observed at this mass ratio could not have resulted from the ignition of explosively dispersed fuel. It is hypothesized that contained, burning charge acted as a heat source instead. The increase in temperature within the test article heated the liquid phase fuel, producing and igniting a small amount of fuel vapor. Alternatively, it is possible that the small fuel burn fraction observed is an artifact of noise or a slight calibration drift in the pressure transducers. With this interpretation, the results indicate that fuel burn can only be avoided by not bursting the test article. This is not a desirable outcome, but it demonstrates that kerosene is very sensitive to ignition when explosively dispersed in the test configuration.
3.2. Imaging

A sequence of images from a video taken with the high speed camera in the large test chamber is shown in Figure 13. Several important features can be observed from these images that may provide some insight to the mechanism behind the ignition of the fuel. A ring of bright particles is seen around the fireball in image 2. These particles are believed to be hot, burning clumps of aluminum that have been ejected from the test article. An optically thick cloud is observed to the left of the fireball in image 7. This is believed to be part of a cloud of fuel vapor that has not been obscured due to saturation from the intensity of the fireball. This cloud ignites and flame structures develop in subsequent images, with the cloud fully burning by image 37. Note that the fuel cloud likely exists in other regions of the image in the same time period, but those regions cannot be observed due to saturation. The jettison of large amounts of particles is seen in image 14. It is not clear if these particles are fragments of the test article or un-vaporized fuel droplets. Assuming the latter, this may account for the unburnt fraction of fuel, as the droplets are dispersed beyond the range of the fireball and thus do not ignite. The particles are also unlikely to be burning clumps of aluminum as they do not self-illuminate and are present even beyond image 37, which is a time
period well after the flash powder should have completely burned. An optically thick cloud is observed at the top of the fireball in image 30. This cloud grows in size over the next few images and most likely comprises primarily of soot resulting from the locally fuel-rich combustion of the fuel, though no composition analysis of the cloud was conducted. Several burning particles are seen emerging from the fireball at the top left in image 37. These particles are believed to be burning fragments of the test article since they reflect off the chamber walls and are observed at a much later time period than any of the other particles discussed before.

Integrating all of the information obtained from these images, the following ignition mechanism is proposed. The blast from the flash powder dispenses the fuel into a vapor cloud centered about the test article. Some of the dispersed fuel is sufficiently heated by the burning of the charge within the test article and ignites as the fuel cloud expands and mixes with air. The burning flash powder releases enough heat to scorch the test article, as evidenced by fragments collected in the aftermath of water baseline tests. Since the energy required to ignite fuel decreases with increasing temperature, some of the fuel is expected to burn while being ejected from the test article as long as sufficient mixing with air occurs [10]. The stoichiometric air-fuel-ratio of kerosene is 15.6:1, which can be determined using the process described in Section 2.2. Knowing this, the volume of a stoichiometric cloud of kerosene and air at 20 °C and 1 atm is calculated to be about 1.4 ft³. It is difficult to measure the exact size of the actual fuel cloud in Figure 13 due to saturation from the fireball. However, image 7 provides evidence that the span of the cloud may be as large as 3 ft across before significant fuel burn occurs. Note that the fuel cloud is irregular in shape, which makes estimation of its volume very difficult. Despite this uncertainty, the apparent span of the cloud is greater than the diameter of a 1.4 ft³ sphere, which is only about 1.4 ft. The irregularity of
the fuel cloud shape, along with its large span relative to the diameter of a sphere of stoichiometrically mixed kerosene and air, suggests that while mixing of the fuel and air occurs, there exist locally rich and locally lean regions. Specifically, the optically thick portion of the cloud observed in image 7, as well as any other similar regions that may be obscured by saturation, are believed to represent locally rich regions of fuel-air mixture. Consequently, burning aluminum from the flash powder is ejected into the fuel cloud. These particles create local hot zones within the fuel cloud, heating the vapor there beyond its auto-ignition point and causing the fuel to burn. Once ignition is occurs, the heat released by the combustion allows the process to continue until the entire fuel cloud is consumed. The sensitivity of the test configuration is attributed to the hot zones created within the locally rich regions of the fuel cloud by the dispersal of burning aluminum particles.
Figure 13: Image sequence from high speed camera.
Figure 13 (cont.)
3.3. Ignition Characteristics

Additional temporal information regarding the ignition of kerosene in the test configuration can be gained by directly analyzing the pressure traces obtained from the transducers. Figure 14 plots the blast pressure for mass ratios 1.67, 0.24, and 0.09 over a short time range, with dashed stems marking the times at which peak overpressure is observed. These mass ratios are significant as they represent the observed upper limit of the fuel burn fraction, the beginning of decrease in the fuel burn fraction, and the lower limit of the fuel burn fraction. It can be seen that an increase in mass ratio leads to an increase in rise time as well as duration of the blast wave. From a mass ratio of 0.09 to a mass ratio of 1.67, the rise time increases by about 40% while the duration increases by about 43%. These effects are believed to be an artifact of the sensor response time, which is about 0.05 μs. Since the peak overpressure is greater with a larger mass ratio, the pressure trace is expected to rise and fall slower with increasing mass ratio.

Figure 14: Pressure traces over short time range, varying mass ratio.
Figure 15 plots the same information as Figure 14, but over a long time range instead. It is observed that most of the fuel burns by about 50 ms in all cases, as the pressure traces for all mass ratios appear to level off by this time. However, upon closer inspection the pressure trace for a mass ratio of 0.09 actually continues to increase slowly beyond 50 ms. In fact, this behavior is present for larger mass ratios, but to a lesser degree. This result reveals that some of the overall pressure rise from the event is associated with afterburn of a portion of the fuel. Afterburn causes a slow increase in pressure, with most of the energy released going into heat instead. While energy is still released, afterburn of fuel is less dangerous compared to fast deflagration or detonation of fuel, as a sharp rise in pressure and a large impulse are necessary to inflict substantial damage.

![Pressure traces over long time range, varying mass ratio.](image)
Figures 16-18 plot the pressure trace with kerosene fuel against that of the water baseline for mass ratios 1.67, 0.09, and 0.06 over a long time range. Additionally, the pressure traces in Figures 17 and 18 have been smoothed with a span of 0.1 ms. Recall that the test article did not rupture at a mass ratio of 0.06. Comparing these figures, it can be seen that the portion of the overall pressure rise associated with afterburn increases with decreasing mass ratio. Notably, at a mass ratio of 0.06, no blast wave can be discerned, and the pressure simply rises slowly at an almost linear rate. This observation supports the previous assertion that some fuel did in fact vaporize and ignite within the test article due to heat from the contained and burning flash powder at this mass ratio.

![Pressure traces](image)

**Figure 16**: Pressure traces over long time range, mass ratio = 1.67.
Figure 17: Pressure traces over long time range, mass ratio = 0.09.

Figure 18: Pressure traces over long time range, mass ratio = 0.06.
On the other hand, Figures 19 and 20 plot the same information as Figures 16 and 17, but over a short time range. It is observed that there are two inflections in both pressure traces at around 0.13 ms and 0.27 ms. The blast wave appears to decay slower in this time range for the water baseline, while a local maximum followed by a local minimum is present with kerosene. These small humps and dips also appear throughout the rest of the pressure trace. Given this information, it is believed that a hump and a dip do exist in the aforementioned time range for the water baseline. However, the magnitude of these features may not be large enough for them to appear as a local maximum and local minimum, as observed with kerosene. The humps and dips also appear to almost line up between both figures, but are much more subtle with the smaller mass ratio. It is hypothesized that these features result from reflections of the blast wave from physical obstructions in the blast chamber. Particularly, the blast wave is suspected to reflect off the anvils that provide axial confinement of the test article. As these anvils are in close proximity with the test article, and in extension the point of ignition of the flash powder, waves reflected off them are expected to arrive at the sensor with only a small delay behind the primary blast wave. The reflected waves should also be greater in magnitude for the kerosene tests, since some of the fuel dispersed when the test article bursts burns early in the event due to heat released by the burning flash powder, as discussed before. These proposed behaviors are consistent with the features observed in the pressure traces.
Figure 19: Pressure traces over short time range, mass ratio = 1.67.

Figure 20: Pressure traces over short time range, mass ratio = 0.09.
3.4. Wall Effects

As two blast chambers of significantly different sizes were used in this study, it becomes possible to quantify the effects of the walls on fuel burn. Henceforth, the 4’ x 4’ x 4’ chamber is referred to as the small chamber, while the 8’ x 8’ x 10’ chamber is referred to as the large chamber. Figure 21 plots the pressure trace with kerosene fuel at mass ratio 1.67 in the large chamber against that in the small chamber over a short time range. The rise time of the blast wave is almost exactly the same in both chambers, but the duration seems to be slightly shorter in the small chamber. This difference is attributed to waves reflecting off the confinement anvils, as outlined above. These reflected waves pass by the transducer over much shorter time intervals and with greater intensity in the small chamber. As such, a reflected wave might have passed over the transducer at such a time that its negative phase caused a dip in the positive phase of the primary blast wave, resulting in an apparently shorter duration.

As no reflections from the chamber walls are observed in Figure 21, it is useful to calculate the expected time of arrival of such waves and plot the pressure traces over an appropriate time range. Even though dispersion of fuel and fragments occurs following the burst of the test article, the blast chambers are filled primarily with air. Additionally, no detonation is observed in any of the tests. As such, the speed of the blast wave through the chambers is taken to be the speed of sound through air, which is about 343 m/s. One can convert this value to units more useful in the test configuration, obtaining approximately 1.13 ft/ms. The pressure transducers are known to be located approximately 0.25 ft and 1.33 ft away from the walls in the small and large blast chambers. Dividing twice the distances by the speed of the blast wave, one obtains a time constant of about 0.4 ms and 2.4 ms between reflected waves for each blast chamber. Note that this an
oversimplification in order to provide a rough estimate on the time constants. The pressure traces should then be plotted over 5 ms in order to observe at least two reflected waves in the large chamber, as shown in Figure 22. From this figure, one can see that the reflected waves arrive at time intervals relatively close to the estimated time constants. The first reflected wave in the small chamber is notably missing, but it is believed to be hidden by the negative phase of the primary blast wave. It can be seen that the reflected waves are significantly less pronounced in the large chamber, to the point of being difficult to observe. This decrease in magnitude of the reflected waves is attributed to the increased distance between the point of ignition and the chamber walls. Additionally, the walls of the large chamber are lined with acoustic foam, which further dampens reflected waves.

![Pressure traces over short time range, mass ratio = 1.67.](image)

Figure 21: Pressure traces over short time range, mass ratio = 1.67.
Figure 22: Pressure traces over time range for reflected waves, mass ratio = 1.67.

Figure 23 plots the same information as Figures 21 and 22, but over a long time range instead. It can be seen that the pressure trace in the small chamber exhibits the slow, long-term pressure rise associated with afterburn, as discussed previously. However, the pressure trace in the large chamber stays mostly constant over the same time range. This observation, combined with the above comparison of the strength of reflected waves in both chambers, suggests a link between reflected waves and fuel afterburn. It is proposed that sufficiently strong reflected waves collide within the fuel cloud, compressing and heating regions of fuel. At the same time, the passage of the pressure waves through the fuel cloud promotes additional mixing of the fuel with air. These two effects together encourage remaining pockets of fuel that did not burn at earlier times to ignite. As such, the fuel burn fraction is expected to be artificially inflated by wall effects in the small blast chamber. The fuel burn fractions for a mass ratio of 1.67 in both the large and small chambers are listed in Table 3. The results reveal that wall effects may be responsible for as much as 11%
of fuel burn fraction due to afterburn initiated by reflected shock waves. This is significant, as it demonstrates that confining fuel-air explosions increases the destructive yield due to afterburn resulting from reflected waves [11, 12].

![Figure 23: Pressure traces over long time range, mass ratio = 1.67.]

Table 3: Fuel burn fraction at mass ratio 1.67, varying chamber size.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>52.93</td>
<td>129.73</td>
<td>94.78</td>
<td>66.96</td>
<td>52%</td>
</tr>
<tr>
<td>Small</td>
<td>53.04</td>
<td>129.08</td>
<td>104.38</td>
<td>81.51</td>
<td>63%</td>
</tr>
</tbody>
</table>

3.5. Repeatability and Uncertainty

Figure 24 plots the pressure trace with kerosene fuel at mass ratio 1.67 in three different tests over a short time range, while Figure 25 plots the same information, but with water. The water baselines
exhibit excellent repeatability with an error of approximately ± 1%, which affirms the consistent nature of the flash powder charge. On the other hand, the peak overpressure of the tests with kerosene fuel have an error of approximately ± 10%. This discrepancy is unlikely to arise from misalignment of the pressure transducers. Even though the peak overpressure scales as the square of the distance from the sensor to the point of ignition, such a deviation would also appear in the data for the water baselines. Instead, it is proposed that the difference in peak overpressure results from a calibration drift in the pressure sensors between different tests.

Figure 24: Kerosene pressure traces over short time range, mass ratio = 1.67.
Figure 25: Water pressure traces over short time range, mass ratio = 1.67.

Table 4 lists three baseline tests with water while Table 5 lists three tests with kerosene fuel. A variation of 2% in lost energy fraction and 6% in fuel burn fraction is observed. The very minor variation in lost energy fraction further supports the assertion that the flash powder charge burns consistently, while the greater variation in fuel burn fraction, which is related to the QSP, reveals that the deviation between the repeated kerosene fuel tests exists throughout the entire span of the pressure trace and is not limited to only the blast pressure. Figure 26, which plots the same information as Figure 24 over a long time range,\(^2\) provides further evidence to support this idea, as a clear offset can be observed between the three repeated tests. Knowing this, the variation in pressure can be explained by a drift in the calibration of the pressure transducers. The fact that this drift is only apparent with fuel and not with water suggests that the piezoresistive transducers are affected by the presence of burning fuel. Most likely, combustion products from burning fuel, such

\(^2\) Note that the pressure traces have been smoothed with a span of 0.1 ms.
as soot, are deposited on the diaphragm of the transducer. The added mass causes the diaphragm to physically respond differently to pressure, thus resulting in a calibration drift. While some combustion products are produced from the burning of the flash powder in the water baseline tests, the majority of the charge burns within the test article before it ruptures. As the added uncertainty arising from a calibration drift is undesirable, it is suggested that a pressure calibration be conducted before and after every test.

Table 4: Water baseline tests, mass ratio = 1.67.

<table>
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</thead>
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<tr>
<td>10</td>
<td>52.93</td>
<td>23.50</td>
<td>29.44</td>
<td>56%</td>
</tr>
<tr>
<td>11</td>
<td>53.15</td>
<td>22.85</td>
<td>30.30</td>
<td>57%</td>
</tr>
<tr>
<td>12</td>
<td>52.93</td>
<td>22.17</td>
<td>30.77</td>
<td>58%</td>
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</table>

Table 5: Kerosene fuel tests, mass ratio = 1.67.

<table>
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<th></th>
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</tr>
</thead>
<tbody>
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<td>13</td>
<td>53.04</td>
<td>128.87</td>
<td>100.72</td>
<td>77.12</td>
<td>60%</td>
</tr>
<tr>
<td>14</td>
<td>53.04</td>
<td>129.30</td>
<td>105.36</td>
<td>82.62</td>
<td>64%</td>
</tr>
<tr>
<td>15</td>
<td>53.04</td>
<td>129.30</td>
<td>107.06</td>
<td>84.79</td>
<td>66%</td>
</tr>
</tbody>
</table>
Figure 26: Kerosene pressure traces over long time range, mass ratio = 1.67.

3.6. Sensor Type

A PCB 137 piezoelectric dynamic pressure sensor was also used in some of the initial tests in this study. Piezoelectric sensors generate an electrical charge by mechanically stressing a sensing material. A static load produces a constant charge in the sensor. However, this charge is dissipated by electrical resistance within the sensing system, causing the signal to decay. For this reason, piezoelectric sensors do not provide useful measurements for events changing slower than the time constant for charge decay [13]. While the PCB 137 pressure sensor provided significantly improved resolution of the blast wave, it was not very useful in gathering data for the fuel burn fraction. As previously discussed, the fuel burn fraction is related to the QSP, which is characterized over a time scale long enough for signal decay to occur due to the intrinsic characteristics of piezoelectric sensors outlined above. Nevertheless, it is instructive to compare the blast wave as characterized by both the piezoresistive and the piezoelectric transducers.
Figure 27 plots the pressure trace with no fuel and a charge mass consistent with the amount that would have been used in a test with mass ratio 1.67. Note that water was not loaded into the fuel annulus. The most immediately obvious difference between the data recorded by the two sensors is that the rise time is significantly shorter with the piezoelectric sensor, as expected from its increased resolution. A second, sharp pressure rise is also observed at around 0.74 ms after the arrival of the primary blast wave. This is clearly a reflected wave, and the difference in the time of arrival of this reflected wave when compared to the data presented previously in the discussion on wall effects can be attributed to the fact that the piezoelectric sensor is positioned differently from the piezoresistive sensors within the blast chamber. Setting aside the rise time of the blast wave, the duration of the blast wave remains fairly consistent between both sensors. This makes sense, as the data for both sensors is drawn from the same test, and the charge mass is exactly the same. With this knowledge, there does not appear to be any advantage to using the piezoelectric sensor, despite its superior resolution.
Figure 27: Pressure traces over short time range, varying sensor type.
4.1. Summary and Conclusions

The primary motivation of this study is to explore the ignition limits of explosively dispersed fuel, with special emphasis on finding a lower limit in the context of safety. Kerosene was explosively dispersed by an APP charge from a cylindrical test article in the research conducted. An upper limit of 63% fuel burn fraction in the test configuration was observed at a charge-to-fuel mass ratio between 0.24 and 0.47. The addition of more charge did not appear to increase the fuel burn fraction, and instead burst the test article into smaller fragments. Based on the trend of lost energy vs. mass ratio, it was hypothesized that a lower limit may exist on the average size of the test article fragments. A desired lower limit of 0% fuel burn fraction was not observed in this study. Instead, it was found that the charge would fail to burst the test article before such a point was reached. This occurred at a mass ratio of 0.06. A small amount of fuel burn fraction of 2% was recorded at this mass ratio, which may have resulted from noise or a calibration drift in the sensors. Regardless of the accuracy of this fuel burn fraction, conclusions could not be drawn regarding ignition limits as the fuel was not explosively dispersed.

An examination of the wall effects of the small blast chamber was also conducted to better understand the presence of fuel afterburn. It was discovered that the reflections of the blast wave off the walls of the small chamber were strong enough to compress and heat the fuel cloud. These pressure waves also induced mixing of the fuel with air as they passed through the fuel cloud. On the other hand, the walls of the large chamber were farther away from the point of ignition and lined with foam. This resulted in significantly weaker reflected waves observed in the tests.
conducted in that chamber. Due to the lessened intensity of the reflected waves, afterburn was reduced to such a degree that the pressure trace no longer continued to rise over a long time range after 50 ms. This important result demonstrated that the confinement of fuel-air explosions has a significant impact on the fuel burn fraction, as a 11% decrease in fuel burn was observed when tests were conducted in the large chamber.

This study reveals that kerosene is very sensitive to ignition when explosively dispersed in the test configuration. It is believed that hot, burning aluminum powder is dispersed into locally rich regions of the fuel cloud when the test article bursts. The ejected powder creates local hot zones, heating the vapor beyond its auto-ignition temperature and causing the fuel to ignite and burn. With this proposed mechanism, it is likely that any fuel ignited in the test configuration will only deflagrate and not detonate as there is no identifiable process to accelerate the flame front.

4.2. Recommendations for Future Work

If future testing occurs, one of the first steps would be to improve the resolution of the recorded data. The critical mass ratio at which the fuel burn fraction reaches a maximum can then be determined with greater accuracy. The scope of the study can also be expanded to include mass ratios holding charge mass constant instead of fuel mass. Additionally, a test article with different geometry may be implemented to explore larger or smaller mass ratios. Given the apparent sensitivity of the system and the safety context of the study, it may also be desirable to vary the chemistry of the charge and the fuel. The charge may even be doped with additives in an effort to desensitize the fuel.
The research conducted for this study revealed the importance of lost energy and test article fragment size in drawing conclusions on and predicting the trends of fuel burn fraction. As such, a more rigorous study of the debris field from the tests can be conducted to gain better insight on the energy partition of the system. Wall effects were also revealed to have a significant impact on fuel afterburn. An appreciable decrease in fuel burn fraction was observed when reflected waves from the chamber walls were dampened by increased distance and the use of an acoustic foam lining. As such, the small chamber may be lined with foam in an effort to reduce the intensity of the reflected waves. Finally, better imaging work can be done by lowering the exposure of the camera or the f-number of the lens. This would allow for the better characterization of fuel clouds and flame structures as the fireball develops. A higher frame rate is also desirable to obtain more information at an early time period.
### APPENDIX A: DC AMPLIFIER SETTINGS

Table A.1: DC amplifier settings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Exc. (V)</td>
<td>10.00</td>
</tr>
<tr>
<td>Sensitivity (mV/EU)</td>
<td>3.500</td>
</tr>
<tr>
<td>Output Scaling (mV(EU)</td>
<td>2582</td>
</tr>
<tr>
<td>LP Filter (kHz)</td>
<td>10.00</td>
</tr>
<tr>
<td>Auto-Zero</td>
<td>ON</td>
</tr>
<tr>
<td>Shunt Calibration</td>
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APPENDIX B: PRESSURE CALIBRATION

Table B.1: Pressure calibration data.

<table>
<thead>
<tr>
<th>Pressure [psi]</th>
<th>Lollypop North [V]</th>
<th>Lollypop East [V]</th>
</tr>
</thead>
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<tr>
<td>-0.06</td>
<td>-0.001</td>
<td>0.005</td>
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<tr>
<td>0.5</td>
<td>0.311</td>
<td>0.624</td>
</tr>
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<td>1</td>
<td>0.586</td>
<td>1.174</td>
</tr>
<tr>
<td>1.5</td>
<td>0.856</td>
<td>1.709</td>
</tr>
<tr>
<td>2</td>
<td>1.130</td>
<td>2.249</td>
</tr>
<tr>
<td>2.5</td>
<td>1.409</td>
<td>2.810</td>
</tr>
<tr>
<td>3</td>
<td>1.682</td>
<td>3.348</td>
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<tr>
<td>3.5</td>
<td>1.959</td>
<td>3.899</td>
</tr>
<tr>
<td>4</td>
<td>2.223</td>
<td>4.430</td>
</tr>
</tbody>
</table>

Table B.2: Pressure calibration linear fit.

<table>
<thead>
<tr>
<th></th>
<th>Lollypop North</th>
<th>Lollypop East</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$ [psi/V]</td>
<td>1.823</td>
<td>0.917</td>
</tr>
<tr>
<td>$b$ [psi]</td>
<td>-0.064</td>
<td>-0.070</td>
</tr>
<tr>
<td>RSQ</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Figure B.1: Pressure calibration plot.
APPENDIX C: BLAST PROCESSING CODE

```
function Blast_GUI

    % Clean up
    close all
    clear all
    clc

    % Files and channels per file
    n = 3;
    m = 4;

    % UIControl positions
    xpos = [0.53 0.62 0.68 0.75 0.82 0.89];
    ypos = 0.93;
    xwidth = [0.07 0.04 0.05 0.05 0.06 0.06];
    yheight = 0.03;
    yspace = 0.01;
    channel_list = {'A','B','C','D'};

    % Initialize variables
    file = zeros(1,n);
    channel = zeros(n,m);
    slope = zeros(n,m);
    v_int = zeros(n,m);
    plot_type = zeros(n,m);
    plot_select = zeros(n,m);
    mf_coeff = zeros(n,m);
    mf_select = zeros(n,m);
    temp_figure = 0;
    temp_axes = 0;
    t_min = 0;
    t_max = 0;
    click = zeros(1,3);
    align_toa = 0;
    colors = cell(n,m);
    Time = cell(1,n);
    T0 = zeros(1,n);
    Ch = cell(n,m);
    Pmax = zeros(n,m);
    Pmax_time = zeros(n,m);
    TOA = zeros(n,m);
    P_TOA = zeros(n,m);
    TOE = zeros(n,m);
    P_TOE = zeros(n,m);
    Pmin = zeros(n,m);

Figure C.1: Blast processing code.
```
Figure C.1 (cont.)
for i = 1:n

% File input
file(i) = uicontrol('Style','pushbutton','String', '', ...
    'FontWeight','bold','FontUnits','normalized','Value',i, ...
    'Units','normalized','Position',[xpos(i) ...
    ypos-(yheight+1.5*yspace)*m-(yheight+1.5*yspace)*m*(i-1) ...
    xwidth(i) (yheight+yspace)*m-0.01], 'Callback', ...
    @(fileopen_Callback));
setappdata(file(i), 'Value', i);

for j = 1:m

% Channel input
channel(i,j) = uicontrol('Style','edit','String', 'channel_list(i)', ...
    'FontWeight','bold','FontUnits','normalized', ...
    'Enabled','inactive','BackgroundColor', [0.8 0.8 0.8], 'Units','normalized','Position', [xpos(2) ...
    ypos-2*yspace-(yheight+yspace)*j-(yheight+1.5*yspace)*m*(i-1) xwidth(2) yheight]);

% Slope input
slope(i,j) = uicontrol('Style','edit','String', '1', ...
    'FontWeight','bold','FontUnits','normalized', ...
    'BackgroundColor',[1 1 1], 'Units','normalized', ...
    'Position', [xpos(3) ...
    ypos-2*yspace-(yheight+yspace)*j-(yheight+1.5*yspace)*m*(i-1) xwidth(3) yheight]);

% Y-intercept input
y_int(i,j) = uicontrol('Style','edit','String', '0', ...
    'FontWeight','bold','FontUnits','normalized', ...
    'BackgroundColor',[1 1 1], 'Units','normalized', ...
    'Position', [xpos(4) ...
    ypos-2*yspace-(yheight+yspace)*j-(yheight+1.5*yspace)*m*(i-1) xwidth(4) yheight]);

% Plot type input
plot_type(i,j) = uicontrol('Style','popupmenu','String', ...
    {'QSF','Blast'}, 'FontWeight','bold','FontUnits', ...
    'normalized','Value',i,'BackgroundColor', [1 1 1], ...
    'Units','normalized','Position', [xpos(5) ...
    ypos-2*yspace-(yheight+yspace)*j-(yheight+1.5*yspace)*m*(i-1) xwidth(5)-0.02 yheight], 'Callback', ...
    @(popup_Callback));
plot_select(i,j) = uicontrol('Style','checkbox','String', ..., 
    '',  'FontWeight','bold','FontUnits','normalized', ...
Figure C.1 (cont.)
Figure C.1 (cont.)

```matlab
[1 1 1], 'Units', 'normalized', 'Position', [xpos(1) ...
  ypos-4*yheight-16*yspace-(yheight+yspace)*m ...
  -(yheight+1.5*yspace)*m*(n-1) xpos(2)-xpos(1)+xwidth(2) ...
  2*yheight+yspace]);

save_plot = uicontrol('Style', 'pushbutton', 'String', 'Save', ...
  'FontWeight', 'bold', 'FontUnits', 'normalized', 'Units', ...
  'normalized', 'Position', [xpos(3) ...
  ypos-4*yheight-16*yspace-(yheight+yspace)*m ...
  -(yheight+1.5*yspace)*m*(n-1) xpos(4)-xpos(3)+xwidth(4) ...
  2*yheight+yspace], 'Callback', [@save_Callback]);

process = uicontrol('Style', 'pushbutton', 'String', 'Process Data', ...
  'FontWeight', 'bold', 'FontUnits', 'normalized', 'Value', 0, 'Units', ...
  'normalized', 'Position', [xpos(5) ...
  ypos-4*yheight-16*yspace-(yheight+yspace)*m ...
  -(yheight+1.5*yspace)*m*(n-1) xpos(4)-xpos(3)+xwidth(4) ...
  2*yheight+yspace], 'Callback', [@process_Callback]);

% Display table for parameters
blast_parameters = {'Avg QSP [psi]', 'T0 QSP [psi]', 'Peak [psi]', ...
  'TOA [ms]', 'Rise Time [ms]', 'Duration [ms]', 'Impulse [psi-ms]', ...
  'Nf Impulse [psi-ms]', 'T 10/90 [ms]'};

names = cell(1,n*m);
for i = 1:n
  for j = 1:m
    names{j+m*(i-1)} = [num2str(i) ' ' channel_list{j}];
  end
end

names{size(names,2)+1} = 'Average';
table = uitable('FontUnits', 'normalized', 'Units', 'normalized', '...
  'Position', [0.02 0.02 0.47 0.47], 'ColumnName', blast_parameters, ...
  'RowName', names);

% Popup callback
function popup_Callback(source, ~)
  val = get(source, 'Value');
  switch val
    case 1
      setappdata(source, 'Value', 1);
    case 2
      setappdata(source, 'Value', 2);
  end
end

% Fileopen callback
```
function fileopen_Callback(source,~)
    num = getappdata(source, 'Value');
    old_flm = getappdata(file(num), 'fname');
    old_flpth = getappdata(file(num), 'fpath');
    [flm, flpth] = uigetfile(['.mat', 'All Files']);
    setappdata(file(num), 'fname', flm);
    setappdata(file(num), 'fpath', flpth);
    if (ischar(flm) == 1) & (ischar(flpth) == 1)
        set(file(num), 'String', flm);
    else
        setappdata(file(num), 'fname', old_flm);
        setappdata(file(num), 'fpath', old_flpth);
    end
end

function process_Callback(~,~)

    % Clean up
    cla(hax)
    clc
    hold on

    % Create colormap
    colorful = colormap(hsv);
    spacing = round(length(colorful)/(n*m));
    for i = 1:n
        for j = 1:m
            colors(i, j) = colorful(((i-1)*3+j)*spacing, :);
        end
    end

    % Load file data
    if ischar(getappdata(file(1), 'fname')) == 1
        A = 0;
        B = 0;
        C = 0;
        D = 0;
    end
end

Figure C.1 (cont.)
Length = 0;
Tinterval = 0;
Tstart = 0;
ExtraSamples = 0;
RequestedLength = 0;

load_file = strcat(getappdata(file(i), 'fpath'), ...
getappdata(file(i), 'fname'));
load(load_file)

for j = 1:m
    Time(i,j) = (Tstart:Tinterval:Tstart+Tinterval* ... 
                  (Length-1))*1000;
    Data = zeros(length(Time(i,j)),4);
end

for j = 1:m
    Data(:,j) = eval(channel_list{j});
end

% Remove saturated data
Data(~isfinite(Data)) = 0;

% Find T = 0 ms
T0(i) = find(Time(i,j)<0,1,'last');

% Apply calibration & correct zero offset
for j = 1:m
    Ch(i,j) = Data(:,j)* ... 
              str2double(get(slope(i,j),'string')) + ... 
              str2double(get(y_int(i,j),'string'));
    Ch(i,j) = Ch(i,j) - mean(Ch(i,j)(1:T0(i)));
end

end

% Process data
for j = 1:m

    if get(plot_select(i,j), 'Value') == 1

        % Set up figure to find blast wave
        temp_figure = figure('NumberTitle', 'off', 'Units', ...
                               'normalized', 'position', [0.2 0.25 0.6 0.5]);
        temp_axes = axes('Position', [0.06 0.12 0.43 0.84]);
        temp_panel = uipanel('BorderType', 'line', ...
                              'HighlightColor', [0 0 0], 'Position', ...
Figure C.1 (cont.)
Figure C.1 (cont.)
Figure C.1 (cont.)

```matlab
(t_click-50:t_click+50), 'MinPeakHeight', ...
mean(Ch(i,j)(t_click-50:t_click+50)), 'SortStr', ...
'descend');
Fmax_index = temp_ind(1) + t_click - 51;
Pmax(i,j) = Ch(i,j)(Fmax_index);
Pmax_time(i,j) = Time(i,j)(Fmax_index);

% Find TOE
 t_click = find(Time(i,j)<click(end),1,'last');
[-,temp_end] = findpeaks(-Ch(i,j) ...
(t_click-50:t_click+50), 'MinPeakHeight', ...)
mean(-Ch(i,j)(t_click-50:t_click+50)));
TOE_index = temp_ind(end) + t_click - 51;

% Update TOA & TOE if pressure is negative
if Ch(i,j)(TOA_index) < 0
    zero_index = find(Ch(i,j) ...
    (TOA_index:Fmax_index)>0,1,'first');
    TOA_index = zero_index + TOA_index - 1;
end

if Ch(i,j)(TOE_index) < 0
    zero_index = find(Ch(i,j) ...
    (Fmax_index:TOE_index)>0,1,'last');
    TOE_index = zero_index + Fmax_index - 1;
end

TOA(i,j) = Time(i,j)(TOA_index);
P_TOA(i,j) = Ch(i,j)(TOA_index);
TOE(i,j) = Time(i,j)(TOE_index);
P_TOE(i,j) = Ch(i,j)(TOE_index);

% Find min
Pmin(i,j) = min(Ch(i,j)(Fmax_index:end));

% Calculate average QSP
QSP_index = round((TOE_index+length(Ch(i,j)))/2);
QSP = mean(Ch(i,j)(QSP_index:end));

% Calculate linreg QSP
LinFit = polyfit(Time(i,j)(QSP_index:end),Ch(i,j) ...
(OQP_index:end),1);
LinCurve(i,j) = LinFit(1)*Time(i,j) + LinFit(2);
QSP_L = LinCurve(i,j)(TO(i));

% Calculate impulse
Impulse = trapz(Time(i,j)(TOA_index:TOE_index), ...
Figure C.1 (cont.)
\begin{verbatim}
ExpPressure = Ch(i,j)(Pmax_index:TOE_index);
ExpDecay = @(const,ExpTime) P0 + const(1)* ... 
(1-ExpTime./const(2)).* ...
   exp(-(const(3)/const(2)).*ExpTime);
   [const,~,~,~,~] = lsqcurvefit(ExpDecay, ...
const,ExpTime,ExpPressure,[],[],options);
LastIndex = find(Time(i,j)<const(2),1,'last');
mf_TOE(i,j) = Time(i,j)(LastIndex);
ExpTime = Time(i,j)(Pmax_index:LastIndex);
ExpCurve = P0 + const(1)* ... 
(1-ExpTime./const(2)).* ...
   exp(-(const(3)/const(2)).*ExpTime);
mf_max(i,j) = ExpCurve(1);

% Truncate if long tail
if const(2) > Time(i,j)(Pmax_index) + 2
   LastIndex = find(ExpCurve>0.01,1,...
   'last') + Pmax_index;
   mf_TOE(i,j) = Time(i,j)(LastIndex);
end
ExpCurve = ExpCurve(1:LastIndex - ...
   Pmax_index + 1);

% Linear rise fit
RiseFit = polyfit([TOA(i,j) Time(i,j) ...
   (Pmax_index),[Ch(i,j) ... 
   (TOA_index) ExpCurve(1)],1);
FirstIndex = find(Time(i,j)> ...
   (-RiseFit(2)/RiseFit(1)),1,'first');
mf_TOE(i,j) = Time(i,j)(FirstIndex);
RiseCurve = RiseFit(1)*Time(i,j) ...
   (FirstIndex:Pmax_index-1)+ RiseFit(2);

% Combine linear rise & exponential decay
Friedlander = [RiseCurve; ExpCurve];
Fried_Time = Time(i,j)(FirstIndex:LastIndex);

% Calculate impulse & plot Friedlander fit
Fried_Imp = trapz(Fried_Time,Friedlander);
plot(Fried_Time,Friedlander,'color', ...
   [colors(i,j)],'LineStyle','--', ...
   'LineWidth',2);

hello_world(((i-1)*3+j),8) = Fried_Imp;
end
\end{verbatim}
Area = cumtrapz(Time(i,j)(TOA_index:TOE_index), ...
    Ch(i,j)(TOA_index:TOE_index));
T_10index = find(Area>0.1*Area(end),1,'first');
T_90index = find(Area>0.9*Area(end),1,'first');
T_1090 = (Time(i,j)(T_90index)-Time(i,j) ...
    (T_10index));
stem([TOA(i,j) Pmax_time(i,j) TOE(i,j)], ...
    [P_TOA(i,j) Pmax(i,j) P_TOE(i,j)],'color', ...
    [colors(i,j)],'LineStyle','--','LineWidth',2);

% Use Friedlander limits if they exist
for i = 1:n
    for j = 1:m
        if mf_TOA(i,j) == 0
            TOA(i,j) = mf_TOA(i,j);
        end
    end
end

for i = 1:n
    for j = 1:m
        if mf_TOE(i,j) == 0
            TOE(i,j) = mf_TOE(i,j);
        end
    end
end

% Fudge empty TOA values
for i = 1:n
    for j = 1:m
        if TOA(i,j) == 0
            TOA(i,j) = max(cell2mat(reshape( ...
                Time,[],i)));
        end
    end
end

Tmin = floor(min(TOA(:)/0.1)*0.1);
Tmax = ceil(max(TOE(:)/0.1)*0.1);

% Use Friedlander limits if they exist
for i = 1:n
    for j = 1:m
        if mf_max(i,j) == 0
            Pmax(i,j) = mf_max(i,j);
        end
    end
end

Figure C.1 (cont.)
function plot_Callback(~, ~)

    % QSP time range
    if get(display_type,'Value') == 1
        Tmin = 0;
        Tmax = floor(max(cell2mat(reshape(Time, [], 1)))/20)*20;
    elseif get(display_type,'Value') == 2
        Imin = floor(min(TOA(:))/0.1)*0.1;
        Tmax = floor(max(TOA(:))/0.1)*0.1;
    end

    % Calculate averages
    for i = 1:size(hello_world, 2)
        hello_world(end, i) = mean(nonzeros(hello_world([1:n*n], i)));

        if isnan(hello_world(end, i)) == 1
            hello_world(end, i) = 0;
        end
    end

    set(table, 'Data', hello_world)
end
Tmax = ceil(max(TOE(:))/0.1)*0.1;
end

xlim([Tmin Tmax]);
ylim([floor(min(Pmin(:)))] max(Pmax(:))]);
end

function tmin_minus_Callback(~,~,timestep)
    t_min = t_min - timestep;
    set(temp_axes,'xlim',[t_min t_max]);
end

function tmin_plus_Callback(~,~,timestep)
    if t_min + timestep < t_max
        t_min = t_min + timestep;
        set(temp_axes,'xlim',[t_min t_max]);
    end
end

function tmax_minus_Callback(~,~,timestep)
    if t_max - timestep > t_min
        t_max = t_max - timestep;
        set(temp_axes,'xlim',[t_min t_max]);
    end
end

function tmax_plus_Callback(~,~,timestep)
    t_max = t_max + timestep;
    set(temp_axes,'xlim',[t_min t_max]);
end

function save_Callback(~,~)
    f2 = figure('Name','Blast Analysis','NumberTitle','off',...
    'Units','normalized','position',[0.2 0.25 0.6 0.5]);
    s = copyobj(fig1,f2);
    set(s,'Units','normalized','Position',[0.12 0.12 0.8 0.8]);
end

function align_Callback(~,~)
    % Clean up
    cla(fig1)
    clc

Figure C.1 (cont.)
Figure C.1 (cont.)
end

end

align_toa = 0;

% QSP time range
if get(display_type,'Value') == 1
    Tmin = 0;
    Tmax = floor(max(cell2mat(reshape(Time,[],1)))/20)*20;
    % Blast pressure time range
elseif get(display_type,'Value') == 2
    Tmin = floor(min(TOR(:))/0.1)*0.1;
    Tmax = ceil(max(TOE(:))/0.1)*0.1;
end

xlim([Tmin Tmax]);
ylim([floor(min(Fmin(:))) ceil(max(Fmax(:)))]);

end

hold off

end
REFERENCES


