BLAST DIAGNOSTIC TOOLS AND TECHNIQUES: A REVIEW

BY

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THESIS

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ABSTRACT

Pressure measurements are essential in determining the energy output from shock waves generated by high explosives. Thus, it is imperative to choose appropriate sensors and measurement techniques to consistently acquire useful data. Past studies conducted in diagnostics of energetic materials were focused on the energy release and the material properties, but very few, if any, placed an emphasis on the actual diagnostic tools and techniques. There are two main types of pressure transducers utilized in the industry today: piezoresistive and piezoelectric. Piezoresistive sensors experience a change in internal resistance when the sensing material is subjected to mechanical strain, while piezoelectric sensors generate an electric charge when placed under a similar condition. In addition to the two industry standards the Manganin pressure sensor also plays an important role in blast diagnostics. This type of sensor represents a niche part of the pressure transducer market and are primarily used to capture the detonation pressure for high explosives. In this study, appropriate measurement techniques, in addition to the tools utilized, were examined to achieve seamless data collection. Electric noise reduction and data loss prevention techniques were explored in this study. Some of these techniques include: adding feed-through terminator to reduce signal output, creating protective barriers surrounding signal cables, and reducing amplifier-to-gauge cable length. Through preparation and application of appropriate techniques, valuable data can be adequately acquired on a consistent basis with minimal disturbances.

I dedicate this thesis to my parents and President John F. Kennedy

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CHAPTER 1

INTRODUCTION TO BLAST DIAGNOSTIC TOOLS

1.1 Chapter Overview

The purpose of this investigation is to create a complete guide on the instruments and techniques utilized in the measurement of shock wave pressures generated from detonations of explosives in both confined chambers and open-field environments. Sample data were acquired from previous tests to illustrate case studies where there is electric noise in the test data, unexpected signal patterns, and other anomalies in which the data collected is rendered unusable; following initial diagnosis of the test signal, appropriate counter-measures are then explored to mitigate the associated risks. The experiments conducted can be split into two main categories: confined metal casing detonations and explosions with fuel combustion. Confined casing detonations were conducted inside one of two blast chambers in Mechanical Engineering Laboratory, while detonation tests with combustion of JP-10 fuel were conducted in both the large-scale Quonset hut blast chamber and in an open field environment.

Applicable pressure transducers such as the piezoresistive type, the piezoelectric type, and thin-film Manganin gauges are described in this study. These pressure transducers respond differently to shock waves generated from high explosives due to their unique properties. The workhorse pressure transducers utilized in charge detonation experiments are manufactured by Kulite, PCB Piezotronics, and Gems Sensor. They split into two main categories: piezoelectric and piezoresistive. The physics that governs these two types of pressure transducers are unique, and they respond differently to dynamic and static pressure. In addition to the piezoelectric type and piezoresistive type pressure sensors, the single-use Manganin gauge also plays a vital role in blast diagnostics. The Manganin sensing element experiences a resistance change when it is subjected to compressive stress, but the gauge is destroyed for each test that is conducted. It requires an external pulsation lasting ~100 μs, and it is more difficult (and expensive) to use compared to other gauges. Pressure transducers for explosive diagnostics must have fast response times since the window of opportunity to acquire the changes in pressure is narrow. As illustrated by the picture in Figure 1.1, the rise and fall in the initial peak pressure for a standard detonation test inside a sealed chamber lasts ~0.3 ms; this time period is even shorter for Manganin gauges, where the peak detonation pressure can only be acquired in ~1.5 μs before the gauge is destroyed by the blast.

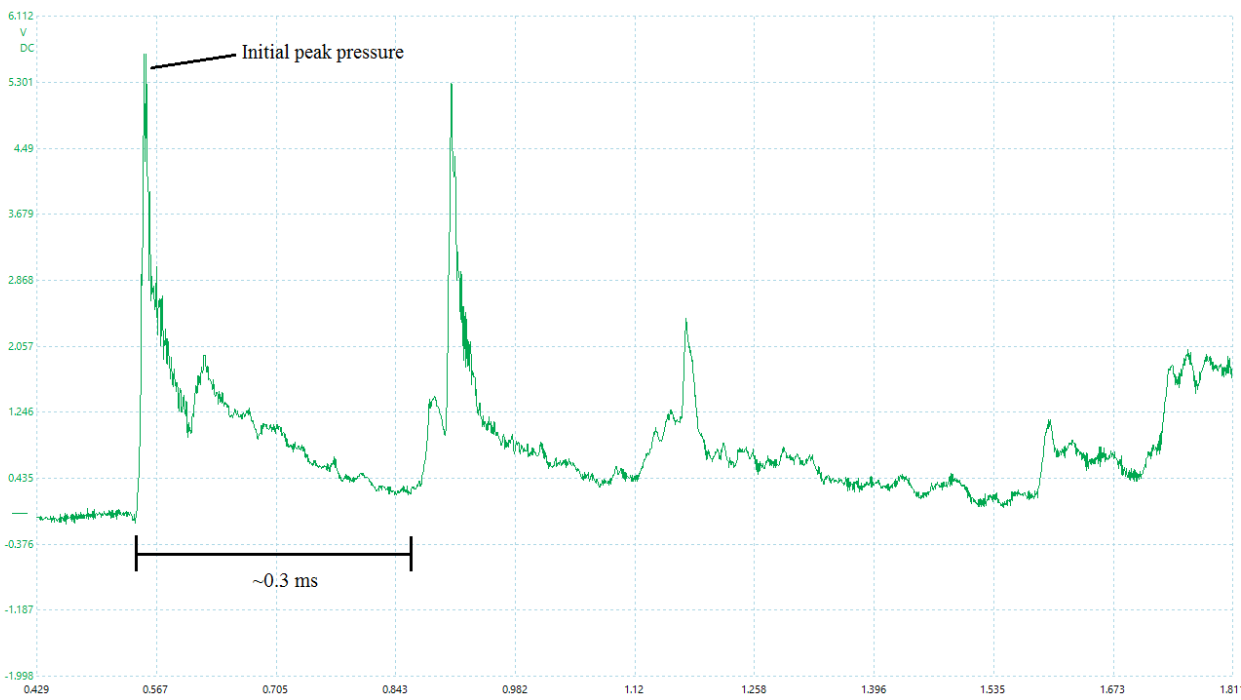

Figure 1.1 Duration of Pressure Change for a Closed Chamber Detonation

The distinct signal patterns captured in a confined environment differs from that of an open field environment, but it creates an opportunity to assess and compare the pressure data acquired under such different test conditions. The shock waves generated by high explosives in a closed chamber environment experience reflections between the chamber walls, this generates more oscillations in the test signal in comparison to open field tests. These disparate settings also call for selective gauge positioning to account for height and distance differentials to create an effective comparison among the pressure readings.

From data recorded in past closed chamber and open field charge detonation experiments, the two central complications stemmed from the data acquisition process are electric noise and signal cable integrity. Cable damage by fragments often creates signal loss and impact of these fragments can also induce unwanted transients in addition to rampant oscillations. This study provides ample illustrations on when things do go wrong during testing, and gives the appropriate counter measures to mitigate noise and avoid unusable data. To counter data loss and test signal noise, preventive techniques such as the addition of protective layers, utilization of redundant gauges, and addition of feed-through terminators will be explored in detail.

1.2 Piezoresistive Pressure Transducer

The piezoresistive effect governs the behavior for piezoresistive pressure transducers when the material inside the sensing element experiences a change in electrical resistance as it is subjected to an external mechanical strain [1, 2]. The piezoresistive pressure transducers utilized in charge detonation experiments are manufactured by Kulite. These sensors fall under the model number XTEL-190L-100A. The maximum pressure for these pressure transducers is rated at 100 psig (689.5 kPa). The XTEL series can capture both the dynamic pressure and the quasi-static pressure. Unlike the piezoelectric transducer, the pressure sensor from Kulite is much smaller and requires a custom-made containment structure as shown in Figure 1.2. The structure consists of an insertion port, a blast interface, and a protective structure for the USB connector. The design for the sensor containment structure is not definitive and future improvements can be made to reduce cable exposure. When positioning the gauge inside test chambers, the blast interface should be oriented in a position where it can effectively "cut" the pressure wave generated from an explosion. Without the blast interface, a direct frontal exposure to shock waves can cause significant noise.

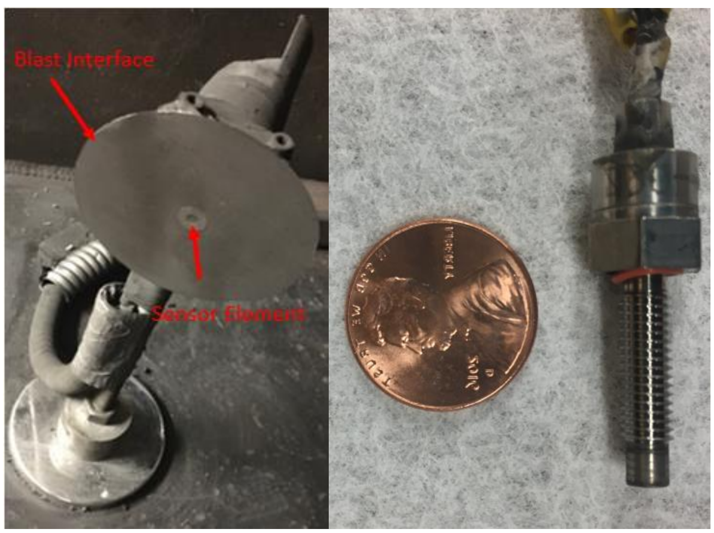

Figure 1.2 Piezoresistive Sensor Containment Structure (Left) and Sensing Element (Right)

The XTEL-190L-100A requires a signal conditioner (Endevco 136 Amplifier) during the data acquisition process. The amplifier's front and rear panels are shown in Figure 1.3. The Endevco amplifier, unlike the ICP amplifier for piezoelectric sensors, requires specific settings for excitation voltage, scaling, sensitivity, and low pass filter frequency, as indicated by Table 1.1. In addition, the individual pressure transducers connected to the amplifier must be zeroed each time that the amplifier is turned on. The settings on the Endevco 136 amplifier are not definitive, and they can change according to the limits of the data acquisition device or the specific sensor model [3]. For example, if the captured signal exceeds the voltage threshold for the data acquisition device, the output scaling or sensitivity can be adjusted on the amplifier to reduce the voltage output. The Endevco 136 is not the only amplifier compatible with the XTEL sensors from Kulite, alternative amplifiers in the market can also provide signal conditioning.

Figure 1.3 Front and Back Panels of the Endevco 136 Amplifier and Signal Conditioner for Kulite Piezoresistive Sensors

One of the easiest ways to determine if there is a fault in the cable or in the sensing element is the Auto-Zero function. When the function provides a reading that displays “Err4”, this indicates that the amplifier is not recognizing the piezoresistive sensor (function error) [3]. The best procedure to tackle this issue is to check for cable damage to ensure that the amplifier is still connected to the sensor. On occasions, the sensing element might be at fault, if the test signal is experiencing transients on a consistent basis when there is no visible damage to the signal cable, the sensing element needs to be examined and replaced if necessary.

Table 1.1 Endevco 136 Amplifier Settings for Kulite XTEL Piezoresistive Sensors

Setting	**Value**
Voltage Excitation (V)	10
Sensitivity (mV/EU)	17
Output Scaling (mV/EU)	2582
LP Filter (kHz)	10
Auto-Zero	ON
Shunt Calibration	OFF

The secondary piezoresistive sensors utilized in high explosive testing are manufactured by Gems Sensor & Controls, it is connected to a constant DC power supply and does not require signal conditioning through an amplifier. Similar to the Kulite piezoresistive sensor the Gems sensor is also capable of capturing both the initial peak pressure and the quasi-static pressure. Inside the confined casing test chamber the Gems sensor is connected to an internal QSP port, so it can only provide quasi-static pressure readings in the current chamber setup. To prevent saturation in the test signal, it is recommended that the BNC cable connecting the sensor to the measurement device has an inline terminator. The sensor is designed for measuring pressure in a sealed enclosure. In an open field environment, it is more desirable to acquire the pressure data using the PCB pressure probe. Figure 1.4 is a photograph of the Gems sensor, which is connected to the power supply/measurement device on the right and the gas valve on the left.

Figure 1.4 Gems #2200 Piezoresistive Pressure Transducer

1.3 Piezoelectric Pressure Transducer

In contrast to the piezoresistive effect a piezoelectric transducer generates an electric charge when the sensing material experiences an external mechanical strain [4]. The piezoelectric transducers utilized for charge detonation experiments are manufactured by PCB Piezotronics and they fall under the model number 137B23B. The sensor contains a quartz piezoelectric element encased inside FeNi36, it is an alloy recognized for its ultra-low thermal expansion coefficient [5]. The thermal properties of FeNi36 is ideal for high pressure and temperature applications such as shock wave diagnostics for high explosives. When mounting the PCB pressure probe, the sensing element must face the blast in an axial direction and elevated from the ground to a similar level with the blast source. In an open field test environment, the sensing element should not be facing the bottom and it should always be oriented in the vertical plane with respect to the ground to avoid reflected shock waves [5]. The sensing element is sensitive to intense light sources and flash heat generated by the explosion as these effects can cause the collection of unwanted data from the pressure probe and influence the actual pressure data, the best practice to counter this issue is to cover the sensing element with a strip of electric tape (or other thermal insulating materials) to reduce the absorbed heat. The photograph shown in Figure 1.5 illustrates a properly mounted PCB pressure probe inside a blast chamber and a strip of electric tape can be seen covering the sensing element to mitigate flash heat. Unlike the Kulite piezoresistive sensor, the PCB pressure probe does not require an external structure to protect the sensor. The sensing element for the PCB piezoelectric pressure transducer is encased inside an Aluminum containment structure and the sensor only requires a BNC cable to connect the gauge to the ICP amplifier.

Figure 1.5 Mounted PCB Piezoelectric Pressure Probe

The PCB pressure probe is powered using an external ICP amplifier and the connections are straight-forward and marked with the appropriate labels. The amplifier provides signal conditioning before the test signal is sent to the data acquisition device. As shown in Figure 1.6, the front panel consists of the power switch and the sensor condition read out. The connected sensors with no faults in the BNC cables readout ‘OK’, while unconnected channel will indicate an ‘Open’ circuit. When the readout indicates ‘Short’, there is a fault in the cable and the damaged BNC cable needs to be replaced. The PCB pressure probe is extraordinarily durable, it can survive intense dynamic pressure waves consistently and has never failed in past experiments. The piezoelectric pressure transducer from PCB Piezotronics is more convenient to use for open field charge detonation experiments in comparison to the piezoresistive transducers from Kulite, but it is much more susceptible to electric noise during the data acquisition process in part due to the piezoelectric effect.

Figure 1.6 Front and Back Panels of the ICP Amplifier and Signal Conditioner for PCB Piezoelectric Pressure Sensors

1.4 Manganin Pressure Gauge

The material Manganin consists of manganese, nickel, and copper [6]. The material properties are unique in the sense that the resistance changes when the material is placed under mechanical strain [6]. Similar to piezoresistive gauges, the pressure is determined through resistance change by pulsing the gauge with an external power supply, the CK2-50/0.050-300. The setup and the data acquisition process are much more complicated when compared to the Kulite and PCB pressure transducers. The Manganin gauges used for charge detonation experiments are manufactured by Dynasen and the company offers different types of Manganin gauges that fall within various pressure ranges. The two main types of non-strain gauges compatible with the CK2 power supply are the 50-ohm Manganin gauge and the 0.05-ohm low impedance Manganin gauge. The 50-ohm option is rated from 5 to 100 kBars and its model number is MN4-50-EK with the nominal resistance around 50 ohms. As shown in Figure 1.7, the MN4-50-EK is a thin strip of metal that contains two copper tabs on its end section. Using a stripped BNC cable (RG58/U or RG174/U) with matching impedance, the BNC center conductor is soldered to one tab, while the shield is soldered to the other. It is recommended that potted epoxy be added to the solder junction after the soldering is complete to prevent damage to the connection. The low impedance gauge is rated from 100 kBars to 500 kBars and its model number is MN-10-0.050-EFEP. The gauge contains 4 tabs as illustrated by the picture in Figure 1.8. Two of the tabs are pulsed by the power supply, while the other two tabs transmit the test signal. The BNC cables for low impedance gauges are 50 ohms, the same BNC cables utilized for the MN-4-50-EK.

Figure 1.7 Soldered MN4-50-EK Manganin Gauge (Sensing Element Marked with a Cross)

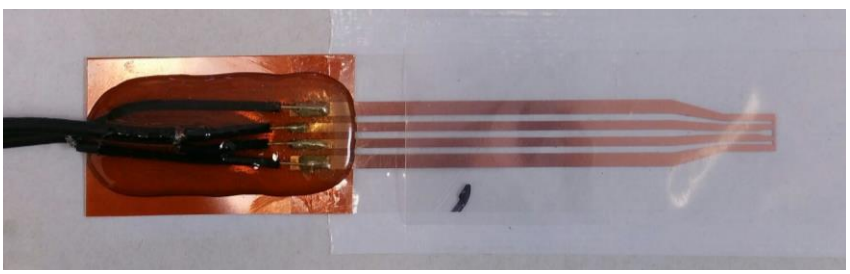

Figure 1.8 Soldered MN-10-0.050-EFEP Manganin Gauge with Potted Epoxy

When pulsing the MN4-50-EK using the CK-2 power supply, appropriate connections and bridge balance must be achieved prior to the experiment. The discharge from the power supply originates from an internal capacitor that is charged before the start of each pulsation [7]. To change the charge voltage, hold down the discharge switch and turn the voltage knob until a desired charge voltage has been reached. The CK-2 has two signal outputs, the 50-ohm option and the 75-ohm option. If the cable length needed between the power supply and the data acquisition device is short (less than 2 meters), the 75-ohm option is preferred, because the signal is un-attenuated and preserves the fast response time from the bridge network [7]. The 50-ohm option is used when the cable length required is longer than 2 meters. It has an attenuated signal, but it has a matching impedance with a built-in cable/follower that preserves the test signal over much longer distances. The unit can be triggered reliably by an external source with 6 V or higher, and this can be accomplished using a simple pulse/delay generator [7]. Each gauge carries a slightly different resistance value and the internal bridge in the power supply must be balanced using the correct knob. To operate, one needs to press down on the balance switch and rotate the 50-ohm balance knob in a direction that minimizes the reading on the front panel of the power supply. Generally speaking, the reading on the power supply should indicate a value near zero when the bridge is balanced, but sometimes it may still continue to be unbalanced. To verify the internal bridge balance, one must fire the power supply and look for a flat ~0 V signal on the data collection device before each test. Figure 1.9 provides a clear illustration on the possible connections that can be made with the 50-ohm Manganin gauge.

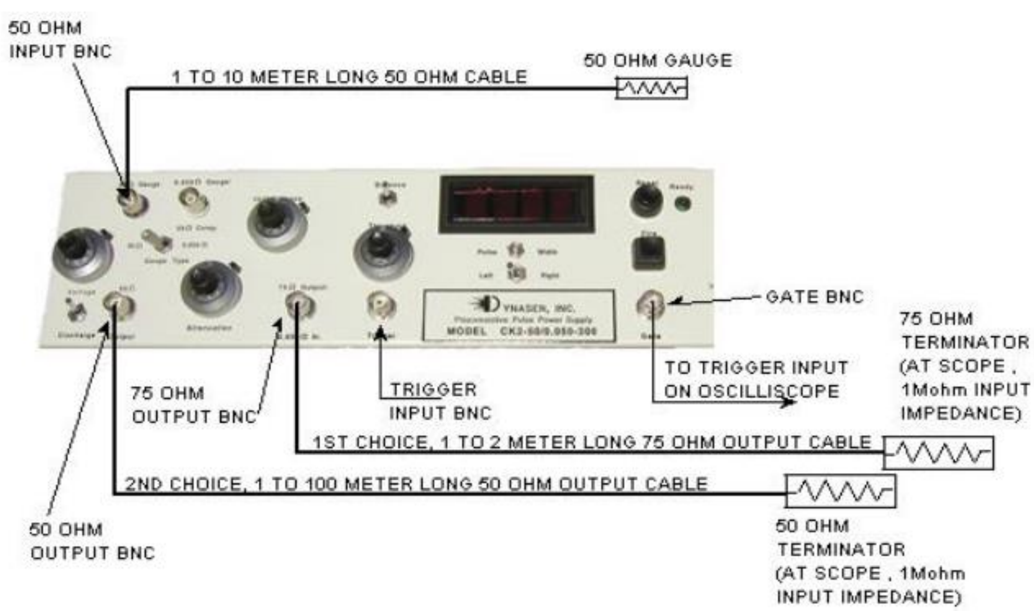

Figure 1.9 Connection Options for MN4-50-EK. Figure taken from [7]

The data analysis portion for the 50-ohm Manganin gauge requires the user to calculate the K50 constant, this constant is a conversion factor used during the data analysis process when the percent change in resistance is converted to pressure (compressive stress). It is recommended that the user employs a variable resistor box to calculate the K50 constant. Here one needs to set the resistor box at 50 ohms, balance the bridge, press reset and then fire the power supply [7]. The user should observe a flat 0 V signal on the data acquisition device, then increase the resistance to 55 ohms, press reset and fire the unit. There should be an observed voltage trace due to an increase in voltage from resistance change, the increase in voltage represents a simulated situation in which the gauge experiences compressive stress. The following Equations 1.1 and 1.2 best represent the signal conversion process [7]. Note that the K50 constant indicates that the 50-ohm output option is used during the data acquisition process. If the 75-ohm output option is used instead, one must re-calculate the constant. The equations for both the 75-ohm option and the 50-ohm option are the same. The only difference is that the 50-ohm output has an attenuation factor, but that does not affect the equations as long as the change in output voltage is correctly recorded.

$$K_{50} = \left[\frac{\Delta Vc}{\left[\frac{R_1}{R_G + R_1} \right] - \left[\frac{R_1}{R_G + \Delta R_G + 86.6} \right]} \right] \tag{Eq 1.1}$$

$$[50\Omega\,\text{output}] \left(\frac{\Delta R}{R_G} \right)\% = \left[\frac{R_1}{R_G} \left[\frac{1}{\left[\frac{R_1}{R_G + R_1} \right] - \frac{Vs}{K_{50}}} \right] - 1 - \frac{R_1}{R_G} \right] \times 100 \tag{Eq 1.2}$$

where: Vs = Test signal

ΔVc = Output voltage as produced by simulation, when $R_G \rightarrow R_G + \Delta R_G$

$R_1 = 86.6\Omega$

R_G = Gauge resistance

The MN-10-0.050-EFEP gauges requires a different setup compared to the 50-ohm Manganin gauge. The pulsation BNC cable is connected to the power supply while the signal BNC cable can be connected directly to the data acquisition device as illustrated by Figure 1.10. This option is only viable when the signal BNC cable is relatively short. If a longer distance is required between the power supply and the data acquisition device, one must connect the signal BNC cable to the 75-ohm output and use the 50-ohm output as the signal port, as illustrated by the picture in Figure 1.11. The low-impedance gauge does not require a bridge balance prior to the experiment. Just set a charge voltage and fire the unit when the appropriates connections have been achieved. The data analysis portion does not require the user to calculate a constant and the conversion process is best represented by Equation 1.3 below [7].

$$\left(\frac{\Delta \mathrm{R}}{\mathrm{R_G}}\right)\% = \left(\frac{Vs - \Delta Vc}{\Delta Vc}\right) \times 100 \qquad \text{(Eq 1.3)}$$

where: $Vs = \text{Test signal}$

$\Delta Vc = \text{Gauge activation voltage}$

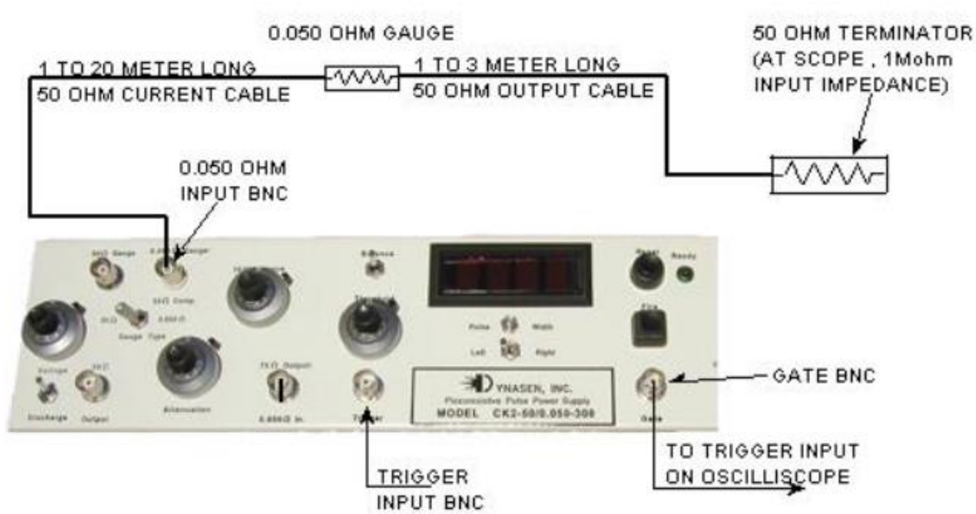

Figure 1.10 Connection Option 1 for MN-10-0.050-EFEP. Figure taken from [7]

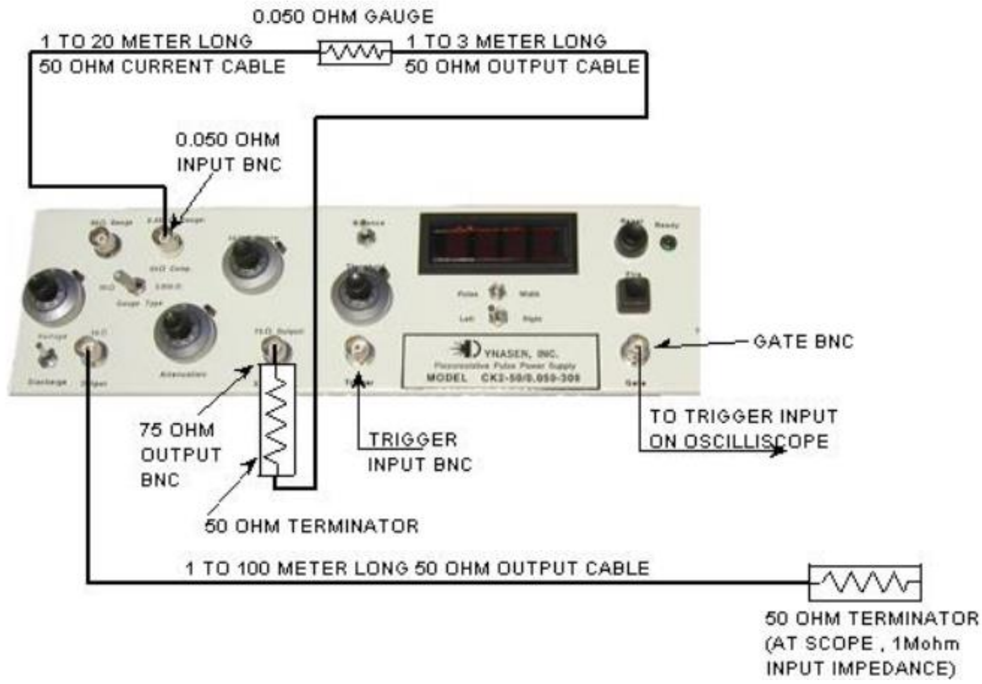

Figure 1.11 Connection Option 2 for MN-10-0.050-EFEP. Figure taken from [7]

Although the procedural steps are more complicated in comparison to the piezoresistive and piezoelectric pressure transducers, the Manganin gauges do have greater pressure ratings and are positioned at a point-blank range from the blast source, which provides an opportunity to acquire the detonation pressure for high explosives in comparison to measurements obtained through the application of traditional pressure transducers in industry.

1.5 Data Acquisition Device

The data collection device used for all experiments conducted is manufactured by Pico Technology. It is similar to a traditional benchtop oscilloscope, but with a much more compact exterior, as shown in Figure 1.12. The 4-channel USB powered PicoScope has high data sampling rates (up to 2 giga samples per second) with a wide selection of time resolutions, in addition to pre-trigger capabilities. It is ideal for short-time events such as explosive detonations.

Figure 1.12 Pico Technology Data Acquisition Device

The overvoltage protection for each unit is different. For PicoScope 3424, the unit has a maximum signal voltage of 20 V, with a 100 V overvoltage protection [8]. For PicoScope 4424, the maximum signal voltage is capped at 50 V with a 200 V overvoltage protection [9]. It is detrimental for the measurement device to receive a signal outside its maximum voltage threshold and supplying a high voltage signal without attenuation can cause a ‘blowout’ for the input channel acquiring the signal. If the signal voltage is expected to be large, one must use a feed-through terminator to attenuate the test signal below the channel’s maximum threshold.

PicoScope 6, the software that controls the data acquisition device, is provided by the manufacturer. As illustrated by Figure 1.13, the settings can be selected using the Picoscope GUI and can vary depending on the device model number. The PicoScope can be triggered using an external source at a selected threshold or a self-trigger by selecting the input channel for test signals as the source [10]. The sampling rate does not reflect the amount of data points captured. For example, using a collection time of 20 μs per division versus a collection time of 10 ms per division would result in different amounts of data points, even if the sampling rates are the same.

For 20 μs per division, the amount of data that can be captured during this period is much smaller compared to a collection time of 10 ms per division.

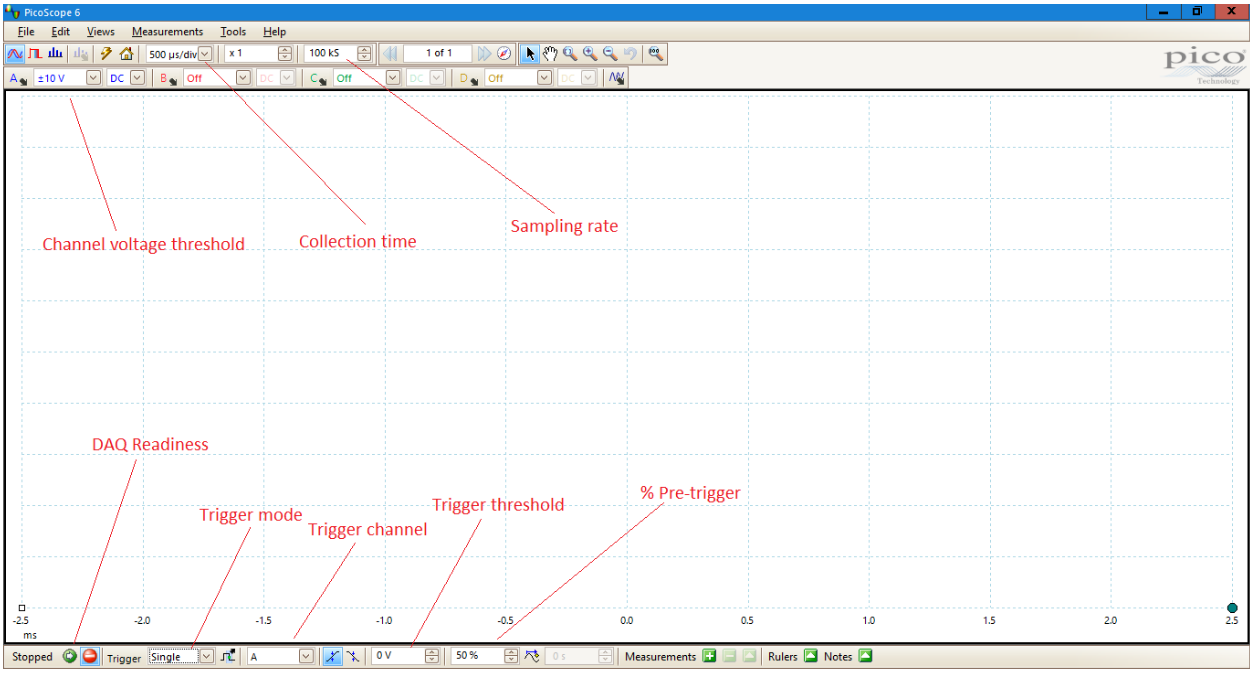

Figure 1.13 GUI for PicoScope 6

1.6 Optic Diagnostic Tools

There are two types of high-speed imaging tools utilized in charge detonation experiments to visually capture the explosion process of metal casings and the combustion process of JP-10 fuel. During open field experiments and double detonation experiments inside the Quonset hut blast chamber where mobility of the instrument is desirable, the Phantom v5.2 is the primary optic diagnostic tool for explosive testing with JP-10 fuel combustion. At full resolution, the Phantom v5.2 can capture up to 1000 frames per second, and the unit can be triggered reliably using an external TTL pulse using a delay generator [11]. The term TTL stands for Transistor-Transistor-Logic, the TTL signal has a set of standard output voltage and current in addition to a minimum pulse width. When initially connecting the Phantom v5.2 to the computer, the user needs to input the IP address and the subnet mask manually before the computer recognizes the camera. Under Internet Protocol 4, the user is required to change the IP address to 100.100.100.1 accompanied by a subnet mask of 255.255.0.0 after connecting the camera. The external setup for the Phantom v5.2 is illustrated in Figure 1.14. The Phantom high speed camera utilizes PCC 2.7 (Phantom Camera Control 2.7) as the plug-in software for capturing quick time events and footage post-processing. The adjustment of camera settings can be accomplished using the software as illustrated in Figure 1.15. The limits for these settings, however, will depend on the camera model. For example, the maximum frame rate for the Phantom v7.1 can capture up to 6,683 frames per second using a resolution size of 800 x 600, while the Phantom v5.2 when using a similar resolution, can only provide around 1667 frames per second [11]. The most common lens utilized for charge detonation experiments are 50 mm and 55mm. Alternatives such as wide-angle lens can also be utilized during testing depending on the nature of the experiment and distance from blast source.

Figure 1.14 Setup for Phantom v5.2 High Speed Camera with a 55 mm Lens

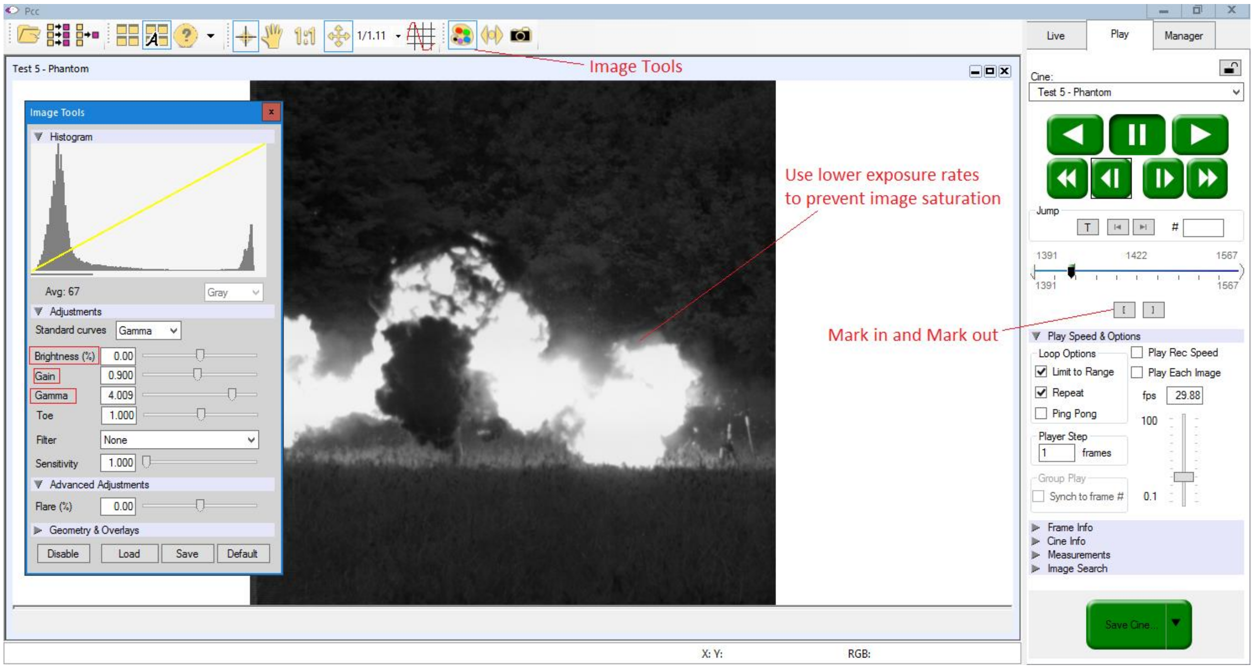

Figure 1.15 Post-processing of Footage using PCC 2.7

Under different lighting conditions, the appropriate exposure rate should be set so that there is no significant saturation in the captured footage. It is typical for the exposure rate to be set between 5 to 10 μs for experiments inside a test chamber with long-term illumination, while the field tests typically require a higher exposure rate at approximately 20 μs depending on the sunlight. There is a maximum sampling rate for each exposure rate setting. Higher exposure rates lead to smaller sampling rates. It is recommended that the user minimizes the exposure rate and maximizes the sampling rate during testing, since this approach not only increases the number of frames captured, but also prevents image saturation in the captured footage. If the captured footage was too dark due to a low exposure rate, the user can adjust the gamma (luminance value) and the gain (ratio of brightness to incident illumination) to increase the visibility, until the desired image quality has been achieved. To ensure a clear footage was captured during testing, the camera must be in focus by making appropriate adjustments to the lens. After the adjustments to the camera lens are complete, the user may increase the sampling rate to its maximum and then select the appropriate exposure rate prior to the experiment, as shown in Figure 1.16.

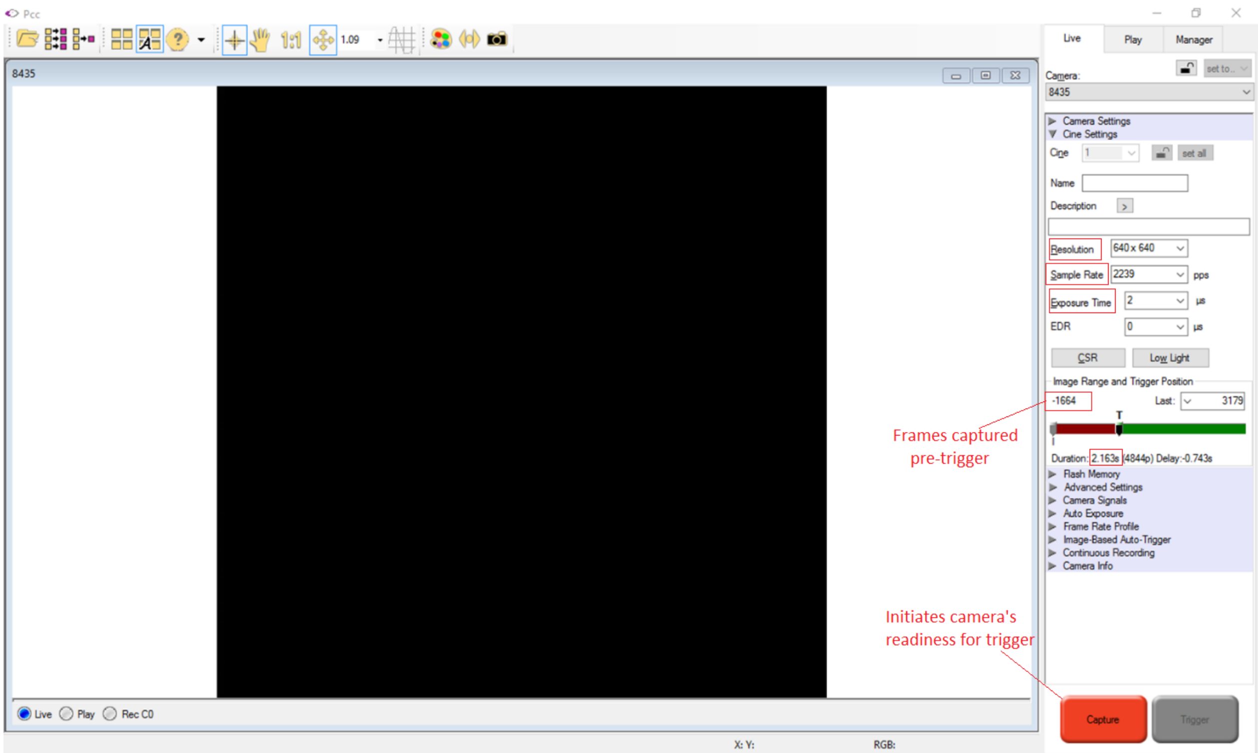

Figure 1.16 PCC 2.7 Settings for Phantom v5.2 Prior to Testing

The optic diagnostics equipment utilized for the confined casing blast chamber is not as mobile and compact compared to the Phantom v5.2, but it can provide both high speed photography with very small time steps and spectral diagnostics. The HSFC pro is an image intensifier camera that can capture up to 4 high resolution images with a time step of 1 ns. The explosives' reactivity during testing can be visualized easily using the HSFC pro in addition to the information obtained from the spectral lines. Of note when using the HSFC pro is that the exposure should be minimized when aligning the camera and recording the explosion, the camera is very sensitive to light intensity. An excessively large exposure rate can cause an internal 'blowout' and permanent damage to the camera.

CHAPTER 2

EXPERIMENTAL SETUPS FOR CHARGE DETONATION TESTS

2.1 Chapter Overview

Confined casing experiments are conducted inside one of the smaller blast chambers in Mechanical Engineering Laboratory, while detonation tests with fuel combustion are conducted inside a larger blast chamber located in the Quonset hut. Experimental setup of pressure sensors and optic diagnostic tools are executed differently in the two chambers due to the disparate natures of the experiments. There are distinct differences in signal pattern due to the containment volume, gauge placements, and the shock wave propagation/reflection inside the test chamber. For example, quasi-static pressure oscillations are relatively mild in the test signal for experiments conducted inside a chamber with a larger containment volume. In an open field environment, only the initial peak pressure can be acquired because the shock wave propagates far from the source until the energy has dissipated. Despite the nuances in experimental setup, the relevant procedures in mitigating electric noise while preventing undesirable data loss due to faults in electrical instruments and cables are very similar.

2.2 Confined Casing Test Configuration

The small-scale chamber in Mechanical Engineering Laboratory is a cubic containment structure with 48 inch sides. It is outfitted with 2 PCB pencil probes, 2 Kulite pressure probes, and 2 Gems pressure sensors. Redundancy in the number of pressure gauges are necessary to ensure that the data is consistent and accurate. The internal pressure sensors manufactured by Kulite and PCB

Piezotronics are placed 24 inches from the detonation source along the diagonals of the blast chamber as shown in Figure 2.1. To ensure that a difference in vertical distance does not influence the test data, the sensing element for the Kulite sensor has a height differential of 1 inch from its counterpart. An additional horizontal PCB pressure probe can be mounted in the same plane as the detonation source and is located 20.5 inches from the center of the blast source while the other sensors have a vertical offset. The Gems pressure transducers are situated on the outside of the chamber. There is a quasi-static pressure (QSP) port inside the chamber that feeds the pressure to the respective sensors.

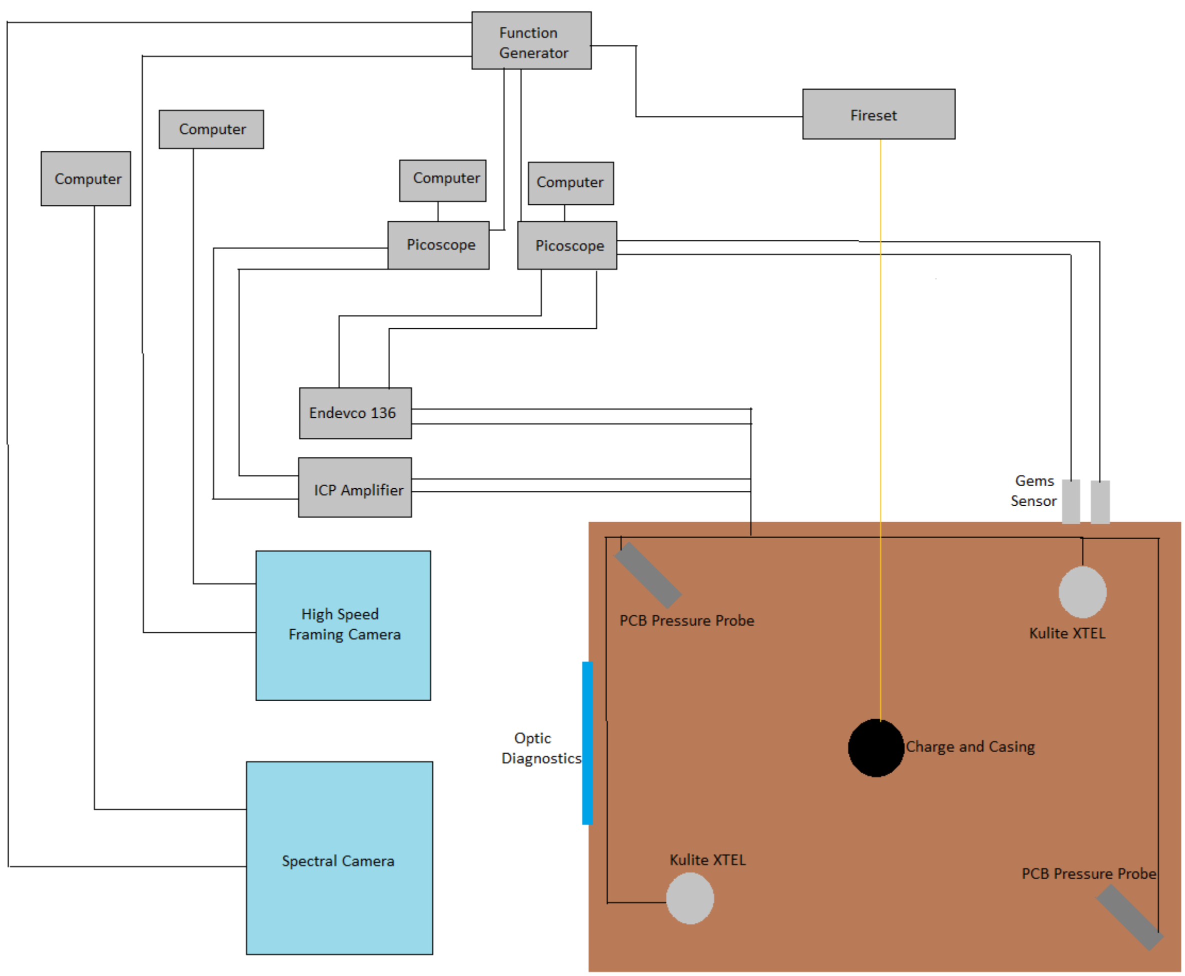

Figure 2.1 Instrument Setup for Confined Casing Blast Chamber

The confinement is achieved through the application of two stainless-steel posts, the bottom post is attached to a baseplate while the top post is secured to the ceiling of the chamber using a heavy duty 4-bolt clamp structure, as illustrated in Figure 2.2. At the steel post interface, low-density polyethylene spacers are added to secure the anvils and to create a shock absorber effect so that the stainless-steel posts would not be damaged. After the casing and the charge are added between the top and the bottom anvils, the top post is then lowered to an appropriate level to secure and to immobilize the casing and the charge.

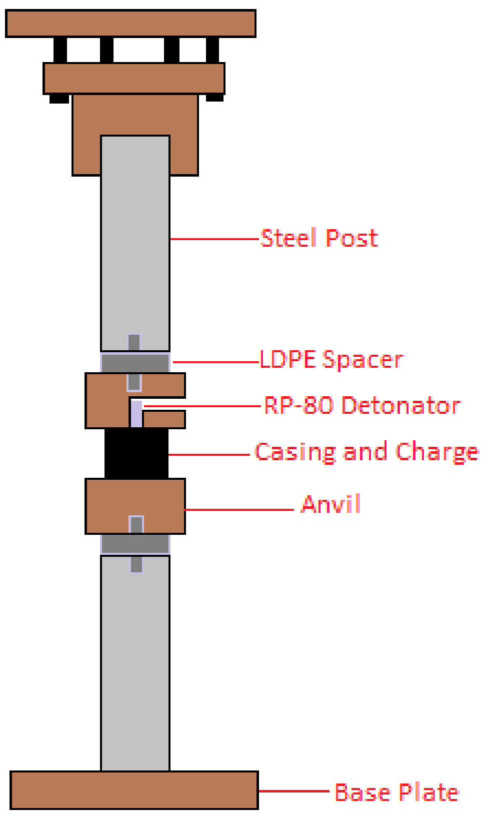

Figure 2.2 Schematic for Confinement Setup Inside Confined Casing Test Chamber

Confined casing experiments often create excessive fragments inside the blast chamber. So, it is imperative to preserve the structural integrity of the chamber and to prolongate its life by adding additional steel plates to the chamber walls to absorb the fragments engendered from the experiments. The window facing the high-speed framing cameras is protected using a 11/16-inch-thick clear cast acrylic sheet. Although the 11/16-inch-thick acrylic sheet can survive when the test specimen experiences mild reactions, it should still be inspected for every test to prevent damage to the chamber window. The blast chamber for confined casing experiments also contains a port for an oxygen sensor for charge detonation experiments in an inert environment. The oxygen level is sampled by pumping air inside the chamber through a UV flux oxygen sensor located on the exterior. After each experiment, the entire chamber is vented using compressed air through pressurization and de-pressurization cycles with the recommended venting time from 10 to 15 minutes. For health safety, it is desirable to wait for an additional 5 minutes before opening the chamber doors to ensure that the solid particulates have settled inside the chamber.

2.3 Fuel Combustion Test Configuration

The test chamber inside the Quonset hut is outfitted with 2 Kulite piezoresistive sensors, 1 PCB piezoelectric sensor, and two photodiodes. Two piezoresistive sensors are mounted across from each other on the side of the chamber, with the PCB pressure probe mounted on the center of the ceiling. The gauges should be aligned for the sensing elements to be in the same vertical plane as the detonated charge. Long-term illumination inside the chamber is achieved through the application of two flash bulbs mounted near the chamber window facing the camera. The experiments inside the Quonset hut requires two firesets to execute a double detonation. The first detonation sets off the explosive Delrin container for JP-10 and the second detonation ignites the fuel. The burning of the JP-10 fuel is captured using the Phantom v5.2 camera with a wide-angle lens. Photodiodes are placed behind diffusers at two corners of the chamber to capture the luminous intensity emitted from the combustion of the fuel. The chamber windows are well above the detonation source. So, it is not necessary to add clear cast acrylic sheets to protect against damage. Since the detonation tests are not confined and there are no metal fragments, energy-absorbing foams are placed throughout the internal chamber walls to protect against the Delrin fragments and flash heat. The chamber schematic and exterior setup for double detonation tests with JP-10 fuel is best illustrated by Figure 2.3. The venting process for the Quonset hut blast chamber is more primitive since it is not sealed completely and it does not have a gas line with compressed air at standby. The circulation of air to the outside is accomplished through an electric fan inside the chamber and two directional fans leading the airflow. It is highly recommended that the full 15-minutes venting time is honored to avoid unwanted fumes leftover from the combustion process.

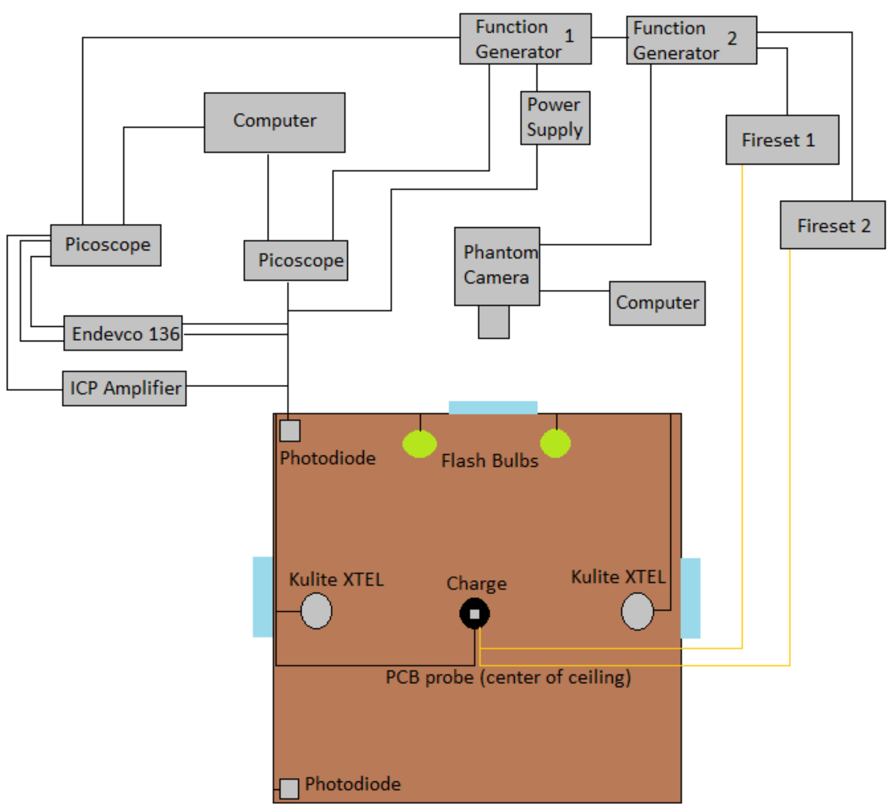

Figure 2.3 Schematic for Instrumentation Setup inside the Fuel Combustion Test Chamber

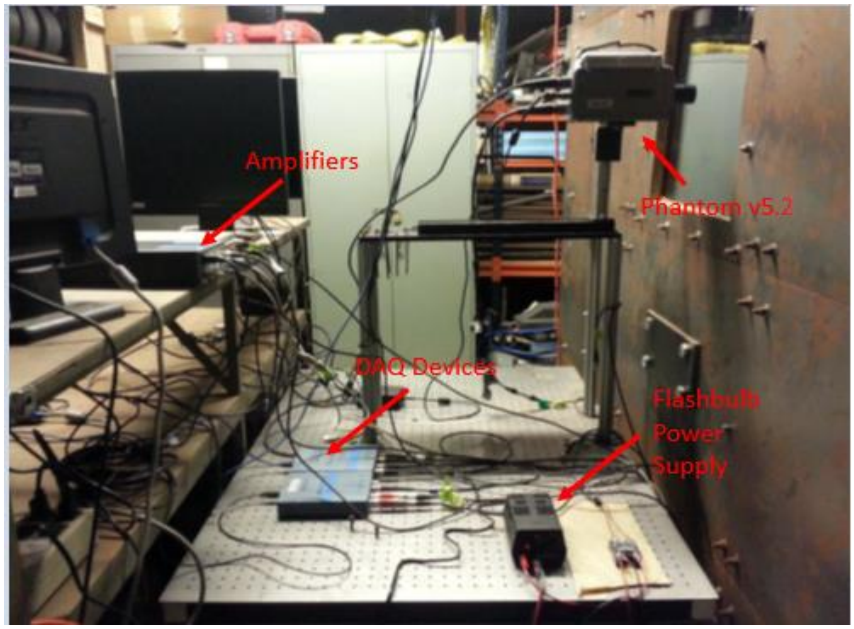

Figure 2.4 External Setup for the Fuel Combustion Test Chamber

Similar to the confined casing test chamber, all exposed cables should be protected from fragments and flash heat. Inside the Quonset hut blast chamber the signal cables are housed inside metal pipes with only a few segments of exposure. There are two fireset cables inside the chamber, one is responsible for the first detonation; while the other is responsible for the second. Since there is a time delay of 5 ms between the two detonations, it is highly desirable to protect the second fireset cable against the Delrin fragments generated from the first detonation, even though the time difference is very small.

2.4 Open Field Test Configuration

Open field charge detonation experiments utilize three PCB pressure probes and a single Phantom v5.2 camera for optic diagnostics. The first pressure probe is placed 10 ft from the source and another is placed 20 ft from the source and in line with the first probe. The last PCB pressure probe is placed 10 ft from the source at a 45-degree angle offset. Other configurations can also be implemented by creating 20 degree offsets between the probes coupled with increasing gauge distance from the detonation source. The charge mount consists of a hardened hollow steel cube and a 1-inch-thick steel base plate. A wooden block is inserted between the tube interface and the charge to preserve the integrity of the hollow steel tube. The field test configurations are similar to the experiments conducted inside the Quonset hut blast chamber, and the charge detonations are conducted with air and water before adding JP-10 fuel. Pressure data captured from both air and water detonations serve as inert comparisons to the performance with JP-10. Previous field tests used double detonations with a relay, but the most recent outdoor test series utilized a single charge to spread the JP-10 and a booster to ignite the fuel cloud. To ensure proper mixing and burning of the JP-10, the Phantom v5.2 was used to capture the combustion process. The camera is located ~200 ft from the source and the footage is captured using a 50mm adjustable lens. Depending on weather conditions the exposure rate should not be set greater than 20 μs and the sampling rate should be maximized. If the image is too dark even after increasing the gamma and adjusting the gain, one must increase the exposure rate beyond 20 μs until the desired image quality has been achieved. It is recommended that the exposure rate selected for the Phantom v5.2 is low, since a longer exposure rate can cause image saturation and creates a situation in which the combustion process of the JP-10 cannot be clearly isolated from the rest of the footage. All electronic instruments can be powered using a 3000-watt gasoline powered generator, the general setup for the field test is best illustrated by Figure 2.5.

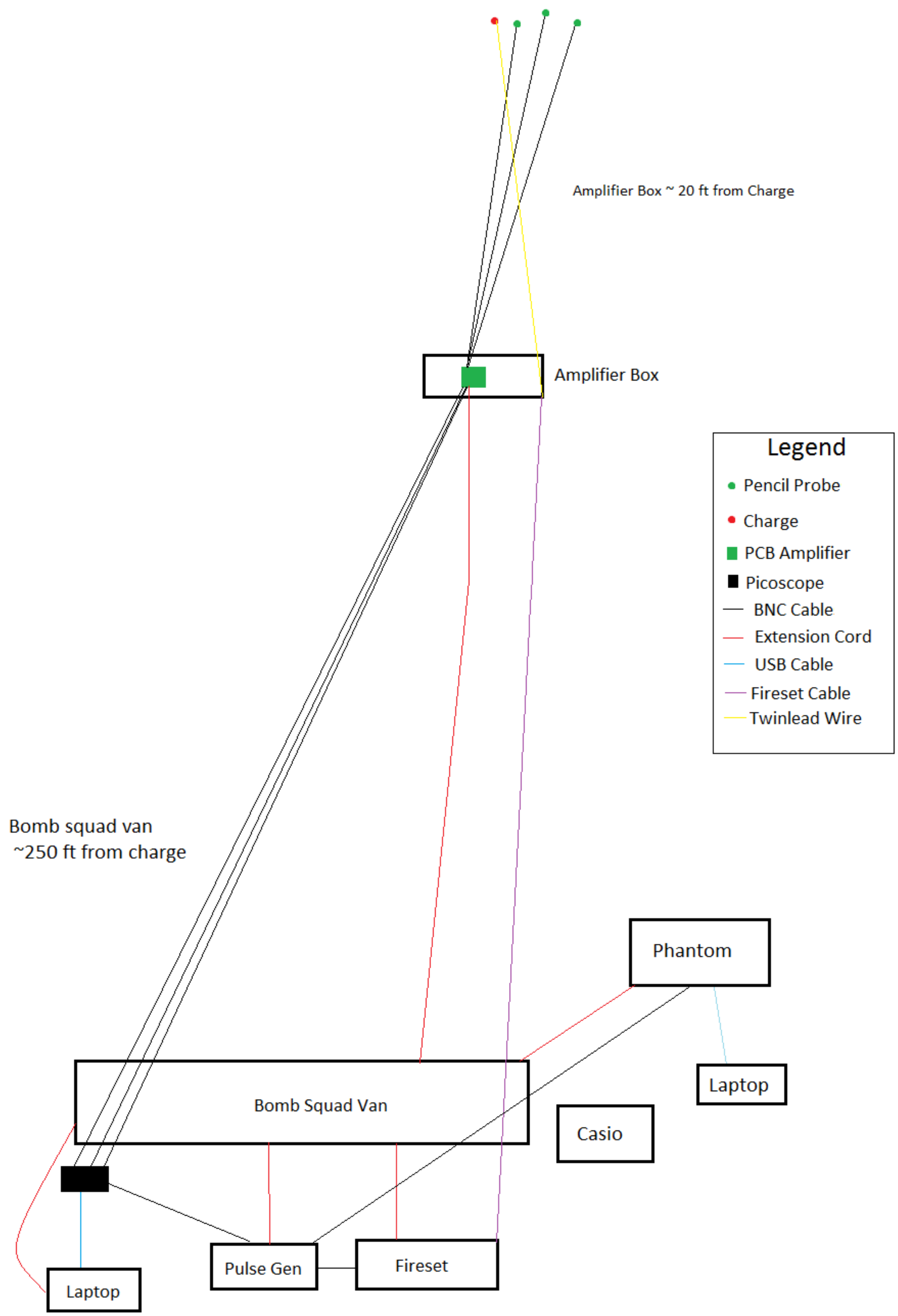

Figure 2.5 General Setup for Open Field Charge Detonation Experiments

CHAPTER 3

BLAST DIAGNOSTIC TECHNIQUES AND PRACTICES

3.1 Chapter Overview

Under different test conditions the test signal acquired from explosive testing are distinct for each experimental setup. Under a closed chamber environment, shock wave reflections from chamber walls will induce oscillations in the test signals, while in an open field environment, the signals will experience a more traditional rise and fall instead of pressure oscillations. Since both electric noise and cable damage will cause distinct patterns, countermeasures will be explored in subsequent sections to resolve these issues. Gauge mounts are unique for both the piezoresistive type and piezoelectric type pressure transducers. It is necessary to safely secure the gauges prior to the experiment to prevent shifts in gauge positioning. The change in sensing element to blast source distance can cause unwanted nuances in test data. It is recommended that frequent measurements are made to ensure gauges are aligned properly. The calibration procedures for Kulite and Gems sensors are easier to accomplish compared to both the PCB pressure probe and the Manganin pressure sensors. The piezoresistive gauges can be calibrated using static pressure by pressurizing a sealed enclosure, while piezoelectric gauges must be calibrated using dynamic pressure waves. Common issues associated with electronic instruments and appropriate safety practices with high explosives will be examined below.

3.2 Signal Interpretations

A textbook interpretation of a standard shock wave will include an initial rise and a subsequent fall in the pressure signal, as shown in Figure 3.1. Following the drop, the pressure decays below atmospheric, before returning to the initial ambient pressure. But inside a sealed chamber, the rise and fall in the test signal is coupled with dampening oscillations as the shock wave reflects back and forth between the chamber walls [12, 13]. These oscillations, as illustrated by Figure 3.2, will eventually dissipate. This region defines the quasi-static pressure [13]. For the piezoelectric pressure transducer, the region for dampened oscillations in the test signal can also be observed, but this region does not represent the quasi-static pressure. The piezoelectric pressure transducer can only capture the dynamic pressure waves. The only useful data available from the piezoelectric type PCB pressure probe is the initial peak pressure. For the Kulite piezoresistive sensor, both the initial peak pressure and the quasi-static pressure can be acquired during testing.

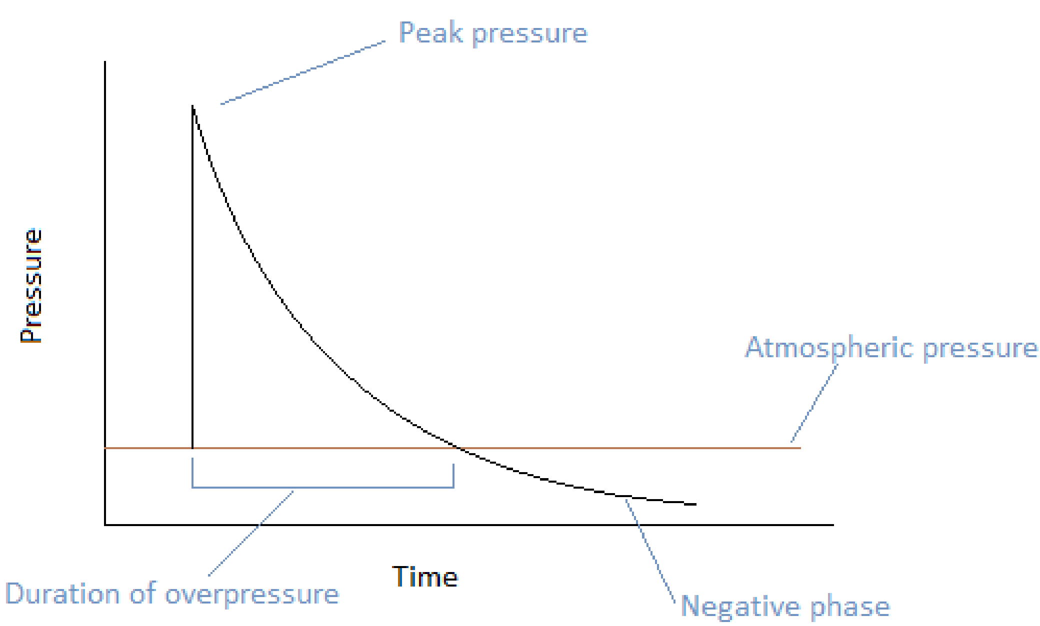

Figure 3.1 Text Book Definition of a Blast Wave Pressure Curve

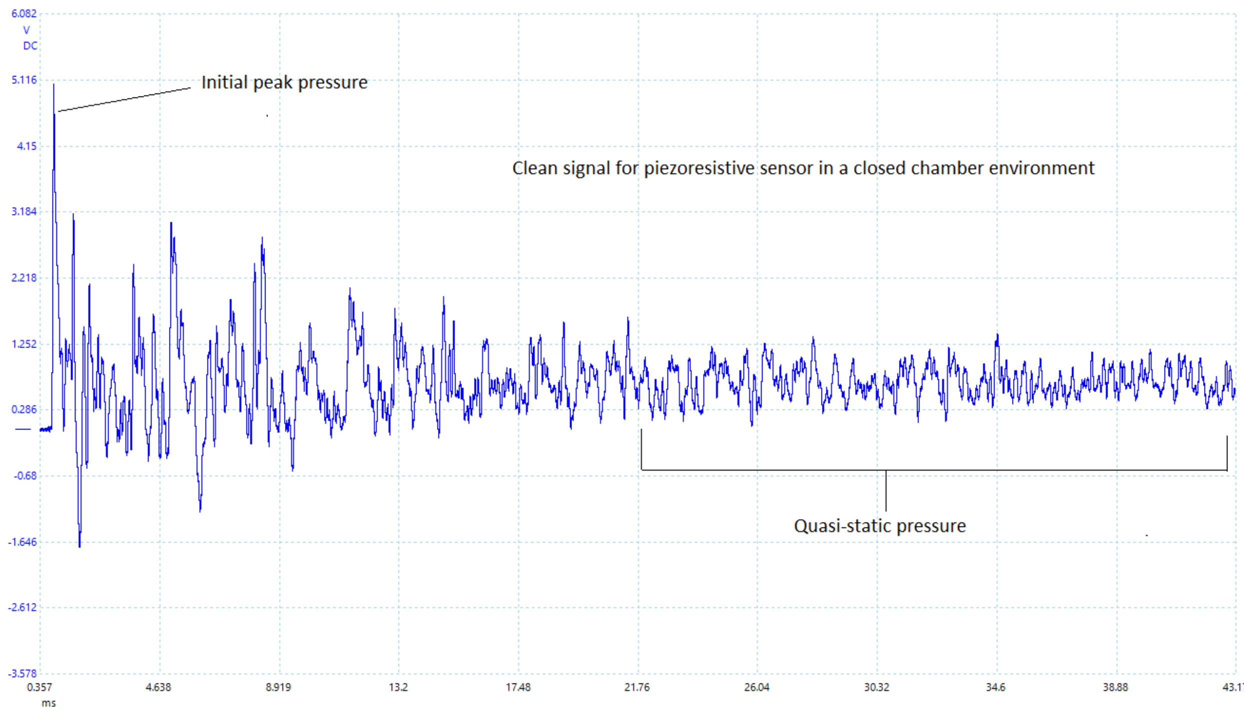

Figure 3.2 Test Signal for Kulite Piezoresistive Pressure Transducer in a Closed Chamber Environment

Redundancy in the number of pressure transducers is vital in assessing the accuracy of the data. The two Kulite piezoresistive sensors inside the confined casing test chamber are placed in the same vertical plane with respect to each other, the sensor distance to the blast source for both gauges are 24 inches. In the test signal, for similarly scaled piezoresistive sensors, the voltage traces should be similar. This indicates that there is consistency in the data. Sometimes, the piezoresistive sensors utilized during testing are scaled differently and the voltage readings for one sensor maybe larger than the other by a factor of two. But once the signals have been converted to pressure, the pressure curves should fall on top of each other, verifying the consistency of the data. Figure 3.3 illustrates the signal for a pair of similarly scaled Kulite piezoresistive sensors.

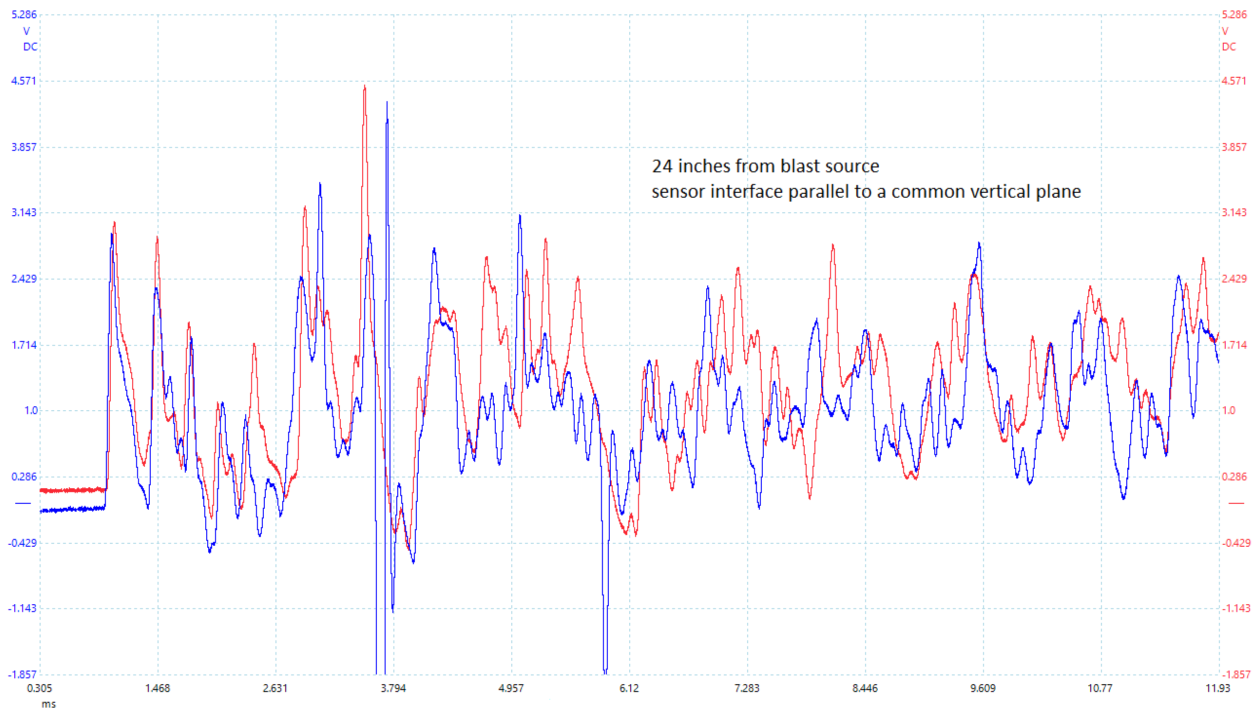

Figure 3.3 Test Signal for Similarly Scaled Kulite Piezoresistive Sensors

In an open field environment shock waves are not confined and they propagate radially until the energy generated from the explosion has been dissipated. There should be no significant oscillations in quick successions since the signal flatlines at around 0 volts very quickly. The peak pressure arrival time will depend on the distance between the gauge and the blast source. In addition, angle offsets between individual pressure gauges can also affect the test signal. Figure 3.4 highlights the typical signal captured in an open field environment for a stagnation explosion. It is also representative of the type of signals expected for plain explosions and explosions with alternative configurations in an open field environment.

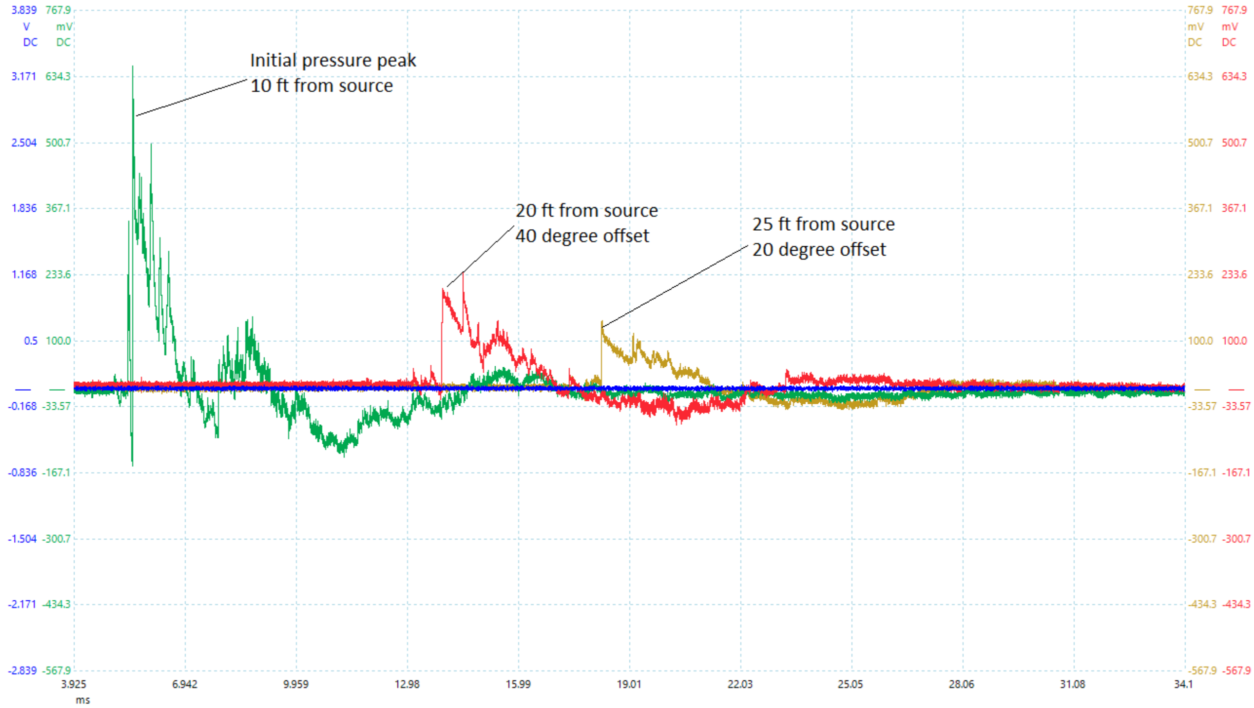

Figure 3.4 Test Signal for an Open Field Stagnation Explosion with Water

Inside the blast chamber with a larger containment volume, the pressure signal tends to decrease for both piezoelectric and piezoresistive pressure transducers, this observation is most notable in the initial peak pressure captured during explosive testing with fuel combustion. Due to a larger containment volume, the oscillations observed in the quasi-static region for piezoresistive pressure transducers are smaller in comparison to the confined casing test chamber. The PCB pressure probe, located in the ceiling of the chamber, should experience a relatively small initial peak pressure due to the longer gauge-to-charge distance. In a more confined detonation test by directing the JP-10 fire ball upward, the PCB pressure probe should display a much higher peak pressure where saturation can also occur. Figure 3.5 illustrates the distinct features that separates the pressure signals inside the Quonset hut blast chamber from the confined casing test chamber.

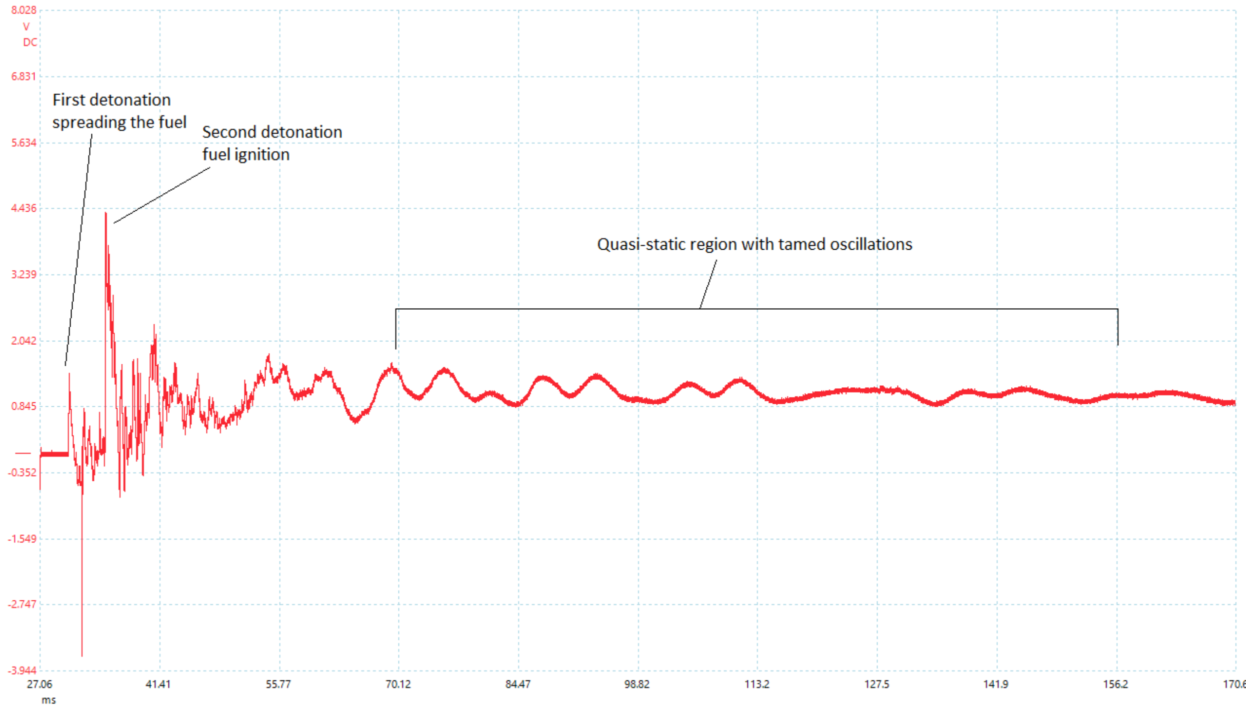

Figure 3.5 Test Signal for a Double Detonation Test with JP-10 Combustion

In assessing the signal collected from the testing process, the telltale signs of a cable damage can be observed by a sharp rise in voltage readings with a subsequent loss in signal, as shown in Figure 3.6. Saturated transients and oscillations of the test signal in Figure 3.7 are caused by the deterioration of the sensing element, and can often be confused with fragment impacts, as illustrated in Figure 3.8. One of the easiest ways to distinguish between these two separate incidents is to repeat the charge detonation experiments to see if the signal peaks are still present. If it occurs on a regular basis, then the sensing element needs to be replaced. Another way to distinguish between these two incidents is to examine the duration of the undesired transients in the signal. The impact of fragmentations does not last very long, so if the duration of these oscillation is on the scale of 10 to 20 ms, then the sensing element is at fault.

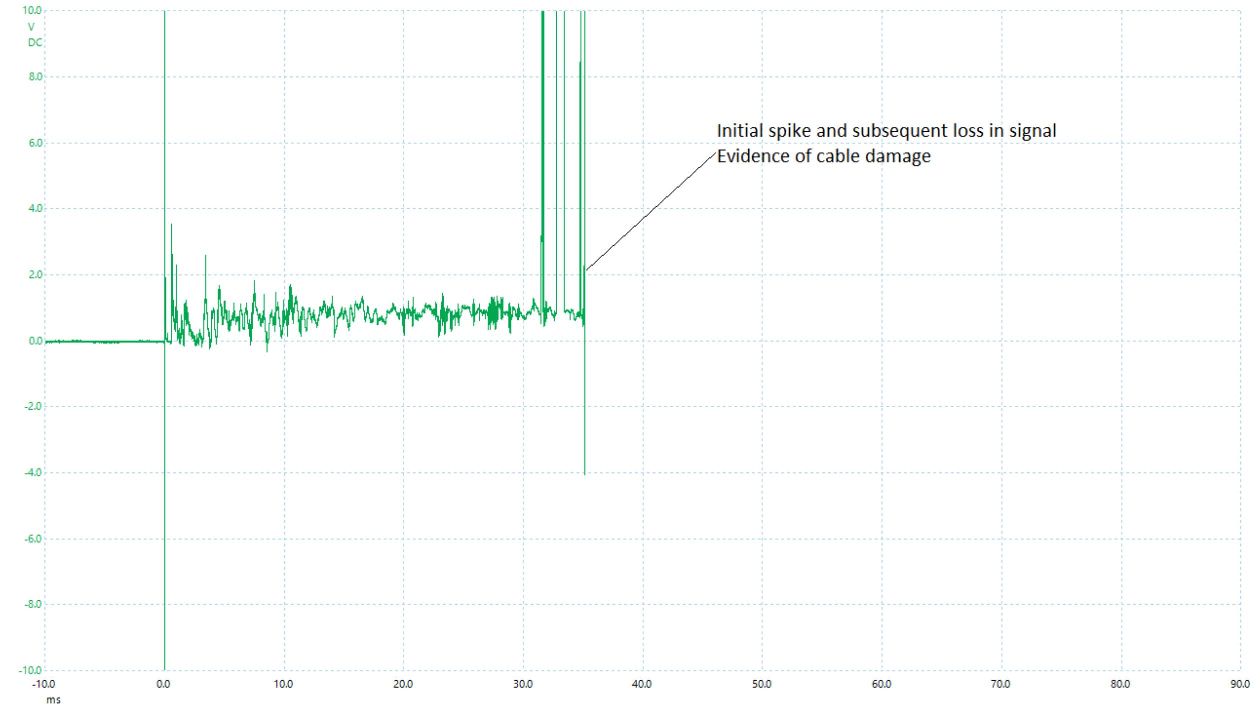

Figure 3.6 Test Signal for PCB Piezoelectric Sensor with Cable Damage

Figure 3.7 Test Signal for Kulite Piezoresistive Sensing Elements in Critical Condition

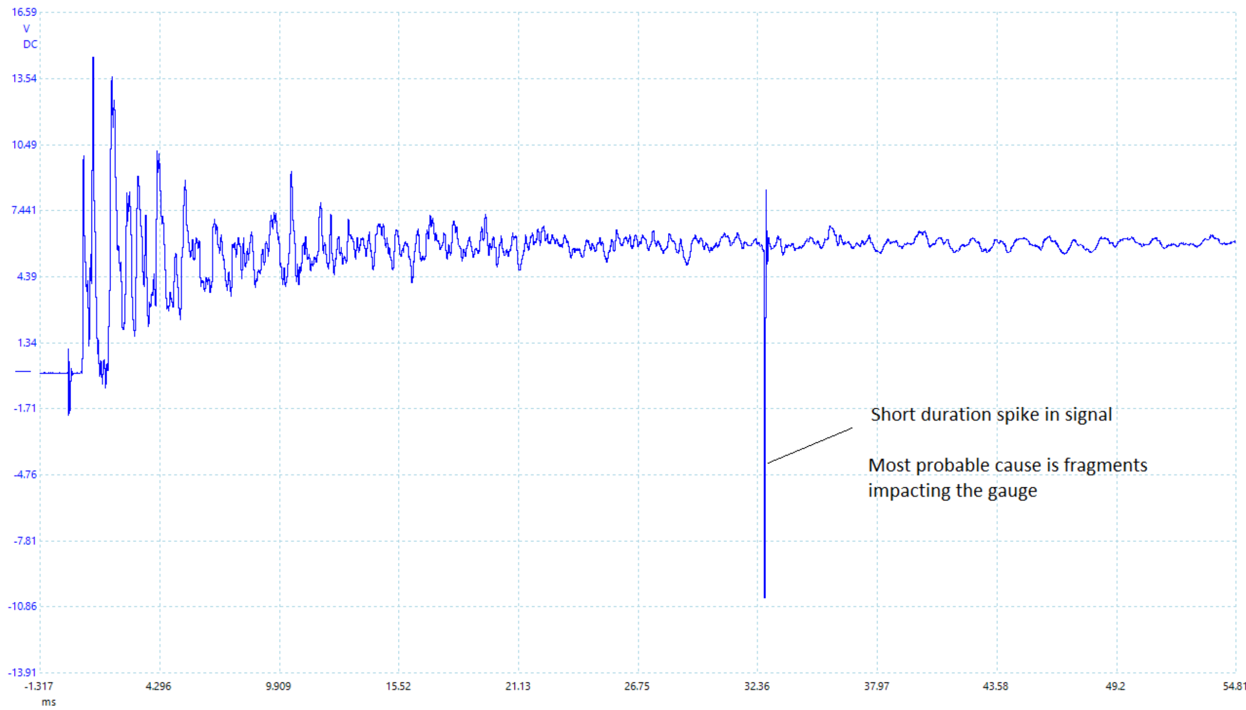

Figure 3.8 Test Signal for Fragment Collisions with Gauge

The 50 ohm Manganin gauge manufactured by Dynasen has a maximum pressure rating at 100 kBars. The gauge will saturate if the detonation pressure of the specimen is beyond this limit. The saturation can sometimes generate false pressure signals, as illustrated in Figure 3.9. The explosive in this experiment was detonated at approximately 9 μs, the false pressure peak was present at around 20 μs; actual measurement of the detonation pressure will only take 1 to 2 μs. The electric noise at the time of detonation is caused by the FS-43 fireset. Thus, it is highly recommended that the user employs a low-noise fireset (battery powered) during charge detonation experiments with the CK-2 pulse power supply.

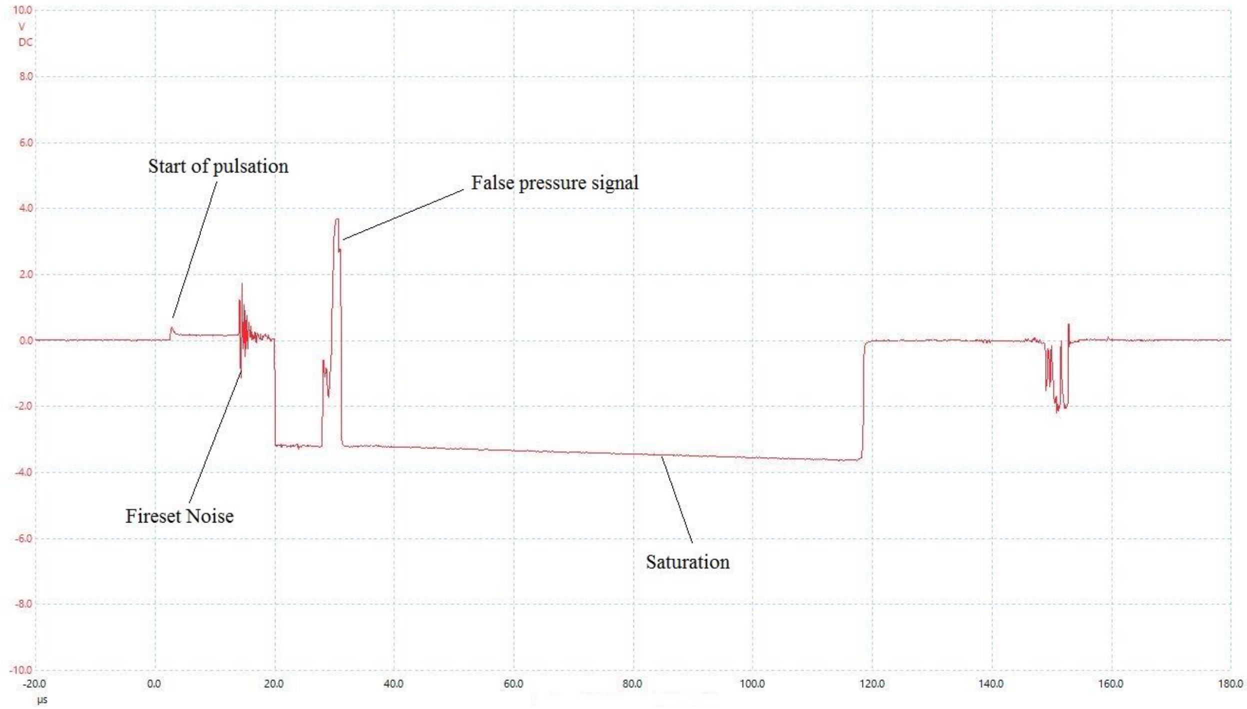

Figure 3.9 False Pressure Signal for Saturated MN-4-50-EK

The ideal test signal acquired from a low-impedance 0.05-ohm Manganin gauge can be best represented by the illustration shown in Figure 3.10 [7]. This ideal signal will change under different test conditions. In actual detonation experiments, the compressive stress profile will not be a perfect parabola, as shown in Figure 3.10, since the Manganin gauge will be destroyed when measurements are made during the detonation process [6]. The sensing material properties and the subsequent compressive stress profile will change as the reaction propagates along the specimen. The 50-ohm Manganin gauge's ideal response is similar to that of a low-impedance gauge; the only difference is that during the pulsation period, the voltage drop across the 50-ohm gauge should be zero. This is due to the fact that the internal bridge inside the CK-2 pulse power supply is balanced, unlike the low-impedance gauge where the bridge balance is not necessary prior to the data acquisition process.

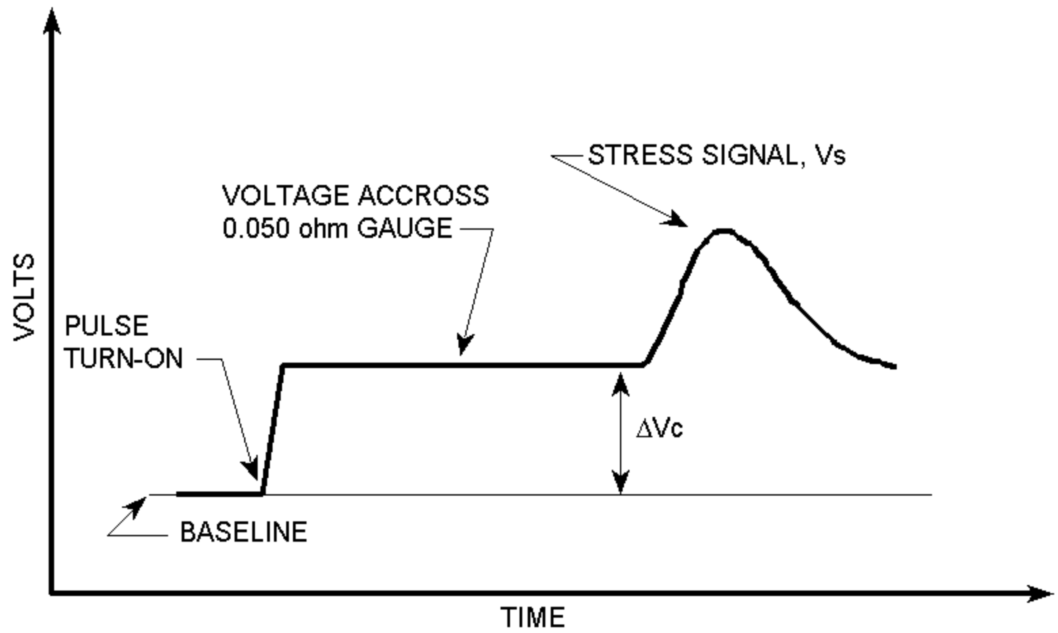

Figure 3.10 Ideal Test Signal for MN-10-0.050-EFEP. Figure taken from [7]

Electric noise during the data acquisition process is a major issue, so it is often necessary to use low-noise cables leading from the fireset to the charge. In cases of wave reflections with Manganin pressure sensors, it is recommended that an inline terminator with matching impedance is added to the receiving end of the output. A properly secured gauge mount is also another factor in preventing electric noise, and pressure gauges that are not properly secured can wobble during testing, causing unwanted electric noise stemming from such movements. To mitigate potential electric noise, one might employ a shielded BNC cable with a ferrite bead or use a ferrite core noise suppressor clamp-on for the BNC cable. On occasions, there occurs unavoidable noise due to the nature of the shock wave and the piezoelectric effect even after preventive measures have been implemented. The test signal in Figure 3.11 illustrates the electric noise from the PCB pressure probe closest to the implosion explosions during open field testing. Overall, the piezoelectric type PCB pressure probe tend to experience more noise compared to the Kulite and the Gems piezoresistive sensors. This is another good example of why redundancy and the need for multiple gauges positioned in a similar fashion are necessary during blast diagnostics to verify the consistency and the accuracy of the pressure data.

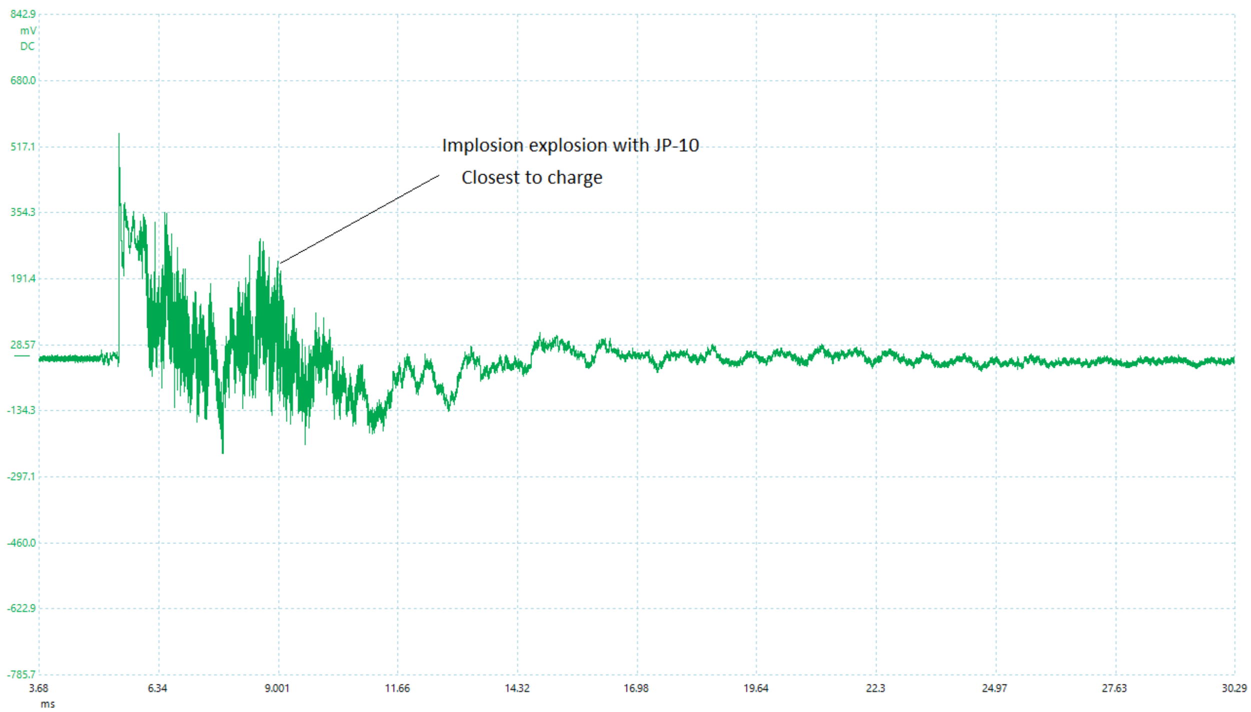

Figure 3.11 Test Signal for Implosion Explosion in an Open Field Environment with JP-10 Combustion

3.3 Equipment and Sensor Troubleshoot

The piezoresistive sensor manufactured by Kulite requires an external amplifier/signal conditioner to supply an excitation voltage to the sensing element during the data acquisition process. The amplifier utilized in current experiments is the Endevco 136, a 3-channel DC voltage amplifier. The Endevco 136 is not the only amplifier compatible with the XTEL series pressure sensors, alternative amplifiers in the market can also provide signal conditioning. A frequent issue encountered when using the amplifier is that the channels tend to report an error when using the Auto-Zero function. As mentioned in previous sections, the error message is most likely caused by a fault in the cable, so the user must look for external damages to the cable before moving forward. If there are no visible damages, try switching to a different channel on the Endevco 136 and use the Auto-Zero function again. If the error persists, then restart the amplifier. The sensing element has 4 colored wires, each of them should match the 4 colored wires inside a stripped USB cable, as shown in Figure 3.12. It is highly recommended that heat shrink tubes are used to connect the 4 individual wires instead of solder, since the heat shrink tubes are more adequate in securing the connection and are less likely to break apart. If the error message is still active after verification of cable integrity, power cycling of the amplifier, and utilization of alternative channels, the user then should check the connection for the four wires between the sensing element and the USB cable. If the issue is still present after implementing the methods listed above, one must replace the sensor.

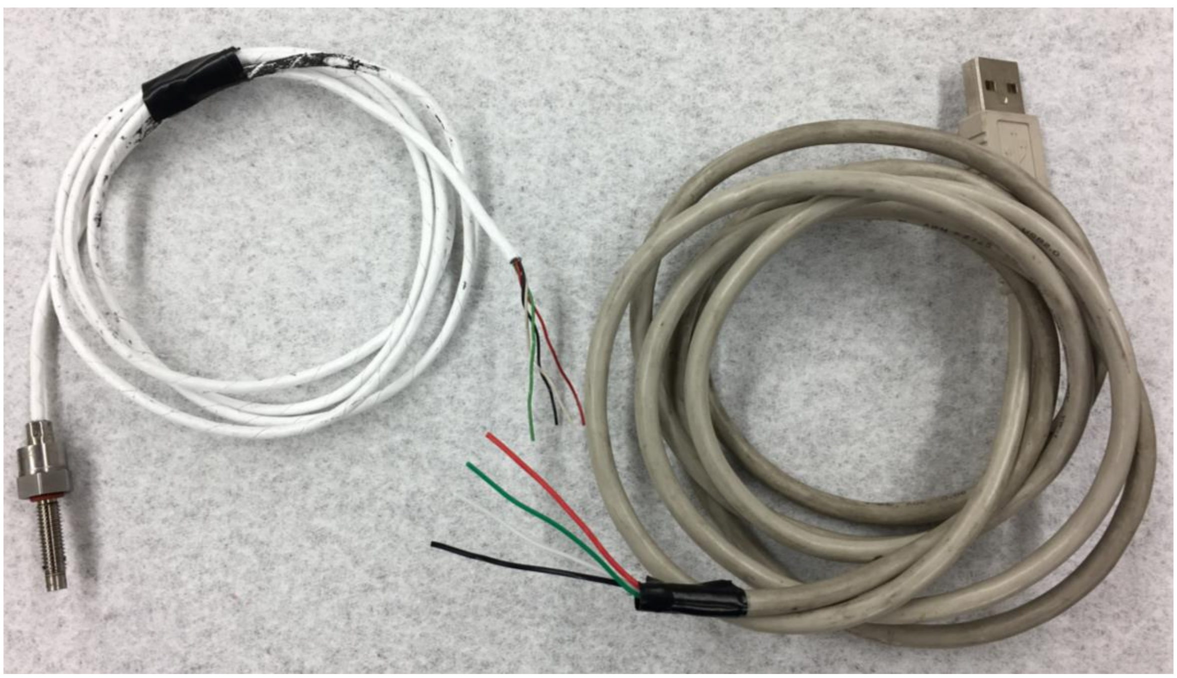

Figure 3.12 Matching Wires Between Piezoresistive Sensing Element and USB Cable

The sensing element for the PCB pressure probe is already encased inside an Aluminum containment structure. These piezoelectric pressure probes tend to experience more noise, but are very resistant to fragments and flash heat. The only thing that requires attention for the PCB pressure probes is BNC cable protection. The front panel of the ICP amplifier has three simple readings for the condition of the pressure probe. When the needle on the front of the amplifier reads ‘open’ or ‘short,’ one must check the BNC signal cable’s integrity. As mentioned previously, cable damage has always the central issue causing a ‘short’ or an ‘open’ circuit indicator since the sensing element inside the Aluminum containment structure has never failed. One thing to note is that the sensing element should be covered with electric tape or other thermal insulating material, to prevent signal distortions from flash heat generated during high explosive testing.

To ensure that all instruments are working properly, bridge wire tests are performed at least three times prior to the actual experiment. It is imperative to ensure that the camera and the PicoScope triggered during the bridge wire tests. A common issue associated with the PicoScope is that the apparent readiness displayed on the GUI is not indicative of the unit’s readiness for a trigger. To avoid this, one must make sure that the red LED light on the front panel is lit before setting off the charge. The spark generated from the bridge wire is also a validation for the camera positioning, appropriate exposure rates, and timings on the high-speed framing cameras prior to the actual experiment.

3.4 Gauge Mount Design

Since the piezoresistive sensing element is relatively small and fragile, a custom containment structure was made to accommodate the sensing element and reduce cable exposure to the blast. As illustrated in Figure 3.13 and Figure 3.14, this consists of a main protective piece housing the USB connection to the sensing element, a blast interface, and a threaded insert that contains the Kulite XTEL piezoresistive pressure transducer. Containment structure design for the small piezoresistive sensor is not definitive, further improvements can be made to existing design to further reduce any connection exposure. For example, half of the protective piece was originally designed to be open to the external environment for ease of access to the connection between the sensing element and the USB cable. This opening can be removed by creating a solid hollow cylinder as the protective piece, so that the entire connection is encased inside steel and protected from external flash heat or high-density fragments generated during testing.

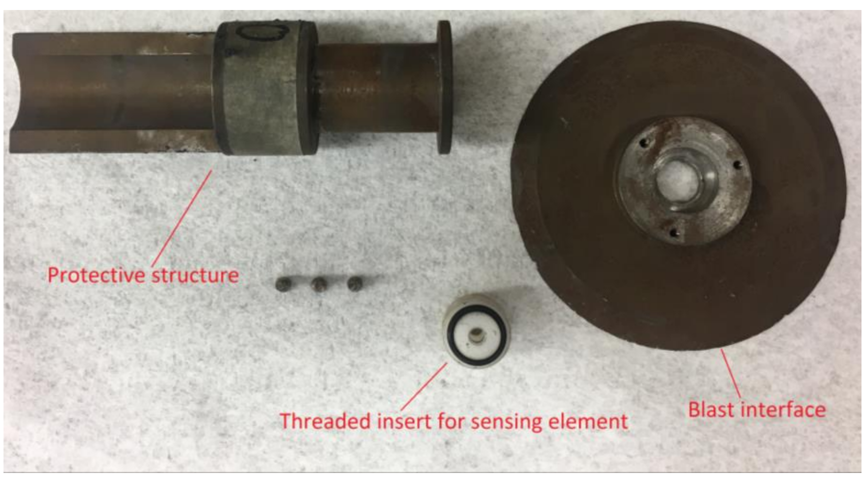

Figure 3.13 Components of Containment Structure for Kulite XTEL Piezoresistive Sensor

Figure 3.14 Assembled Containment Structure for Kulite XTEL Piezoresistive Sensor

The piezoelectric sensing element for the PCB pressure probe is encased inside an Aluminum containment structure. The Aluminum exterior is relatively durable and the it only requires an external mount to secure the gauge. The mounts utilized during high explosive testing immobilizes the pressure gauge by tightening a bolt insert that pushes up against the Aluminum exterior. Repeated test series can cause deep indentations on the gauge exterior, so it often leads to undesirable signals due to gauge movements. And the situation is often exacerbated from electric noise amplified due to the piezoelectric effect. To counter these minor movements, the PCB pressure probe is inserted inside a Delrin shock absorber as illustrated in Figure 3.15; the Delrin piece mitigates the gauge movements when the shock wave propagates. As a result, noise in the test signal are effectively managed through the application of a shock absorber.

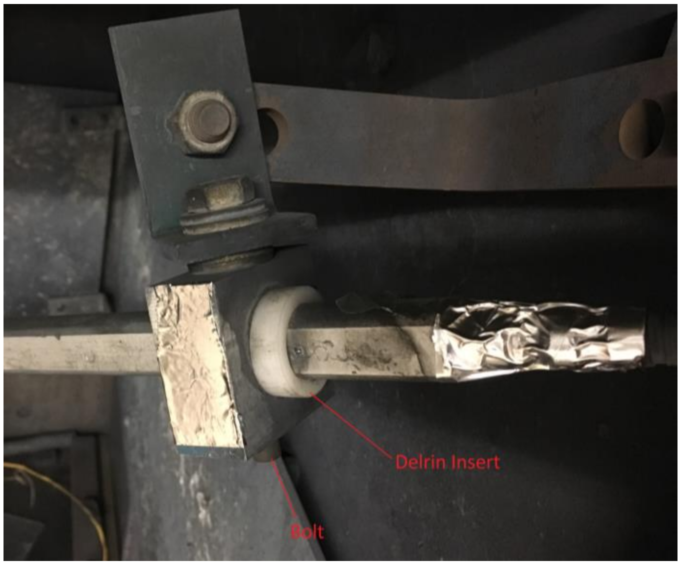

Figure 3.15 Mounted PCB Pressure Probe with Delrin Shock Absorber

Manganin gauges are single-use pressure sensors, used mainly to capture the detonation pressure of high explosives. These special gauges can be mounted in two primary configurations: inside the test specimen or on the back surface of the test specimen. In-material placement can measure material bulk properties and detonation pressure, while back surface placement can measure the wave profile [6]. Figure 3.16 best illustrates the various placement configurations for Manganin gauges.

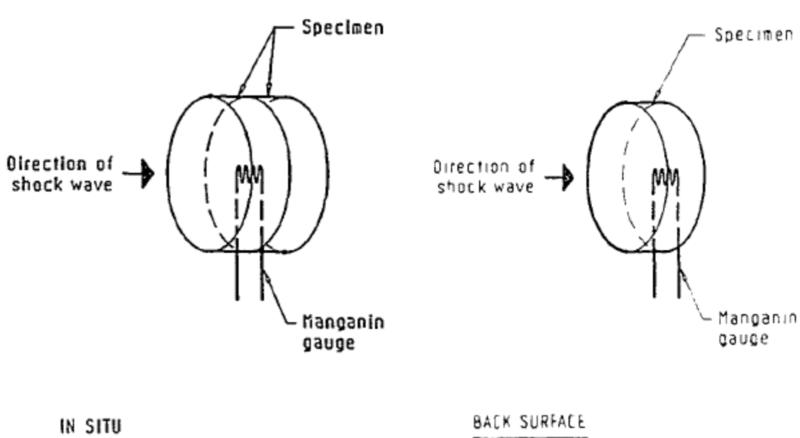

Figure 3.16 Placements for Manganin Gauge, In-Material(Left), Back Surface(Right). Figure taken from [6]

3.5 Gauge Calibration

Piezoresistive gauge calibrations for the Kulite XTEL and the Gems sensor are performed inside an enclosed environment through the pressurization of a sealed chamber using compressed air. The chamber pressure is increased at 1 psi increments up to 5 psi; after the final pressurization, the chamber undergoes depressurization at 1 psi increments until it reaches atmospheric pressure. When conducting calibration of piezoresistive gauges, it is not always necessary to use 5 psi as the maximum pressure or 1 psi increments. The only requirement is that there are enough data points when the final calibration curve is plotted. The relationship between pressure and voltage should be linear and the root mean square error, R^2 of the calibration curve should have a value that is close to unity, as shown in Figure 3.17. Table 3.1 illustrates a sample set of calibration data for the Kulite XTEL and Gems piezoresistive sensor.

Table 3.1 Sample Calibration Data for Piezoresistive Sensors

Pressure (psi)	Kulite XTEL 2 (V)	Kulite XTEL 4 (V)	Gems Sensor 1 (V)	Gems Sensor 2 (V)
0	0	0	11.72	0.791
1	0.393	0.371	12.26	0.8182
2	0.767	0.738	12.78	0.8415
3	1.142	1.109	13.3	0.8723
4	1.515	1.477	13.83	0.8997
3	1.167	1.135	13.3	0.8723
2	0.784	0.754	12.79	0.8452
1	0.411	0.388	12.25	0.8183
0	0	0	11.72	0.791

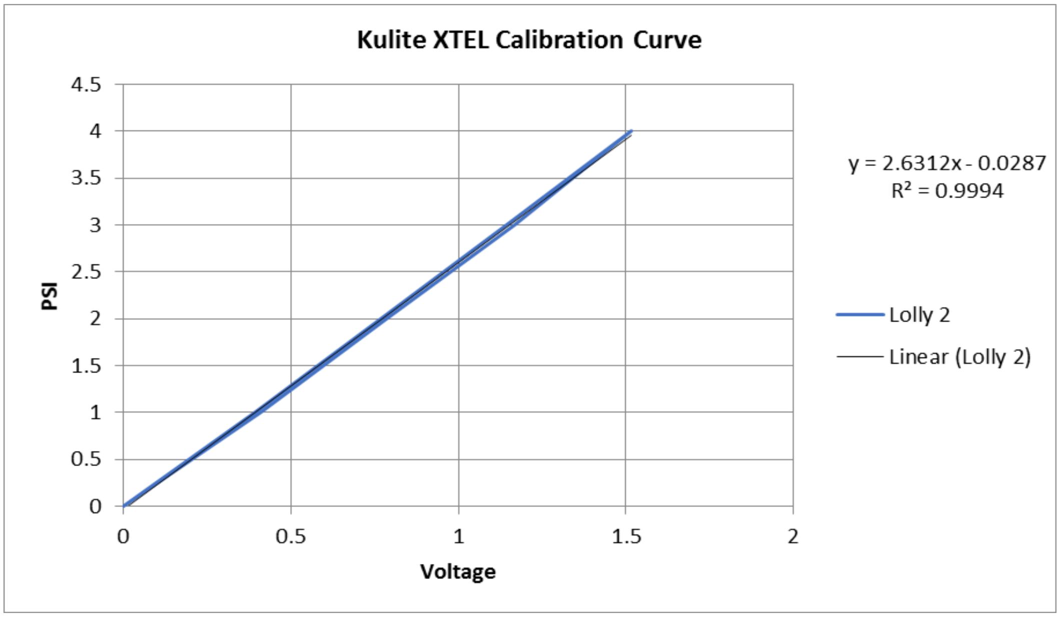

Figure 3.17 Sample Calibration Curve for Kulite XTEL

The gauge calibrations tend to shift overtime after repeated charge detonation experiments. It is again recommended that new calibrations be performed after each new test series. The PCB piezoelectric pressure probe cannot be calibrated using static pressure, because the sensing element responds only to dynamic pressure waves. The manufacturer does provide a calibration curve, and the gauge does not require repeated calibrations. The 137B23B series pressure probes have similar calibration curves with relatively small differences, these calibration curves can be cross-checked by detonating a small charge with the sensing elements positioned at equal distances from the charge. The user should observe similar signal patterns across all pressure probes.

3.6 Safety

The dangers surrounding experiments with high explosives are numerous, so that it is imperative to exercise caution and safe practices under a high-stress environment to effectively prevent catastrophic disasters. First and foremost, knowing the upper limits of the chamber capacity is vital in assessing the scope of the experiment. The user should also take into consideration the nature of these experiments when implementing preventive measures. For example, charge detonation tests with steel casings generate metal fragments with higher density in comparison to Aluminum alloy casings. It is recommended that an extra layer of the clear cast acrylic is added to protected the chamber window from failure. Gas valves leading to low-pressure instruments should be turned off prior to the experiment and visual inspections should be made to ensure that gas ports leading to sensitive instruments are turned off.

For experiments conducted inside a sealed blast chamber, it is imperative to fully honor the standard venting time allocated for that chamber. If combustibles are still present, one must pressurize the chamber with Nitrogen gas up to 4 or 5 psi and then depressurize it immediately, this step must be repeated multiple times until the reactions have dissipated. After the blast chamber has been thoroughly vented, one should wait for particulates inside the chamber to settle before opening the chamber doors. It is highly recommended that a respirator is worn when conducting repairs and clean-ups after the chamber door is opened.

The primary fireset utilized in high explosive testing is the Teledyne Reynolds FS-43, which can discharge 4 kV with a 1.5 kA peak current. When loading a charge inside the test chamber or in an open field environment, one must remove the fireset keys from the unit as a safety precaution. When the unit is not firing, the shunt must be inserted inside the firing module, as shown in Figure 3.18 to create a low-resistance current path that eliminates the risks of residual electric charges from flowing into the detonation wires.

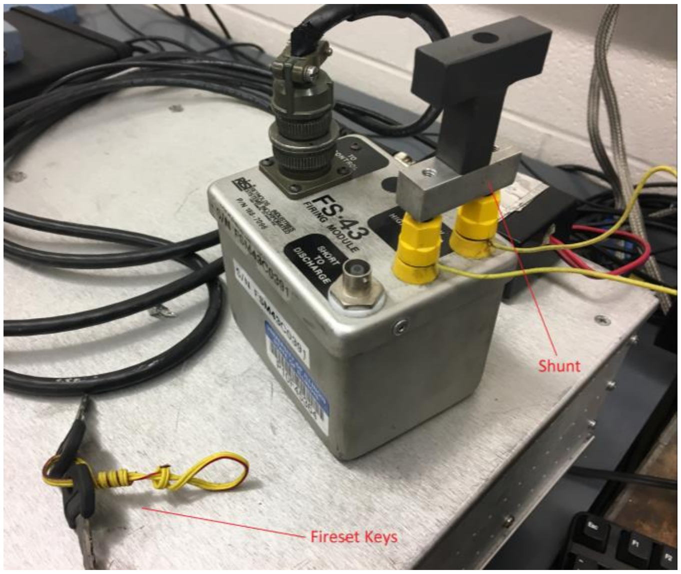

Figure 3.18 FS-43 Fireset Safely Shunted with Keys Removed

The thin twin-lead wire attached to the firing module does not have a perfect insulation. When the FS-43 fireset sends high voltage electricity through the wire, a significant magnetic field is generated during the process. An inductive pickup secured around the fireset cables detects a signal valued at 150 V on average. Thus, one should not position these cables in close proximity to sensitive instruments, because the large electric field induced by the magnetic field can cause internal damage to electronic instruments. If the twin-lead wires must be placed near electronic instruments, then heavy duty magnetic shields around the fireset cables are required. Even though there are insulations around the twin-lead wires, do not attempt to touch the wires when the fireset is in operation. When a bridge wire test is performed to verify the readiness of lab instruments, one must wait for the fireset to discharge completely before touching the bridge wire setup.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary and Conclusions

In this study, appropriate data acquisition instruments and techniques were examined for charge detonation experiments in various settings. Sensor selection and appropriate gauge placements should account for the scale and the nature of the experiment. Preventive techniques such as fortification of signal cables and application of ferrite beads can effectively reduce unwanted electric noise and data loss. Telltale signs of cable damage, fragment impacts, deteriorating sensing elements, and nuanced test environments can be determined by examining the test signal. Safe practices and fortification of the test chamber are necessary to mitigate dangers during experiments with high explosives.

- Manufacturers of pressure transducers include PCB Piezotronics, Dynasen, Gems Sensor & Control, and Kulite. The piezoelectric gauges manufactured by PCB Piezotronics are used to capture the dynamic peak pressure, while piezoresistive gauges from Kulite can be used to capture both the initial peak pressure and the quasi-static pressure. The Gems piezoresistive sensor is a set of redundant gauges utilized in the confined casing test chamber to provide redundant quasi-static pressure readings during charge detonation experiments. Thin-film Manganin gauges from Dynasen are used to measure the detonation pressure, and the gauges are compatible with the CK-2 power supply split into the 50-ohm option and the 0.05-ohm option. The low-impedance option is used for high detonation pressures ranging from 50 kBars to 500 kBars while the 50-ohm option is rated at 100 kBars.

- Signal cable exposure should be minimized from the blast source, protective structures are necessary to prevent unwanted data loss during the experiment. Electric noise can be reduced by using low-noise battery powered firesets, ferrite core suppressors, low-noise fireset cables, insulations, and terminators. In addition, insecure gauge mounts have a considerable influence on piezoelectric pressure transducers, since these sensors tend to experience more electric noise compared to its piezoresistive counterparts.
- Appropriate exposure rates for high-speed cameras should be selected to prevent over-saturation in a captured footage while maximizing the frame rate. If the footage captured using the Phantom v5.2 is too dark due to a low exposure rate, the gamma and gain can be adjusted during post-processing in PCC 2.7 until the desire image quality has been achieved.
- To prevent an internal ‘blowout’, instruments such as the PicoScope data acquisition device should be protected from an electric surge using a feed-through terminator if the test signal exceeds the device’s overvoltage protection. A low exposure rate is necessary when operating the HSFC pro high speed framing camera due to the camera’s high sensitivity to luminous light sources.
- Safety is paramount during charge detonation experiments. Shunting the fireset and removing the keys when loading the charge is imperative to ensure that unintended ignition do not happen. Fortification of test chamber windows using clear cast acrylic sheets can effectively prevent chamber window failures during experiment.

- The piezoresistive pressure transducers manufactured by Kulite and Gems Sensor & Control should be frequently calibrated since the calibrations shift over time. The calibration for these piezoresistive sensors can be achieved using static pressure through pressurization of a sealed chamber. Piezoelectric sensors from PCB Piezotronics do not respond to static pressure, and must be calibrated using dynamic pressure.

4.2 Recommendations and Future Work

Advanced and innovative pressure transducers may likely become available in the future, so new studies will be necessary to explore the applicable tools and techniques relevant to blast diagnostics. Alternative pressure transducers in the market today can also effectively diagnose the pressure release from high explosive testing, this warrants further study to examine the feasibility of alternative transducers and their ability to obtain pressure measurements. Diagnostic tools in high-speed imaging are not limited to the Phantom and the HSFC pro, further efforts can be made to examine existing imaging tools for their compatibility with blast diagnostics. Under nuanced test configurations, additional changes can be made to the existing techniques suggested in this review to suit the needs of a particular experiment.

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