

MEASURING EXPLOSIVE AIRBLAST OF
REMOTE AVALANCHE CONTROL SYSTEMS

by

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DEDICATION

I dedicate this thesis to my parents, Tristan and Christan, and my sister Mahri... and Riley 🐾

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ABSTRACT

This research was established to evaluate the explosive blast waves from operational remote avalanche control systems (RACS). Testing was performed on Gazex, O'Bellx, and Wyssen Tower systems installed near Alta, Utah. Air pressures were measured in many directions and at a range of distances around each explosive using high-pressure microphones and custom measurement equipment. The air pressure data from each system was then evaluated based on the peak pressures generated, effective blast wave energy, the rate at which pressure increased, and the decay of these parameters with distance. Distinct differences, and some similarities, between the explosives tested were found that both validated and expanded upon previous research efforts. It was found that an 11-lb Pentolite charge (designed to be deployed from a Wyssen Tower) had the strongest effects overall, followed by the standard 11-lb gel emulsion charge from a Wyssen Tower, then by the 1.5 m³ Gazex system (which was comparable to the gel charge in the direction of the exploder, but weaker in other directions), and lastly by the O'Bellx system (which had a more localized, but more symmetric, effect than the Gazex). In addition, many other tests were conducted utilizing 2-lb Pentolite charges, simulated Avalanche Guard charges, flat-field testing of Wyssen Tower gel emulsion and Pentolite charges, and explosives or RACS placed near unique terrain features. The 2-lb Pentolite testing validated the instrumentation for this project and showed that the equipment performed similarly to other systems from prior research efforts. The simulated Avalanche Guard charge was shown to have a very similar effect to the 11-lb gel emulsion charge. Flat-field testing of the Wyssen Tower charges showed similar blast wave strengths as was observed at the operational tower but indicated differences in the symmetry of the waves when compared to the operational tower. Lastly, the initial investigation of terrain features indicated that features such as cliffs and gullies can increase the directionality of an explosive. Overall, this work will provide avalanche control experts with much needed performance data on operational RACS and will also help to facilitate future work in this subject area.

1. INTRODUCTION

1.1 Background

Avalanches are complex, powerful, and dangerous forces of nature that afflict many snow-covered regions around the world. Fundamentally, an avalanche is a mass of snow and occasionally rock, vegetation, and ice, that travels rapidly downslope. These events can be initiated naturally or artificially, deliberately or inadvertently, and often have devastating effects on life and infrastructure (Jürg Schweizer et al., 2003).

Since 1951, there has been 1,109 reported avalanche fatalities in the United States with an average of 16 fatalities per year. In more recent years, this number has been closer to 27 deaths per year – likely due to increasing utilization and development of alpine terrain (Colorado Avalanche Information Center, 2020). In certain cases, a single event can kill or injure dozens of people such as the historic 1910 avalanche in Wellington, Washington which took the lives of 96 (Mapes, 2010), or the more recent Rigopiano avalanche in Italy during the winter of 2017 that claimed the lives of 29 people (Frigo et al., 2018). The yearly avalanche tragedies throughout the world exemplify the need for improved research and tools to control avalanche danger.

The subject of snow and avalanche research is a growing discipline that began to take form in the 1930's. Well-documented research did not arise until 1936 with the formation of the Swiss Federal Institute for Snow and Avalanche Research (National Research Council, 1990; Pudasaini & Kolumban, 2007). Since then, the field has grown substantially and its discoveries have enabled society to better understand, predict, and mitigate the danger posed by avalanches.

Traditionally, avalanche risk has been mitigated by a combination of avalanche education, forecasting and public warnings, modification and closures of the terrain, and most directly through artificial avalanche release (Höller, 2007; National Research Council, 1990). Despite the growing number of people who encounter and recreate in avalanche terrain, regions such as Colorado have seen a relative decrease in the number and proportion of avalanche fatalities which could likely be attributed to years of snow and avalanche research and to enhanced implementation of safety measures (Jekich et al., 2016). As such, it is incredibly important to continue to study and improve avalanche control measures to further reduce avalanche danger. As will be discussed below, the focus of this research is the evolving use of explosives and explosive systems to artificially trigger avalanches.

1.2 Avalanches

1.2.1 Avalanche Classification

Before considering avalanche control practices, it is crucial to first investigate the fundamental concepts and methods behind avalanches and avalanche release. Avalanches are primarily defined as either loose-snow or slab avalanches but can also be further classified as wet- or dry-snow avalanches and can also be characterized by their size. The distinction between wet and dry refers directly to the snowpack conditions, whereas the loose-snow and slab terminology refers to the initiation, structure, and behavior of an avalanche.

Wet-snow implies that a notable amount of liquid-phase water, from precipitation and/or melting conditions, exists within the snowpack. Conversely, dry-snow avalanches contain very little or no liquid water. Loose-snow avalanches typically initiate at a distinct location spreading

out slightly as they travel downhill and are primarily comprised of non-cohesive snow. These avalanches are typically smaller in magnitude and are consequently less destructive. Slab avalanches on the other hand involve the widespread release of a cohesive snow layer, or slab, above a pervasive weaker snow layer. These avalanches are particularly dangerous because of their propensity to initiate over large distances (across, below, or even above the initial failure point) and because of their ability to rapidly transport a considerable amount of snow (American Avalanche Association & National Avalanche Center, n.d.; Baggi & Schweizer, 2009; National Research Council, 1990; Simioni, 2017).

Loose-snow and slab avalanches can develop in both wet- and dry-snow conditions, but dry slab avalanches typically wield the most destructive power, and are thus the primary focus of avalanche research and control (LaChapelle, 1977). As such, dry slab avalanches are also the major point of interest in this research and will be exclusively discussed below unless stated otherwise.

1.2.2 Avalanche Initiation

Studying and deciphering avalanche starting conditions and initiation mechanics are ongoing and arduous undertakings. Much of avalanche research has focused on these topics in order to more successfully predict and mitigate avalanche risk by developing effective artificial avalanche release practices. Although a considerable quantity and breadth of research has been performed on avalanches and their complex behavior, the following discussion is meant only to be a general overview of the areas of interest to this research.

In simple terms, avalanche initiation can be categorized into two primary starting mechanisms. First, when an additional load is introduced to the snowpack that exceeds the

current strength of the snowpack (or some portion of the snowpack) or when the snowpack's current strength is reduced such that the existing load is sufficient to trigger a slide or via some combination of the two factors. In the first case, the increase in load could be from a human, new precipitation, wind-transported snow (wind-loading), a previous avalanche, or from an explosion among other less common possibilities. In the second case, snowpack strength is typically reduced through meteorological changes that alter the structural properties of the snowpack (National Research Council, 1990).

For either initiation mode, the resulting failure method for a dry slab avalanche is best described as a common material fracture process in snow.

1.2.3 Snow as a Material

When analyzed as a material, snow exhibits very unusual, complex, and variable behavior – worthy of research spanning many decades. The purpose of the following discussion is to provide a brief overview and explanation on snow's fundamental characteristics and behaviors. It is also important to note that these characteristics and behaviors can change rapidly due to environmental conditions, loading regimes, and the loading history among other variables – adding to the complex nature of snow (Nicot, 2004).

Snow, which is essentially a lattice of deposited ice particles, is defined by a typically high and variable porosity with significant compressibility. Additionally, snow exists at high homologous temperatures (i.e., existing at temperatures close to its melting point). The combination of these characteristics means that, when deposited, snow is prone to thermodynamic-driven metamorphism. The primary form of metamorphism is via a process known as sintering. Snow sintering is simply the growth of solid bonds between snow particles.

This process is crucial to the well-documented phenomenon of snowpack strengthening over time and is responsible, in part, to the formation of slab avalanches due in part to its role in the cohesiveness of snow slabs (Peinke et al., 2019; Shapiro et al., 1997). Similarly, snow is generally considered to be a nonhomogeneous material since many variables can alter its properties spatially. One obvious example of this heterogeneity is snowpack layering whereby naturally deposited snow exhibits multiple distinctive layers with visually and measurably different properties.¹ One type of snow layer that is frequently discussed due to its critical role in avalanche formation is known as a weak layer (Figure 1). Although these weak layers can be formed through a variety of mechanisms and can take on a variety of structures, they consistently have a higher porosity and lower strength than adjacent layers. Furthermore, weak layers exhibit a clearly anisotropic behavior with a shear strength that is about an order of magnitude less than its compressive strength (Jürg Schweizer et al., 2016; Shapiro et al., 1997). Interestingly though, despite the high variability and apparent anisotropy of snow microstructures, it has been shown that snow can also be considered as an isotropic material under certain conditions (natural snow, limited metamorphism, uniform grain structures, and limited deformation) (Cresseri & Jommi, 2005; Desrues et al., 1980).

¹ It should be noted that even within these distinct snowpack layers there is still often considerable inhomogeneity.



Figure 1 An example of a collapsed weak layer (Jürg Schweizer et al., 2016)

An additional characteristic of snow that is of great importance to avalanche control is its nonlinear and strain-rate dependent behavior. It has been shown that a significant increase in the rate of deformation of a snowpack can measurably decrease its effective strength. This same relationship has also been shown to exist between strain-rate and toughness for snow (Jürg Schweizer, 1998). Along these lines, snow is known to demonstrate a nonlinear viscous and ductile behavior at low rates of deformation and a brittle behavior at higher rates (Figure 2). This ductile-to-brittle transition, where the effective strength of snow is highest, is reported to occur at strain rates of about 10^{-4} to 10^{-3} s^{-1} (Jürg Schweizer, 1999).

In the context of avalanche control, snow's rate dependent behavior simply means that faster loading rates (assuming all other loading factors are equal) will be more successful at initiating a failure within a snowpack.

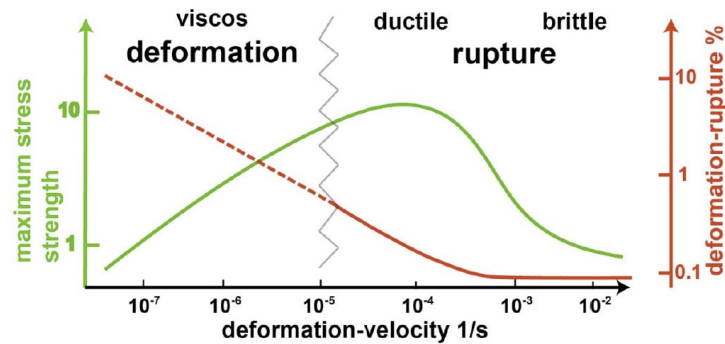


Figure 2 Graph depicting the strain-rate dependent strength of snow (Gubler et al., 2012).

This strain-rate dependency exhibited by snow is thought to be the result of the competing effects of the sintering process and the opposing damage process (failure of the bonds between snow particles) (Jürg Schweizer, 1999). Specifically, Schweizer hypothesizes that at lower strain-rates the ice bonds in the snow structure can heal/reform (sinter) at approximately the same rate they are broken (damage) – leading to the distinctive nonlinear and fluid-like viscous behavior. Conversely, at higher strain-rates, Schweizer contends that the damage process begins to dominate, and the bonds between snow particles are broken much quicker than they can be reformed through sintering – thus leading to a brittle failure. This concept of competing sintering and damage processes was further investigated and ultimately supported using a fiber bundle model that included bond-breakage and healing which was able to accurately reproduce the rate-dependent strength of snow (Reiweger et al., 2009). Another significant finding from this research was that inclusion of the sintering process was essential for realistic behavior on timescales on the order of seconds – consistent also with empirical findings which found that sintering between snow particles could take place on a sub-second interval depending on bonding temperature and pressure (Szabo & Schneebeli, 2007).

1.2.4 Avalanche Failure Process

Having discussed some of the noteworthy characteristics of snow as a material, the failure process of a dry slab avalanche can now be examined in greater detail. As is thoroughly detailed in the work of Schweizer et al. (Jürg Schweizer et al., 2016), the failure process of a slab avalanche is often considered from a fracture mechanics approach, and can be adequately represented as a four-step process: (i) initial failure within a weak layer (below a cohesive slab layer) of the snowpack, (ii) onset of crack propagation, (iii) widespread crack propagation across the slope, and (iv) the ultimate tensile failure and sliding of the slab (Figure 3). Furthermore, due to the complexity of fracture processes within a natural multi-layered snowpack, the slab avalanche snowpack is typically considered as a simplified three-layer system with a base layer, intermediate weak layer, and the upper slab layer.

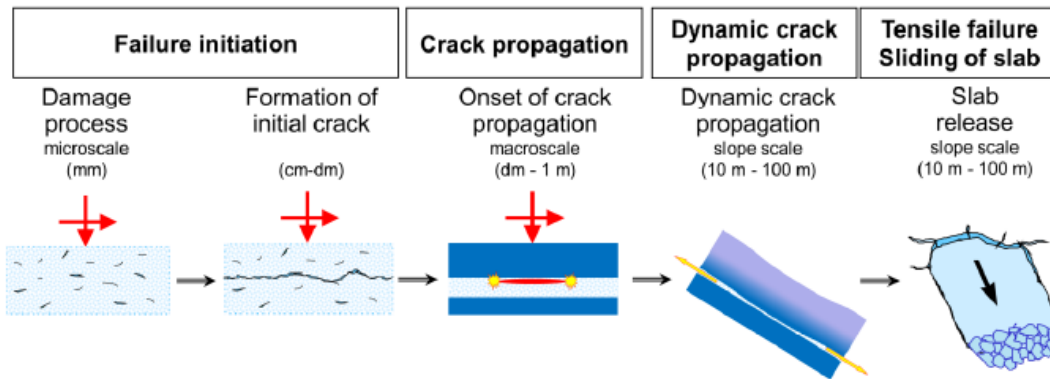


Figure 3 Illustration of the four stage avalanche failure process as proposed by Schweizer et al. (Jürg Schweizer et al., 2016).

The first step of the slab avalanche failure process occurs when the current strength of the weak layer is exceeded by a new load or when the layer strength is reduced such that it cannot support the existing load. Under these conditions, damage within the snowpack accumulates, and

initial cracks are formed within the weak layer. As mentioned above, weak layers can take on a variety of structures, they are more porous and weaker than adjacent layers, and weak layers exhibit a clearly anisotropic behavior with a shear strength that is about an order of magnitude less than its compressive strength. This implies that the formation of the initial crack in the weak layer is likely the result of the shear component of the triggering load.² The magnitude and rate of this initial weak layer damage depends on the nature of the trigger. Natural avalanches are typically characterized by a slow growth of damage (minutes, hours, or longer) at the microscopic level (0.1 to 1 mm – the scale of inter-particle bonds). Artificial avalanches, such as those triggered by recreationists or explosives, involve rapid damage (on the order of seconds) and are of a macroscopic scale (0.1 to 1 m). Aside from this initial discrepancy the remainder of the crack formation process is identical for natural and artificial avalanches. Namely, the process can continue in one of three ways: (i) the crack may halt immediately and begin to heal, (ii) it may grow to a subcritical length and then begin to heal, (iii) or in the case of a slab avalanche, the crack may reach a critical length – leading to the second stage of the slab failure process: the onset of crack propagation.

For the second stage of slab avalanche failure, the concept of interest is the critical crack length required to overcome the weak layer's specific fracture energy (analogous to strength). For more conventional materials, this critical crack length, r_c , is readily expressed in terms of measurable/calculable quantities such as the elastic modulus, specific fracture energy, and

² The frequently observed “collapse” of weak layer is thus more likely the result of a shear failure rather than the direct indication of a compressive failure. For more information on this concept, the reader is directed to the work of Schweizer et al. (Jürg Schweizer et al., 2016).

applied stress. However, for snow this calculation is not feasible due to its variable and unknown behavior and material properties. Nonetheless, observational and experimental work including the propagation saw test (PST) and numerical simulations of the PST have supported previous estimates of critical crack lengths of about 1 m (summarized in Schweizer et al., 2016). If the initial damage results in a crack that reaches and surpasses the critical crack length for the weak layer of interest, the crack will then rapidly propagate across the slope – the third step in the slab avalanche failure process.

The dynamic crack propagation portion of the slab failure process is quite simply the rapid growth of the crack across the slope. It is known that this process is directly related to the ultimate slab size of the avalanche and is likely a function of crack speed among other variables, but the exact relationship is unclear at present. Crack speed is also still relatively unknown. It is expected to be less than $100 \frac{\text{m}}{\text{s}}$, and may be closer $20 \frac{\text{m}}{\text{s}}$ based on more recent experiments involving particle tracking velocimetry and the PST (summarized in Schweizer et al., 2016).

After the crack has quickly spread across the slope, the crack eventually terminates – defining the size and location of the avalanche. Immediately following crack arrest, the slab layer above the weak layer is subject to a tensile failure, becoming fully detached from the snowpack, and begins to slide downslope leaving behind a distinctive wall at the upper boundary known as the crown (Figure 4).



Figure 4 Image showing the crown remaining after the detachment and sliding of a slab avalanche (Jürg Schweizer et al., 2003).

It is important to reiterate that the above discussion of avalanche initiation, snow mechanics, and the slab avalanche failure process is not meant to be an exhaustive account, but rather an informative introduction to the concepts of particular importance to the following section on artificial avalanche release. For more information on the above topics the reader is directed to the work of the abovementioned authors (Jürg Schweizer et al., 2016).

1.3 Artificial Avalanche Initiation

Based on the evolution and growth of snow and avalanche research, the practice of artificial avalanche control is also continuously evolving.³ Although methodologies and

³ Artificial avalanche initiation is also often referred to as artificial release, avalanche control, preventative triggering, preventative release, and other similar terminology.

technologies vary by region and by era, the primary objective and principles remain the same. Fundamentally, artificial avalanche release involves the intentional triggering of an avalanche during a time when the danger to life and infrastructure is minimal. This technique enables smaller and less destructive avalanches to be released rather than a large, unpredictable, unintentional, and deadly avalanche (Höller, 2007; National Research Council, 1990).

There are several methods for artificially triggering an avalanche, but historically the most common approach has been with explosives (Höller, 2007). Interestingly, this tactic was utilized even before avalanche research began to take form; first, as a weapon during World War I to trigger avalanches above enemy forces, and later as a tool to reduce avalanche risk. During the 1930s in Switzerland, explosives (initially rockets and mortars, and later hand-charges and military ordinances) were used to trigger small avalanches – possibly the first use of explosives as a means of protection from larger avalanches. This practice was then brought to the United States and studied in depth by Montgomery (Monty) Atwater among others at Alta, Utah (Armstrong & Williams, 1986; Atwater, 1968; Fraser, 1978; Perla, 1978).

1.3.1 Explosive Avalanche Control

Explosives have been the tool of choice for many years because of their convenience, availability, and their capacity to rapidly transform stored chemical energy into a powerful pressure wave suitable to initiate snowpack failure. The detonation of an explosive charge typically generates an inelastic blast wave known as a shockwave in the close vicinity of the explosion. This shockwave then degrades into a large-amplitude wave known as an N-wave and finally into a small-amplitude acoustic wave at larger distances from the explosion (Figure 5) (Gubler et al., 2012; Reuter & Schweizer, 2009). The velocity of the elastic wave is independent

of the pressure amplitude – unlike the shockwave region (Simioni et al., 2014). The radial attenuation of the blast wave over snow is the result of a spherical volume growth (geometrical expansion), energy lost to the compression and fracturing of the snow (since snow is the most absorptive naturally occurring ground cover), frictional forces, and interactions within snow's porous microstructure (Simioni, 2017). Additionally, as the wave front travels and attenuates, it produces three distinct zones of response within the snowpack. The zone nearest the detonation is characterized by substantial fracturing and permanent deformation and is known as the cratering zone, the second zone has less significant permanent deformation, and the most distant zone has no permanent deformation (Albert, 1983).

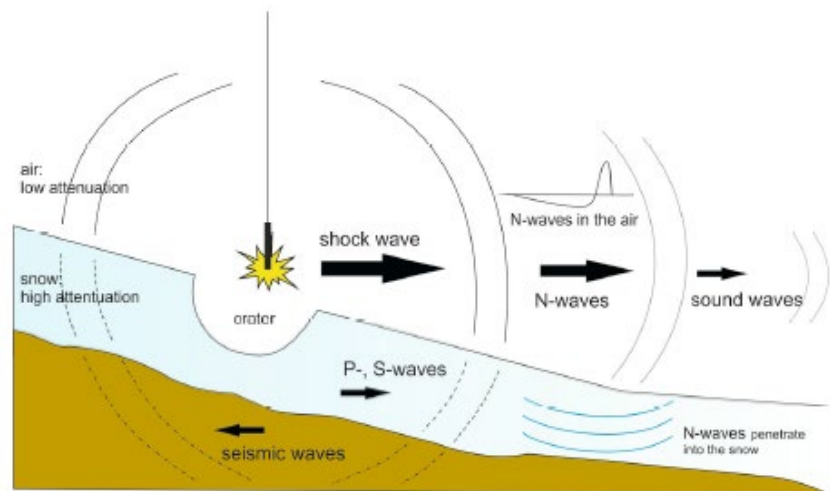


Figure 5 Illustration of the blast wave generated by an explosive (Gubler et al., 2012).

The N-waves generated by an explosion are characterized by an initial period with a sudden positive increase in pressure from atmospheric pressure to a peak pressure followed by a longer-duration period of negative pressure (Figure 6). These waves can penetrate the intergranular pores of snow and the sudden pressure jump can generate significant stresses

within the microstructure of the snow – leading to the formation of cracks and thus avalanche initiation (Gubler, 1977; Gubler et al., 2012; Johnson et al., 1994; Miller et al., 2011; Simioni et al., 2014). These waves are also of particular importance because they are the most distal waveform capable of causing failure, since the shockwave is more than sufficient to fracture the snow, and a small amplitude acoustic wave is unlikely to trigger an avalanche (Reuter & Schweizer, 2009). This has been further supported by the work of Wooldridge (2013) which found that avalanche explosives could locally strengthen the snow close to the explosion rather than promote slab failure due to the significant compaction and disruption of the weak layer – indicating that the successful initiation of an avalanche is more likely due to far-field effects. Meaning that, even though many researchers have focused on the cratering and shockwaves generated by various explosives, a thorough understanding of the blast region beyond the shockwave is critical to quantify and compare the effective ranges of various avalanche control explosives (Gubler, 1977).

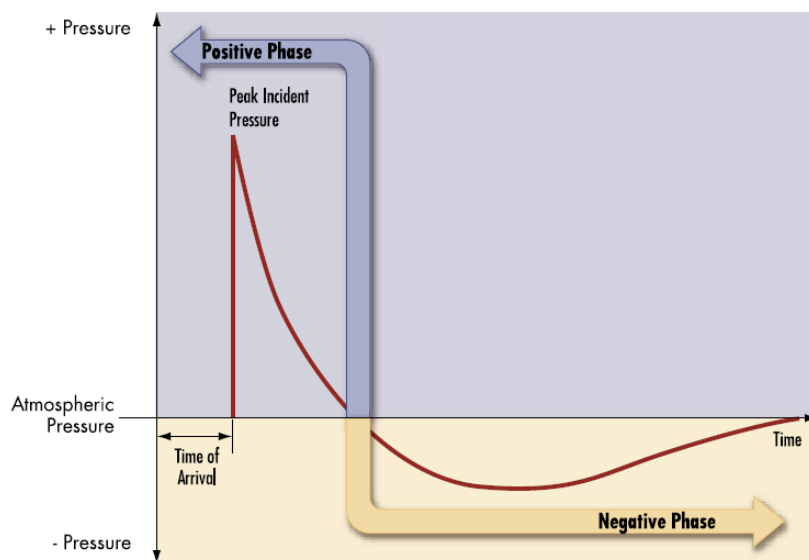


Figure 6 Typical pressure-time behavior of a blast wave (FEMA, 2003).

Additionally, as detailed by Bones (2012), the characterization of the blast wave is important to sufficiently compare the various waveforms produced by different explosives. Bones named the three independent characteristics necessary to fully describe a blast wave: (i) the blast overpressure, (ii) the blast duration, and (iii) the impulse. The blast overpressure is simply the difference between the ambient air pressure and the peak pressure generated by the blast wave. The duration (total time of waveform) and impulse (area underneath the pressure-time curve) of the wave are closely related to the destructive power of a blast wave (e.g. a blast wave with a large overpressure but negligible duration and impulse might have minor destructive capability). However, as it relates to explosive avalanche control, it is also important to consider the rate at which the pressure initially rises from ambient pressure to the overpressure (Miller et al., 2011). This is thought to be important due to snow's rate dependent behavior since higher rates will presumably result in a lower effective snow strength and thus a more likely snow failure – though the magnitude of this effect is presently unclear when comparing the blast waves of various avalanche explosives.

1.3.2 Past Research on Explosive Avalanche Control

Much of the early explosive avalanche control research sought to determine the ideal type, quantity, and placement of explosives in order to optimize explosive effectiveness (Bones, 2012). Through these research efforts and years of practical observations, it has been determined that high-speed explosives roughly equivalent to 1 kg of TNT (Pentolite being one of the most commonly employed) are well-suited to successful avalanche control efforts (LaChapelle, 1977). High-speed refers to the velocity at which the shockwave travels through the explosive upon detonation (Velocity of Detonation or VOD). High-speed explosives (also known as high

explosives) include materials such as TNT and Pentolite with VOD's of 6,900 m/s and 7,400 m/s, respectively. Low-speed, or low explosives, include gunpowder or propane with VODs less than 2000 m/s (Gubler et al., 2012). High explosives have largely become the tool of choice due primarily to improved stability, safety, and longevity, and to a lesser extent, due to the belief that they are more effective at initiating slab avalanches – though this has not been extensively confirmed (Perla, 1976).

Another valuable discovery from early avalanche research was the realization that elevating explosive charges by 1-2 meters above the snow surface can significantly improve the efficacy of avalanche control efforts (Gubler, 1977). However, it has also been shown that elevating a charge to scaled detonation heights beyond about $2 \text{ m} * \text{kg}^{-\frac{1}{3}}$ provides diminishing returns due to increased geometrical expansion and attenuation of the blast wave before it impacts the snow (Johnson et al., 1994; Miller et al., 2011). The improved effectiveness of elevated charges is the result of less explosive energy being lost in the formation of a larger crater – as is the case with buried charges. When a buried explosive charge is detonated, significant energy is lost to the inelastic compaction of the snow and very little energy is propagated beyond the crater – resulting in drastic attenuation of the blast wave of a buried charge. For elevated charges, more energy can be transferred from an air blast wave to the snow because the mechanical impedances of air and uncompacted snow are more similar (due to the high porosity of snow) than with the direct coupling between a buried explosive and the snow (Johnson et al., 1994).

As discussed previously, the powerful blast wave created by an explosion is particularly effective at triggering avalanches because it can affect a large volume of snow – making it more

likely to produce a crack in a localized area of greater instability (aka “weak spot”) – and the wave front results in large deformation rates which reduces the effective strength of snow (Binger et al., 2006; Gubler et al., 2012). In general, snow slab failure is achieved when the applied pressure exceeds the local strength of the weak layer and a critical crack is formed (Johnson et al., 1994; Simioni et al., 2014). However, due to the inherent variability of snow, the pressure magnitude and rate needed to achieve weak layer crack propagation, and thus the effective range of an explosive, is not constant spatially, nor temporally, nor is the value explicitly known (Albert, 1983; Johnson et al., 1994; LaChapelle, 1977; Miller et al., 2011).

Nevertheless, many researchers have attempted to define the pressures necessary to reliably trigger an avalanche or confirm that the stability of an avalanche-prone slope is adequately safe. The most commonly cited pressure values are based on an assumed weak layer strength of approximately 1 kPa, or less, and range from 200 Pa to 3.5 kPa of additional surface pressure (Gubler, 1977; Johnson et al., 1994; Mellor, 1985; Reuter & Schweizer, 2009; J. Schweizer & Camponovo, 2001; Jürg Schweizer, 1999; Thumlert & Jamieson, 2014).

There is also ongoing discussion regarding the importance of the rate of pressure rise in the definition of an effective range. Some researchers contend that the effective range of an explosive is best defined as the distance at which a predetermined minimal rate of pressure rise and thus deformation speed is achieved – this relates to the knowledge that snow strength decreases at large rates of deformation (Gubler et al., 2012). Others have found that the magnitude of the pressure alone can be used as a reasonable approximation for the snowpack response and thus could be used to define an effective range depending on snow conditions (Simioni et al., 2016). Ultimately, due to the inherent variability, there is still no definitive

agreement on the definition of an effective range for the various avalanche control methods.

Thus, at present, the general practice utilized by avalanche control experts is to select explosives with large overpressures and higher speeds to increase the likelihood of a successful trigger.

It should be noted that this work is not intended to provide nor expand on a definition for the effective range of avalanche control explosives. This work is only intended to determine and provide measurements and comparisons of the blast wave characteristics of a variety of modern operational avalanche control explosives and explosive systems – such that any current or future effective range criteria can be used to compare the devices included in this work. However, to assist in the presentation of this data, the frequently cited effective range cutoff of 1 kPa maximum overpressure was used.

1.4 Remote Avalanche Control Systems (RACS)

Today, avalanche control practitioners still frequently use the traditional means of explosive avalanche control such as military artillery, cable-car, helicopter bombing, and hand-charges (particularly in the U.S.), but newer avalanche control tools known as remote avalanche control systems (RACS) are also beginning to see increased use, with thousands in operation around the world. RACS are permanent (yet some are removable) and reusable devices that are installed in avalanche terrain and can be activated electronically from a great distance. These systems either drop a solid explosive (SE) to be detonated above the snowpack or ignite a combustible gas such as hydrogen or propane to generate a directed gas explosion (DGE). Although there are several other systems that can also be considered to be RACS such as a cable

car, the most common systems deployed today (and the systems of interest to this research) are:

(i) the Wyssen Tower, (ii) Gazex, (iii) O'Bellx, and the (iv) Avalanche Guard systems.

1.4.1 Wyssen Tower

The Wyssen Tower is a large mast that extends outward and above the snow cover (Figure 7). Atop this mast is a magazine (removable by helicopter) that stores up to 12 prepackaged SE charges which can be remotely released and suspended on a tether above the snow surface where the charge will detonate. These SE charges can be up to 5 kg each and can be prepared with a variety of typical explosive substances (Gubler & Wyssen, 2002).

Fundamentally, the Wyssen tower is an automated and sophisticated method of remotely suspending and igniting a SE charge. As such, the behavior/performance of the Wyssen tower is expected to be comparable to the SE charges themselves (without the Wyssen tower) when suspended at similar heights.

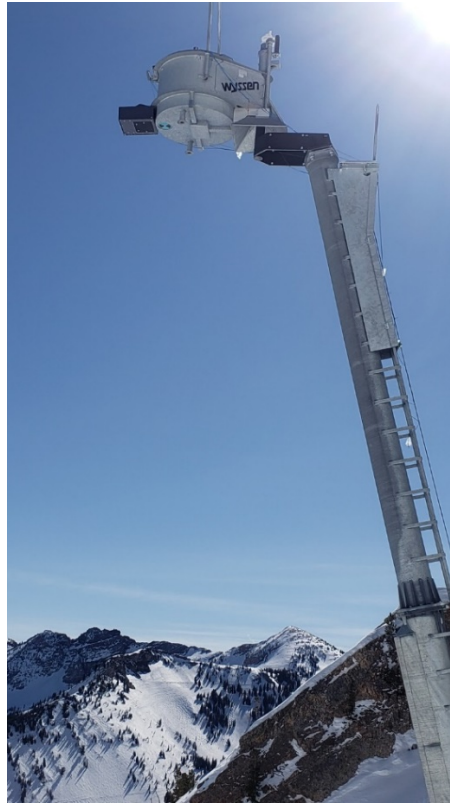


Figure 7 Operational Wyssen Tower near Alta, Utah.

1.4.2 Gazex

The Gazex is a DGE system with a permanently installed steel pipe that protrudes horizontally from the avalanche slope (Figure 8). This pipe, which has been offered in various volumes from 0.8 m^3 to 4.5 m^3 , is filled with propane and oxygen from a distant and refuellable gas storage container. This mixture is then ignited within the pipe and the combustion gasses are rapidly expelled from the open end of the pipe and towards the snowpack.



Figure 8 Operational 3.0 m³ Gazex installed near Alta, Utah.

1.4.3 O'Bellx and Daisybell

The O'Bellx system is another DGE device that relies on the combustion of a hydrogen-oxygen mixture within an egg-shaped vessel (Figure 9) with an approximate volume of 0.35 m³ (Berthet-Rambaud et al., 2008). The manufacturers of this device also offer a similar system known as the Daisybell (Figure 10) which is designed to be suspended underneath a helicopter to facilitate mobile blasting.



Figure 9 Several operational O'Bellx systems installed at Alta, Utah.



Figure 10 Daisybell system being used in the Chamonix Valley (Berthet-Ramnaud et al., 2008).

1.4.4 Avalanche Guard

The Avalanche Guard is a mortar-style system that can launch 2.5 or 5 kg SE charges (Figure 11). These charges can travel up to distances of 200 m before they impact the snow, become partially buried, and are then detonated (Inauen-Schätti, n.d.).



Figure 11 Installed Avalanche Guard system (Rice Jr. et al., n.d.).

1.4.5 Modern Use of RACS

There are multiple reasons for the ongoing technological shift from traditional avalanche control practices to RACS. For many years there has been growing concern about the safety and practicality of manual avalanche control operations such as hand-charges, helicopter bombing, and artillery. Traditional avalanche control practices (apart from artillery methods) require the manual setup and direct handling of explosive devices. Not only does this process involve some risk associated with storing and handling explosives, but it also requires practitioners to

encounter avalanche terrain – an inherently risky business (and expensive for helicopter bombing). Although this process is practiced successfully with great caution and training, and few accidents have been reported in recent years, there is still a history of some unfortunate fatalities such as the two 1973 deaths at Mammoth Mountain, California (National Research Council, 1990; Perla, 1978). Furthermore, manual methods can be time-consuming and often rely on favorable weather conditions to access the avalanche terrain. This restricts the amount of terrain that can be covered and the timing of control efforts to periods after a snowstorm when the snowpack may have begun to stabilize – making successful avalanche release more difficult (Simioni, 2017). Although artillery methods can generally alleviate the abovementioned issues, they still rely on expensive and limited access to military weapons and ammunition which frequently detonate at or below the snow surface, and can cause dangerous shrapnel to be thrown great distances (Elder & Newcomb, 1996; Gubler et al., 2012; Liebermann, 2002; National Research Council, 1990; Perla, 1978). Although investment costs are higher, the appeal of modern RACS is that they can be operated from a remote and safe location, they can be operated during any weather conditions, can be fired multiple times in quick succession, and are often less burdened by governmental regulations (Gubler et al., 2012; Liebermann, 2002; Simioni, 2017).

1.4.6 Current State of RACS Research

Modern remote avalanche control systems were first introduced in 1987 with the Gazex system; though the concept of a permanent and remote avalanche control device had certainly been proposed before (LaChapelle, 1977; Perla, 1978). Despite the growing interest in, and successful utilization of RACS, much is still unknown about them – including their performance. As discussed above, since the early 1900's much research has been performed on explosive

avalanche control. However, very little of this research has attempted to quantify and directly compare the performance of various operational RACS. The most relevant research specifically focused on RACS, which will be discussed in greater detail below, has come from such authors as Jacob Schippers (1994), Kelly Elder and Rod Newcomb (1996), Stephen Lieberman (2002), Ernesto Bassetti et al. (2008), Philippe Berthet-Rambaud et al. (2009; 2010, 2008; Fanny & Berthet-Rambaud, 2010), Emma Suriñach (2011), Hansueli Gubler et al. (2012), and Stephan Simioni et al. (Simioni, 2017; Simioni et al., 2014, 2017, 2016; 2018).

1.4.6.1 Jacob Schippers One of the first papers published about RACS was from Jacob Schippers (Jacob Schippers, 1994) who was the original developer of the Gazex system and the former President of Technologie d'Alpine de Sécurité (TAS) – the manufacturer of Gazex, O'Bellx, and Daisybell among other technologies. Schippers' paper was primarily an introductory, operational, and marketing-based overview of the recently developed Gazex system. Although the paper was limited in its discussion of test methods and results, it did provide some valuable insight into the probable performance of Gazex systems.

Some of the most significant conclusions from this paper are that the blast duration of the Gazex system is longer in duration than traditional solid explosives. This is an expected result since high-speed explosives such as Pentolite have a VOD of 7,400 m/s whereas low-speed explosives like propane have an ignition velocity near 1,200 m/s (Bassetti et al., 2008; Gubler et al., 2012). Additionally, Schippers concluded that 1 kg of a propane-oxygen gas mixture can produce a shockwave equivalent to that from 8 kg of TNT, and that a single 1.5 m³ Gazex installation at 7,500 feet in elevation is equivalent to 15 kg of TNT. Schippers also describes the “radius of action” of Gazex to be between 150 and 450 feet (45 m – 137 m) – though he does not

define the “radius of action”. Finally, Schippers also claims that the “area of action” of a Gazex device is larger than with traditional explosives and that the blast wave from a 3 m³ Gazex peaks at 40 mb (or 4 kPa) at 183 feet ($\approx$ 56 m) above a snow-covered surface. Although the basis for the above conclusions are not explicitly detailed, they do still provide meaningful values for comparison with other work.

1.4.6.2 Kelly Elder and Rod Newcomb The next paper focused on RACS was from Kelly Elder and Rod Newcomb (Elder & Newcomb, 1996) who provided detailed observations from multi-year tests on several operational Gazex installations on Teton Pass in Wyoming. Although this research was primarily qualitative in its observations and conclusions, it did indicate that the snow depth was affected within about 10 to 40 m from the Gazex supports and the snow strength was measurably affected within about 10 to 35 m. Elder and Newcomb also concluded that the Gazex system was effective for surface snow layers, but not for deeper layers, and that the placement and spacing of Gazex devices is critical for successful operation.

1.4.6.3 Stephen Lieberman Stephen Lieberman (Liebermann, 2002), in conjunction with TAS, provided updated information to the paper from Schippers (Jacob Schippers, 1994), but did not include additional descriptions of test methods and results. Lieberman claimed that the detonation of a 1 kg propane-oxygen mixture was equivalent to a 0.8 m³ Gazex system and was much more powerful than a 1 kg solid explosive. Further, Lieberman described the effect of a Gazex explosion on the snow surface in terms of three avalanche triggering modes: (i) the direct “pushing” effect of the blast wave on the snow, (ii) the uplift of the surrounding snow due to the negative pressure region of the blast wave, and (iii) the seismic effects from the Gazex

foundation. These modes have also been noted for explosions in general by Chernouss et al. (2006).

1.4.6.4 Ernesto Bassetti et al. Another paper from TAS, written by Bassetti et al. (Bassetti et al., 2008), further detailed the performance of the Gazex system. Although the paper was not exhaustive in its descriptions of testing, it did provide several additional performance values for Gazex. Namely, the researchers found that the combustion gasses had an ejection velocity at the mouth of the exploder of 1,200 m/s and a velocity of 500 to 600 m/s as they reached the snow – indicating a supersonic region. Additionally, the paper provided the figure shown below (Figure 12) which was one of the first graphical depictions of the effective range of a Gazex system. This figure indicates that the blast wave from a Gazex could result in a pressure of 25 millibar (or 2.5 kPa) over an area with a radius of 100 m and that a wedge-shaped region directly downhill from the exploder was subject to the aforementioned “pushing effect”. However, the test methods and parameters used to create the figure are not sufficiently detailed in the paper.

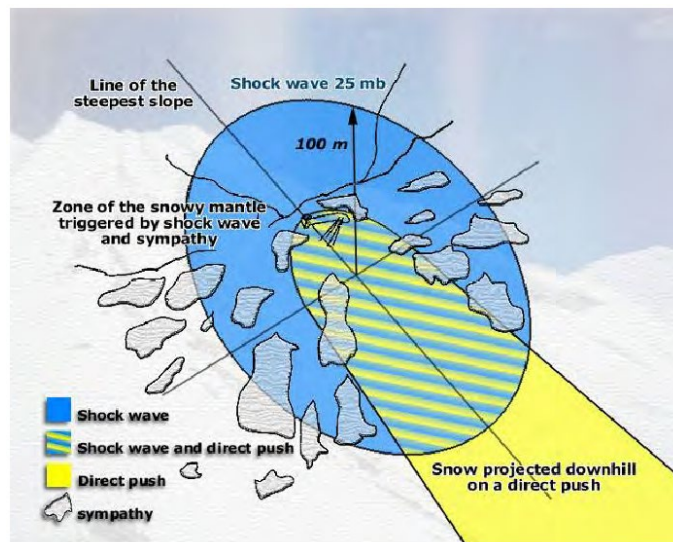


Figure 12 Illustration of the range and effects of a Gazex system (Bassetti et al., 2008).

1.4.6.5 Philippe Berthet-Rambaud et al. Philippe Berthet-Rambaud (Berthet-Rambaud, 2009; Berthet-Rambaud et al., 2008, 2010; Fanny & Berthet-Rambaud, 2010) worked with TAS and many other researchers over a span from 2008 to 2010 to provide some of the only research performed to-date on the, then newly developed, O'Belx and Daisybell systems.

The first paper served as a marketing-based introduction to the Daisybell system (Berthet-Rambaud et al., 2008). One noteworthy conclusion from this paper was that a Daisybell fired 3 m above bare ground produced a blast wave peaking at 80 mb (or 8 kPa) at a distance of 12 m horizontally. Berthet-Rambaud et al. also noted that the blast wave was comparable in magnitude to a 0.8 m³ Gazex device, but the blast duration for the Daisybell was about two times shorter (Figure 13). An additional measurement taken above a snow cover indicated that the Daisybell could produce a blast wave with a peak amplitude of 25 mb or (2.5 kPa) at a distance of 25 m.

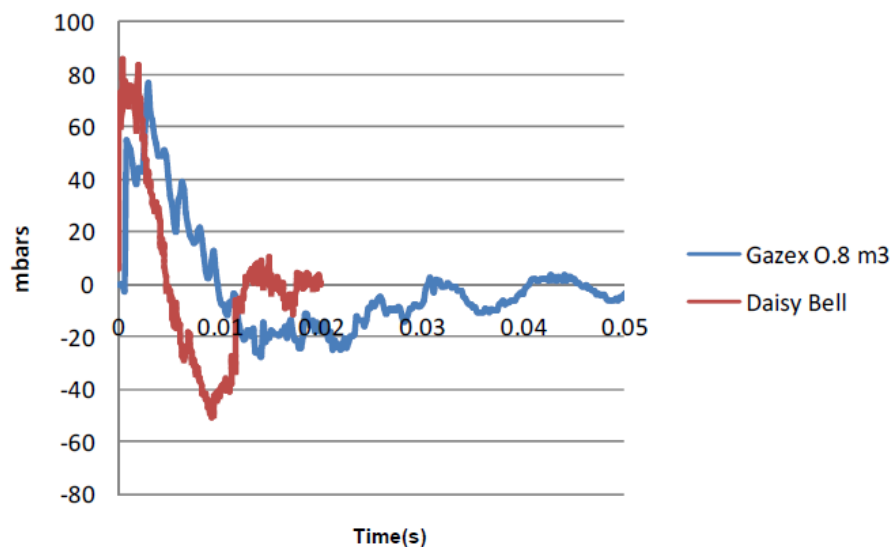


Figure 13 Graph comparing the blast pressures measured over time for the Gazex and Daisybell systems (Berthet-Rambaud et al., 2008).

Another paper published in 2010 provided some pressure measurements for the newly developed O'Bellx system (Berthet-Rambaud et al., 2010). Using a blast pressure probe (137A22 from PCB Piezotronics) and a data acquisition system with a sample rate of 50 kHz, Berthet-Rambaud et al. determined that the incident blast wave from an O'Bellx device could reach 1,200 millibar (or 120 kPa) at a distance of 1.5 m and 275 mb (or 27.5 kPa) at a distance of 3.5 m.

1.4.6.6 Emma Suriñach In 2011, researchers investigated the ability of seismic disturbances from operational Gazex systems to initiate an avalanche at distances outside the immediate blast wave region (Suriñach et al., 2011). This research indicated that the ground accelerations generated by the Gazex device tested were about six times too low to reliably trigger an avalanche at large distances outside the blast region. Based on an earlier paper from an Italian researcher, A. Tamanini, Suriñach et al. also defined the effective blast radius of a Gazex to be the maximum distance at which a maximum pressure of 3.5 kPa is achieved. This was given as 40 m for a 0.8 m³ Gazex device and 69 m for a 3 m³ device – based on earlier measurements.

1.4.6.7 Hansueli Gubler et al. Hansueli Gubler worked with Samuel Wyssen and Arnold Kogeinig in 2012 to develop a handbook for Wyssen Avalanche Control – manufacturer of the Wyssen Tower (Gubler et al., 2012). The intent of this paper was to provide a general discussion and comparison among the many avalanche control methods. As such, this paper does not

exhaustively cover the testing methods and results obtained, but it does provide many useful comparisons between the Gazex, Wyssen Tower, and the O'Bellx and Daisybell systems.

For the purposes of comparing avalanche control methods, Gubler et al. defined the effective range of a method to be the maximum distance at which some predetermined minimal deformation speed is reached in the snowpack. The deformation speed is considered by Gubler et al. to be related to the rate of pressure rise of the blast wave and is thought to be proportional to the additional stresses encountered within the snowpack. On that basis, Gubler et al. concluded that even though the pressure magnitude for the 4 kg solid explosive tested was nearly equivalent to that from the 4.5 m³ Gazex device, the difference in pressure rise rates result in a significant difference in the effective range – with the solid explosive being more effective at larger distances. More specifically, Gubler et al. found that the solid explosives tested had the fastest pressure rise and the largest effective range of about 135 m, the O'Bellx and Daisybell systems had the next fastest pressure rise, but had the smallest effective range due to the limited gas volume, and lastly the Gazex system had the slowest pressure rise (3 times slower than the solid explosive) and an effective range of approximately 100 m (Figure 14 and Table 1). However, Gubler et al. also noted that the measurements taken for the 4.5 m³ Gazex system were done so at an angle of 45° off-axis from the front of the exploder – making them only indirectly comparable to the measurements take for other systems.

Table 1 Effective ranges of various avalanche control methods as presented in Gubler et al. (Gubler et al., 2012). Values in parentheses are claimed to be 40% too large (Gubler et al., 2012).

Height of detonation point	Charge weight	Radius R_N to prevent natural initialization	Radius R_S to prevent initialization by single skier
Detonation above snow (2-3 m) Detonation above snow (2-3 m)	5 kg 1.5 kg	135 m 85 m	70 m 50 m
Gazex (forwards) Gazex (45° sideways) Gazex (forwards)	$3 m^3$ $3 m^3$ $1.5 m^3$	approx. 70 m (120 m) approx. 50 m (100 m) approx. 50 m (100 m)	50 % -70 % of R_N
Hand charge	1.5 kg	30 m	-----
buried projectile	<1.5 kg	15 m	-----

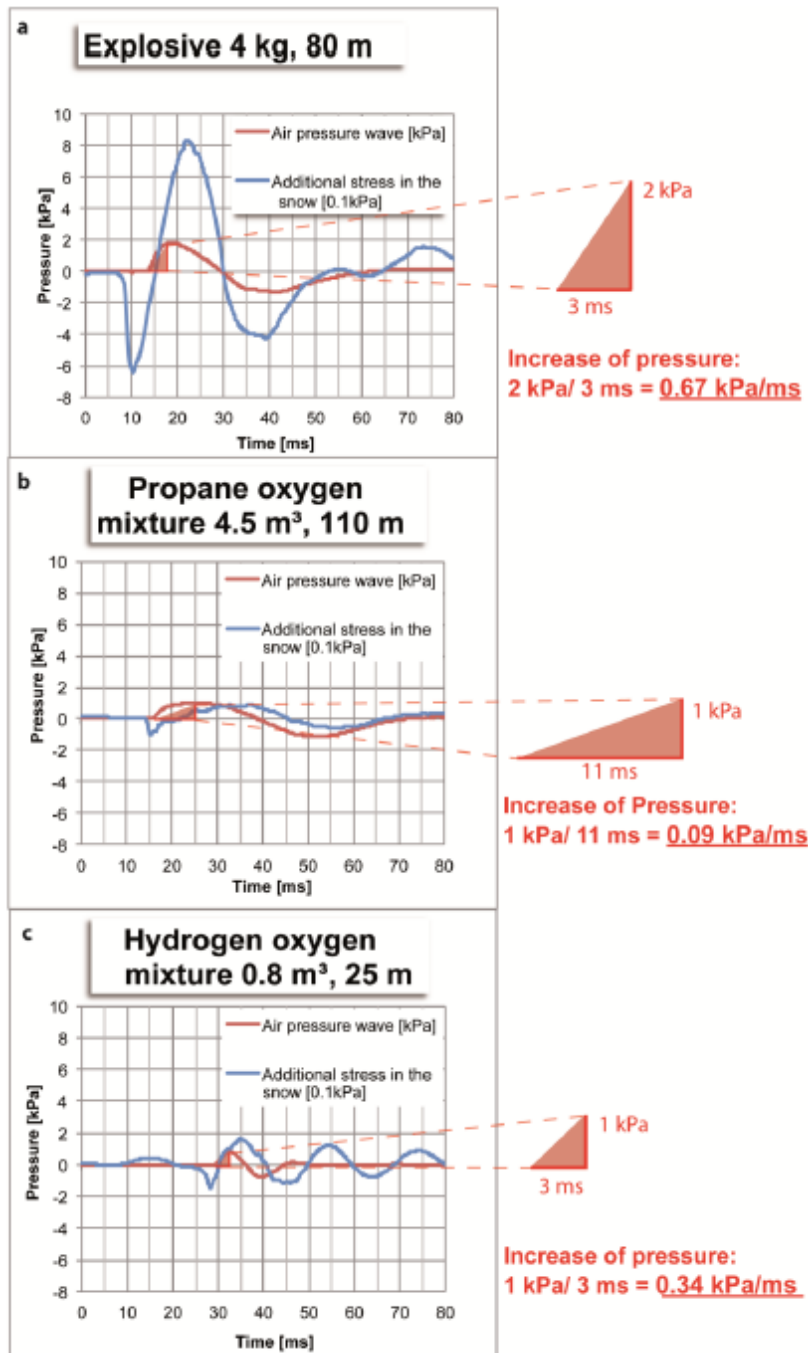


Figure 14 Results supplied by Gubler et al. (2012) for the pressure-time profile (red) and the calculated snowpack stresses (blue) associated with the blast waves from a 4 kg solid explosive (a), 4.5 m³ Gazex (b), and a 0.8 m³ Daisybell (c). The values taken for the Gazex installation (b) were measured at 45° off of the main axis of the device and are not directly comparable to the other results presented in this figure.

1.4.6.8 Stephan Simioni et al. Perhaps the most extensive, independent, and well-documented RACS research accomplished to-date has been by Stephan Simioni et al. (Simioni, 2017; Simioni et al., 2014, 2017, 2016; Simioni & Schweizer, 2018). Simioni (2017) orchestrated numerous tests using a representative Gazex prototype in a flat and open field (Figure 15).



Figure 15 Prototype Gazex system utilized by Simioni (Simioni, 2017).

Simioni also conducted many other side-by-side tests with solid explosives as well as tests using an operational Gazex to provide data for comparison. Using a custom measurement system originally developed by Tichota et al. (2010) and Bones (Bones, 2012), Simioni took measurements of the blast wave pressures via microphones placed above the snow surface by about 5 cm, at distances from the exploder ranging from about 11 m to 50 m, and placed along two axes – one directly in line with the exploder axis (x-axis), and one off-axis at an angle

ranging from 23° to 37° (y-axis) – to capture the expectedly non-symmetrical blast wave (Figure 16). Measurements of the snowpack accelerations were also taken using accelerometers buried at different depths and distances within the snowpack to investigate the response of the snow subjected to different avalanche control methods (SE and DGE). For a complete description of the testing methods and equipment utilized, the reader is referred to Simioni (Simioni, 2017).

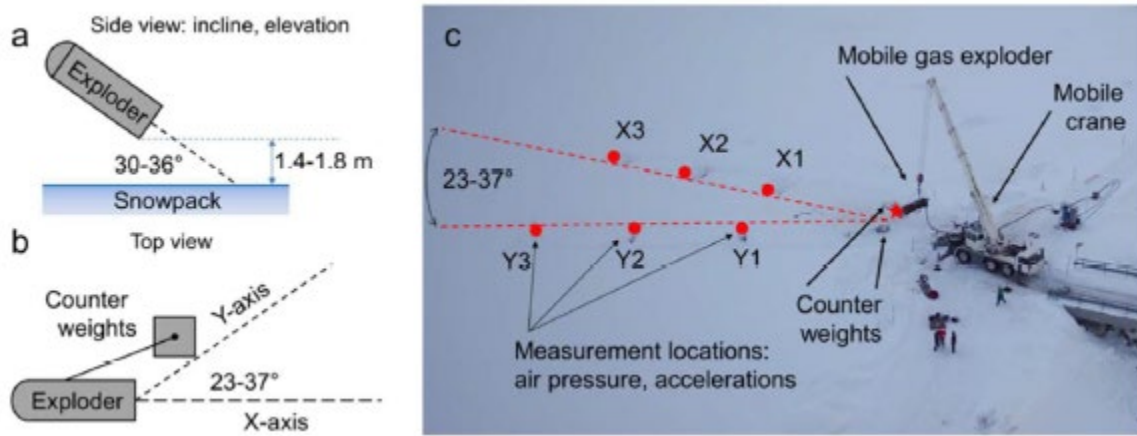


Figure 16 Testing setup utilized by Simioni (Simioni, 2017) for tests conducted with a prototype Gazex.

One particularly valuable result from Simioni's work was the development of a scaling factor for the non-spherical explosion of a Gazex. For traditional explosives that produce a symmetrical and spherical blast wave, a scaling law exists that allows the blast effects of different charge masses to be compared. However, this was not the case for the unique directed gas explosion of the Gazex system. Based on the results of his testing, Simioni derived the following relationship for the scaled distance, x' , of a Gazex explosion with gas mass, m_G [1].

$$x' = x * m_G^{-0.65} \quad [1]$$

Simioni also derived the following expressions for the decay of the Gazex blast wave overpressure with scaled distance along the x-axis [2], and along the y-axis [3]. As can be seen by the comparison of the two equations below, it was determined that the overpressure decay along the x-axis was nearly identical to the decay along the y-axis, regardless of the angle between the axes (up to 37°).⁴ In other words, within about 75° of the exploder opening there was no measurable variation in the decay of the blast wave.

$$P_{MAX}^X = 10^{5.68} * x'^{-1.68} \quad [2]$$

$$P_{MAX}^Y = 10^{5.61} * x'^{-1.65} \quad [3]$$

In addition to directly measuring the Gazex overpressures, which ranged from 17.5 kPa at a scaled distance of 9 m kg^{-0.65} to 0.3 kPa at 88 m kg^{-0.65}, Simioni also calculated the maximum derivative of the pressure (or the maximum rate of pressure increase of the wave front). These values ranged from 7.0 x 10⁷ Pa s⁻¹ at a scaled distance of 9 m kg^{-0.65} to 5.5 x 10⁵ Pa s⁻¹ at 88 m kg^{-0.65}. Furthermore, Simioni also developed expressions for the decay of the maximum pressure rate with scaled distance along the x-axis [4], and along the y-axis [5]. It was found that the air pressure derivatives decayed very similarly to the overpressures themselves.

$$P_{tMAX}^X = 10^{9.27} * x'^{-1.86} \quad [4]$$

⁴ As mentioned in Simioni's work (2017) it was not feasible to obtain measurements at larger angles due to the placement of the prototype Gazex counterweights. However, some measurements were taken at an angle of 89° though these tests were performed above dry ground.

$$P_{tMAX}^Y = 10^{8.78} * x'^{-1.50} \quad [5]$$

As mentioned above, Simioni and Schweizer (Simioni & Schweizer, 2018) also conducted numerous side-by-side tests with solid explosives to compare the effects of a DGE and SE. The solid explosive used for the testing was Riomon T1 with a charge mass ranging from 2.4 kg to 4.8 kg. This explosive was elevated above the snow surface by about 2 m. Comparison of the measurements for the solid explosive and the prototype Gazex indicated that they are quite comparable in their effects – particularly within 37° of the exploder axis on either side. Simioni and Schweizer determined that a 1.8 kg gas charge produced overpressures of 6 kPa at 20 m, 1 kPa at 57 m, 0.59 kPa at 80 m which were very similar to the overpressures and snowpack accelerations from a 4.5 kg solid explosive charge. Based on the comparative tests, Simioni (Simioni, 2017) was also able to produce isoline figures of the pressure fields from the prototype Gazex and the solid explosive (Figure 17). In doing so, it was observed that the solid explosives had expectedly circular/symmetrical pressure isolines while the prototype Gazex had bulb-shaped isolines (stronger pressures along the exploder axis) at shorter distances, but circular/symmetrical isolines at greater distances.

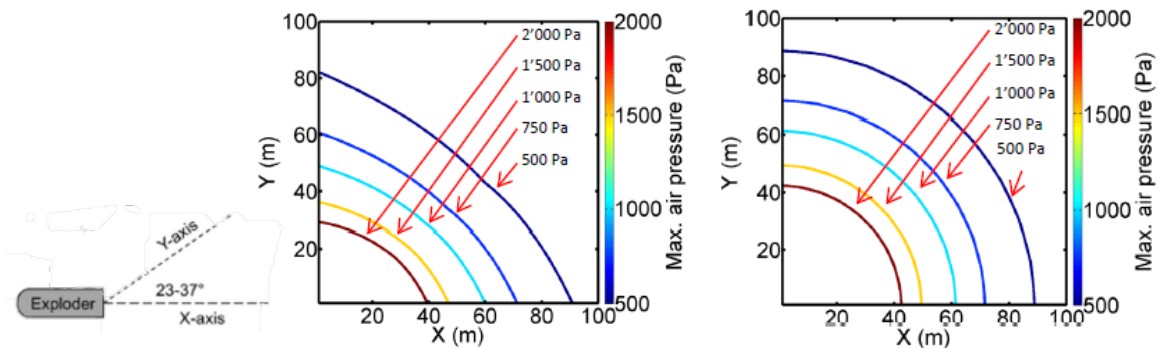


Figure 17 Peak pressure isolines presented in Simioni (Simioni, 2017) for the blast waves of the prototype Gazex (left) and 4.5 kg of Riomon T1 (right)

Air pressure derivatives were also compared for the prototype Gazex and the solid explosives. It was found that the pressure rise rate was between $10\text{-}30\text{ MPa s}^{-1}$ for both at a distance of about 15 m – with solid explosives having a slightly faster pressure rise on average. Regardless, for both explosive types, the rate quickly decayed to a value of about 1 MPa s^{-1} at a distance of 80 m.

As an additional means of comparison and validation of testing methods, Simioni (Simioni, 2017) also performed multiple tests on an operational 1.5 m^3 Gazex located at the Jakobshorn ski area in Davos, Switzerland. The operational exploder utilized is located at an elevation of 2480 m or 8136 ft on a southwest-facing slope with an inclination of $30^\circ - 40^\circ$ (Figure 18).



Figure 18 Operational 1.5 m^3 Gazex installation at the Jakobshorn ski area utilized by Simioni (Simioni, 2017) for comparison testing.

Although the testing of the operational Gazex was somewhat limited compared to previous flat-field testing with the prototype Gazex, measurements were taken in a very similar manner and led to many important observations. Overpressures from the operational Gazex reached values of 8.2 kPa and 3.4 kPa at distances of 14.9 m and 29.9 m along the exploder axis, respectively. At a 91° angle from the exploder axis, overpressures reached 3.5 kPa at 15.8 m and 1.7 kPa at 24.5 m. The decay of the overpressures was more pronounced along the perpendicular axis than along the exploder axis, and the ratio of the pressures along the perpendicular axis to the exploder axis was found to be between 0.5 and 0.3. Thus, pressures along the perpendicular axis were consistently lower, even at large distances. An additional measurement directly behind the exploder revealed that the overpressure reached a value of 5.33 kPa at a distance of 10.2 m behind the Gazex opening. Further analysis of the operational Gazex overpressures yielded isolines like those presented above (Figure 17), but with a much more distinct bulb-shape, even at large distances. It was also noted that the decay of the overpressures was generally less strong for the operational Gazex than the prototype Gazex or solid explosives, but were considered to be in agreement overall (Figure 19).

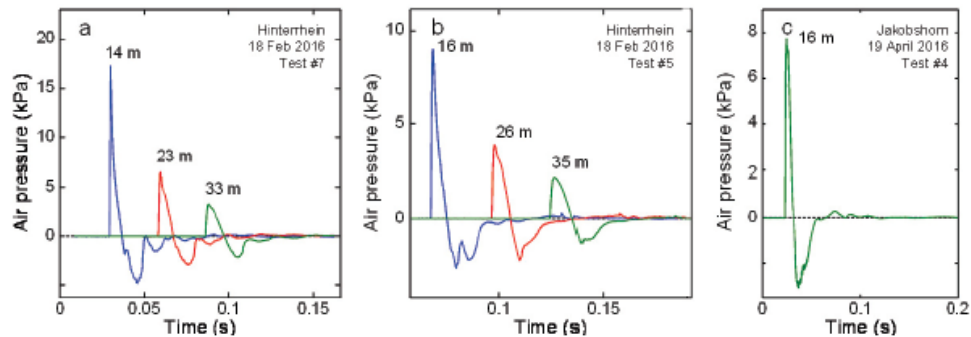


Figure 19 Example pressure-time data from Simioni and Schweizer (2018) for a 4.8 kg Riomon T1 explosive charge (a), prototype Gazex device (with 1.7 kg gas mixture) (b), and an operational 1.5 m³ Gazex installation (c).

In addition to the quantitative results obtained from the operational Gazex testing, Simioni (Simioni, 2017) also provided many important observations and conclusions about in-situ RACS testing. First, although the testing was found to have reasonable reproducibility and results were generally comparable to flat-field tests, sensitivity to nearby terrain was observed for the operational Gazex. Furthermore, the agreement of flat-field and operational results highlighted the value of flat-field testing which has the benefits of reduced risk, ease of testing, and improved reproducibility. Nevertheless, Simioni acknowledged some drawbacks of flat-field testing with the prototype Gazex device including the limitation of off-axis measurement locations to angles less than 37° and differences in device design, performance, and thus limited applicability of results to operational devices.

The velocities of the blast waves were also calculated to determine the presence of a supersonic region. For the prototype and operational Gazex systems, at the distances where measurements were taken, the wave speeds were found to be between $322 \frac{\text{m}}{\text{s}}$ and $339 \frac{\text{m}}{\text{s}}$. Thus, the blast wave was determined to be an acoustic wave rather than a shock wave. However, shock waves were observed for solid explosives with the shock wave decaying to an acoustic wave somewhere within 17 m to 30 m from the blast.

Another interesting conclusion from Simioni's flat-field testing (Simioni, 2017; Simioni et al., 2017) was the effect of snowpack conditions and exploder incline and elevation on test results. During the first winter of flat-field testing, snow depth was approximately 80 cm with a 2 cm freeze-thaw crust at the surface and an overall average density of 335 kg m^{-3} . The snow was dry and relatively warm during the first half of the testing days and became slightly moist later in the day. During the second winter of testing, snow depth was about 60 cm to 70 cm with an

average density of about 285 kg m^{-3} . Despite these variations in snow conditions, Simioni et al. (Simioni et al., 2017) concluded that there were no significant differences in overpressure decay due to the changing conditions experienced. During these testing periods, the incline and elevation of the prototype Gazex were also varied (though they were kept within the possible inclines and elevations of installed Gazex systems). Despite this variation, no clear trend was observed for the measured air pressures or snowpack accelerations based on incline nor elevation. Although, it was observed that the lowest exploder incline (28°) resulted in the most rapid decay of overpressure with distance – a counter-intuitive result.

Furthermore, careful comparison of pressure measurements and snowpack acceleration measurements (i.e. direct measurements of the snowpack response) indicated that the decay of the snowpack accelerations was more rapid than the decay of the overpressures or air pressure derivatives, but less rapid than the decay of the air pressure energy equivalent which was calculated by integrating the square of the air pressure over time [6].

$$P_{energy} = \int P(t)^2 dt \quad (Pa^2s) \quad [6]$$

As such, Simioni and Schweizer (Simioni & Schweizer, 2018) concluded that the decay of the overpressure and air pressure energy equivalent can be used as a lower and upper bound, respectively, for the effects within the snowpack. As a result of this observed relationship, it can also be recognized that the snowpack response can then be reasonably described using measurements of air pressure alone rather than snowpack accelerations which are difficult to measure and are sensitive to snowpack conditions among many other variables (Berthet-Rambaud et al., 2010; Simioni et al., 2017).

One final conclusion provided by Simioni and Schweizer (Simioni & Schweizer, 2018), based on additional measurements and high-speed videography of weak layer failure during the explosive testing, was that the snowpack effects of both DGE and SE explosions are very large at small distances (<40 m) and will almost certainly lead to weak layer failure. However, at larger distances (>60 m) the blast effects attenuate rapidly and weak layer failure at these distances is more likely the result of rapid crack propagation from an initial failure nearer the point of detonation rather than the blast wave itself. As such, Simioni and Schweizer contend that the concept of the “effective radius” or “effective range” of avalanche control methods must be further investigated since it appears that the effectiveness of avalanche control methods is driven more by near-field effects and crack propagation than the far-field pressures and or loading rates of different methods.

1.5 Summary of Existing Work

After a thorough review and consideration of the previous scientific work relating to snow, avalanches, artificial avalanche control, explosives, and remote avalanche control systems, several key conclusions can be drawn about the current body of scientific work:

- 1) Snow is an inherently complex and variable material. Thus, measuring, interpreting, and predicting its behavior is a daunting but meaningful endeavor.
- 2) Avalanches are incredibly complex powerful forces of nature capable of causing significant harm. Continued research into and improvement of

avalanche control methods are increasingly important as the development and utilization of avalanche terrain continues.

- 3) Although a significant amount of research has been performed relating to explosive avalanche control methods and much has been gained from this research, there is a significant lack in research on more modern and emergent methods such as remote avalanche control methods.
- 4) The current body of RACS-related research is quite limited in quantity, and much of the existing work is lacking in descriptions of test methods or discussions of results.
- 5) There is not an agreed-upon standard for quantifying the effective range of various explosive avalanche control methods. Some base the range upon the blast wave overpressures alone while others include deformation rate in the definition. Still, others have more recently suggested an entire rethinking of the concept.
- 6) The work of Stephan Simioni et al. (Simioni, 2017; Simioni et al., 2014, 2017, 2016; Simioni & Schweizer, 2018) represents the most complete and well-documented research on modern explosive avalanche control methods.
- 7) There is still a need for a direct comparison among the various explosive avalanche control methods and operational RAC-types employed today.

2. RESEARCH METHODS

2.1 Need

The existing research described in Chapter 1 has improved understanding of modern avalanche control devices such as RACS, but much is still unknown – including practical comparisons of their performance. Additionally, much of the current information has either been provided by manufacturers of these systems or has primarily focused on non-operational and experimental systems. The current deficit in RACS research has left avalanche control experts with limited information to support the evaluation, planning, installation, and operation of these devices. As such, a clearer understanding and comparison of the blast waves generated by these systems is needed to improve avalanche control efforts.

2.2 Objectives

The stimulus for this research project was the growing need to better understand modern RACS by measuring, describing, and comparing their performance characteristics. Of particular interest to avalanche control practitioners was an in-situ analysis and comparison of the blast waves produced by the commonly deployed RAC-types. As a result, this research project was established with the primary goal of measuring the air pressures generated by the blast waves of a variety of installed and operational RACS.

2.2.1 Data Collected

The purpose of measuring air pressures from avalanche explosives, as has been discussed in previous research with similar objectives (Bones, 2012; Simioni, 2017; Tichota et al., 2010), is in

part, to evaluate the load that is imparted onto the snow surface as a means of quantifying its ability to initiate an avalanche. Although there is currently no agreed upon criteria relating air pressure and the effective range of an avalanche explosive (see Section 1.3.2), and prior work has often also included snowpack response measurements via accelerometers imbedded in the snowpack to assess the relationship between air pressure and snowpack response, air pressure measurements alone have been shown to be an effective tool for assessing an explosive's ability to initiate failure within the snowpack (Simioni et al., 2016).

For the purposes of this research, air pressure measurements have several distinct advantages over other measurements such as snowpack accelerations. For instance, snowpack accelerations, while illuminating in terms of snowpack response, are indirect in their evaluation of blast wave characteristics due to the additional influence of variable snowpack conditions. Air pressure, on the other hand, offers a more direct assessment of the blast wave – although snow surface and environmental conditions do still play a role in the attenuation of the blast wave (Albert & Hole, 2001). This is valuable since the primary goal of this project is to provide a side-by-side comparison of the blast waves from a variety of operational RACS rather than how those blast waves translate into a snowpack response. An additional advantage of foregoing measurements of snowpack accelerations for this work was the reduction and simplification of the required instrumentation and associated logistics – a particularly valuable benefit for testing being conducted at operational RAC systems installed in challenging and dangerous terrain. The instrumentation for this research will be discussed in greater detail in Section 2.3. Lastly, many important quantities which can be used to compare explosives can also be calculated from measurements of air pressure. The quantities of particular use for this work include maximum pressure (or overpressure), energy equivalent, and the time-derivative of the air pressure (i.e., the rate of pressure increase).

Despite the advantages and suitability of air pressure measurements for this research, there are also distinct challenges associated with comparing operational RACS based on in-situ measurements of the blast wave pressures. In particular, unique terrain and foliage features near operational installations may influence the strength and behavior of the resulting blast waves. This makes it challenging to fully characterize the blast wave of a “generic” RAC system without limiting the applicability of the results to the specific installation(s) measured. To minimize the influence of local terrain and foliage and to generalize the results to the greatest extent, specific “open slope” testing locations were selected such that the RACS installations were located on a snow-covered portion of the slope away from any large and distinct terrain or foliage features. In addition, a portion of this research also focused on conducting measurements at installations *with* noteworthy terrain and foliage features to compare against the open slope data to better understand the magnitude and behavior of any terrain effects. For simplicity, these testing sequences were referred to as “open slope” or “baseline testing” and “terrain testing”, and were carried out in Phase 2 and Phase 3 of the testing plan (see Section 2.4), respectively.

2.2.1.1 Maximum Air Pressure/Overpressure As mentioned above, many useful quantities can be ascertained from the high-speed measurements of air pressure from an explosive blast wave. One of the most commonly utilized and cited metrics is the maximum air pressure or overpressure since it is an effective measure of overall explosive strength and can be used to show the decay of the blast wave with distance (Bones, 2012; Simioni, 2017). As expected, this value can be determined by simply finding the maximum air pressure recorded.

2.2.1.2 Air Pressure Rate Another quantity that can be determined from high-speed air pressure recordings of explosive blasts is the rate of increase of pressure, or pressure rise rate,

(i.e., the time-derivative of the pressure) when the wavefront first reaches the acoustic sensor. For explosive blast waves, this initial increase in pressure is quite rapid as shown in Figure 6 above. In practice, this initial increase in pressure has a large but finite value which decreases with increasing distance from the blast (Figure 20).

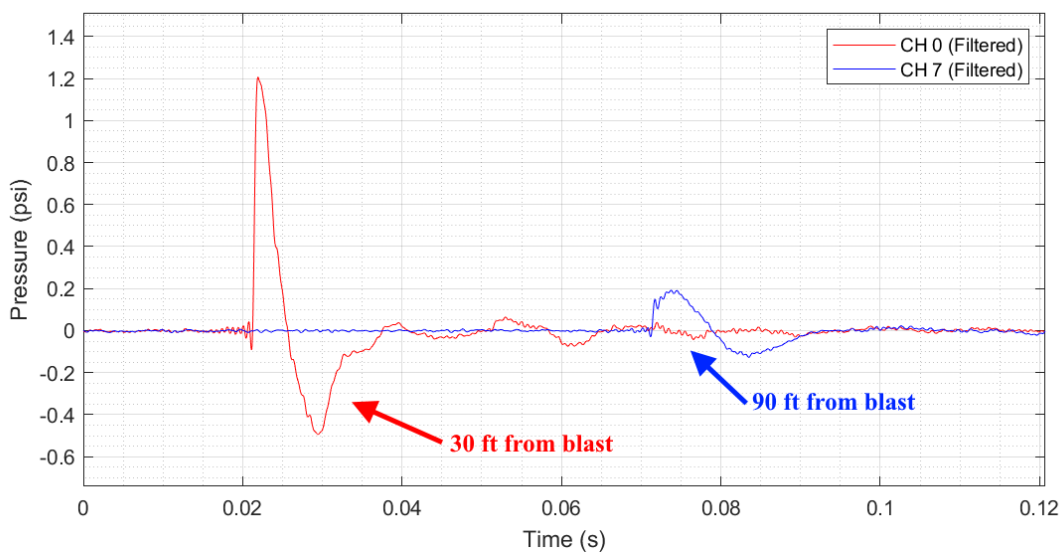


Figure 20 A graph showing the decay of the blast wave from an O’Bellx system. Note the decrease in pressure magnitude and rise rate from the sensor located at 30 feet to the sensor located at 90 feet.

As has been discussed in prior work, this rate of pressure increase can be useful for assessing the deformation rates achieved within the snowpack by the blast wave (Gubler et al., 2012). It is believed, though not thoroughly studied, that explosives with faster detonation speeds (e.g., Pentolite) yield more rapid pressure increases than slower explosives (e.g., propane) and will result in higher deformation rates within the snowpack and thus be more effective at initiating snowpack failure due to the rate-dependent behavior of snow discussed previously (see Section 1.2.3). Regardless of the ultimate role that pressure rate plays in the efficacy of different

explosives, it is undoubtedly a valuable parameter for investigating blast wave decay and for comparing the blast waves from different explosives. As such, calculations of the pressure rates were included in this work.

However, determination of the pressure rate from pressure-time data is not as trivial as finding the maximum pressure. In particular, because the data is collected as a discrete set of data points, it is not possible to simply take the time-derivative of a known equation. To calculate the time-derivative of such data it is necessary to utilize computer-based numerical methods to approximate the derivatives. In short, numerical methods use finite difference operators which utilize Taylor series expansions to approximate the derivative at discrete data points.

For this research, a multi-part numerical differentiation scheme was used within a MATLAB script (see APPENDIX B). For the first and last data points of a recording (i.e., the very first and last values recorded by the acoustic sensor) a forward [7] and backward finite difference operator [10] were used, respectively. For the second and second-to-last data points a central finite difference operator [8] was used. Lastly, for all other data points a fourth-order finite difference operator [9] was used.

$$f'_j = \frac{f_{j+1} - f_j}{\Delta t} \quad [7]$$

$$f'_j = \frac{f_{j+1} - f_{j-1}}{2\Delta t} \quad [8]$$

$$f'_j = \frac{f_{j-2} - 8f_{j-1} + 8f_{j+1} - 8f_{j+2}}{12\Delta t} \quad [9]$$

$$f'_j = \frac{f_j - f_{j-1}}{\Delta t} \quad [10]$$

When combined, these finite difference operators provide an estimate for the time-derivative of the pressure-time data at each data point. To then determine the pressure rate of the blast wave, multiple methods are possible. For instance, the maximum value of the calculated derivatives could be considered to be the rate of pressure increase, but this method is highly sensitive to noise within the data and is not representative of the rate throughout the impulse. As a result, the method employed in this work was to calculate an average of the calculated derivatives over the time period from the onset of the pressure increase to the identified maximum pressure.

In addition to the numerical derivatives utilized, an alternative simplified method of determining pressure rate was also performed to compare against the calculated average numerical time-derivatives. This method simply involved taking the maximum pressure recorded and dividing by the time between the onset of the pressure rise and the instant when the maximum pressure was reached. This, in effect, approximates the pressure increase directly as a straight line beginning at zero pressure at the onset of the pressure increase and terminating at the peak pressure.

Both methods for determining the pressure rate of increase were used in this work and are illustrated and compared in Figure 21.

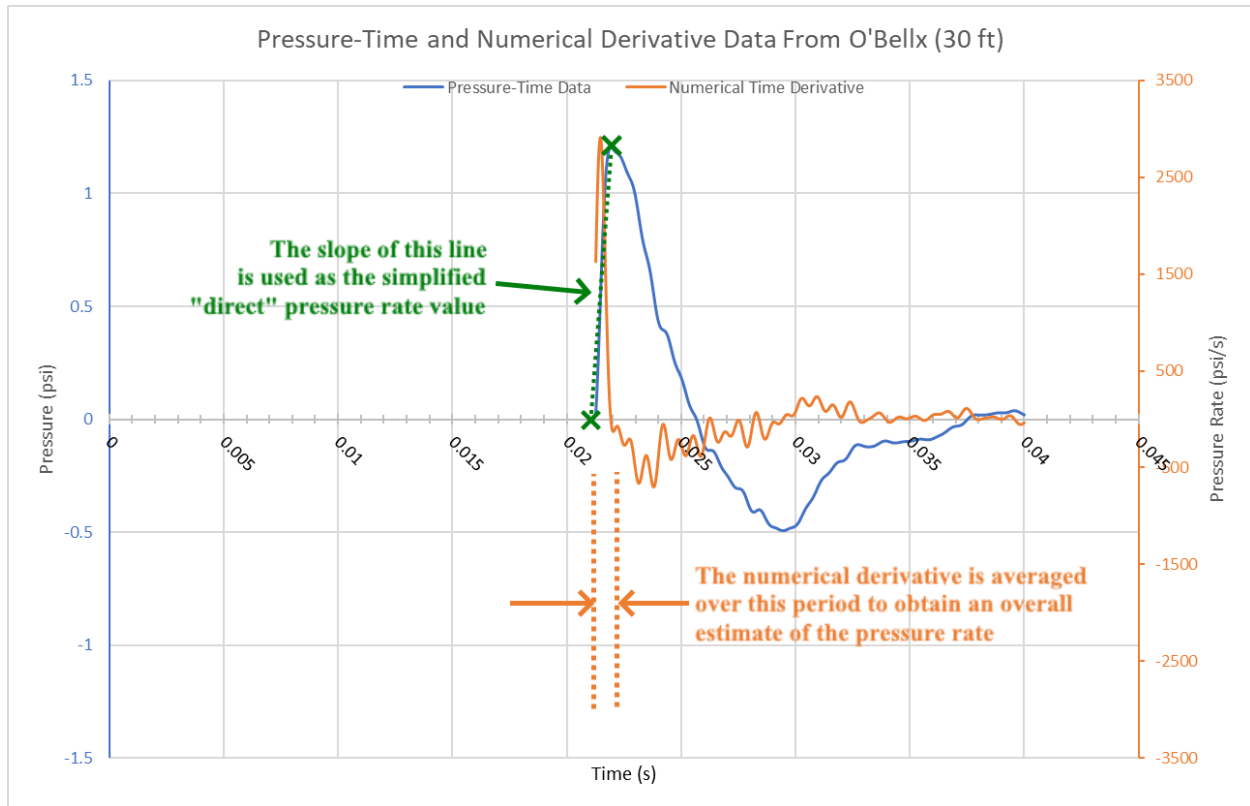


Figure 21 A graph showing a comparison of the calculated numerical derivative and direct derivative method utilized to determine the rate of pressure increase.

2.2.1.3 Air Pressure Energy Equivalent The next quantity of interest obtainable from the pressure-time data was the equivalent energy of the blast wave. This quantity is particularly useful because it incorporates the blast wave magnitude *and* duration to provide a representation of the overall energy of the blast wave – which may be a good indication of the damage potential of the blast wave (Bones, 2012; Simioni et al., 2017). This metric was utilized in similar work by Simioni (2017) and is quite similar to the measure of blast wave impulse which has been more widely used in past research on explosives (Bones, 2012). The energy equivalent utilized for this work is simply the time integral of the squared air pressure [11] (i.e., the area under the squared pressure-time curve). By contrast, impulse is the time integral of the air pressure alone (i.e., the

area under the positive region and above the negative region of the pressure-time curve). Both provide information about the magnitude and duration of a given blast wave, but the positive and negative pressure regions of a blast wave tend to be equal and opposite in area, and thus the impulse of any given blast wave tends toward zero. This, then, does not translate conveniently into a measure of the damage potential to the snowpack of a blast wave (unless the impulse of the positive and negative regions are considered separately) since the negative pressures may also play an important role in snowpack failure (J Schippers et al., 2002; Wooldridge, 2013). Alternatively, the energy equivalent metric described above includes the magnitude of both the positive and negative regions together. A comparison of these two integral quantities are shown in Figure 22.

$$P_{\text{energy}} = \int p^2 dt \quad [11]$$

$$\text{Impulse} = \int p dt \quad [12]$$

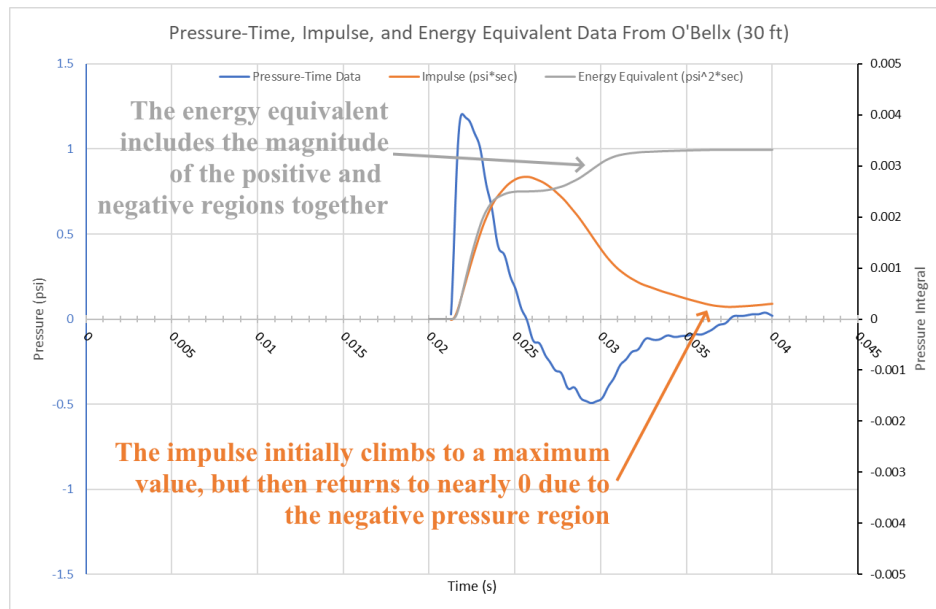


Figure 22 A graph showing a comparison of the cumulative energy equivalent and integral.

Much like the pressure rate calculation described above, the calculation of the energy equivalent integral is nontrivial since the pressure-time data is a collection of discrete data points rather than a known equation. As before, numerical methods are required to carry out this integration. For this work, a simple trapezoidal method [13] was used to perform the integration of the squared air pressure to obtain a value for the energy equivalent of each blast wave measured.

$$\int_0^n f(t)dt \approx \Delta t \left(\frac{1}{2}f_0 + \frac{1}{2}f_n + \sum_{j=1}^{n-1} f_j \right) \quad [13]$$

2.2.1.4 Other Ascertainable Quantities In addition to the aforementioned quantities used for this work (overpressure, pressure rate, and energy equivalent), many other quantities can also be calculated from the same air pressure data. For instance, the minimum air pressure was also determined and recorded which may be helpful for future work. Additionally, the impulse of the blast wave was also calculated as described above and recorded. Lastly, the time of arrival of the blast wave at each acoustic sensor was recorded. This information combined with the locational information of each sensor which was also documented can be used to determine the average velocity of the blast wave between any two in-line sensors. This may be helpful to investigate what, if any, sensors were located in the nonlinear shockwave region of the blast wave (see Section 1.3.1).

2.3 Instrumentation

In order to effectively and accurately measure the blast wave air pressures (and the quantities described above) from a variety of installed and operational RACS, a robust, portable, and reliable measurement system needed to be obtained or created. In general, the primary components for a measurement system for research of this nature includes sensors to measure a physical parameter (pressure sensors in this case) and a data acquisition system (DAQ) to read and record the signals from the sensors. The exact details of the instrumentation setup utilized for this project will be discussed in the following sections.

2.3.1 Basis for Instrumentation/Prior Work

Prior research efforts had made use of widely available National Instruments data acquisition systems (DAQs), an array of accelerometers, and one to two custom 5 psi microphones from Larcor (Bones, 2012; Simioni, 2017; Tichota et al., 2010). Although this exact system (Bones, 2012; Tichota et al., 2010) was available for use in this work, the challenging fieldwork of this project, recent technological improvements, and the testing challenges previously identified (Simioni, 2017) motivated the decision to design and construct a new and custom instrumentation setup for this work. In particular, several necessary design alterations and improvements were identified.

2.3.2 Instrumentation Goals and Improvements

The first necessary instrumentation improvement identified was the need to include additional microphones. Since the primary objective of this project was to characterize the strength, size, shape, behavior, and other characteristics of the blast waves from a variety of

operational explosive systems, it was recognized that a larger number of microphones was necessary. Using additional microphones would allow air pressure measurements to be taken with a finer spatial resolution and reduce the number of tests required at a given device. It was desirable to reduce the number of tests required for each RAC system due to the cost associated with utilizing, and ultimately refilling, an operational RAC system, the concern that the system would be depleted before a weather event that required its operation, and the added logistical challenge of multiple tests and sensor relocations. As such, the first instrumentation design improvement was to include ten microphones in the instrumentation setup. Furthermore, new 10 psi microphones from Larcor were selected instead of the previously used 5 psi microphones to reduce the risk of completely saturating the sensors at close distances as had been seen in prior work with the 5 psi microphones (Bones, 2012).

The next improvement proposed was to select a new data acquisition system (DAQ) or systems (DAQs) to reduce the challenges of setting up the existing heavy, complicated, and wired National Instruments DAQ equipment in backcountry terrain. Due to the increased number of microphones (which would be distributed at great distances around each RAC system), it was recognized that a modular system comprised of multiple separate small-scale DAQs would be preferable to a single main DAQ with connections to all ten microphones. This modular setup would allow the DAQs to be located much closer to the microphones thus reducing the amount of cabling required.

Fortunately, the growing use and support of modern inexpensive microcomputers has sparked the development of many compatible hardware accessories with a variety of applications. One such accessory is the MCC 118 12-Bit Voltage Measurement HAT (Hardware

Attached on Top) produced by Measurement Computing (Figure 23). This inexpensive and compact board offers a plug-and-play⁵ interface with the equally inexpensive, compact, and widely available Raspberry Pi. Once connected and set up, the DAQ HAT offers eight 12-bit analog-to-digital channels with up to 100,000 samples/second per channel and a ± 10 V input range. These values are comparable to many other larger and more expensive data acquisition systems and were well suited for this research. In addition, the power consumption of the DAQ HAT and Raspberry Pi are relatively low meaning that the modular DAQ system could feasibly be powered by a small lightweight battery.

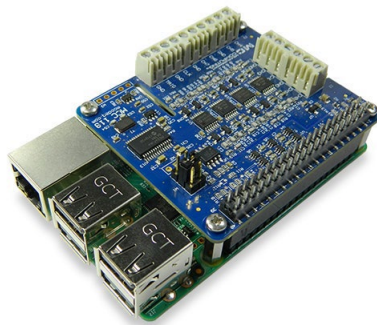


Figure 23 The MCC 118 DAQ HAT produced by Measurement Computing attached to a Model 3B+ Raspberry Pi.

Due to the impressive technical specifications, low cost, modularity, existing hardware and software support, and small size, it was decided to utilize an array of five of these custom Raspberry Pi-based DAQs to read and record the signals from the ten Larcor microphones. This setup would allow each of the five DAQs to be compact, lightweight, and portable, and enable

⁵ The MCC 118 DAQ HAT easily connects and integrates with a Raspberry Pi, but additional software/programming is required for custom data acquisition operation.

them to be located in close proximity to the two connected microphones – thus reducing cabling and streamlining the setup of measurement equipment during testing.

Having established the necessary instrumentation improvements for this research and having selected a custom solution to fulfill those goals, the full instrumentation setup could then be designed, built, and tested. The principal instrumentation components mentioned above, and the supporting hardware and software, will be discussed in greater detail in the following sections.

2.3.3 Acoustic Sensors

The first measurement components selected for this project was the array of ten 10-psi Larcor microphones (Figure 24). These acoustic sensors were similar to those used in previous work, but with a greater pressure limit. These microphones were calibrated by the manufacturer and certified to be within 1 dB of their input values between 1 and 100 Hz. The microphones required an input voltage of +9 to 15 volts and produced an output voltage of 2.5 VDC with no pressure input to the microphone. For pressures between +10 psi and -10 psi, the microphone would then provide a linear response between 0 VDC and 5 VDC, respectively. Each microphone was also equipped with 50 feet of shielded cabling to provide up to 100 feet of separation between two microphones connected to a given DAQ.



Figure 24 The 10 psi Larcor microphones used for this research.

2.3.4 Data Acquisition Systems

As mentioned above, a modular data acquisition system comprised of five separate DAQs was selected to record the pressure data from the ten Larcor microphones. The basis for these systems was the Raspberry Pi microcomputer and the MCC 118 DAQ HAT described above, which together provided a compact and inexpensive yet capable data acquisition system. However, these two components also required a variety of additional supporting hardware and software to provide a complete and operational instrumentation setup with the appropriate functionality for this research.

For example, a power source or sources was also needed to provide the 5 VDC power to the Raspberry Pi, DAQ HAT, and the 9-15 VDC power to the microphones. Additional supporting hardware included LEDs to provide direct visual indications of the status of the custom DAQs and a real time clock (RTC) to allow timestamping of the data files saved. Another critical component for this instrumentation suite was a method for wirelessly communicating with each of the five separate DAQs. Communication with the DAQs was necessary to verify their status and successful operation, control and adjust settings/operation, as

well as trigger the simultaneous recording of all DAQs to capture a blast wave from an explosion. Without wireless communication, the DAQs would have to be wired together – thus complicating the measurement equipment setup and defeating the benefit of having separate DAQs. Further, since these DAQs would be placed in an outdoor, backcountry setting, and would be located several hundred yards apart and several hundred yards away from the operator, a long range and low power method for wireless communication was needed. Packaging was also required to organize, mount, and protect the aforementioned hardware from the harsh temperatures and moisture present in the testing locations and to protect the equipment from the explosive blast wave itself. Lastly, custom software was also required to enable the Raspberry Pi microcomputer to successfully integrate and operate the attached hardware.

After several months of planning, prototyping, and testing, a custom data acquisition package was finally completed (Figure 25 & Figure 26). The details and technical specifications of the components selected will be discussed in the following sections.

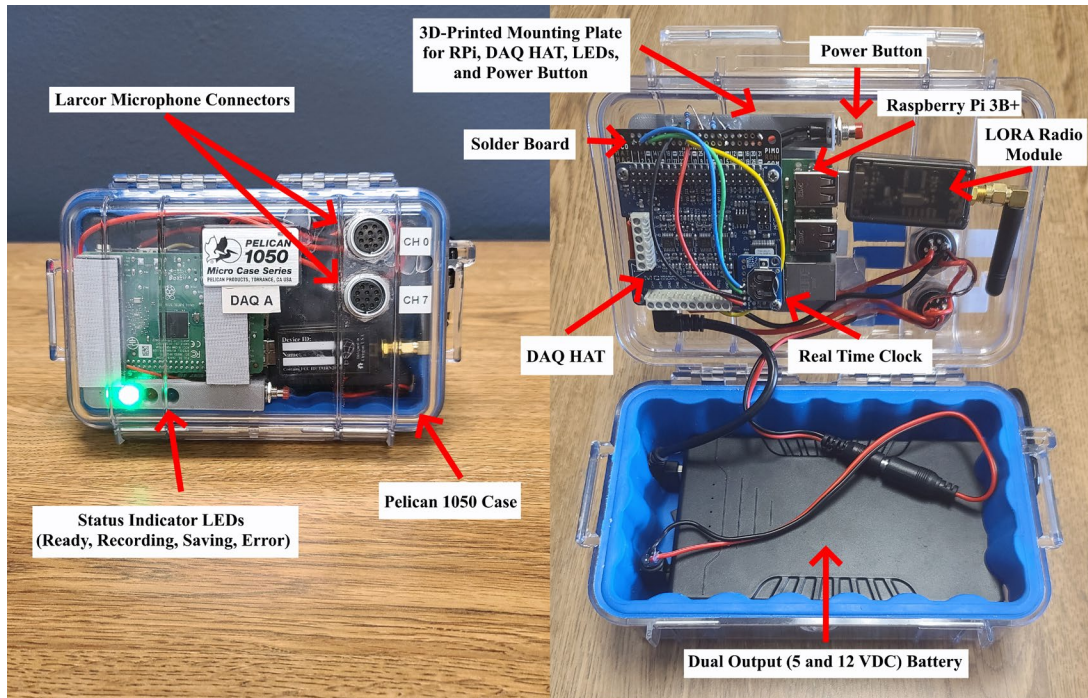


Figure 25 Components of a single data acquisition system (DAQ A).



Figure 26 The fleet of 5 operational DAQs constructed for this project (DAQ A - DAQ E), plus an additional DAQ (DAQ F) constructed as a backup unit.

2.3.4.1 MCC 118 DAQ HAT Due to its small size, low cost, low power consumption, extensive hardware and software support, and competitive performance characteristics, the MCC 118 DAQ HAT from Measurement Computing was selected as the foundation for the custom DAQs. The board offers eight 12-bit input channels (only channels 0 and 7 were used for this work)⁶ offering up to 100,000 samples/second per channel. Thus, a sample rate of 50,000 samples/second was used for each microphone in this research. The accuracy of these boards, as provided by the manufacturer, are as follows:

- Range: +/- 10V
- Gain Error (% of reading): 0.098 max
- Offset Error: 11 mV max
- Absolute Accuracy at Full Scale: 20.8 mV
- Gain Temperature Coefficient (mV/°C): 0.016
- Offset Temperature Coefficient (mV/°C): 0.87

In addition, laboratory measurements with the Larcor microphones and these DAQ HAT boards were conducted and directly compared against a similar National Instruments DAQ (NI 9205). It was found that the two DAQ systems performed quite similarly and yielded noise levels of about 0.2 V (or about 0.05 psi for the units used in this work). Based on additional laboratory testing and attempts to eliminate noise, the source of this noise was determined to be from the large length of cabling between the DAQs and acoustic sensors, but was deemed acceptable based on the goals and other sources of error for this research.

⁶ Channels 0 and 7 were used on the DAQ HATs to avoid potential crosstalk from using adjacent channels.

2.3.4.2 Raspberry Pi 3B+ In addition to the DAQ HAT board, a Raspberry Pi microcomputer with a 40-pin GPIO (General Purpose Input Output) header was also necessary to control and record data from the MCC 118 board. As such, the Raspberry Pi Model 3B+ was selected due to its proven performance, wide availability, low cost, and improved processing speeds over previous models. The Raspberry Pi OS (Operating System) 10 (Buster; released 08/20/2020) was installed onto a 128 GB microSD card and provided the operating system for the microcomputers. These microcomputers then required initial setup and adjustment of some settings to support the hardware and additional software required.

2.3.4.3 Power Supply One particularly unique component of these custom DAQs was the power supply. Because the Raspberry Pi, DAQ HATs, and associated electronics required a supply voltage of 5 VDC, and the Larcor microphones required a supply voltage of 9-15 VDC, a dual output power supply was chosen for these systems. Fortunately, a compact and inexpensive lithium-ion battery pack was available from the manufacturer TalentCell that had both 5 and 12 VDC regulated outputs and a battery status indicator. After thorough testing, it was found that this 6,000 mAh battery offered a convenient and reliable solution and provided sufficient capacity and throughput to power the custom DAQ systems during multiple hours of field testing.

2.3.4.4 LORA Communication One of the largest challenges faced during the development of the custom DAQ systems was determining a suitable method for communicating with and controlling the separate units. The first solutions considered were Wi-Fi or Bluetooth since the necessary hardware was already built into the Raspberry Pi microcomputer and either

technology would provide the benefit of being able to immediately download and verify data collection on a portable computer in the field. However, these technologies have a limited range without the use of additional specialized equipment and would likely be insufficient for the field work of this project. Moreover, these technologies also require significant electrical power, and may deplete the battery packs too quickly for a typical day of field work.

After much research and testing, an alternative solution was discovered and selected. LORA (Long Range) radio which uses the license-free frequency of 915 MHz offers long distance and low power data transmission via a simple and small radio module – ideal for this application. Though this technology does not have the fast data rates of Wi-Fi or Bluetooth, it is sufficient to send and receive small messages over great distances. This is ideal for this application which only requires simple radio messages to be sent to and from the DAQs to communicate their status and to trigger their recording. An additional benefit of this technology is the wide array of existing hardware, software, and support available to integrate this technology.

The LORA hardware selected for this project was the Ronoth LoStik (Figure 27). This module was well suited for this project due to its simple USB interface, small size, existing software support, and impressive claimed range of up to 15 km.



Figure 27 Ronoth LoStik used to provide radio-based communication to and from the DAQs.

2.3.4.5 Real Time Clock (RTC) Another component added to the DAQ systems was a real-time clock. This device enables the Raspberry Pi to keep an accurate account of the date and time even when completely removed from power. This was a necessary feature for this data acquisition equipment since the data files on each DAQ were saved with the current date and time to help organize and keep track of the many data files created during a day of testing. The RTC selected for this project was the Adafruit DS3231 due to its small size and its integrated temperature sensor which adjusts for temperature drift of the clock (Figure 28).

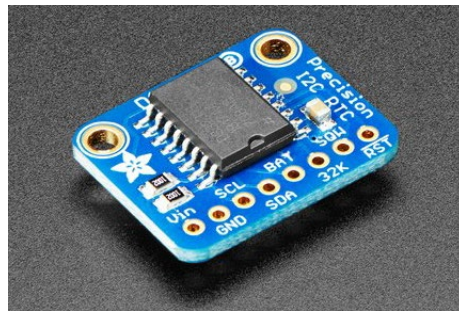


Figure 28 The DS3231 real time clock used for the DAQs.

2.3.4.6 Packaging The final, and perhaps most crucial, physical element of the custom data acquisition systems was the container for the aforementioned hardware. Not only did the packaging need to be compact and lightweight to help with transport and setup of the equipment in backcountry terrain, but it also needed to be robust to protect the electronics from the elements and explosive blast waves. To meet these needs a Pelican 1050 Micro Case was selected (Figure 29). Not only did this case provide sufficient protection against weather and moisture, it also provided protection against significant pressures, and offered a clear lid which enabled the use of status LEDs for the DAQs. In addition, this case also provided an impressively good fit for the

hardware selected; there was enough room for everything to be mounted safely, but not too much room that the case was excessively bulky.

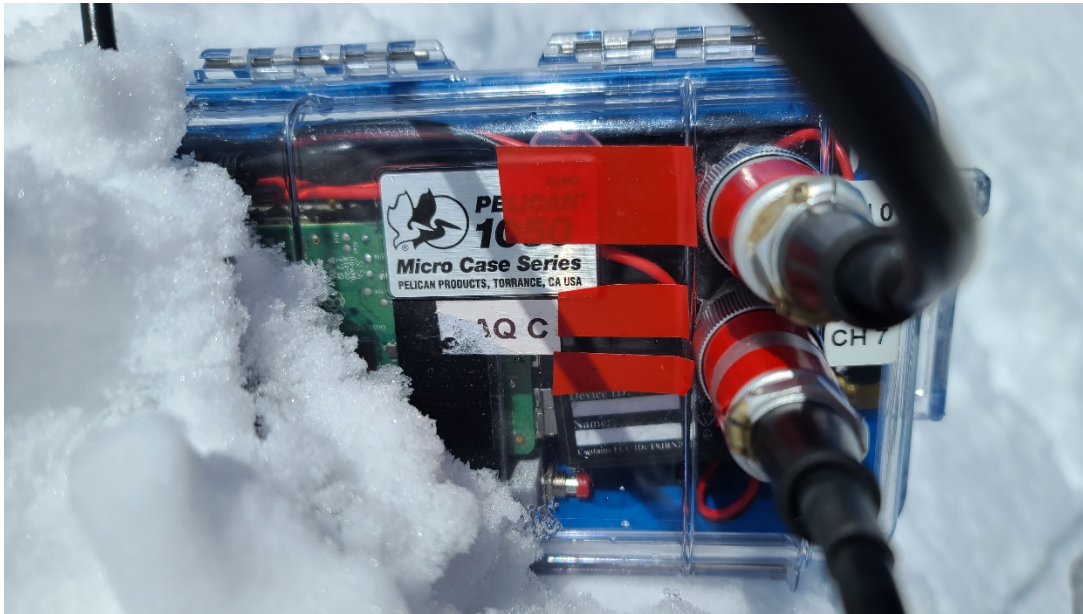


Figure 29 The Pelican 1050 Micro Case selected to protect the DAQs from the harsh environment.

2.3.4.7 Software Another critical aspect of the custom DAQs used for this research was the custom software created to control all of the hardware attached to the Raspberry Pi. This software was assembled, in part, from existing open-source codes designed to control individual components used in the equipment. The coding language utilized was Python due to its cross-hardware support and the use of existing code (Figure 30).

```

1  #!/usr/bin/env python3
2  # -*- coding: utf-8 -*-
3
4  """
5      Description:
6          This code conducts a finite high sample rate data acquisition
7          scan using an MCC118 DAQ Hat. This program also utilizes a
8          Ronoth LoStik as a method to initiate the scan using a long-
9          distance LoRa radio signal on the 913 MHz band. The data is
10         then saved to a CSV file onboard Raspberry Pi.
11     """
12
13     import sys
14     import time
15     import serial
16     import os
17     import csv
18     import errno
19     import binascii
20     import RPi.GPIO as GPIO
21     import glob
22     from serial.threaded import LineReader, ReaderThread
23     from daqhats import mcc118, OptionFlags, TriggerModes, HatIDs, HatError
24     from daqhats_utils import select_hat_device, enum_mask_to_string, \
25         chan_list_to_mask
26     from datetime import datetime
27
28     # Name and number of the DAQ system that this instance of the code is
29     # installed. These values are used for file naming and radio response
30     # sequencing.
31     DAQ_NAME = 'DAQ_A'
32     DAQ_NUM = 1
33
34     # Total number of DAQ/RADIO Systems in measurement array (this value is
35     # used for timing the radio responses from each DAQ).
36     NUM_OF_DAQS = 6

```

Figure 30 The first 36 lines of the Python script used to control DAQ A. Note, lines 31, 32, and 36 were adjusted based on the specific DAQ and total number of DAQs.

The Python script was responsible first for providing each DAQ with its own unique identification (e.g., DAQ A, DAQ B, DAQ C,...) which allowed for wireless communication to and from all DAQs and for saved data to be traced back to the DAQ which recorded it.

The script also handled incoming and outgoing radio communications through the LoStik USB module. Examples of incoming radio communications included a “trigger recording” message, adjustment of recording and recording delay timing, shutdown message, and a request

for the number of successfully saved data files. Examples of outgoing radio messages included a confirmation that the DAQ was primed and ready to record, a confirmation that recording had been initiated, a message including the number of saved data files, and confirmation that the DAQ would shut down. An important aspect for successful communication was ensuring that each DAQ would stagger its radio message response so that each radio message could be received separately by the operator.

The script also controlled many digital input and outputs of the Raspberry Pi including status LEDs and the trigger signal which was responsible for electronically triggering the DAQ HAT to begin recording data. Importantly, the script also controlled the setup and triggering of the MCC 118 DAQ HAT as well as the saving of data from the DAQ HAT to the nonvolatile microSD card storage of the Raspberry Pi. The script also recorded and saved a text-based log file of the terminal window outputs of the script which could be used later to trace and troubleshoot issues with DAQ performance. Lastly, the script was setup to re-run itself when completed such that the DAQs would be prepared to do multiple tests in a row.

2.3.5 LORA Transceiver

In addition to the custom DAQ systems designed and built for this research, it was also necessary to develop a method for wirelessly monitoring and controlling the DAQs from a safe distance during field testing of explosives. The first method utilized was a standard laptop computer equipped with two Rionth LoStiks – one for transmitting radio messages and one for receiving messages. This setup allowed communication to and from the DAQs, but was cumbersome for field testing, had limited battery life, was unable to be held high to improve radio range, and it was found that the folding screen of the laptop would occasionally interrupt

radio transmission and reception. As such, a custom radio transceiver device was developed to provide a compact, long-lasting, and reliable means of communicating with the DAQs in the field (Figure 31).

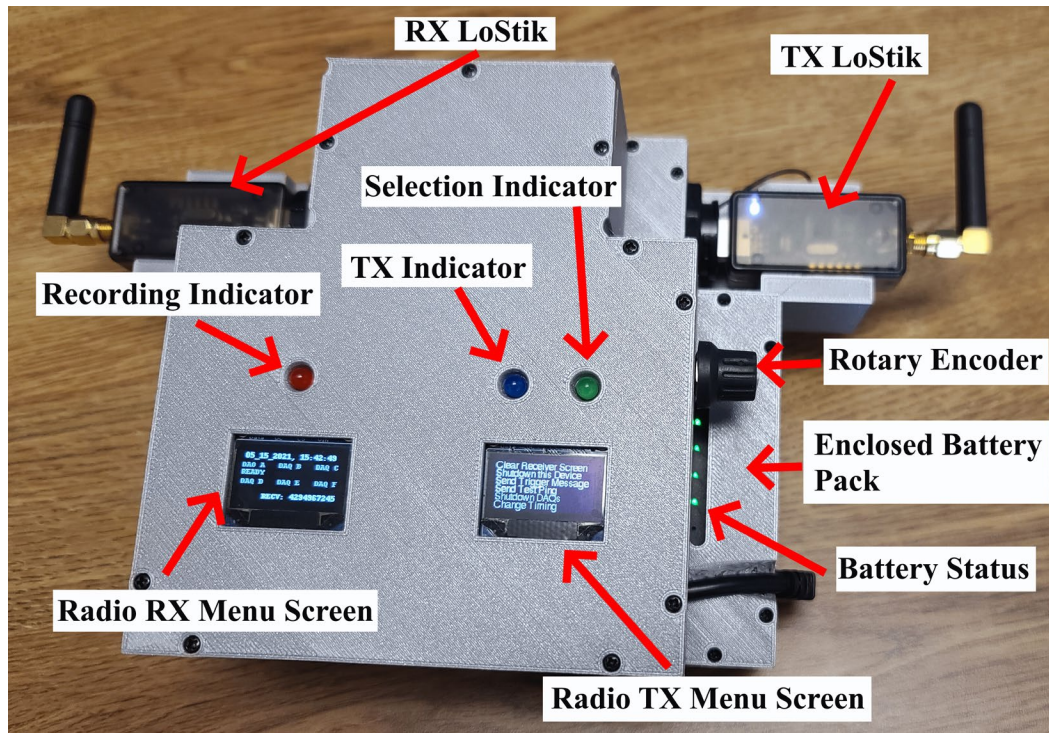


Figure 31 Components of the LORA-based transceiver.

The primary components for this device included a Raspberry Pi 3B+ and two LoStiks – one dedicated to receiving radio messages and one dedicated to transmitting. The device also utilized two small low-power OLED displays. The left display was used for displaying the status and radio responses from each DAQ. The right display displayed a menu interface with many options including: resetting the left display, shutting down the transceiver, sending trigger message to all DAQs to initiate recording, sending test “PING” message to all DAQs to confirm radio reception and to confirm the number of saved files, sending a shutdown message to all

DAQs, and to change the recording duration and/or the recording delay (i.e., the time it takes from sending the trigger message to when the DAQs begin recording). To navigate this menu, a rotary encoder was installed that enabled the user to scroll up and down and select a menu item by pressing the rotary encoder inward. The transceiver also included 3 LED indicators – one to show when recording had started and stopped on the DAQs, one to show when a radio message had been sent, and one to show when a menu item had been selected. Lastly, the transceiver also utilized the same battery packs selected for the DAQs as its power source.

2.4 Testing Plan

Having established the primary goals for this research project and having developed the instrumentation systems to help achieve those goals, the next step in this work was to determine the type, quantity, setup, and locations of suitable testing. As such, a testing plan was established to define the proposed tests for the entirety of this project.

For clarity and planning purposes, the testing plan was broken down into a hierarchical structure. The topmost category of the testing plan was referred to as the “phase” – of which there were three. Each phase had its own distinct timeline and objectives. Within each phase, there were many “devices” included for testing. These devices are a subcategory of the phase and describe what RAC-device and/or explosive material will be used for testing. Then, for any given device of any given testing phase, there are one or more “sets”. Sets were used to define a group of one or more tests that involve a similar measurement equipment arrangement and a similar goal. Lastly, within each set there were one or more tests proposed – where each test constituted

a single explosive. Each testing phase, its primary goals, and the devices, sets, and tests conducted within it will be described in the following sections.

Based on this hierarchical structure of the testing plan, and to help distinguish data, each test proposed was given its own unique identification number using the following format:

Phase Number.(5-character device name).Set Number.Test Number

For example, the third test conducted during the first set on a 0.8 m^3 Gazex device during the second phase would be given the identification number: **2.(08GAZ).1.3** . The 5-character device names (which will be described in greater details in the tests where they were used) for this work are as follows (Table 2).

Table 2 Descriptions of the short-hand identifiers used in the testing plan for this work.

Device Identifier	Description
08GAZ	refers to an operational 0.8 m^3 Gazex installation
15GAZ	refers to an operational 1.5 m^3 Gazex installation
OBELL	refers to an operational O’Bellx installation
OBRCK	refers to an operational O’Bellx installation placed on a distinct rock outcropping
PENFF	refers to a Pentolite-based simulated Wyssen Tower charge detonated in an open, snow-covered, flat field
GELFF	refers to the traditional emulsified gel Wyssen Tower charge detonated in an open, snow-covered, flat field
PENWT	refers to a Pentolite-based simulated Wyssen Tower charge deployed from an operational Wyssen Tower
GELWT	refers to the traditional emulsified gel Wyssen Tower charge deployed from an operational Wyssen Tower
GUARD	refers to a Pentolite-based simulated Avalanche Guard mortar charge detonated below the snow surface
PNCLF	refers to a Pentolite-based simulated Wyssen Tower charge detonated just in front of a large rock cliff

PGLY1	refers to a half-sized ⁷ Pentolite-based simulated Wyssen Tower charge detonated in a distinct gully
PGLY2	refers to a Pentolite-based simulated Wyssen Tower charge detonated in a distinct gully
2#PEN	refers to a 2-lb Pentolite charge detonated in an open snow-covered field

2.4.1 Phase 1 – Instrumentation Validation

The primary goal of Phase 1 of the testing plan for this project was to validate the newly developed measurement equipment with several full-scale field tests – the results of which could be compared to past work to confirm the accuracy of the results produced. In particular, the first phase of the testing plan was designed to confirm that the measurement equipment could be successfully and efficiently deployed and utilized in the field and produce accurate results. This testing phase also sought to determine a suitable placement of the microphones and to utilize actual blast data to develop data processing methods.

Phase 1 was simple in design, consisting of a single proposed explosive device, two testing sets, and a total of three separate tests. The explosives selected for Phase 1 testing were 2-lb Pentolite charges due to their availability and the ability to directly compare results with the work of Bones (2012). The device identification given to these tests was 2#PEN. The testing was conducted in a slightly inclined, open, snow field located near Bridger Bowl, Montana (Figure 32).

⁷ The half sized Pentolite charge test was not originally proposed – it was the result of an improper detonation of the full sized charge.



Figure 32 Approximate testing location for Phase 1 of the test plan ($45^{\circ}48'19.23''\text{N}$, $110^{\circ}54'38.18''\text{W}$).

The first testing set consisted of a single test with the goal of ascertaining the height above the snow that the microphones should be placed to avoid impact from snow while maintaining an accurate representation of the overpressure at the snow surface. This test also provided an opportunity for comparison with the results provided by Bones (2012). To achieve this, the following arrangement of DAQs, the explosive, and the microphones was utilized (Figure 33 and Table 3).

Table 3 The distances utilized for the first test of the first set of the first phase of the test plan.

TEST: 1.(2#PEN).1.1	
D	22.97 ft (7 m)
Hb	3.28 ft (1m)
H1	2 in
H2	6in
H3	1 ft
H4	1.5 ft
H5	2 ft
H6	3 ft
H7	4 ft
H8	5 ft

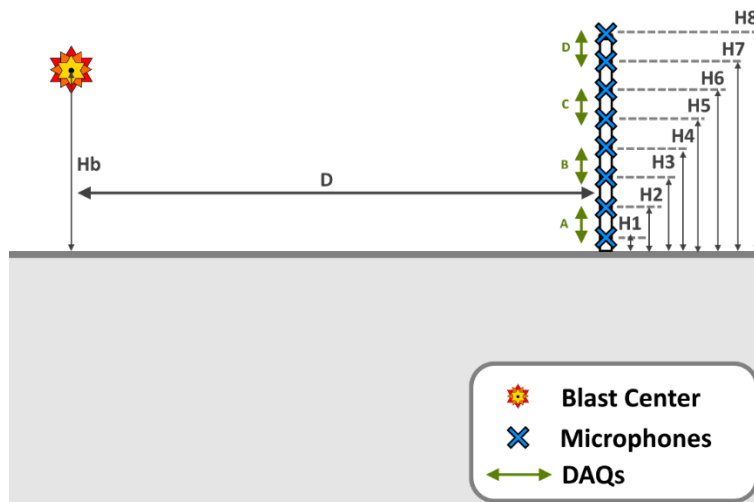


Figure 33 Test layout for the first test of the first set of the first phase of the test plan.

The second testing set included two additional tests. The purpose of this testing set was to make general observations and adjustments of the experimental setup such as:

- Setup difficulties/inefficiencies
- Logistics of the microphone placement (radial and angular measurements, method of attachment, protection from snow/blast/etc., placement relative to DAQs, etc.)
- Radio reception from base computer to DAQs and vice versa (considering effects of terrain, foliage, DAQs buried beneath snow, etc.)
- Timing of blast and recording (feasibility of ensuring that blast occurs within the recording window)
- Necessary data handling and processing
- Compare to results provided by Bones (2012) and Simioni (2017)

The first test of this set placed the explosive at 3.28 feet (1 m) above the snow surface, and utilized the following arrangement of DAQs and microphones (placed six inches above the snow surface) (Figure 34).

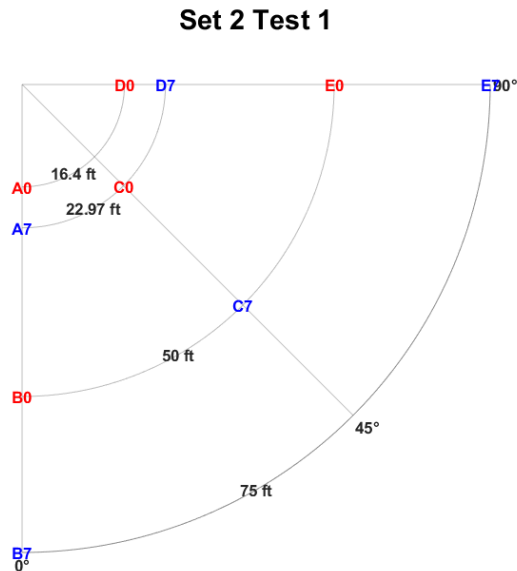


Figure 34 Microphone layout for the first test of the second set of the first phase.

It should also be noted at this point that all remaining tests described in the following sections will utilize similar plan-view diagrams as is shown in Figure 34. In these diagrams, the alpha-numerical labels each refer to an individual microphone location where the letter refers to the DAQ connected to that microphone (e.g., DAQ A) and the number refers to which channel of the DAQ that microphone is connected to (i.e., Channel 0 or Channel 7). Further, the radii in these diagrams are shown in feet, and the 0° axis was defined to either be directly downslope for solid explosives detonated on a slope or directly in line with the primary axis of the device for directional explosive systems (i.e., operational Gazex or O’Bellx devices).

The second test of this set utilized a similar layout with slightly adjusted distances to assess the equipment’s ability to record overpressure values at larger distances than previously recorded. This test also placed the charge at 3.28 feet (1 m) above the snow surface, and utilized a similar arrangement of DAQs and microphones (placed six inches above the snow surface) (Figure 35).

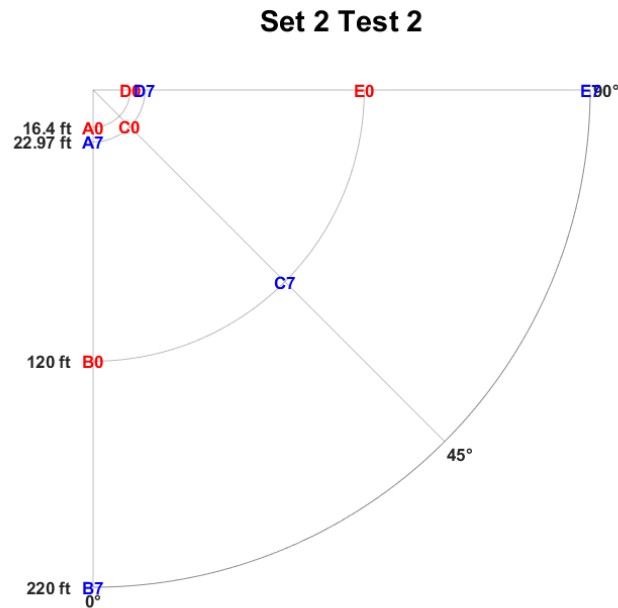


Figure 35 Microphone layout for the second test of the second set of the first phase.

2.4.2 Phase 2 – Open Slope/Baseline RACS Testing

Based on the lessons learned and data gathered from Phase 1 testing, which will be discussed in greater detail in CHAPTERS 3 and 4, refinements to the measurement equipment were made, testing logistics were improved, and the planning of field testing for Phase 2 and Phase 3 was made easier. In addition, the testing of Phase 1 indicated that placing the microphones approximately six inches above and parallel to the snow surface would be appropriate for field testing during Phase 2 and 3. As such, this height and orientation was used for all testing described below unless otherwise noted.

The second phase of the test plan shared its primary objective with that of the research project as a whole – measuring and comparing the baseline/open-slope blast waves of a variety of installed and operational avalanche control explosives. Due to the importance of these tests to

the overall success of the research, this testing phase was the most extensive testing sequence performed – consisting of eight proposed devices (seven were ultimately tested) and resulting in a total of 315 different microphone measurements being conducted. The devices proposed for this testing phase included:

- 0.8 m³ Gazex
- 1.5 m³ Gazex
- O’Bellx
- Operational Wyssen Tower deploying its standard gel emulsion charge
- Operational Wyssen Tower deploying a prototype Pentolite-based charge
- A standard Wyssen Tower gel emulsion charge being detonated in a flat, open, snowy field
- A prototype Pentolite-based Wyssen Tower charge being detonated in a flat, open, snowy field
- A Pentolite-based simulated Avalanche Guard mortar charge detonated below the snow surface in a flat, open, snowy field

The sets, tests, and equipment layouts for each of the above devices as tested in Phase 2 will be described in the following sections.

2.4.2.1 0.8 m³ Gazex Testing One device proposed in Phase 2 of the testing plan was a 0.8 m³ Gazex device. The intended testing site was either device E11 or E13 in Snowbird Village near Alta, Utah (Figure 36).



Figure 36 The two 0.8 m³ Gazex installations proposed for baseline testing in Phase 2 of the testing plan (40°35'6.38"N 111°39'33.81"W).

It was intended to perform a total of four tests at either of these devices to measure the blast waves produced by an open-slope installation of a 0.8 m³ Gazex device. However, due to a loss of snow cover at the time of testing, it would have been impractical and likely futile to conduct testing at these locations (Figure 37). As such, these proposed tests were unfortunately declined, and will not appear in the results or conclusions sections of this document.



Figure 37 Lack of snow cover at the proposed testing locations for the 0.8 m³ Gazex device.

2.4.2.2 1.5 m³ Gazex Testing Another device included in the open slope focused testing of Phase 2 was an operational 1.5 m³ Gazex device. The testing site chosen was device 48 located in the Hellgate area near Alta, Utah (Figure 38 and Figure 39). This site was selected because it was the most accessible and open 1.5 m³ Gazex device available in the area. This device was located at an elevation of about 9,400 feet on a slope with an incline of approximately 35° and an easterly aspect. Conditions at the time of testing were overcast and snowing with temperatures of about 30°F. Snowpack depth was approximately 260 cm and conditions were typical late-season conditions with a surface melt and an overall moist to wet moisture content with the top 20 cm of the snowpack being from a storm in the week prior.

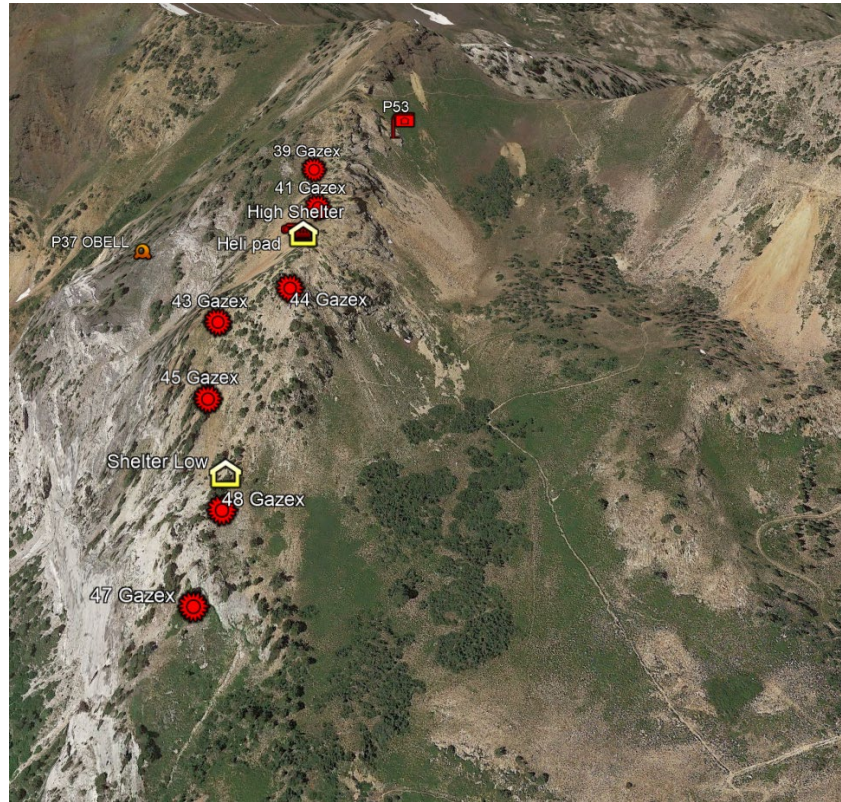


Figure 38 Gazex devices in the Hellgate near Alta, Utah, including device 48 which was selected for open slope testing in Phase 2 of the testing plan (40°35'29.61"N 111°38'53.64"W).



Figure 39 The 1.5 m³ Gazex device selected for testing in Phase 2 of the testing plan.

Ultimately, the testing conducted at this device differed slightly from the originally proposed testing due to challenging and potentially dangerous conditions present at the time of testing. In particular, the initial testing plan called for two testing sets and a total of four tests to be conducted with measurements being performed along the 0°, 30°, 60°, 90°, 120°, 150°, and 180° axes. However, due to hazardous conditions at the time of testing, it was not feasible to move the locations of the microphones as frequently as originally proposed. Instead, measurements were only conducted along the 0°, 60°, 90°, and 120° axes. It was, however, possible to perform a slightly improved total of five tests at this location due to the time savings of reduced movement of microphones between tests. The device identification given to these tests was 15GAZ. The testing, as performed, will now be discussed.

The first testing set of the 1.5 m³ Gazex system was comprised of three tests with the following layout of measurement equipment (Figure 40). These tests were focused on the 60°, 90°, and 120° axes, and all microphones remained in the same locations to address the repeatability of the Gazex blasts.

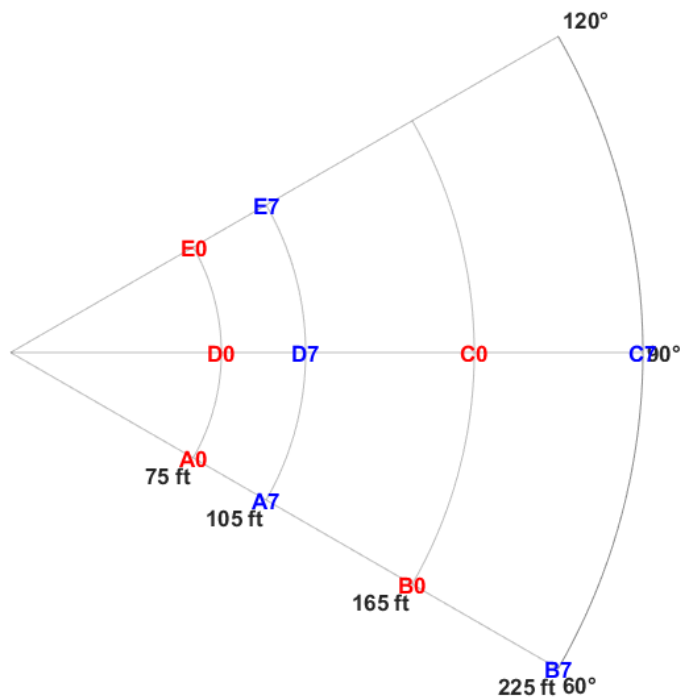


Figure 40 Microphone layout utilized for all three tests of the first set of the 1.5 m³ Gazex device.

The second testing set of the 1.5 m³ Gazex system was comprised of two tests with a slightly adjusted layout of measurement equipment (Figure 41). These tests were focused on the 0° axis. However, microphones were also left in the same locations along the 60° axis to compare the blast strengths across all five tests conducted at this RAC system.

A summary of all locations surveyed across all five tests, and the number of measurements conducted at each location, during the open slope testing of this 1.5 m³ Gazex system can be found in Figure 42.

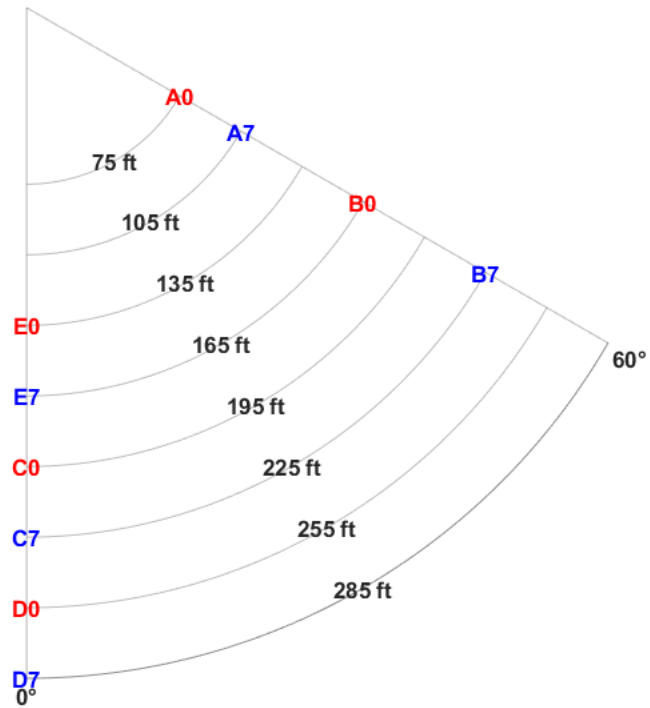


Figure 41 Microphone layout utilized for both tests of the second set of the 1.5 m³ Gazex device.

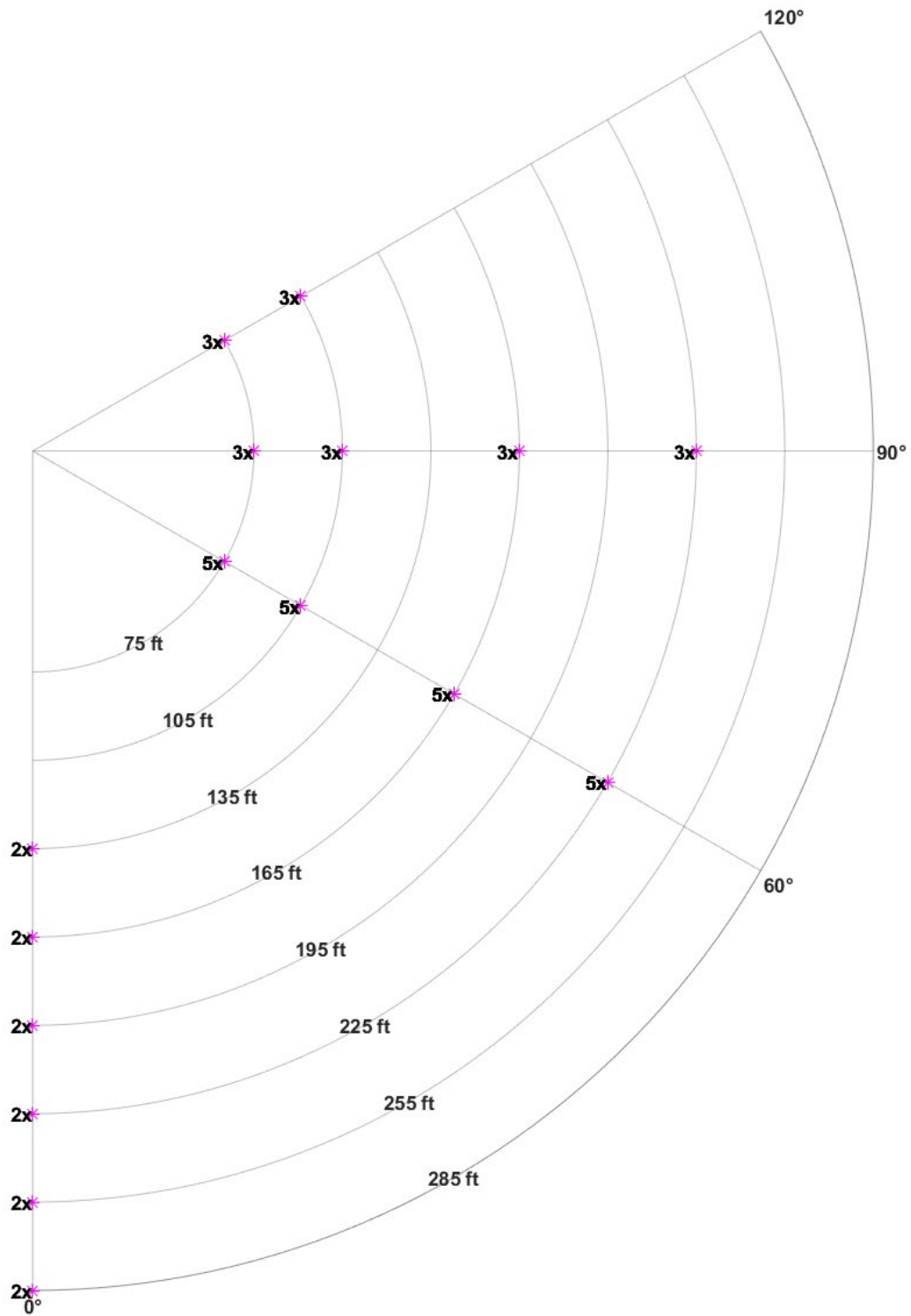


Figure 42 Microphone locations and quantity summary of all five tests of the 1.5 m³ Gazex.

2.4.2.3 O’Bellx Testing Another RAC system included in Phase 2 testing was the O’Bellx. The operational installation chosen was the southernmost device located on the eastern slopes of Mount Baldy in the Alta ski resort (Figure 43). This testing site was selected due to its easy accessibility and because it was the only available device with a moderately open snowfield – though there were still some nearby rock features. This device was located at an elevation of about 10,600 feet on a slope with an incline of approximately 35° and a northeasterly aspect. Conditions at the time of testing were sunny and clear with temperatures varying from a low of 15 to a high of 35°F , relative humidity of 30-40%, and winds less than 10 mph. Snowpack depth was approximately 260 cm and conditions were typical late-season conditions with a frozen surface melt layer that began to thaw towards the end of testing, and an overall moist to wet moisture content with the top 20 cm of the snowpack being from a storm in the week prior.



Figure 43 O’Bellx device selected for open slope testing at the Alta ski resort ($40^{\circ}34'3.65''\text{N}$ $111^{\circ}38'0.21''\text{W}$).

Much like the testing conducted at the 1.5 m³ Gazex, snow conditions at the O'Bellx site also proved to be challenging at the time of testing. As such, slight modifications to the testing plan, which originally consisted of two sets and a total of four tests, were also necessary for this device. For example, microphone placement along the 60° and 90° axes were limited to only two distances, 50 and 70 feet, due to reduced snow cover which exposed rocks that prevented microphone placement at greater distances. Furthermore, an additional test beyond the initially proposed four tests was performed due to a surplus of time and testing resources – this enabled the first test layout to be repeated for further evaluation of repeatability. The testing of this device was given the device identification OBELL and will now be discussed in greater detail.

The first set included four tests with a similar layout of measurement equipment. These four tests included microphones along the 0°, 30°, 60°, and 90° axes at varying distances from 30 to 170 feet. The microphones remained in the same locations for the first two tests, and two microphones along the 0° axis also remained in place for all four tests to help evaluate the repeatability of the O'Bellx device. The layout of microphones used for the first two tests are shown in Figure 44. The layouts used for the third and fourth tests are then shown in Figure 45 and Figure 46, respectively.

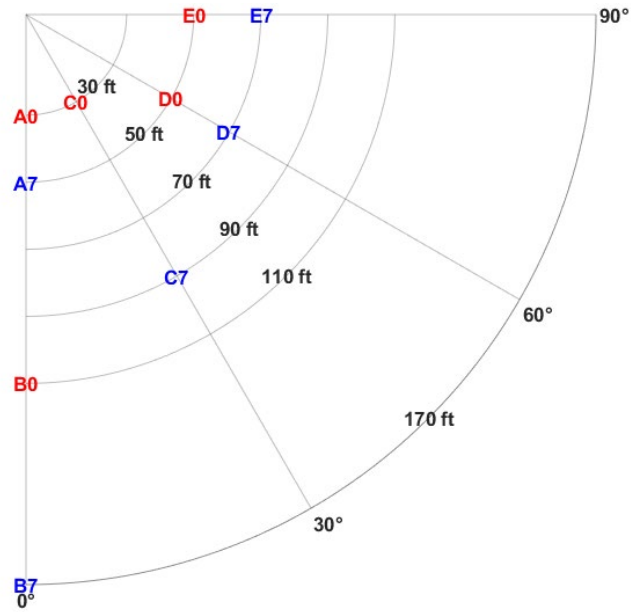


Figure 44 Microphone layout utilized for the first two tests of the first set of the O'Belx device

Set 1 Test 3

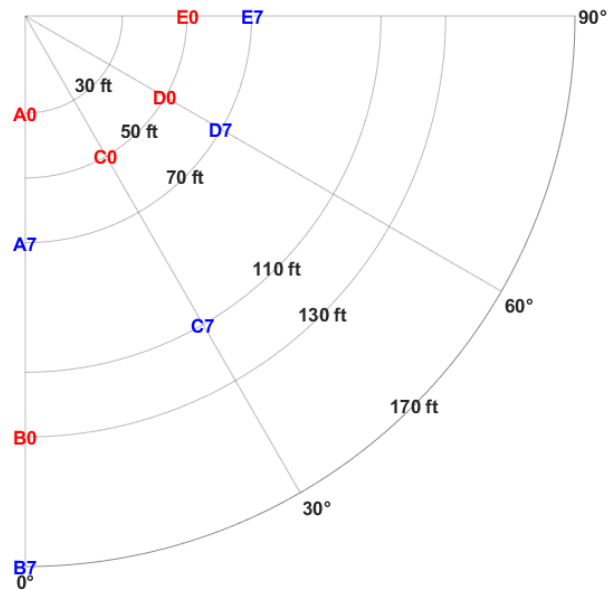


Figure 45 Microphone layout utilized for the third test of the first set of the O'Belx device

Set 1 Test 4

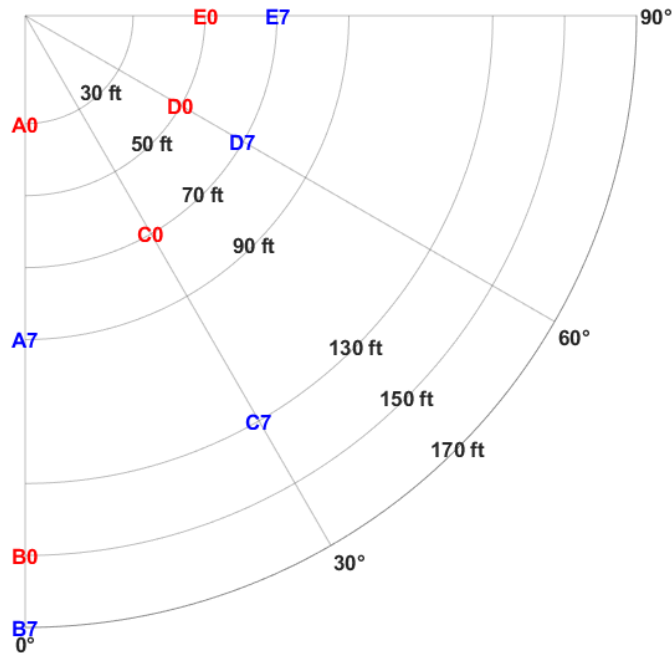


Figure 46 Microphone layout utilized for the fourth test of the first set of the O'Bellx device

The second testing set of the O'Bellx system included only a single test. The goal of this test was to investigate the behavior of the blast wave behind (i.e., uphill) of the RAC system. Accordingly, most microphones were relocated to the 120°, 150°, and 180° axes at distances between 15 and 50 feet for this test. However, two microphones were also left in place along the 0° axis to directly compare blast strength to the previous four tests. The exact arrangement of equipment utilized for this test can be seen in Figure 47.

Additionally, a summary of all locations surveyed across all five tests, and the number of measurements conducted at each location, during the open slope testing of the O'Bellx system can be found in Figure 48.

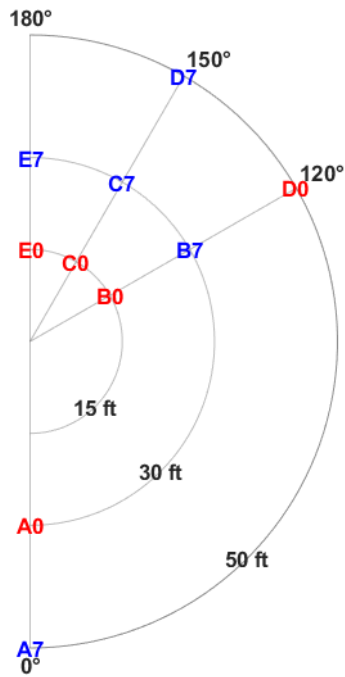
Set 2 Test 1

Figure 47 Microphone layout utilized for the first, and only, test of the second set of the O'Belx device

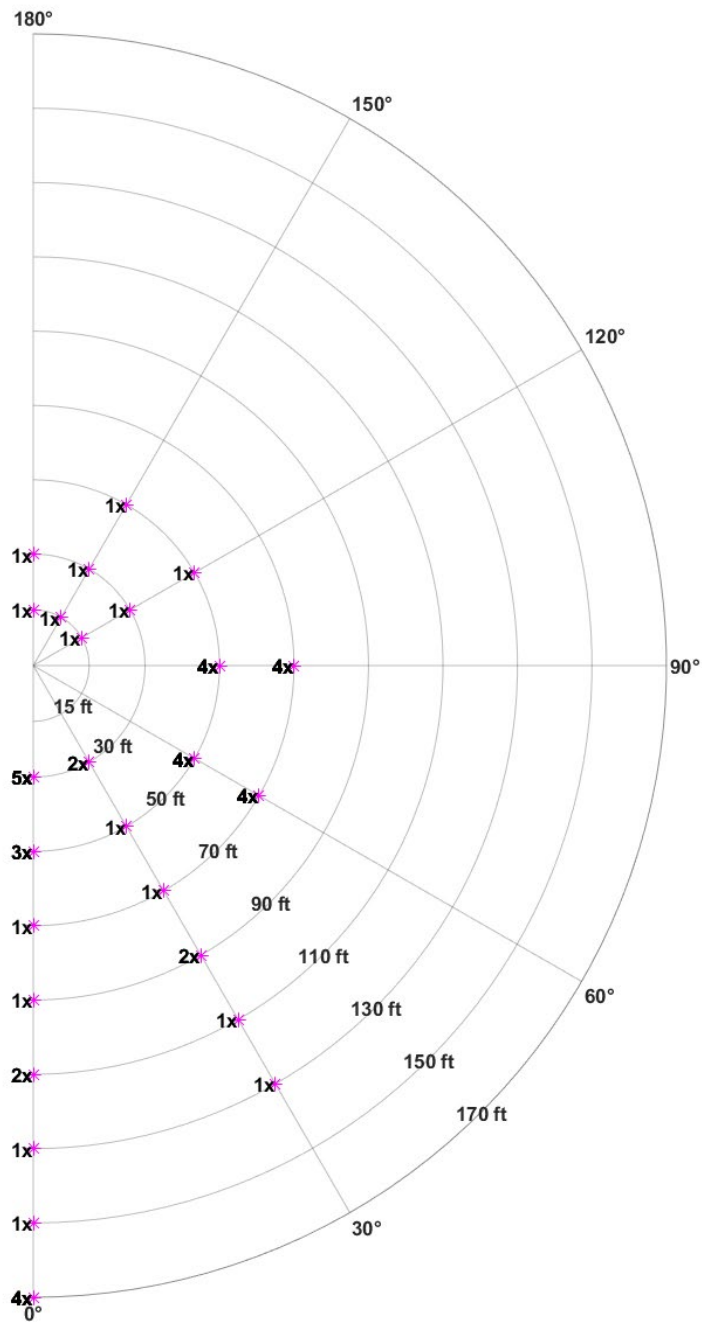


Figure 48 Microphone locations and quantity summary of all five tests of the O'Bellx device

2.4.2.4 Flat-Field Wyssen Tower Gel Charge Testing The baseline testing of the Wyssen Tower RAC system was conducted in a different manner than the devices described above. Rather than exclusively testing at an operational system, Wyssen Tower testing was first conducted in a flat, open, snow covered field, and then later compared against measurements taken at an operational system installed on an open slope (see Section 2.4.2.6 for a description of the comparison testing performed at an operational system).

There were two primary reasons for performing flat-field measurements. First, it was hypothesized that the explosive blast wave would propagate similarly over a flat, open, snow-covered field as over an open, snow-covered slope, and it was desired to perform testing to confirm or refute this hypothesis to inform future testing practices. Secondly, the location of the chosen operational Wyssen Tower made it challenging to perform multiple tests with varying equipment arrangements – thus flat-field testing presented a convenient and practical method of testing the Wyssen Tower explosives.

A single testing set consisting of three tests was conducted in a flat-field area east of Mount Baldy in the Alta ski area (Figure 50) using the standard 5 kg (11 lb) gel emulsion charge and charge container from an operational Wyssen Tower (Figure 49) suspended at a representative height of 2 m on a bamboo stick (Figure 51). The device identification given to these tests was GELFF. The testing site was located at an elevation of about 10,250 feet. Conditions at the time of testing were clear with temperatures of about 22°F, relative humidity of 55-60%, and winds of about 10 mph. Snowpack depth was approximately 100 cm.



Figure 49 The standard charge container from a Wyssen Tower

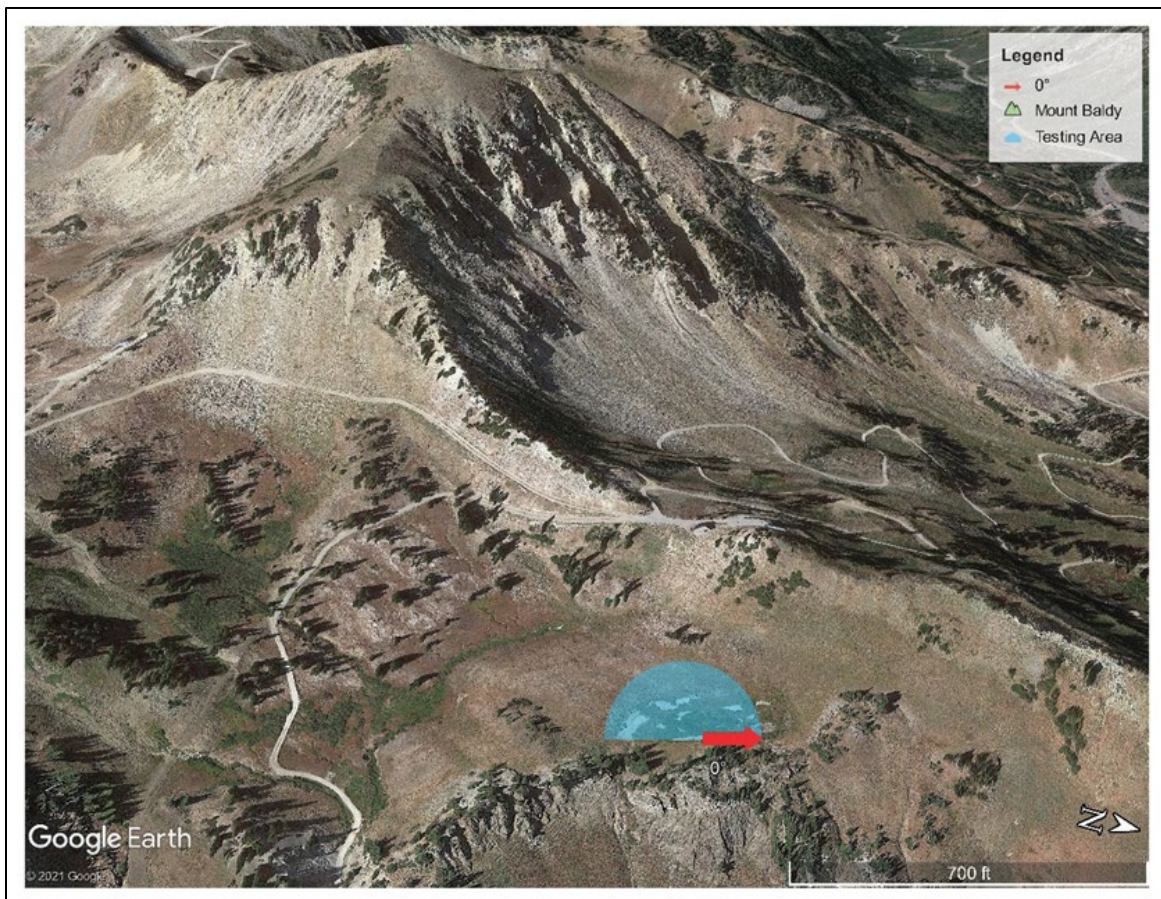


Figure 50 Approximate location, size, and orientation, of the flat-field utilized for the flat-field explosive testing conducted in Phase 2 of the testing plan ($40^{\circ}34'19.91''\text{N}$ $111^{\circ}37'45.57''\text{W}$).



Figure 51 A photo looking southwest across the snow-field utilized for the flat-field explosive testing conducted in Phase 2 of the testing plan.

The microphones for these three tests were arranged along the 0° , 45° , 90° , 135° , and 180° axes at distances ranging from 54 feet to 225 feet to investigate the assumed symmetric behavior of the Wyssen Tower gel emulsion charge. All microphones were relocated between each test except for those along the 45° axis which were left in place to help quantify the repeatability of the three gel emulsion charges utilized. The layouts utilized for these three tests can be seen in Figure 52, Figure 53, and Figure 54, and a summary of all locations surveyed, and the number of measurements conducted at each location, during the flat-field testing of the gel emulsion Wyssen Tower charge can be found in Figure 55.

Set 1 Test 1

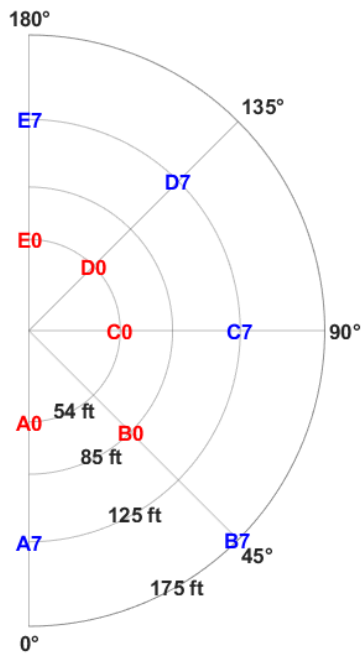


Figure 52 Microphone layout utilized for the first test of the first set of the flat-field testing.

Set 1 Test 2

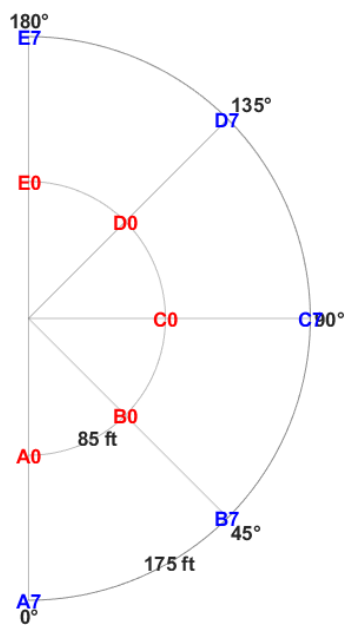


Figure 53 Microphone layout utilized for the second test of the first set of the flat-field testing.

Set 1 Test 3

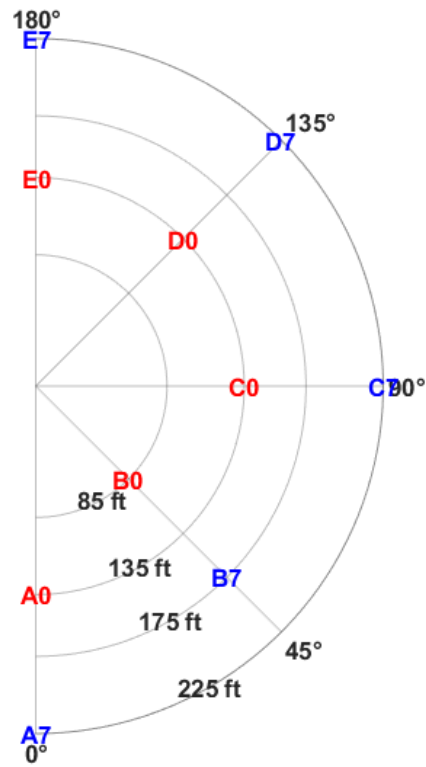


Figure 54 Microphone layout utilized for the third test of the first set of the flat-field testing.

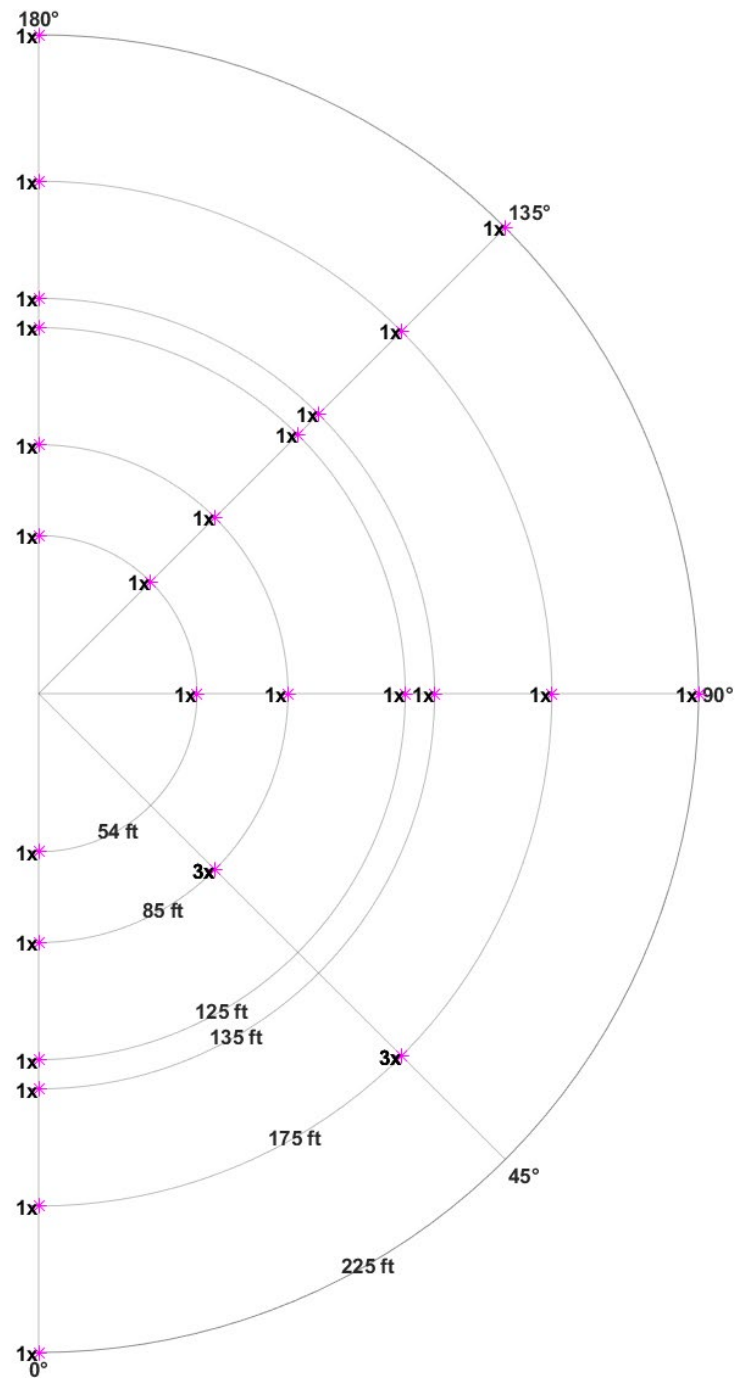


Figure 55 Microphone locations and quantity summary for flat-field testing.

2.4.2.5 Flat-Field Wyssen Tower Pentolite Charge Testing In addition to the flat-field testing of the gel emulsion charge used in operational Wyssen Towers, which was described in the previous section, a direct request was made by avalanche control practitioners to also investigate and compare the blast waves produced by a prototype Pentolite-based Wyssen Tower charge which was being developed at the time. The charges provided at the time were a combination of two 5 lb cast Pentolite charges assembled to detonate simultaneously and to closely match the form factor of the gel emulsion Wyssen Tower charge (Figure 56).



Figure 56 An illustration of the orientation of the two 5 lb cast Pentolite charges assembled to approximate a Pentolite-based Wyssen Tower charge

To address the request made by avalanche control practitioners, a series of three flat-field tests were also performed using these prototype Pentolite-based Wyssen Tower charges. These tests were conducted at the same location, using the same equipment arrangements, and were performed concurrently with the flat-field testing of the gel emulsion charge (see Section 2.4.2.4 and associated figures for a description of the testing performed). The device identification number given to these tests was PENFF.

2.4.2.6 Operational Wyssen Tower with Gel Charge Testing As mentioned above, it was also necessary to evaluate the validity of the flat-field Wyssen Tower testing by conducting

comparison testing at an operational Wyssen Tower RAC system. The device selected for this testing was known as device P53 and was located in the Cardiff Bowl area north of Alta, Utah (Figure 57 and Figure 58). This device was located at an elevation of about 10,000 feet on a slope with an incline of approximately 30° and a northeasterly aspect. Conditions at the time of testing were sunny and clear with temperatures varying from 30°F to 35°F , relative humidity of 32-40%, and gusty winds ranging from 5 to 30 mph. Snowpack depth was approximately 260 cm and conditions were typical late-season conditions with a surface melt and an overall moist to wet moisture content with the top 20 cm of the snowpack being from a storm in the week prior.



Figure 57 Location of the Wyssen Tower system for Phase 2 open slope testing ($40^\circ35'39.71''\text{N}$ $111^\circ39'5.73''\text{W}$).



Figure 58 The Wyssen Tower RAC system selected for open slope testing in Phase 2.

A total of three tests using the standard gel emulsion charge were conducted at this location and were given the device identification GELWT. The measurement equipment was arranged similarly to the flat-field testing (see Section 2.4.2.4), but microphones were not relocated between for these tests due to timing and weather constraints on the day of testing. The microphones for these three tests were again arranged along the 0° , 45° , 90° , 135° , and 180° axes, and placed at various distances used in the flat-field testing (ranging from 85 feet to 225 feet) to provide direct comparisons between the flat-field and operational device testing. A detailed breakdown of the microphone placement for the operational testing of the Wyssen Tower can be seen in Figure 59. A summary showing the quantity of measurements at each location for this testing can also be found in Figure 60.

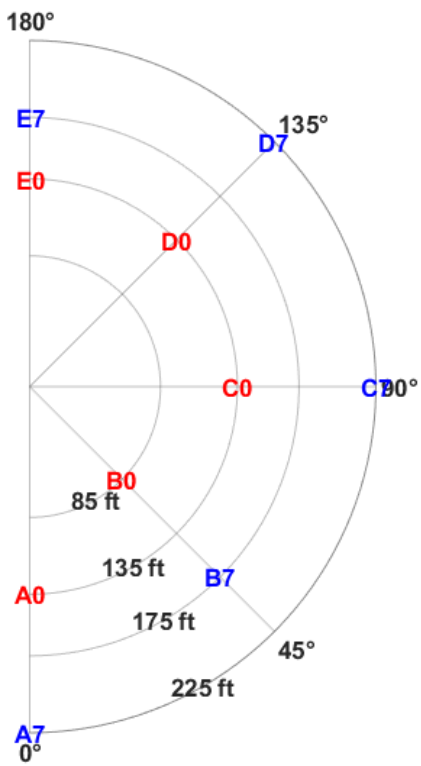


Figure 59 Microphone arrangement utilized for all testing conducted at the operational Wyssen Tower system

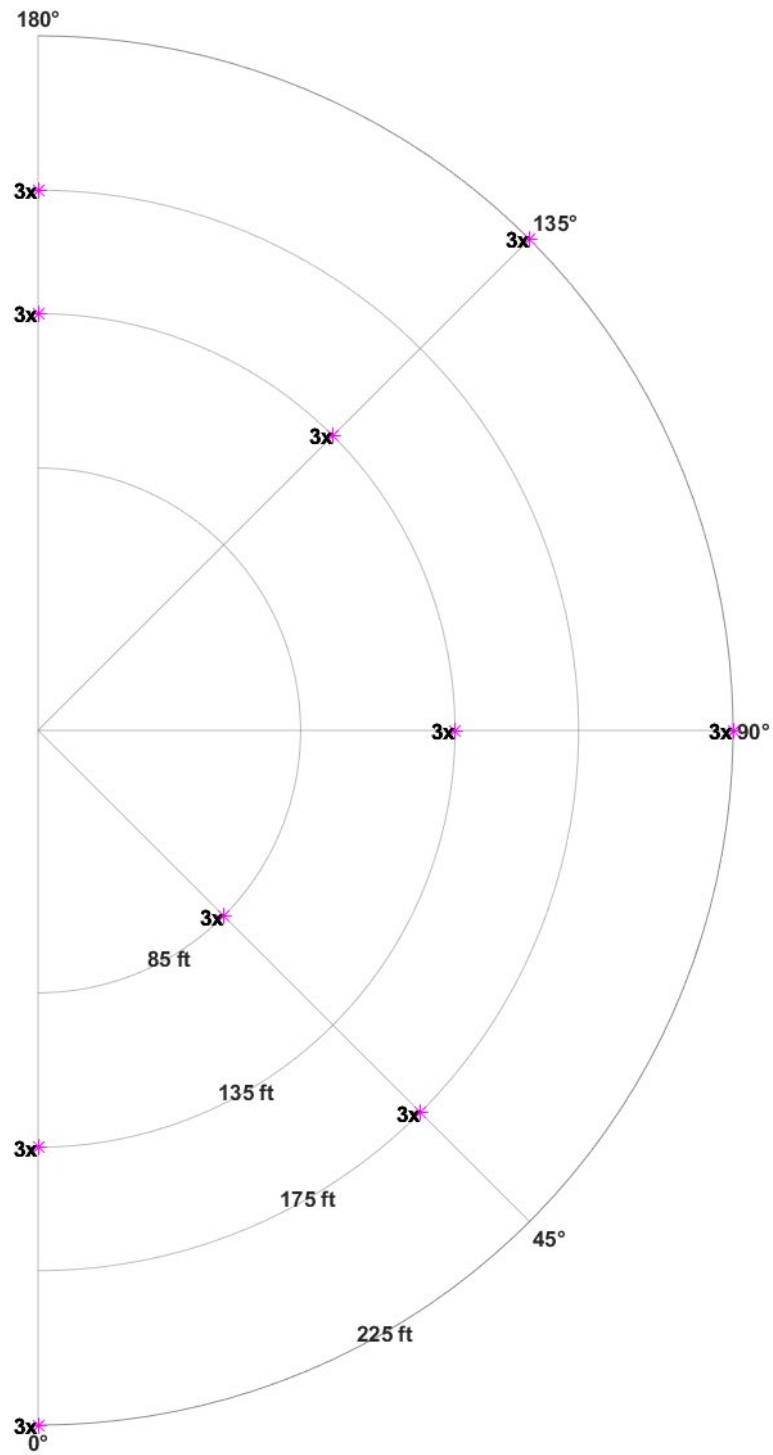


Figure 60 Microphone locations and quantity summary for operational Wyssen Tower testing.

2.4.2.7 Operational Wyssen Tower with Pentolite Charge Testing A request was made by avalanche control experts to also conduct testing of a custom cast Pentolite charge deployed from the operational Wyssen Tower. The charges provided for this testing were custom cast Pentolite (60% PETN and 40% TNT) charges manufactured by Accurate Energetic Systems. Each charge had a charge mass of 5 kg (11 lbs) and were specifically designed to integrate with Wyssen Tower charge containers (Figure 49). Although the charge mass of these Pentolite charges were slightly larger than those used during the flat-field testing, it was still of interest and educational value to the avalanche control practitioners to compare the results of the flat-field and operational Wyssen Tower testing.

As such, a series of three tests were also performed using these Pentolite-based Wyssen Tower charges. These tests were conducted at the same location, using the same equipment arrangements, and were performed concurrently with the operational testing of the gel emulsion charge (see Section 2.4.2.6 and associated figures for a description of the testing performed). The device identification number given to these tests was PENWT.

2.4.2.8 Flat-Field Simulated Avalanche Guard Testing Lastly, due to another request made by avalanche control experts, a series of three flat-field tests were also conducted using a custom 4 kg Pentolite-based charge assembled from four 1 kg cast Pentolite charges (Figure 61) buried approximately 20 cm below the surface of the snow to approximate the mortar charge of the Avalanche Guard RAC system. These tests were conducted at the same location, using the same equipment arrangements, and were performed concurrently with the flat-field testing of the Wyssen Tower gel emulsion charge (see Section 2.4.2.4 and associated figures for a description of the testing performed). The device identification number given to these tests was GUARD.

Unfortunately, comparison testing using an actual Avalanche Guard mortar charge was not possible for this research. Consequently, these flat-field tests and the results obtained are not representative of an operational Avalanche Guard system and only provide an account of the testing conducted and results produced for the interested parties.



Figure 61 An illustration of the orientation of the four 1 kg cast Pentolite charges assembled to approximate the mortar charge from an Avalanche Guard System

2.4.3 Phase 3 – Terrain Effects Testing

As introduced previously, the third and final phase of the testing plan was focused solely on investigating the influence of terrain features on the blast waves generated by avalanche control explosives. To accomplish this, blast pressure data was obtained at several locations with unique terrain features such as ridges, cliffs, and foliage nearby to determine what, if any, effects these features have on the device's overpressure decay, overpressure rate decay, and other relevant parameters. To make these assessments, the data collected in this phase was compared to the baseline data collected in the previous testing phase for each explosive.

However, due to the innumerable variability of testing sites and terrain features it is improbable to be able to fully define and characterize the influence of terrain effects. Any results obtained are inherently limited in applicability to the testing sites or locations with very similar conditions. Accordingly, the testing conducted in Phase 3 is not intended to be a complete account of the influence of terrain effects, but rather has been tailored to investigate three key

terrain features which have been identified by avalanche control experts to be of particular interest.

The first item of interest was the effect of placing a solid explosive charge directly at the base of a large cliff. The second condition considered and investigated was the placement of an explosive on the top of a ridge. The last feature considered was the placement of an explosive at the top of a sloped gully with foliage along both sides. The testing locations chosen to investigate these features were carefully chosen to minimize the influence of other unrelated terrain features and to generalize the results to the greatest extent possible (i.e., testing sites were chosen where the predominate terrain feature was the feature being studied). These testing sites and the testing conducted at each will be described in the following sections.

2.4.3.1 Large Cliff The first terrain feature studied was the effect of placing an explosive charge at the base of a large rock cliff. It was anticipated that the cliff would reflect much of the explosive energy and help to extend the blast wave effects further downslope of the cliff. To investigate this concept, a testing site was chosen that included a large rock cliff with a large open snow field downslope of the cliff (Figure 62). This testing site was located at an elevation of about 10,600 feet on a slope with an incline of approximately 30° and a northeasterly aspect. Conditions at the time of testing were sunny and clear with temperatures ranging from 15°F to 20°F, relative humidity of 30-40%, and winds less than 10 mph. Snowpack depth was approximately 260 cm and conditions were typical late-season conditions with a surface melt layer, and an overall moist to wet moisture content with the top 20 cm of the snowpack being from a storm in the week prior.



Figure 62 The cliff testing location selected for Phase 3 cliff terrain feature testing (40°34'5.45"N 111°38'1.00"W).

This location was ideal because it offered an accessible and open slope location where the only notable terrain feature was the rock cliff itself. This enabled the measurement equipment to be setup in similar conditions and at the same distances used for the flat-field and operational Wyssen Tower testing described in Phase 2. Accordingly, the same Pentolite-based custom Wyssen Tower charge used for the operational system testing (see Section 2.4.2.7) was also used for this test – allowing for a straightforward comparison between the tests. The Pentolite charge was placed 2 m above the snow surface and about 2 m in front of the cliff face. A single test at this location was performed using the following arrangement of microphones (Figure 63). This test was given the device identification PNCLF.

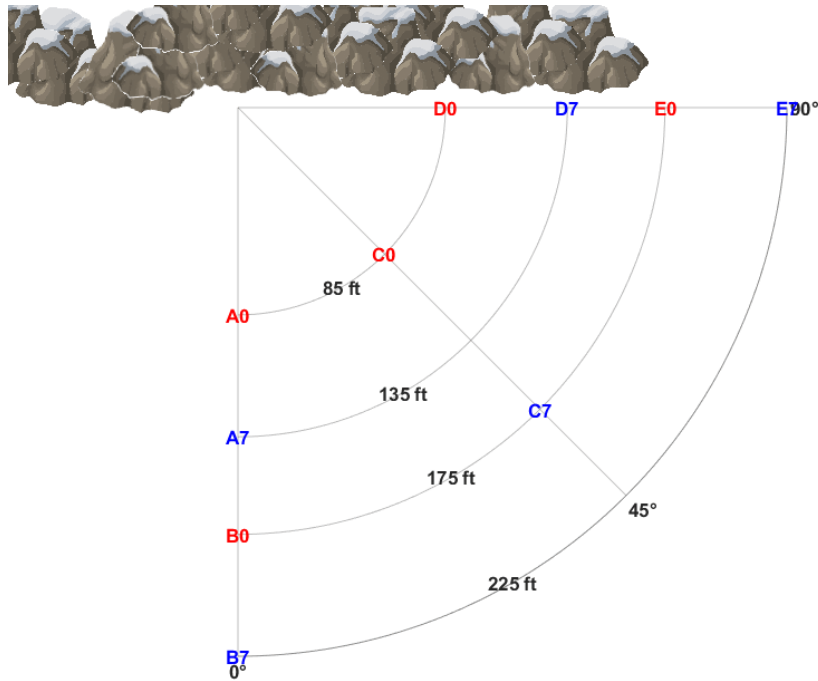


Figure 63 Measurement equipment arrangement utilized for the cliff terrain test conducted in Phase 3 of the testing plan. Note, the cliff is not to scale.

2.4.3.2 Ridge The next terrain feature considered was the effect of placing an explosive directly on top of a distinct ridge. Avalanche control experts desired to know if such a placement could enable the blast wave to be split across the ridge, and what diminishing effects on the blast wave strength that may have. To investigate this, the northernmost O’Bellx device at the Alta ski area was selected. This O’Bellx was selected due to its unique placement above a rock ridge with open snowfields on either side of the rock feature (Figure 64). This testing site was located at an elevation of about 10,600 feet on a slope with an incline of approximately 30° and a northeasterly aspect. Conditions at the time of testing were sunny and clear with temperatures ranging from 20 °F to 30°F, relative humidity of 30-40%, and winds less than 10 mph. Snowpack depth was approximately 260 cm and conditions were typical late-season conditions

with a surface melt layer, and an overall moist to wet moisture content with the top 20 cm of the snowpack being from a storm in the week prior.



Figure 64 The O'Bellx device selected for ridge terrain effects testing during Phase 3 ($40^{\circ}34'7.69''\text{N}$ $111^{\circ}38'1.25''\text{W}$).

This testing site was well-suited to assess the effects of the terrain feature in question. Apart from the ridge itself, the testing site was open and free from other obvious terrain features, and had very similar conditions to the O'Bellx device tested during the baseline testing of Phase 2 (see Section 2.4.2.3). As such, a similar measurement equipment arrangement was also utilized to facilitate the comparison of results between the baseline and ridge effects testing of the O'Bellx system. A single test was conducted at this location and was given the identification OBRCK. The microphone arrangement for that test is shown in Figure 65. However, it should be noted that this figure is a mirror-image of the arrangement used in the field. All angles and distances shown are correct, but the microphones were installed to the left of the rock ridge rather than the right.

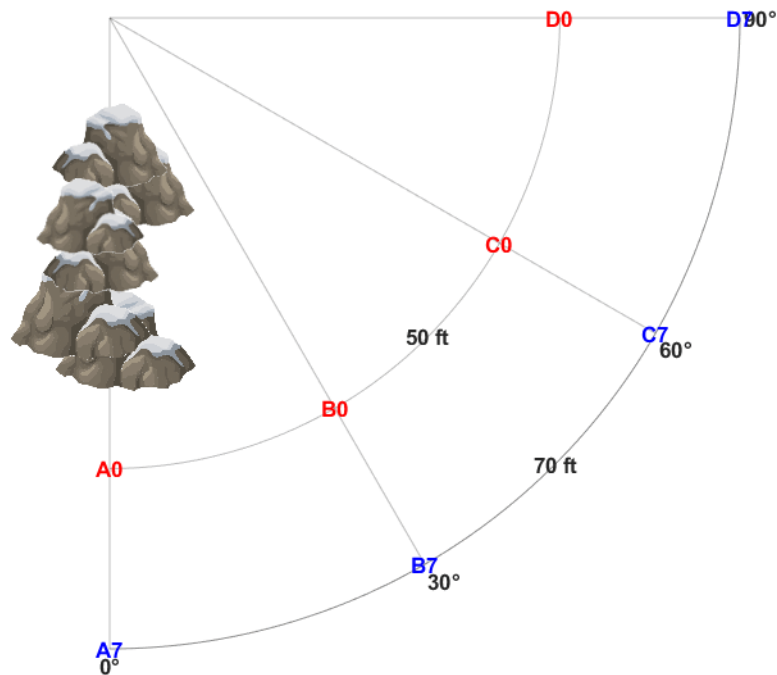


Figure 65 Microphone layout utilized for the ridge terrain effect testing conducted at the northernmost O’Bellx device at Alta, Utah. Note, ridge is not to scale, and illustration is a mirror image of the actual arrangement.

2.4.3.3 Gully with Foliage The final terrain feature included in Phase 3 testing was a gully with foliage on both edges. This test was of interest to avalanche control experts for two reasons: to see if the foliage would measurably attenuate the blast outside of the gully and to see if the concave-shape and foliage of the gully would confine and extend the blast wave further downslope. To assess these terrain effects, a gully in the Alta ski area was selected as the testing site. This gully met all of the criteria described above but was not located in an area with open slope conditions outside of the gully (i.e., other nearby terrain features may play a role in the results obtained at this location) (Figure 66). The testing site was located at an elevation of about 9,800 feet on a slope with an incline of approximately 25° and a northerly aspect. Conditions at the time of testing were sunny and clear with temperatures of about 40°F, relative humidity of

about 25%, and winds less than 10 mph. Snowpack depth was approximately 260 cm and conditions were typical late-season conditions with a surface melt layer, and an overall moist to wet moisture content with the top 20 cm of the snowpack being from a storm in the week prior.



Figure 66 The gully selected for terrain effects testing in Phase 3 (40°34'36.79"N 111°38'9.24"W).

Testing at this location was conducted using the same Pentolite-based custom Wyssen Tower charge used for the cliff terrain test and for the operational Wyssen Tower testing (see Section 2.4.2.7). The Pentolite charge was placed at the uppermost part of the gully and located 2 m above the snow surface.

Two tests were ultimately conducted at this location due to a malfunction of the explosive charge during the first test. During the first test, half of the 5 kg (11 lb) custom Pentolite charge became detached and was not detonated – resulting in an effective charge mass of 2.5 kg (5.5 lb). This test was given the device identification PGLY1. During the second test the entire Pentolite

charge was detonated successfully. This test was given the device identification PGLY2. Both tests were performed using the following arrangement of microphones (Figure 67). However, it should be noted that this figure is also a mirror-image of the arrangement used in the field. All angles and distances shown are correct, but the microphones were installed to the left of the rock ridge rather than the right.

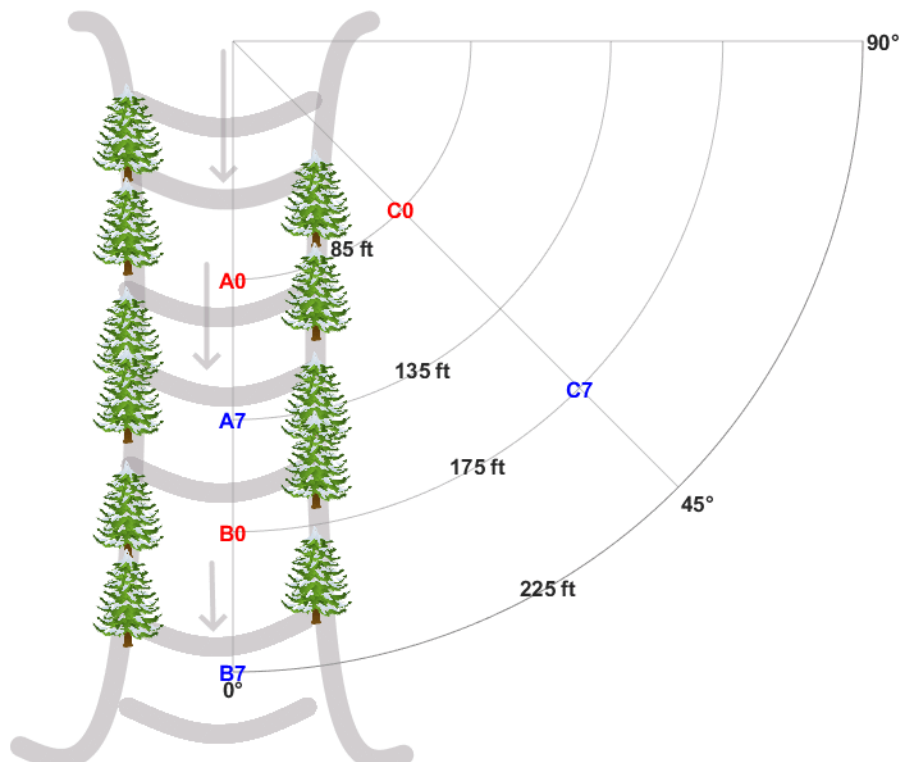


Figure 67 Equipment arrangement utilized for both tests conducted at the gully as part of Phase 3 terrain effects testing. Note, foliage and gully are not to scale, and illustration is a mirror image of the actual arrangement.

2.5 Data Handling and Processing

The testing plan described in the previous section guided the collection of a large amount of air pressure data from a wide variety of avalanche control explosives and testing

arrangements. More exactly, a total of 315 microphone measurements or 945,000,000 discrete data points were collected during the Phase 1, 2 and 3 testing of this research. Due to the large volume of data it was crucial to develop a robust, user-friendly, and largely automated method for saving, organizing, processing, and presenting the data. This was accomplished using a multi-stage system comprised of four MATLAB scripts written to handle, save, and progressively process the data. Each of the four steps, the associated MATLAB script, and the processing methods employed in each will be discussed in the following sections. The MATLAB scripts can also be found in APPENDIX B.

2.5.1 Data Trimming and Conversion to Pressure

The first step in the data processing procedure was handled by a MATLAB script entitled “DataTrimmer.m”. However, the purpose of this program extended beyond simply trimming the recorded data. This program was responsible for converting the voltage data recorded by the DAQs into pressure data, plotting this data, then trimming the data to only the explosive event, replotting, performing initial calculations, and lastly saving the converted and trimmed data file.

The conversion from voltage to pressure was a very straightforward calculation. As described in Section 2.3.3, the microphones produced a linear voltage response between 0 and 5 VDC corresponding to pressures of +10 psi and -10 psi, respectively. Accordingly, a simple equation could be written to convert from voltage to pressure [14].

$$Pressure = -4 * Volts + 10 \quad [14]$$

After converting the data to pressure using the above equation, the script would then identify the portion of the recording that contained the blast so that the data file could be

trimmed. This was a necessary step due to the long duration of the original recording from each DAQ. Throughout the course of this research the DAQs recorded data for sixty seconds to ensure that explosive events, with variable timing, could be reliably captured within the recording window. As a result, the explosive signal which typically endured only for a fraction of a second, constituted a very small portion of the total recording. This made it challenging to view and analyze the relevant blast data without first trimming the data file.

After trimming the data to a one-second window containing the blast wave signal from each microphone recorded on the DAQ, the program would then confirm the selection with the user and allow the user to make adjustments to the trimmed window.

After any adjustments by the user, the script would then prompt the user to save the converted and trimmed data file to a new location using a hierarchical file organization scheme based on the testing identification number described in Section 2.4. This allowed the large amount of data collected over the course of the project to remain reliably organized and allow each microphone recording to be traced back to the exact location and test where it was created.

2.5.2 Data Processing

After converting the voltage data from the DAQs to pressures, and after trimming the recording to a more manageable duration, the next step in the data analysis used for this project was to perform calculations on the data to obtain the values such as maximum pressure, energy equivalent, and other quantities as described in Section 2.2. However, as mentioned in Section 2.3.4.1, the presence of electronic noise in the data made it necessary to first apply an appropriate filtering method to reduce the noise so that the blast signal could be distinguished from the noise and the subsequently calculated quantities would be consistent and representative of the blast

signal rather than the artificial electronic noise. This filtering, subsequent calculations, and saving of data was done using a MATLAB script entitled “DataProcessor.m” which will be described in the following sections.

2.5.2.1 Noise To select an appropriate filtering method for this work, it was necessary to examine the noise carefully. As such, the first step of the data processing MATLAB script was to utilize MATLAB’s built-in Fourier analysis tools to determine, graph, and examine the spectral content of the unfiltered data. This, in turn, made it possible to better understand the frequency content of both the explosive blast wave signals and the electronic noise. This process was performed for every recording obtained in this research, which revealed a clear trend. In particular, it was discovered that the electronic noise was isolated to high frequencies in the range of 15,000-25,000 Hz whereas the blast wave signal was primarily composed of frequencies less than 3,000 Hz (Figure 68). The low-frequency spectral composition of blast waves is consistent with previous work which found very little frequency content above 500 Hz for solid and gas-based explosive signals (Simioni et al., 2014, 2017). As a result, it was quite possible, and highly effective, to apply a simple low pass filter (LPF) to largely remove the high-frequency noise from the recordings (Figure 69). This was done by, again, utilizing the built-in Fourier analysis and processing tools in MATLAB. For most recordings, a LPF with a cutoff frequency of 1,500 Hz was used, but for some recordings, where the strength of the measured

blast wave was close to the noise floor, slight adjustments to this filter were required to adequately distinguish the blast wave signal from the noise.

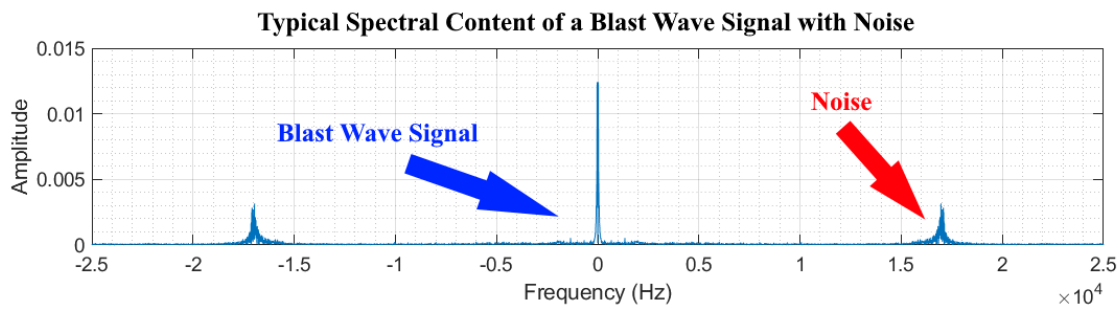


Figure 68 Typical frequency content of an unfiltered microphone recording.

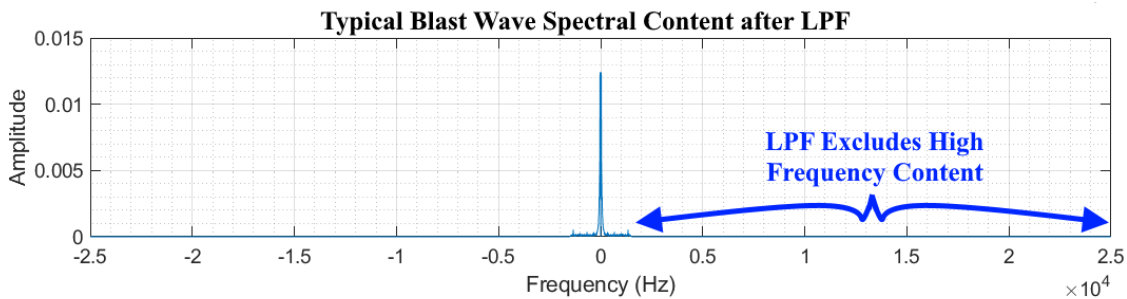


Figure 69 Typical frequency content of a filtered microphone recording.

2.5.2.2 Determining Overpressure Following the filtering of the data, the next step in the data processing script was to begin calculating or determining the quantities of interest (see Section 2.2). The first quantity, overpressure, was the most straightforward. The maximum air pressure, and the time when it occurred, was found by simply utilizing the maximum finding function, `max()`, built into MATLAB. These quantities were then saved to a unique MATLAB .MAT file which could then be queried by subsequent scripts to complete the analyses and graphing for a given explosive.

2.5.2.3 Determining Air Pressure Rate The next calculation performed in the data processing script was to determine the air pressure rate. This value was calculated using both the numerical derivative and the direct calculation methods described in Section 2.2.1.2. The values obtained through both methods were then saved to the abovementioned .MAT file.

2.5.2.4 Determining Air Pressure Energy Equivalent Next, the data processing script would also determine the energy equivalent of the blast wave using the numerical integration trapezoidal method described in Section 2.2.1.3. This value was then also saved to the .MAT file.

2.5.2.5 Other Quantities Calculated The DataProcessor.m MATLAB script also performed other calculations that weren't directly used in this work such as impulse (which was also calculated using the trapezoidal method). Furthermore, the script would also save the filtered data, Fourier-transformed data, numerical derivative and integral data, and these additional calculations to a new location using the hierarchical file organization scheme based on the testing identification number described in Section 2.4. The purpose in calculating these additional quantities and saving all of this processed data was so that the data, whether used or unused for this work, could be easily utilized in future work, adapted to calculate other important quantities or conduct further analyses, or used for comparison purposes with future work.

2.5.3 Test Compiling

After trimming and filtering the data from each microphone recording, and after calculating the values of interest from that data, the next stage of the multi-stage data processing system was to compile the calculated values into a spreadsheet format, which was then used in

the subsequent step, to conduct summary analyses and graphing of a given explosive or explosive system.

This proved to be a challenging step since each type of explosive tested consisted of multiple individual tests and many more independent microphone recordings from a variety of distances and angles around the explosives. Furthermore, the data processed from each DAQ had no direct record of which explosive, which test, or which location the data was from.

Accordingly, it was necessary to combine the locational and test numbering information from the Testing Plan (see Section 2.4) with the measured and calculated data from the DAQs themselves (see Section 2.5.2) into a master spreadsheet that contained all of the locational information, test numbering, and important calculated quantities for a given microphone recording. The custom MATLAB script that performed this operation was known as the “DataCompiler.m” script, and the spreadsheet that it produced was named the “Master Spreadsheet.xlsx” (see APPENDIX A for a copy of the Master Spreadsheet).

In short, the compiling script utilized a graphical user interface (GUI) to walk the user through the selection of the test layout for a given explosive from the Testing Plan. It would then populate testing layout graphs containing the layout of each microphone like those seen in Section 2.4 and continue to visually walk the user through the selection of the .MAT files with the data for each microphone in the selected testing sequence. These .MAT files were produced by the previous script and saved to file and folder locations based on the hierarchical test numbering scheme described previously – which made them easy to find by the compiling script. After the .MAT file for each microphone in the selected testing sequence was selected and imported, the compiling script would then check to make sure none of the selected data was

incorrectly selected or already existed in the Master Spreadsheet. If the data did already exist in the Master Spreadsheet, the compiling script would produce tables of the new and existing data (highlighting any similarities) and ask the user to either overwrite or duplicate the existing data in the Master Spreadsheet or skip the new entry altogether. Once these checks had been completed for each .MAT file, the compiling script would then produce an updated Master Spreadsheet with the new entries highlighted, ask the user to enter any relevant notes to the entries, and finally ask the user to save the Master Spreadsheet. The reason for compiling all of the locational, test numbering, and calculated data into a single spreadsheet format was so that the data would be accessible to the subsequent MATLAB script and to other software which may be used in the future to further evaluate the data from this work.

2.5.4 Graphing and Analysis

The final step of the multi-stage data processing methodology used in this work was to take the information contained within the Master Spreadsheet and produce summarized analyses and graphs for each type of explosive investigated. More particularly, the goals of this stage were to produce three-dimensional plots of the data collected for each explosive type, find mathematical expressions to help describe the behavior of the data, and create additional two-dimensional plots that would also help to illustrate those mathematical expressions. These goals were accomplished by the final MATLAB script entitled “DeviceProcessor.m”.

Due to the complexity of the data, the use of polar/cylindrical coordinate systems, and the specific desired graphing needs, a built-in MATLAB plotting solution was not available for the three-dimensional plotting of the data. Thankfully, an open source MATLAB function was

available (Garrard, 2021), which, after some slight modifications enabled the three-dimensional plotting of the explosive blast wave data using a polar coordinate system.

Together, these two scripts enabled any of the aforementioned quantities of interest (overpressure, energy equivalent, etc.) to be quickly and easily plotted in a total of four initial plots. Two of these plots (a three-dimensional surface plot and a two-dimensional contour plot) were created using data that was bilinearly interpolated between the discrete microphone measurement locations using the built-in MATLAB function, `scatteredInterpolant()`. These bilinearly interpolated plots offered a straightforward representation of the behavior and shape of the collected data across all angles and radii measured, but were largely unused in this work and will not appear in Chapters 3 or 4. For a more refined representation of the data, another three-dimensional surface plot and a two-dimensional contour plot were created using fitted power law equations along each angle where microphones were located and linearly interpolated data on the angles between those measured angles. The power law equations were calculated for each measured angle by utilizing the built-in MATLAB function, `fit()` which applied the fit directly to the measured data. Power law fitting was applied in this work since it has been used frequently in previous work and often produces a very good fit for blast wave behavior (Simioni, 2017). For these surface and contour plots, symmetry across the 0° - 180° axis was assumed, and the data was reflected across this axis for illustrative purposes. In most cases, these graphs provided a useful and informative general illustration of the shape, directionality, and behavior of the blast wave quantity being examined.

The `DeviceProcessor.m` script also created several two-dimensional axial “slice” plots which showed the relationship between the quantity of interest and radial distance along a single

axis. A total of up to nine slice plots (one along each of the 0° , 30° , 45° , 60° , 90° , 120° , 135° , 150° , and 180° axes) were created to more clearly illustrate the power law expression along measured angles and to more clearly show the interpolated data on non-measured angles. Furthermore, the script also enabled the user to specify radial extrapolation conditions for the power law fits. For instance, the user could choose to extrapolate the calculated power law fits out to a specific radius or to the radius at which a specific value is reached. If a value was specified (e.g., the point at which a 1 kPa or 0.145 overpressure is reached), this value and the radius at which the power law reaches that value would also be specified on the axial slice plots of measured angles and on the contour plot of the power law fitted data.

After these best fit equations and figures had been created, the script would then allow the user to save the figures and equations to a summary file location organized by the explosive device being summarized, the tests included in the summary, and the quantity of interest being examined. The summaries, power law fits, and plots created by this script are the primary means of conveying the results of this research and will be presented thoroughly in the following chapter for each RACS device tested and for each quantity of interest considered.

2.5.5 Sources of Error

Having, in this chapter, considered the project objectives and the instrumentation, testing plan, and the data processing methods developed to achieve those objectives, the last critical consideration before presenting the results obtained in this research, is to discuss the potential and known sources of error in this work. Some sources of error in this work are apparent and quantifiable while others are not explicitly known – both will be discussed in this section.

The known and quantifiable sources of error include the inherent sensor and measurement equipment errors discussed in Section 2.3, the electronic noise discussed in Sections 2.3.4.1 and 2.5.2.1, and the measurement error associated with the laser rangefinders used to locate microphones during field work which was specified to be ± 9 ft at a range of 3,000 ft (Vortex, 2021). In particular, it was discovered that the electronic noise seemed to affect the results of the pressure rate calculations for some testing sequences due to artificially steep oscillations from the noise. Similarly, it was found that imperfect distancing and/or orientations of the microphones seemed to result in measurably higher or lower pressures at distances close to the blast center. Distances further from the blast center did not seem to have appreciable variations due to microphone placement inaccuracies.

Sources of error whose magnitude is unknown were also undoubtedly present in this work. While it is difficult to quantify what effect these sources may (or may not) have had on the final results of this work, it is still essential to discuss them so that the results of this present work may be understood in their full context and any future work may benefit from these identified potential sources of error. One such source of error included variable snow conditions. While most testing was performed over a two day period in April of 2021, there was still some variability in the snow conditions over those two days and particularly when compared to Phase 1 testing which was conducted in December of 2020 in Montana or the flat-field testing which was conducted in January of 2021 (see Section 2.4 for more detailed discussions of snow conditions during testing).

3. RESULTS

For organizational purposes, the results below will be presented according to the portion of the testing plan in which the data was collected. For the sections below, the overpressure, energy equivalent, and pressure rate results will be presented unless otherwise noted. Results will be shown using a combination of surface and contour plots (reflected across the 0°-180° axis) to illustrate the spatial behavior of the blast wave parameter being discussed, axial slice plots to illustrate the decay of the blast wave parameter with distance along each measured axis, and tables to summarize results and calculations. Additionally, a summary of all calculated and measured quantities for all tests can be found in the Master Spreadsheet (APPENDIX A).

3.1 Phase 1 Results

Phase 1 of the testing plan focused on utilizing, validating, and refining the newly developed measurement equipment. As such, the focus of these tests was on high-level qualitative evaluations and quantitative assessments of pressure data to validate equipment performance and not on detailed comparisons of blast wave behavior. Accordingly, the results of these tests will only include measured overpressures and not the energy equivalent or pressure rise rate results included in later testing.

3.1.1 Pentolite Testing Set 1 (Microphone Height Test) Results

The first test focused on an assessment of suitable microphone placement above the snow surface (Figure 70). The goal of this testing was to determine the maximum height above the snow that the microphones could be placed while still being representative of the air pressures at

the snow surface. It was necessary to place microphones as high as possible to avoid potential issues with snow sluffing and blocking the microphones as described in prior research (Simioni, 2017).



Figure 70 Experimental setup for the microphone height test.

The results of this test indicated a nearly linear behavior of increasing peak pressure with increased microphone height (Table 4). Once plotted it was also observed that measurements at and below a 1 ft height seemed to be closely grouped in terms of peak pressure magnitude, and a

small jump in measured peak pressure occurred between the 1 ft and 1.5 ft measurement heights (Figure 71). However, there were no obvious outliers that would indicate a marked change in blast wave behavior at a given height for the test setup and distances used in this test.

Table 4 Measured peak pressures vs. microphone height above snow surface

Microphone Height (ft)	Peak Pressure (psi)
0.17	2.72
0.50	2.63
1.00	2.87
1.50	3.30
2.00	3.38
3.00	3.70
4.00	3.72
5.00	3.80

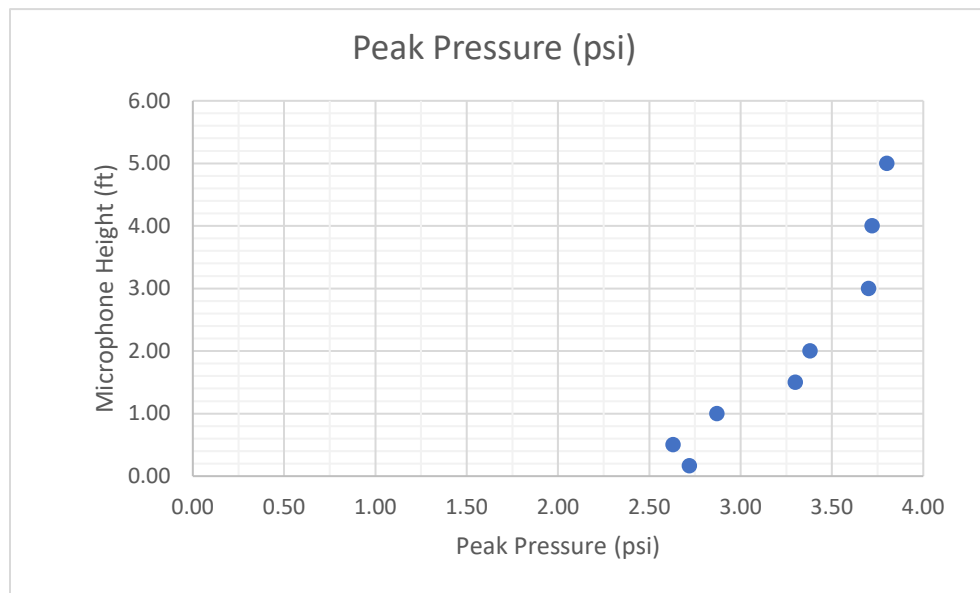


Figure 71 Measured peak pressures (x-axis) vs. microphone height (y-axis)

3.1.2 Pentolite Testing Set 2 Results

The second testing set of the Phase 1 testing involving 2-lb Pentolite charges included two separate tests which were primarily intended to identify any logistical and equipment field

testing challenges prior to Phase 2, but were also designed in such a way that the results could be compared to testing performed by Bones (2012) and Simioni (2017) to further assess the measurement systems and data processing methods.

Peak pressure results of these tests are shown in the table below (Table 5) and illustrated in the following figures (Figure 72 - Figure 76).

Table 5 Peak pressures collected during the 2-lb Pentolite charge testing of Phase 1, Set 2⁸

Microphone Angle (°)	Microphone Radial Distance (ft)	Maximum Pressure (psi)
0	16	4.600
0	23	2.576
0	50	0.733
0	75	0.415
45	23	2.280
45	50	0.731
90	10	7.404
90	23	1.841
90	50	0.738
90	75	0.362
0	16	4.898
0	23	2.674
0	120	0.220
0	220	0.103
45	23	2.794
45	120	0.214
90	10	7.637
90	23	2.209
90	120	0.214
90	220	0.099

⁸ The most proximal measurements taken on the 90° axis were actually placed at a distance of approximately 10 ft rather than the intended 16 ft. This change is reflected in this table and the following figures

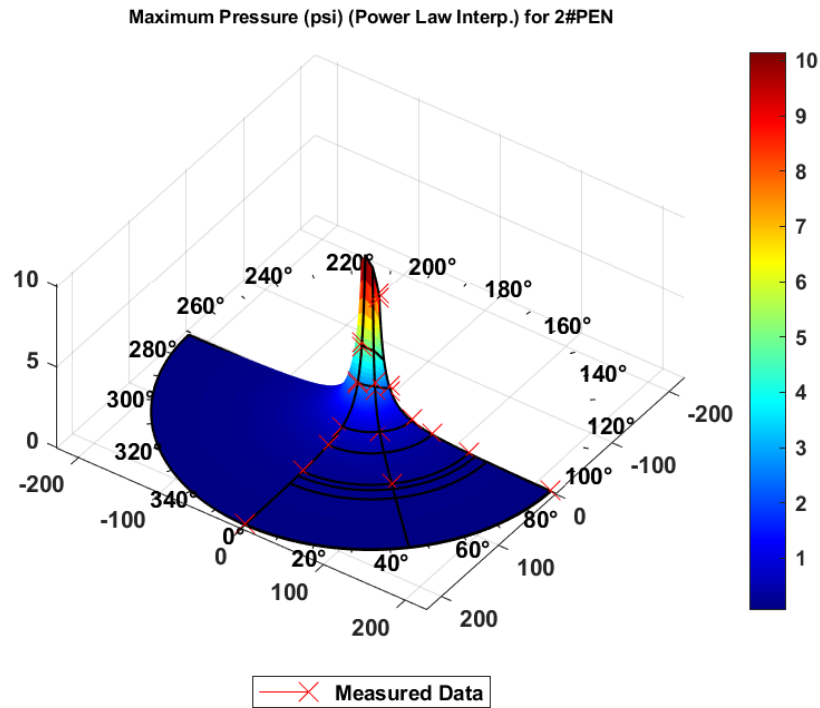


Figure 72 Surface plot of the power law fitted peak pressure data of the 2-lb Pentolite charge testing of Phase 1, Set 2

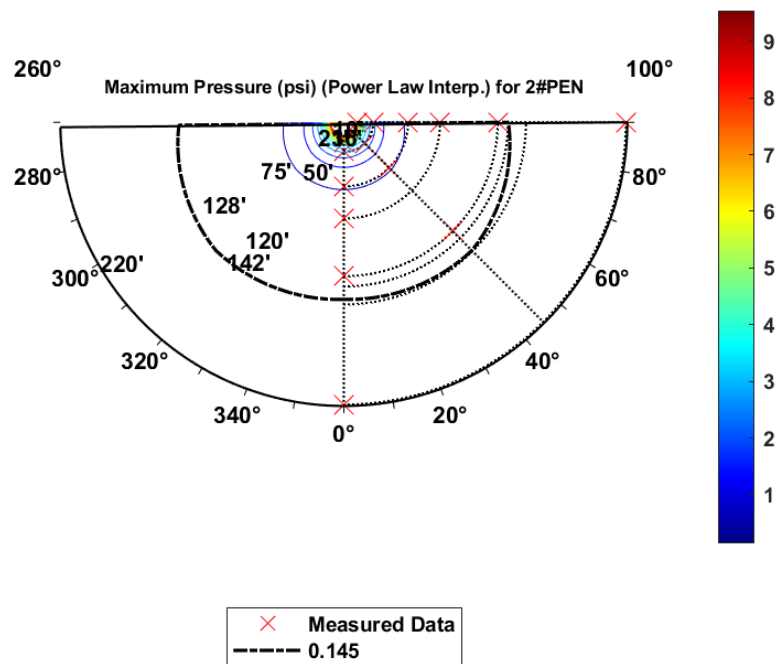


Figure 73 Contour plot of the power law fitted peak pressure data of the 2-lb Pentolite charge testing of Phase 1, Set 2. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

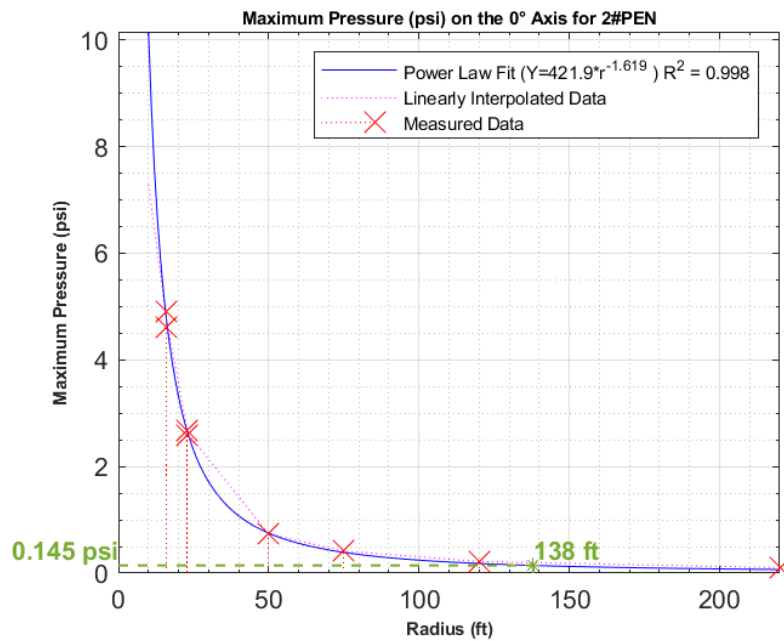


Figure 74 Slice plot along the 0° axis showing the power law fitted peak pressure data of the 2-lb Pentolite charge testing of Phase 1, Set 2. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

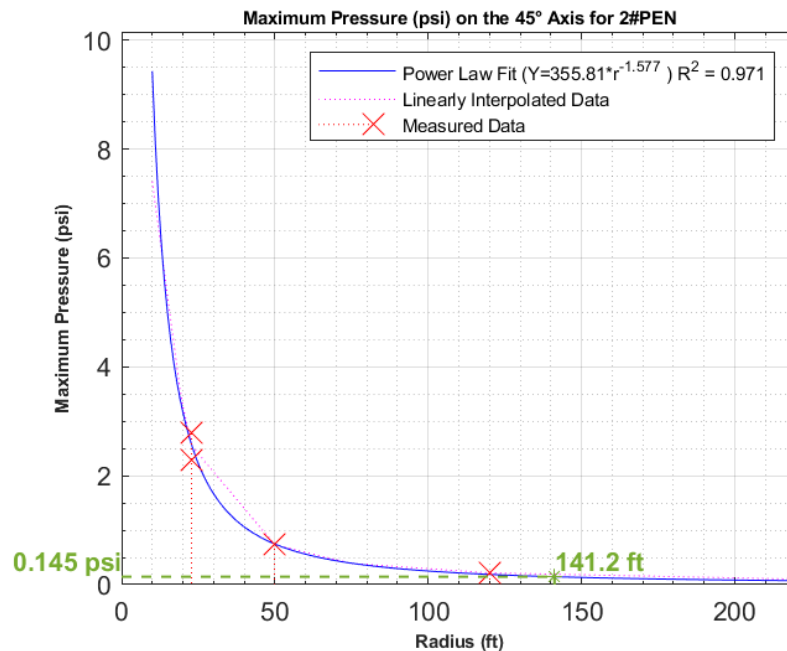


Figure 75 Slice plot along the 45° axis showing the power law fitted peak pressure data of the 2-lb Pentolite charge testing of Phase 1, Set 2. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

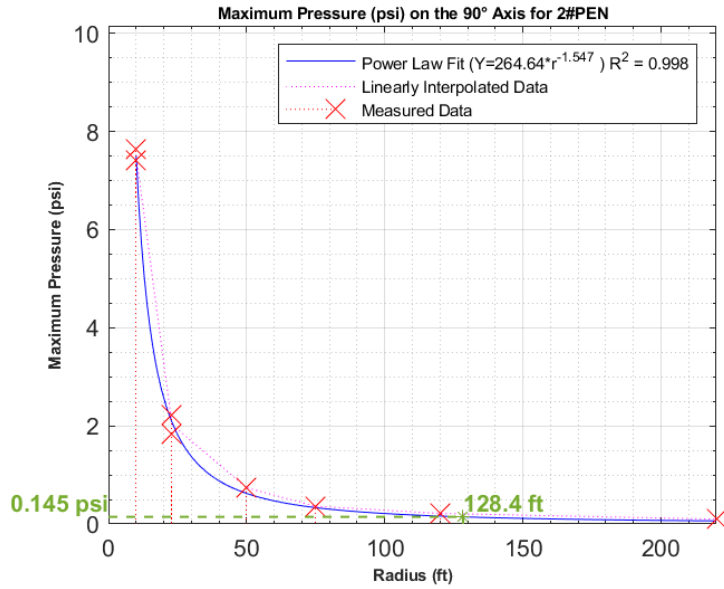


Figure 76 Slice plot along the 90° axis showing the power law fitted peak pressure data of the 2-lb Pentolite charge testing of Phase 1, Set 2. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

Peak pressures ranged from 7.6 psi at a radial distance of 10 ft to 0.1 psi at a radial distance of 220 ft. Furthermore, the blast wave was expectedly symmetric with similar behaviors observed along the 0°, 45°, and 90° axes. Along each axis, peak pressures decayed significantly with radial distance and closely followed a power law of the form $p = a * r^{-b}$, where p is the peak pressure, r is the radial distance, and a and b are the power law coefficients which are detailed in the following table (Table 6). Based on these power laws, it was also determined that the reference peak pressure of 1 kPa or 0.145 psi was reached at a distance of about 128 – 141 ft.

Table 6 Power law coefficients for the peak pressure data along each of the measured axes for the 2-lb Pentolite charge testing of Phase 1, Set 2.

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	422	1.62	0.998
45	356	1.58	0.971
90	265	1.55	0.998

3.2 Phase 2 Results

As discussed previously, Phase 2 of this project sought to provide baseline performance data for the selected RAC systems. To do this, an extensive sequence of testing was performed on seven devices. This testing enabled blast wave pressure data to be collected from the RAC devices, from which several key performance metrics could be evaluated and compared. Namely, the peak pressures, energy equivalents, and pressure rise rates of the blast wave were determined for each device and will be summarized in the following sections.

3.2.1 1.5 m³ Gazex

The results from the testing performed at the operational 1.5 m³ Gazex offered many interesting observations and comparisons. Beginning first with peak pressure, the surface and contour plots of peak pressures illustrated a distinct and expected directional effect (Figure 77 and Figure 78). This is further shown by the axial slice plots which indicate a much stronger but more rapidly decaying wavefront along the 0° axis than the 60°, 90°, and 120° axes (Figure 79 - Figure 82). The power law coefficients fit to each of these axes are shown in Table 7. Based on these power laws, it was also determined that the reference peak pressure of 1 kPa or 0.145 psi was reached at a distance of about 230 ft on the 0° axis, 155 ft on the 60° axis, 113 ft on the 90° axis, and 82 ft on the 120° axis. Lastly, the peak pressure results also indicated a high level of repeatability between tests based on the consistency of measured peak pressures by microphones left in the same position during multiple tests.

Table 7 Power law coefficients for the peak pressure data along each of the measured axes for Gazex tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	593	1.53	0.991
60	125	1.34	0.973
90	83	1.35	0.969
120	25	1.17	0.981

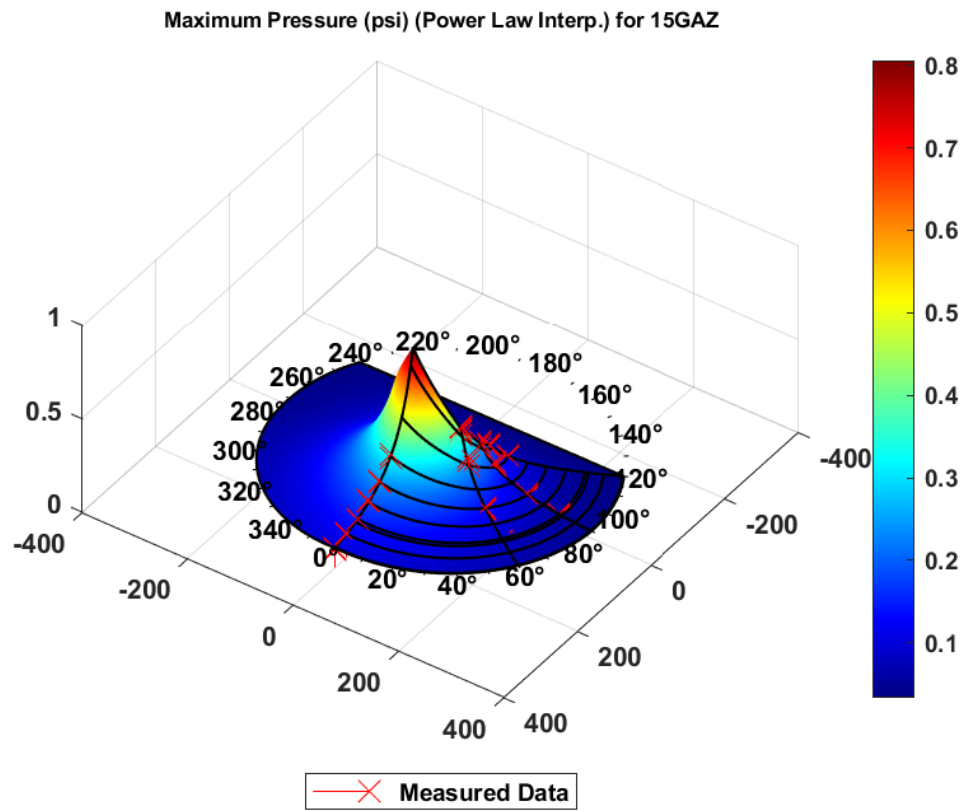


Figure 77 Surface plot of the power law fitted peak pressure data from the Gazex testing

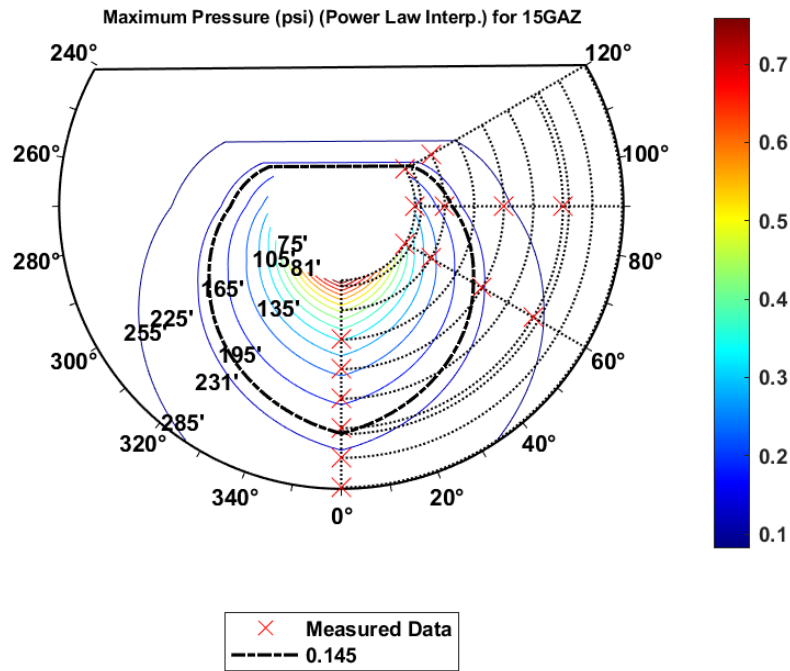


Figure 78 Contour plot of the power law fitted peak pressure data from the Gazex testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

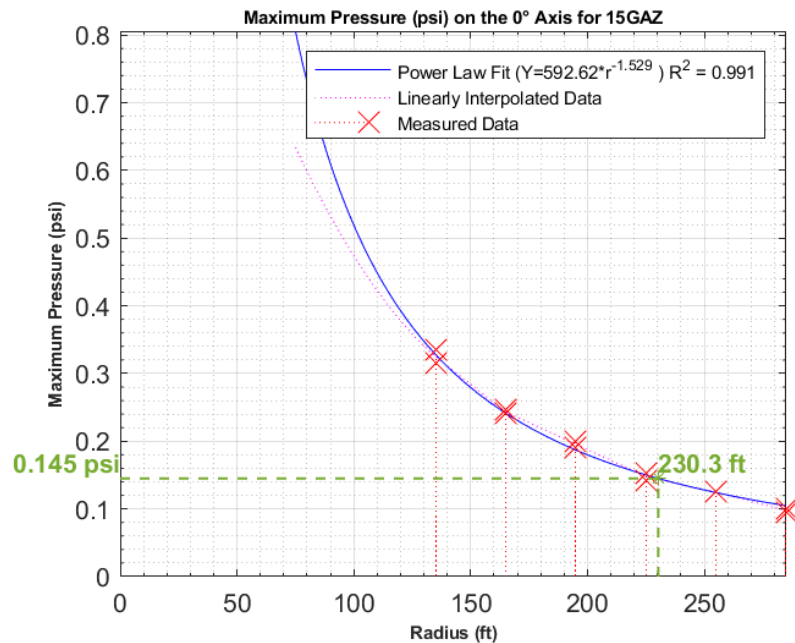


Figure 79 Slice plot along the 0° axis showing the power law fitted peak pressure data for Gazex. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

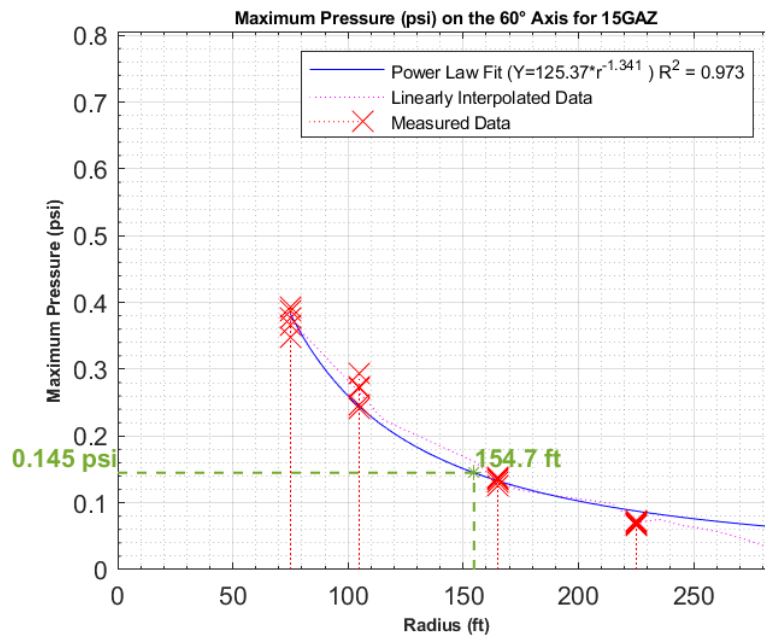


Figure 80 Slice plot along the 60° axis showing the power law fitted peak pressure data for Gazex. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

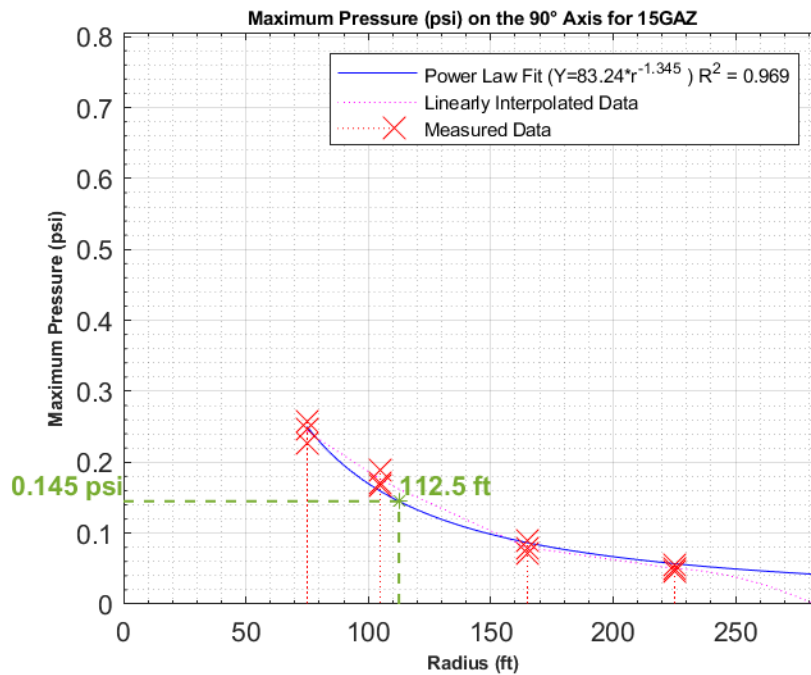


Figure 81 Slice plot along the 90° axis showing the power law fitted peak pressure data for Gazex. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

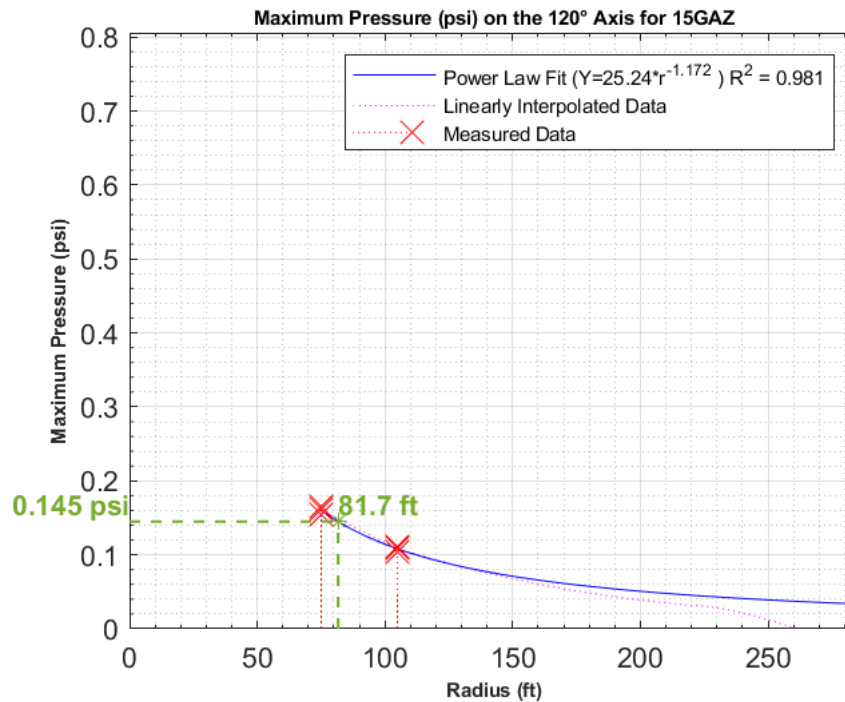


Figure 82 Slice plot along the 120° axis showing the power law fitted peak pressure data for Gazex. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

The energy equivalent results obtained from these tests also exhibited a directional behavior (Figure 83 and Figure 84). As with peak pressure, energy equivalent was highest along the 0° axis and decayed more strongly with radial distance than along the 60°, 90°, and 120° axes. However, a notable difference was that the decay of the energy equivalent was higher along all axes than for peak pressure. The power law coefficients describing the decay of the energy equivalent can be found in Table 8. Lastly, much like the peak pressure results, a high level of repeatability between tests can be inferred for the energy equivalent results due to the consistency of the results from microphones left in position for multiple tests.

Table 8 A table of the power law coefficients for energy equivalent for Gazex tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	322	2.60	0.998
60	23	2.25	0.979
90	2.58	1.98	0.961
120	0.56	1.87	0.835

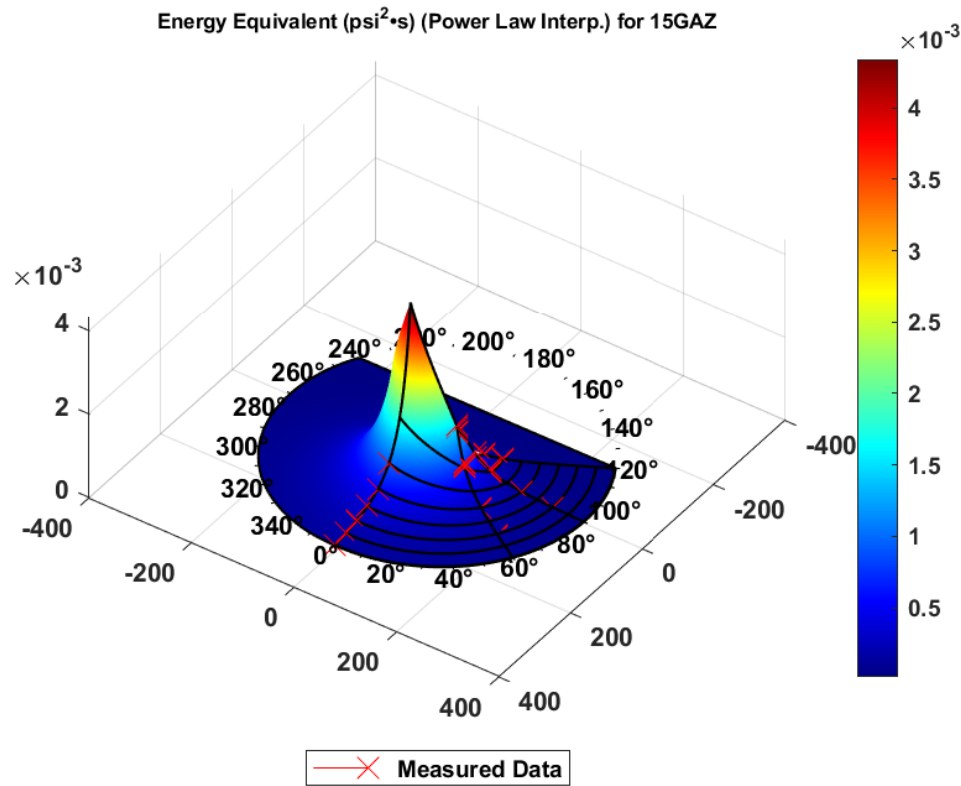


Figure 83 Surface plot of the power law fitted energy equivalent data from the Gazex testing

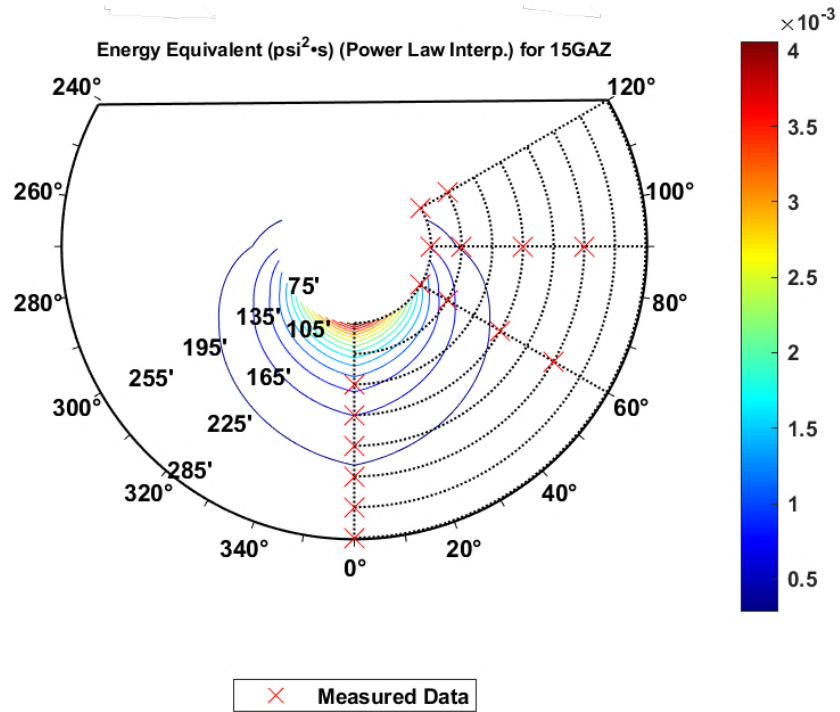


Figure 84 Contour plot of the power law fitted energy equivalent data from the Gazex testing.

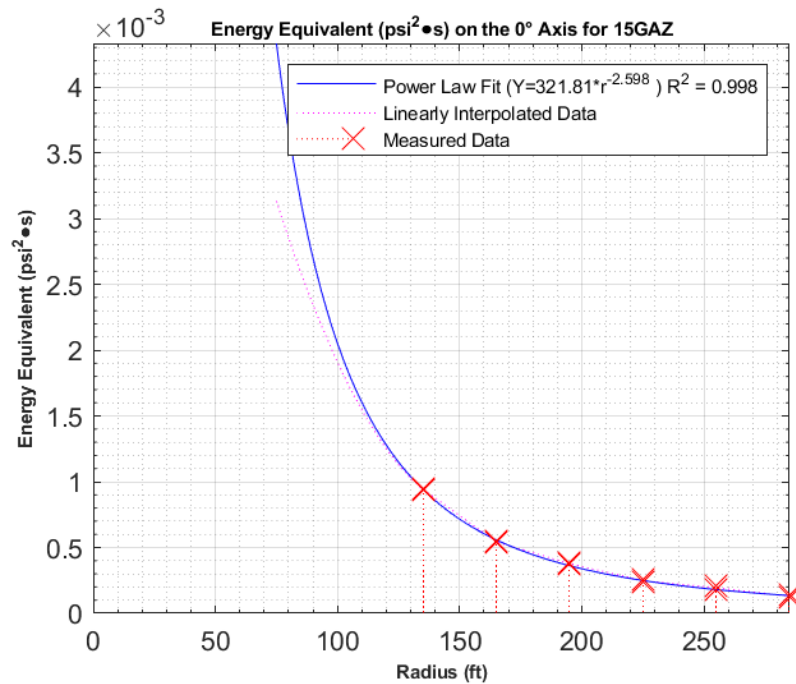


Figure 85 Slice plot along the 0° axis showing the power law fitted energy equivalent data for Gazex.

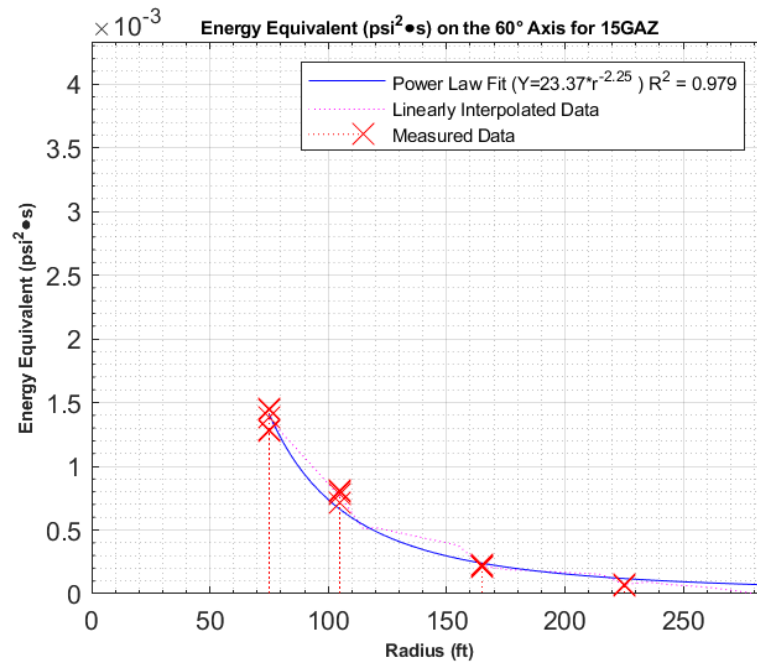


Figure 86 Slice plot along the 60° axis showing the power law fitted energy equivalent data for Gazex.

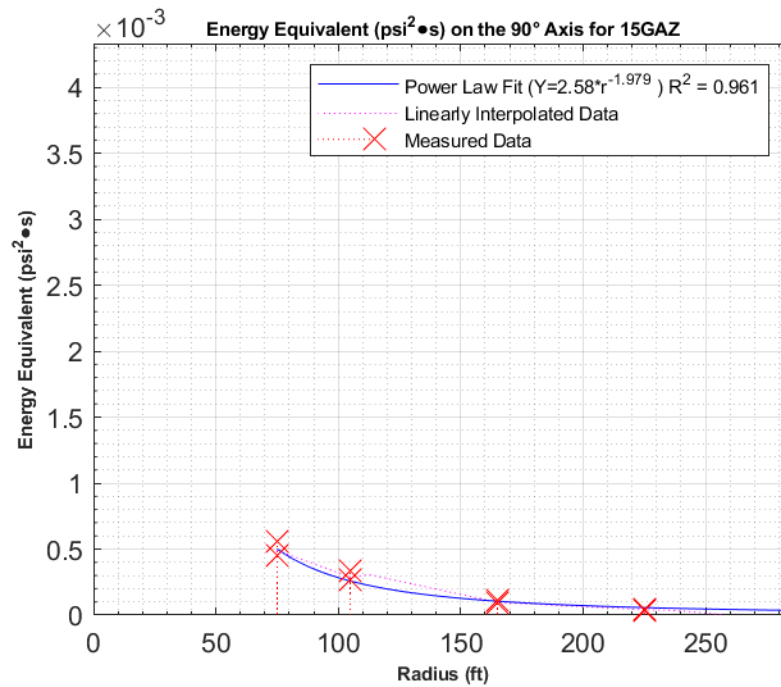


Figure 87 Slice plot along the 90° axis showing the power law fitted energy equivalent data for Gazex.

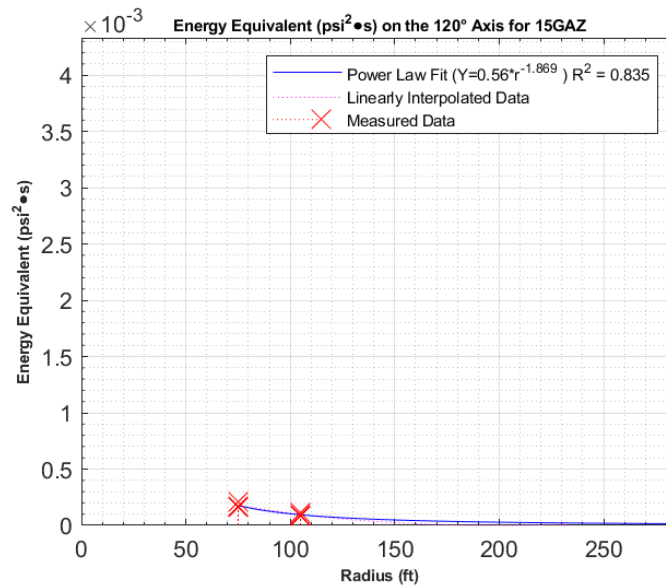


Figure 88 Slice plot along the 120° axis showing the power law fitted energy equivalent data for Gazex.

The last quantity considered for the Gazex tests was the pressure rise rate. As described above (see Section 2.2.1.2), this quantity was calculated in two ways – using a numerical derivative method, and by a direct linear approximation of the slope. Upon evaluating the results of these tests, it was observed that both methods produced very similar pressure rise rate values, but the numerical derivative method was more sensitive to noise and electronic artifacts. Accordingly, it was decided to utilize the direct linear approximation method for the results shown below. Nonetheless, the results were still noticeably impacted by electronic noise and do not have the same quality of fit as was achieved for the peak pressure and energy equivalent results, particularly along the 0° and 120° axes. As with the peak pressure and energy equivalent results, the pressure rise rate results show a distinct directional behavior (Figure 89 and Figure 90) with rapid radial decay along each axis measured (Figure 91 - Figure 94). Power law fit coefficients describing this radial decay can be found in Table 9.

Table 9 A table of the power law coefficients for pressure rise rate for Gazex tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	2.86e3	0.73	0.152
60	9.83e5	2.11	0.949
90	9.21e5	2.14	0.906
120	8.77e3	1.22	0.419

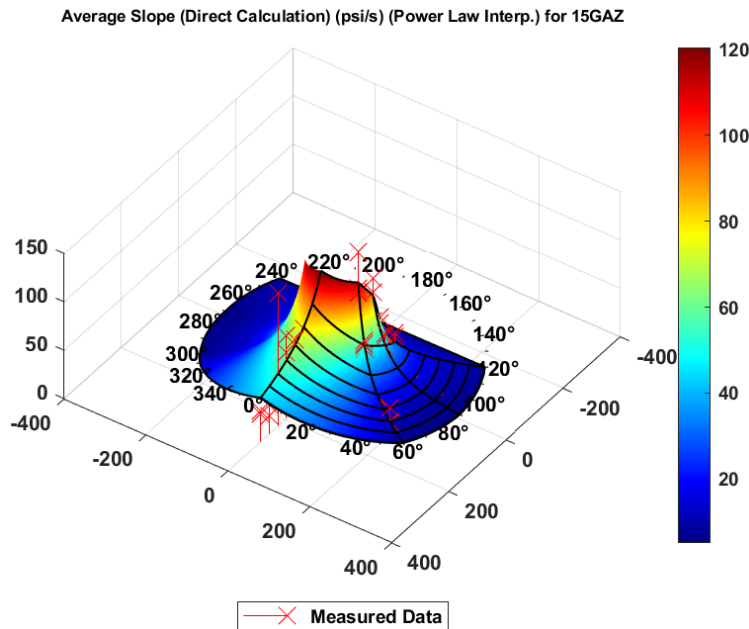


Figure 89 Surface plot of the power law fitted, pressure rise rate data from the Gazex testing

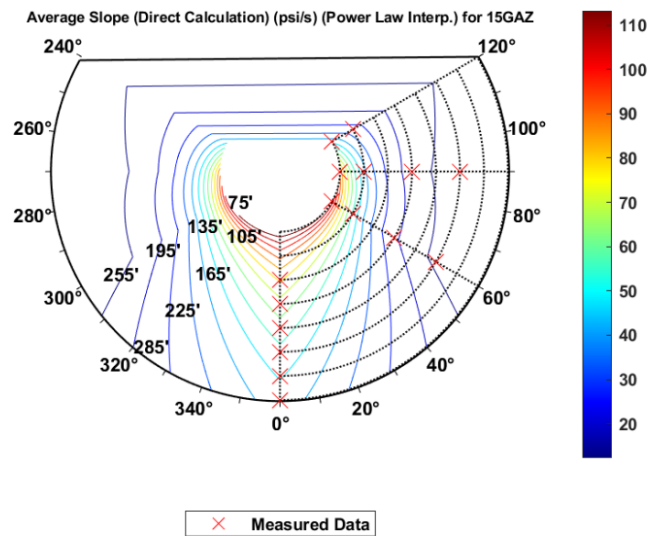


Figure 90 Contour plot of the power law fitted, pressure rise rate data from the Gazex testing.

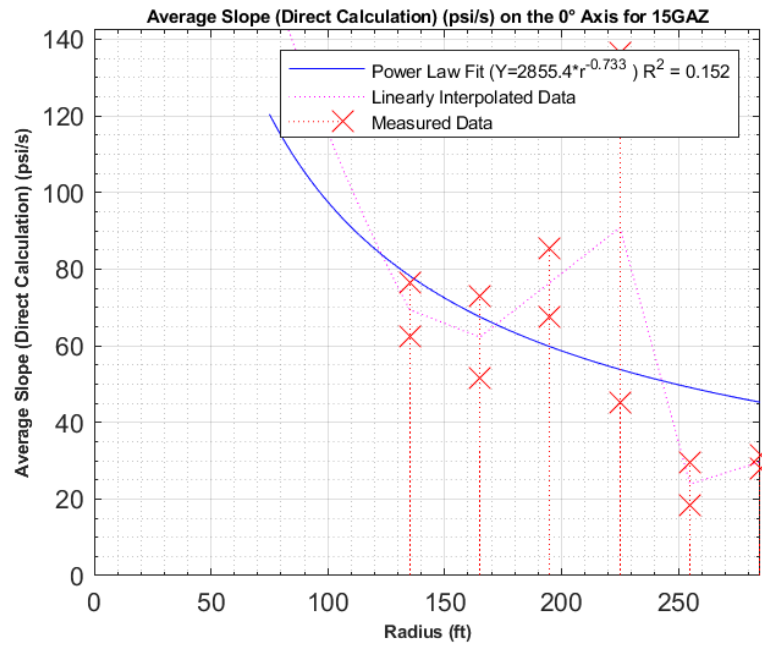


Figure 91 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for Gazex.

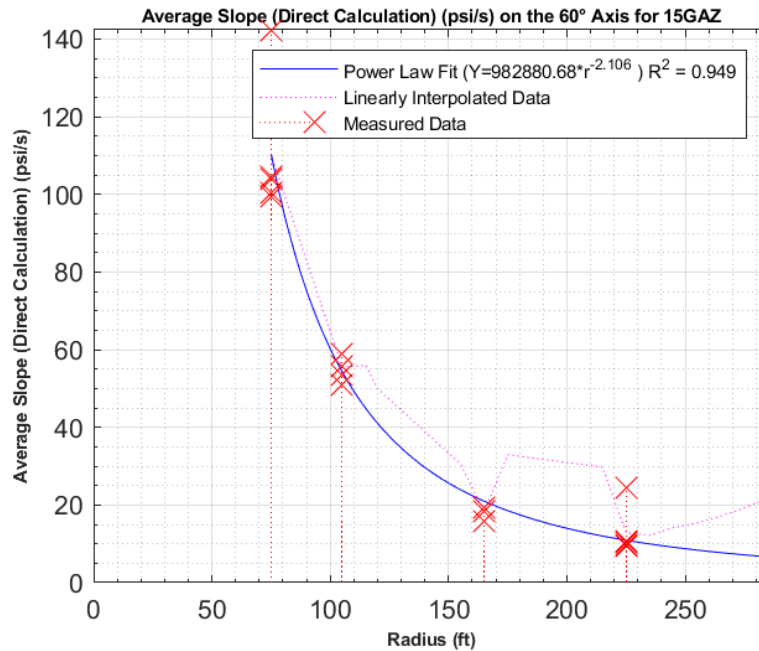


Figure 92 Slice plot along the 60° axis showing the power law fitted pressure rise rate data for Gazex.

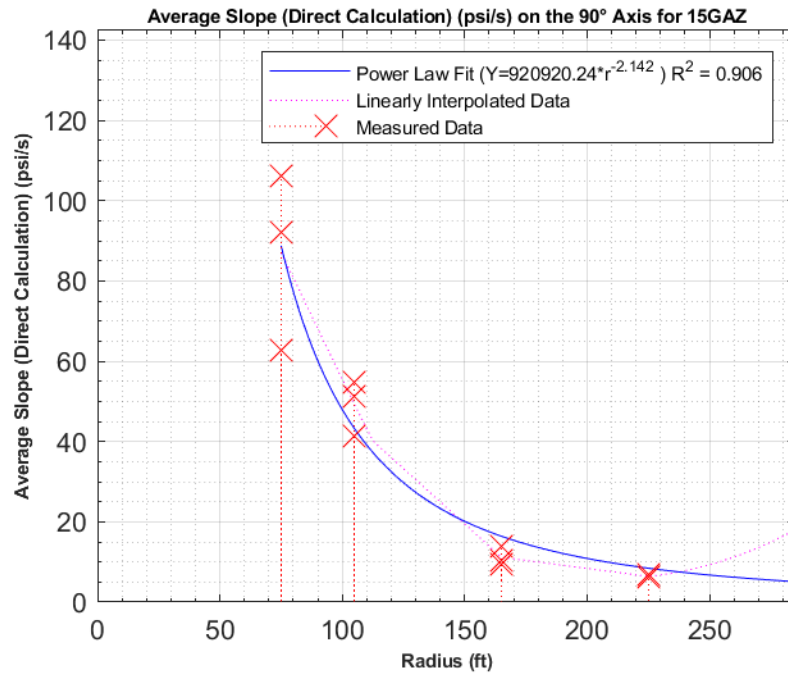


Figure 93 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for Gazex.

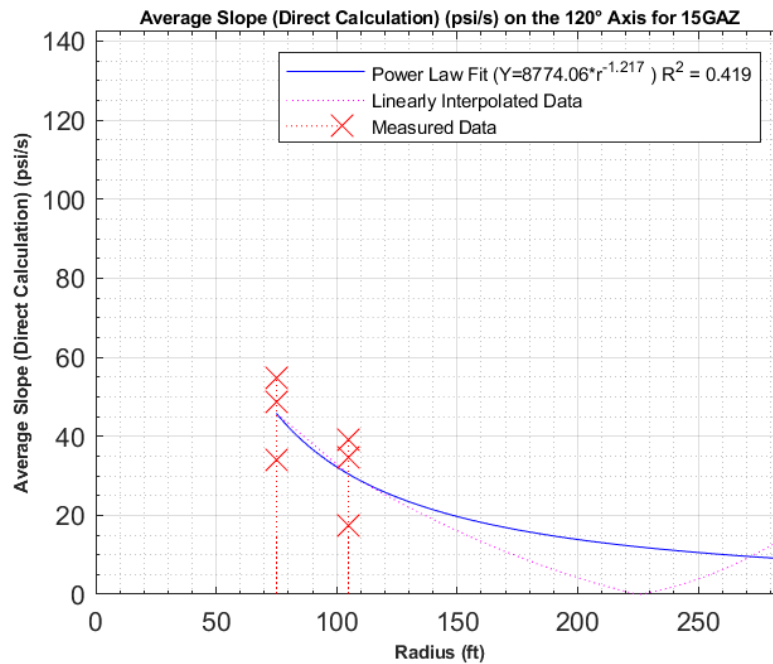


Figure 94 Slice plot along the 120° axis showing the power law fitted pressure rise rate data for Gazex.

3.2.2 O’Bellx

Peak pressures measured at the O’Bellx also provided interesting observations. Primarily, the results indicated that the O’Bellx system had a directional blast wave profile at close distances, and a surprisingly circular profile at larger distances (Figure 95 and Figure 96). More exactly, it was noted that the 0° and 30° axes had measurably higher peak pressures than the 120°, 150°, and 180° axes for distances of about 50 ft or less, but at greater distances, the peak pressures were much closer in magnitude. Another unexpected result was also observed on the 60° and 90° axes. Namely, it was found that the measured peak pressures on these axes were higher along the 60° and 90° axes than along the 0° and 30° axes at a radial distance of 70 ft. This is believed to be the combination of unintended terrain effects, and the unfortunate shortcoming of only being able to survey two distances on these axes due to limited snow cover – both of which will be discussed in greater detail in the following chapter. This strange behavior is best summarized by the calculated radial location of the reference peak pressure of 1 kPa or 0.145 psi. From the power law fits (Table 10), it was determined that this reference peak pressure would be reached at a distance of about 100-115 ft on the 0°, 30°, 120°, 150°, and 180° axes, and a surprising 188 and 245 ft on the 60° and 90° axes, respectively (Figure 97 - Figure 103).

Table 10 A table of the power law coefficients for the peak pressure data along each of the measured axes for O’Bellx tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	297	1.61	0.995
30	804	1.85	1.000
60	21	0.95	0.989
90	6.89	0.70	0.976
120	77	1.37	1.000
150	23	1.08	0.996
180	40	1.23	1.000

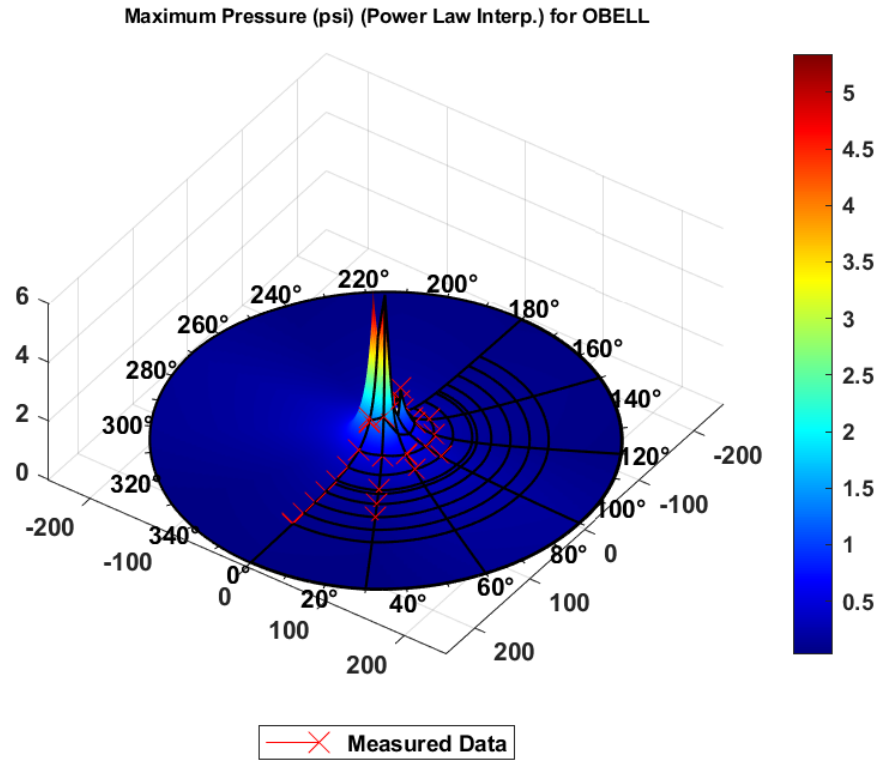


Figure 95 Surface plot of the power law fitted peak pressure data from the O'Bellx testing

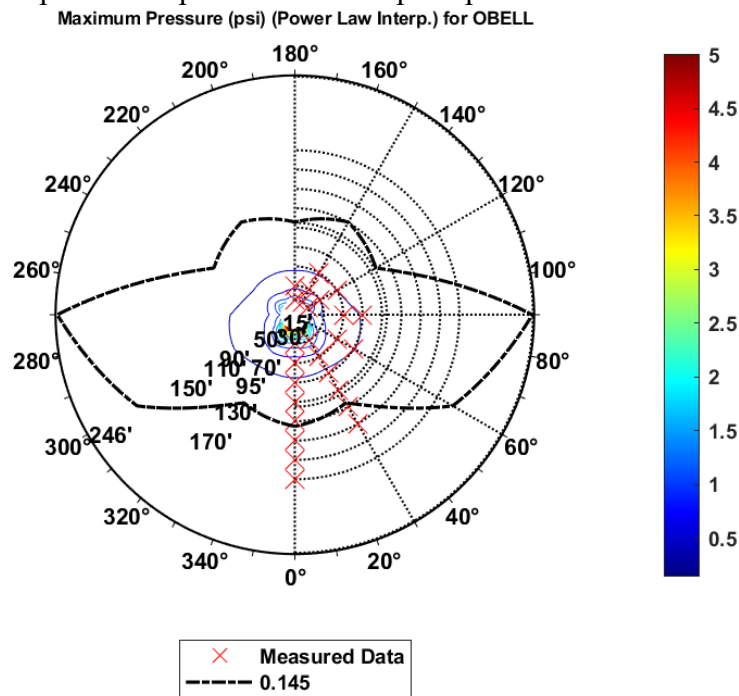


Figure 96 Contour plot of the power law fitted peak pressure data from the O'Bellx testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

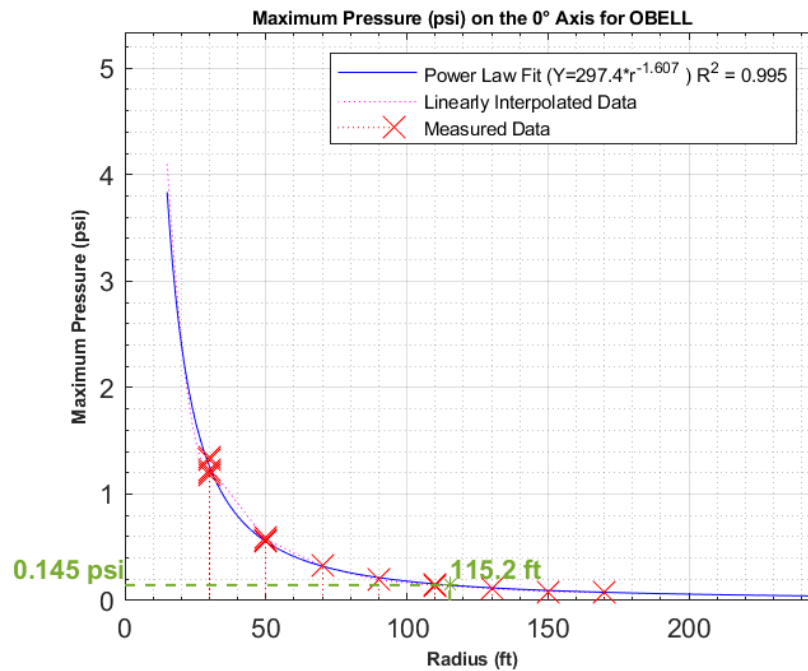


Figure 97 Slice plot along the 0° axis showing the power law fitted peak pressure data for O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

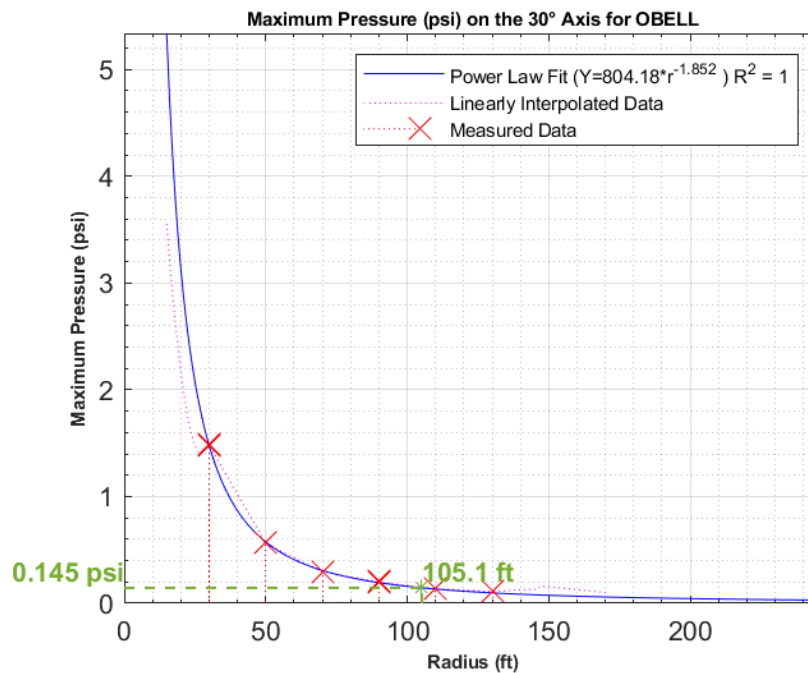


Figure 98 Slice plot along the 30° axis showing the power law fitted peak pressure data for O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

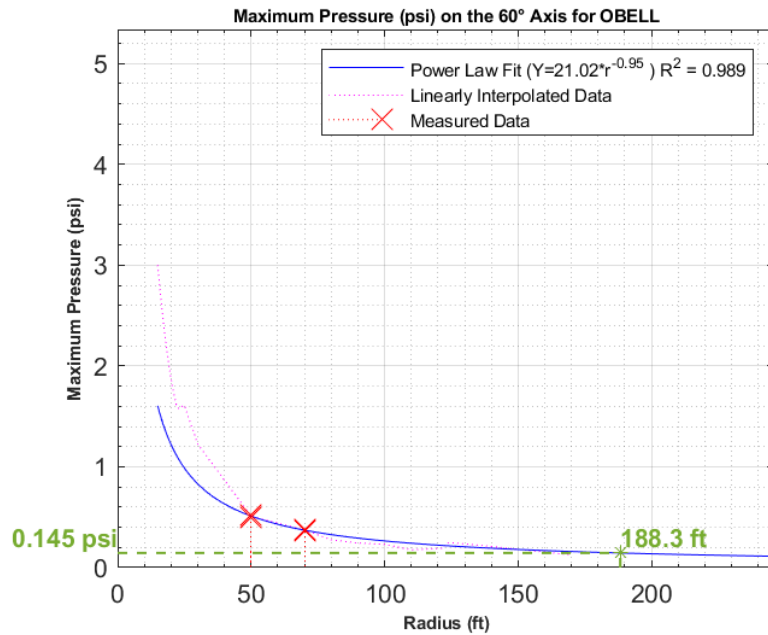


Figure 99 Slice plot along the 60° axis showing the power law fitted peak pressure data for O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

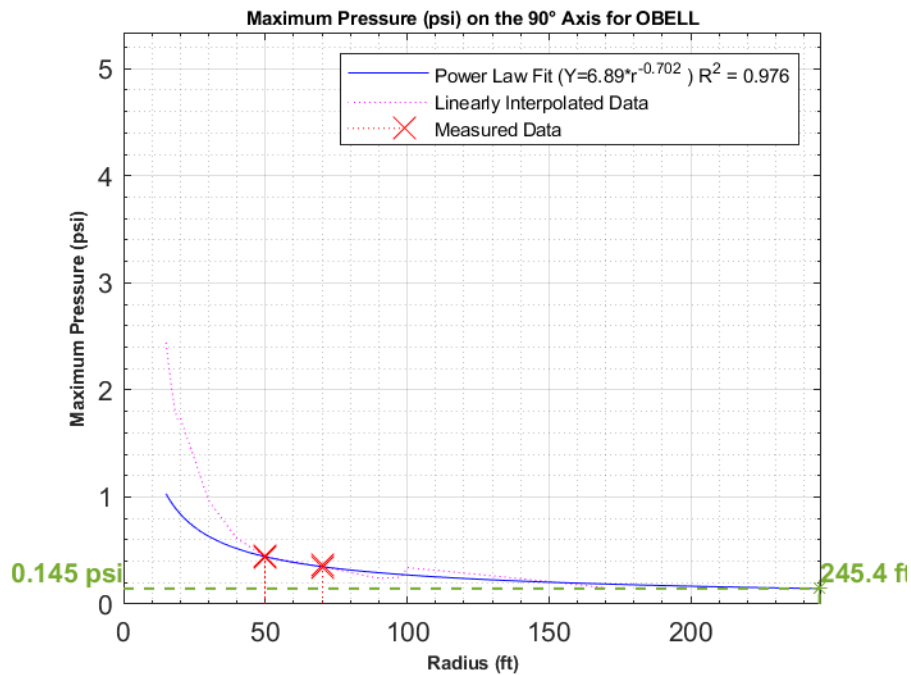


Figure 100 Slice plot along the 90° axis showing the power law fitted peak pressure data for O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

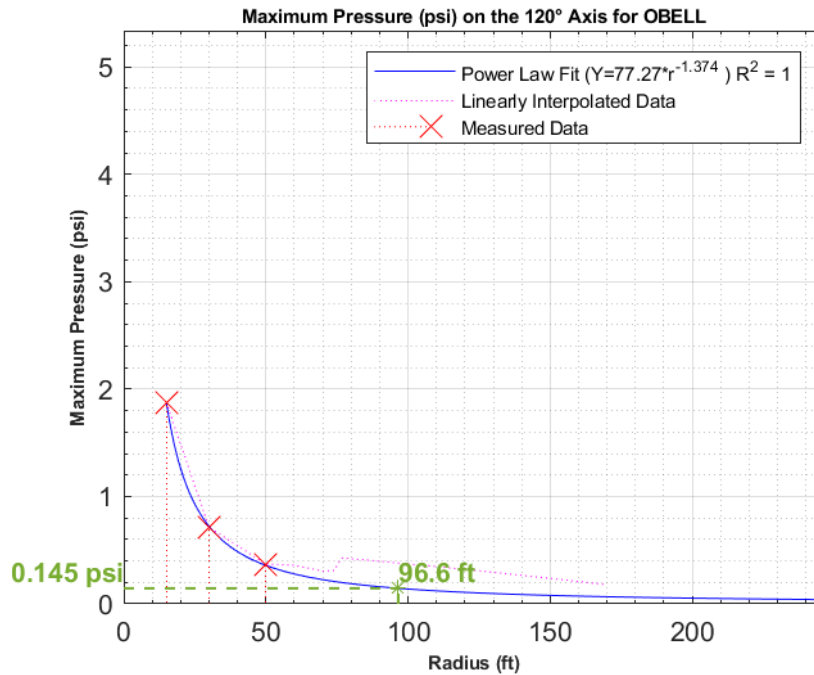


Figure 101 Slice plot along the 120° axis showing the power law fitted peak pressure data for O’Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

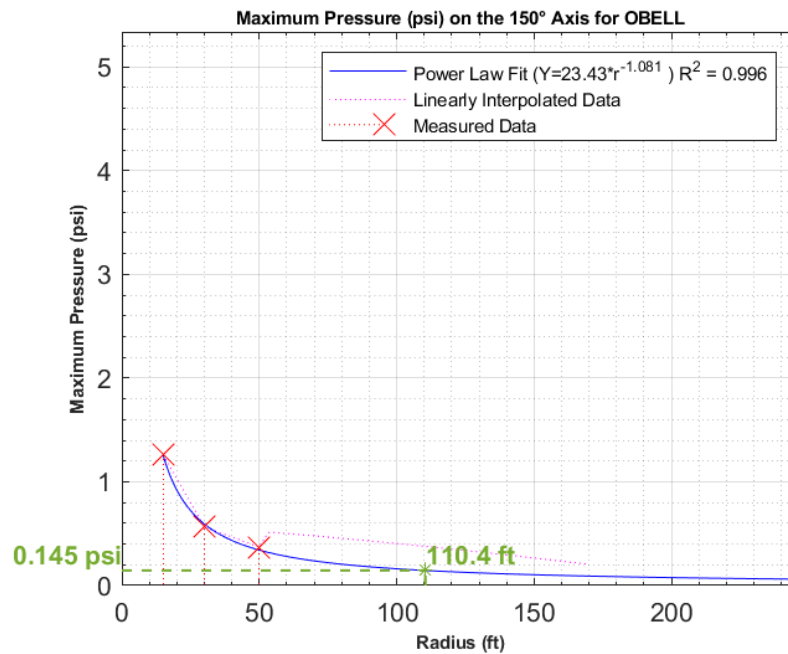


Figure 102 Slice plot along the 150° axis showing the power law fitted peak pressure data for O’Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

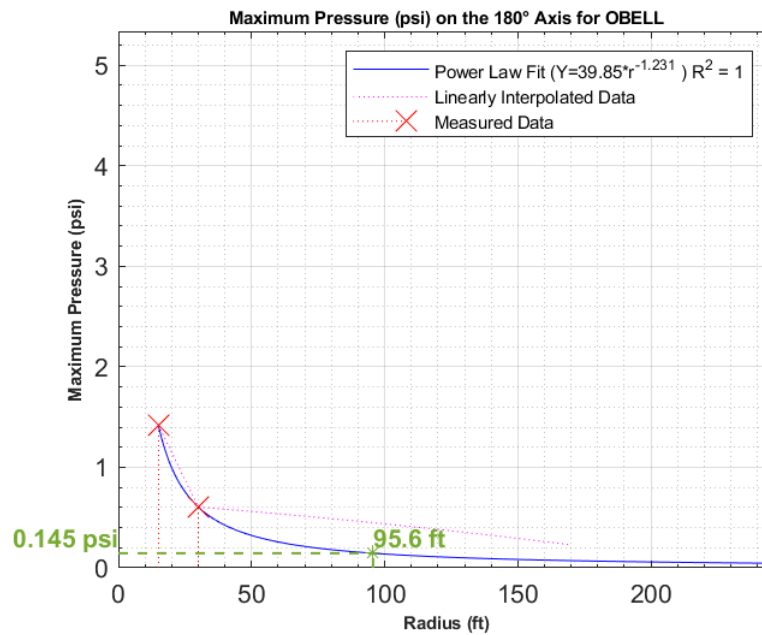


Figure 103 Slice plot along the 180° axis showing the power law fitted peak pressure data for O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

The energy equivalent results from the O'Bellx testing yielded similar observations and challenges as the peak pressure data. Evaluation of the energy equivalent results showed a directional profile for distances of about 50 ft or less, and a circular profile at larger distances (Figure 104 and Figure 105). Energy equivalent was higher along the 0° and 30° axes for these smaller radial distances but was about equal along all axes for greater radial distances (Figure 106 - Figure 112). Energy equivalent decayed very strongly with radial distance along all axes with the exception of the 60° and 90° axes which displayed the same behavior described for peak pressure results. In fact, the calculated power law for the 90° axis indicated a nonsensical positive power law exponent coefficient, indicated by an *, since the calculated energy equivalent at 70 ft was slightly greater than at 50 ft. The power law coefficients can be found in Table 11.

Table 11 A table of the power law coefficients for the energy equivalent data along each of the measured axes for O'Belx tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	14	2.44	0.994
30	34	2.63	0.999
60	0.31	1.46	0.997
90	0	-0.23*	0.844
120	2.31	2.22	0.999
150	0.79	2.00	0.996
180	1.49	2.22	1.000

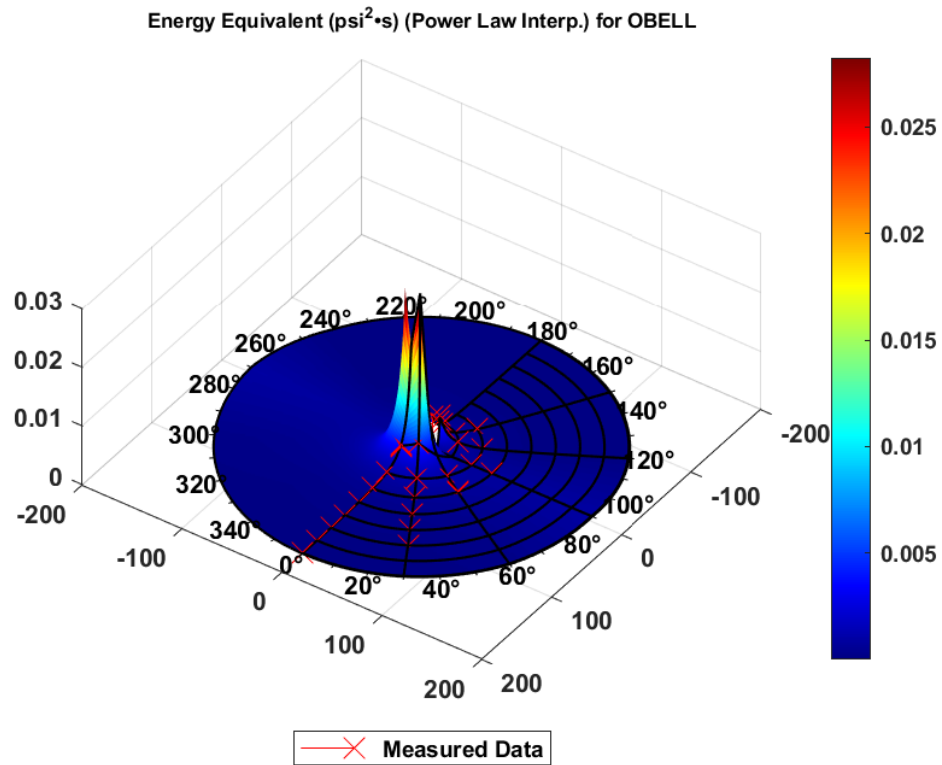


Figure 104 Surface plot of the power law fitted energy equivalent data from the O'Belx testing

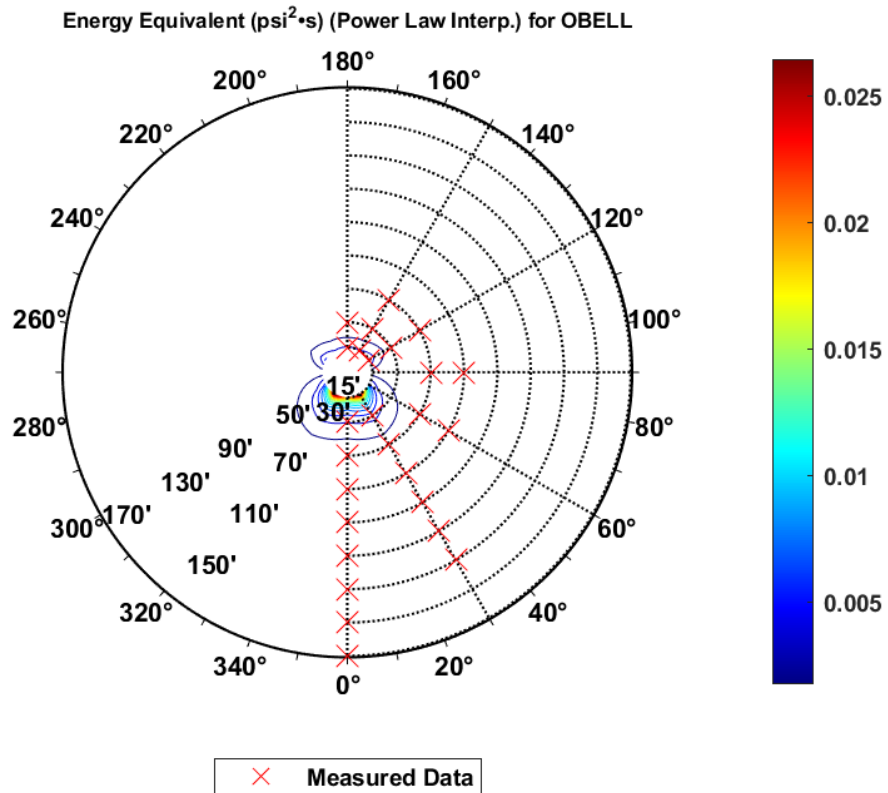


Figure 105 Contour plot of the power law fitted energy equivalent data from the O'Bellex testing.

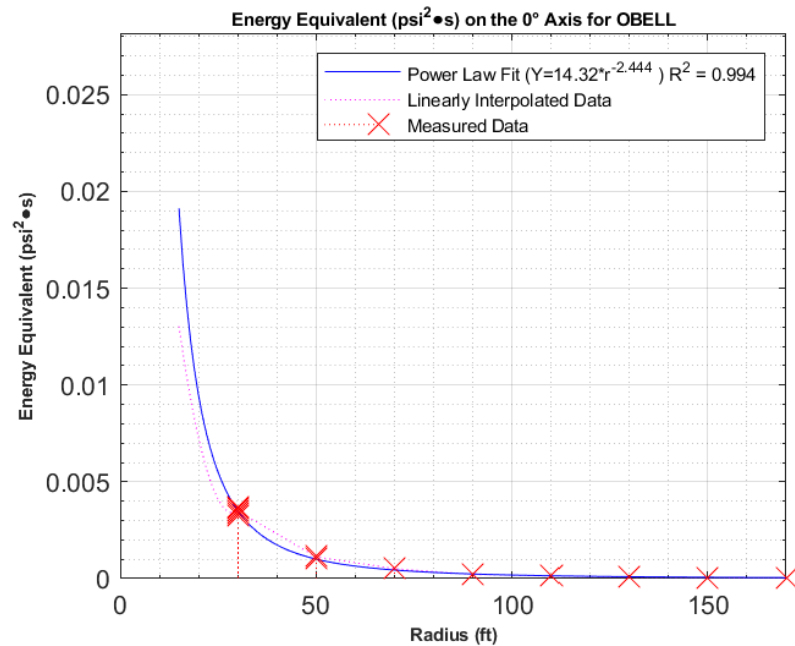


Figure 106 Slice plot along the 0° axis showing the power law fitted energy equivalent data for O'Bellex.

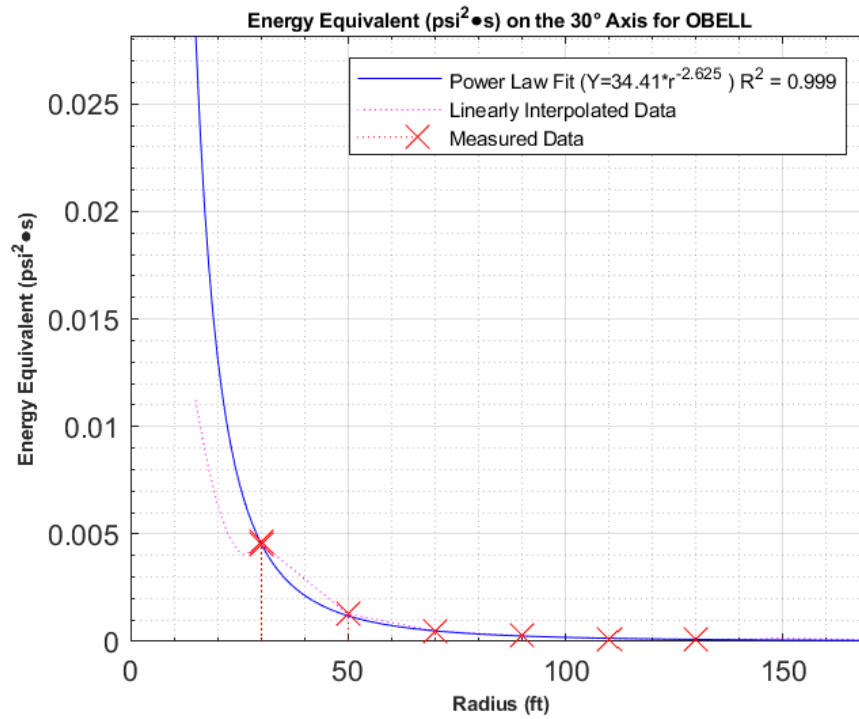


Figure 107 Slice plot along the 30° axis showing the power law fitted energy equivalent data for O'Bellx.

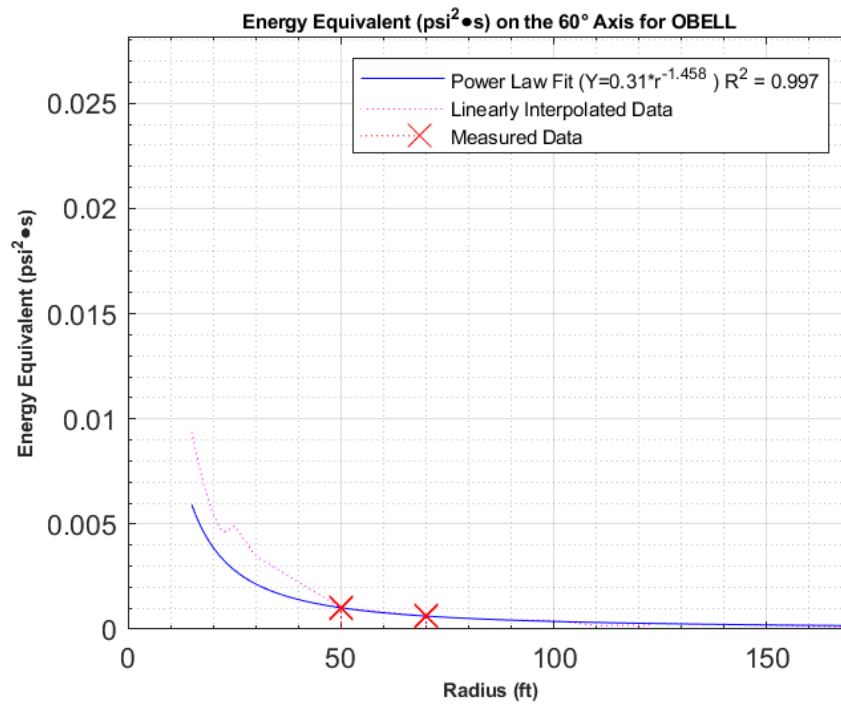


Figure 108 Slice plot along the 60° axis showing the power law fitted energy equivalent data for O'Bellx.

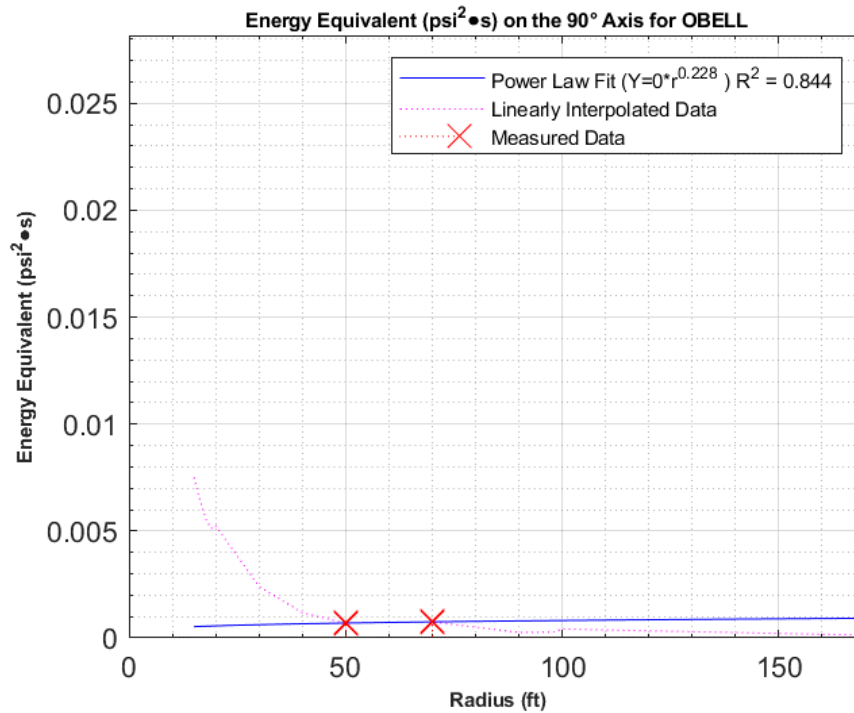


Figure 109 Slice plot along the 90° axis showing the power law fitted energy equivalent data for O'Bellx. Note the nonsensical positive power law exponent.

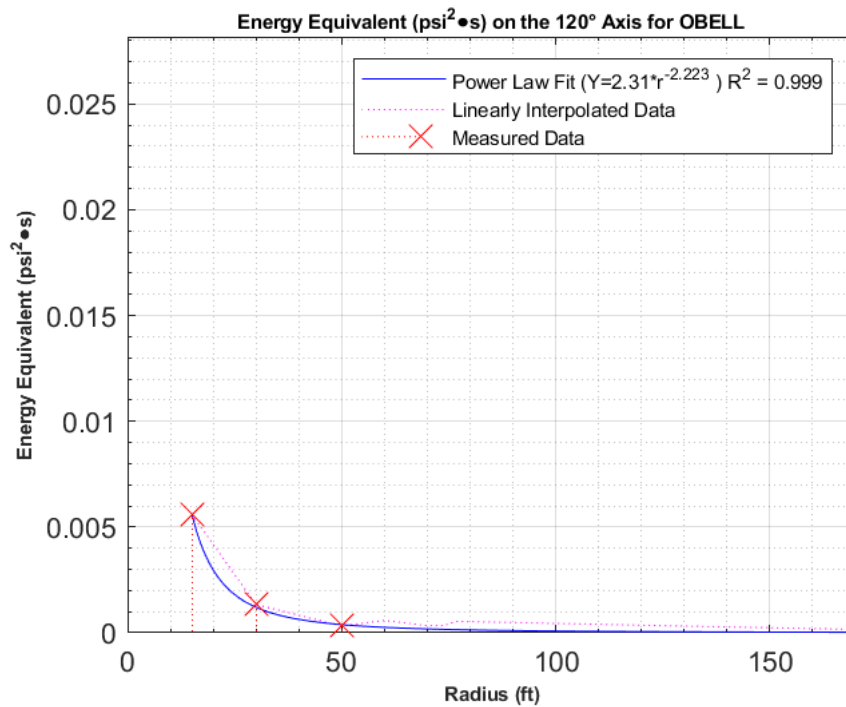


Figure 110 Slice plot along the 120° axis showing the power law fitted energy equivalent data for O'Bellx.

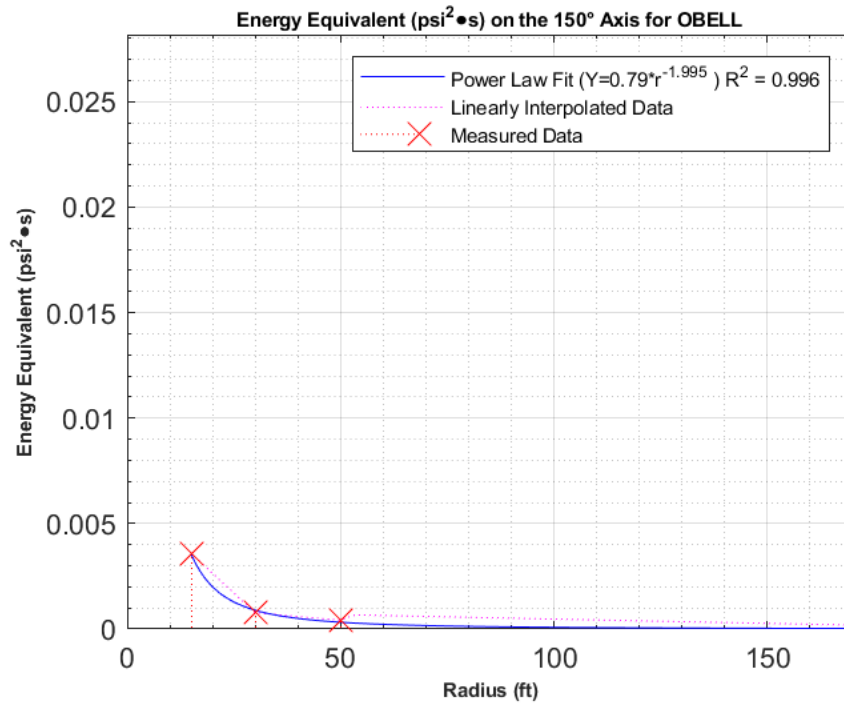


Figure 111 Slice plot along the 150° axis showing the power law fitted energy equivalent data for O'Bellx.

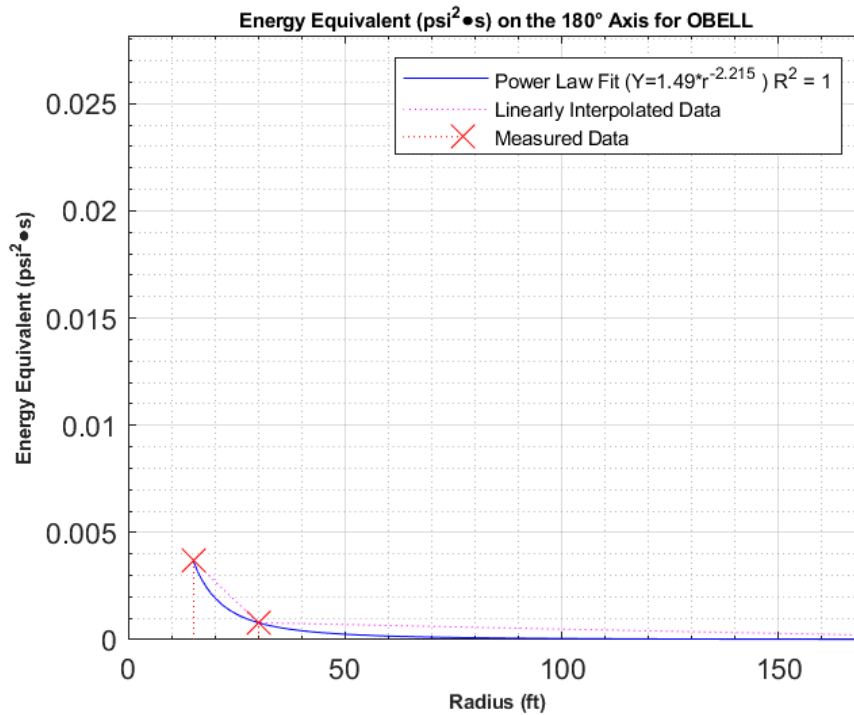


Figure 112 Slice plot along the 180° axis showing the power law fitted energy equivalent data for O'Bellx.

As was done for Gazex pressure rise rate results, the direct linear approximation method was utilized to calculate the O’Bellx pressure rise rates. These results were, again, sensitive to electronic noise and may have also been affected by unintended terrain features as discussed above. Accordingly, the pressure rise rate results again do not have the same quality of fit as was achieved for the peak pressure and energy equivalent results. The pressure rise rate results seem to indicate a directional behavior at close radial distances focused along the 0° and 30° axes, but the lack of clarity along other axes make it difficult to identify the overall spatial behavior of the pressure rise rate for the O’Bellx device (Figure 113 and Figure 114). Power law fits for each axis (Table 12) show a strong decay with radial distance on the 0° and 30° axes, and unclear behavior on the remaining axes (Figure 115 - Figure 121).

Table 12 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for O’Bellx tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	3.18e5	1.68	0.920
30	1.93e6	2.26	1.000
60	1.10e3	0.32	0.920
90	3.87e4	1.05	0.640
120	537	-0.13*	0.313
150	1.49e3	0.33	0.674
180	735	-0.06*	1.000

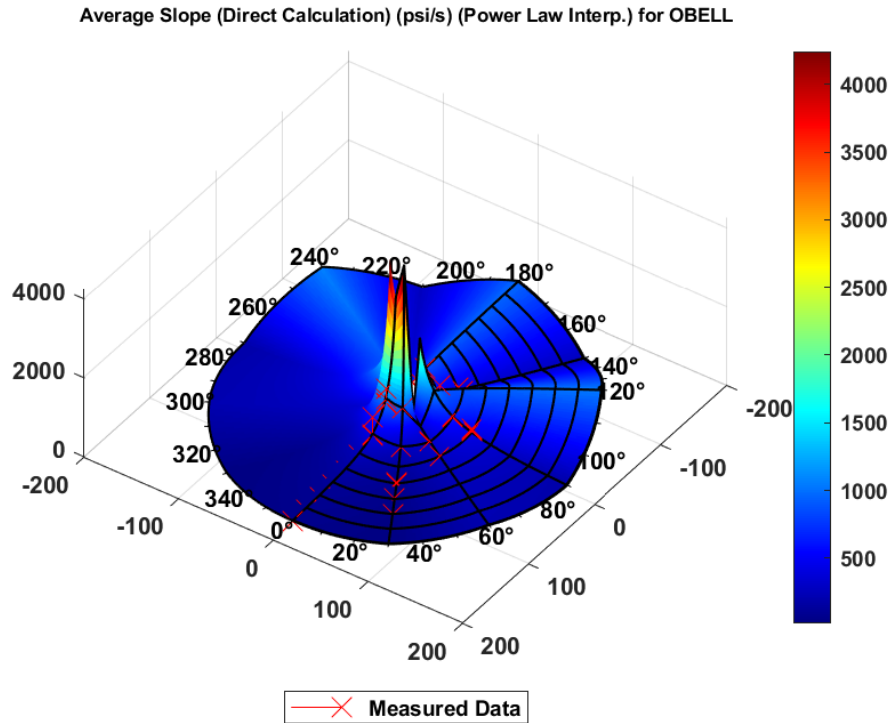


Figure 113 Surface plot of the power law fitted pressure rise rate data from the O'Bellex testing

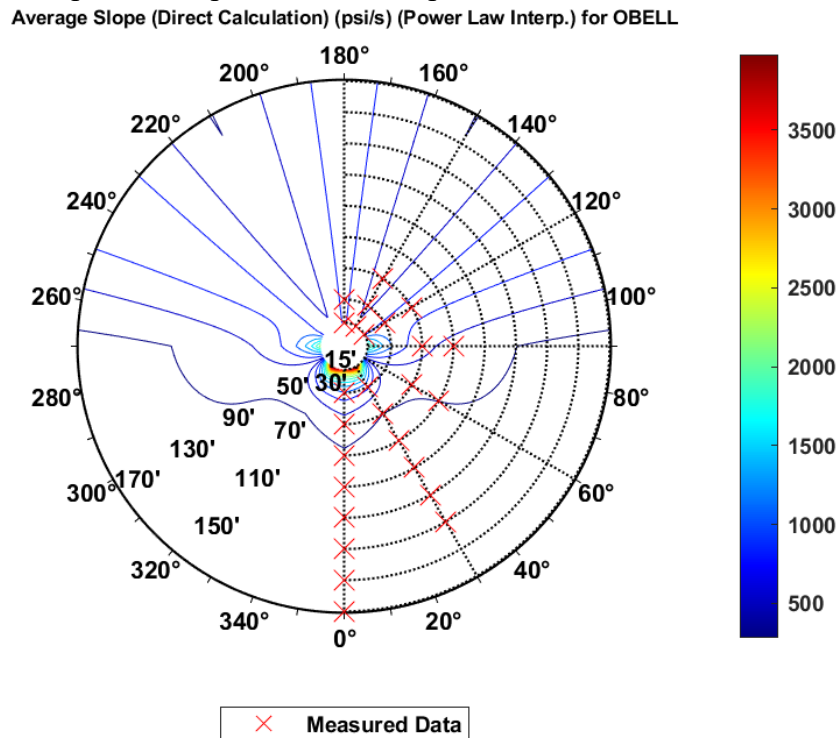


Figure 114 Contour plot of the power law fitted pressure rise rate data from the O'Bellex testing.

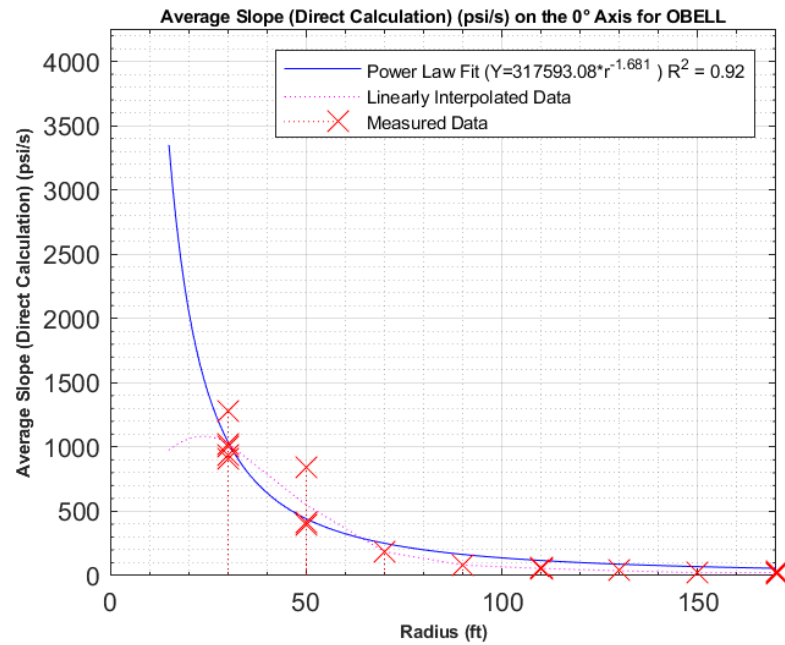


Figure 115 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for O'Bellx.

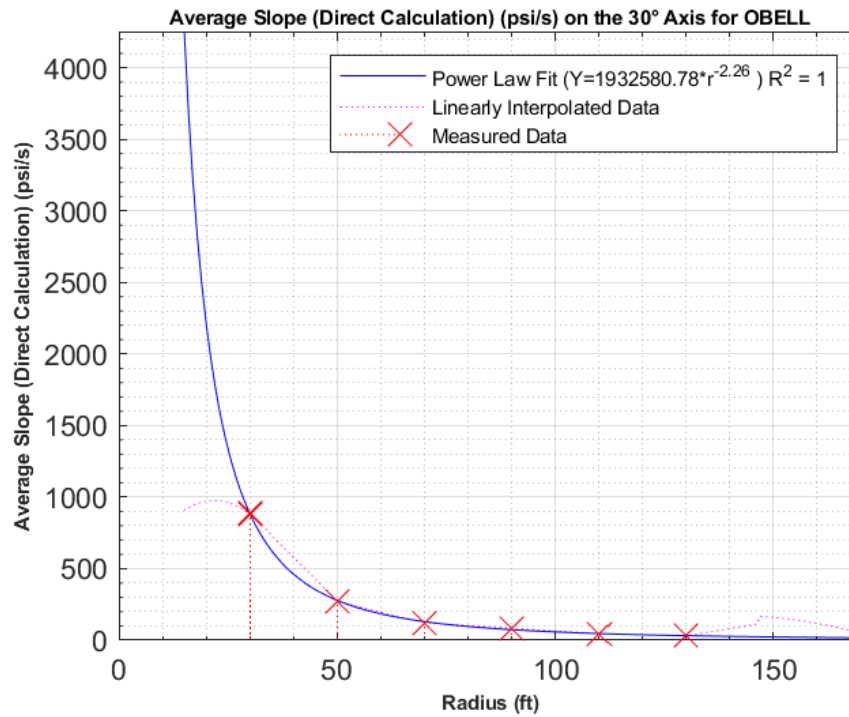


Figure 116 Slice plot along the 30° axis showing the power law fitted pressure rise rate data for O'Bellx.

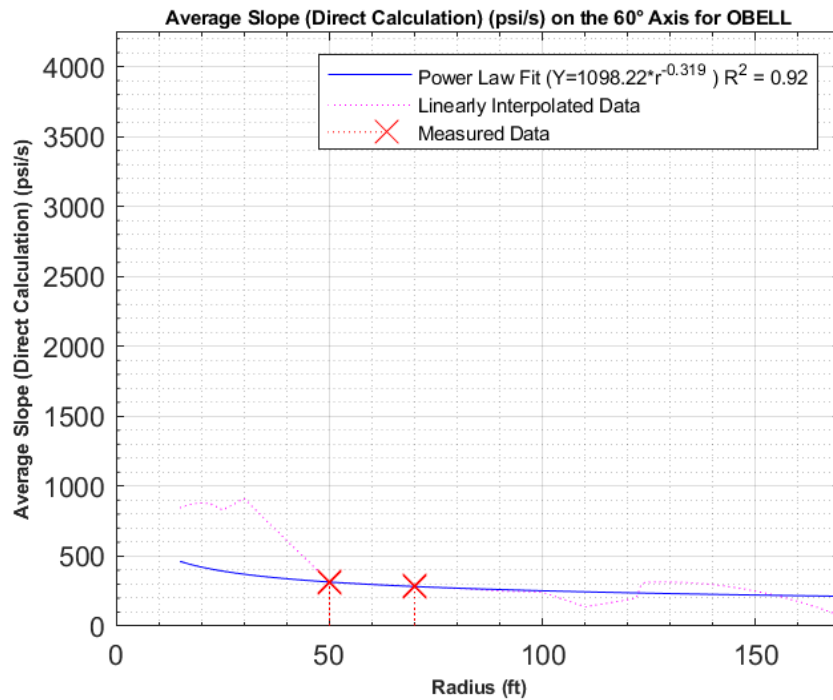


Figure 117 Slice plot along the 60° axis showing the power law fitted pressure rise rate data for O'Bellx.

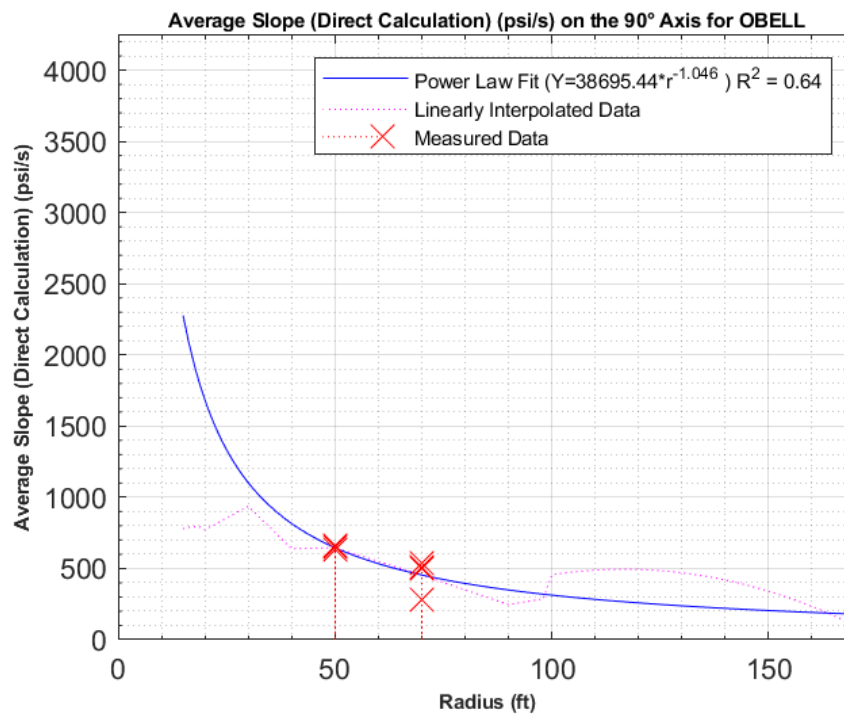


Figure 118 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for O'Bellx.

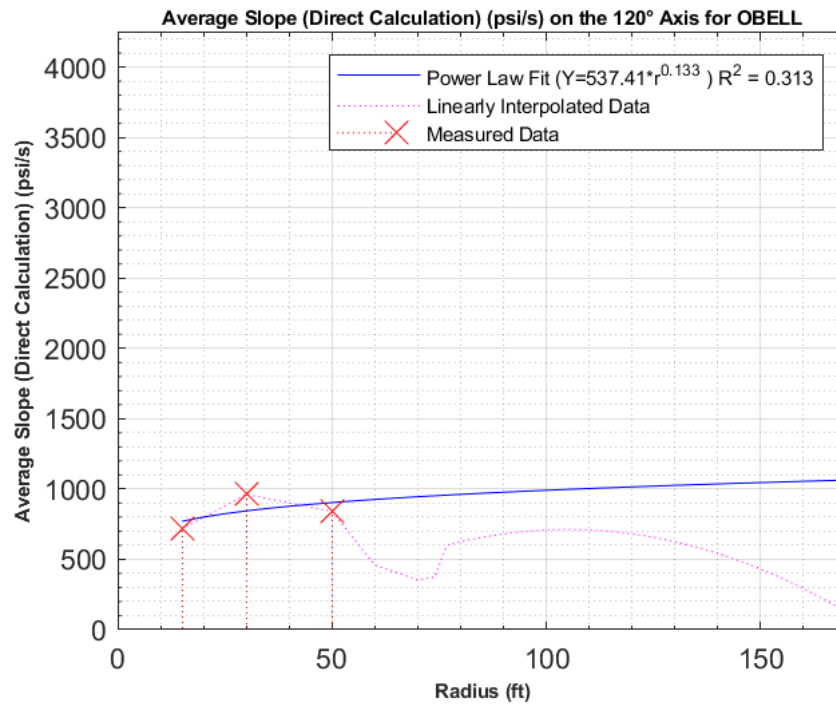


Figure 119 Slice plot along the 120° axis showing the power law fitted pressure rise rate data for O'Bellx. Note the nonsensical positive power law exponent.

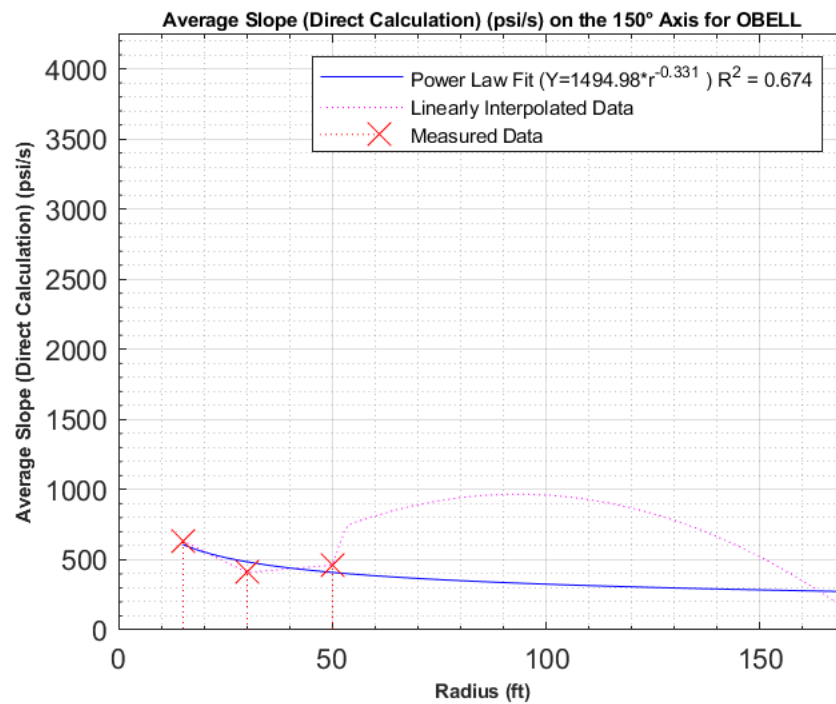


Figure 120 Slice plot along the 150° axis showing the power law fitted pressure rise rate data for O'Bellx.

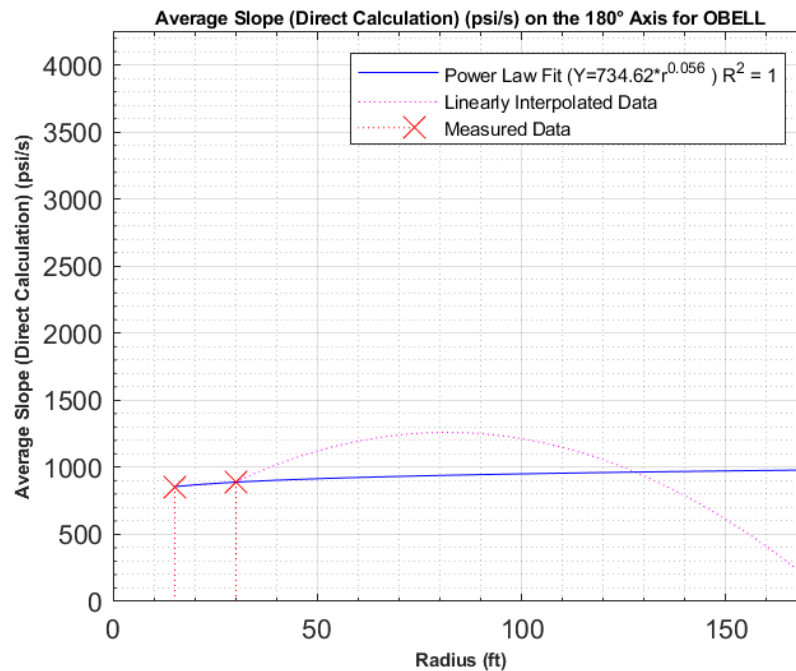


Figure 121 Slice plot along the 180° axis showing the power law fitted pressure rise rate data for O'Belx. Note the nonsensical positive power law exponent.

3.2.3 Flat-Field Gel Charge Wyssen Tower

The pressure data collected from the flat-field testing of the traditional gel emulsion Wyssen Tower charge offered insight into the performance and behavior of the RAC device. Beginning with the peak pressure results, it was found that the charge had a very circular blast profile (i.e., the blast wave was symmetric and behaved similarly along all measured axes) (Figure 122 and Figure 123). In particular, the power laws fit along each measured axis showed similarity in the power law exponent coefficient with the average being -1.41 (Table 13). Additionally, the reference peak pressure of 0.145 psi or 1 kPa was located at radial distances between 234 - 257 ft for all axes (Figure 124 - Figure 128). Lastly, it was shown that the separate charges utilized to carry out this testing produced repeatable results based on the consistency of the measurements taken on the 45° axis which remained in place for all tests (Figure 125).

Table 13 A table of the power law coefficients for the peak pressure data along each of the measured axes for flat-field gel emulsion Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	273	1.38	0.981
45	241	1.35	0.993
90	872	1.59	0.998
135	362	1.41	0.995
180	224	1.34	0.990

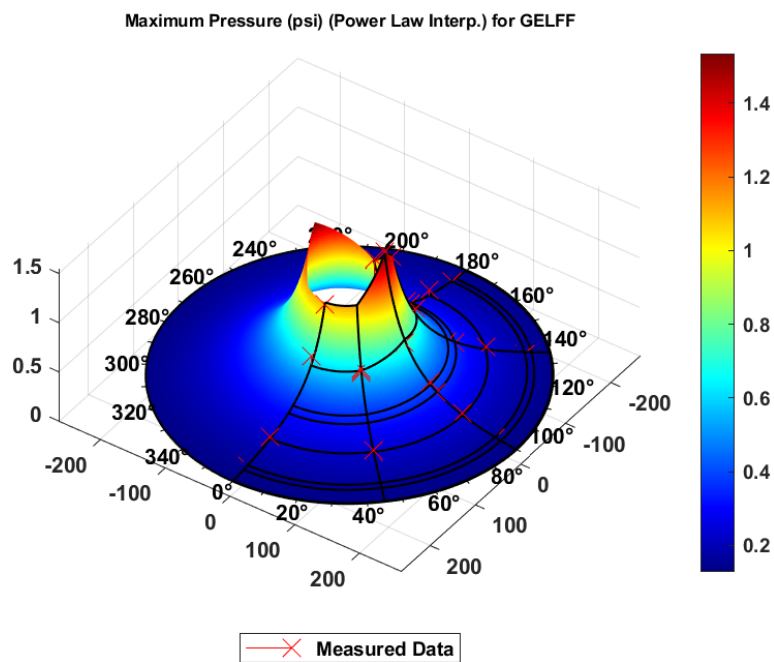


Figure 122 Surface plot of the power law fitted peak pressure data from the flat-field gel emulsion Wyssen Tower charge testing

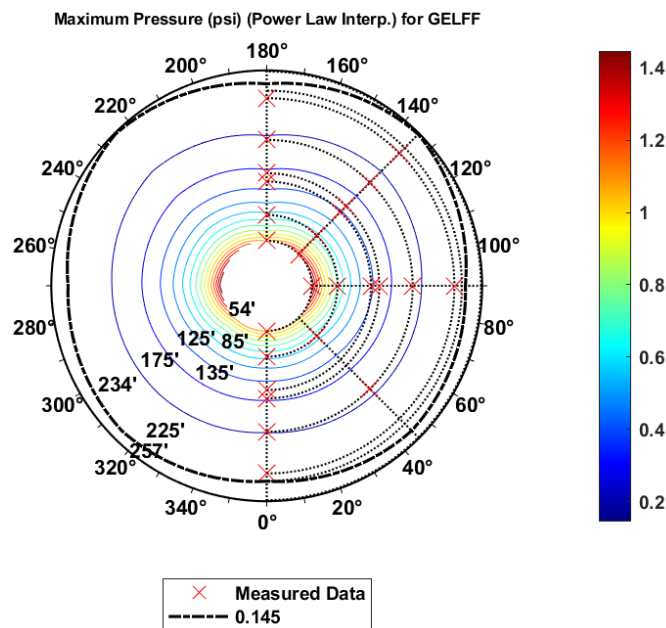


Figure 123 Contour plot of the power law fitted peak pressure data from the flat-field gel emulsion Wyssen Tower charge testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

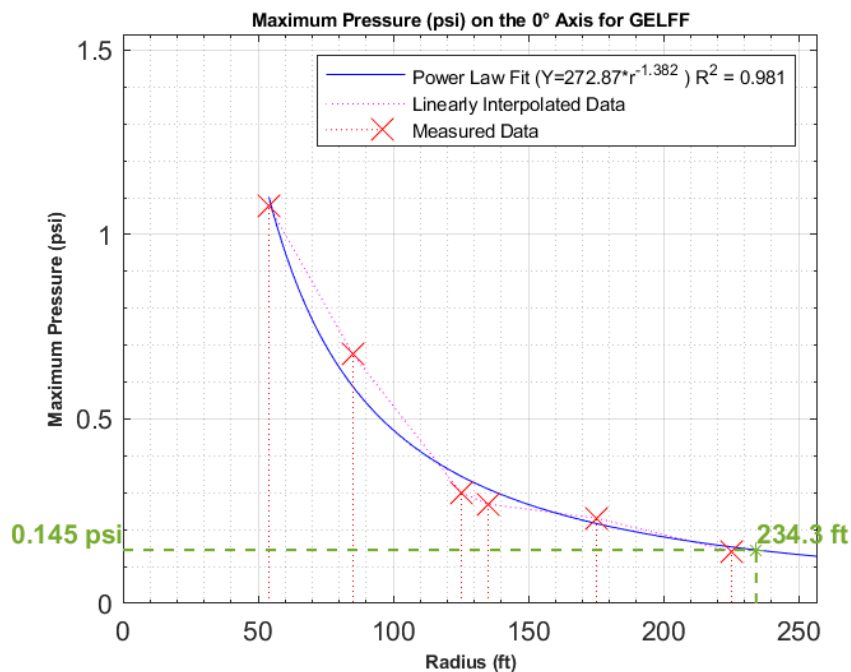


Figure 124 Slice plot along the 0° axis showing the power law fitted peak pressure data for flat-field gel emulsion Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

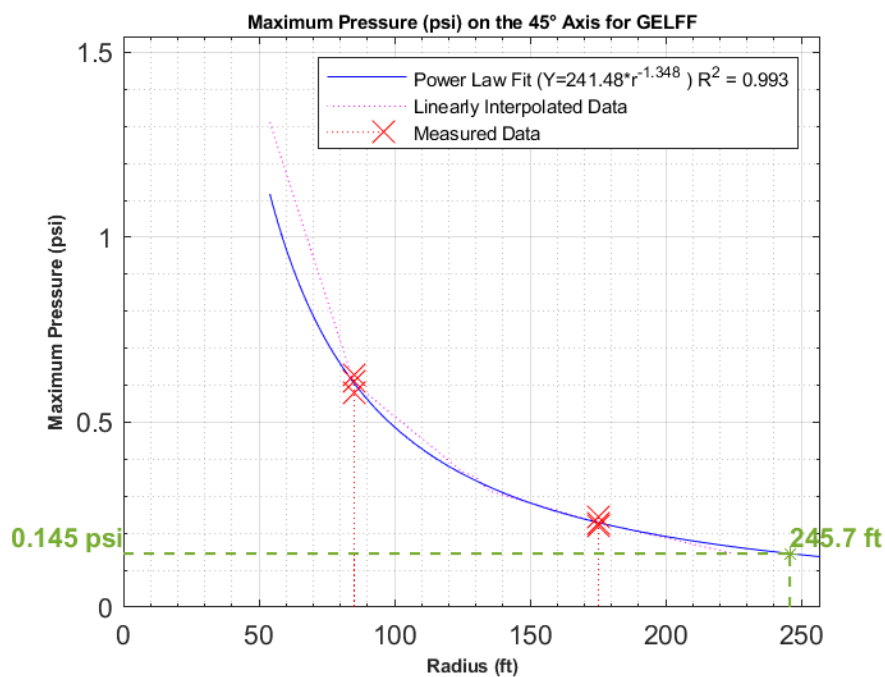


Figure 125 Slice plot along the 45° axis showing the power law fitted peak pressure data for flat-field gel emulsion Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

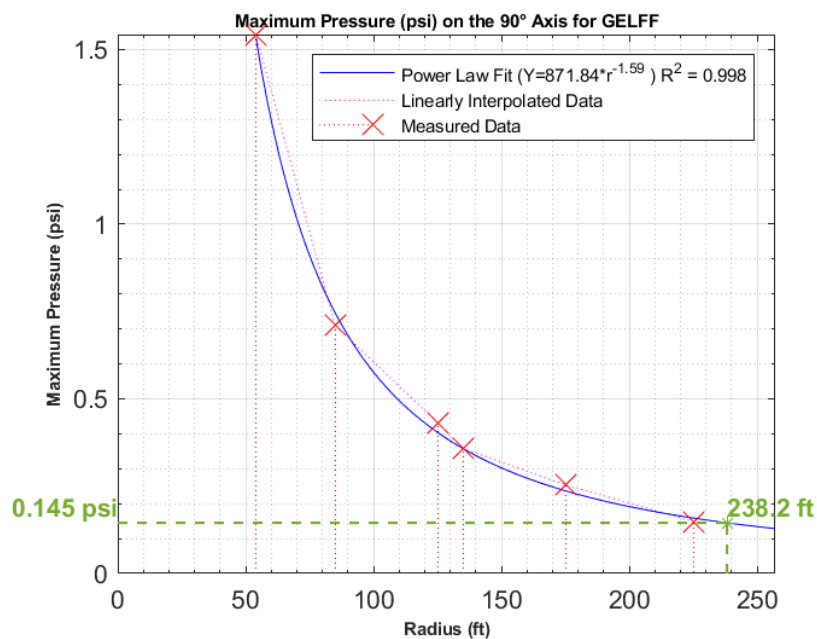


Figure 126 Slice plot along the 90° axis showing the power law fitted peak pressure data for flat-field gel emulsion Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

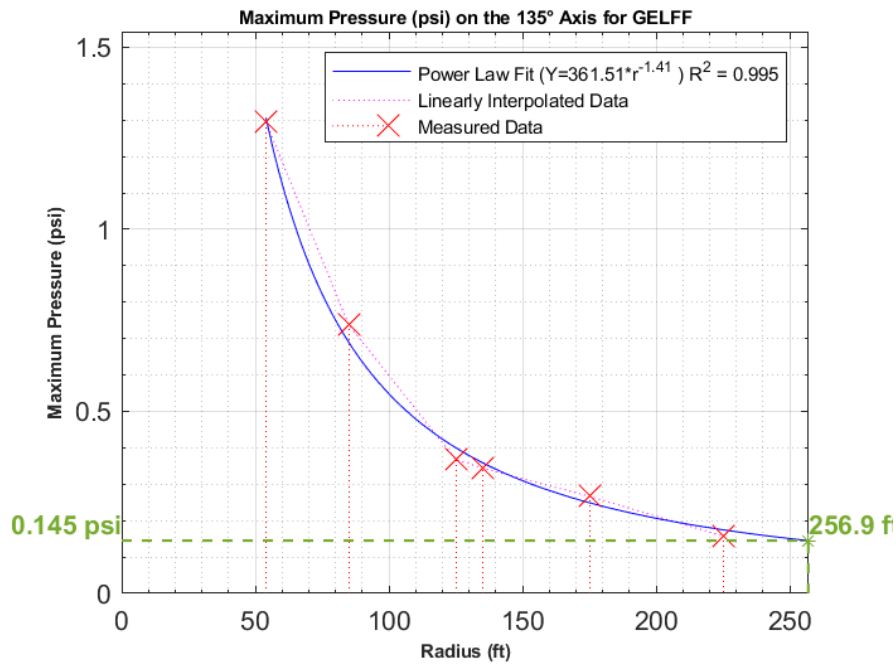


Figure 127 Slice plot along the 135° axis showing the power law fitted peak pressure data for flat-field gel emulsion Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

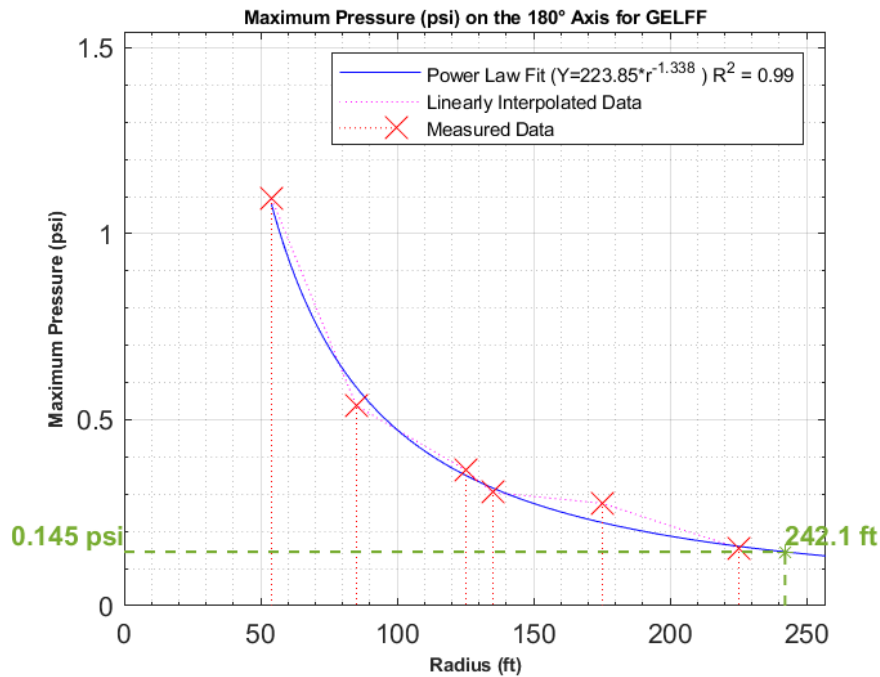


Figure 128 Slice plot along the 180° axis showing the power law fitted peak pressure data for flat-field gel emulsion Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

The energy equivalent results also demonstrated a circular/symmetric profile for the gel emulsion charge (Figure 129 and Figure 130). One notable difference between the energy equivalent and peak pressure results was that the energy equivalent decayed more rapidly with radial distance than peak pressure. Power law fitting for energy equivalent results along each axis indicated an average exponent of -2.14 (Table 14). The energy equivalent and radial distance relationship was very similar along each axis, with the 90° axis having slightly higher values at smaller radial distances (Figure 131 - Figure 135).

Table 14 A table of the power law coefficients for the energy equivalent data along each of the measured axes for flat-field gel emulsion Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	16.4	2.08	0.967
45	11.6	2.00	0.998
90	93.5	2.39	0.999
135	46.2	2.26	0.998
180	10.5	1.99	0.997

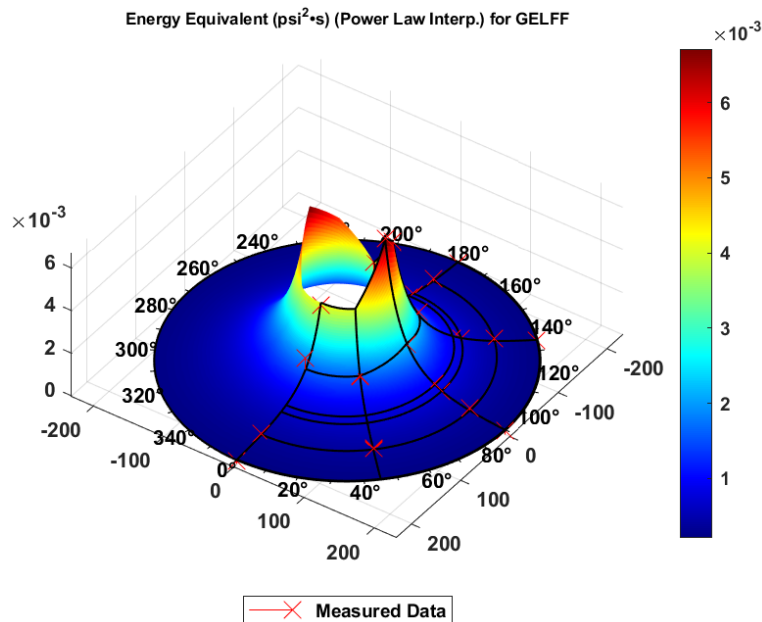


Figure 129 Surface plot of the power law fitted energy equivalent data from the flat-field gel emulsion Wyssen Tower charge testing

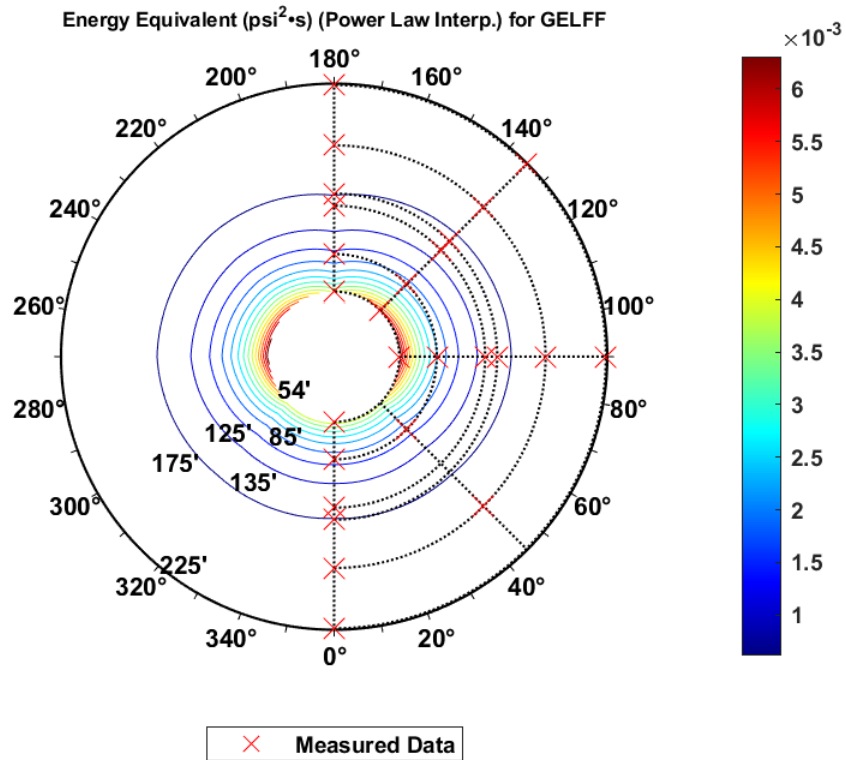


Figure 130 Contour plot of the power law fitted energy equivalent data from the flat-field gel emulsion Wyssen Tower charge testing.

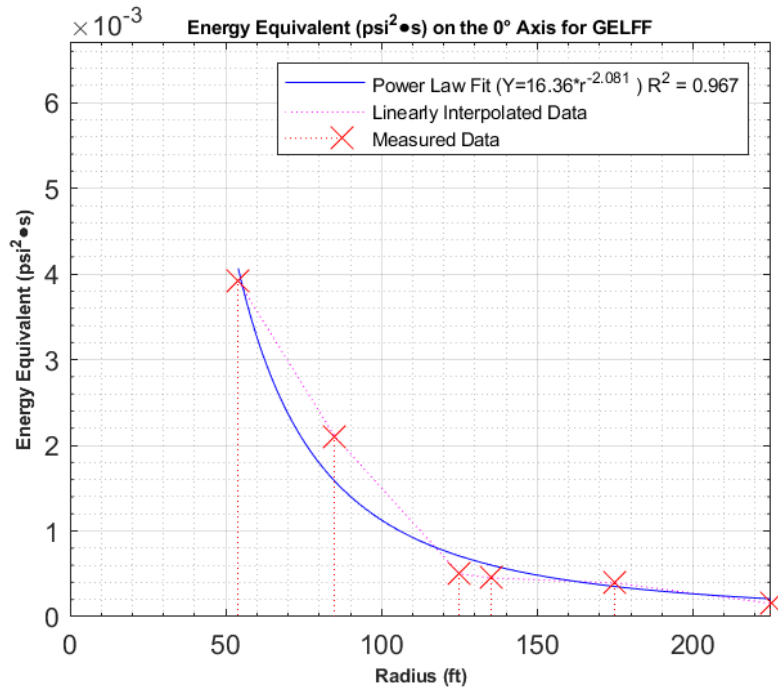


Figure 131 Slice plot along the 0° axis showing the power law fitted energy equivalent data for flat-field gel emulsion Wyssen Tower charge.

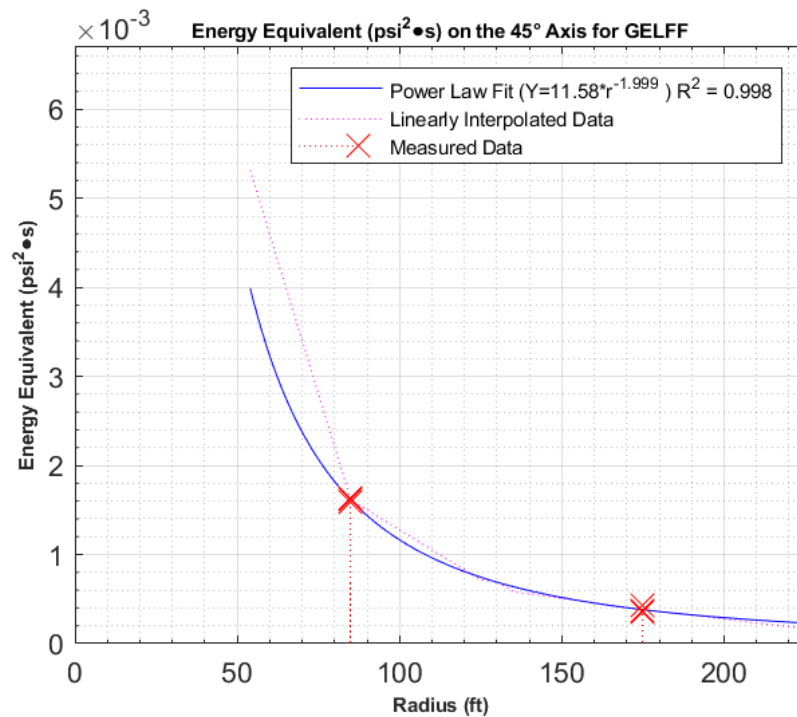


Figure 132 Slice plot along the 45° axis showing the power law fitted energy equivalent data for flat-field gel emulsion Wyssen Tower charge.

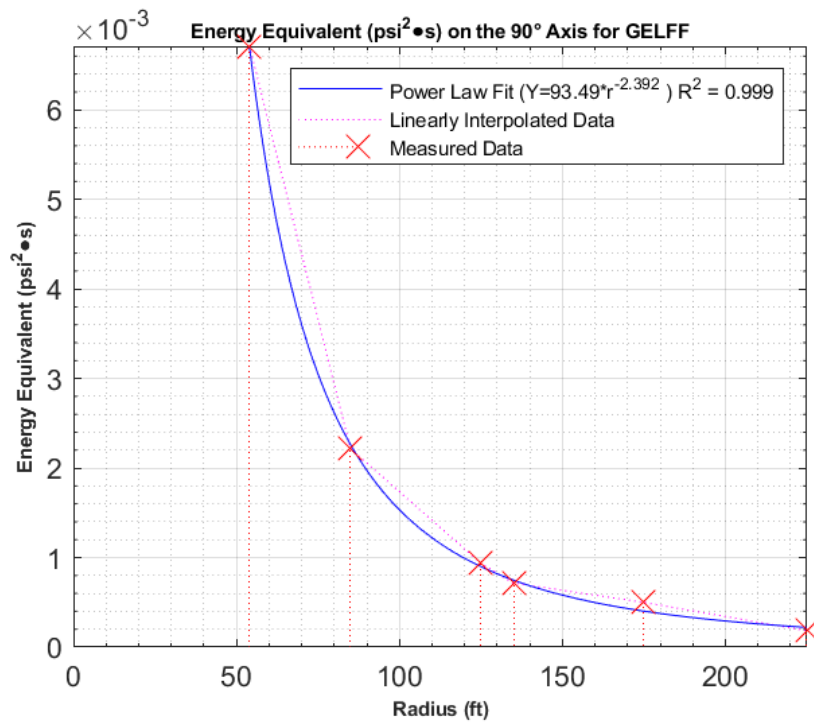


Figure 133 Slice plot along the 90° axis showing the power law fitted energy equivalent data for flat-field gel emulsion Wyssen Tower charge.

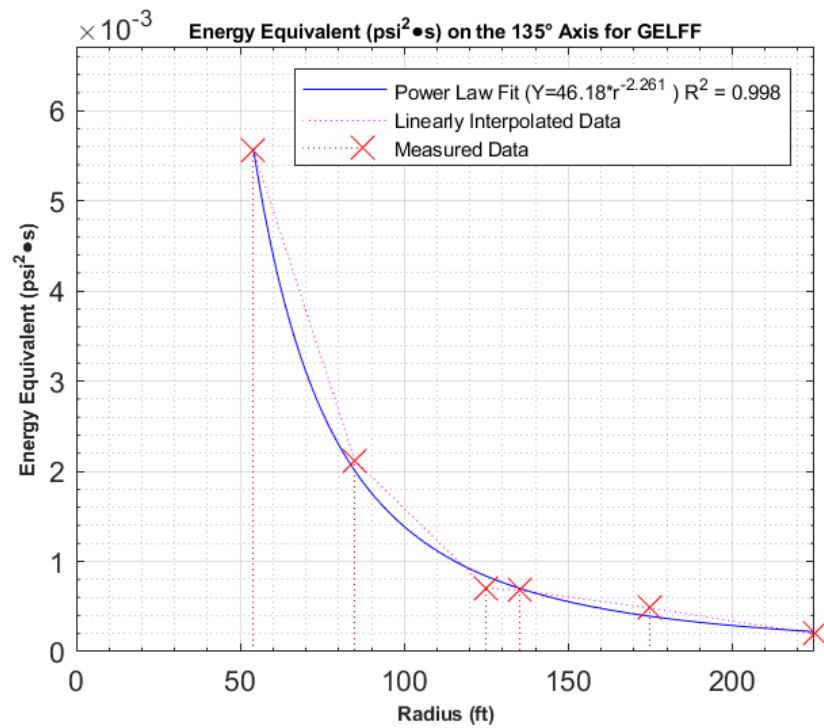


Figure 134 Slice plot along the 135° axis showing the power law fitted energy equivalent data for flat-field gel emulsion Wyssen Tower charge.

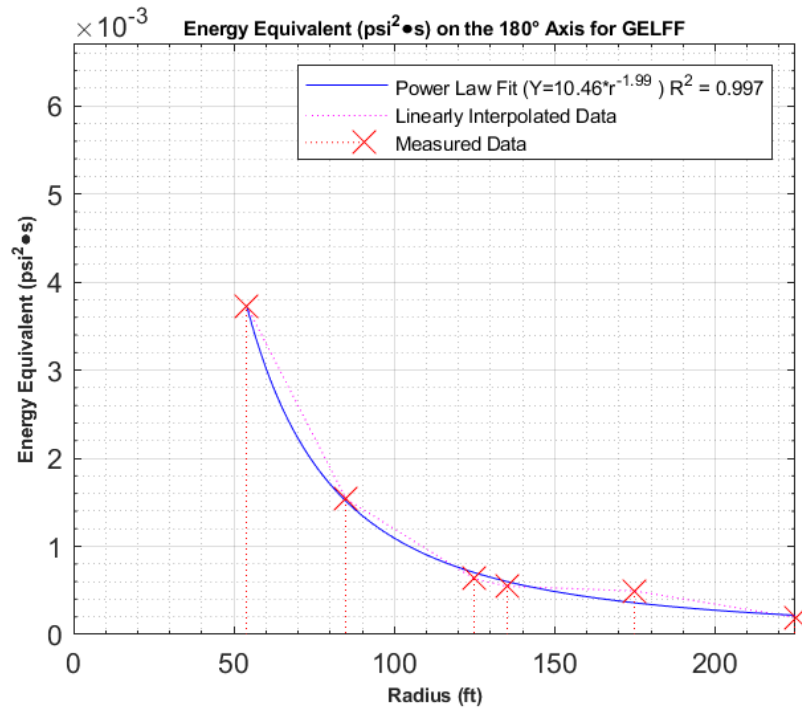


Figure 135 Slice plot along the 180° axis showing the power law fitted energy equivalent data for flat-field gel emulsion Wyssen Tower charge.

The direct linear approximation method was also utilized to calculate the pressure rise rates for the gel emulsion charge. The pressure rise rate results obtained indicate a circular profile for the gel emulsion charge (Figure 136 and Figure 137). Power law fits for each axis show a strong decay with radial distance (Table 15) (similar to the energy equivalent) with an average power law exponent coefficient of -2.1. The pressure rate and radial distance relationship was very similar along each axis, with the 90° axis having slightly higher values at smaller radial distances (Figure 138 - Figure 142).

Table 15 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for flat-field gel emulsion Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	1.52e6	1.90	0.989
45	2.93e6	2.03	0.994
90	2.77e7	2.49	0.998
135	2.74e6	2.00	0.996
180	3.00e6	2.06	0.996

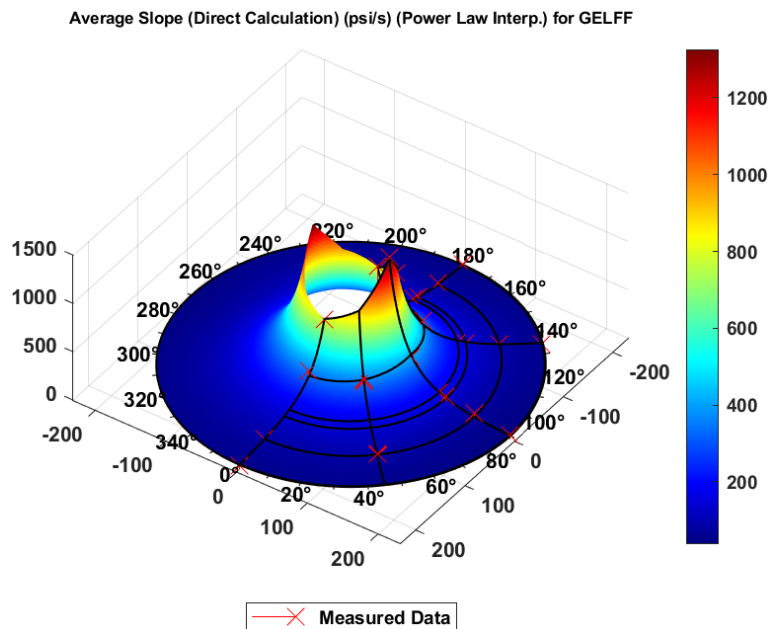


Figure 136 Surface plot of the power law fitted pressure rise rate data from the flat-field gel emulsion Wyssen Tower charge testing

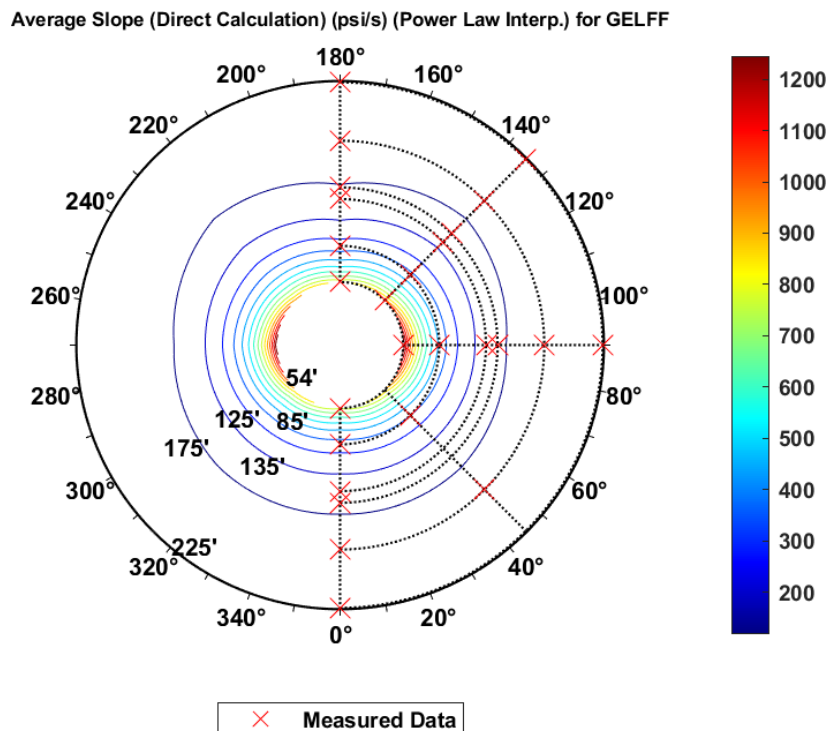


Figure 137 Contour plot of the power law fitted pressure rise rate data from the flat-field gel emulsion Wyssen Tower charge testing.

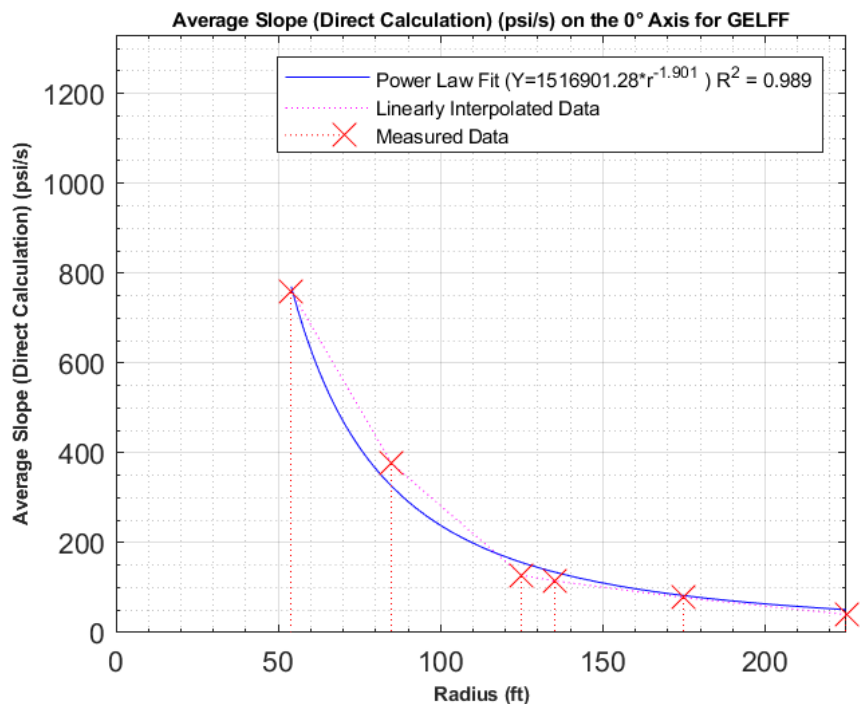


Figure 138 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for flat-field gel emulsion Wyssen Tower charge.

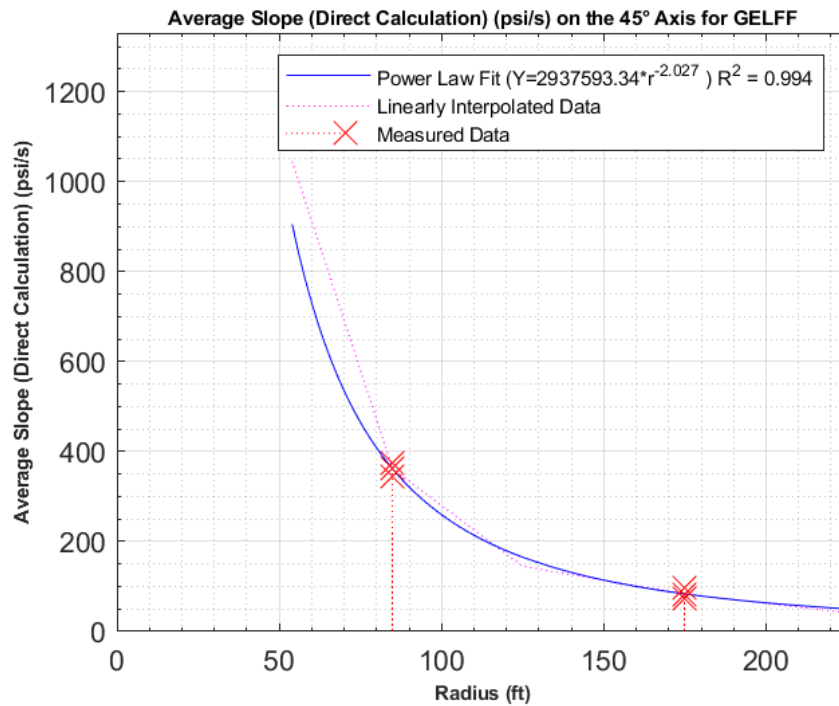


Figure 139 Slice plot along the 45° axis showing the power law fitted pressure rise rate data for flat-field gel emulsion Wyssen Tower charge.

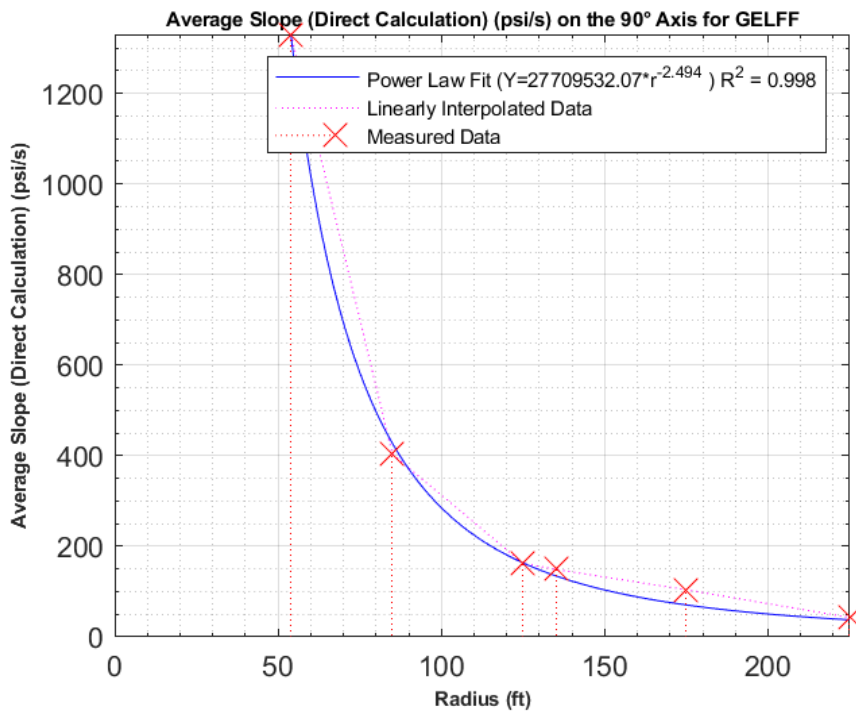


Figure 140 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for flat-field gel emulsion Wyssen Tower charge.

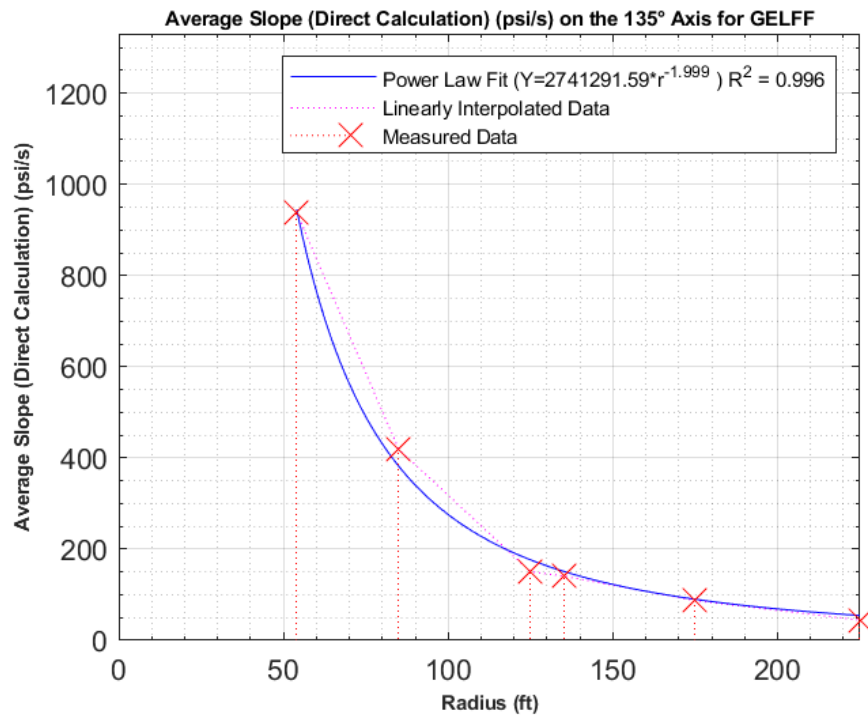


Figure 141 Slice plot along the 135° axis showing the power law fitted pressure rise rate data for flat-field gel emulsion Wyssen Tower charge.

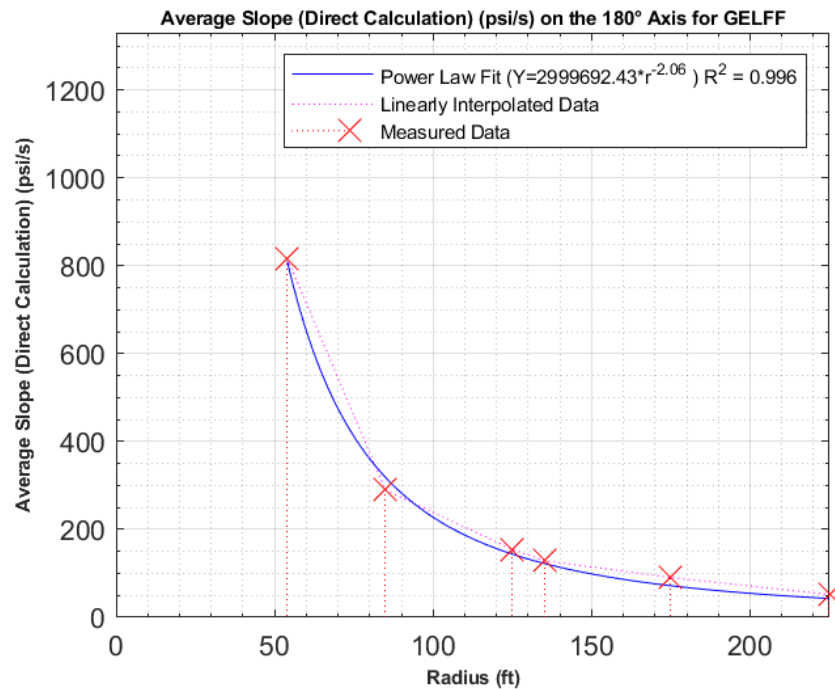


Figure 142 Slice plot along the 180° axis showing the power law fitted pressure rise rate data for flat-field gel emulsion Wyssen Tower charge.

3.2.4 Flat-Field Pentolite Charge Wyssen Tower

As mentioned in Section 2.4.2.5, testing of a prototype Pentolite-based Wyssen Tower charge was also performed alongside the flat-field gel emulsion testing. Though not perfectly representative of the Pentolite charge and charge mass that was being developed for the Wyssen Tower, these tests still provided an ideal opportunity to perform side-by-side testing of comparably sized charges of differing compositions. The peak pressure results of this Pentolite-based prototype Wyssen Tower charge is presented first.

Peak pressures of the Pentolite-based prototype Wyssen Tower charges were measurably higher than other devices tested. The peak pressure results also indicated a highly symmetric/circular profile as expected (Figure 143 and Figure 144). Peak pressures decayed moderately with radial distance along all axes and decayed similarly along all axes with an average power law exponent coefficient of -1.27 (Table 16). Additionally, the reference peak pressure of 0.145 psi or 1 kPa was determined to be reached at radial distances between 404 - 467 ft for all axes (Figure 145 - Figure 149). Lastly, it was shown that the separate charges utilized to carry out this testing produced repeatable results based on the consistency of the measurements taken on the 45° axis which remained in place for all tests (Figure 146).

Table 16 A table of the power law coefficients for the peak pressure data along each of the measured axes for flat-field prototype Pentolite-based Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	352	1.30	0.989
45	448	1.33	0.972
90	402	1.29	0.995
135	342	1.26	0.997
180	197	1.17	0.977

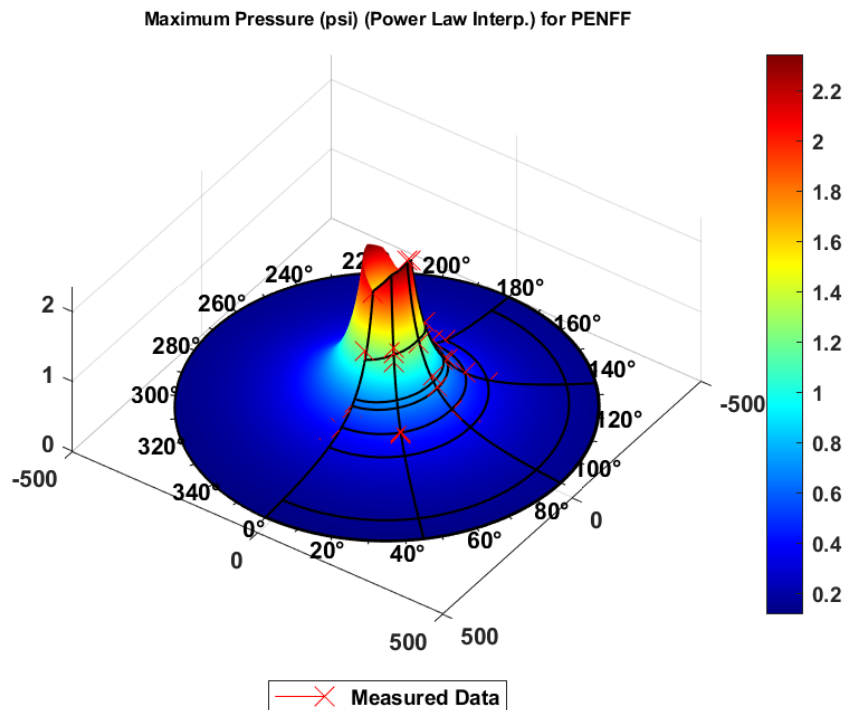


Figure 143 Surface plot of the power law fitted peak pressure data from the flat-field prototype Pentolite-based Wyssen Tower charge testing

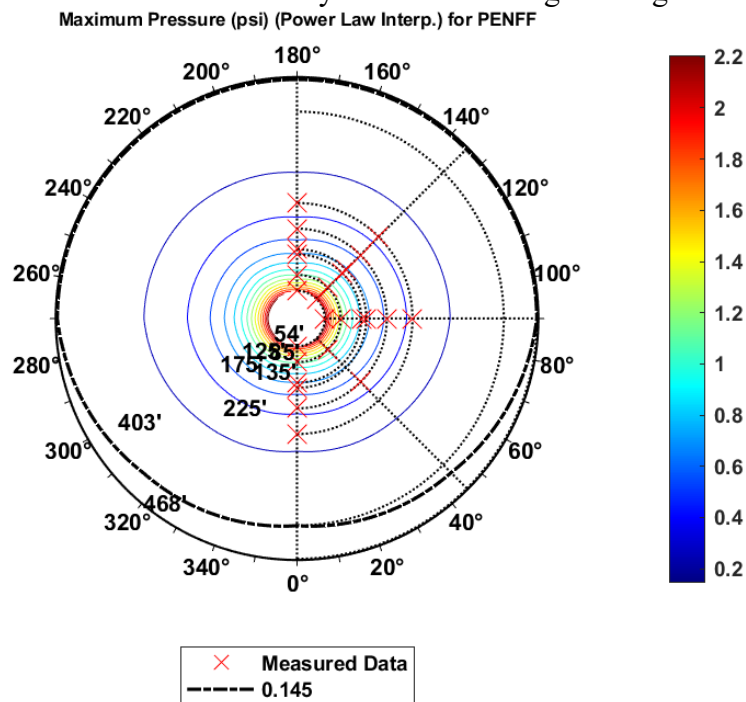


Figure 144 Contour plot of the power law fitted peak pressure data from the flat-field prototype Pentolite-based Wyssen Tower charge testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

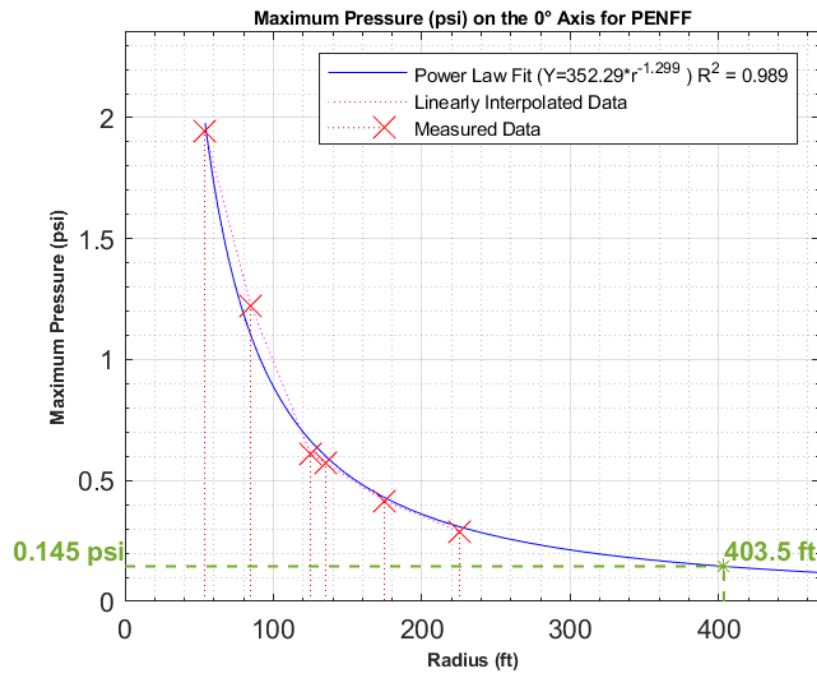


Figure 145 Slice plot along the 0° axis showing the power law fitted peak pressure data for flat-field prototype Pentolite-based Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

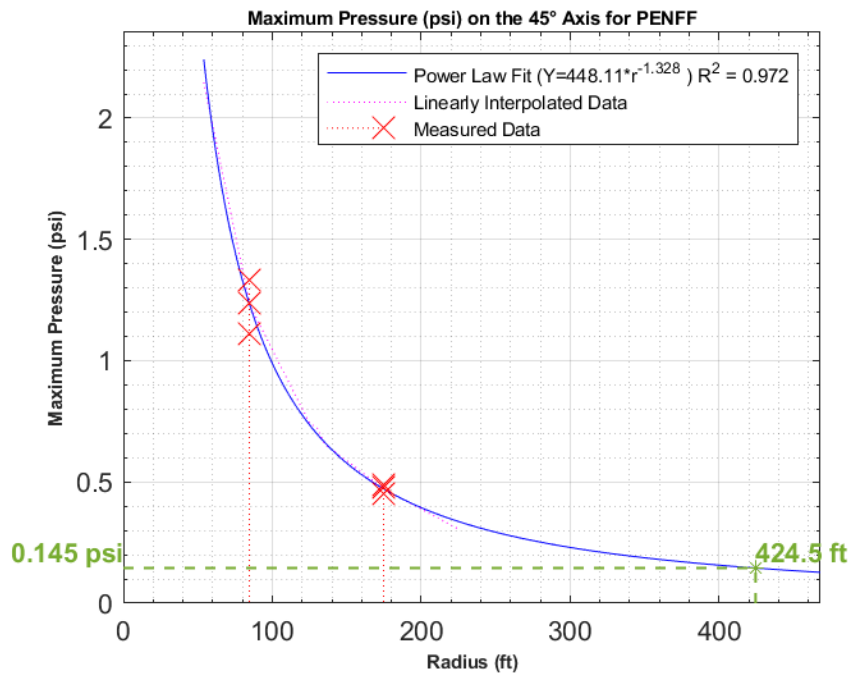


Figure 146 Slice plot along the 45° axis showing the power law fitted peak pressure data for flat-field prototype Pentolite-based Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

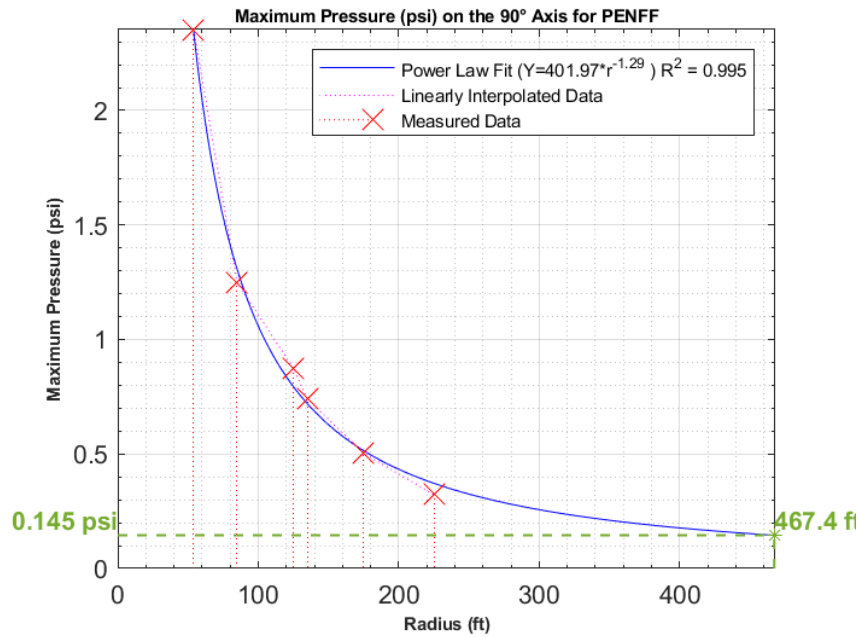


Figure 147 Slice plot along the 90° axis showing the power law fitted peak pressure data for flat-field prototype Pentolite-based Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

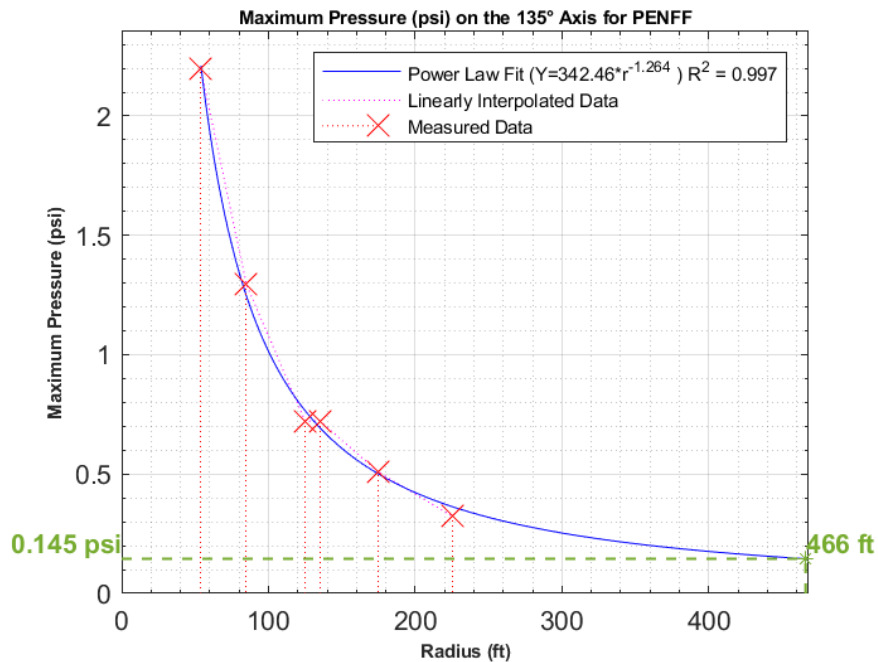


Figure 148 Slice plot along the 135° axis showing the power law fitted peak pressure data for flat-field prototype Pentolite-based Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

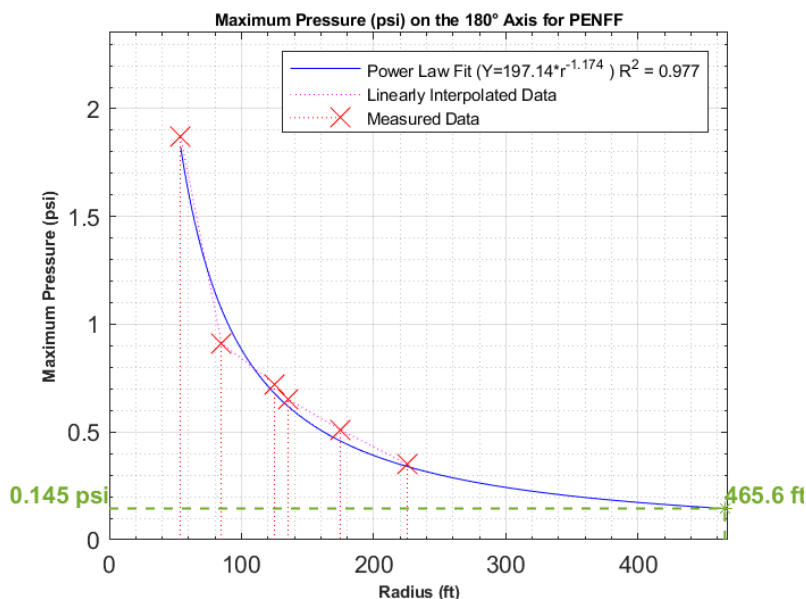


Figure 149 Slice plot along the 180° axis showing the power law fitted peak pressure data for flat-field prototype Pentolite-based Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

The energy equivalent results for the flat-field testing of the prototype Pentolite charge also showed a circular/symmetric profile (Figure 150 and Figure 151). As was noted for previous explosives, the energy equivalent decayed more rapidly with radial distance than peak pressure. Power law fitting for energy equivalent results along each axis indicated an average exponent of -2.15 (Table 17). The energy equivalent and radial distance relationship was very similar along each axis (Figure 152 - Figure 156).

Table 17 A table of the power law coefficients for the energy equivalent data along each of the measured axes for flat-field prototype Pentolite-based Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	82.9	2.16	0.995
45	44.7	2.02	0.948
90	189	2.28	0.995
135	123	2.21	0.999
180	62.2	2.10	0.987

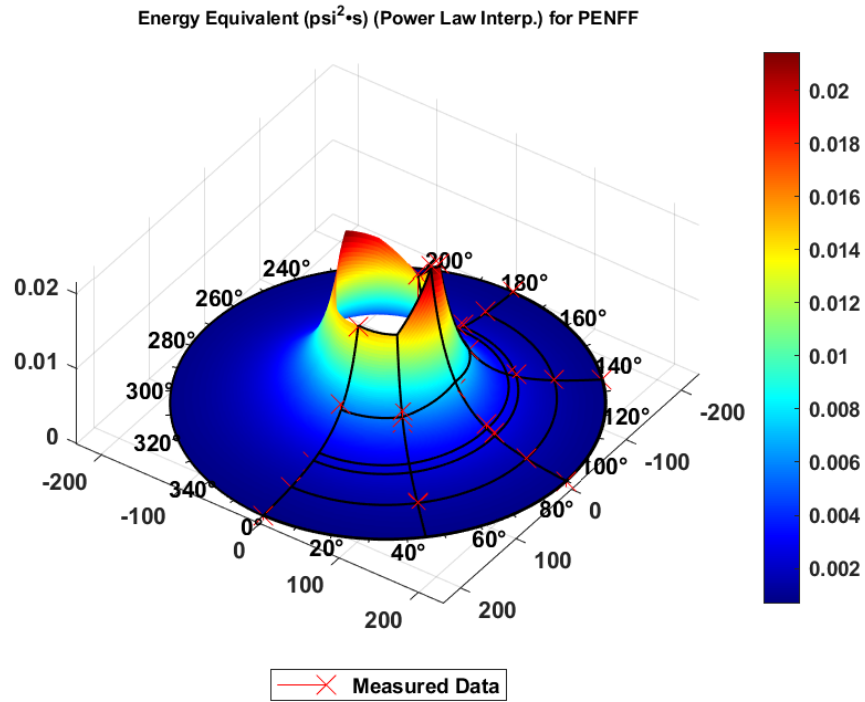


Figure 150 Surface plot of the power law fitted energy equivalent data from the flat-field prototype Pentolite-based Wyssen Tower charge testing

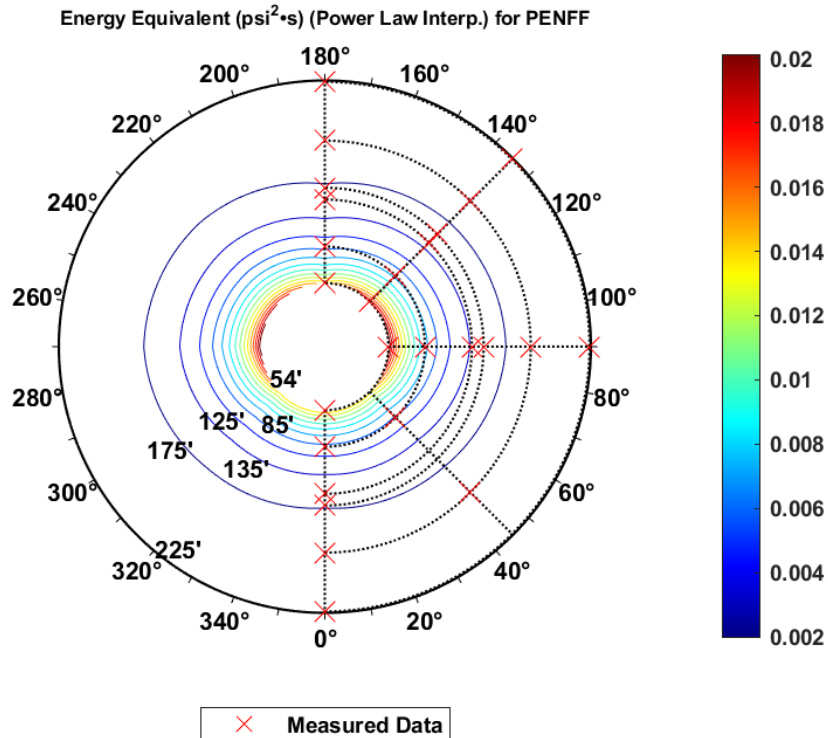


Figure 151 Contour plot of the power law fitted energy equivalent data from the flat-field prototype Pentolite-based Wyssen Tower charge testing.

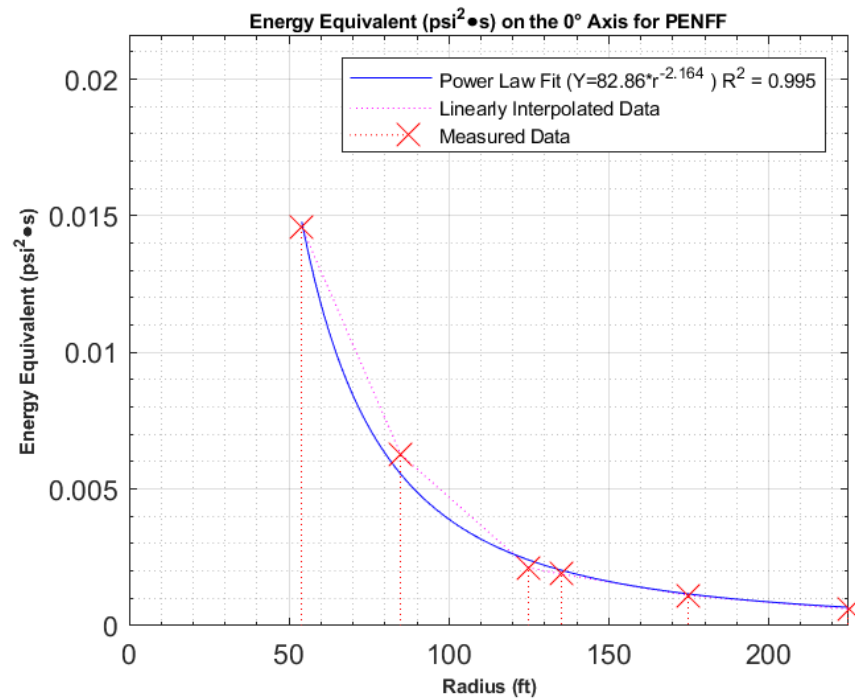


Figure 152 Slice plot along the 0° axis showing the power law fitted energy equivalent data for flat-field prototype Pentolite-based Wyssen Tower charge.

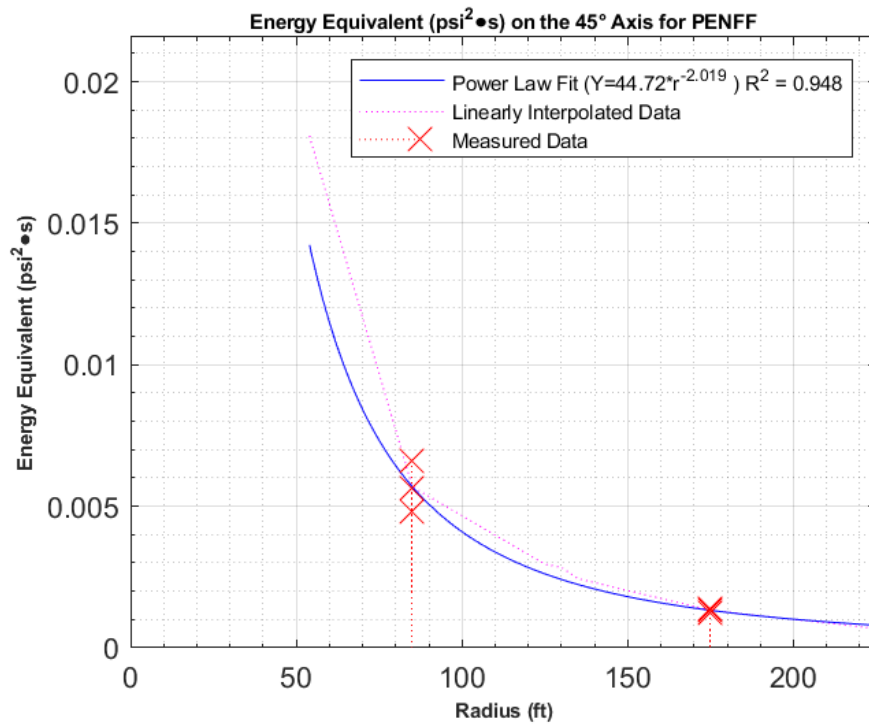


Figure 153 Slice plot along the 45° axis showing the power law fitted energy equivalent data for flat-field prototype Pentolite-based Wyssen Tower charge.

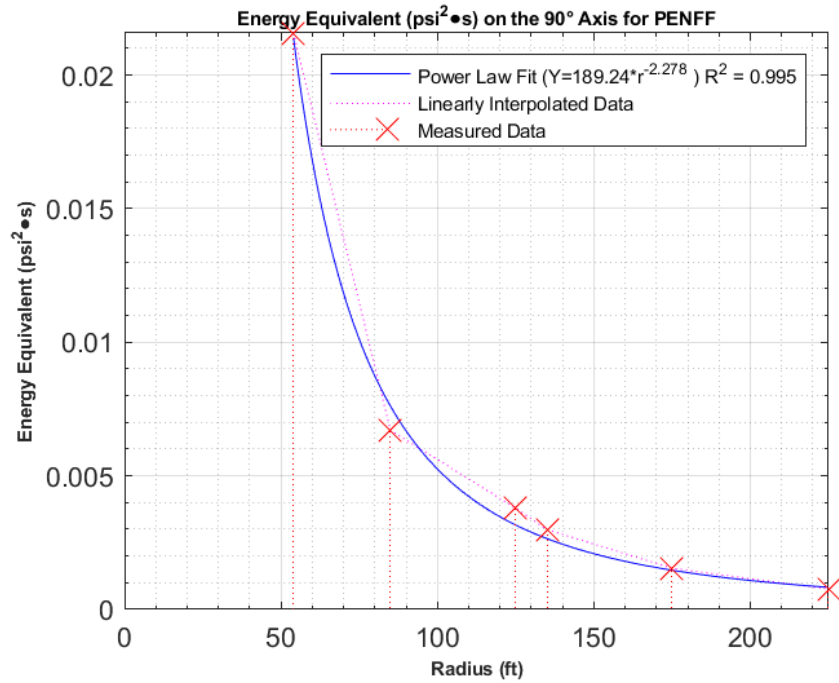


Figure 154 Slice plot along the 90° axis showing the power law fitted energy equivalent data for flat-field prototype Pentolite-based Wyssen Tower charge.

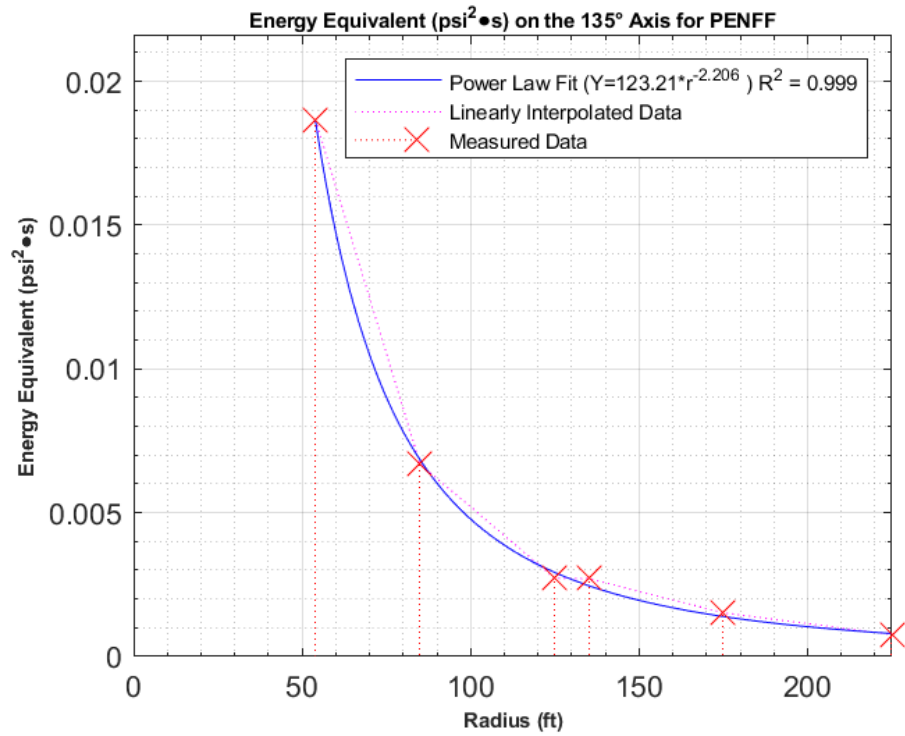


Figure 155 Slice plot along the 135° axis showing the power law fitted energy equivalent data for flat-field prototype Pentolite-based Wyssen Tower charge.

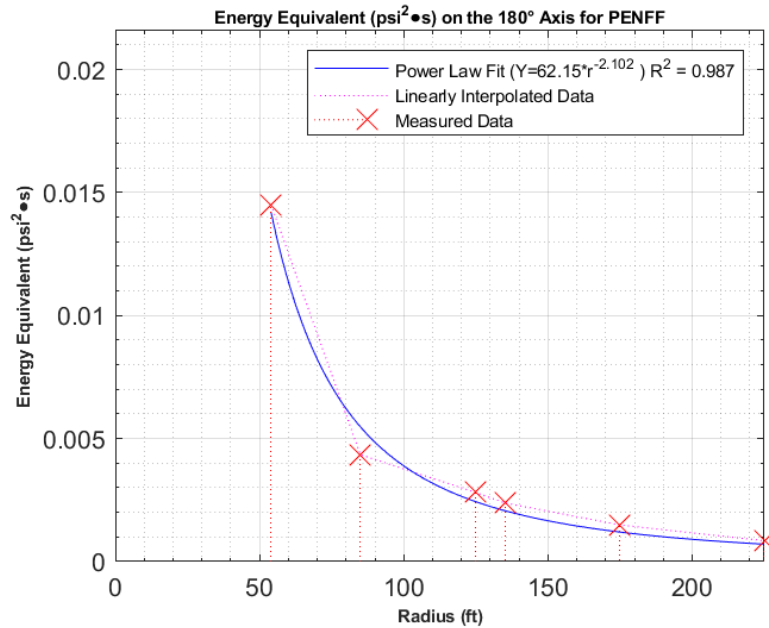


Figure 156 Slice plot along the 180° axis showing the power law fitted energy equivalent data for flat-field prototype Pentolite-based Wyssen Tower charge.

Using the direct linear approximation method, the pressure rise rates for the prototype Pentolite-based Wyssen Tower charge were also determined. These results also indicated a distinctly circular profile for the charge (Figure 157 and Figure 158). Power law fits for each axis show a moderate decay with radial distance (Table 18) with an average power law exponent coefficient of -1.7. The pressure rate and radial distance relationship was very similar along each axis (Figure 159 - Figure 163).

Table 18 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for flat-field prototype Pentolite-based Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	5.54e5	1.54	0.996
45	9.42e6	2.08	0.979
90	9.63e6	2.12	0.991
135	6.00e5	1.53	0.990
180	2.34e5	1.37	0.985

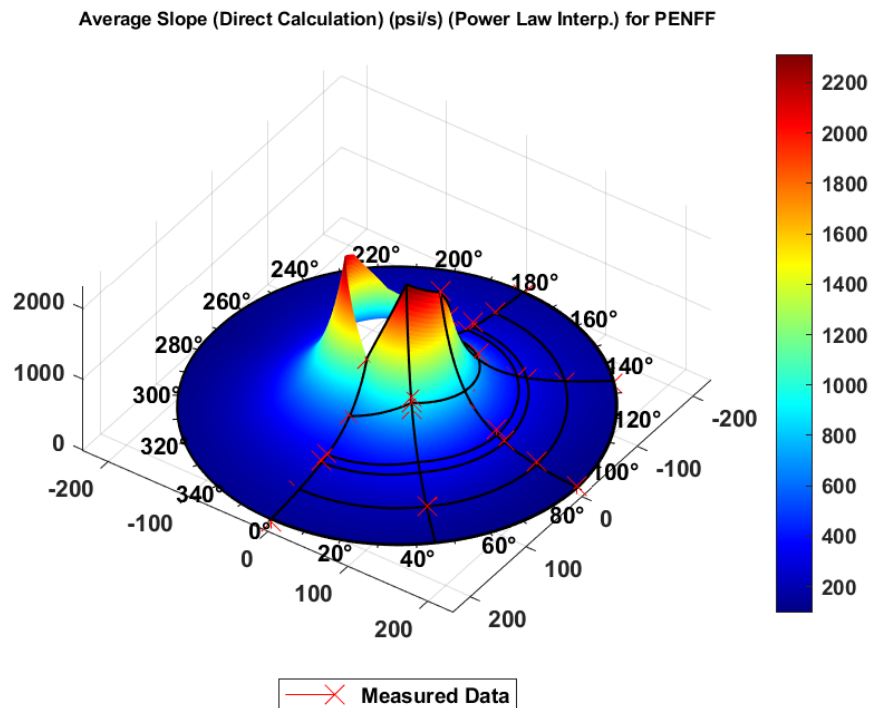


Figure 157 Surface plot of the power law fitted pressure rise rate data from the flat-field prototype Pentolite-based Wyssen Tower charge testing

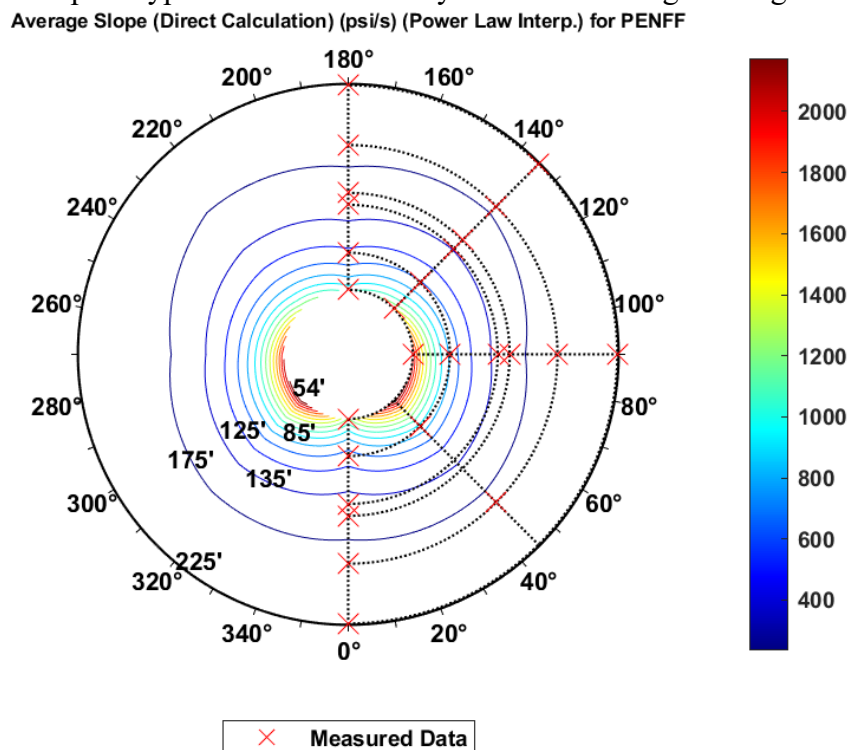


Figure 158 Contour plot of the power law fitted pressure rise rate data from the flat-field prototype Pentolite-based Wyssen Tower charge testing.

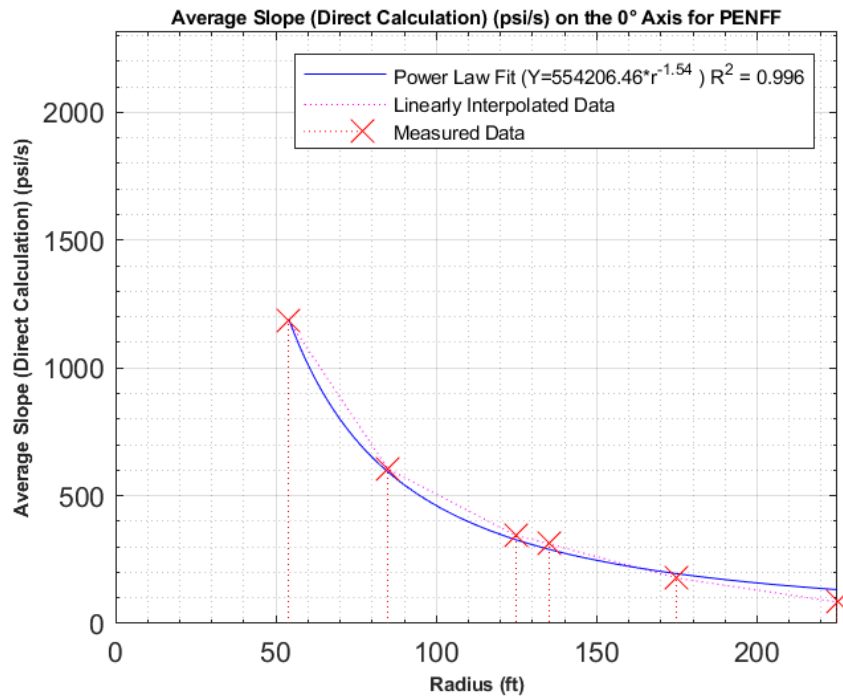


Figure 159 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for flat-field prototype Pentolite-based Wyssen Tower charge.

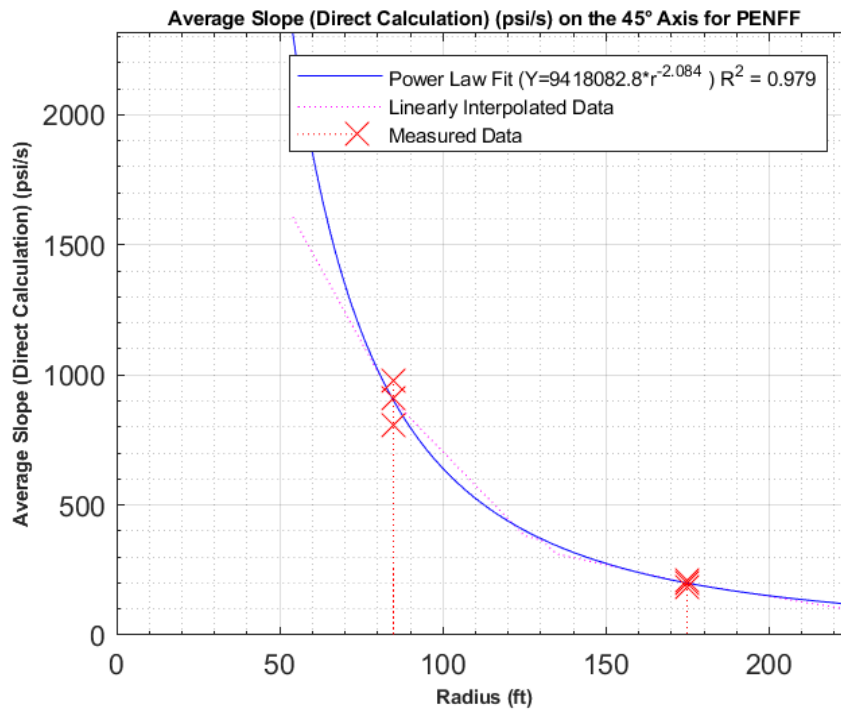


Figure 160 Slice plot along the 45° axis showing the power law fitted pressure rise rate data for flat-field prototype Pentolite-based Wyssen Tower charge.

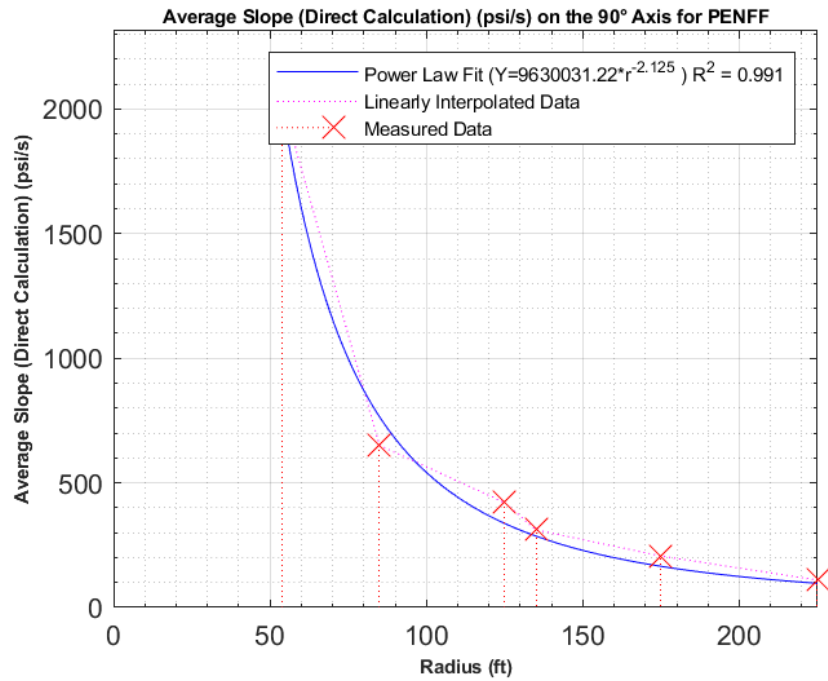


Figure 161 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for flat-field prototype Pentolite-based Wyssen Tower charge.

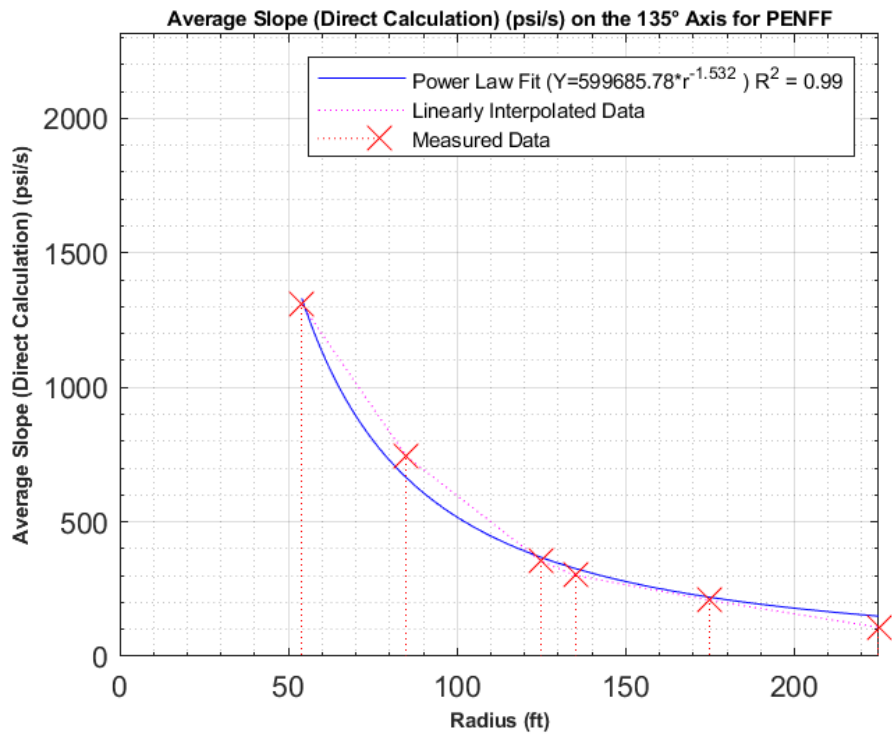


Figure 162 Slice plot along the 135° axis showing the power law fitted pressure rise rate data for flat-field prototype Pentolite-based Wyssen Tower charge.

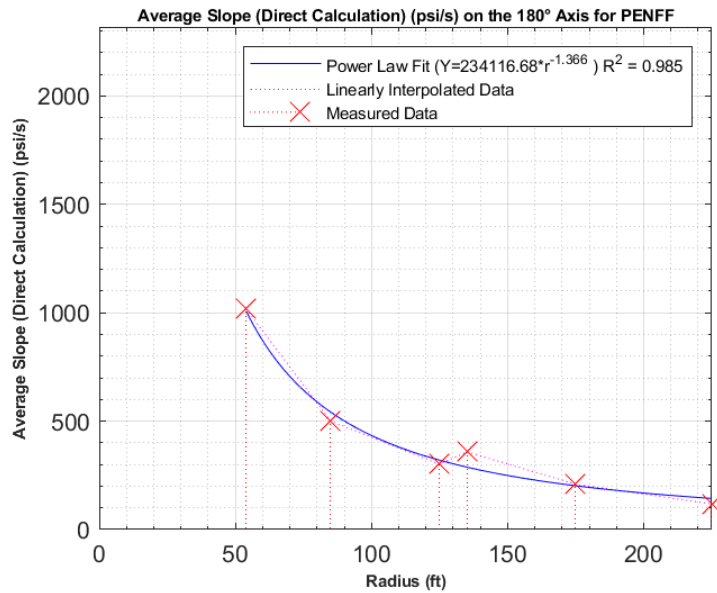


Figure 163 Slice plot along the 180° axis showing the power law fitted pressure rise rate data for flat-field prototype Pentolite-based Wyssen Tower charge.

3.2.5 Operational Gel Charge Wyssen Tower

In order to better understand the flat-field Wyssen Tower results, testing with a similar equipment layout was also conducted at an operational Wyssen Tower installed on a snow-covered open slope (see Section 2.4.2.6). It was hypothesized that the explosives should perform similarly whether detonated in a flat open field or deployed from an operational Wyssen Tower in an open slope setting. This was supported in part, but some notable differences were identified from the results of the gel emulsion charge tests conducted at the operational RAC device.

Based on the power law fitting, peak pressures for the operational Wyssen Tower with gel emulsion charges were found to be higher than those for flat-field testing, but only for radial distances less than about 270 ft, 205 ft, and 94 ft for the 0°, 45°, and 90° axes, respectively. Similarly, peak pressures at the operational tower were lower than the flat-field testing for all radial distances for the 135° and 180° axes.

This interesting and somewhat unexpected behavior can be visualized by considering the peak pressure isolines which were almost circular (as was seen with the flat-field results), but with a distinct flattening of the pressure isolines to the rear (i.e., uphill) of the tower (Figure 164 and Figure 165). This behavior was also demonstrated by the power laws fit to describe the decay of peak pressure with radial distance along each axis (Table 19). These power laws indicated that the peak pressures of the operational RAC system were higher at close range than the flat-field results, but also decayed more rapidly with radial distance than the flat-field results (with the exception of the 135° and 180° axes which decayed similarly to the flat-field testing, but were shown to have lower peak pressures overall). These power laws also indicated that the reference peak pressure of 0.145 psi or 1 kPa was reached at distances of approximately 240 ft on the 0° and 45° axes, approximately 215 ft on the 90° and 135° axes, and about 200 ft on the 180° axis (Figure 166 - Figure 170) whereas this reference peak pressure was reached at greater distances of 234 - 257 ft for all axes for the flat-field tests of this explosive. Lastly, it was also shown that the separate charges utilized to carry out this testing produced repeatable results based on the consistency of the measurements since all microphones remained in place for all tests.

Table 19 A table of the power law coefficients for the peak pressure data along each of the measured axes for gel emulsion operational Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	1109	1.63	0.993
45	1129	1.64	0.998
90	2132	1.79	0.998
135	355	1.46	0.979
180	122	1.27	0.990

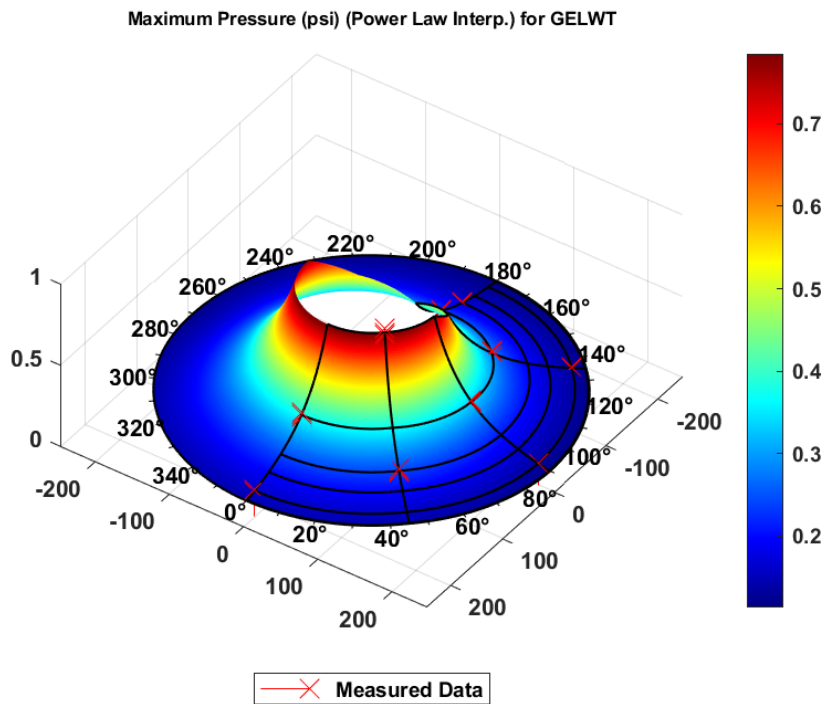


Figure 164 Surface plot of the power law fitted peak pressure data from the gel emulsion operational Wyssen Tower charge testing

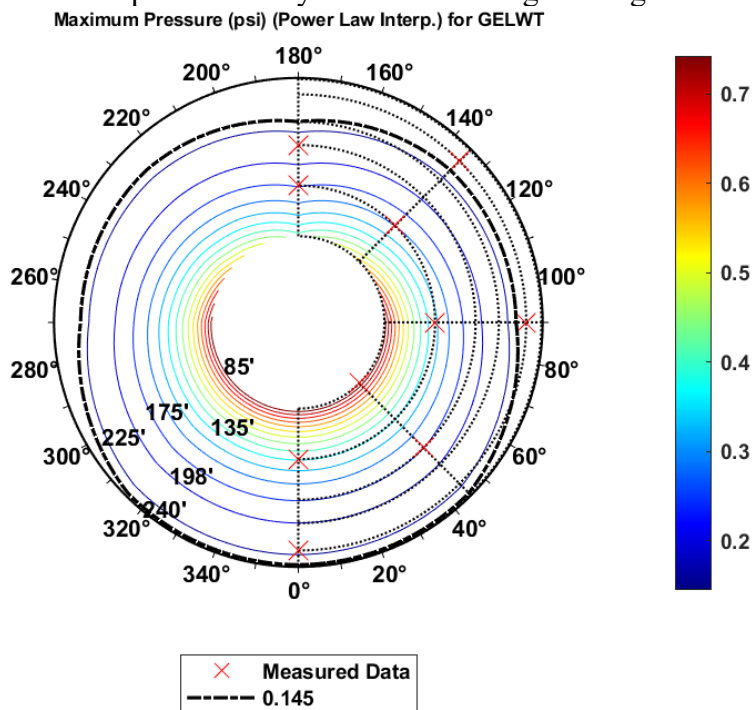


Figure 165 Contour plot of the power law fitted peak pressure data from the gel emulsion operational Wyssen Tower charge testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

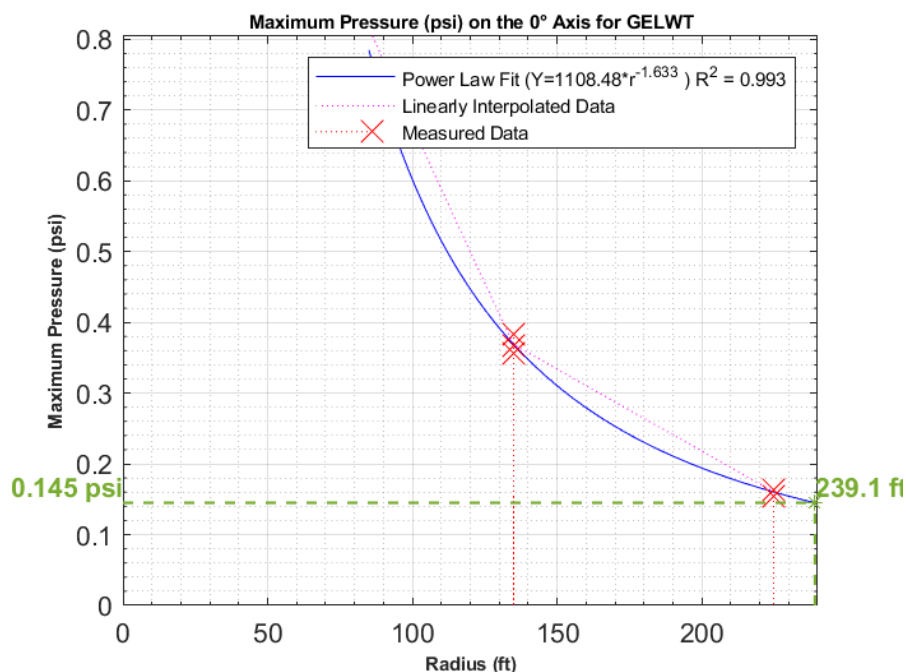


Figure 166 Slice plot along the 0° axis showing the power law fitted peak pressure data for gel emulsion operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

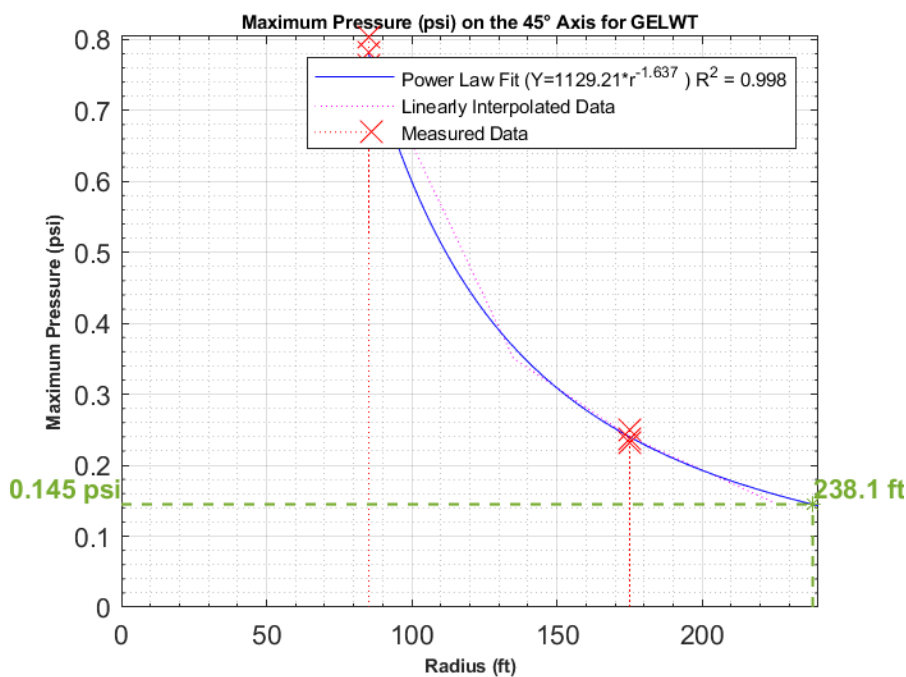


Figure 167 Slice plot along the 45° axis showing the power law fitted peak pressure data for gel emulsion operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

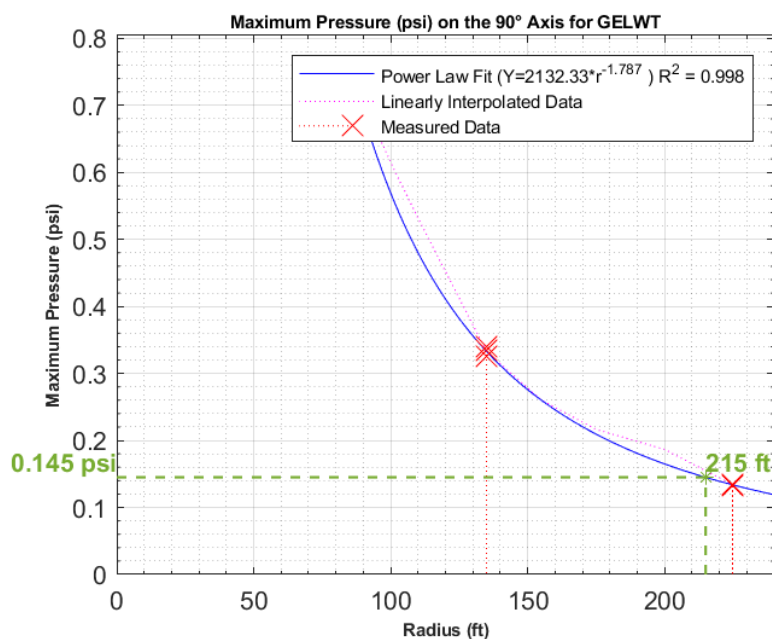


Figure 168 Slice plot along the 90° axis showing the power law fitted peak pressure data for gel emulsion operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

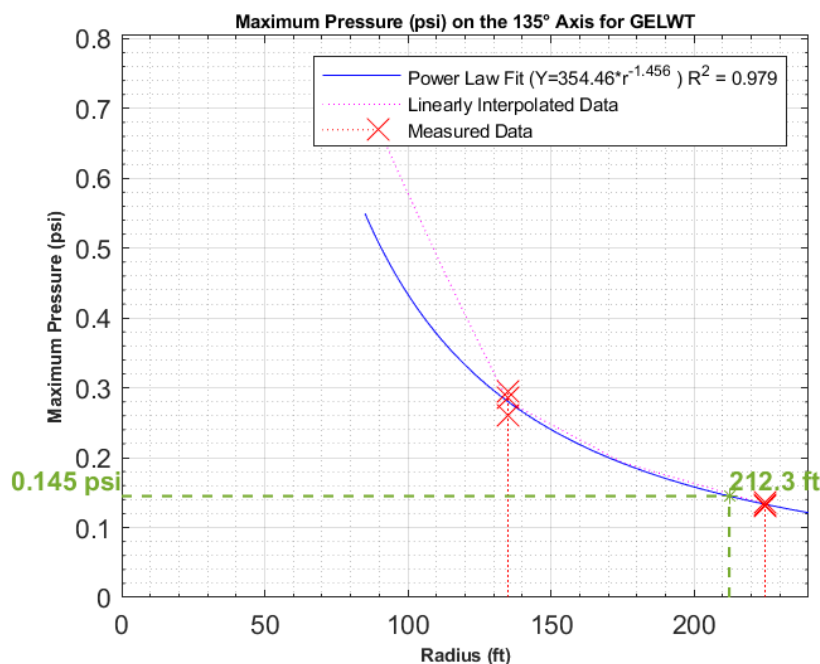


Figure 169 Slice plot along the 135° axis showing the power law fitted peak pressure data for gel emulsion operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

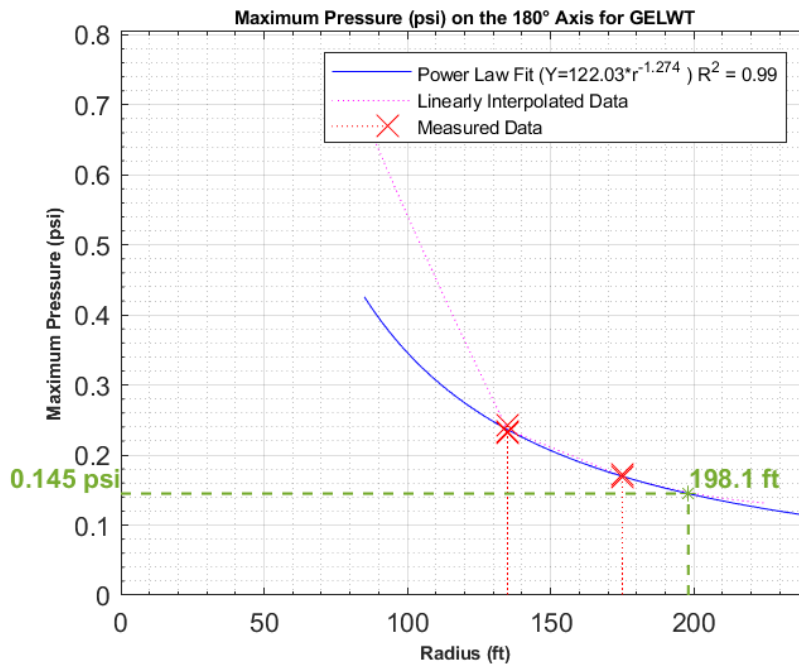


Figure 170 Slice plot along the 180° axis showing the power law fitted peak pressure data for gel emulsion operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

Energy equivalent results obtained from these tests provided many of the same observations as the peak pressure results. Again, the profile was nearly circular with a distinct flattening of the energy equivalent isolines to the rear of the operational Wyssen Tower (Figure 171 and Figure 172). Energy equivalents were shown to be the highest downslope of the RAC system (Figure 173 - Figure 177). Furthermore, the power laws along each axis indicated a stronger response than flat-field results for short ranges, but also showed a stronger decay with radial distance than the flat-field results for all axes. The power laws also indicated a stronger decay of the energy equivalent with radial distance along each axis than for peak pressure (Table 20).

Table 20 A table of the power law coefficients for the energy equivalent data along each of the measured axes for gel emulsion operational Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	331	2.63	0.998
45	333	2.63	0.994
90	938	2.86	0.996
135	71.2	2.39	0.980
180	20.2	2.18	0.993

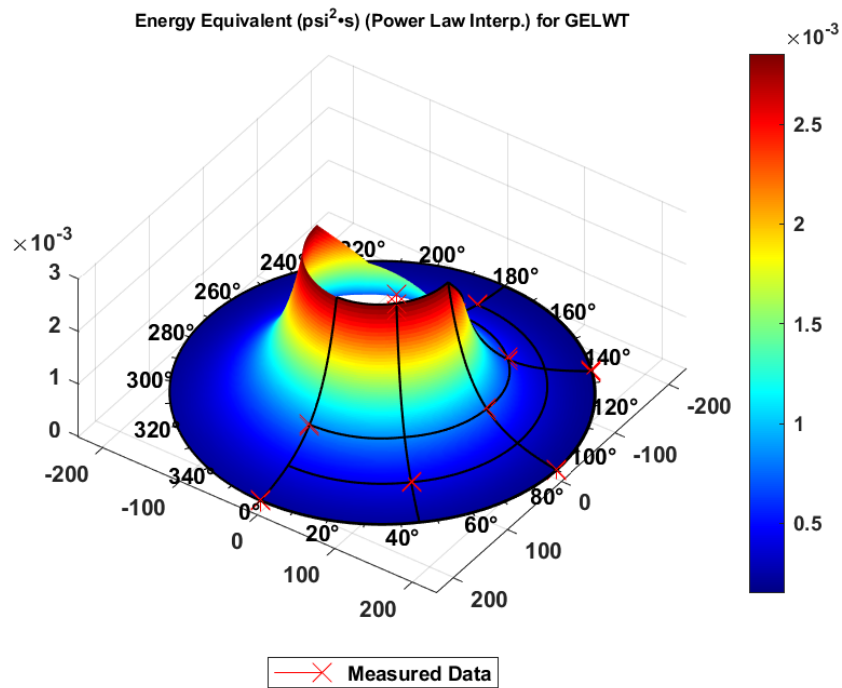


Figure 171 Surface plot of the power law fitted energy equivalent data from the gel emulsion operational Wyssen Tower charge testing

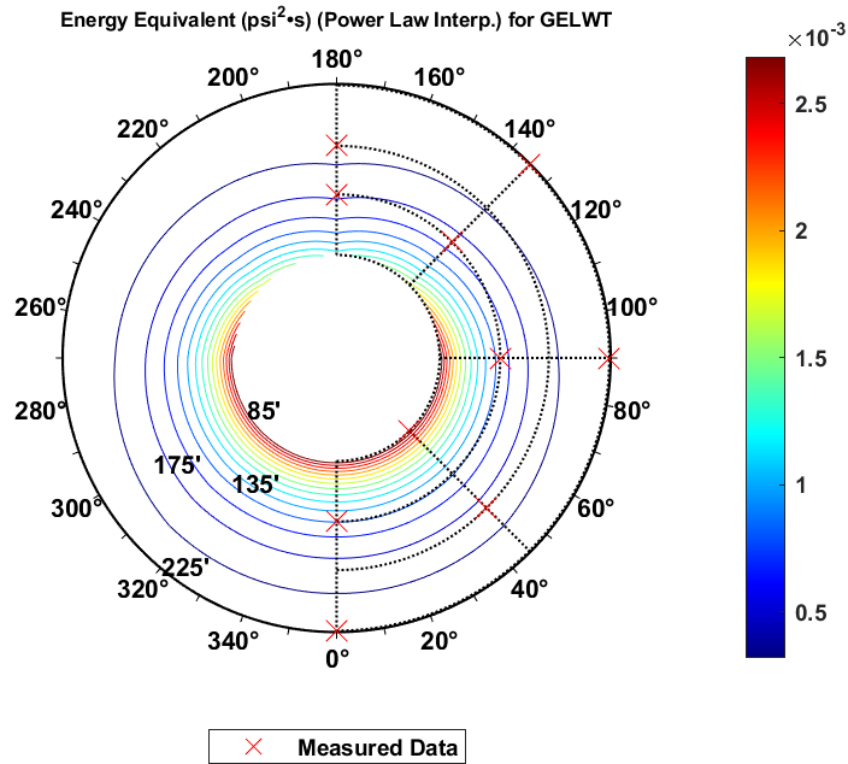


Figure 172 Contour plot of the power law fitted energy equivalent data from the gel emulsion operational Wyssen Tower charge testing.

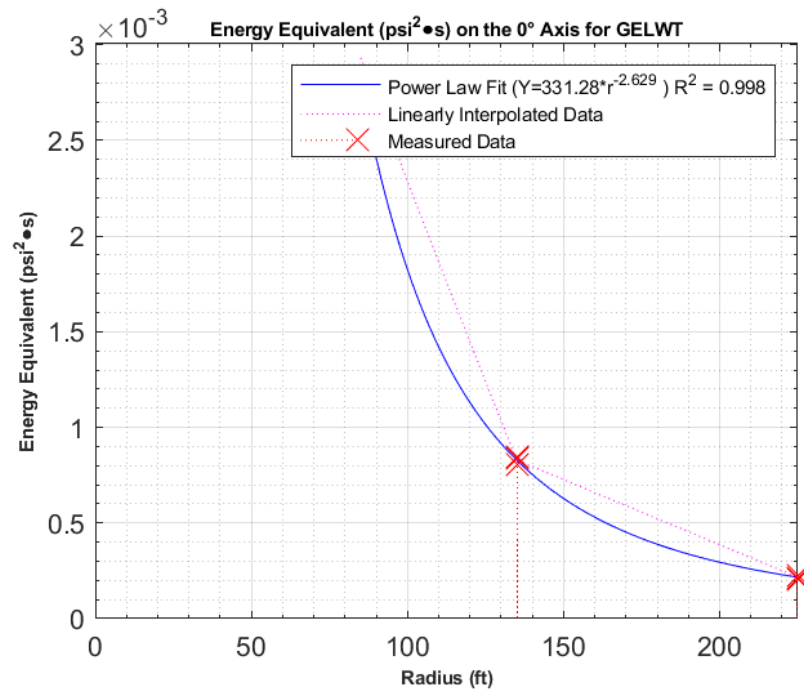


Figure 173 Slice plot along the 0° axis showing the power law fitted energy equivalent data for gel emulsion operational Wyssen Tower charge.

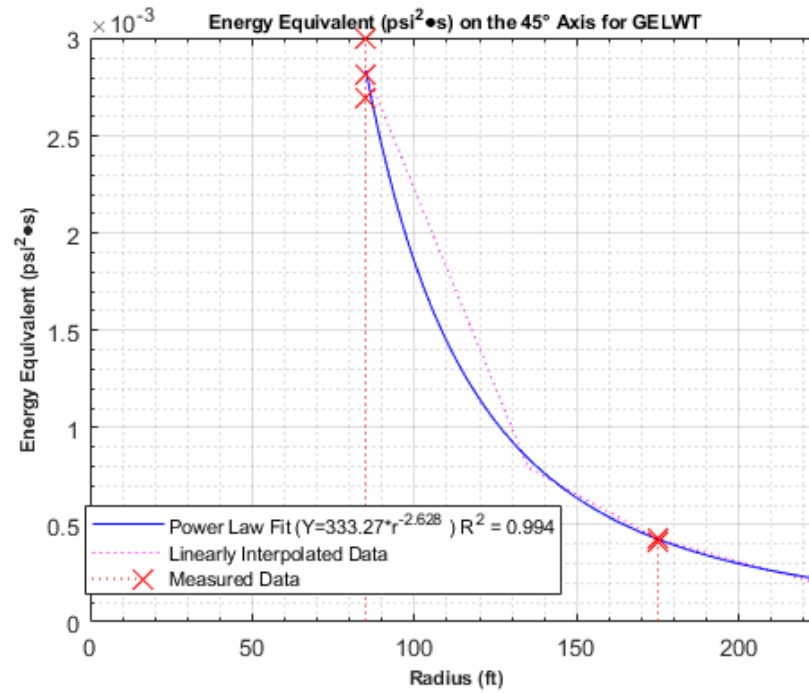


Figure 174 Slice plot along the 45° axis showing the power law fitted energy equivalent data for gel emulsion operational Wyssen Tower charge.

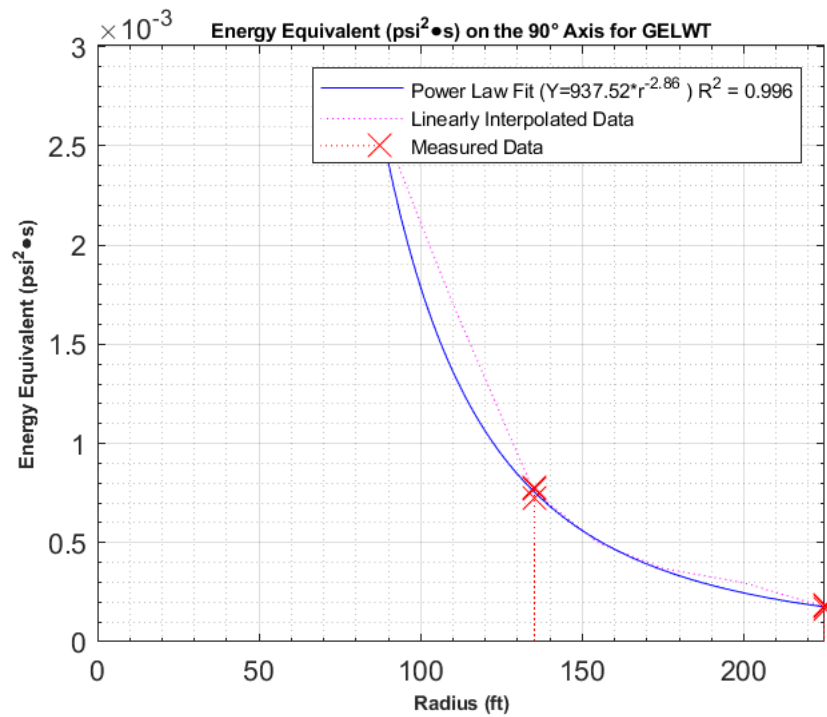


Figure 175 Slice plot along the 90° axis showing the power law fitted energy equivalent data for gel emulsion operational Wyssen Tower charge.

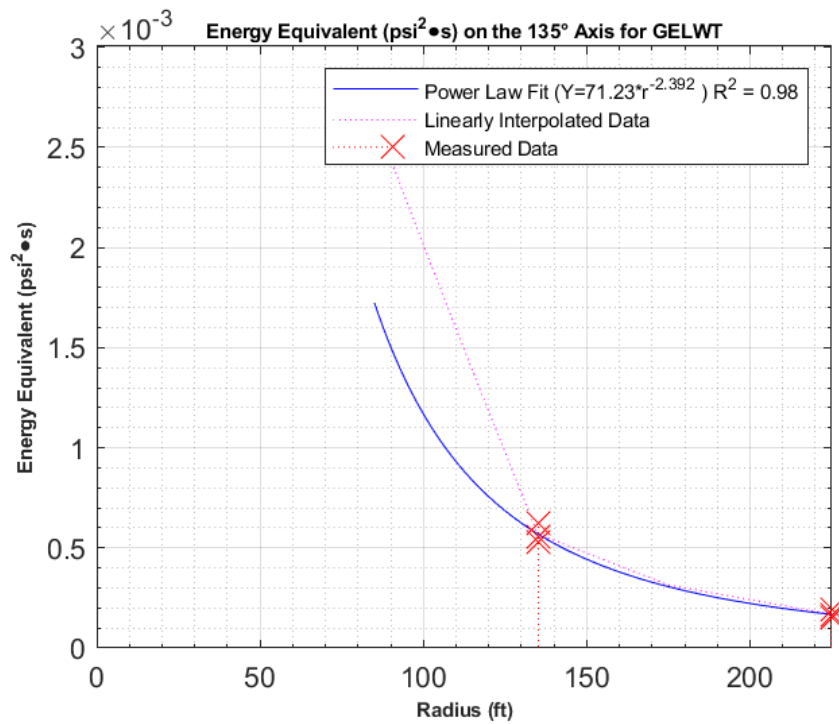


Figure 176 Slice plot along the 135° axis showing the power law fitted energy equivalent data for gel emulsion operational Wyssen Tower charge.

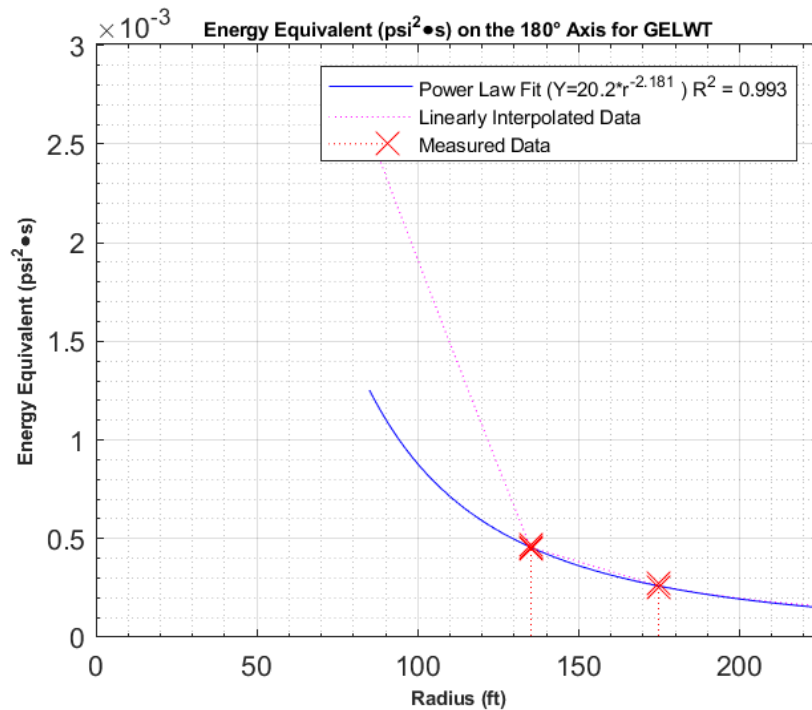


Figure 177 Slice plot along the 180° axis showing the power law fitted energy equivalent data for gel emulsion operational Wyssen Tower charge.

The pressure rise rate results were calculated using the direct linear approximation method for the gel emulsion operational Wyssen Tower charge testing and revealed many of the same trends discussed above for the peak pressure and energy equivalent results. More specifically, the pressure rise rate isolines were, again, approximately circular, but shifted downslope (Figure 178 and Figure 179). Power laws fit to describe the radial decay along each axis (Figure 180 - Figure 184) indicated that the pressure rise rates decayed more strongly with radial distance than peak pressure, but less strongly than energy equivalent (Table 21).

Table 21 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for gel emulsion operational Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	9.56e6	2.28	0.939
45	3.29e6	2.08	0.958
90	5.70e6	2.22	0.996
135	1.23e6	1.94	0.899
180	9.30e4	1.48	0.646

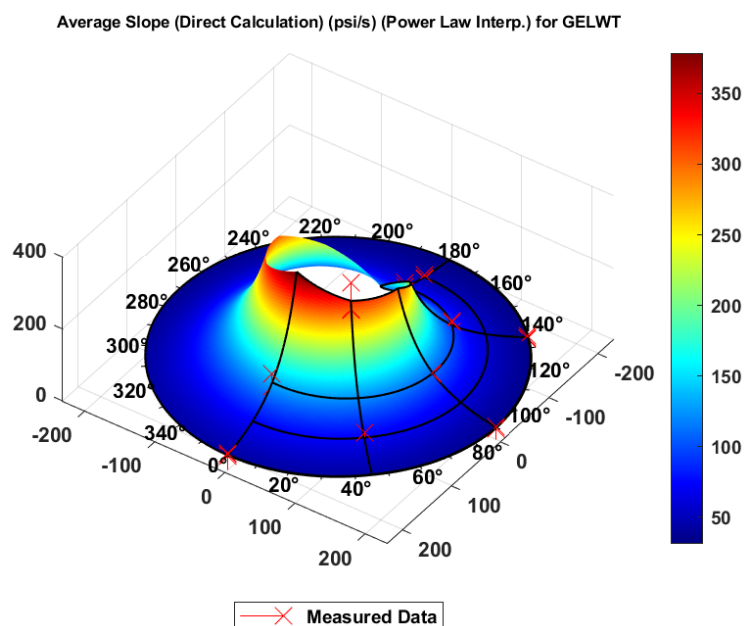


Figure 178 Surface plot of the power law fitted pressure rise rate data from the gel emulsion operational Wyssen Tower charge testing

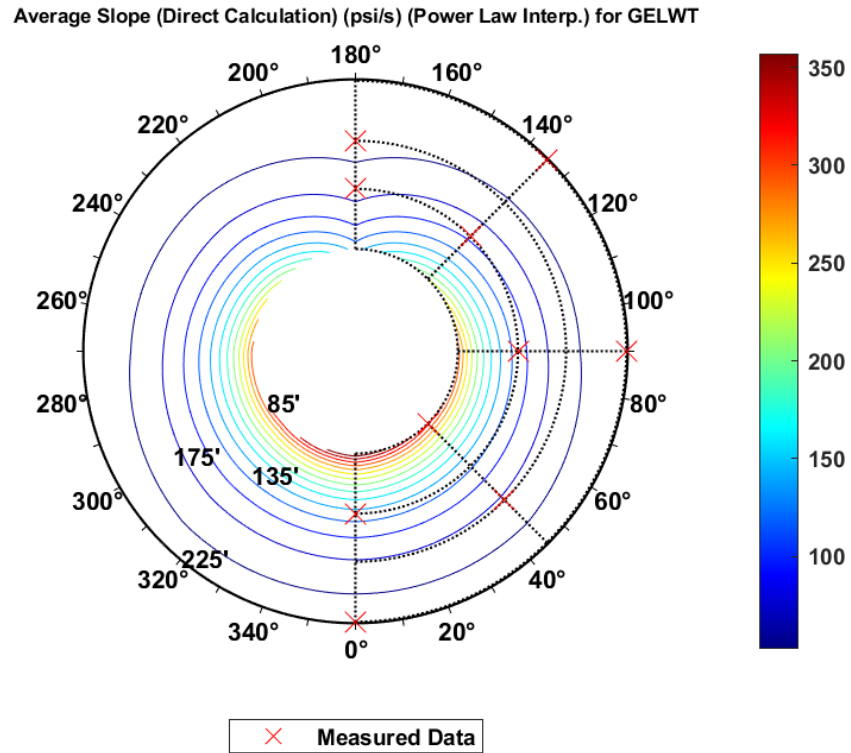


Figure 179 Contour plot of the power law fitted pressure rise rate data from the gel emulsion operational Wyssen Tower charge testing.

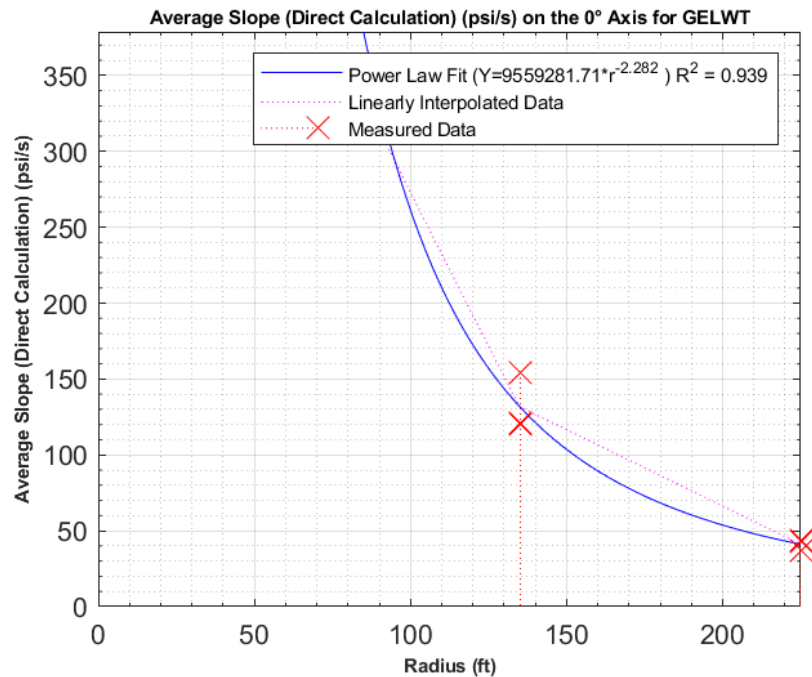


Figure 180 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for gel emulsion operational Wyssen Tower charge.

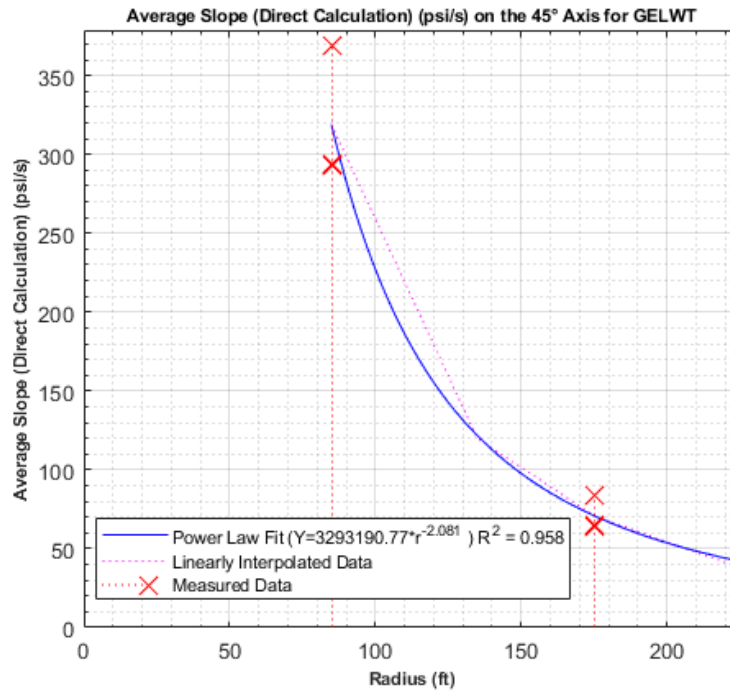


Figure 181 Slice plot along the 45° axis showing the power law fitted pressure rise rate data for gel emulsion operational Wyssen Tower charge.

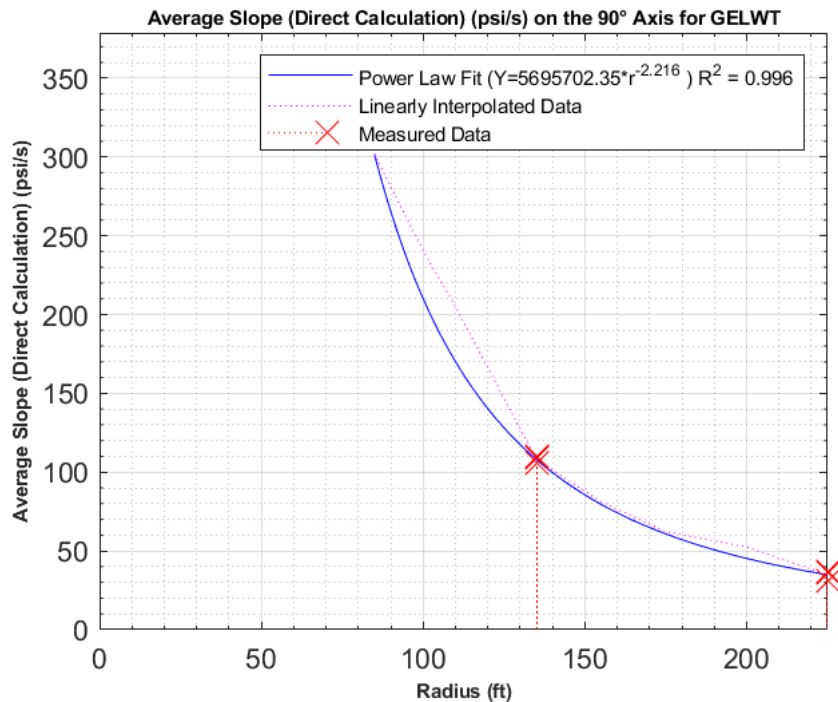


Figure 182 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for gel emulsion operational Wyssen Tower charge.

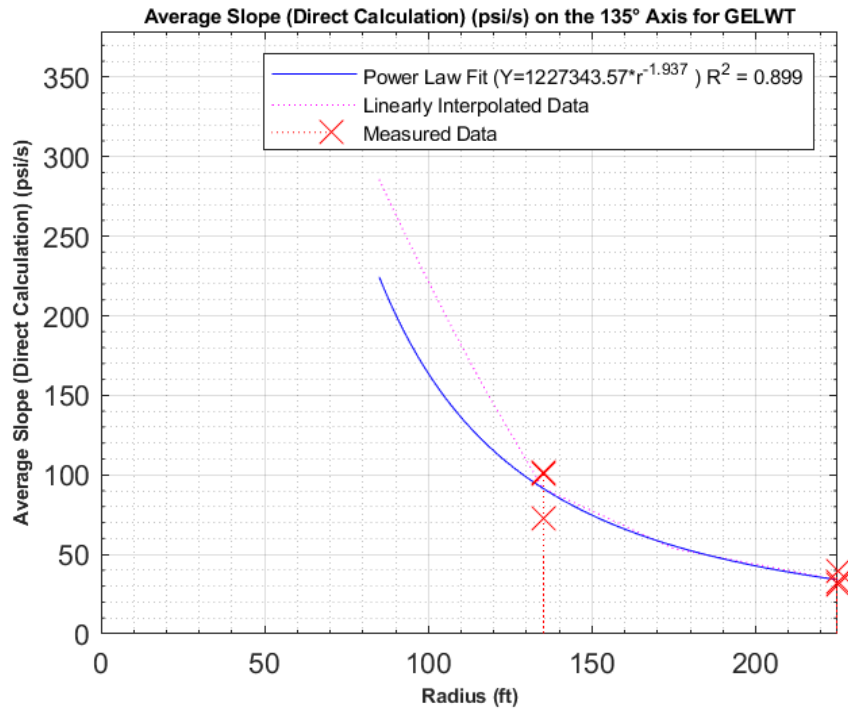


Figure 183 Slice plot along the 135° axis showing the power law fitted pressure rise rate data for gel emulsion operational Wyssen Tower charge.

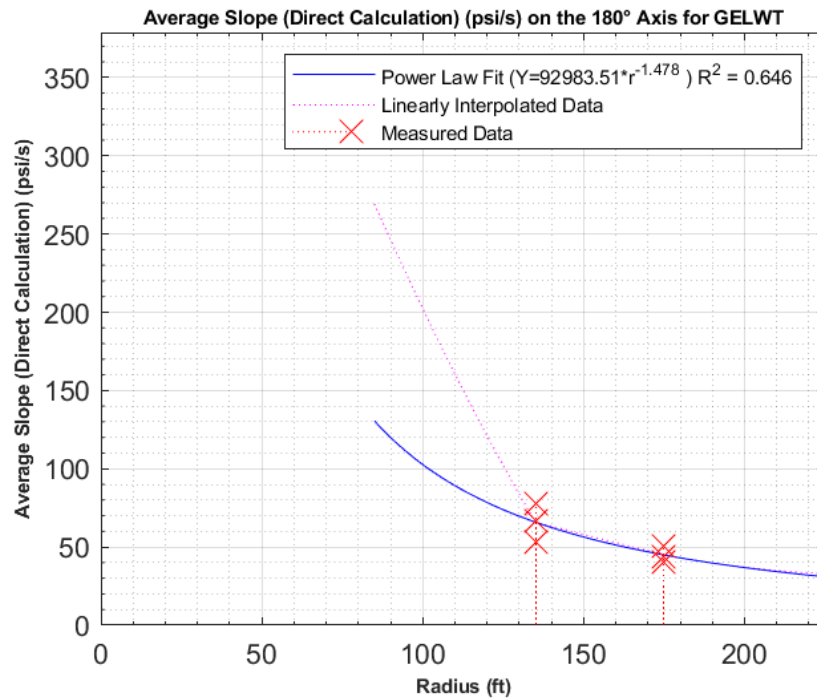


Figure 184 Slice plot along the 180° axis showing the power law fitted pressure rise rate data for gel emulsion operational Wyssen Tower charge.

3.2.6 Operational Pentolite Charge Wyssen Tower

As with the gel emulsion Wyssen Tower charge, comparison testing was also performed at the operational Wyssen Tower for the Pentolite-based charge being developed (see Section 2.4.2.7). Although the mass of the Pentolite charges used at the operational Wyssen Tower differed from those used during the flat-field testing, it was still of interest and educational value to the avalanche control practitioners to compare the results of the flat-field and operational Wyssen Tower testing. The results obtained from the custom Pentolite charge tests conducted at the operational tower are presented below.

Evaluation of the peak pressures generated by Pentolite charges deployed from the operational Wyssen Tower yielded interesting observations like those seen with the gel emulsion charge tests. To begin, it was observed that the charges produced approximately circular isolines with some flattening of the isolines to the rear of the device (Figure 185 and Figure 186). It was also determined from power law fitting that peak pressures for the operational Wyssen Tower with the Pentolite charges were higher than those for flat-field testing, but only for radial distances less than about 200 ft, 150 ft, 65 ft, and 36 ft for the 0°, 45°, 90°, and 135° axes, respectively. Moreover, peak pressures at the operational tower were lower than the flat-field testing for all radial distances along the 180° axis. In other words, the power laws fit to the data indicated that the peak pressures of the operational RAC system decayed more rapidly with radial distance than the flat-field results for each axis (Table 22 and Table 19). These power laws also indicated that the reference peak pressure of 0.145 psi or 1 kPa was reached at distances of approximately 345 ft on the 0° and 45° axes and approximately 300-315 ft on the 90°, 135°, and 180° axes (Figure 187 - Figure 191) whereas this reference peak pressure was reached at greater

distances of 404 ft - 467 ft for the flat-field testing of the – slightly smaller – Pentolite charges. Lastly, it was also shown that the separate charges utilized to carry out this testing produced repeatable results based on the consistency of the measurements since all microphones remained in place for all tests.

Table 22 A table of the power law coefficients for the peak pressure data along each of the measured axes for the Pentolite-based operational Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	2587	1.68	0.994
45	2252	1.65	0.998
90	1579	1.62	0.996
135	876	1.53	0.996
180	181	1.24	0.990

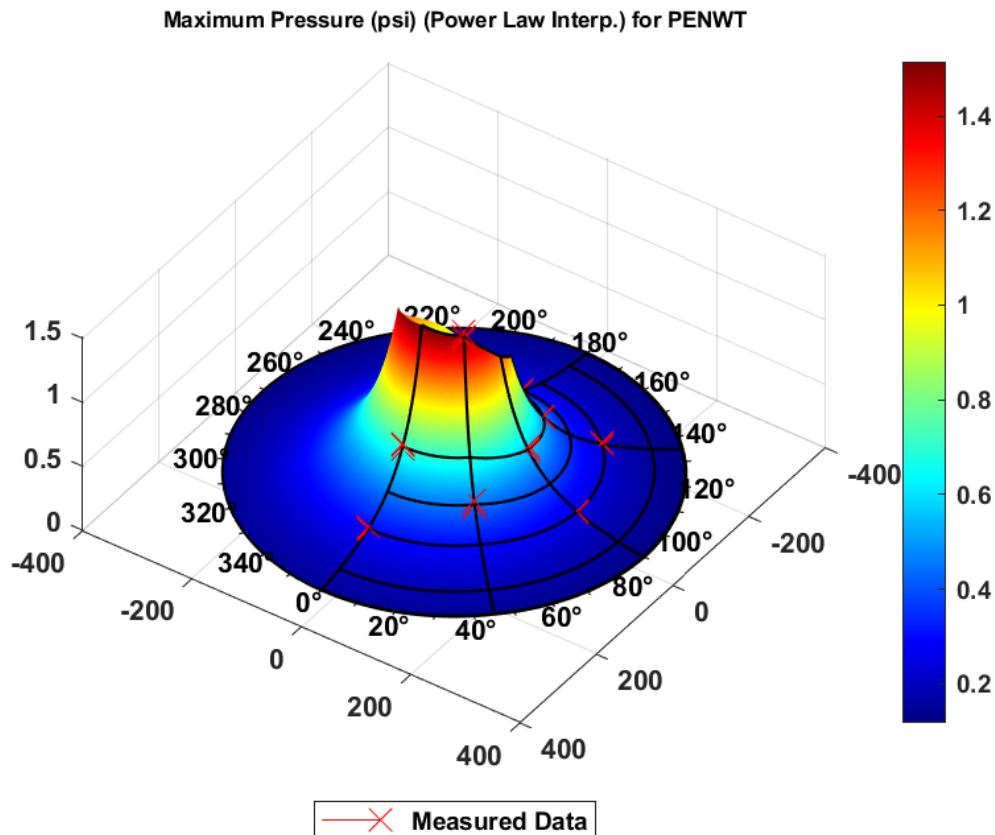


Figure 185 Surface plot of the power law fitted peak pressure data from the Pentolite-based operational Wyssen Tower charge testing

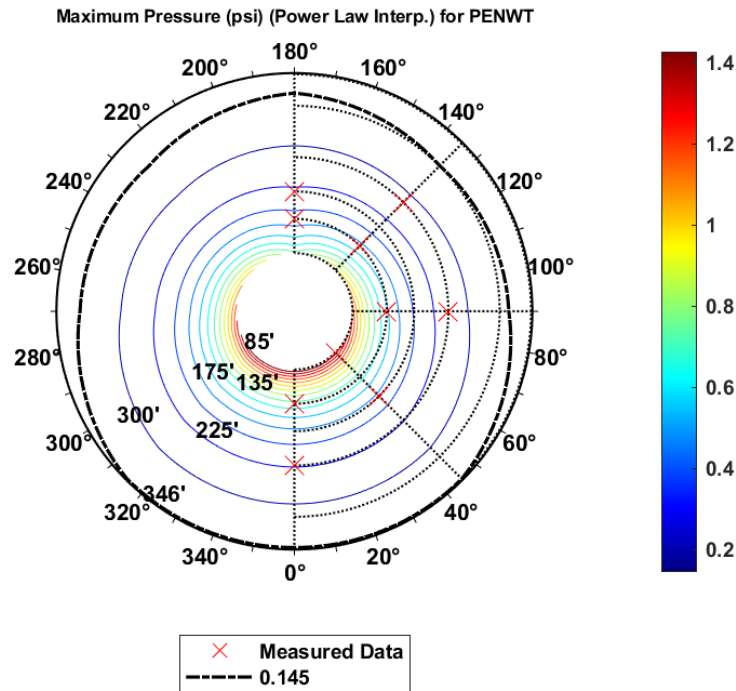


Figure 186 Contour plot of the power law fitted peak pressure data from the Pentolite-based operational Wyssen Tower charge testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

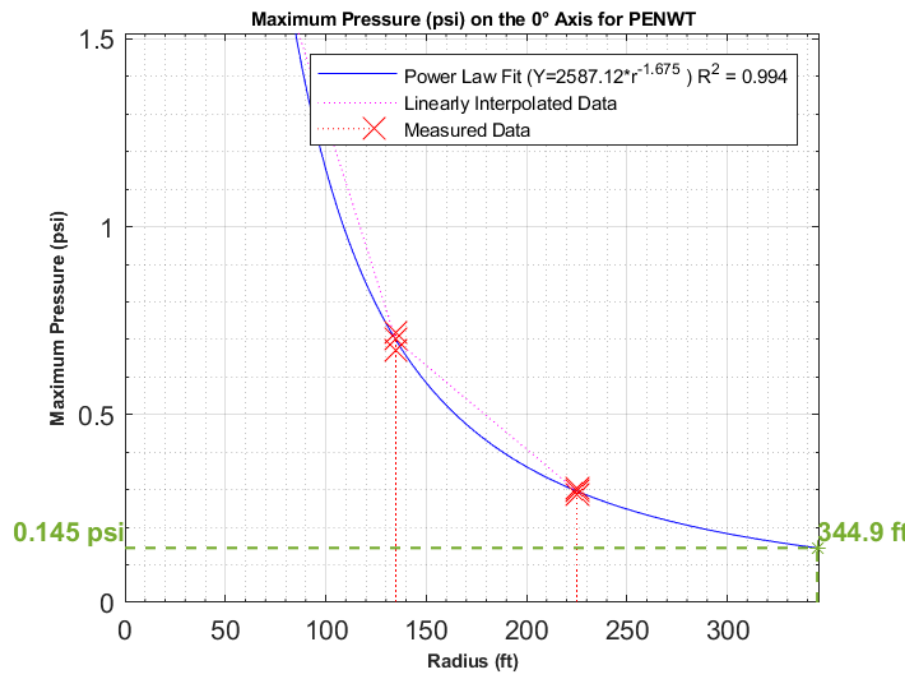


Figure 187 Slice plot along the 0° axis showing the power law fitted peak pressure data for the Pentolite-based operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

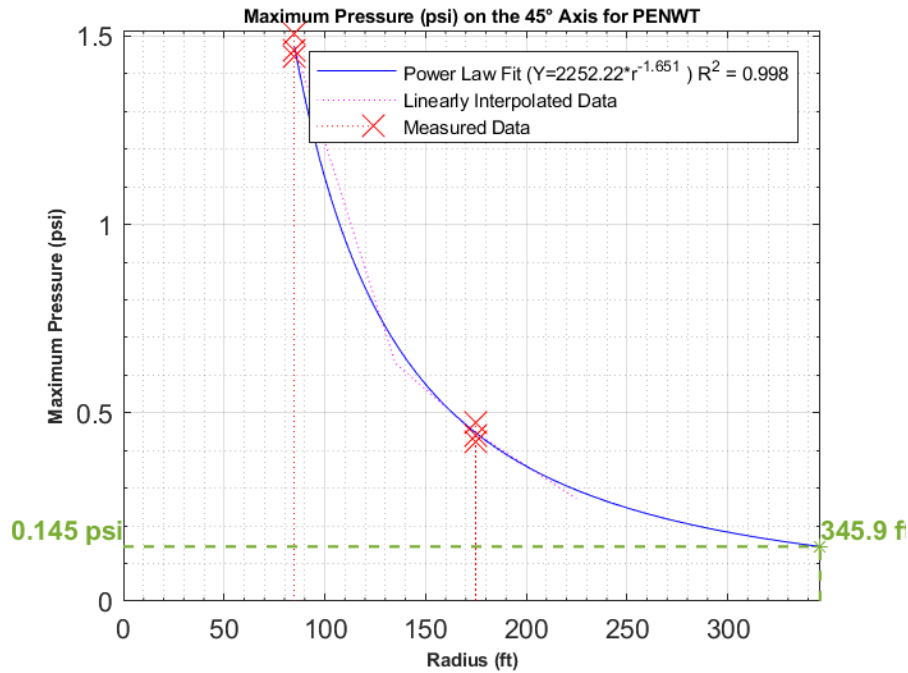


Figure 188 Slice plot along the 45° axis showing the power law fitted peak pressure data for the Pentolite-based operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

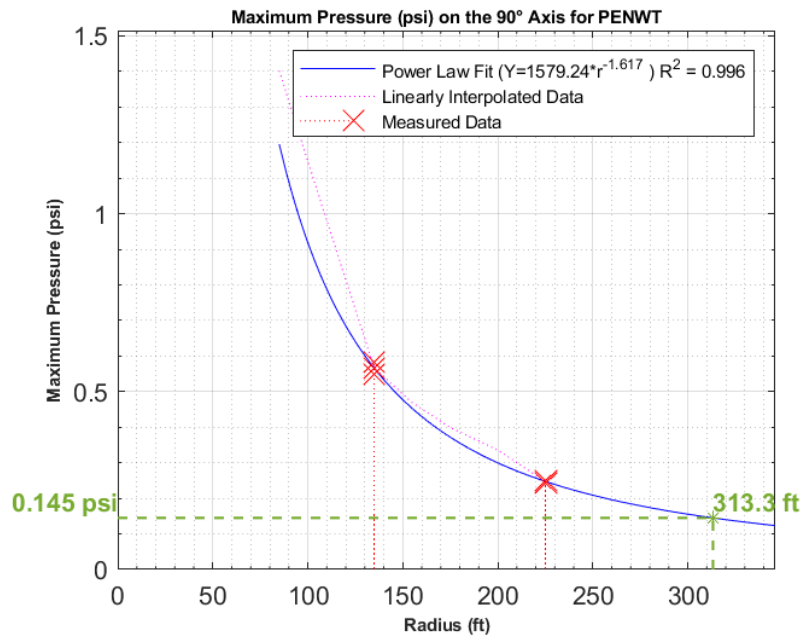


Figure 189 Slice plot along the 90° axis showing the power law fitted peak pressure data for the Pentolite-based operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

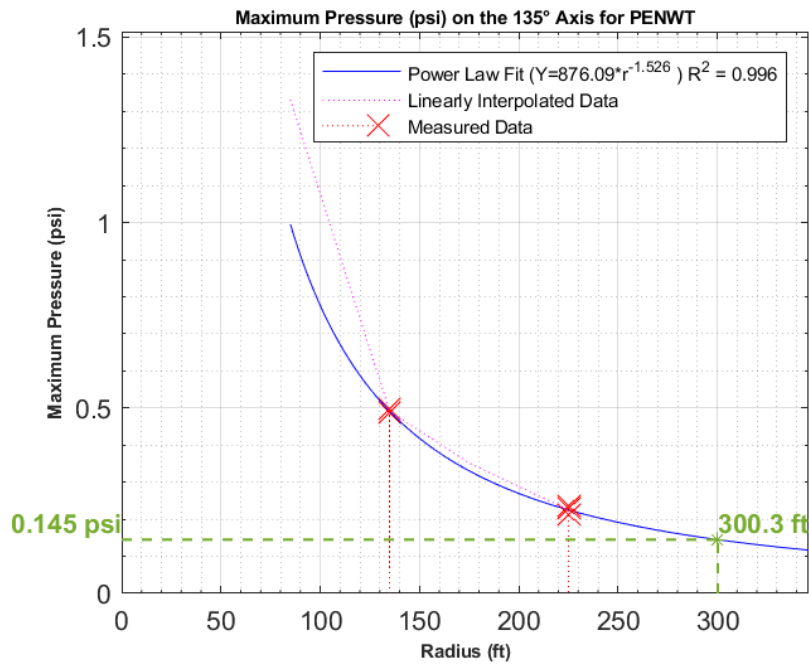


Figure 190 Slice plot along the 135° axis showing the power law fitted peak pressure data for the Pentolite-based operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

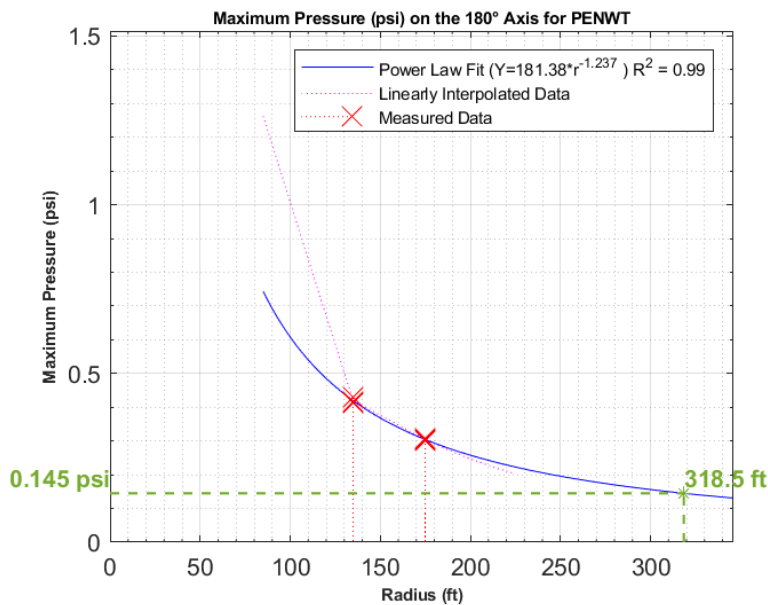


Figure 191 Slice plot along the 180° axis showing the power law fitted peak pressure data for the Pentolite-based operational Wyssen Tower charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

Energy equivalent results obtained from these tests provided many of the same observations as the peak pressure results and demonstrated similar behavior as was observed for the testing of the gel emulsion charges. The profile was, again, nearly circular with a distinct flattening of the isolines to the rear of the operational Wyssen Tower (Figure 192 and Figure 193). Energy equivalents were shown to be highest downslope of the RAC system (Figure 194 - Figure 198). Additionally, the power laws along each axis showed higher energy equivalents than the flat-field results for short ranges on the 0°, 45°, and 90° axes, but also showed a stronger decay with radial distance than the flat-field results for all axes (with the exception of the 180° axis). The power laws also indicated a stronger decay of the energy equivalent with radial distance along each axis than for peak pressure (Table 23).

Table 23 A table of the power law coefficients for the energy equivalent data along each of the measured axes for the Pentolite-based operational Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	636	2.52	0.994
45	461	2.44	0.999
90	443	2.46	0.999
135	115	2.26	0.996
180	27.8	2.01	0.998

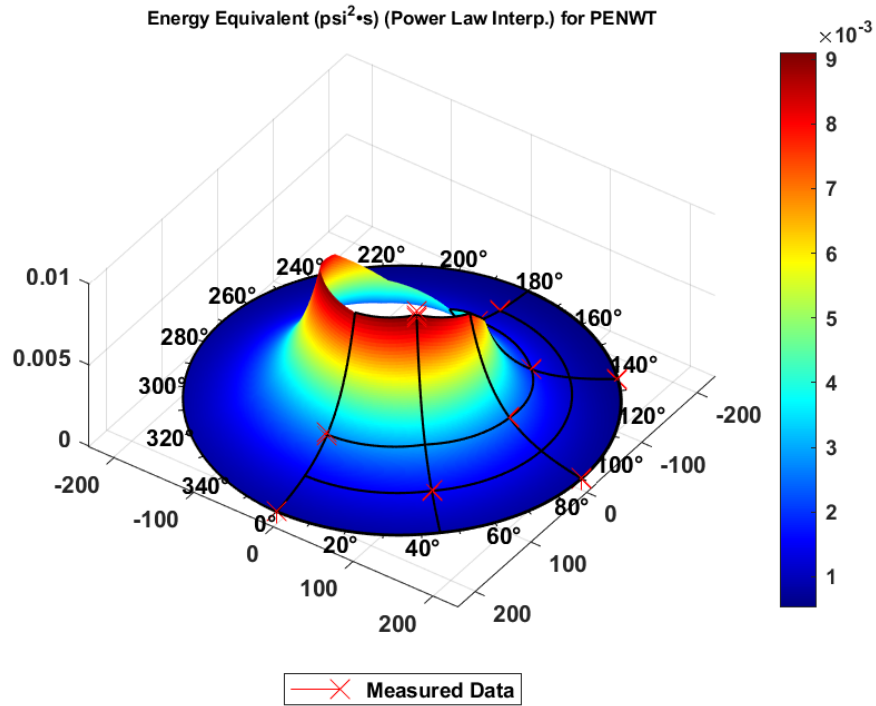


Figure 192 Surface plot of the power law fitted energy equivalent data from the Pentolite-based operational Wyssen Tower charge testing

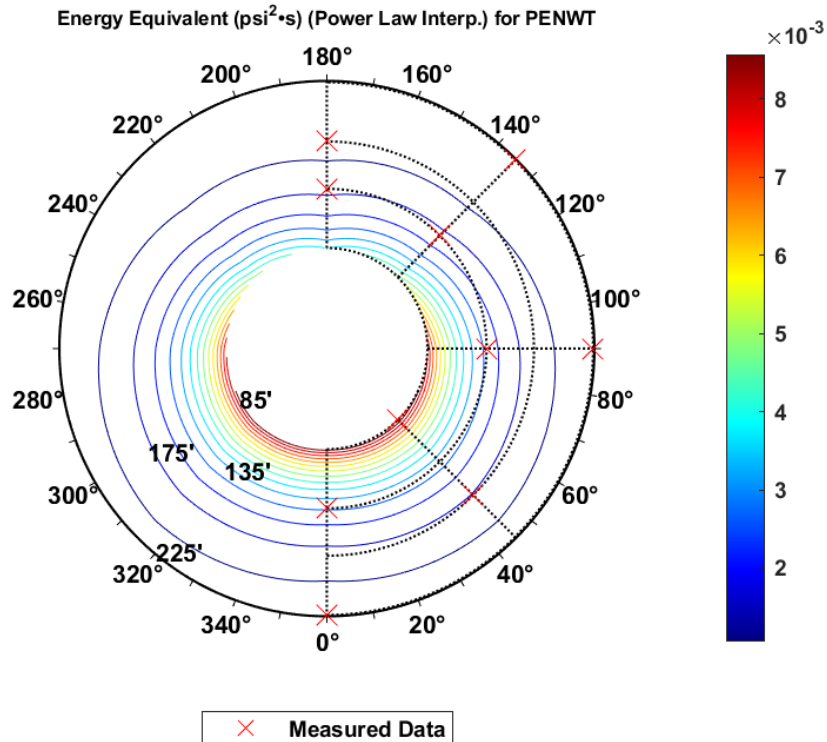


Figure 193 Contour plot of the power law fitted energy equivalent data from the Pentolite-based operational Wyssen Tower charge testing.

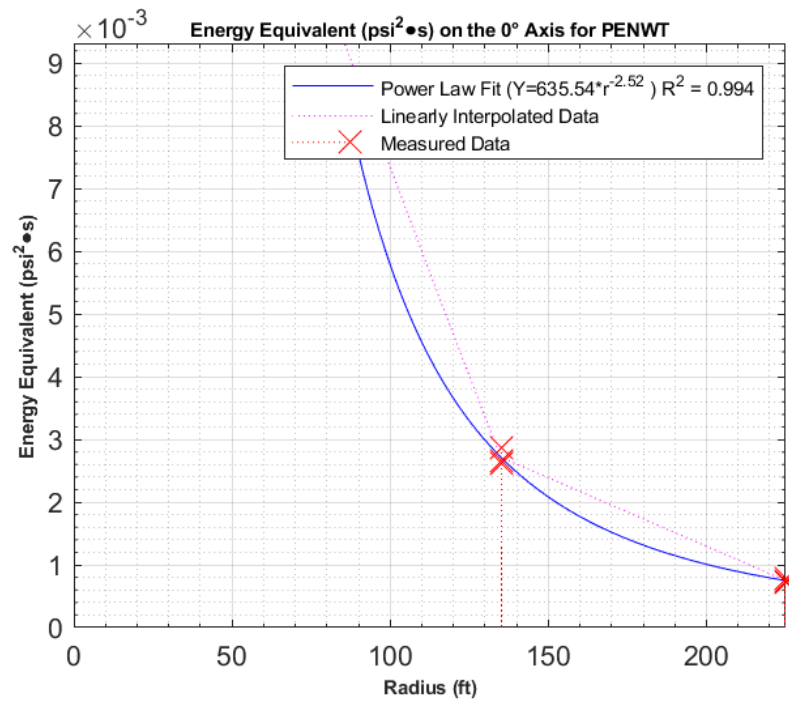


Figure 194 Slice plot along the 0° axis showing the power law fitted energy equivalent data for the Pentolite-based operational Wyssen Tower charge.

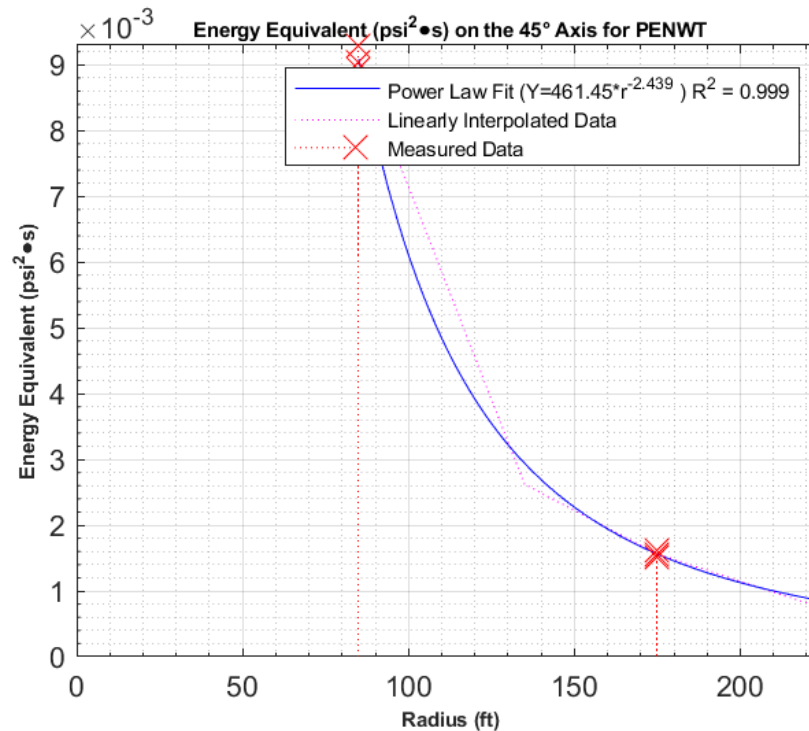


Figure 195 Slice plot along the 45° axis showing the power law fitted energy equivalent data for the Pentolite-based operational Wyssen Tower charge.

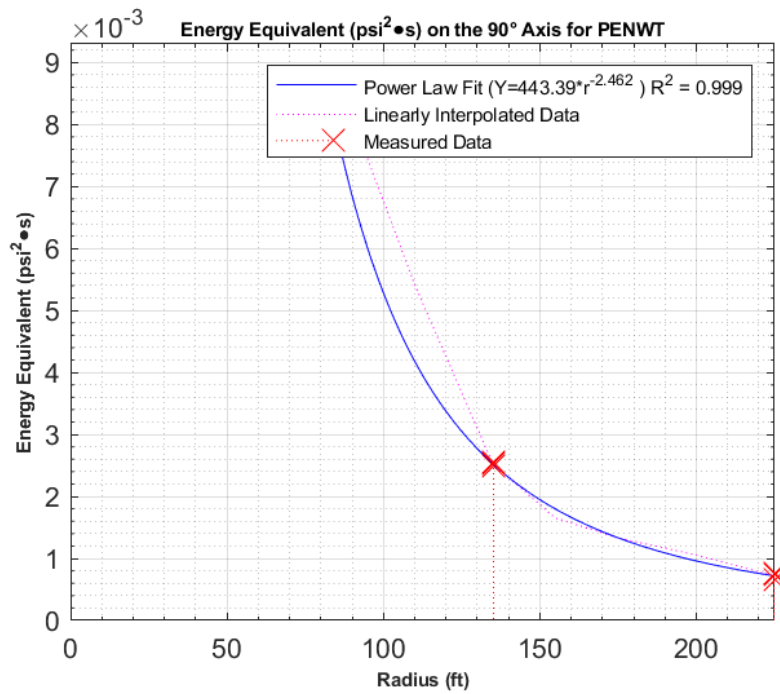


Figure 196 Slice plot along the 90° axis showing the power law fitted energy equivalent data for the Pentolite-based operational Wyssen Tower charge.

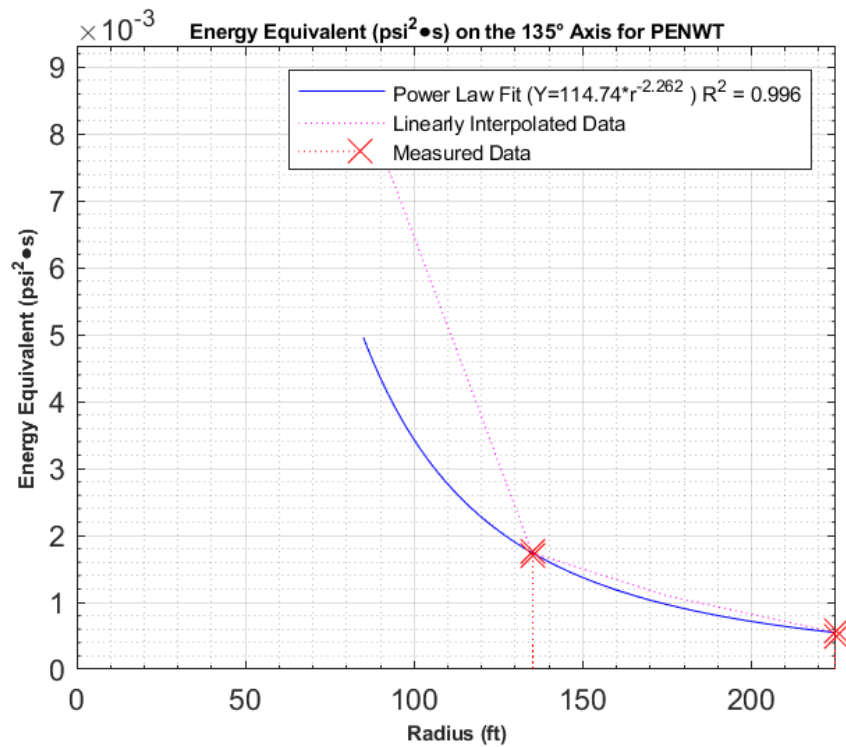


Figure 197 Slice plot along the 135° axis showing the power law fitted energy equivalent data for the Pentolite-based operational Wyssen Tower charge.

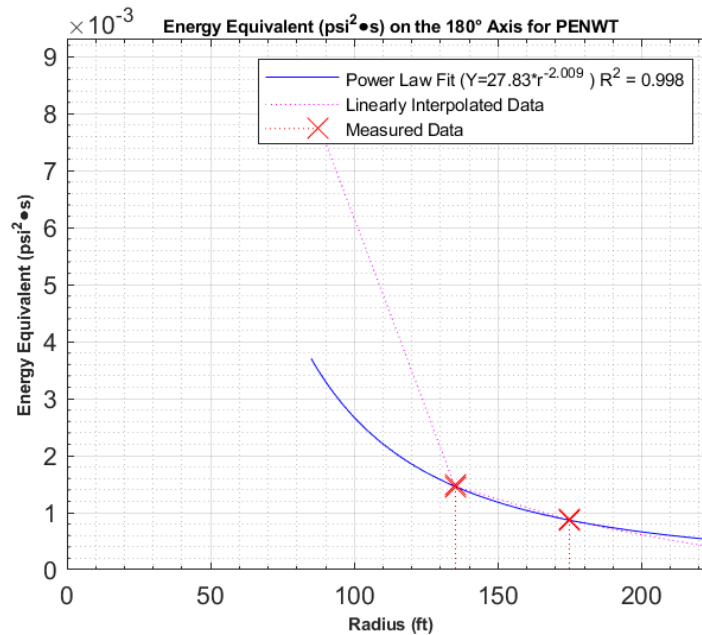


Figure 198 Slice plot along the 180° axis showing the power law fitted energy equivalent data the Pentolite-based operational Wyssen Tower charge.

Lastly, the pressure rise rate results again demonstrated similar trends to those discussed above for the peak pressure and energy equivalent results. More specifically, the pressure rise rate isolines were, again, approximately circular, but shifted downslope (Figure 199 and Figure 200). Power laws fit to describe the radial decay along each axis (Table 24) also indicated that the pressure rise rates decayed much more strongly with radial distance than was observed with flat-field testing (Figure 201 - Figure 205).

Table 24 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for the Pentolite-based operational Wyssen Tower charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	2.38e7	2.31	0.968
45	7.68e6	2.10	0.987
90	1.03e9	3.11	0.849
135	1.46e7	2.31	0.964
180	4.03e7	2.56	0.998

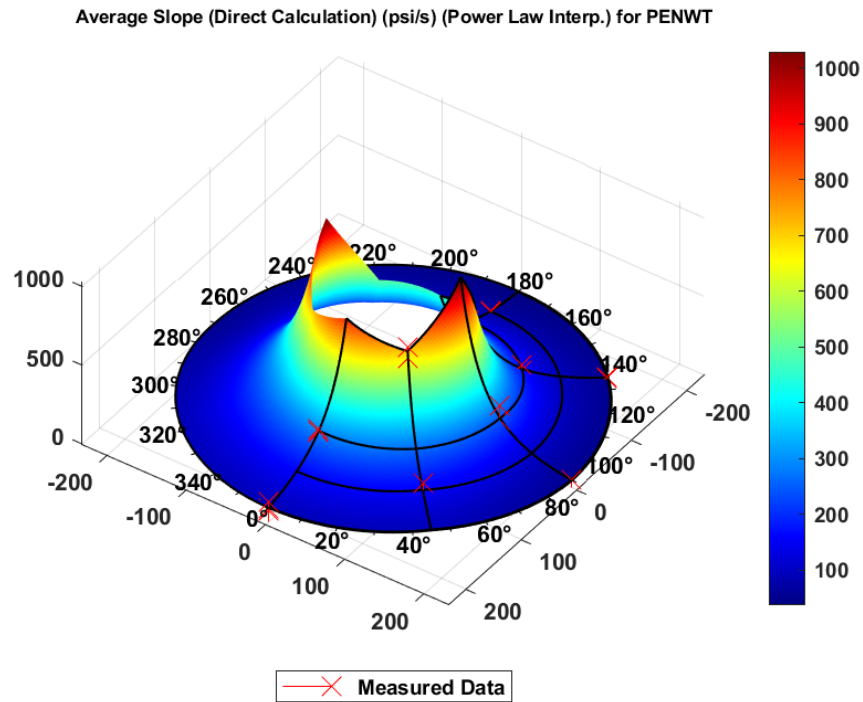


Figure 199 Surface plot of the power law fitted pressure rise rate data from the Pentolite-based operational Wyssen Tower charge testing

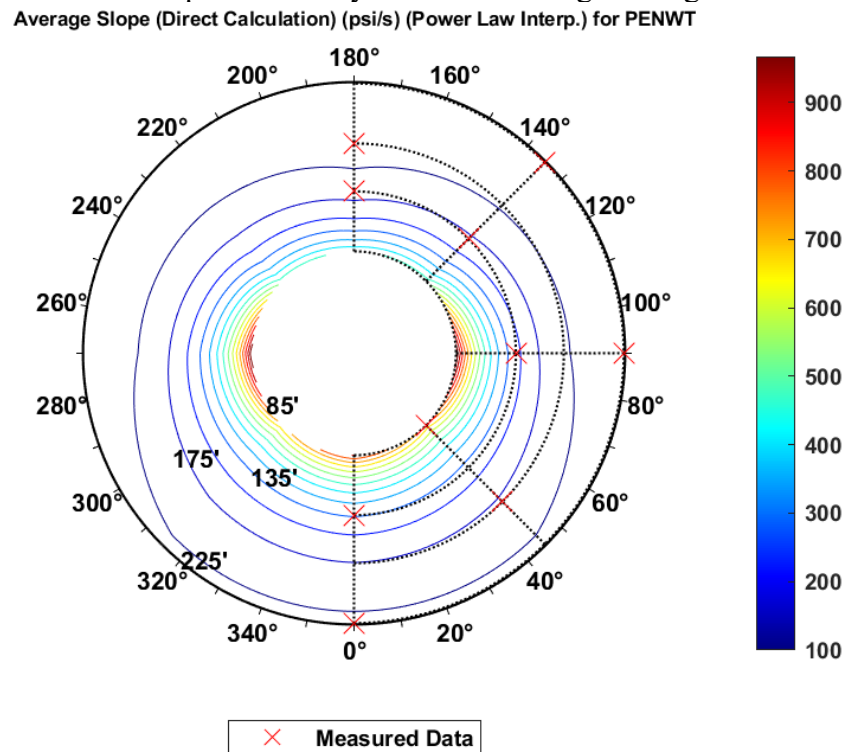


Figure 200 Contour plot of the power law fitted pressure rise rate data from the Pentolite-based operational Wyssen Tower charge testing.

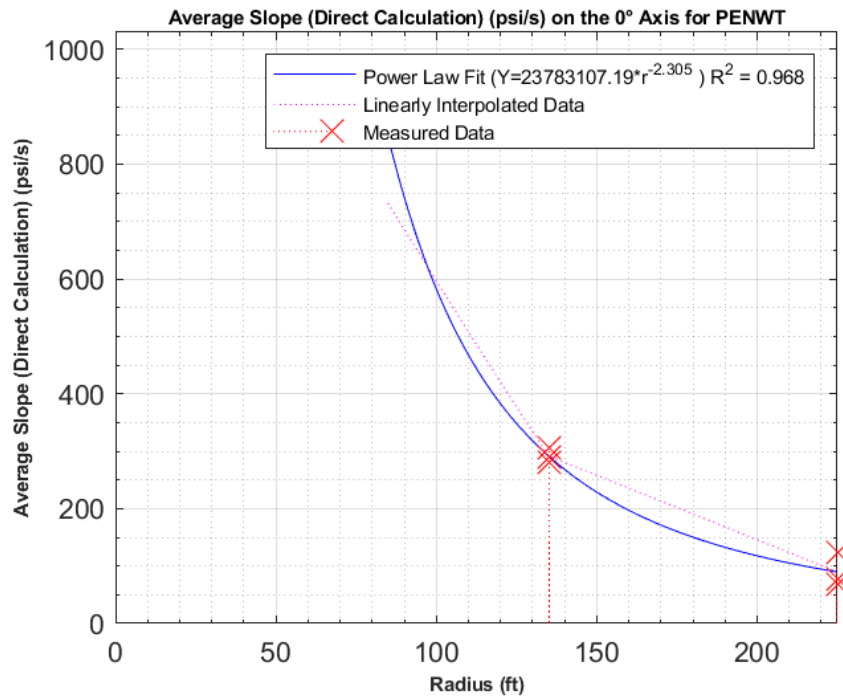


Figure 201 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for the Pentolite-based operational Wyssen Tower charge.

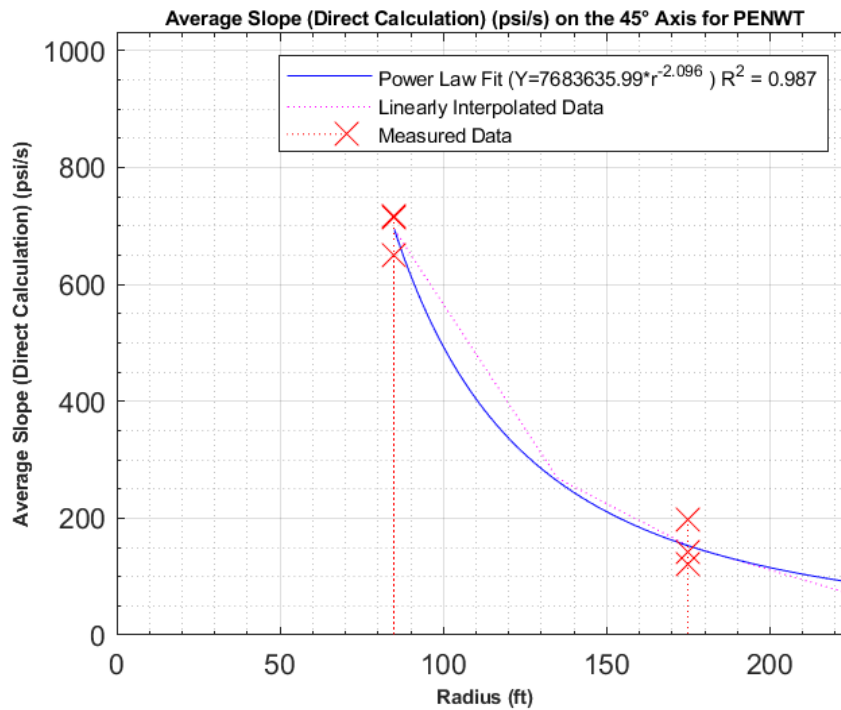


Figure 202 Slice plot along the 45° axis showing the power law fitted pressure rise rate data for the Pentolite-based operational Wyssen Tower charge.

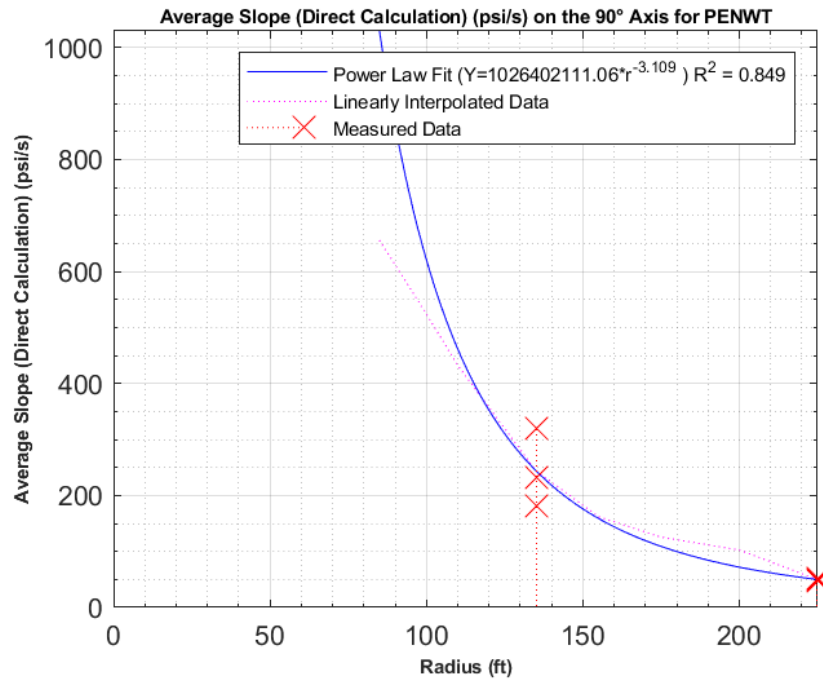


Figure 203 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for the Pentolite-based operational Wyssen Tower charge.

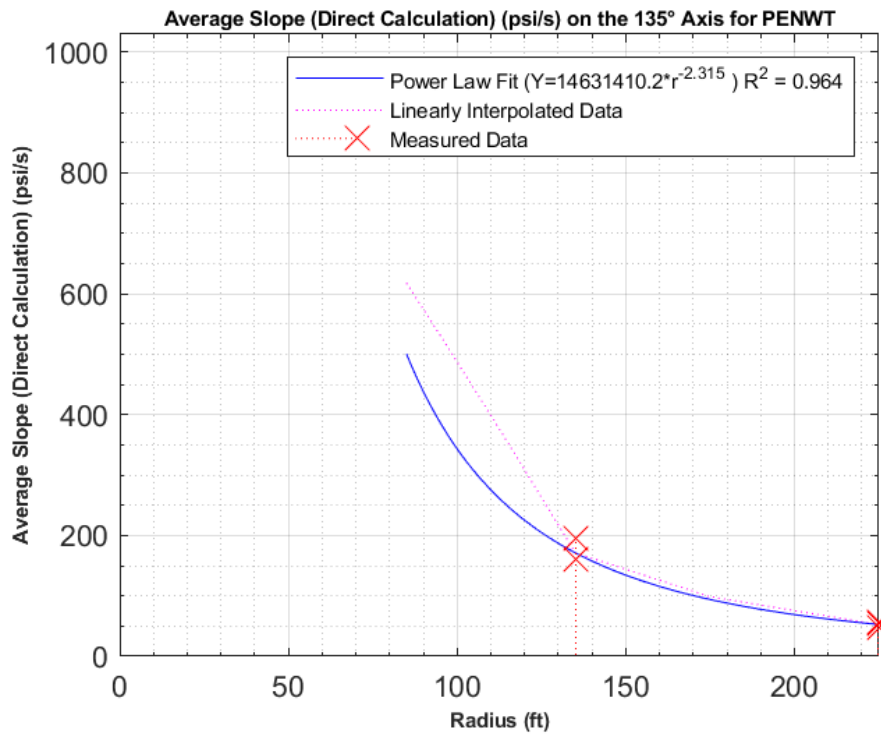


Figure 204 Slice plot along the 135° axis showing the power law fitted pressure rise rate data for the Pentolite-based operational Wyssen Tower charge.

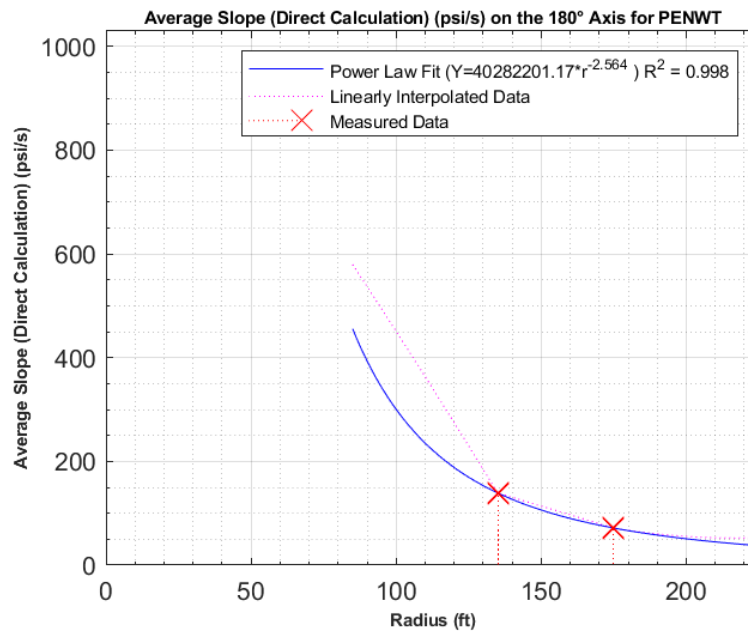


Figure 205 Slice plot along the 180° axis showing the power law fitted pressure rise rate data for the Pentolite-based operational Wyssen Tower charge.

3.2.7 Simulated Avalanche Guard

The last Phase 2 testing results to discuss are those of the flat-field simulated Avalanche Guard tests that were conducted as part of a request made by avalanche control practitioners. Although these tests represent only rough approximations of a true Avalanche Guard explosive, the results of these tests are still be presented herein to provide an account of all testing performed in this work and to provide the information to the interested parties. However, for simplicity and brevity, only the peak pressure results will be presented for this test. If other results are desired, they can be obtained from the Master Spreadsheet (APPENDIX A).

Peak pressures from the simulated Avalanche Guard charges detonated in the flat-field testing sequence showed that the charge had a very circular blast profile (Figure 206 and Figure 207). The power laws fit along each measured axis showed the power law coefficients were very

similar for all axes, with the average exponent, b , being 1.43 (Table 25). Additionally, the reference peak pressure of 0.145 psi or 1 kPa was located at radial distances between 214 - 237 ft for all axes (Figure 208 - Figure 212). Lastly, it was shown that the separate charges utilized to carry out this testing produced repeatable results, but there was slightly more inconsistency for measurements on the 45° axis (which remained in place for all three tests) than was observed for other explosives tested (Figure 209).

Table 25 A table of the power law coefficients for the peak pressure data along each of the measured axes for the flat-field simulated Avalanche Guard charge tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	188	1.33	0.997
45	168	1.29	0.910
90	621	1.54	0.985
135	521	1.50	0.997
180	491	1.51	0.965

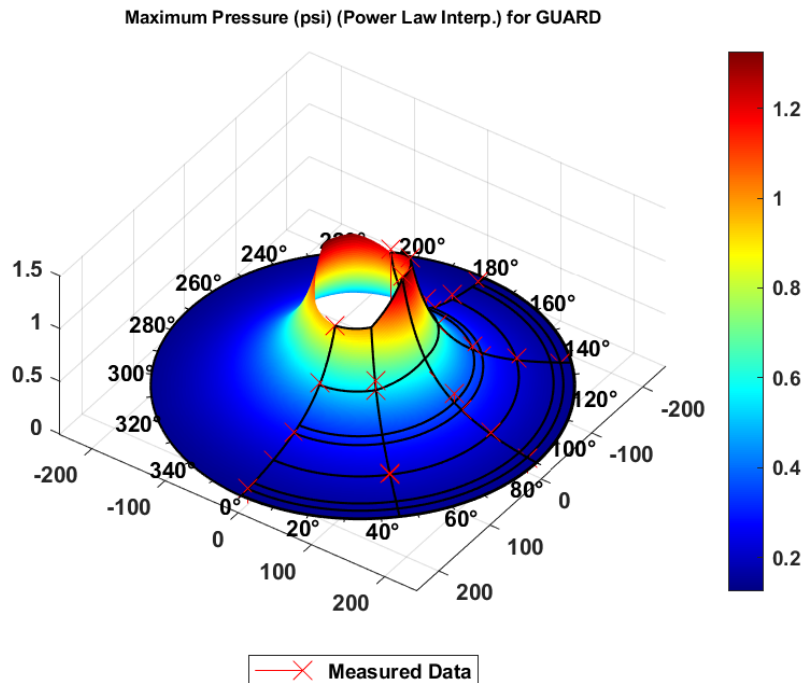


Figure 206 Surface plot of the power law fitted peak pressure data from the flat-field simulated Avalanche Guard charge testing

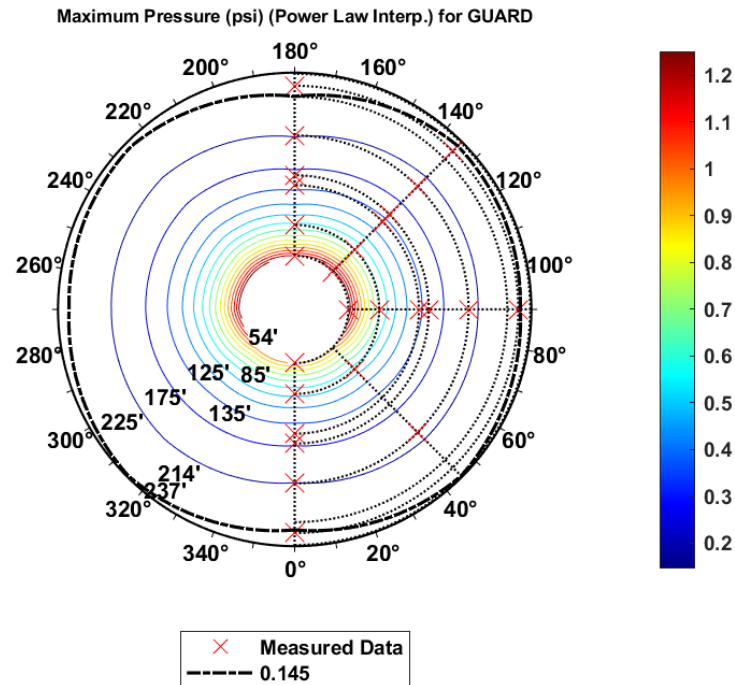


Figure 207 Contour plot of the power law fitted peak pressure data from the flat-field simulated Avalanche Guard charge testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

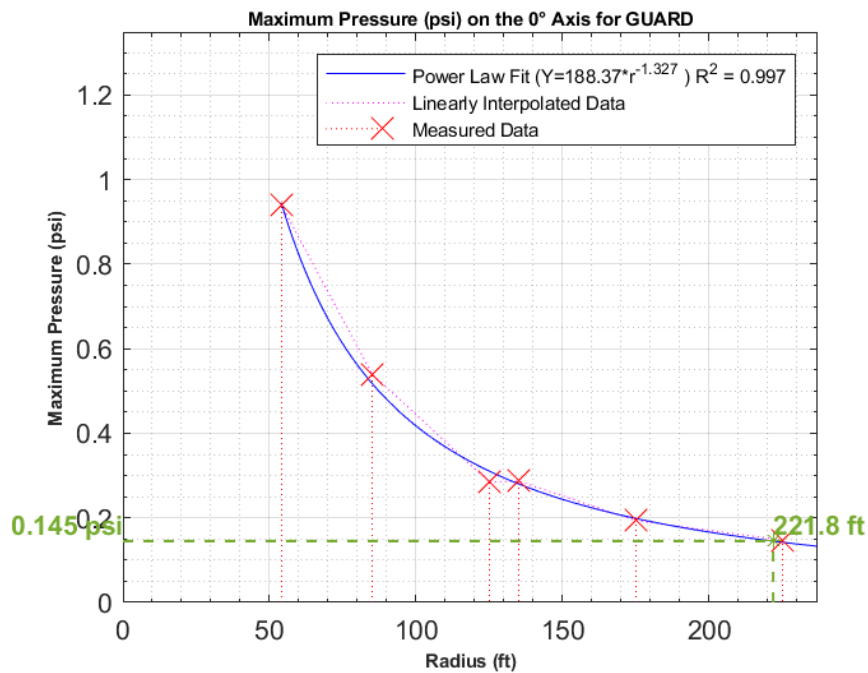


Figure 208 Slice plot along the 0° axis showing the power law fitted peak pressure data for the flat-field simulated Avalanche Guard charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

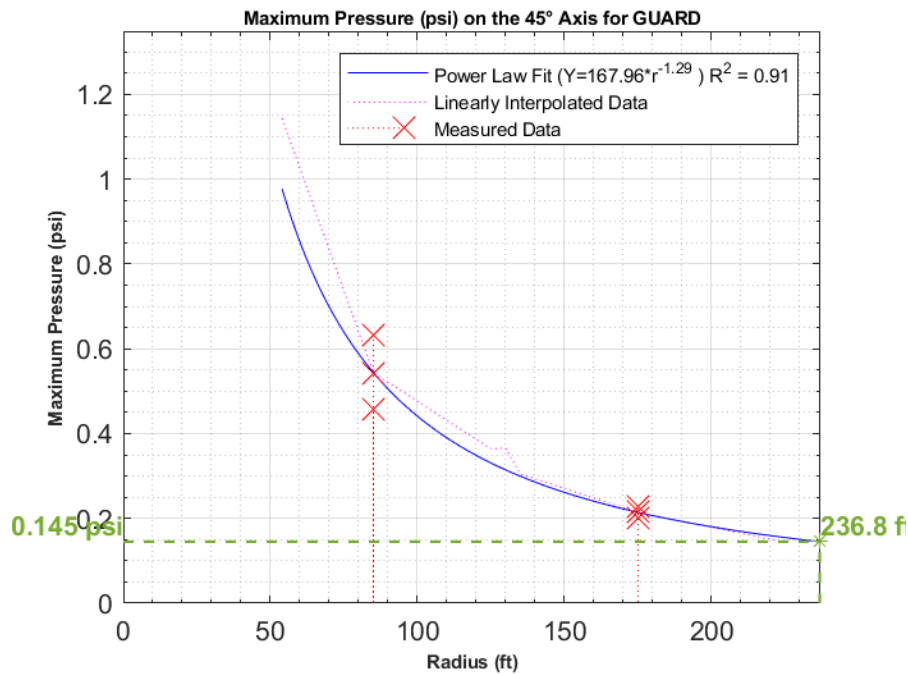


Figure 209 Slice plot along the 45° axis showing the power law fitted peak pressure data for the flat-field simulated Avalanche Guard charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

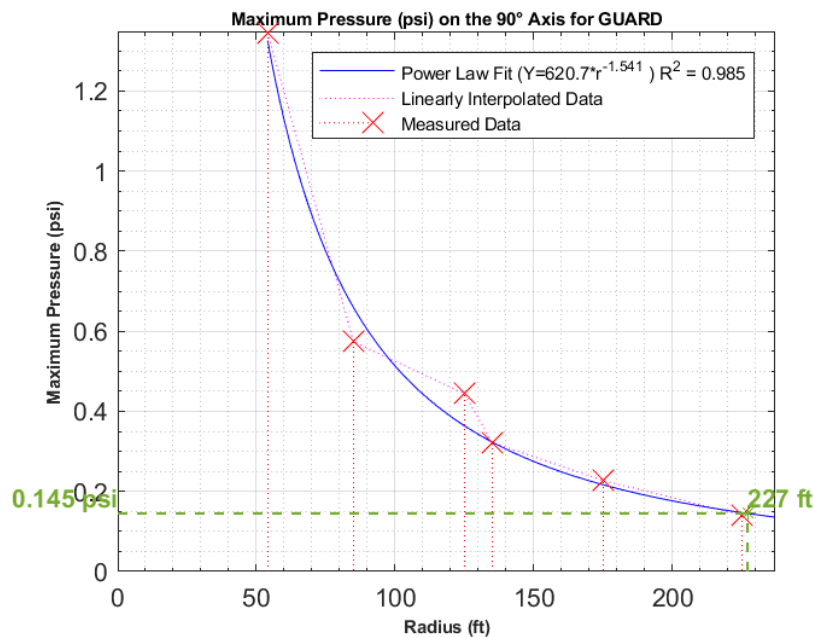


Figure 210 Slice plot along the 90° axis showing the power law fitted peak pressure data for the flat-field simulated Avalanche Guard charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

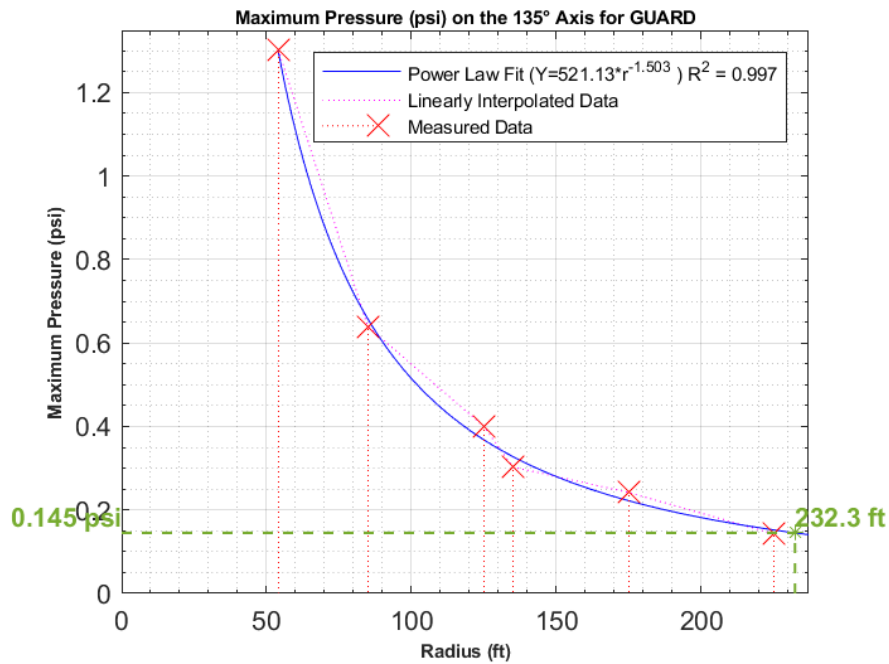


Figure 211 Slice plot along the 135° axis showing the power law fitted peak pressure data for the flat-field simulated Avalanche Guard charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

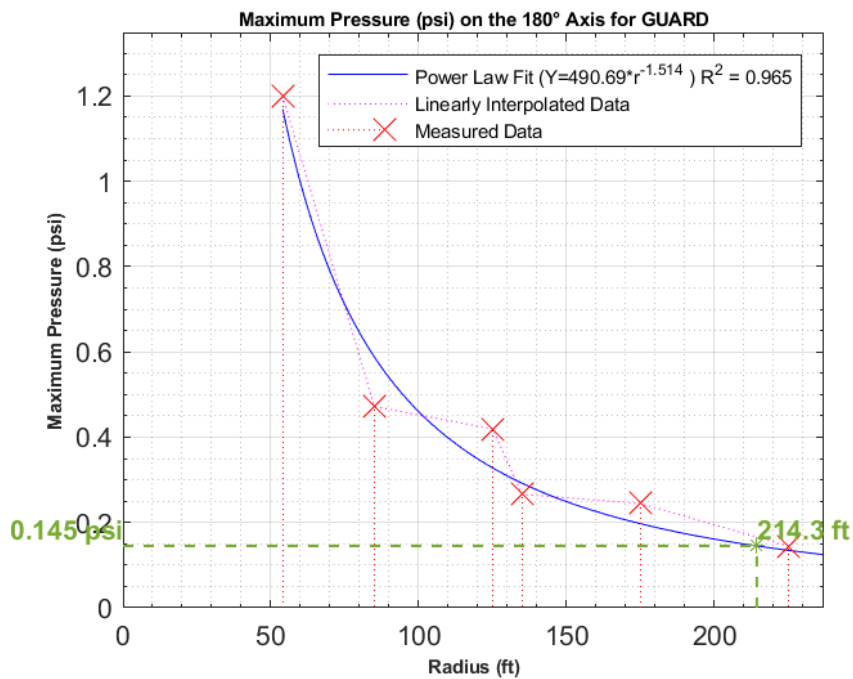


Figure 212 Slice plot along the 180° axis showing the power law fitted peak pressure data for the flat-field simulated Avalanche Guard charge. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

3.3 Phase 3 Results

As discussed previously, Phase 3 of this project sought to provide data from explosives detonated in and around unique terrain features to compare against the baseline performance data collected in Phase 2. It was intended that these comparative tests would provide a better understanding into how terrain features influence the behavior and performance of avalanche control explosives, and how that influence might be leveraged to optimize avalanche control practices. To accomplish this, blast pressure data was obtained at locations with ridges, cliffs, gullies, and foliage nearby to determine what, if any, effects these features have on the device's overpressure decay, energy equivalent decay, and pressure rate decay.

3.3.1 Cliff Terrain Feature

The first terrain feature considered involved placing a Pentolite charge directly in front of a large vertical cliff. The same charge and a similar equipment arrangement from the Pentolite testing at the operational Wyssen Tower were used to conduct this test. The peak pressure, energy equivalent, and pressure rise rate results of this test are presented below.

The peak pressure results of the cliff terrain testing showed a more directional behavior than was observed for the Pentolite tests conducted at the operational Wyssen Tower (Figure 213 and Figure 214). Although the peak pressures were lower at smaller radial distances for the 0° axis, and were lower overall on the 45° and 90° axes than for the Pentolite Wyssen Tower tests, the decay of the peak pressure with radial distance was smaller for this test – particularly on the 0° axis (Table 26). This is further demonstrated by the radial locations of the reference peak pressure of 0.145 psi or 1 kPa (Figure 215 - Figure 217). For the terrain feature testing, this

reference peak pressure was determined by the power laws to be reached at a radial distance of 429 ft, 317 ft, and 280 ft on the 0°, 45°, and 90° axes, respectively. For comparison, the results of the Pentolite testing at the operational Wyssen Tower indicated that this reference pressure was reached at a radial distance of 345 ft, 346 ft, and 313 ft on the 0°, 45°, and 90° axes, respectively.

Table 26 A table of the power law coefficients for the peak pressure data along each of the measured axes for the cliff terrain feature tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	176	1.17	1.000
45	886	1.51	1.000
90	520	1.45	0.963

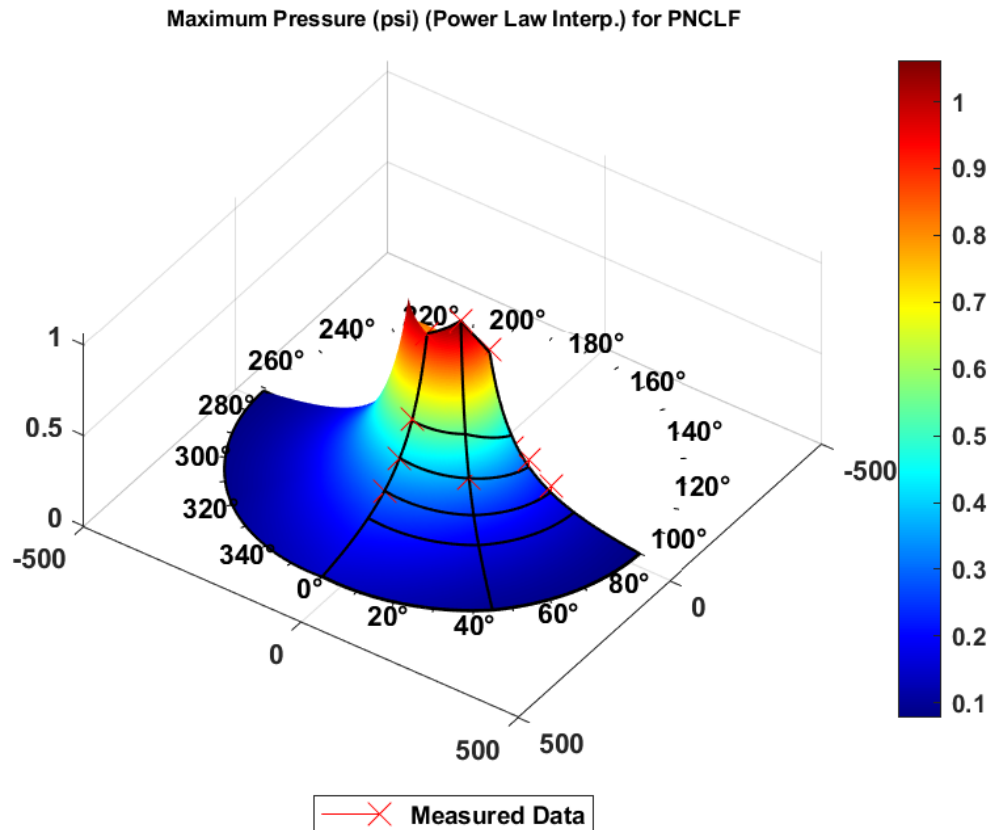


Figure 213 Surface plot of the power law fitted peak pressure data from the cliff terrain feature testing

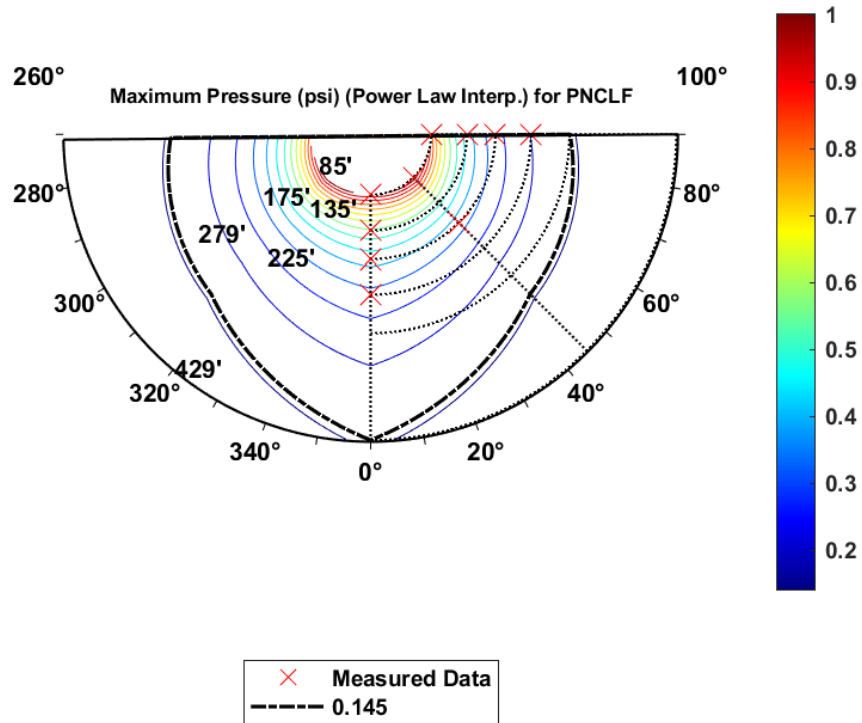


Figure 214 Contour plot of the power law fitted peak pressure data from the cliff terrain feature testing. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

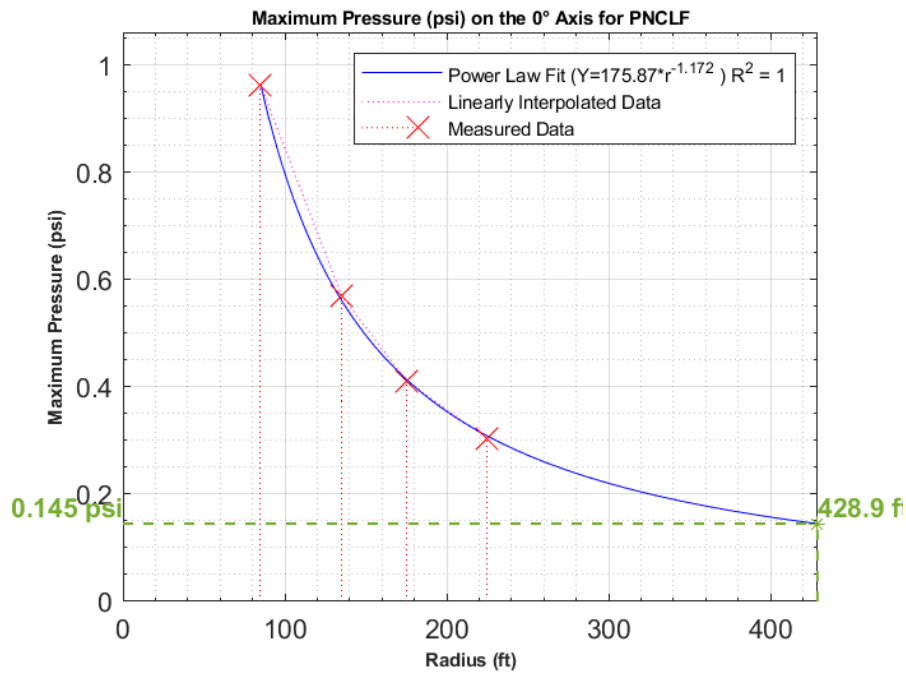


Figure 215 Slice plot along the 0° axis showing the power law fitted peak pressure data for the cliff terrain feature testing. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

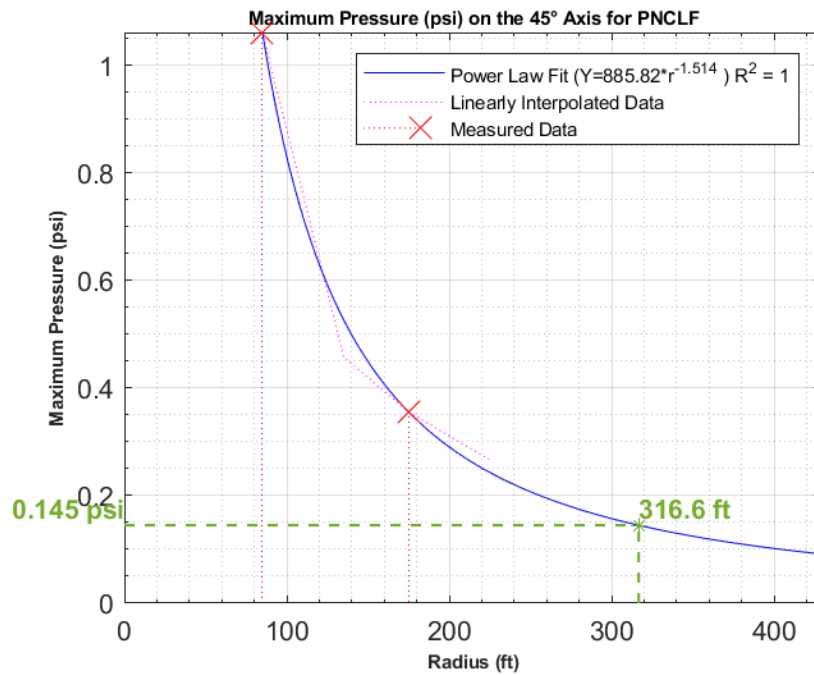


Figure 216 Slice plot along the 45° axis showing the power law fitted peak pressure data for the cliff terrain feature testing. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

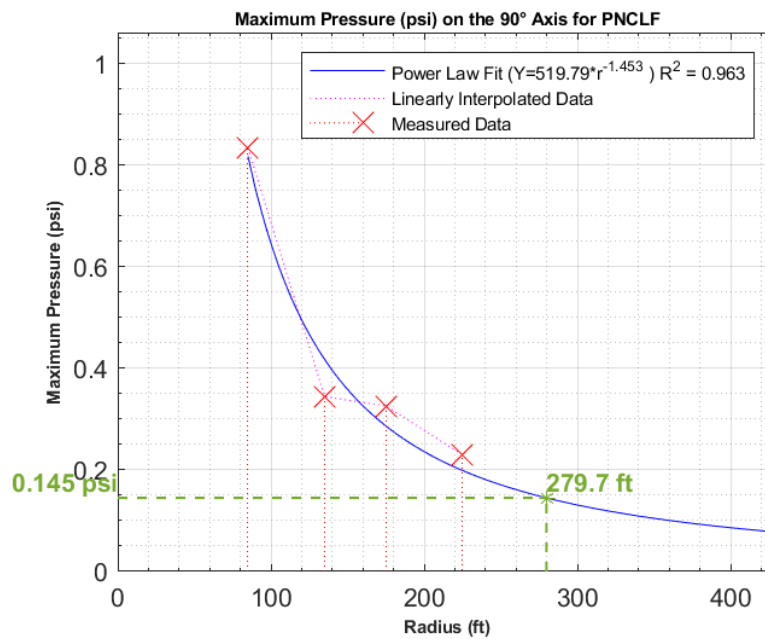


Figure 217 Slice plot along the 90° axis showing the power law fitted peak pressure data for the cliff terrain feature testing. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

The energy equivalent results obtained from this test also depicted a directional isoline profile for the Pentolite charge detonated in front of the cliff (Figure 218 and Figure 219). The power laws fit to describe the radial decay of the energy equivalent, in Table 27, showed that the energy equivalent decayed less strongly on the 0° axis, about as strongly on the 45° axis, and more strongly on the 90° axis than the results from the operational Wyssen Tower tests (Figure 220 - Figure 222). Energy equivalent magnitudes were slightly greater than for the operational Wyssen Tower tests along the 0° axis but were smaller for the 45° and 90° axes.

Table 27 A table of the power law coefficients for the energy equivalent data along each of the measured axes for the cliff terrain feature tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	71.3	2.04	1.000
45	467	2.48	1.000
90	1442	2.84	0.949

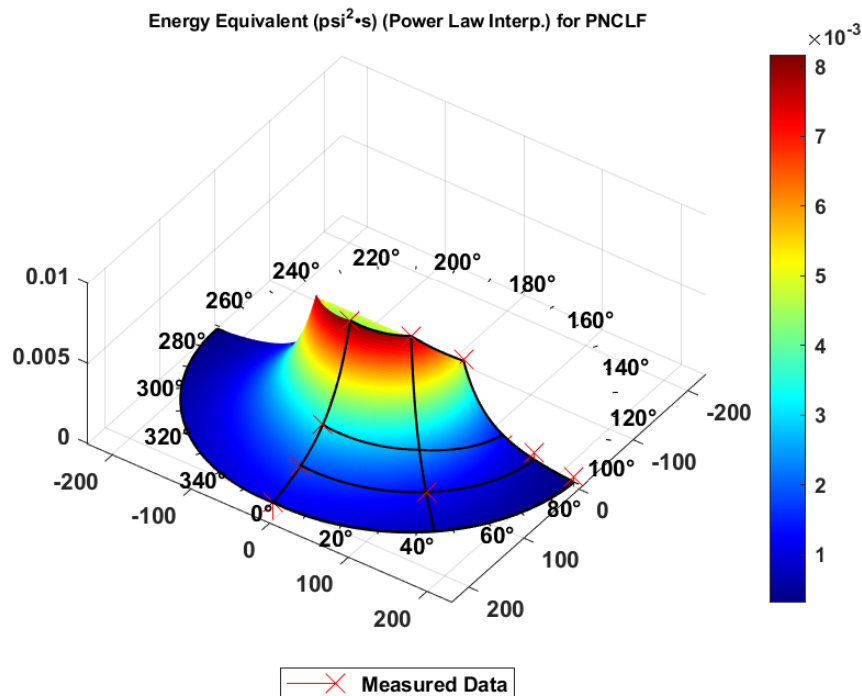


Figure 218 Surface plot of the power law fitted energy equivalent data from the cliff terrain feature testing

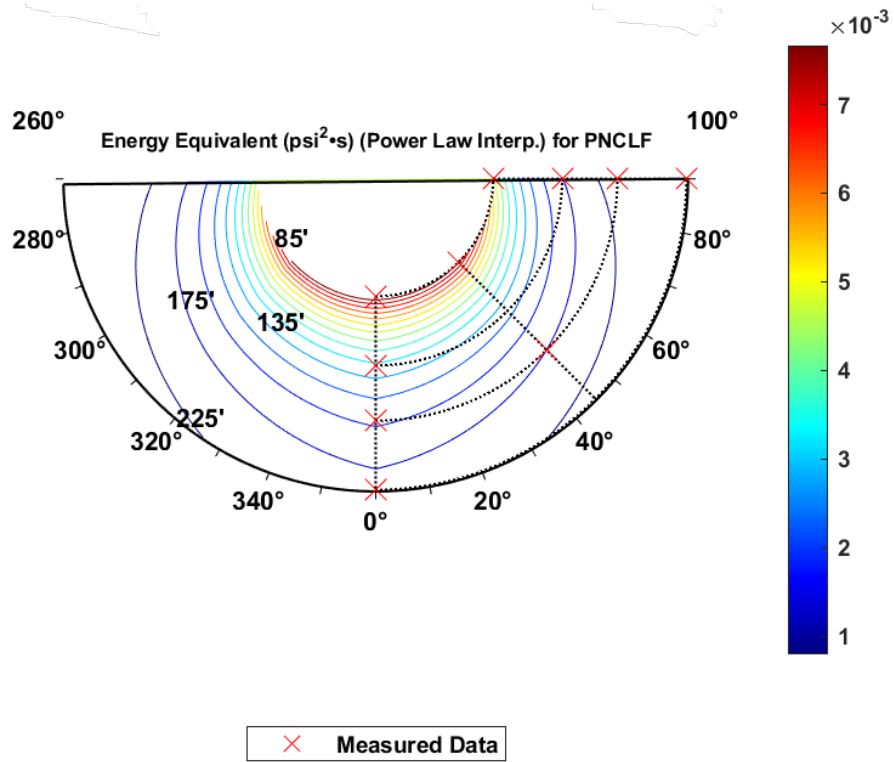


Figure 219 Contour plot of the power law fitted energy equivalent data from the cliff terrain feature testing.

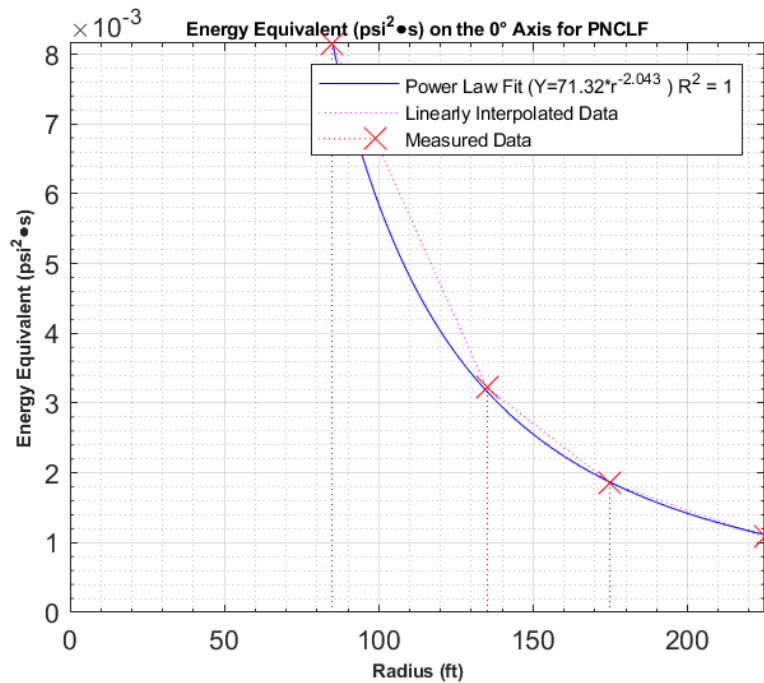


Figure 220 Slice plot along the 0° axis showing the power law fitted energy equivalent data for the cliff terrain feature testing.

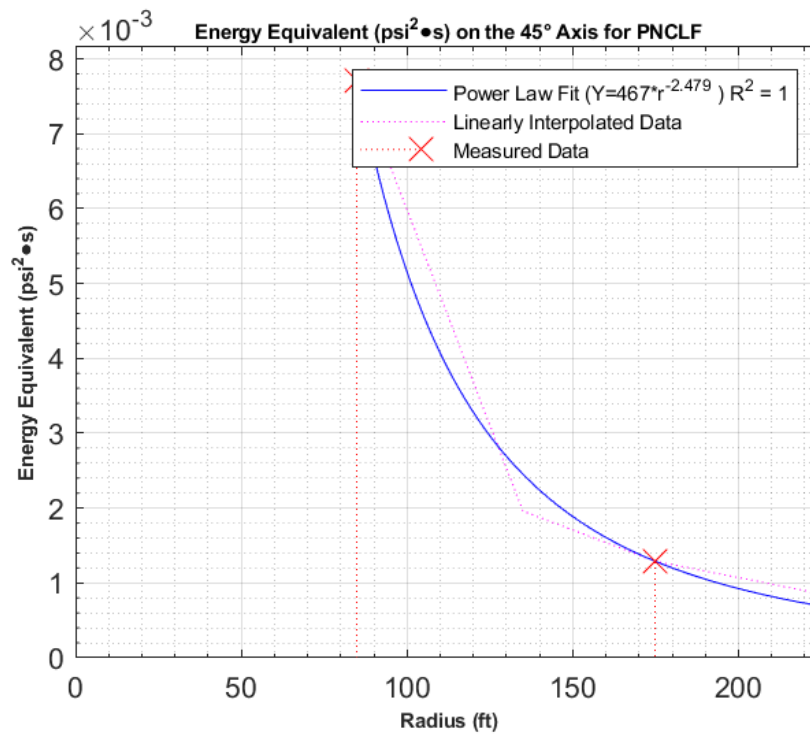


Figure 221 Slice plot along the 45° axis showing the power law fitted energy equivalent data for the cliff terrain feature testing.

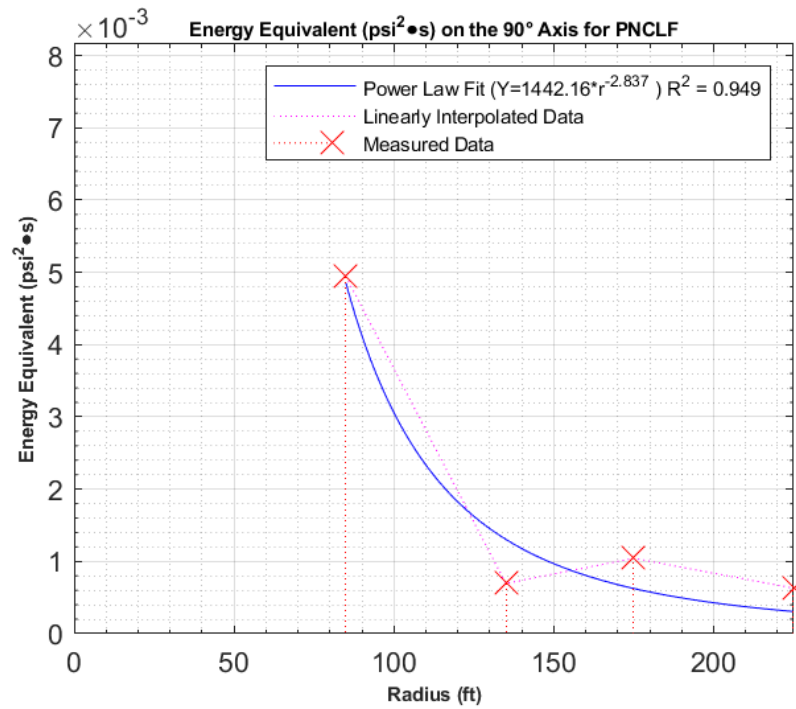


Figure 222 Slice plot along the 90° axis showing the power law fitted energy equivalent data for the cliff terrain feature testing.

The pressure rise rate results revealed similar behavior to the those shown above for energy equivalent. The pressure rise rate isolines were, again, directed downslope, but less distinctly than the peak pressure or energy equivalent results (Figure 223 and Figure 224). Power laws fit to describe the radial decay along each axis (Figure 225-Figure 227 and Table 28) indicated that the pressure rise rates decayed less strongly with radial distance than energy equivalent, but more strongly than peak pressure. It was also observed that the pressure rise rates decayed less strongly for this terrain testing than for the Pentolite testing at the operational Wyssen Tower. However, it was also noted that the pressure rise rate was considerably less than those observed at the operational tower testing, even along the 0° axis.

Table 28 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for the cliff terrain feature tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	2.84e5	1.58	0.999
45	6.23e5	1.76	1.000
90	1.45e7	2.40	0.959

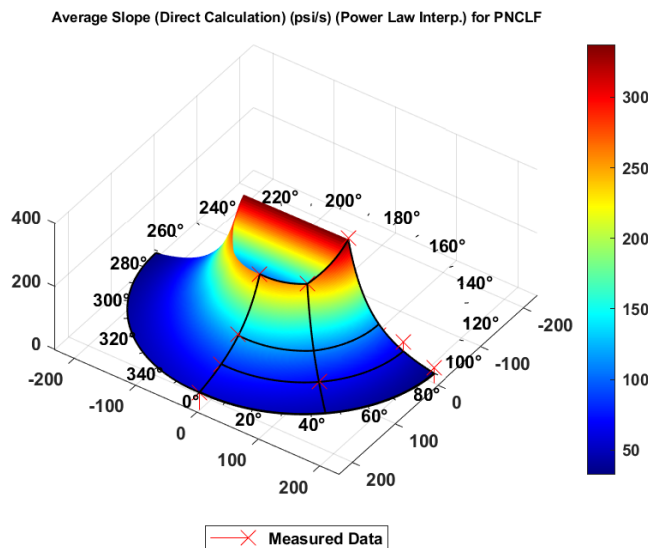


Figure 223 Surface plot of the power law fitted pressure rise rate data from the cliff terrain feature testing

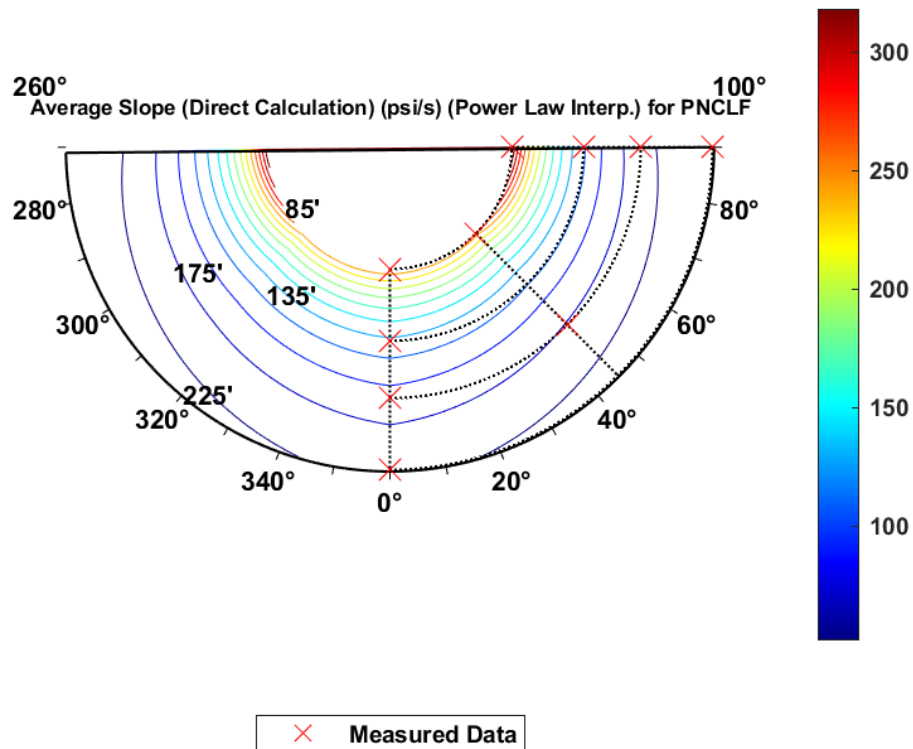


Figure 224 Contour plot of the power law fitted pressure rise rate data from the cliff terrain feature testing.

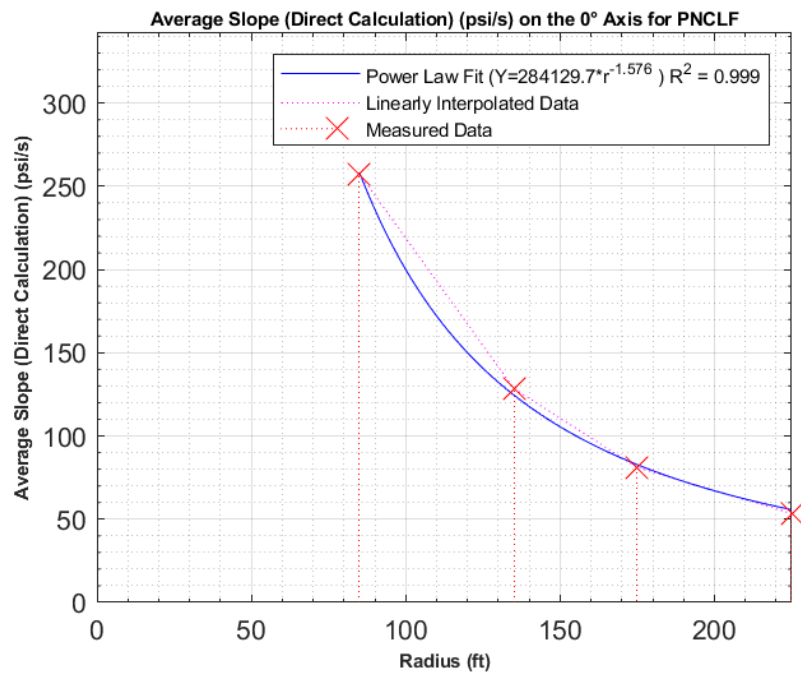


Figure 225 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for the cliff terrain feature testing.

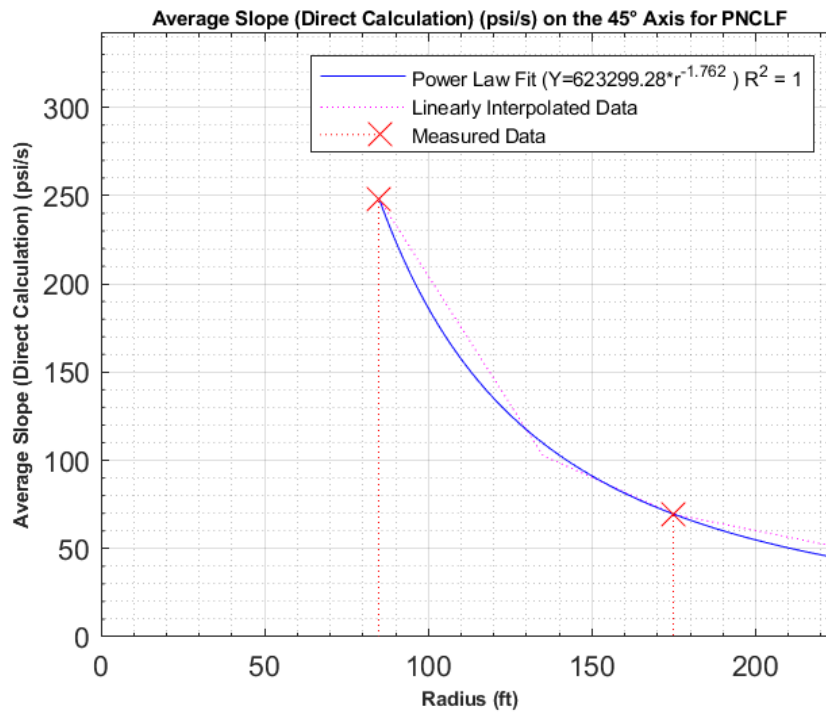


Figure 226 Slice plot along the 45° axis showing the power law fitted pressure rise rate data for the cliff terrain feature testing.

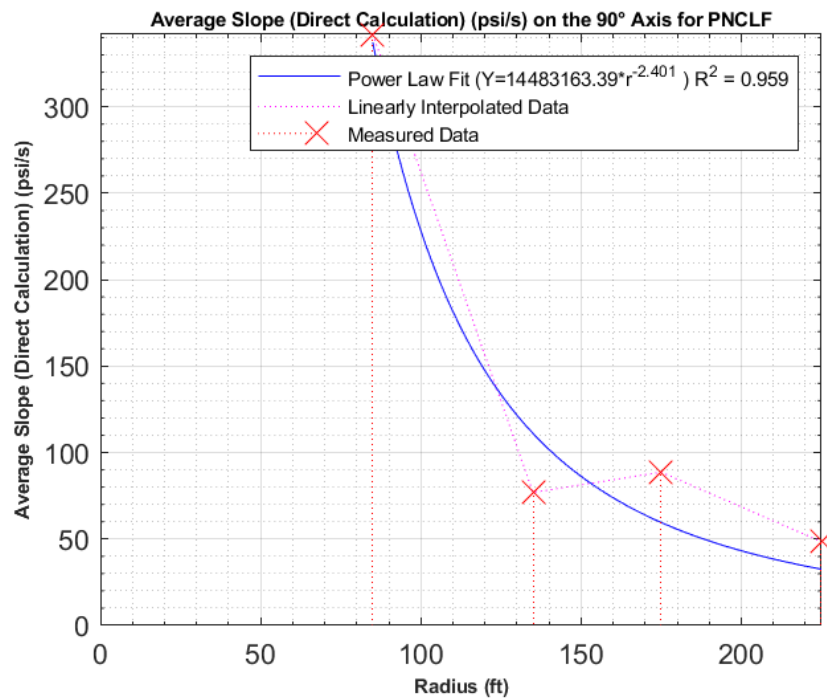


Figure 227 Slice plot along the 90° axis showing the power law fitted pressure rise rate data for the cliff terrain feature testing.

3.3.2 Ridge Terrain Feature

The second feature investigated was the placement of an explosive on the top of a ridge. For this test, an O'Bellx device that had been installed on a rock ridgeline was used, and thus a similar equipment layout to the O'Bellx tests from Phase 2 was utilized to facilitate comparison of the results. Unfortunately, while conducting this test, the one and only microphone failure of this research project occurred, and no data was captured on one of the two microphones placed on the 90° axis. As such, the decision was made to remove the 90° axis from the dataset and evaluate the peak pressure, energy equivalent, and pressure rise rate results along the 0°, 30°, and 60° axes alone. The elimination of the 90° axis made it challenging to properly graph and interpret the pressure measurements of this test. Consequently, only the power laws and slice plots will be presented for this section.

Peak pressures from the O'Bellx installed on the ridgeline yielded surprisingly similar results to those obtained from the O'Bellx tested during Phase 2. In particular, based on the power laws fit to each axis, it was shown that the ridgeline O'Bellx had a directional response focused on the 0° and 30° axes at shorter radial distances, but for distances of 70 ft or greater the 60° axis actually had higher peak pressures (Figure 228 - Figure 230). In this way, the ridgeline O'Bellx had very similar relative behavior between each axis as was found for the Phase 2 O'Bellx. This similarity is best summarized by the calculated radial location of the reference peak pressure of 1 kPa or 0.145 psi. From the power law fits for the ridgeline O'Bellx (Table 29), it was determined that this reference peak pressure would be reached at a distance of about 124 ft on the 0° axis, 109 ft on the 30° axis, and 174 ft on the 60° axis. Similarly, the power law fits for the Phase 2 O'Bellx indicated that this reference peak pressure would be reached at a

distance of 115 ft on the 0° axis, 105 ft on the 30° axis, and 188 ft on the 60° axis. Despite these distinct similarities, there were also two key differences between the two O’Bellx’s tested. First, the peak pressures produced by the ridgeline O’Bellx were lower overall, and secondly, the peak pressures decayed less rapidly with radial distance than the Phase 2 O’Bellx on the 0° and 30° axes but decayed similarly on the 60° axis.

Table 29 A table of the power law coefficients for the peak pressure data along each of the measured axes for the ridgeline O’Bellx tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	59.1	1.25	1.000
30	113	1.42	1.000
60	14.0	0.89	1.000

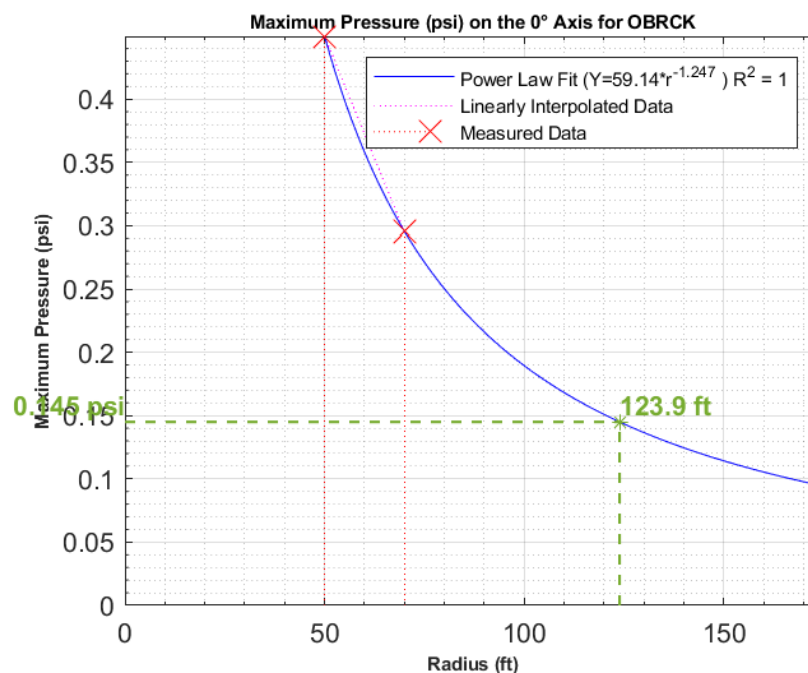


Figure 228 Slice plot along the 0° axis showing the power law fitted peak pressure data for the ridgeline O’Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

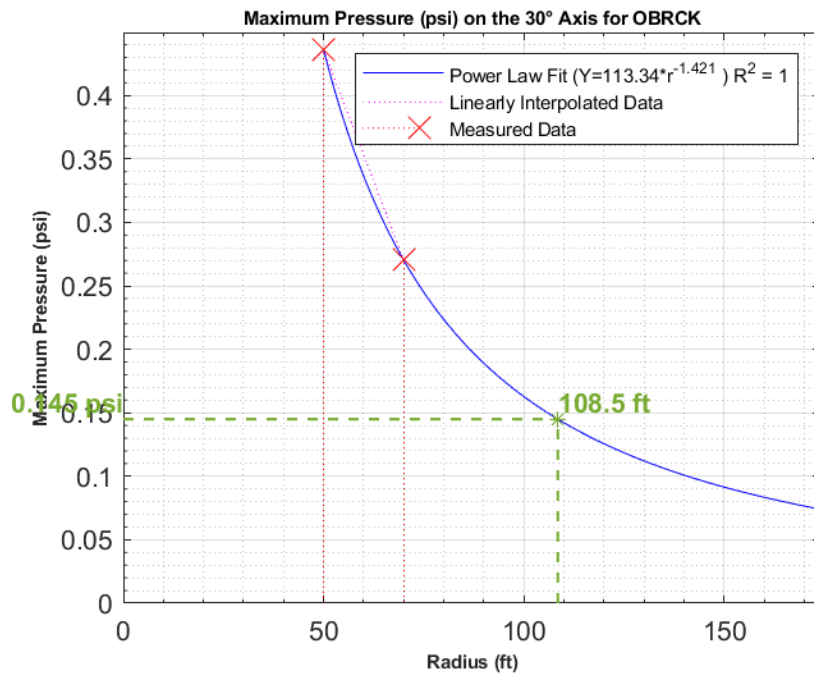


Figure 229 Slice plot along the 30° axis showing the power law fitted peak pressure data for the ridgeline O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

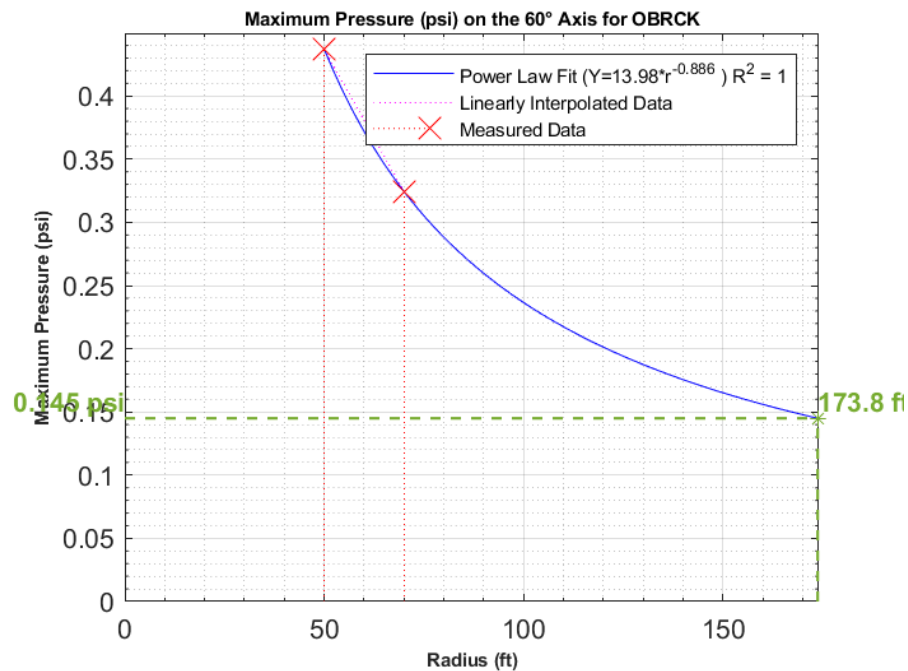


Figure 230 Slice plot along the 60° axis showing the power law fitted peak pressure data for the ridgeline O'Bellx. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

Energy equivalent results for the ridgeline O'Bellx showed a somewhat different response than what had been observed for the energy equivalent results from the Phase 2 O'Bellx. First, the energy equivalent magnitudes were lower overall for the ridgeline O'Bellx. Secondly, the power laws indicated that the energy equivalent of the ridgeline O'Bellx decayed less quickly with radial distance along the 0° and 30° axes, but more quickly along the 60° axis (Table 30). Lastly, the energy equivalent behavior along each axis (Figure 231 - Figure 233) was more similar for the ridgeline O'Bellx than along each axis of the Phase 2 O'Bellx.

Table 30 A table of the power law coefficients for the energy equivalent data along each of the measured axes for the ridgeline O'Bellx tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	1.15	1.92	1.000
30	8.54	2.48	1.000
60	1.78	2.08	1.000

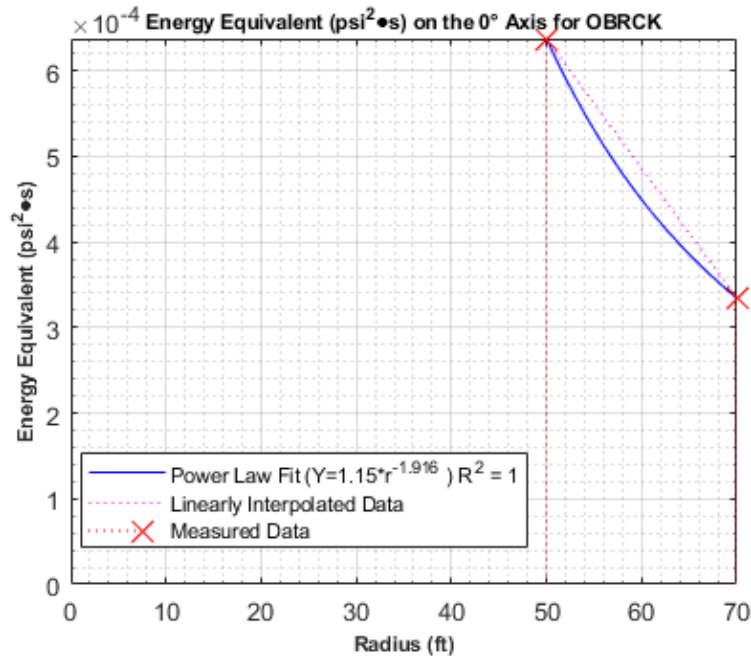


Figure 231 Slice plot along the 0° axis showing the power law fitted energy equivalent data for the ridgeline O'Bellx.

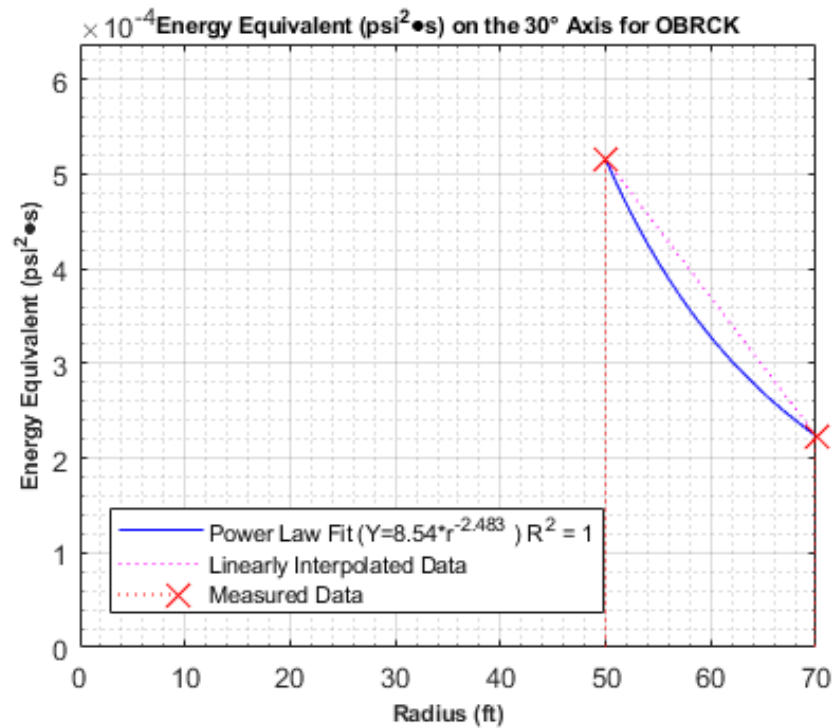


Figure 232 Slice plot along the 30° axis showing the power law fitted energy equivalent data for the ridgeline O'Bellx.

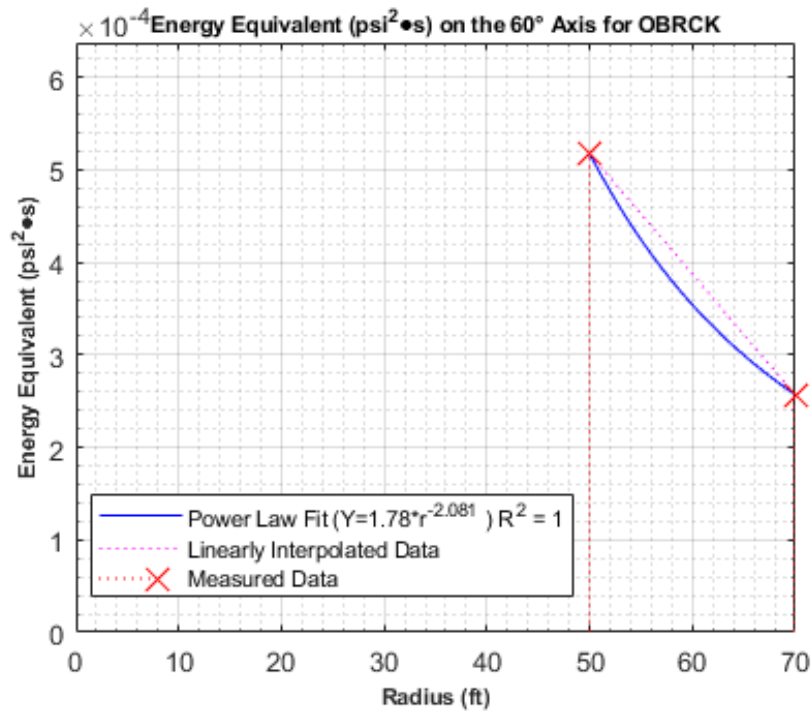


Figure 233 Slice plot along the 60° axis showing the power law fitted energy equivalent data for the ridgeline O'Bellx.

Pressure rise rate results and the power laws used to describe the radial behavior of the pressure rise rates for the ridgeline O’Bellx (Table 31) did not provide a clear understanding of the influence of the terrain feature on pressure rise rate. The results obtained at the ridgeline O’Bellx also differed quite substantially from the results obtained at the Phase 2 O’Bellx. More specifically, the power law fit to the 0° axis of the ridgeline O’Bellx (Figure 234) indicated a counterintuitive growth of the pressure rise rate with radial distance (* as indicated by the positive power law exponent value). As for the 30° axis, the pressure rise rates of the ridgeline O’Bellx were higher in magnitude and decayed less rapidly with radial distance than the Phase 2 O’Bellx (Figure 235). Conversely, the magnitudes of the pressure rise rates were similar on the 60° axes for both O’Bellx’s tested, but the pressure rise rate of the ridgeline O’Bellx was shown to decay more rapidly with radial distance along the 60° axis than was observed for the Phase 2 O’Bellx (Figure 236). Overall, no clear trend or influence from the terrain feature was able to be identified from the pressure rise rate results.

Table 31 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for the ridgeline O’Bellx tests

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	0.064	-2.26*	1.000
30	77791	1.05	1.000
60	6044	0.75	1.000

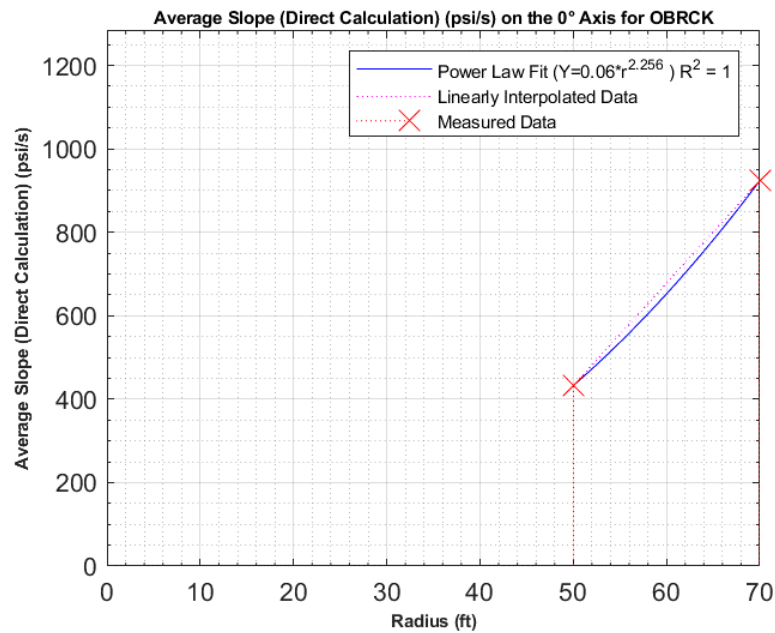


Figure 234 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for the ridgeline O'Belx.

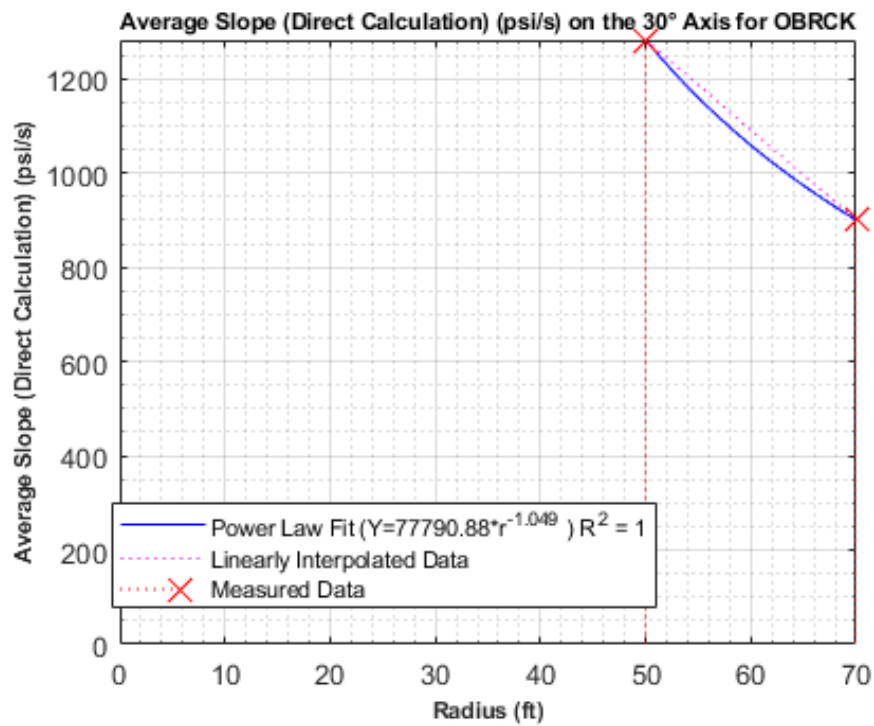


Figure 235 Slice plot along the 30° axis showing the power law fitted pressure rise rate data for the ridgeline O'Belx.

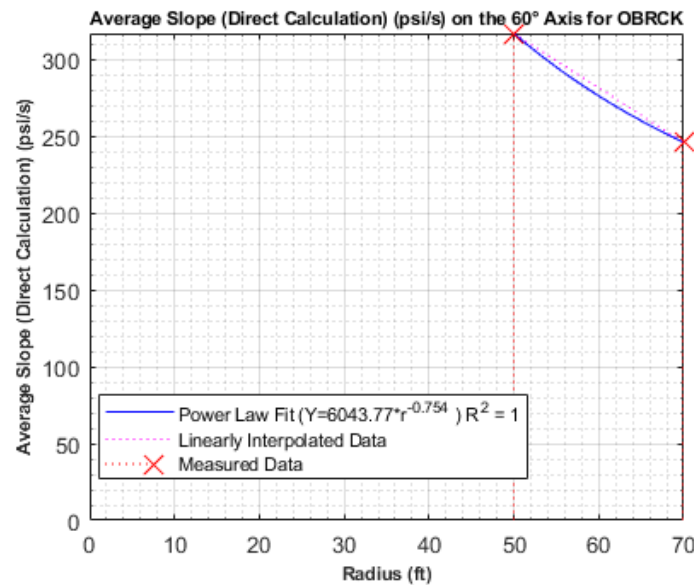


Figure 236 Slice plot along the 60° axis showing the power law fitted pressure rise rate data for the ridgeline O'Bellx.

3.3.3 Gully and Foliage Terrain Feature

The last terrain feature considered was the placement of an explosive at the top of a sloped gully with foliage along both sides. The Pentolite charges used at the operational Wyssen Tower and a similar equipment arrangement were utilized for this testing sequence. As mentioned in Section 2.4.3.3, two tests were ultimately conducted at this location because of a malfunction of the explosive charge during the first test. During the first test, half of the custom Pentolite charge became detached and was not detonated. This test was given the device identification PGLY1. The second test, denoted PGLY2, had a successful detonation of the full charge. The results from both tests are presented below. PGLY2 results are presented first, followed by the peak pressure results of the PGLY1 test. Additionally, for these tests only the 0° and 45° axes were surveyed, making it again difficult to produce the surface and contour plots. As such, only the power laws and slice plots will be presented for this section.

Peak pressures of the PGLY2 test showed a decrease in the radial decay of the pressures for both the 0° and 45° axes when compared against the results of the operational Wyssen Tower Pentolite charge (Table 32). Accordingly, peak pressure magnitudes were smaller for the PGLY2 charge than the operational Wyssen Tower Pentolite charge for distances of about 200 ft or less, but comparable or higher for larger radial distances. This is also demonstrated by the radial location of the reference peak pressure of 0.145 psi or 1 kPa which was calculated based on the power law fits. For the PGLY2 test, the radial location of this reference peak pressure was found to be 490 ft on the 0° axis whereas this distance was 345 ft for the operational Wyssen Tower Pentolite charge and 404 ft for the flat-field testing of the, slightly smaller, Pentolite charge (Figure 237). The calculated radial location of this reference peak pressure on the 45° axis of the PGLY2 test was 859 ft due to the very low radial decay along this axis (Figure 238), but it is expected that additional microphones along this axis may have revealed a stronger decay than reported presently. In general, the peak pressure results of this test indicate greater directionality to the peak pressures when compared against the results from the flat-field or operational Wyssen Tower Pentolite test which both showed very similar behavior along both axes.

Table 32 A table of the power law coefficients for the peak pressure data along each of the measured axes for the gully terrain feature test

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	59.0	0.97	0.993
45	12.3	0.66	1.000

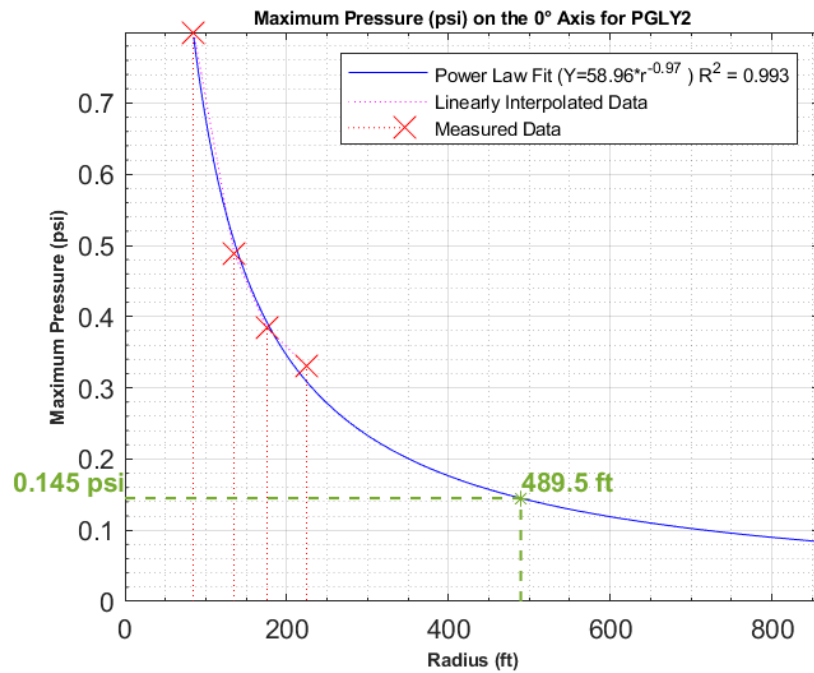


Figure 237 Slice plot along the 0° axis showing the power law fitted peak pressure data for the gully terrain feature test. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

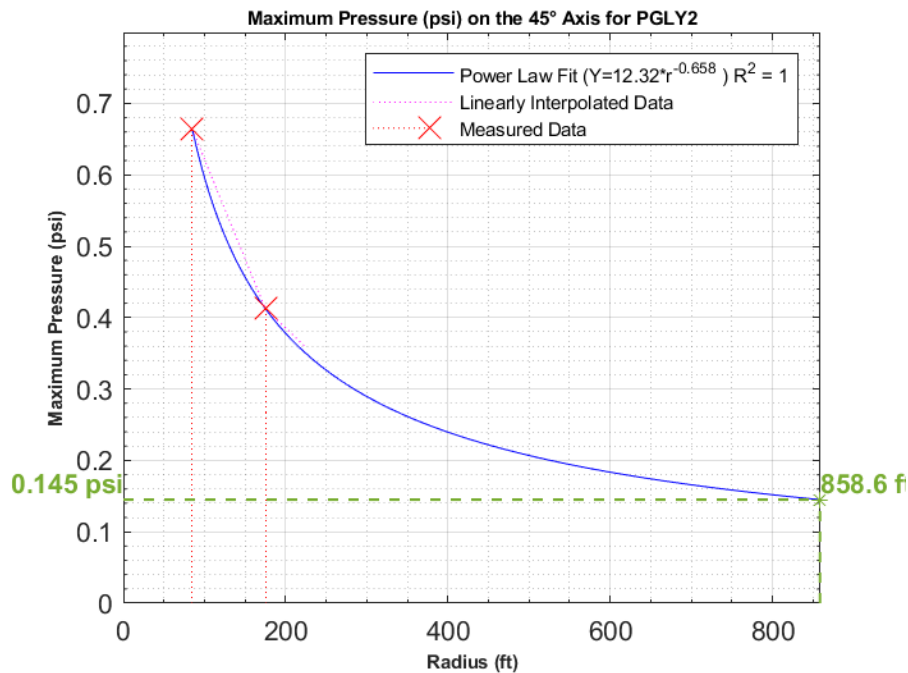


Figure 238 Slice plot along the 45° axis showing the power law fitted peak pressure data for the gully terrain feature test. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

Energy equivalent results from the PGLY2 test also revealed a less substantial radial decay than found from the results of the operational Wyssen Tower Pentolite charge (Table 33). Like peak pressure, energy equivalent magnitudes were smaller for the PGLY2 charge than the operational Wyssen Tower Pentolite charge for distances of about 200 ft or less, but comparable or higher for larger radial distances. Both the 0° and 45° axis also showed similar behavior for the magnitude and radial decay of the energy equivalents (Figure 239 and Figure 240), but the axes were more dissimilar than was observed for the operational Wyssen Tower Pentolite charge.

Table 33 A table of the power law coefficients for the energy equivalent data along each of the measured axes for the gully terrain feature test

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	0.94	1.31	0.999
45	0.29	1.07	1.000

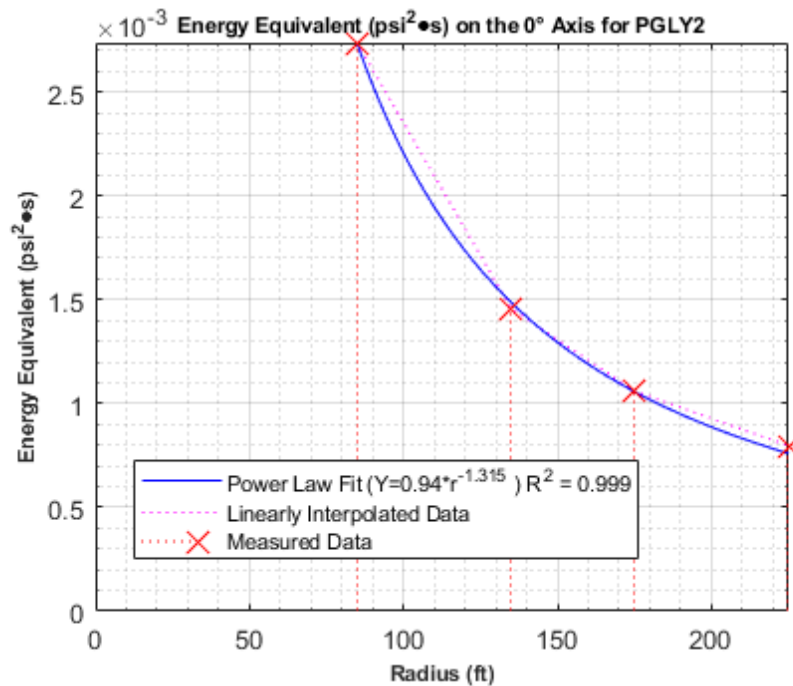


Figure 239 Slice plot along the 0° axis showing the power law fitted energy equivalent data for the gully terrain feature test.

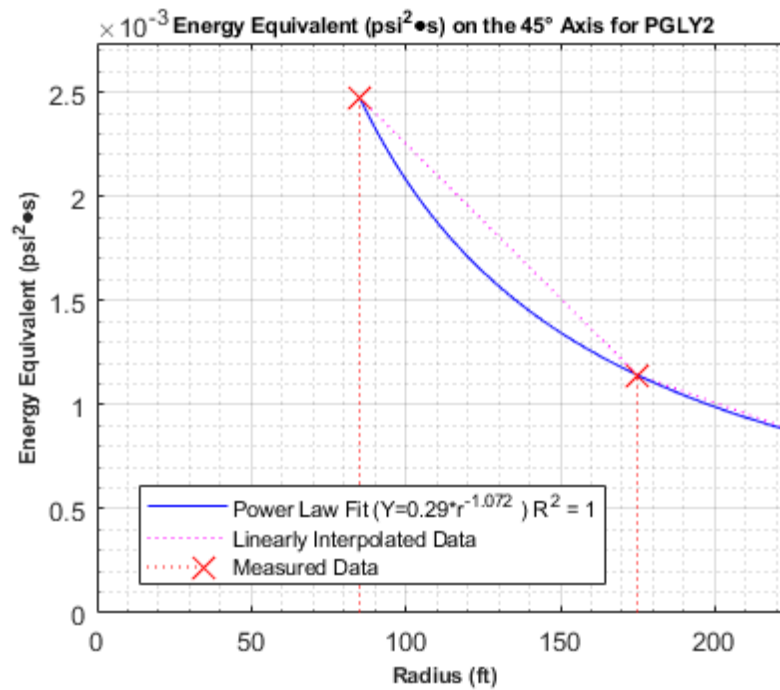


Figure 240 Slice plot along the 45° axis showing the power law fitted energy equivalent data for the gully terrain feature test.

The pressure rise rate results (Table 34) from the PGLY2 test indicated that the 0° axis behaved very similarly to the results from the 0° axis of the operational Wyssen Tower Pentolite charge test in terms of pressure rate magnitude and radial decay (Figure 241). Conversely, the 45° axis of the PGLY2 test showed a substantial decrease in pressure rise rate at a radial distance of 85 ft, little to no change at a radial distance of 175 ft, and an overall reduced radial decay when compared to the results from the operational Wyssen Tower Pentolite charge (Figure 242).

Table 34 A table of the power law coefficients for the pressure rise rate data along each of the measured axes for the gully terrain feature test

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	3.30e7	2.30	0.998
45	1.23e5	1.32	1.000

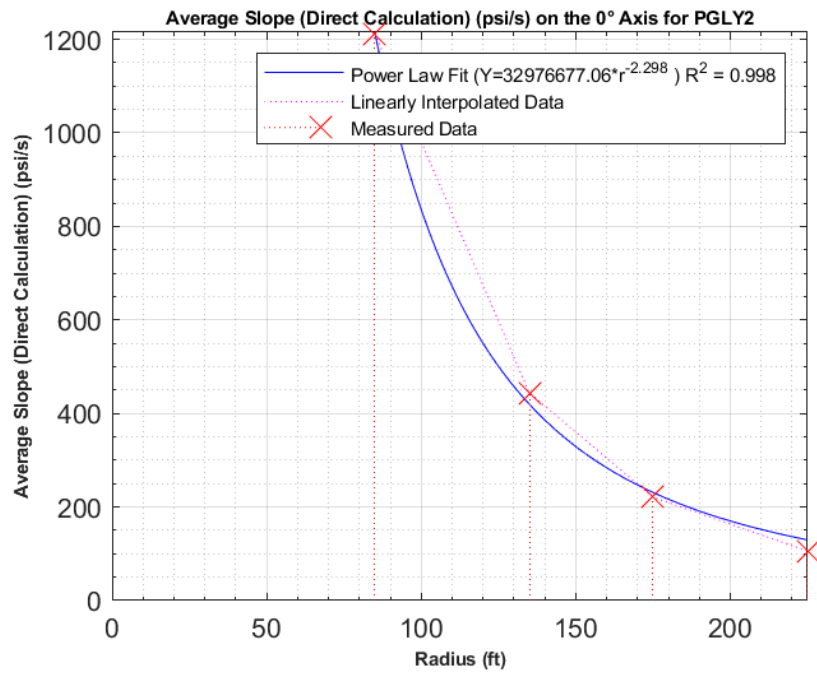


Figure 241 Slice plot along the 0° axis showing the power law fitted pressure rise rate data for the gully terrain feature test.

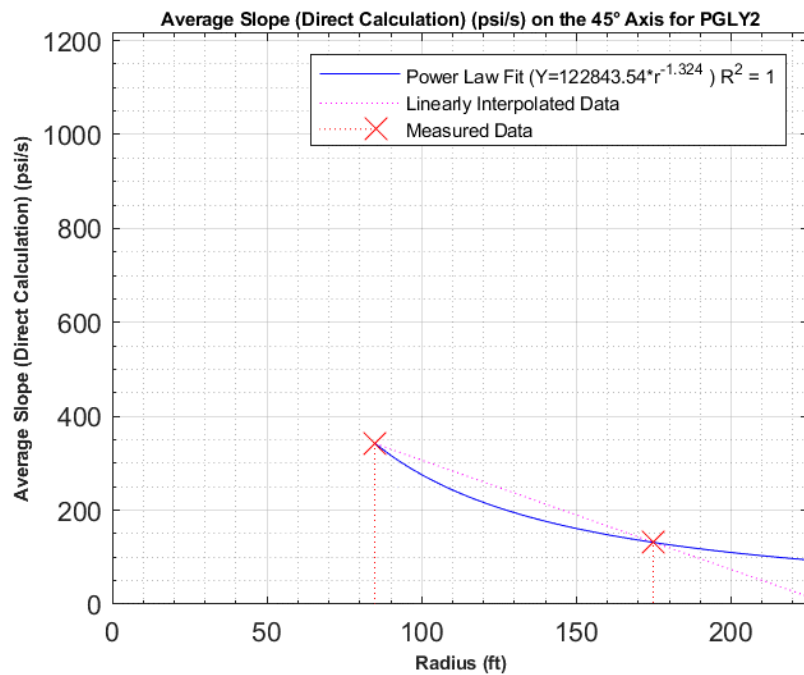


Figure 242 Slice plot along the 45° axis showing the power law fitted pressure rise rate data for the gully terrain feature test.

To share a more complete account of the gully terrain feature testing performed, the peak pressure results of the PGLY1 test (half-sized Pentolite charge) are also presented below. For the energy equivalent and pressure rise rate results for this test the reader is directed to the Master Spreadsheet (APPENDIX A).

As expected, peak pressures from the PGLY1 test were smaller in magnitude than for the PGLY2 test for all measured locations along the 0° and 45° axes – particularly on the 0° axis. The radial decay of the peak pressure for the PGLY1 test was also less strong along the 0° axis than for the PGLY2 test, but the radial decay of the peak pressure on the 45° axis was equal for both tests (Table 35). The radial location of the reference peak pressure of 0.145 psi or 1 kPa was calculated based on the power law fits. For the PGLY1 test, the radial location of this reference peak pressure was found to be 477 ft on the 0° axis and 576 ft on the 45° axis (Figure 243 and Figure 244). For the PGLY2 test, the radial location of this reference peak pressure was found to be 490 ft on the 0° axis and 859 ft on the 45° axis.

Table 35 A table of the power law coefficients for the peak pressure data along each of the measured axes for the PGLY1 test

Axis (°)	Power Law Coefficient a	Power Law Coefficient b	R ²
0	11.7	0.71	0.963
45	9.46	0.66	1.000

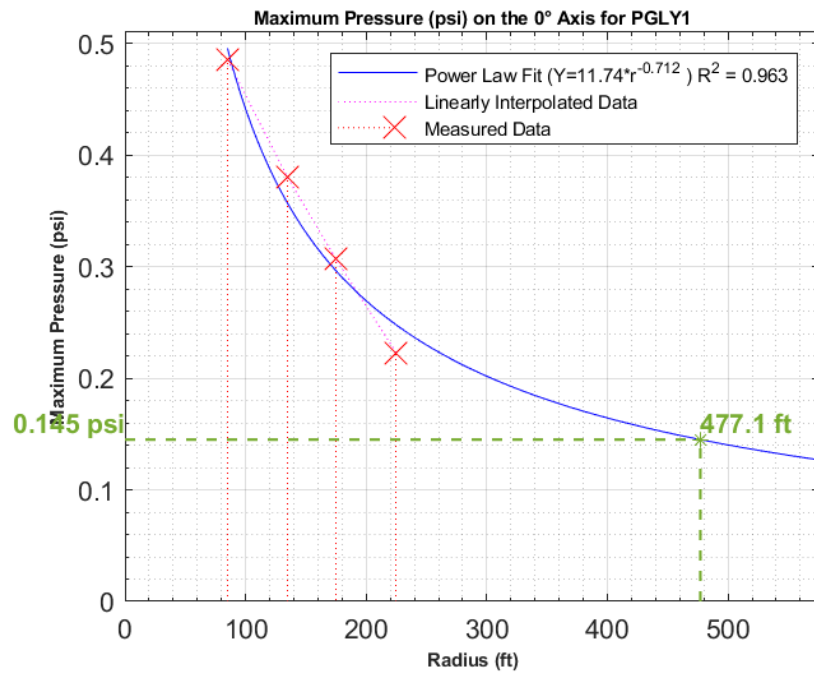


Figure 243 Slice plot along the 0° axis showing the power law fitted peak pressure data for the PGLY1 test. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

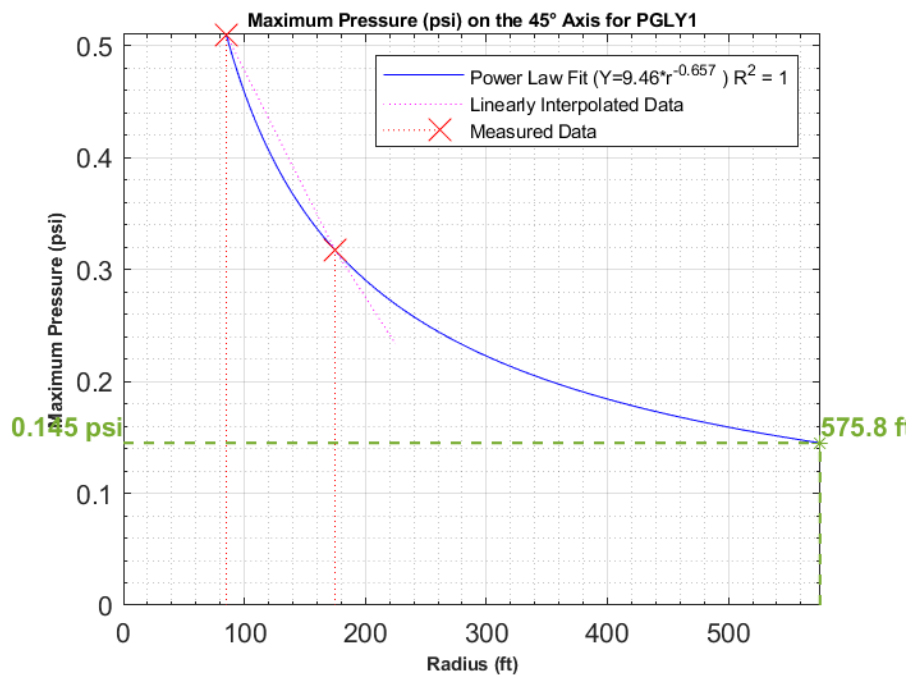


Figure 244 Slice plot along the 45° axis showing the power law fitted peak pressure data for the PGLY1 test. This plot also includes the radius at which the 0.145 psi or 1 kPa pressure is reached based on the fit.

4. DISCUSSION, SUMMARY, AND COMPARISON OF RESULTS

The commentary and comparisons of these results will be organized by the device or testing sequence which produced them, and a general discussion of results will be presented at the end of this chapter.

4.1 Phase 1

The results of Phase 1 allowed for the utilization, validation, and refinement of the newly developed measurement equipment and data processing methods. Furthermore, this phase also highlighted many areas where field operations could be improved and optimized.

4.1.1 Set 1 (Microphone Height Test)

The primary goals of the first test of Phase 1 were to determine if there was a distinct height at which the air pressure measurements changed drastically and no longer accurately described the air pressure at the snow-air interface and to perform a field-testing trial of the measurement equipment. Ultimately, the results of this test provided insight into suitable microphone placement above the snow surface and provided an initial validation of the measurement equipment through comparisons with past work.

Review of the peak pressure versus microphone height data (Table 4 and Figure 71) showed a steady increase in peak air pressure with microphone height and did not reveal any obvious outliers that would indicate a distinct change in air pressure behavior. It was, however, observed that pressures at and below 1 ft above the snowpack were closer in magnitude than measurements at other heights. As a result of this observation and based on the practices and

observations from prior research (Bones, 2012; Simioni, 2017), a microphone placement height of 6 inches was selected for the remainder of testing in this project. This height provided a reasonable representation of the pressure at the snow surface while keeping the microphones high enough to avoid becoming blocked with snow.

In addition to helping identify suitable microphone placement, this test also offered an opportunity to directly compare pressure measurements with the results of Bones (2012) which have been recreated below (Table 36). Comparison of the results showed that the pressure measurements from the elevated microphones in this work were in quite good agreement with the peak pressures from elevated microphones as reported by Bones (2012), but the surface microphones reported lower peak pressures. It is believed that the differences in surface microphones could be the result of varying snow conditions. The present research was performed with a thin and dry snow cover whereas the prior research had been conducted over a moist hard slab snow cover.

Table 36 Peak overpressure results reported by Bones (2012) for 0.9 kg Pentolite charge testing with a 1 m charge height and 7 m radial distance for surface-mounted and elevated microphones

2011-2012 Moist Hard Slab Snow Data for 0.9 kg Pentolite Cast Boosters		
Charge Height	Surface Sensor	1.5 m Elevated Sensor
	Peak Over-pressure (psi)	Peak Over-pressure (psi)
1 m	3.98	3.13
	4.02	3.30
	4.00	3.17
	3.45	3.32
	4.81	3.31
Average	4.05	3.25
Std. Dev.	0.48	0.09

4.1.2 Set 2

The second two tests conducted in Phase 1 focused on the qualitative assessment of field-testing logistics for this work, but also offered another opportunity for comparison with prior work. Regarding the improvement of testing logistics, these tests sparked the development of the LORA transceiver described in Section 2.3.5, the utilization of lightweight and portable aluminum channel sections for microphone mounting, and many other testing practices and procedures that improved field-testing efficiency in Phase 2 and 3.

Regarding the comparison of results with prior work, peak pressures reported at radial distances of 5 and 7 m (Table 5) agreed closely with the peak pressures reported at the same distances by Bones (2012). Further, the power law equations fit to describe the radial decay of the peak pressures along each axis (Table 6) also agreed well with the radial decay reported in prior works and summarized by Simioni (2017) which are recreated below (Table 37). Overall, these comparisons with prior work helped to validate the equipment and data processing methods prior to the full-scale field-testing in Phase 2 and 3.

Table 37 A summary and comparison of the power law exponents fit for a variety of solid explosives from prior work and the present work. Summary recreated from Simioni (2017)

	Power Law Exponent, b
Ingram (1962), Mellor (1973)	1.43
Gubler (1976)	1.125
Albert and Hole (2001)	1.5 to 1.9
Simioni (2017)	1.1 to 2.1
Present Study (Phase 2 Set 2)	1.55 to 1.62

4.2 Phase 2

The focus of Phase 2 of the testing plan was to obtain baseline pressure data from a variety of RACS. This data allowed for an accurate description of the performance of the various RACS described in Chapter 1. The results obtained were generally successful in accomplishing this goal, offered many opportunities for comparisons between devices, and identified areas of potential improvement and expansion for future work. The commentary and comparisons will be provided, in detail, in the following sections, but a brief overview is presented here.

Results from the Gazex testing showed a clear directional behavior (strongest response along the 0° axis) and the results agreed very well with the work of Simioni (2017).

Results of the O’Bellx testing were complicated by unintended terrain effects from a nearby cliff, but still provided some meaningful conclusions. When disregarding the axes believed to be affected by the unintended terrain feature, it was shown that the O’Bellx had a directional behavior for short to moderate radial distances (approximately 0-50 ft), but a reasonably symmetric profile at greater distances. Additionally, it was shown that the device had an overall weaker response than the 1.5 m³ Gazex, as expected. The comparison of the peak pressures, energy equivalents, and pressure rise rates between the O’Bellx and Gazex devices also generally agreed with the findings of Berthet-Rambaud et al. (2008, 2010).

Results from the flat-field testing of the gel emulsion, prototype Pentolite, and simulated Avalanche Guard charges showed an expectedly symmetric behavior. Furthermore, the radial decay of the peak pressures for these devices agreed well with prior work involving solid explosives. It was shown that the simulated Avalanche Guard charge had a nearly identical response to the flat-field testing of the gel emulsion charge. Along these same lines, both the gel

emulsion and simulated Avalanche Guard charges were found to have very similar effects along the 0° axis as the 1.5 m^3 Gazex system, but a much stronger effect for the lateral and uphill directions. As for the flat-field testing of the prototype Pentolite charge, it was shown to have a measurably stronger response (in terms of peak pressure, energy equivalent and pressure rise rate magnitudes) than the other explosives for all measured axes and radii.

Lastly, the comparison testing of the gel emulsion charge and the prototype Pentolite charge at the operational Wyssen Tower indicated slightly different performance for both charges than was observed during flat-field testing. For both charges at the operational RAC system, a non-circular isoline profile was obtained (i.e., the uphill blast wave strength and propagation differed from the downhill direction), and the strength of the explosives differed from their flat-field counterparts along most measured axes. Thus, it was concluded that the present work does not suggest that flat-field testing is an adequate representation of an operational Wyssen Tower system.

4.2.1 1.5 m^3 Gazex

Although data was not able to be collected along the 30° , 150° , and 180° axes for the Gazex system as had been planned, and limited data was collected along the 120° axis, the peak pressure, energy equivalent, and pressure rise rate results all showed a clearly directional behavior for the Gazex system. This was an expected result, but the quality of results obtained and their agreement with the past work of Simioni (2017) were welcome surprises.

In general, it was found that the 0° axis had the highest magnitudes and highest radial decays for the peak pressure, energy equivalent, and pressure rise rate results. These magnitudes and radial decays were also shown to decrease as the angle from the 0° axis increased.

Furthermore, it was found that the peak pressures generally decayed less distinctly with radial distance than pressure rise rate, and pressure rise rate decayed less distinctly than the energy equivalent. This is consistent also with the results of Simioni et al. (2016). This suggests that the duration of the blast wave attenuated more with distance than the strength of the wavefront. It is also known that the energy of a wave decays with the square of its amplitude decay (Simioni et al., 2016)

Another way in which the present work agreed with the findings of Simioni (2017) was the similarity of the power laws fit to describe the radial decay of the peak pressure, energy equivalent, and pressure rise rate. For peak pressure, the present work found that the peak pressure magnitude would decay with radial distance along the 0° axis following a power law with an exponent of 1.53 whereas Simioni (2017) reported this value to be 1.68 for the 0° axis and 1.66 for axes up to 37° . For energy equivalent, the present work found that the energy equivalent would decay with radial distance along the 0° axis following a power law with an exponent of 2.60 whereas Simioni (2017) reported this value to be 2.54 for the 0° axis and 2.5 for axes up to 37° . For pressure rise rate, the present work did not find a similar power law fit for the 0° axis due to the metric's sensitivity to noise – an issue that was also seemingly faced by Simioni & Schweizer (2018) based on the scatter in their figures showing the power law fitting of the pressure rise rate results. However, the present work did provide reasonable power law fits for the pressure rise rate along the 60° and 90° axes which were not provided in the prior work.

This study's agreement with the prior work of Simioni (2017) is perhaps best visualized by utilizing Simioni's power law equations to synthesize data for the 30° axis which was not directly measured in this work. As can be seen in Figure 245 and Figure 246, the incorporation

of peak pressure data along the 30° axis from Simioni (2017) matches almost perfectly with the data presented in Figure 77 and Figure 78. These synthesized pressure values were found by approximating the gas mass of a 1.5 m³ volume of a 1:5 ratio of propane and oxygen using the ideal gas law and an assumed elevation and temperature of 5,500 ft and 0°C, respectively. This resulted in a gas mass of 1.84 kg which could then be utilized in Simioni's (2017) gas mass scaled power law for the 0°-37° axes to calculate expected peak pressures at each of the radial distances in this work.

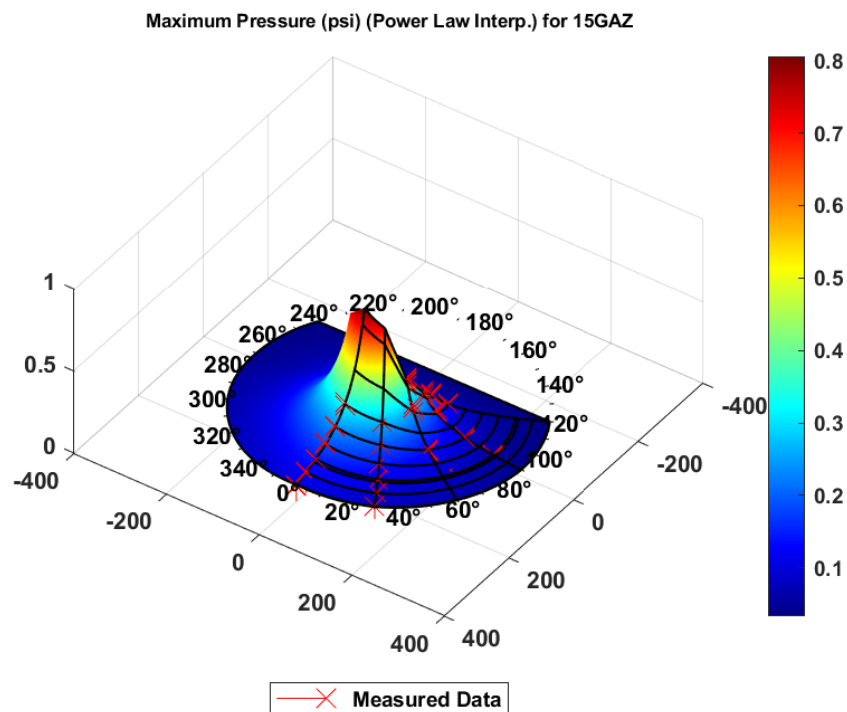


Figure 245 Surface plot of the power law fitted peak pressure data from the Gazex testing and data synthesized from the results of Simioni (2017) included on the 30° axis.

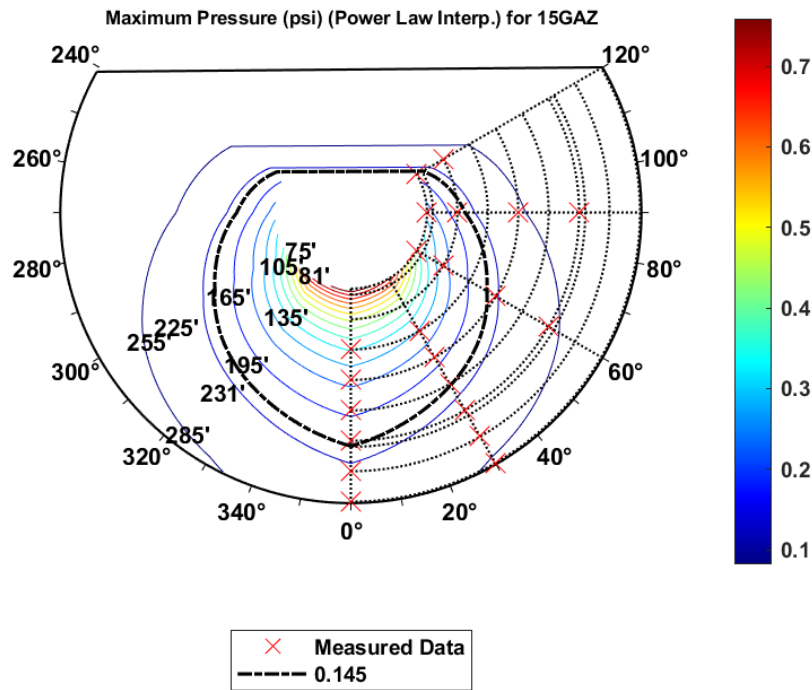


Figure 246 Contour plot of the power law fitted peak pressure data from the Gazex testing and data synthesized from the results of Simioni (2017) included on the 30° axis. This plot also includes the 0.145 psi or 1 kPa pressure isoline for reference.

It should also be noted that while the majority of Simioni's (2017) work involved tests conducted with a prototype gas exploder in a flat field, Simioni (2017) also performed testing at an operational and open-slope 1.5 m³ Gazex system. Comparison with these results also show good agreement with the present study. For peak pressure, the present work found that the peak pressure magnitude decayed with radial distance along the 0° and 90° axes following power laws with exponents of 1.53 and 1.35, respectively, whereas Simioni (2017) reported these values to be 1.27 and 1.57 for the 0° and 90° axes, respectively. For energy equivalent, the present work showed a decay with radial distance along the 0° and 90° axes that followed power laws with exponents of 2.60 and 1.98, respectively, whereas Simioni (2017) reported these value to be 2.01 and 2.65 for the 0° and 90° axes, respectively. For pressure rise rate, the present work found that

the pressure rise rate would decay with radial distance along the 0° and 90° axes following power laws with exponents of 0.73 and 2.14, respectively, whereas Simioni (2017) reported these value to be 0.35 for the 0° axis and 2.54 for the 90° axis.

In summary, the present work has provided further validation to the results reported by Simioni (2017) while also expanding the current body of work by including power law fitting for peak pressure, energy equivalent, and pressure rise rate along the 60°, 90°, and 120° axes.

4.2.2 O’Bellx

The results from the baseline testing of the O’Bellx system in Phase 2 revealed interesting behavior. While these results still offer some insight into the probable performance of the O’Bellx system, it is believed that some results (the 60° and 90° axes specifically) may have been affected by unintended terrain effects and are thus not sufficiently representative of the open-slope (or baseline) performance of an O’Bellx device.

When selecting the Phase 2 O’Bellx test site, care was taken to select a site with the minimal amount of nearby terrain features. While the device chosen was the most open-slope installation available, there was still a distinct and large cliff located approximately 50 ft to the east of the O’Bellx (Figure 43). As a result, it is probable that the blast wave may have been reflected off this cliff and consequently reduced the radial decay of the blast wave along the 60° and 90° axes. This can be visualized in two ways. First, if the 60° and 90° axes are removed from the dataset, it becomes much easier to see the close-range directionality and the long-range circular profile of the system and a more straightforward and believable isoline profile is produced (Figure 247). Secondly, if the pressure vs. time profile of the blast wave is compared at equal distances of 70 ft along the 0° (Figure 248) and 90° axes (Figure 249), it can be observed

that the profile of the blast wave on the 90° axis seems to have a secondary pressure peak not found on the 0° axis, and the overall blast wave duration is slightly increased. It is likely that this is the effect of a reflection from the cliff located at approximately 50 ft on the opposite side of the O'Belx.

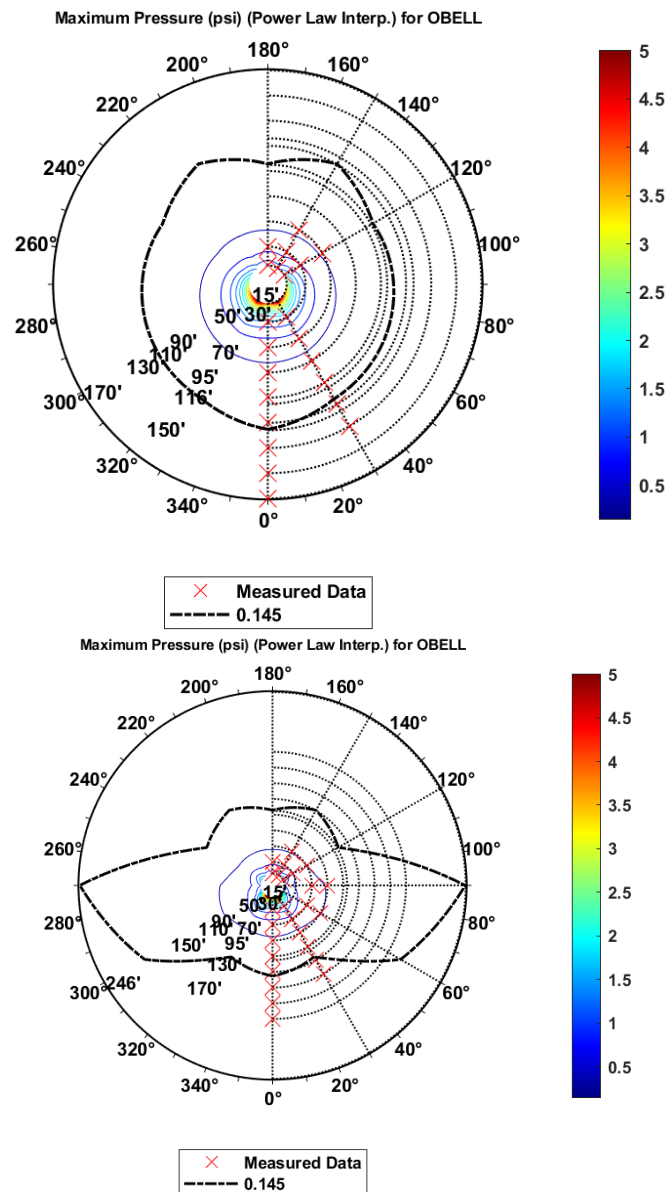


Figure 247 Contour plot of the power law fitted peak pressure data from the O'Belx testing with the 60° and 90° axes removed (top) and original data (bottom).

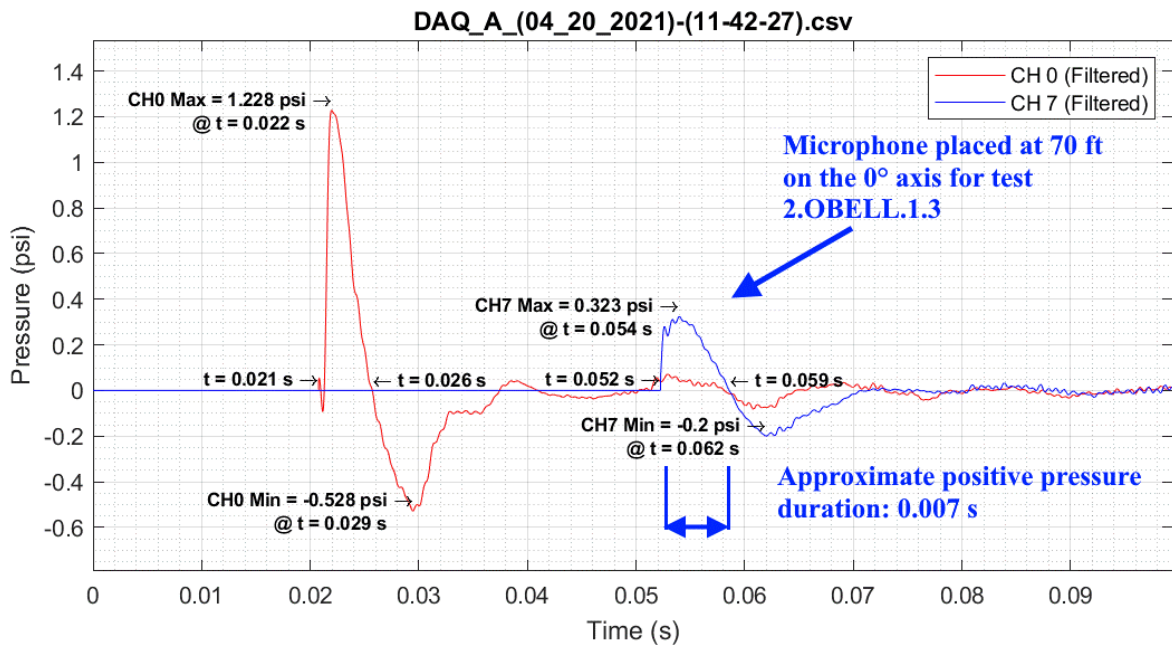


Figure 248 Pressure vs. time profile for the microphone located on the 0° axis at a radial distance of 70 ft for the 2.OBELL.1.3 test

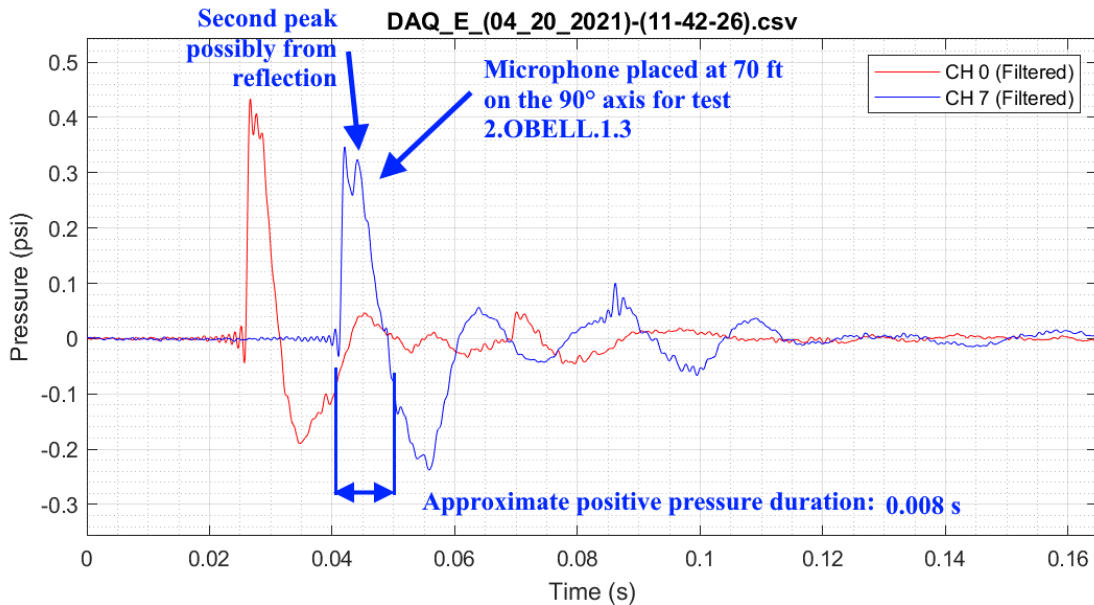


Figure 249 Pressure vs. time profile for the a microphone located on the 90° axis at a radial distance of 70 ft for the 2.OBELL.1.3 test. Note the apparent second pressure peak and slightly increased blast duration.

Despite the challenges faced for the 60° and 90° axes, there were still many valuable takeaways from the O'Bellx results. First off, as was shown for the Gazex device, it was also observed that the radial decay of the O'Bellx energy equivalent was generally stronger than the decay of the pressure rise rate which was, in turn, stronger than the decay of the peak pressure. However, there were some challenges associated with calculating the pressure rise rates due to noise and the unintended terrain effects.

Secondly, by removing the results of the 60° and 90° axes, it was shown that the peak pressure response of the O'Bellx system was directional (i.e., a stronger response along the 0° and 30° axes than other axes) for radial distances of about 50 ft or less, and symmetric, or circular, for greater radial distances. This is different from the Gazex which showed a distinctly directional (i.e., bulb-shaped) profile for all radial distances measured.

Another way in which the two systems can be compared⁹ is by considering the calculated radial location of the 0.145 psi or 1 kPa peak pressure reference isoline. For the O'Bellx system, this reference peak pressure was estimated to be reached at a radial distance of about 100-115 ft on all axes (disregarding the 60° and 90° axes). For the 1.5 m³ Gazex system, this reference peak pressure was reached at about 230 ft on the 0° axis, about 155 ft on the 60° axis, about 113 ft on the 90° axis, and about 82 ft on the 120° axis. This finding suggests that, in terms of peak pressure, the effects of the 1.5 m³ Gazex and O'Bellx systems tested are similar to the side and rear of the systems, but the Gazex has a stronger effect downslope.

⁹ It should be noted that the gas volumes of the two systems are different (with the Gazex being the larger of the two), and could be contributing, in part, to the observed differences between the two systems. Comparisons are shown for illustrative and explanatory purposes.

As mentioned, one way in which the two gas-based systems differed was the magnitudes of the various quantities of interest along the 0° axis. For instance, for the shared radial distances between the O’Bellx and Gazex testing sequences on the 0° axis (135 ft to 170 ft) it was found that the Gazex system had approximately 2 to 3 times higher peak pressures (Figure 250), 5 to 10 times higher energy equivalents (Figure 251), and approximately 2 to 3 times higher pressure rise rates (Figure 252). These are plausible outcomes given the differences in gas volumes of the two systems (1.5 m³ for the Gazex system and approximately 0.35 m³ for the O’Bellx system) and the knowledge from prior work which showed that the propane-based explosion of the Gazex had about twice the duration of the hydrogen-based explosion of the O’Bellx (Berthet-Rambaud et al., 2010, 2008). Peak pressures were also in relative agreement, though slightly lower, than the findings of Berthet-Rambaud et al. (2008) who found, for the similarly sized and designed Daisybell system, peak pressures of 0.36 psi at 82 ft and 1.25 psi at 40 ft.

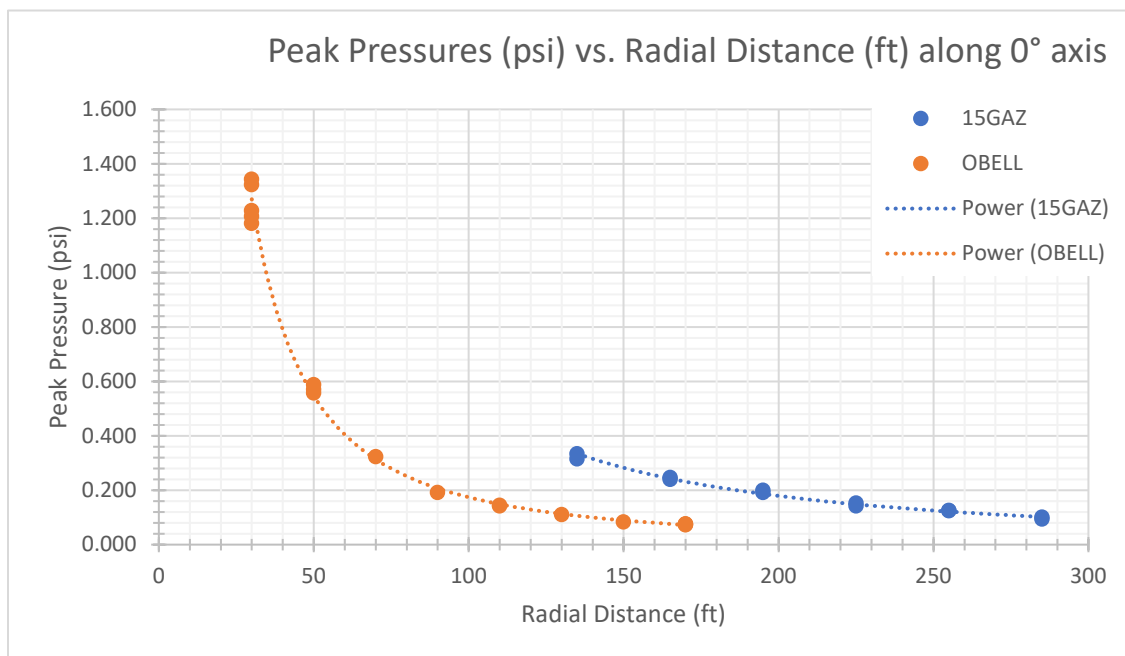
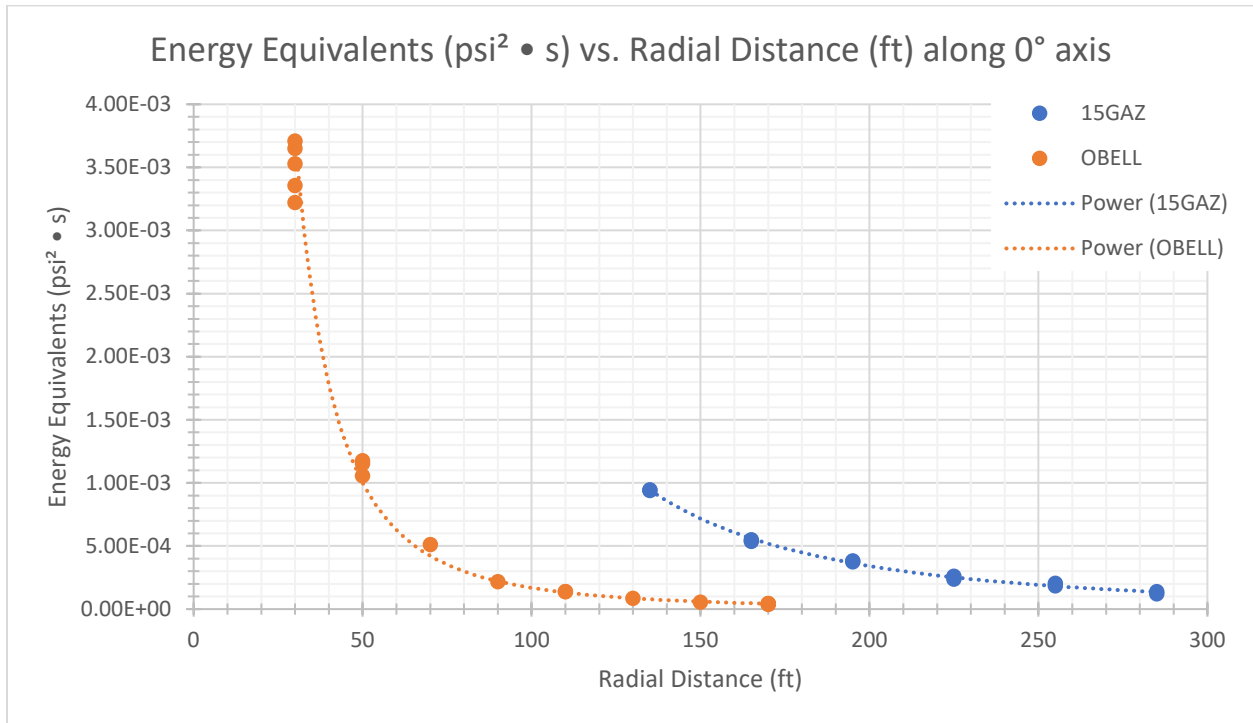
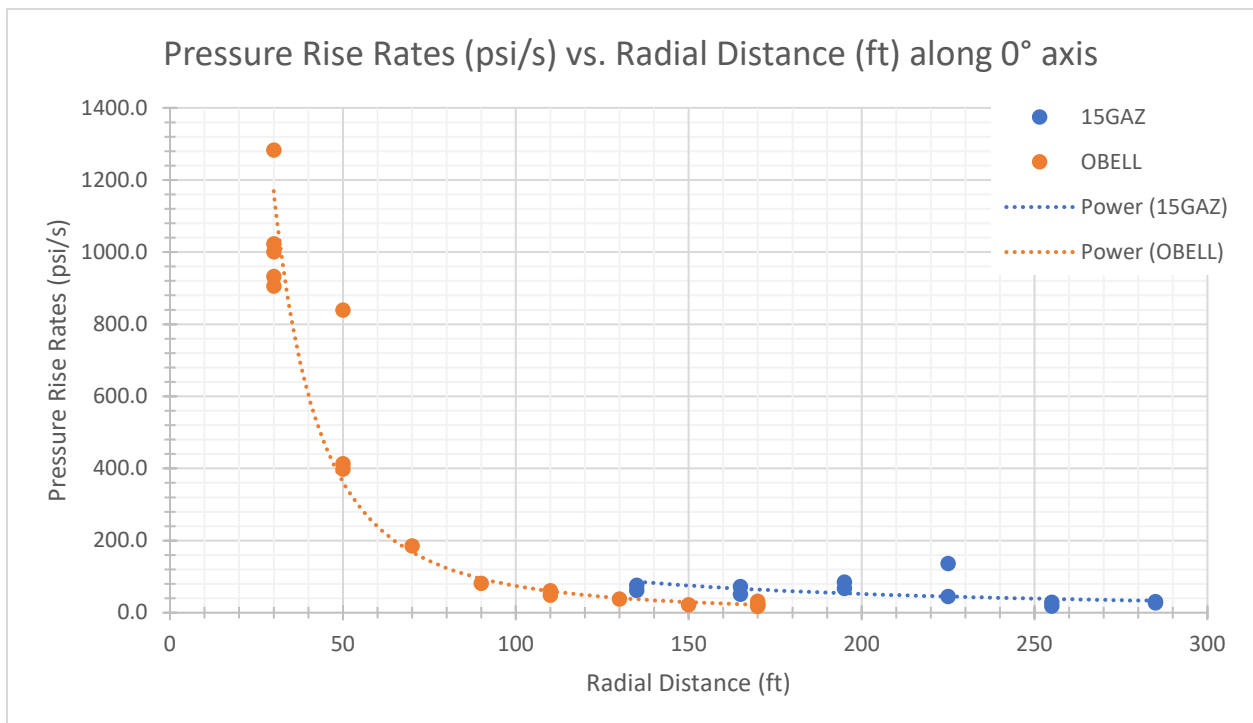


Figure 250 Comparison of 15GAZ and OBELL peak pressure results for the 0° axis

Figure 251 Comparison of 15GAZ and OBELL energy equivalent results for the 0° axisFigure 252 Comparison of 15GAZ and OBELL pressure rise rate results for the 0° axis

4.2.3 Flat-Field Gel Charge Wyssen Tower

Flat-field testing of the Wyssen Tower's gel emulsion charge provided a very convenient, repeatable, and practical method for establishing the baseline performance of the charge which could then be compared against the results obtained from operational system testing and Pentolite-based charge testing. Overall, the results obtained from the flat-field testing sequences were some of the most consistent and highest quality results procured in this research. Additionally, the results were straightforward (i.e., no unexpected findings) and agreed well with the existing and expansive field of work on solid explosives used in avalanche control.

The first takeaway from the gel emulsion flat-field testing was the high level of symmetry observed. Peak pressure, energy equivalent, and pressure rise rates were all found to be very similar in magnitude and radial decay along all measured axes. This is an expected outcome for solid explosives which are known to have spherical wavefronts.

The second key observation from these results was the conformity of the calculated peak pressure power laws with the findings of prior work on solid explosives. As was shown in Table 37, previous research efforts involving solid explosives of varying charge mass and composition found that the peak pressures typically decayed following a power law with an exponent ranging from about 1.1 to 1.9. The present findings showed that the peak pressures of a gel emulsion charge detonated in a flat field decayed following a power law with an average exponent of 1.41. This value makes sense given the previously reported values and the knowledge that spherical wave amplitude decays in a free field following an exponent of 1.

The final significant finding from the gel emulsion flat-field testing was how the charge compared to the Gazex system in terms of peak pressure, energy equivalent, and pressure rise

rate. Comparing along the 0° axis showed a high degree of similarity between the two devices. Peak pressure magnitudes and radial decay were very similar between the gel emulsion and 1.5 m³ Gazex device – with the Gazex having a slightly greater radial decay (Figure 253). This is also expressed by the 1 kPa or 0.145 psi peak pressure reference which was found to be at a radial distance of 234 ft for the flat-field gel emulsion charge (Figure 145) and 230 ft for the Gazex device (Figure 79). The energy equivalents and pressure rise rates also behaved very similarly along the 0° axis for the flat-field gel emulsion and Gazex tests (Figure 254 and Figure 255). However, due to the highly directional profile of the Gazex system, the two systems differed much more along the 90° axis – with the gel emulsion charge having the larger effect (Figure 256 - Figure 258).

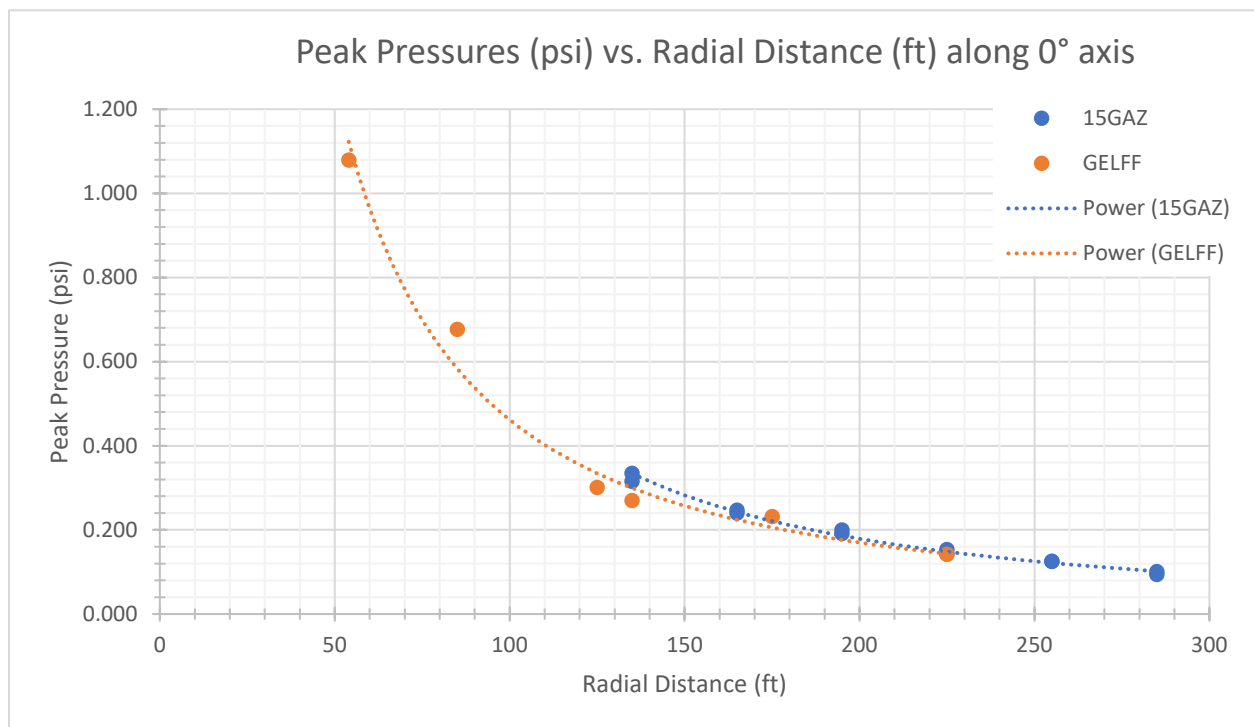
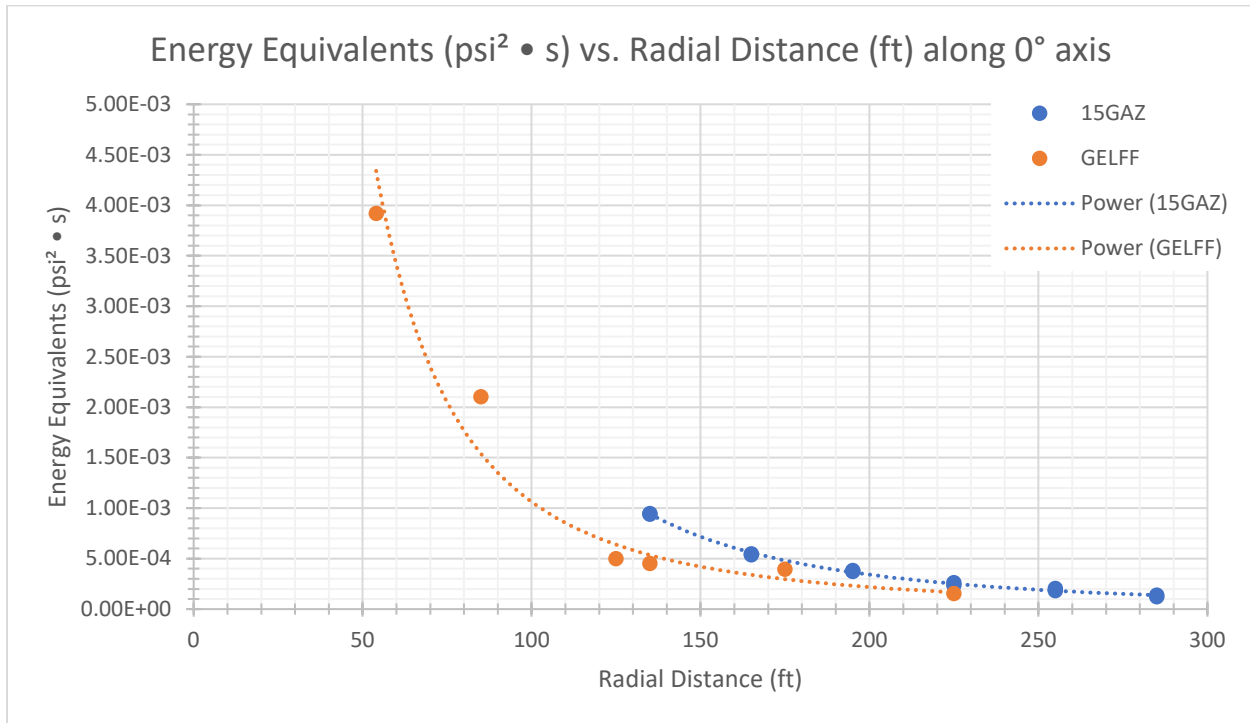
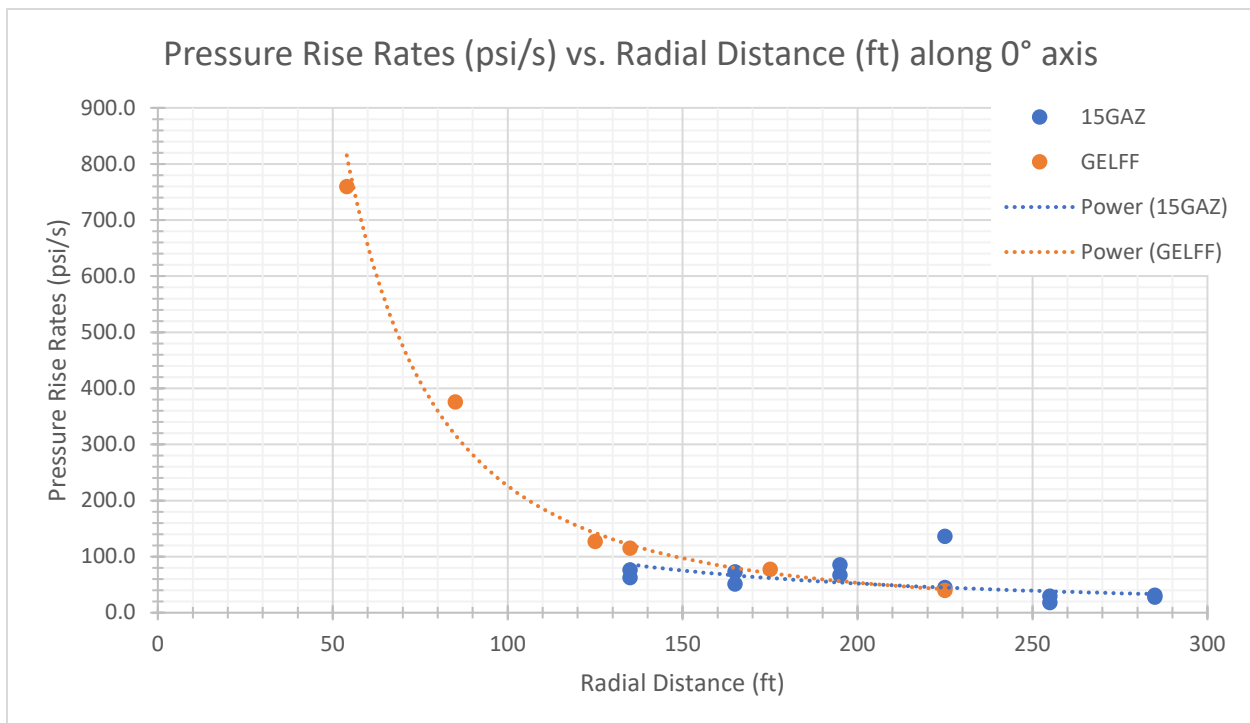


Figure 253 Comparison of 15GAZ and GELFF peak pressure results for the 0° axis

Figure 254 Comparison of 15GAZ and GELFF energy equivalent results for the 0° axisFigure 255 Comparison of 15GAZ and GELFF pressure rise rate results for the 0° axis

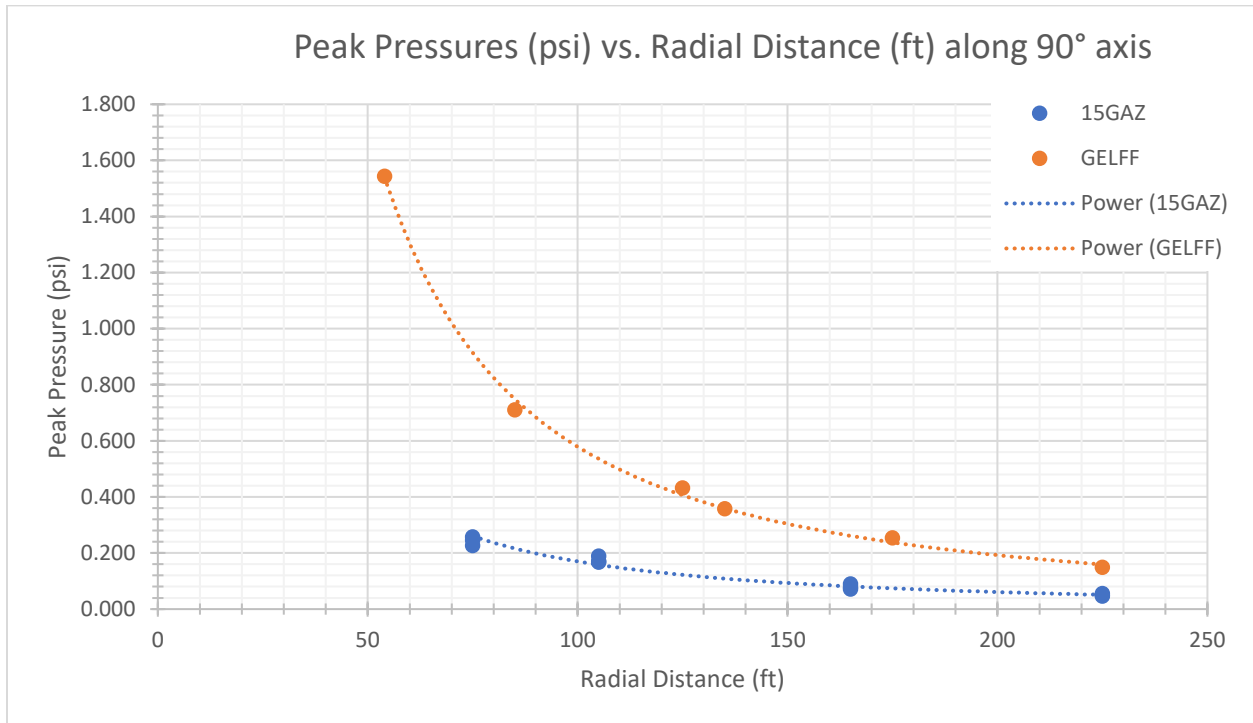


Figure 256 Comparison of 15GAZ and GELFF peak pressure results for the 90° axis

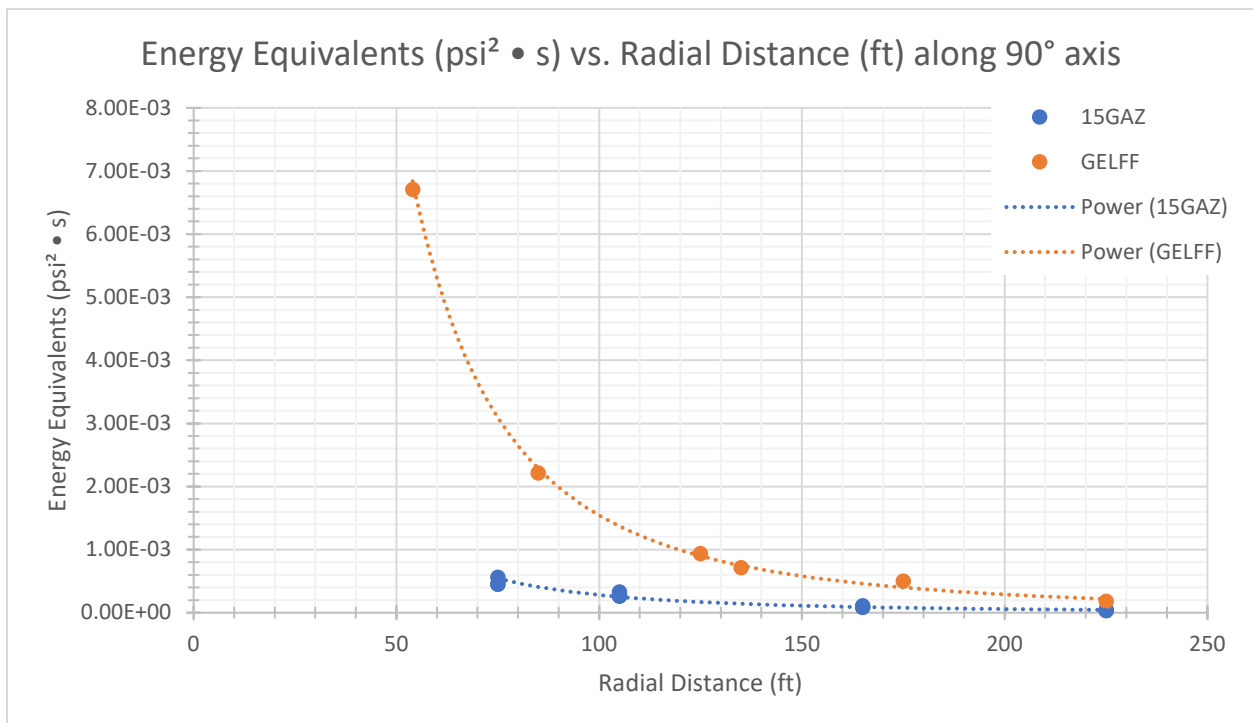


Figure 257 Comparison of 15GAZ and GELFF energy equivalent results for the 90° axis

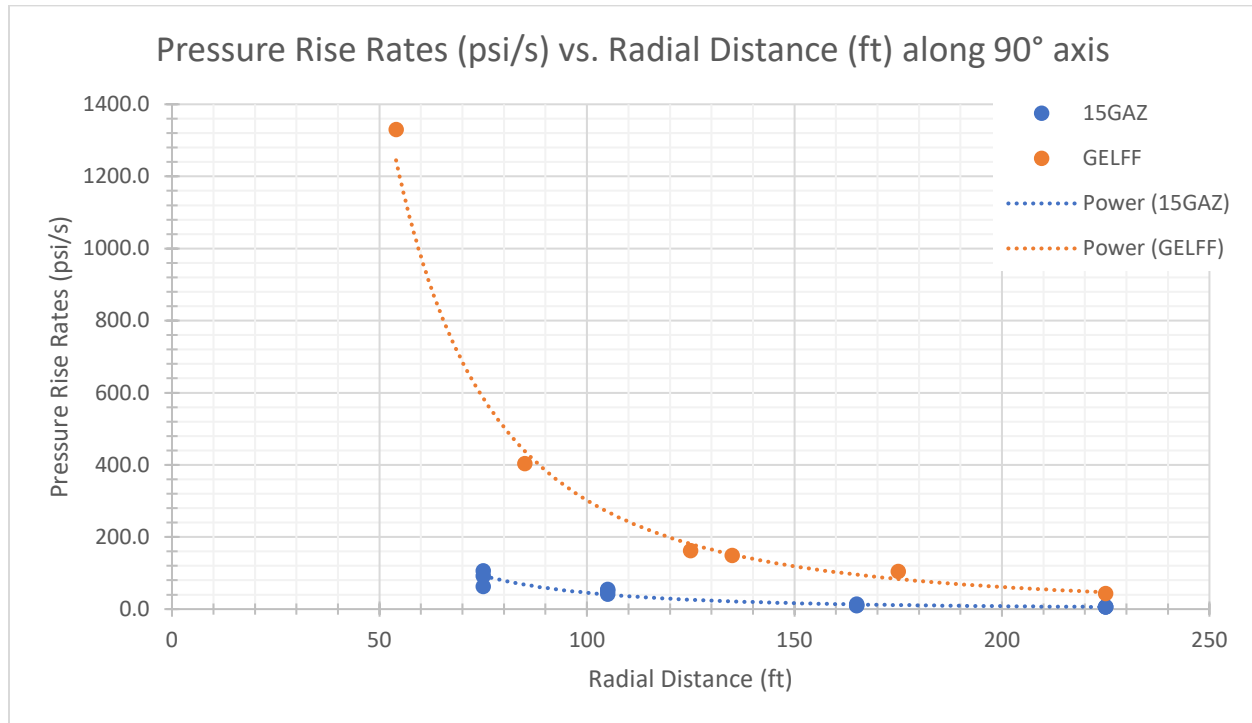


Figure 258 Comparison of 15GAZ and GELFF pressure rise rate results for the 90° axis

4.2.4 Flat-Field Pentolite Charge Wyssen Tower

The flat-field testing results of the prototype Pentolite charge provided similarly consistent, high quality, repeatable, and straightforward results as observed for the gel emulsion charge – though there were some differences between the two charges. The key similarities and differences between these two charges will now be discussed.

To begin, the prototype Pentolite charge showed a high level of symmetry much like the gel emulsion charge. Again, the peak pressure, energy equivalent, and pressure rise rate results showed no preferential direction and behaved similarly along all measured axes – an expected result for a solid explosive charge.

Another similarity between the two charges was the agreement of the peak pressure radial decay with prior work. The peak pressure from the prototype Pentolite charge was found to

decay with radial distance following a power law with an exponent, b , of 1.27 when averaged across all measured axes. Although this is a weaker radial decay than found for the gel emulsion charge, this is still in good agreement with prior research on solid explosives used in avalanche control (Table 37) and is a plausible outcome for a high-speed and high energy density explosive like Pentolite.

Another way in which the prototype Pentolite charge and gel emulsion charge behaved similarly was repeatability of each charge. The microphones along the 45° axis, which were left in place to assess repeatability across all tests of a given explosive type, indicated a high level of consistency in the results for both charges for the more distal microphone (175 ft). At this distance, there was an almost unnoticeable variation in the peak pressure, energy equivalent, or pressure rise rate magnitudes for either charge. However, for the more proximal microphone (85 ft) on the 45° axis there was greater variability in the results for the prototype Pentolite charge. While some of this variability might be attributed to the inherently variable testing conditions of field-based research, the relative increase in variability of the prototype Pentolite charge results indicates that some variability can be assigned to differences in the prototype charges themselves.

A final comparison that can be drawn between the gel emulsion and Pentolite charges is between the magnitudes and radial decay of the peak pressures, energy equivalents, and pressure rise rates for each charge. As already discussed, the radial decay of the peak pressure was slightly more distinct for the gel emulsion charge than the Pentolite charge. While this same relationship was also found for the pressure rise rate results (i.e., the radial decay of the gel emulsion pressure rise rate is stronger than for the Pentolite charge), this result was not found to

be true for the energy equivalent results. In fact, it was found that the radial decay of the energy equivalent was quite similar between the two charges for all axes – with the average power law coefficient, b , being 2.15 and 2.14 for the Pentolite and gel emulsion charges, respectively. In terms of peak pressure, energy equivalent, and pressure rise rate magnitudes, the prototype Pentolite charge was shown to have a measurably stronger response on all measured axes and radii. More specifically, it was observed that the prototype Pentolite charge had approximately twice the peak pressures and pressure rise rates of the gel emulsion charge for all measured radial distances and axes. For energy equivalent, the prototype Pentolite charge was approximately four times higher than the gel emulsion charge for all measured radial distances and axes. This relationship is shown below for the 0° axis only (Figure 259 - Figure 261), but all axes were found to have similar results.

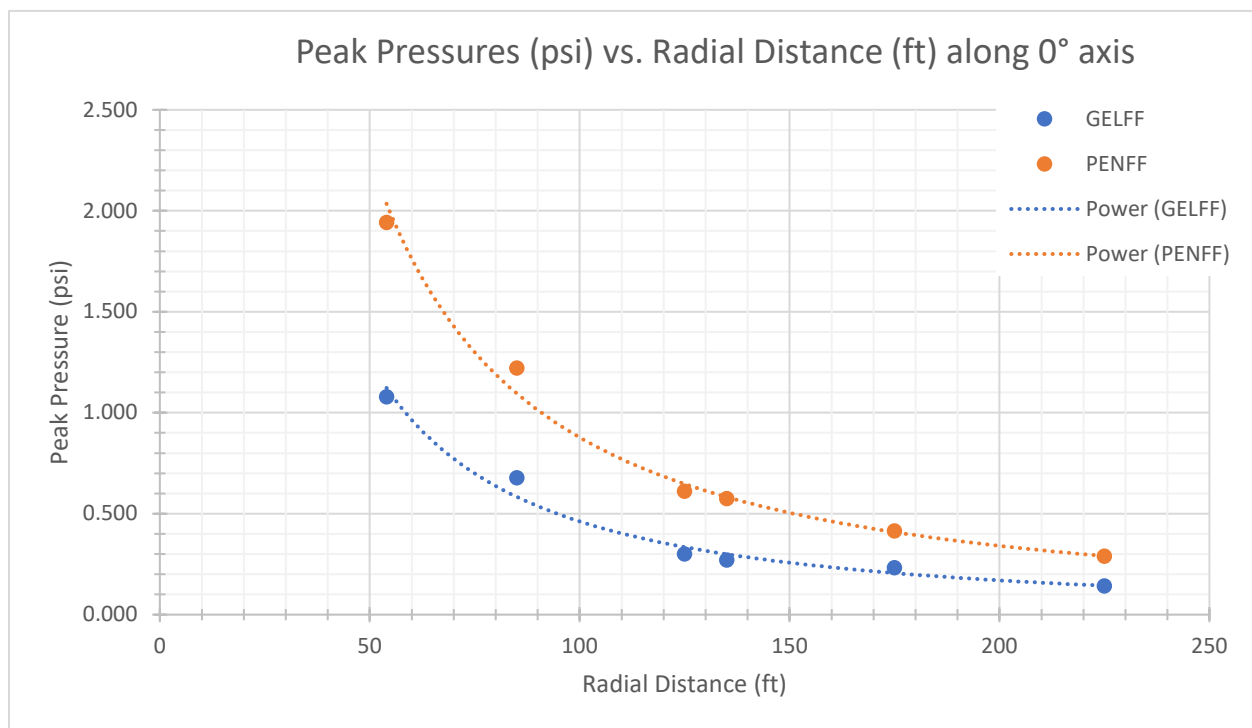


Figure 259 Comparison of PENFF and GELFF peak pressure results for the 0° axis

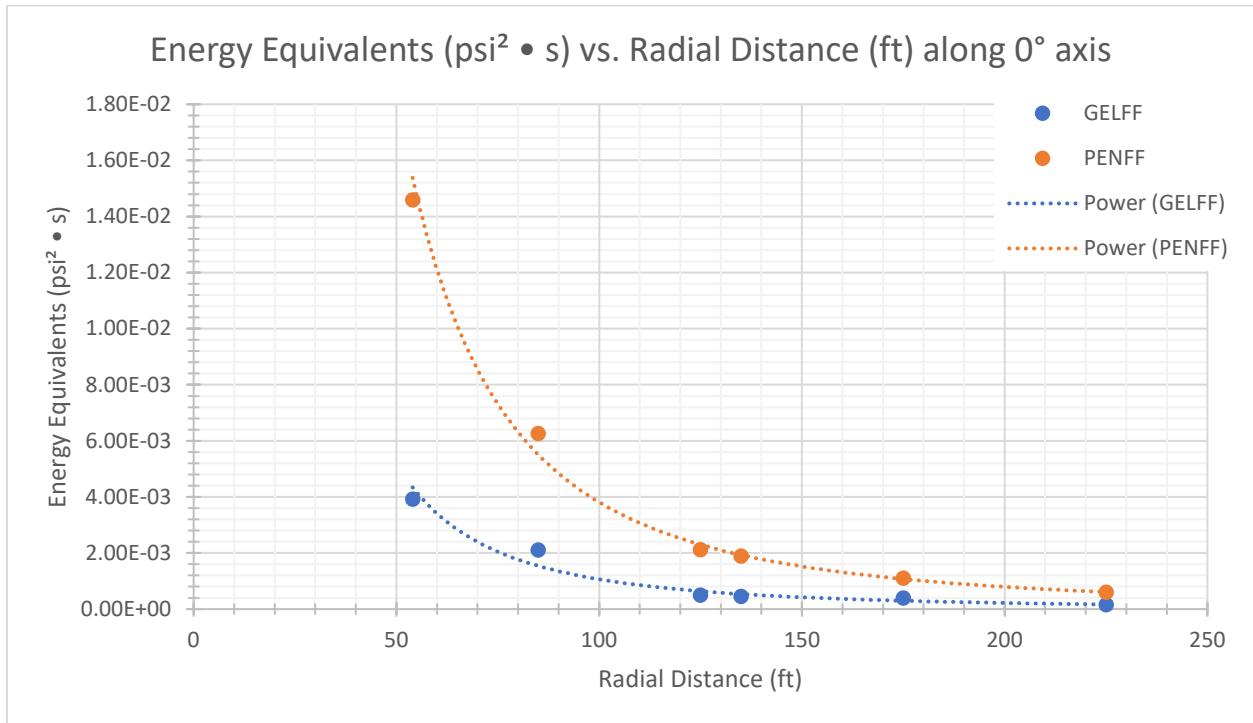


Figure 260 Comparison of PENFF and GELFF energy equivalent results for the 0° axis

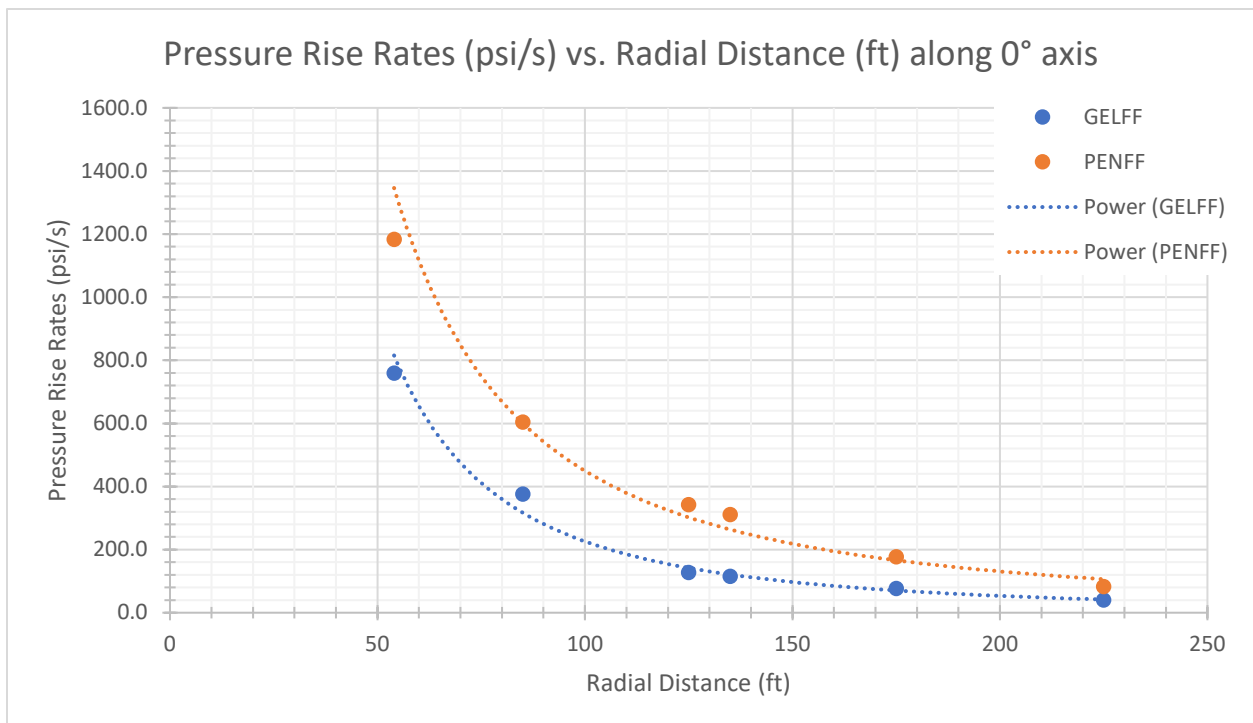


Figure 261 Comparison of PENFF and GELFF pressure rise rate results for the 0° axis

4.2.5 Operational Gel Charge Wyssen Tower

The comparison testing of the gel emulsion charge conducted at the operational Wyssen tower revealed both similarities and differences between the two testing sequences. These similarities and differences were presented in detail in Section 3.2.5, but will be summarized and commented upon here.

In terms of the apparent overall strength, the gel emulsion charges performed similarly in both the flat-field and operational tower settings, but when each measurement axis is compared directly, it can be concluded that the flat-field testing is not entirely representative of the charge performance when deployed from an operational Wyssen Tower. In particular, when deployed from an operational tower installed on an open snow-covered slope, the gel emulsion charge was found (at the measured radial distances) to have slightly higher magnitudes for peak pressure and energy equivalent on the 0° and 45° axes (0° axis shown in Figure 262 and Figure 263), nearly equivalent peak pressure and energy equivalent magnitudes on the 90° axis (Figure 265 and Figure 266), and slightly lower magnitudes for peak pressure and energy equivalent on the 135° and 180° axes (180° axis shown in Figure 268 and Figure 269). Pressure rise rates were shown to be similar (at the measured radial distances) between the operational and flat-field results for all axes (0° and 90° axes shown in Figure 264 and Figure 267, respectively) except for the 180° axis along which the charges deployed from the operational tower were shown to have an approximately 2 times slower pressure rise rate at the measured distances (Figure 270). As for the radial decay of these parameters, it was found that the operational tower had a stronger radial decay of peak pressure except for the 180° axis, stronger radial decay of the energy equivalent along all axes, and approximately equivalent radial decay along all axes for pressure rise rate.

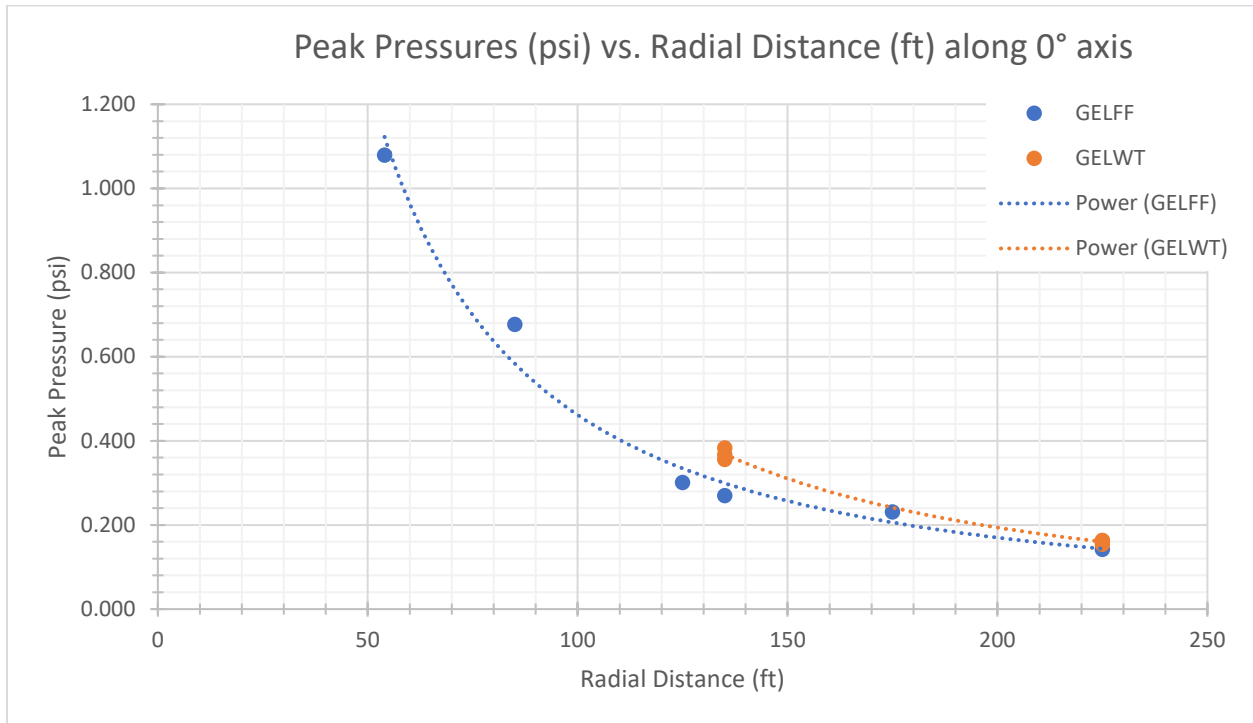


Figure 262 Comparison of GELWT and GELFF peak pressure results for the 0° axis

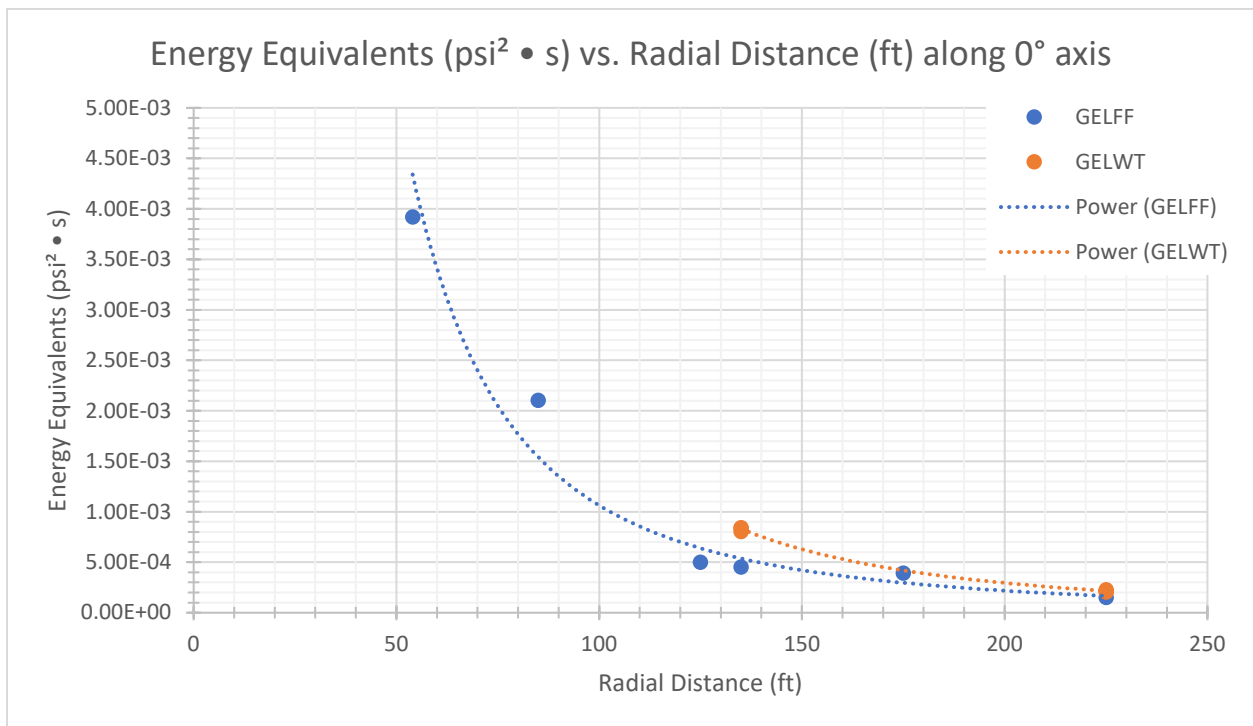


Figure 263 Comparison of GELWT and GELFF energy equivalent results for the 0° axis

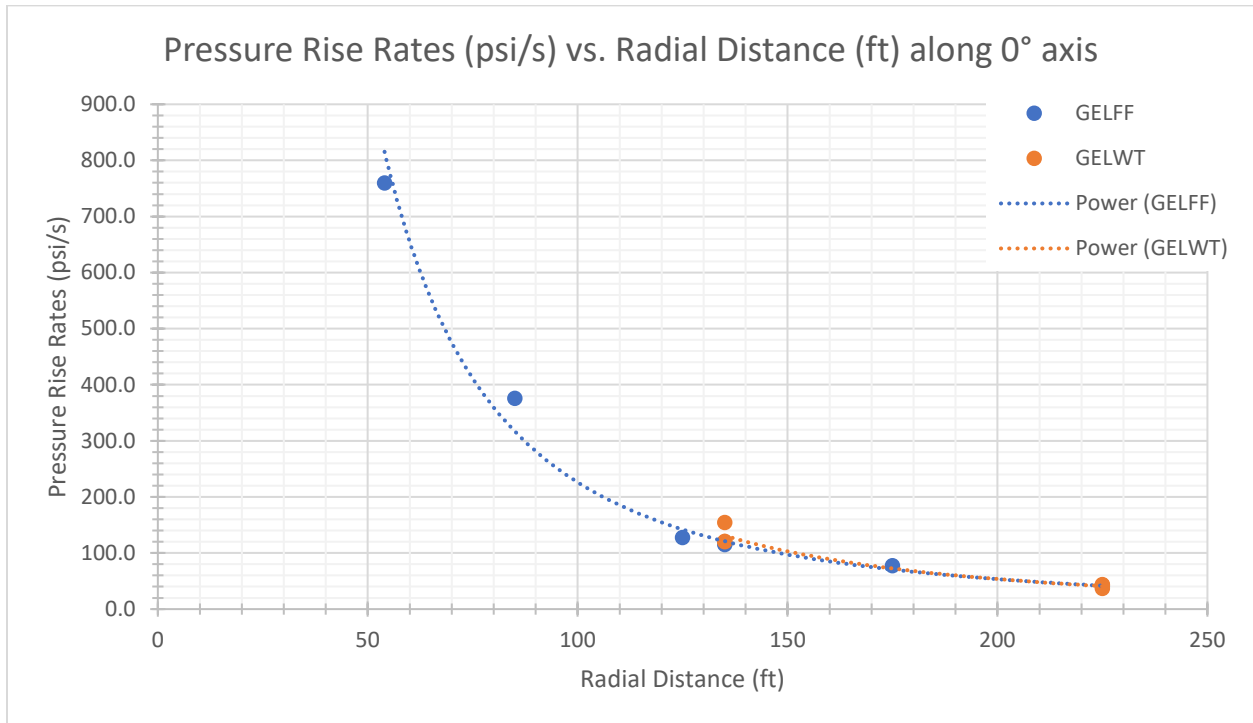


Figure 264 Comparison of GELWT and GELFF pressure rise rate results for the 0° axis

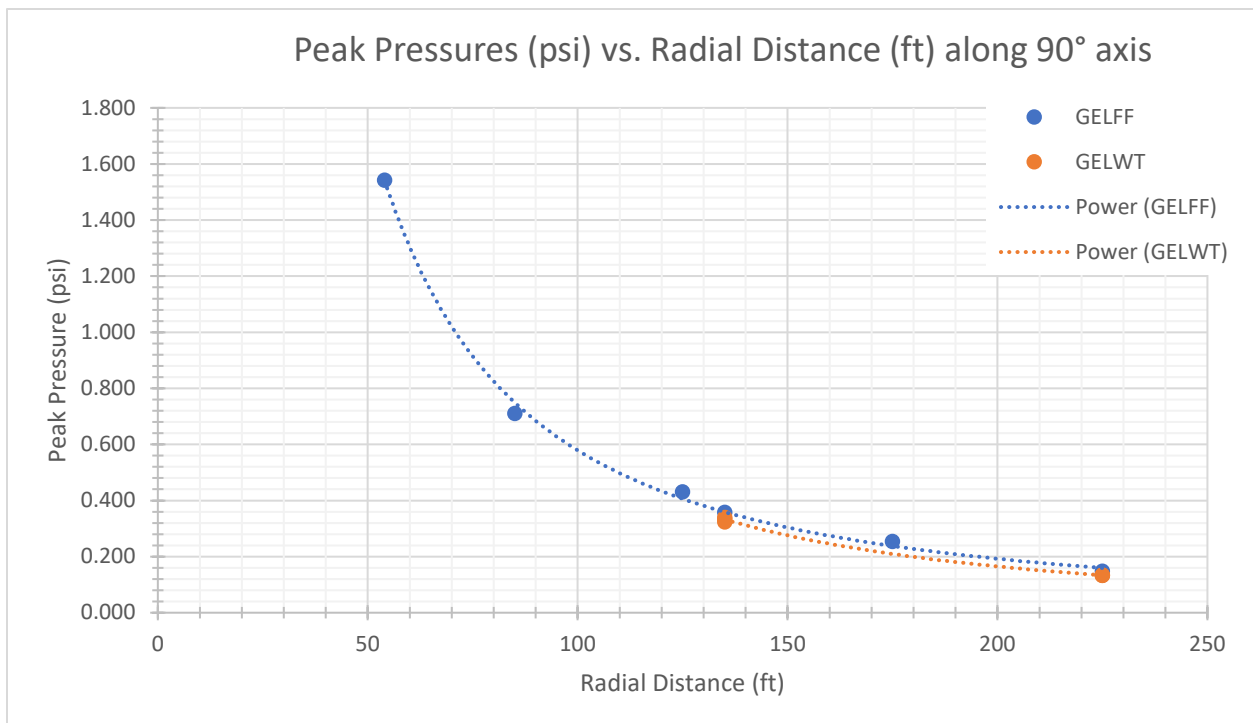


Figure 265 Comparison of GELWT and GELFF peak pressure results for the 90° axis

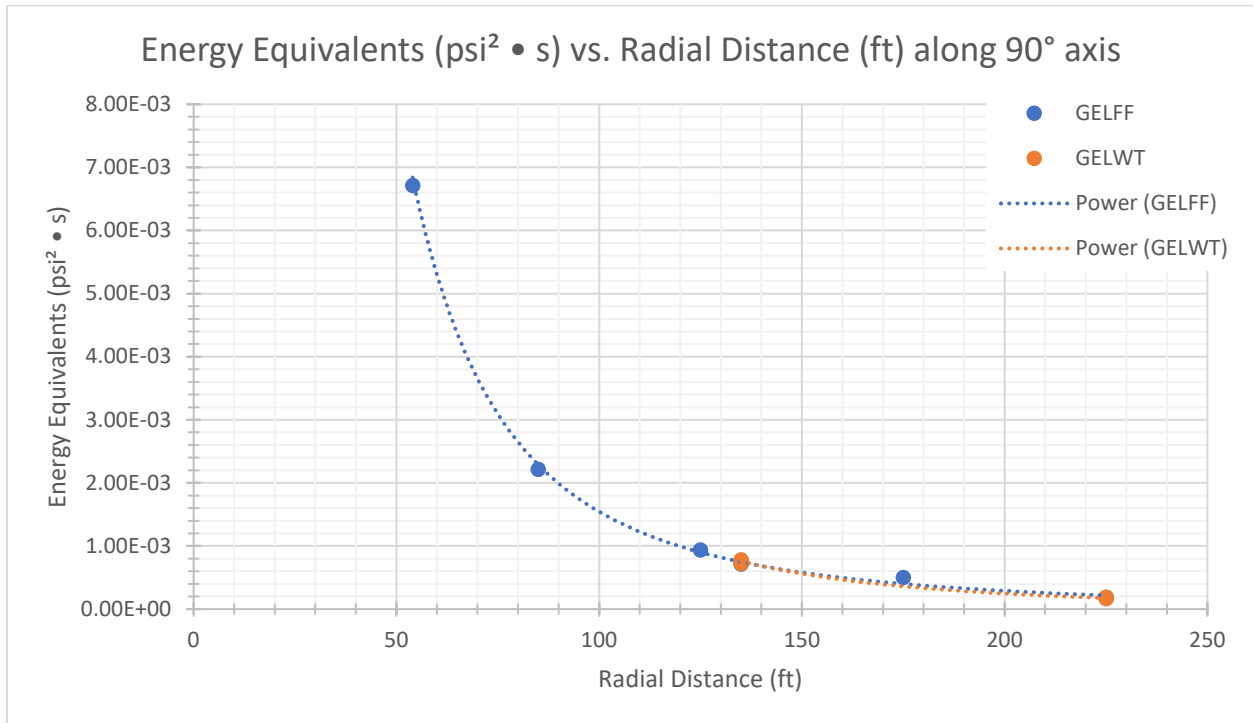


Figure 266 Comparison of GELWT and GELFF energy equivalent results for the 90° axis

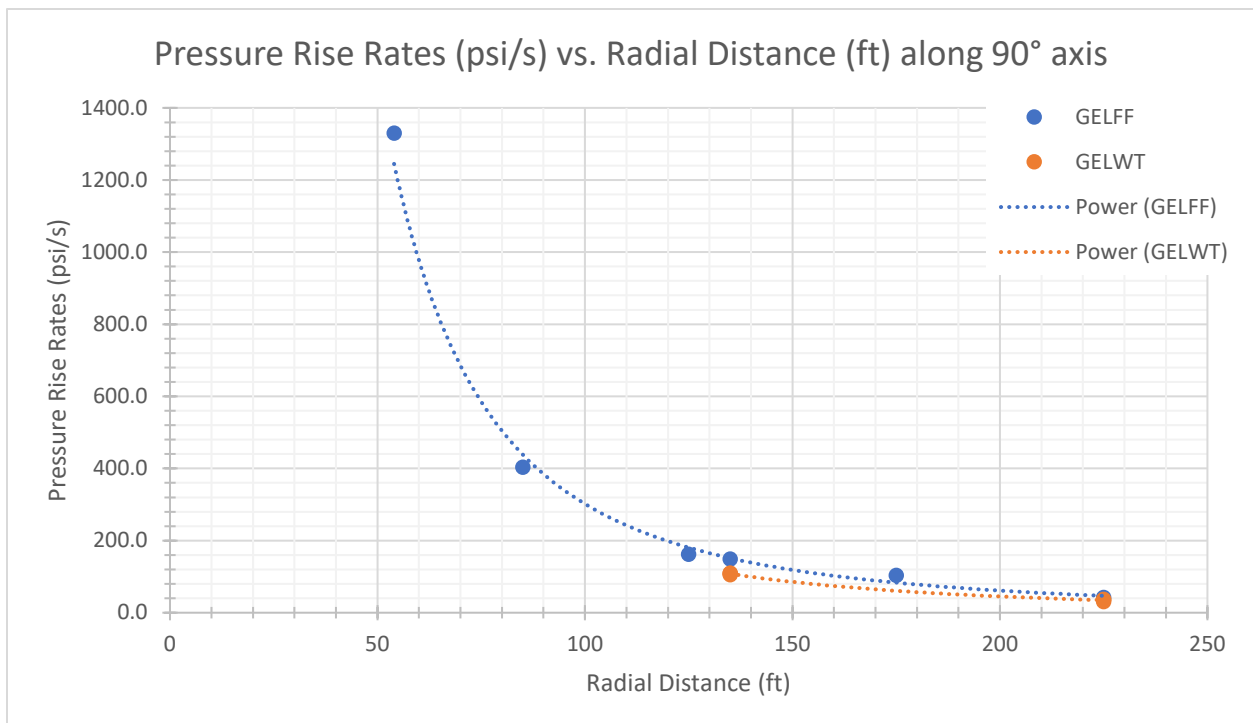


Figure 267 Comparison of GELWT and GELFF pressure rise rate results for the 90° axis

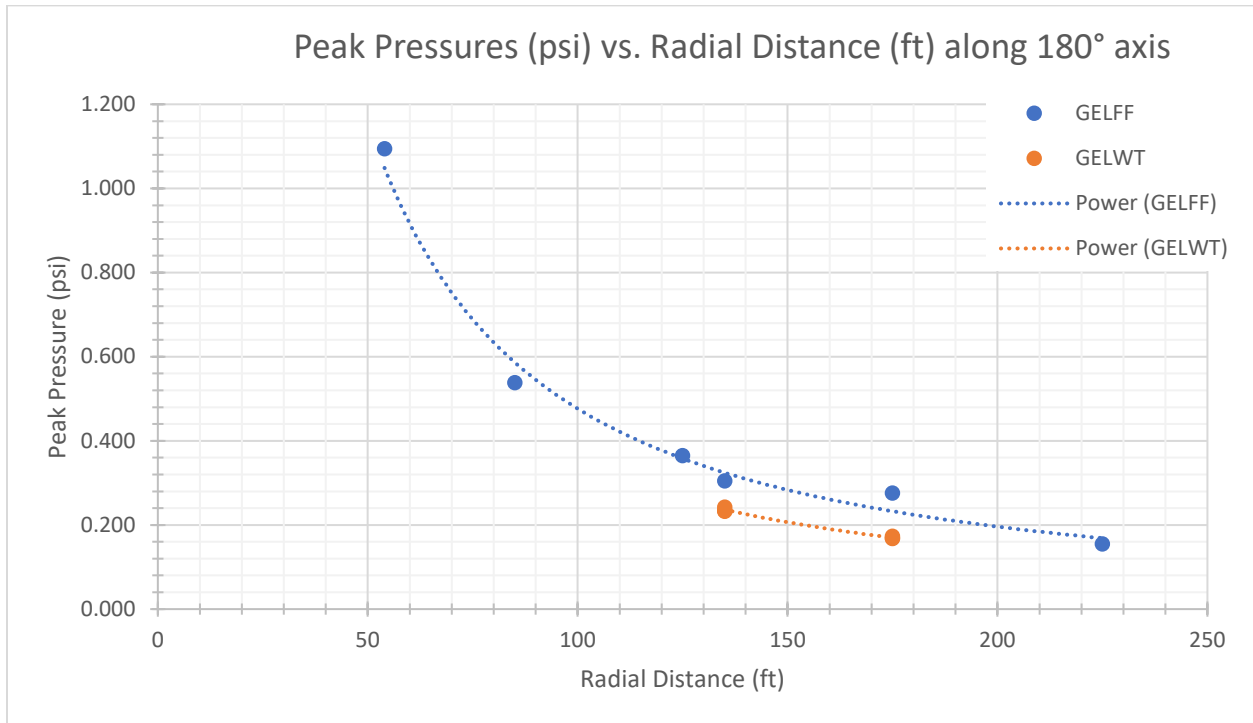


Figure 268 Comparison of GELWT and GELFF peak pressure results for the 180° axis

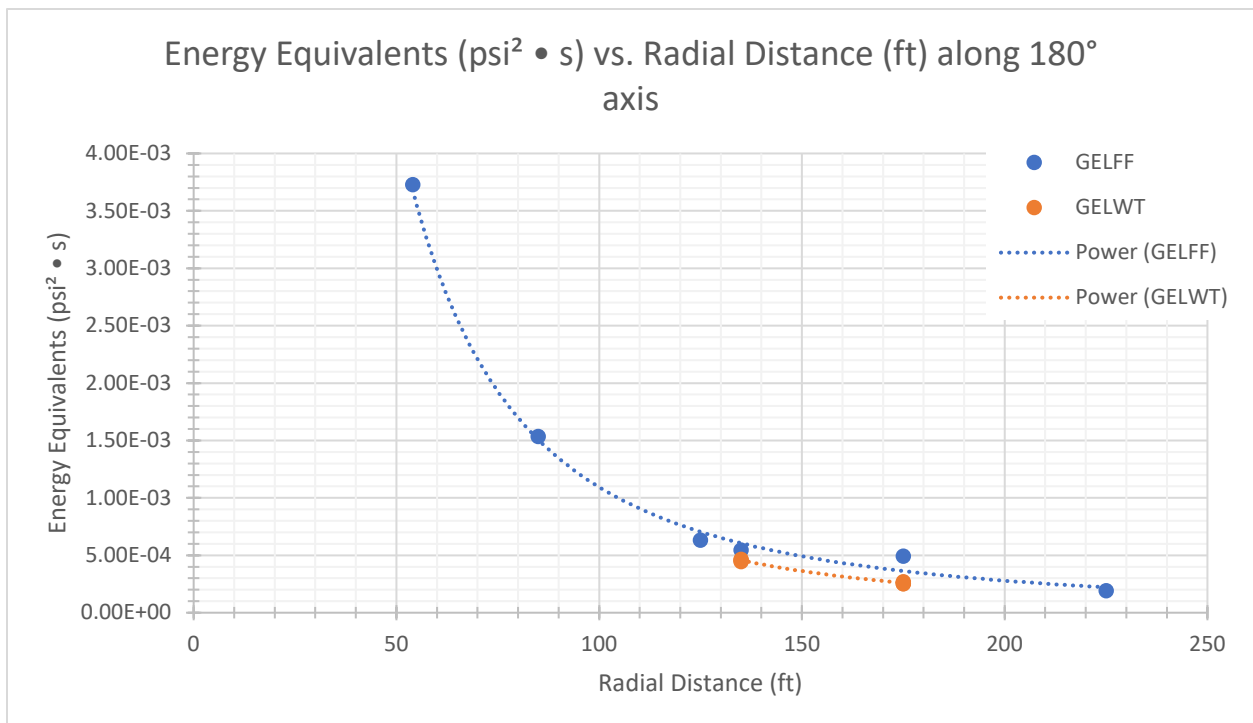


Figure 269 Comparison of GELWT and GELFF energy equivalent results for the 180° axis

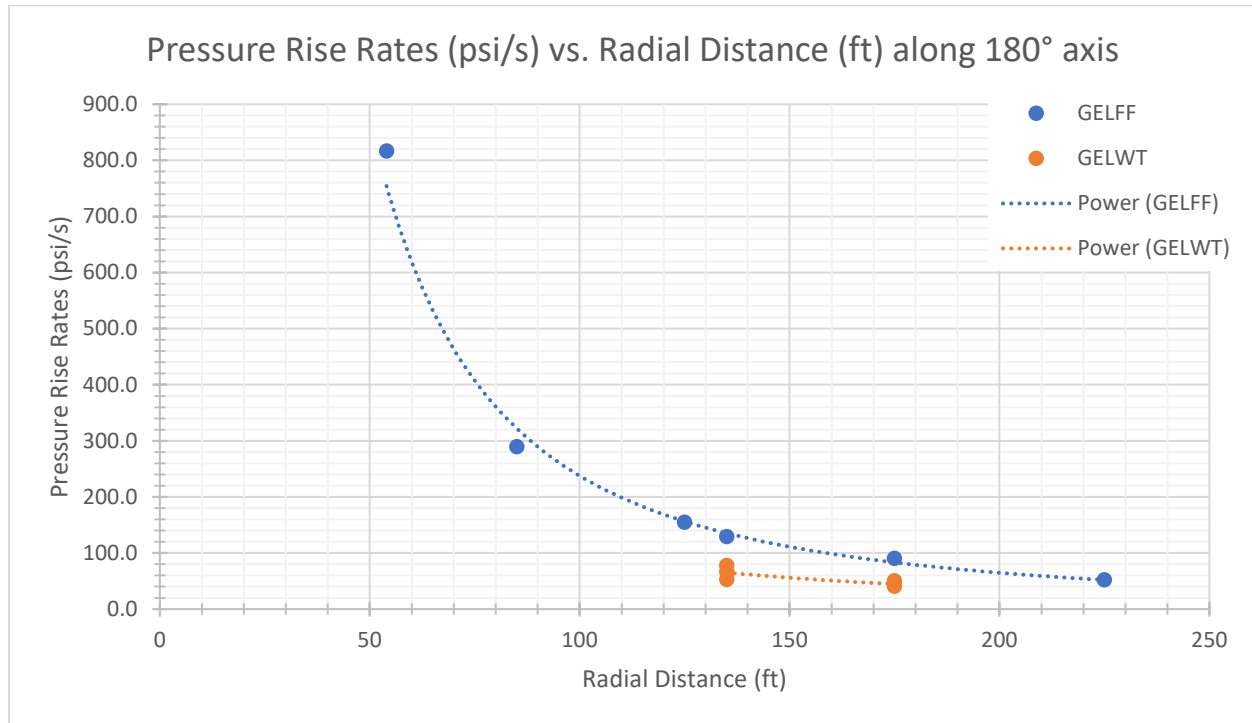


Figure 270 Comparison of GELWT and GELFF pressure rise rate results for the 180° axis

4.2.6 Operational Pentolite Charge Wyssen Tower

Testing of the custom Pentolite charge at the operational Wyssen tower resulted in many of the same conclusions reached for the gel emulsion testing. In this section, the operational testing of the Pentolite charge will first be compared to the flat-field testing of the Pentolite charge. Next, the operational testing of the Pentolite charge will be compared to the operational testing of the gel emulsion charge. And lastly the principal takeaways from the operational testing of the gel emulsion and Pentolite charges will be shared.

4.2.6.1 Operational vs. Flat-Field Testing of Prototype Pentolite Charge As was observed for the gel emulsion charge, the Pentolite charge at the operational RAC system was found (at the measured radial distances) to have slightly higher magnitudes for peak pressure and energy

equivalent on the 0° and 45° axes (0° axis shown in Figure 271 and Figure 272), nearly equivalent peak pressure and energy equivalent magnitudes on the 90° axis (Figure 274 and Figure 275), and slightly lower magnitudes for peak pressure and energy equivalent on the 135° and 180° axes (180° axis shown in Figure 277 and Figure 278). Pressure rise rates were shown to be similar (at the measured radial distances) between the operational and flat-field results (0° and 90° axes shown in Figure 273 and Figure 276, respectively) except for the 135° and 180° axes – along which the charges at the operational tower had an approximately 2 times slower pressure rise rate at the measured distances (180° axis shown in Figure 279). The radial decay of peak pressure, energy equivalent, and pressure rise rate was found to be stronger along all axes than for flat-field testing.

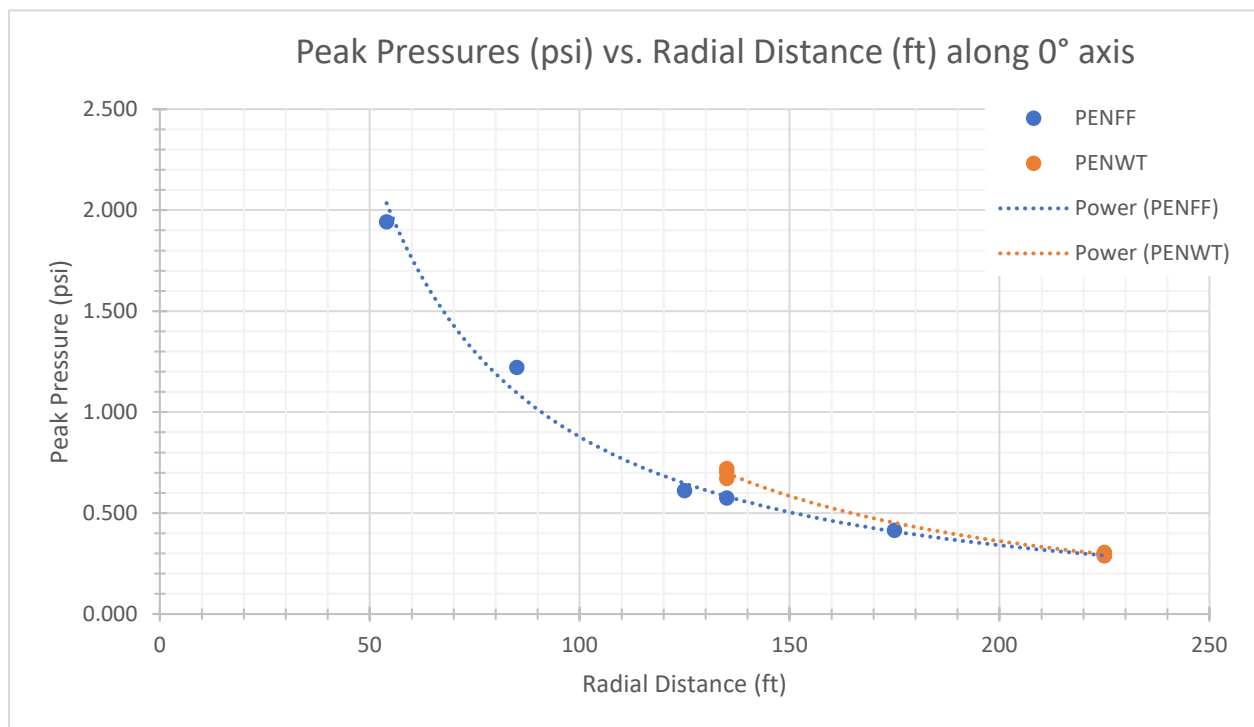


Figure 271 Comparison of PENWT and PENFF peak pressure results for the 0° axis

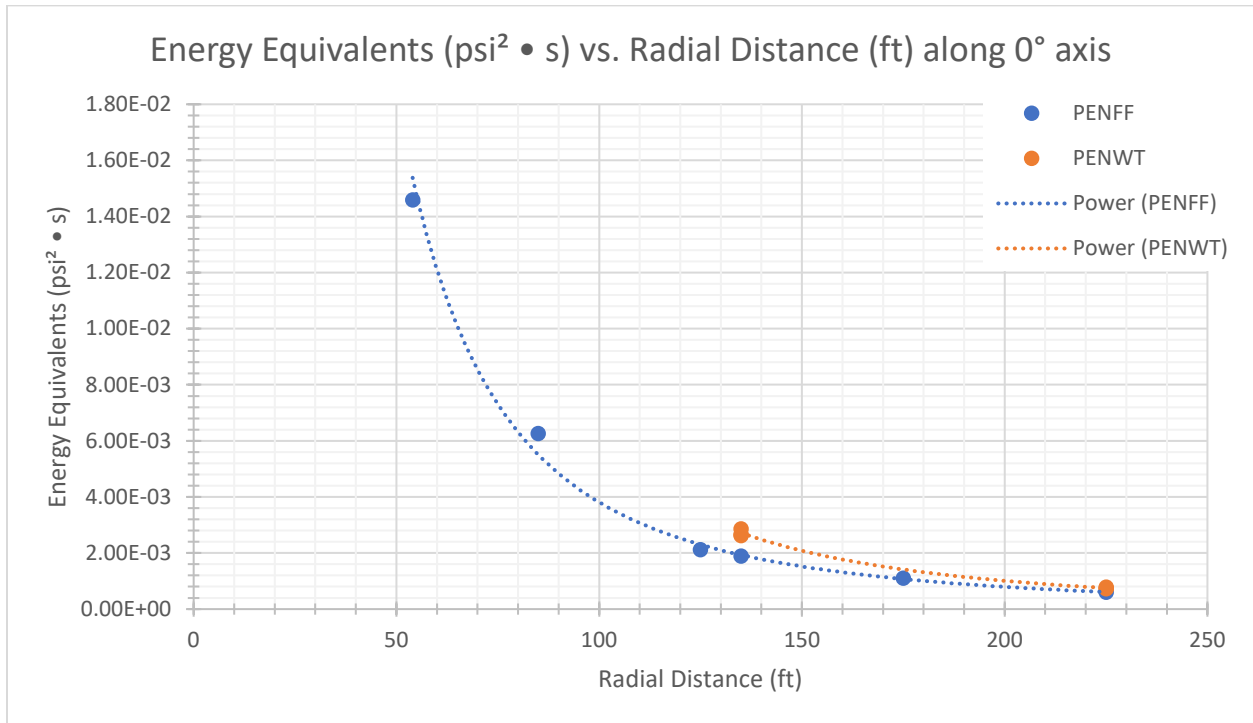


Figure 272 Comparison of PENWT and PENFF energy equivalent results for the 0° axis

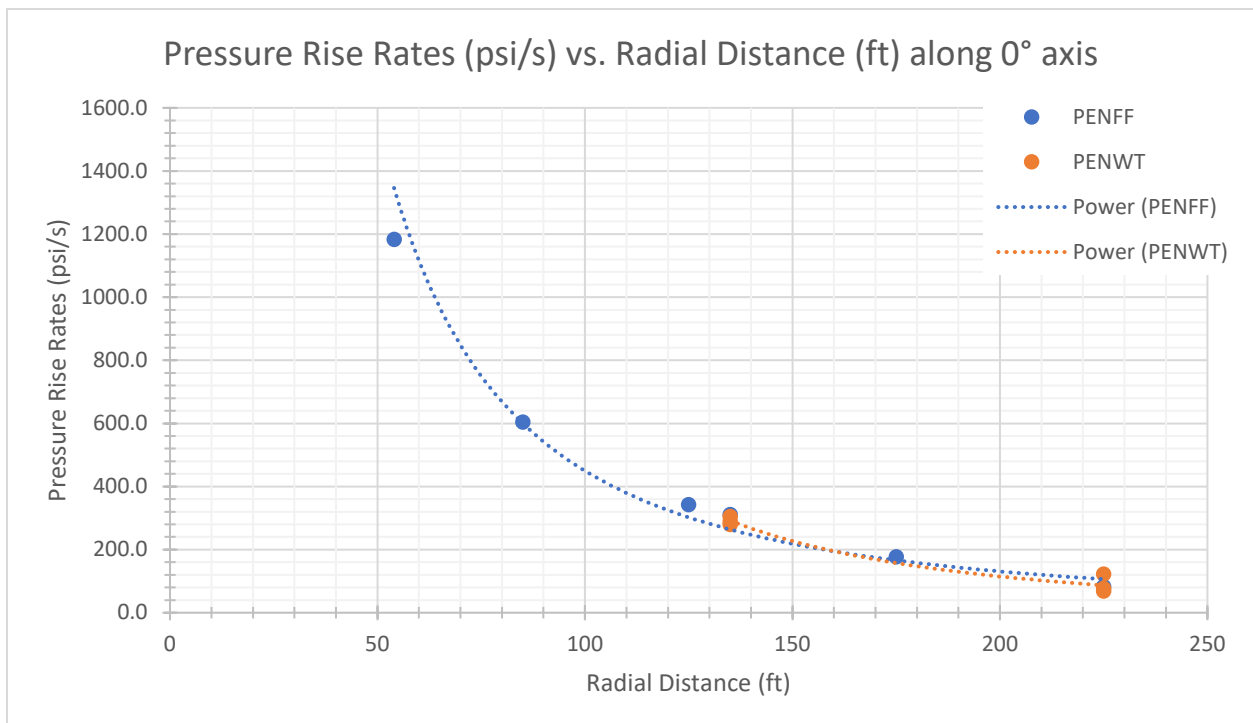


Figure 273 Comparison of PENWT and PENFF pressure rise rate results for the 0° axis

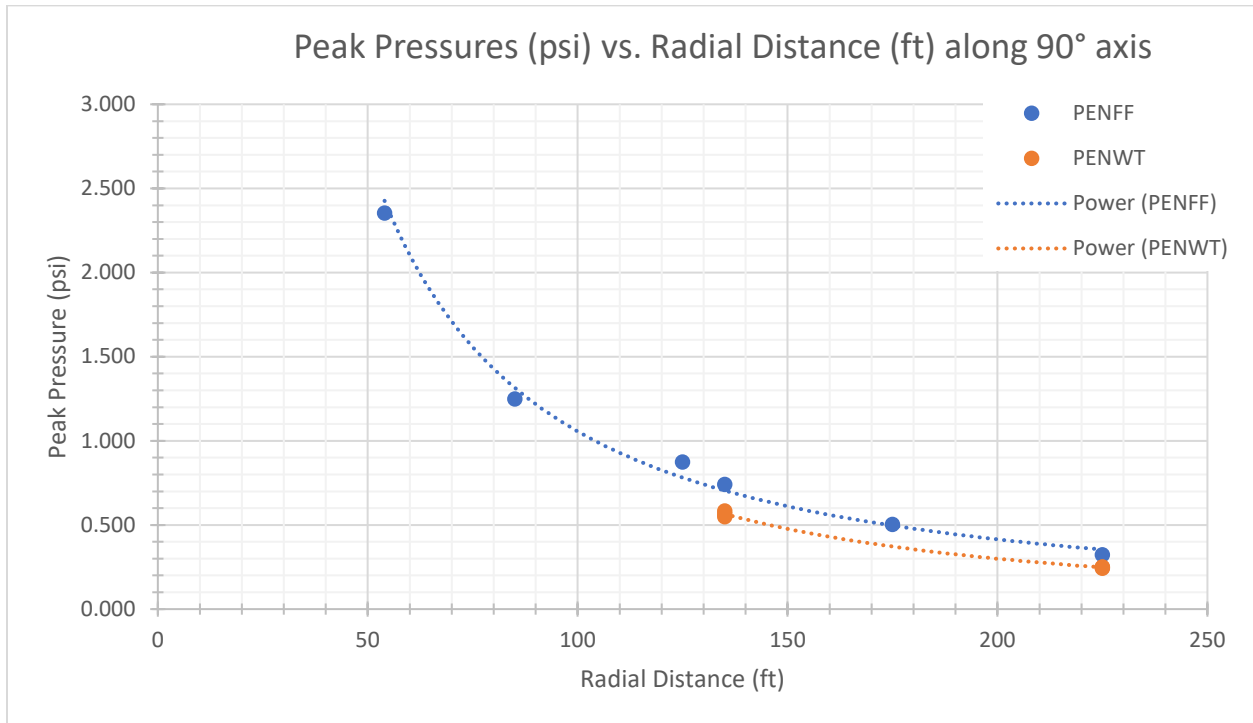


Figure 274 Comparison of PENWT and PENFF peak pressure results for the 90° axis

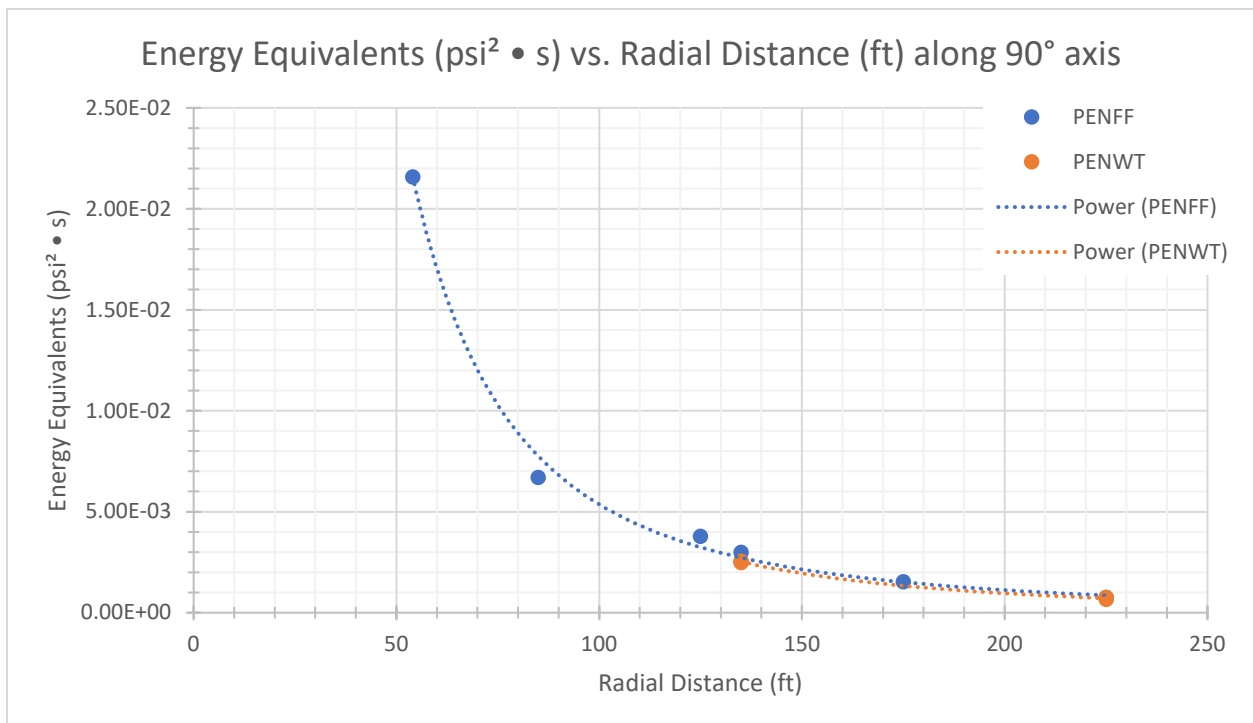


Figure 275 Comparison of PENWT and PENFF energy equivalent results for the 90° axis

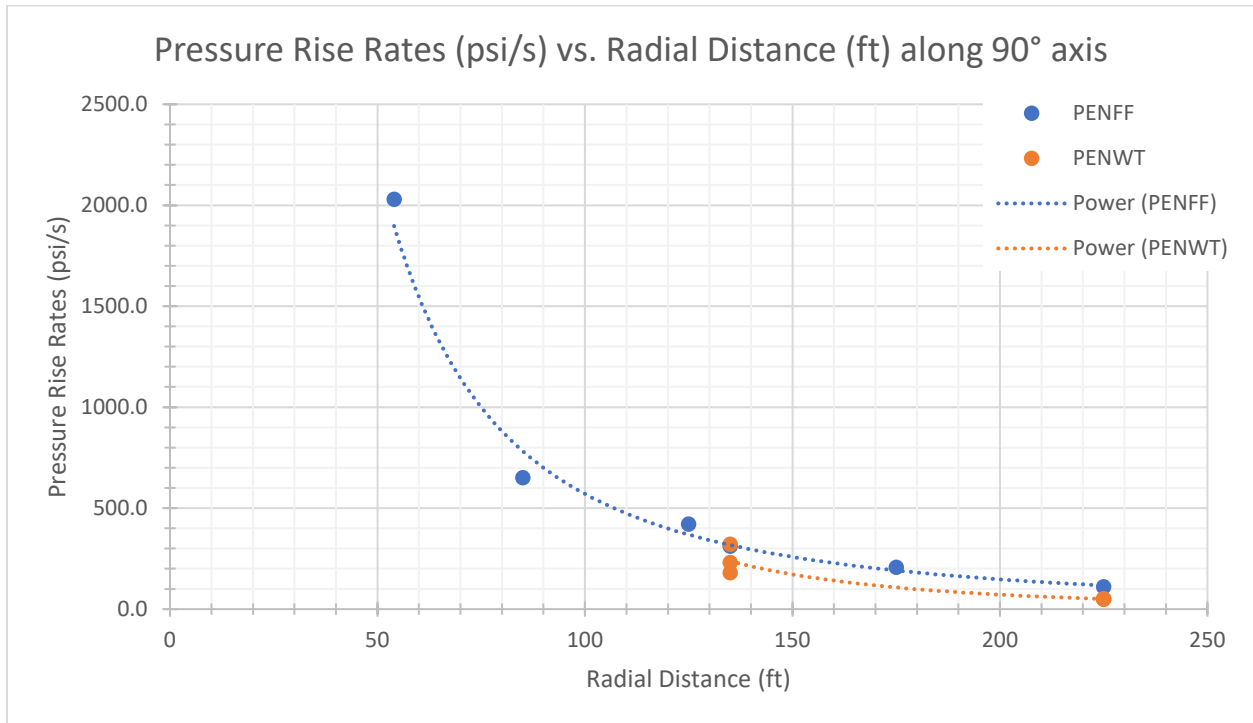


Figure 276 Comparison of PENWT and PENFF pressure rise rate results for the 90° axis

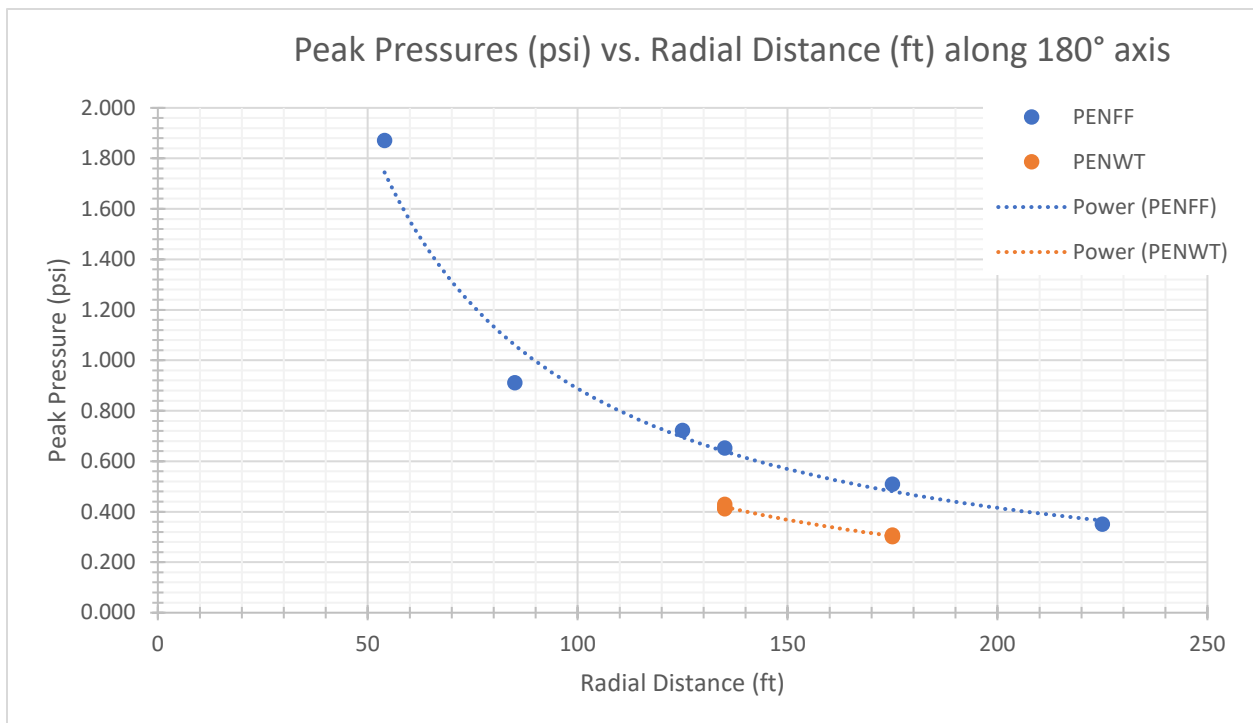


Figure 277 Comparison of PENWT and PENFF peak pressure results for the 180° axis

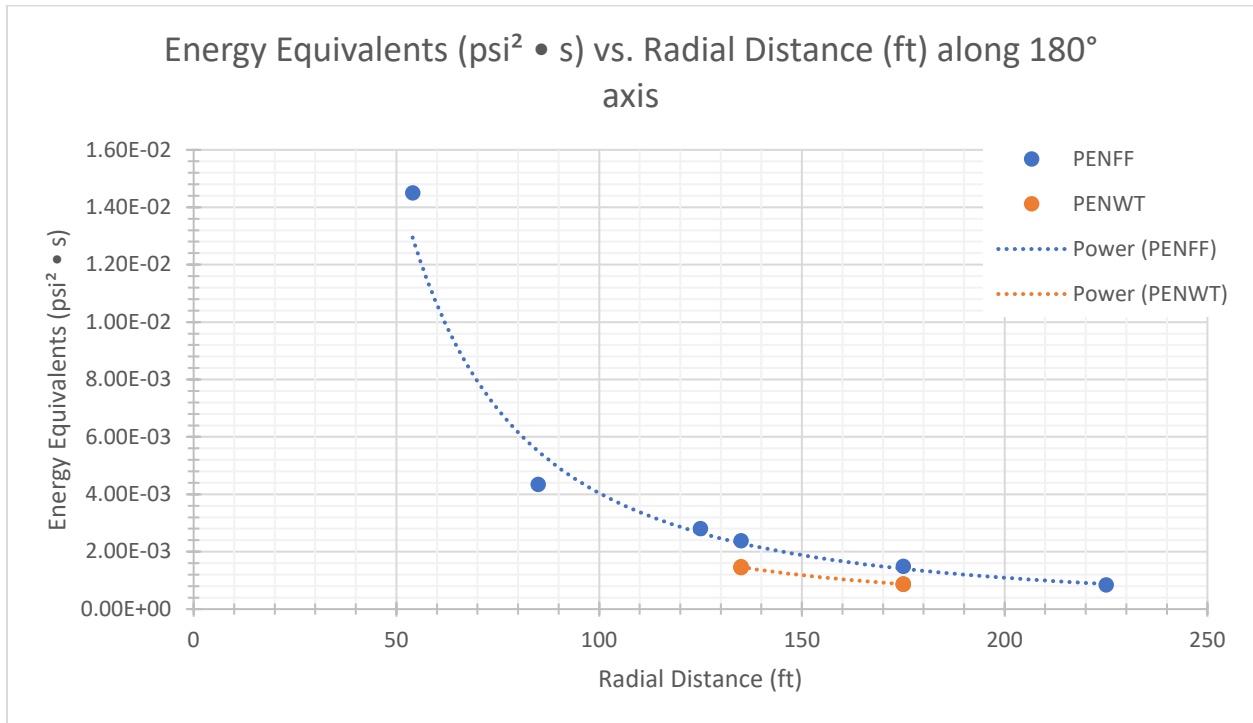


Figure 278 Comparison of PENWT and PENFF energy equivalent results for the 180° axis

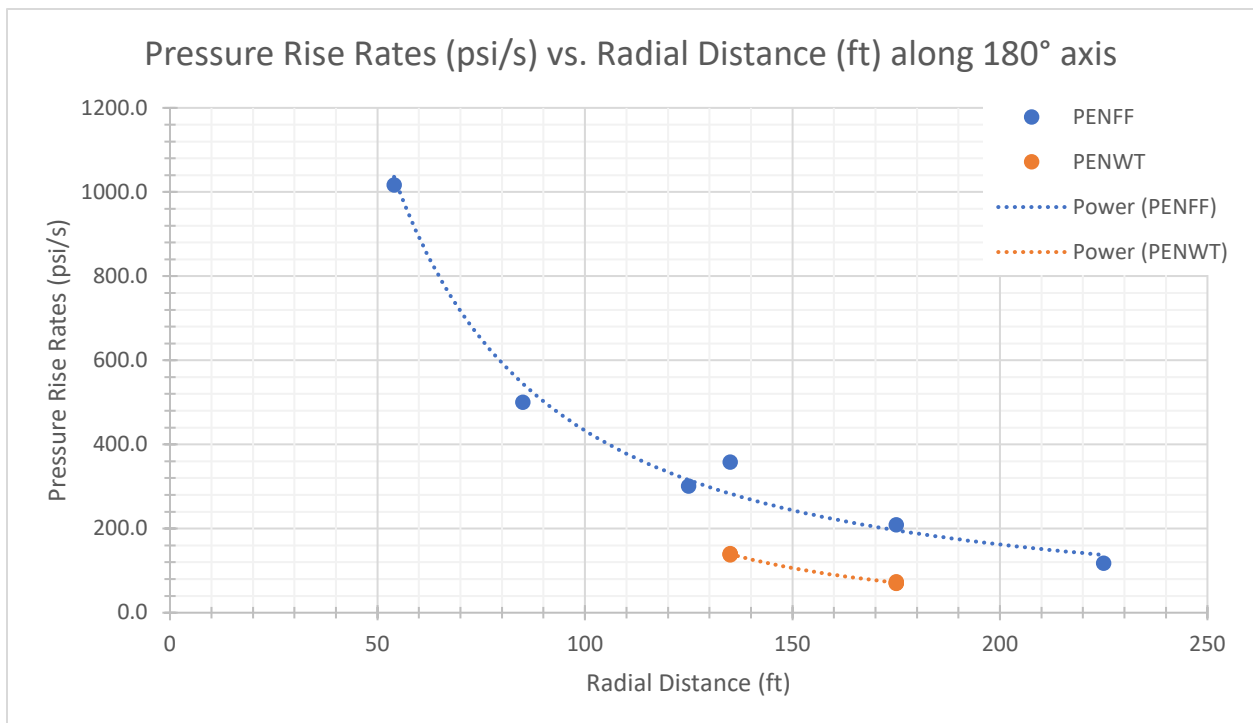


Figure 279 Comparison of PENWT and PENFF pressure rise rate results for the 180° axis

4.2.6.2 Operational Testing of Prototype Pentolite vs. Gel Emulsion Next, as was done for the flat-field results of the gel emulsion and Pentolite charges, the gel emulsion and Pentolite charge results from the operational tower testing can also be compared. One similarity between these results was the non-circular isolines obtained. This differed from the flat-field testing of the charges and was an unexpected result, discussed in more detail in Section 4.2.6.3. The magnitudes of the peak pressure, energy equivalent and pressure rise rate for the Pentolite charge at the operational tower were shown to be greater than the gel emulsion charge on all measured axes and radii. As was shown for the flat-field comparison of the Pentolite and gel emulsion charges, it was also observed that the Pentolite charge had approximately twice the peak pressures and pressure rise rates of the gel emulsion charge and about four times the energy equivalent for all measured radial distances and axes. This relationship is shown below for the 0° axis only (Figure 280 - Figure 282), but all axes were found to have similar results.

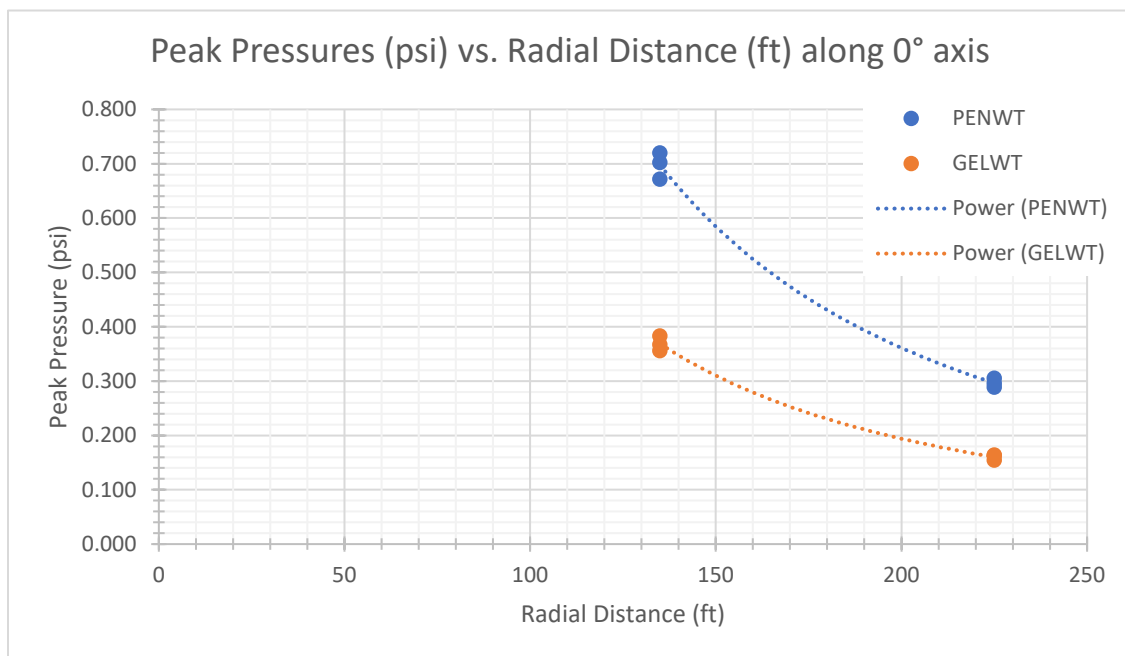


Figure 280 Comparison of PENWT and GELWT peak pressure results for the 0° axis

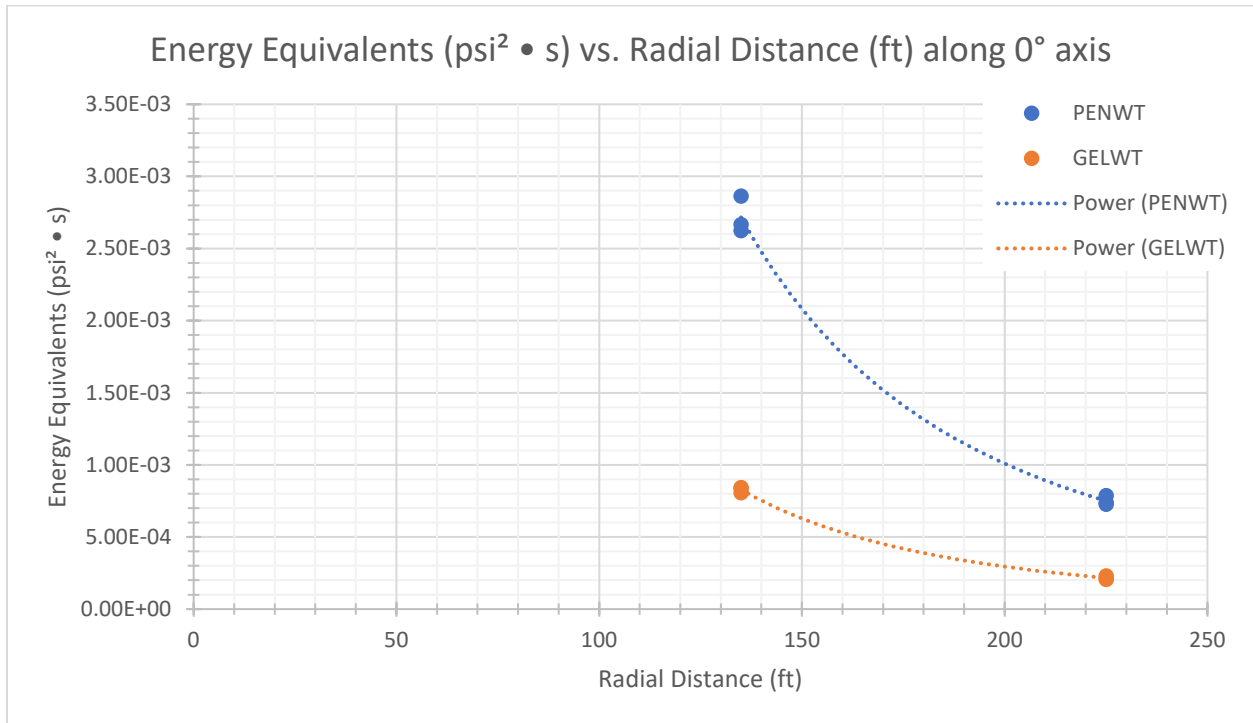


Figure 281 Comparison of PENWT and GELWT energy equivalent results for the 0° axis

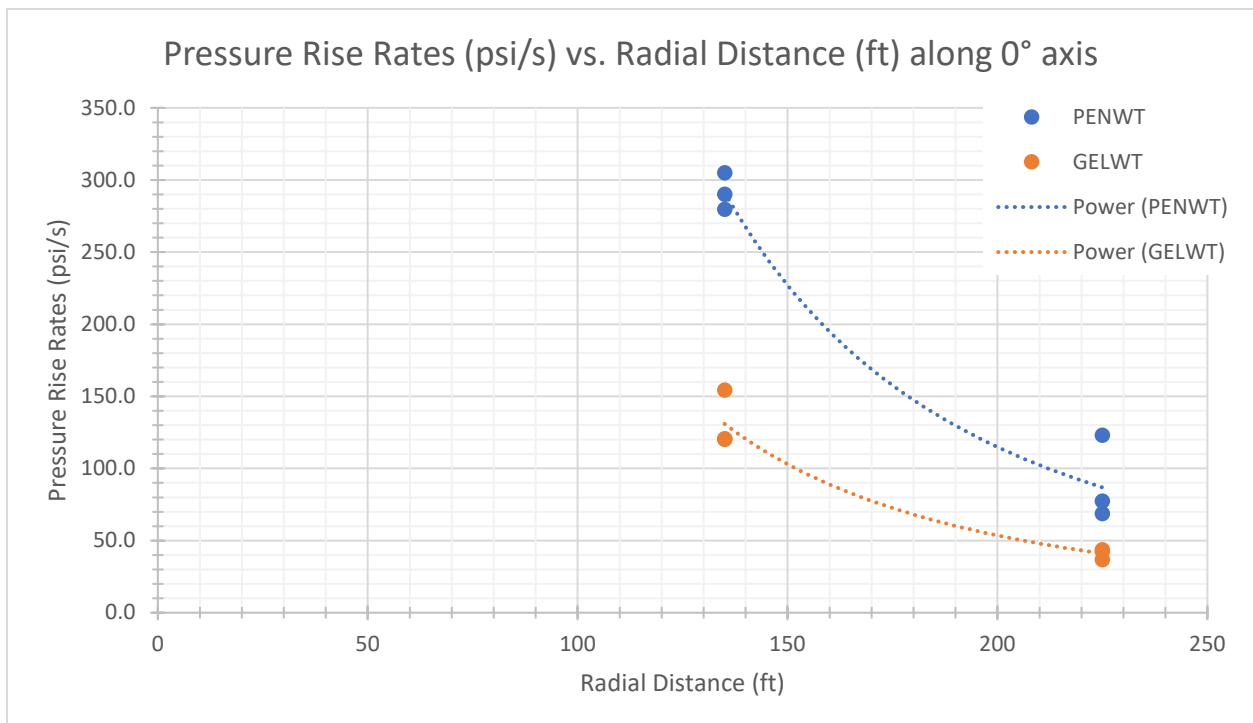


Figure 282 Comparison of PENWT and GELWT pressure rise rate results for the 0° axis

4.2.6.3 General Comments on Operational Testing of Gel and Pentolite Charges As

mentioned previously, the purpose of the gel emulsion and Pentolite comparison testing at the operational Wyssen Tower was to determine if the charges would perform similarly over a flat snow-covered open field as when deployed from an operational RAC system on a snow-covered open slope. Although the same gel emulsion charges and similar Pentolite charges were used in all testing sequences and similar overall blast strengths were observed as expected, the differences in the symmetry, shown by non-circular isolines, of the blast wave profile between flat-field and operational testing was an unexpected outcome. While the sources of this discrepancy are not known, several possibilities have been considered and are described below.

First, it could be the result of geometrical differences between the flat-field and operational testing. In both testing sequences, microphone radial distance was measured parallel to the snow surface for practicality and consistency in testing methods. In the case of a charge detonated on the snow surface this radial distance is also the same as the line-of-sight distance from the blast center to a given microphone and would not change if the snow surface was inclined. However, for an elevated charge, the slope angle will alter the line-of-sight distance between the blast center and microphones – making this distance slightly longer for downhill microphones and shorter for uphill microphones (when compared to a flat-field arrangement). This could be one source of the observed differences, but the difference in line-of-sight distance for a slope angle of 30°-40° is relatively small compared to the radial distances measured in this work. Additionally, it is expected that the uphill microphones would have higher peak pressures than their flat-field counterparts due to the decreased line-of-sight distance that the blast wave must travel (i.e., reduced geometrical divergence of the blast wave).

Another possible source of the observed discrepancies could be snow or environmental conditions. Flat-field testing was conducted in January over a dry snow cover, and operational testing was conducted in April over a moist and dense snowpack (see Section 2.4 for more information on testing conditions). However, if environmental or snowpack conditions were responsible, it is expected that all axes would be affected in the same way, and the blast wave profile would remain symmetric.

The Wyssen Tower itself could also be one possible source of the observed differences. More exactly, the tower mast could be producing a shadowing effect and reducing the uphill strength of the blast wave since the charge is deployed and detonated downslope of the tower and the microphones were placed directly upslope of the tower mast.

Lastly, it is also possible that the differences between flat-field and operational Wyssen Tower testing reported herein could be the result of the limited microphone locations utilized during operational system testing. As mentioned in Section 2.4.2.6, only two locations along each axis were included in the operational system testing sequence due to timing and weather constraints. Although multiple tests were conducted, showing a high level of repeatability for both explosives and provided multiple data points to help determine the power law fits, the limitation of two radial distances makes it challenging to find a power law curve suitable to describe the blast wave decay over a wider range of radial distances. As such, the power laws presented herein for the operational Wyssen Tower may not adequately reflect the actual radial decay of the peak pressure, energy equivalent, or pressure rise rates. This, however, does not invalidate the peak pressure and energy equivalent magnitudes themselves – which still indicated a non-symmetric behavior for operational Wyssen Tower testing.

In any case, the present work does not suggest that flat-field testing is an adequate representation of the blast wave behavior at an operational Wyssen Tower RAC system. Further testing with additional microphone locations is recommended to better understand the observed differences (and the source of those differences) between flat-field and operational Wyssen Tower testing.

4.2.7 Simulated Avalanche Guard

Lastly, Phase 2 results from the simulated Avalanche Guard will now be discussed. As mentioned above, these tests were conducted primarily out of the interest of avalanche control practitioners and are only meant to represent a rough approximation of the charge from an operational Avalanche Guard. The results of these tests can be summarized quite concisely. It was found that the peak pressure, energy equivalent, and pressure rise rates of the simulated Avalanche Guard charges were a near perfect match with the results of the flat-field gel emulsion charge testing in terms of magnitude and radial decay across all measured axes and radii. The agreement of these parameters is shown below for the 0° axis (Figure 283 - Figure 285), but all axes showed a similar level of agreement.

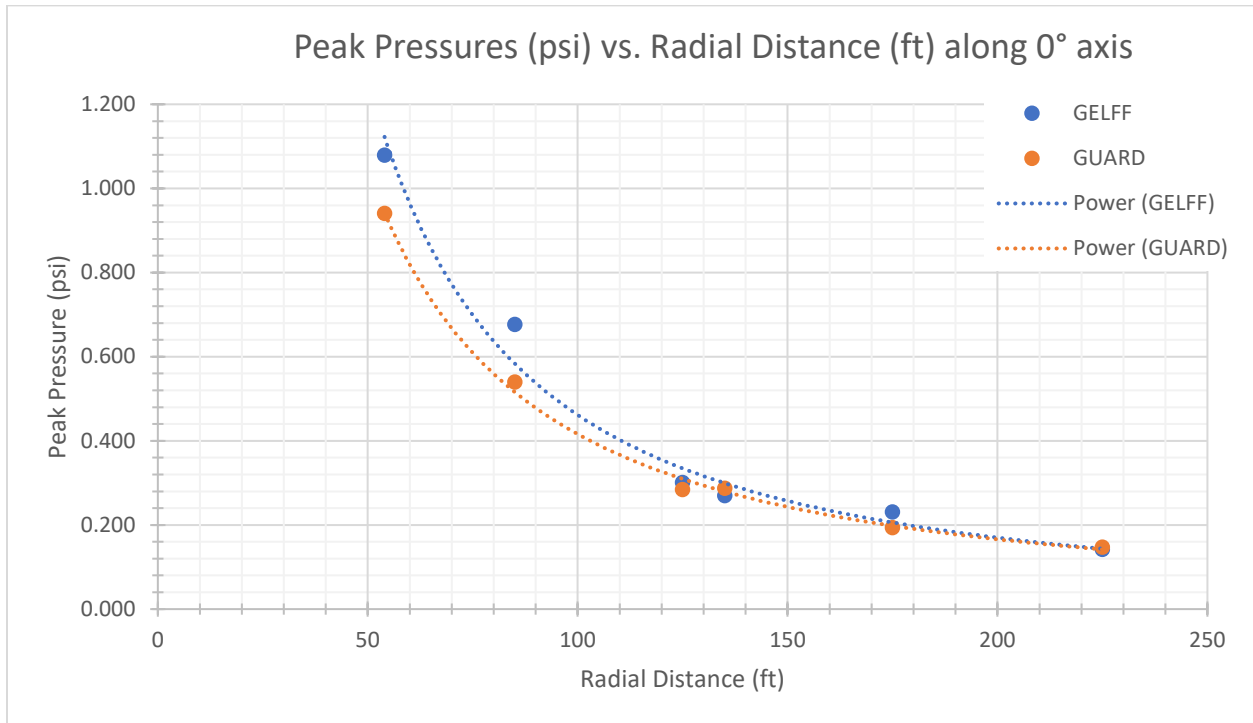


Figure 283 Comparison of GUARD and GELFF peak pressure results for the 0° axis

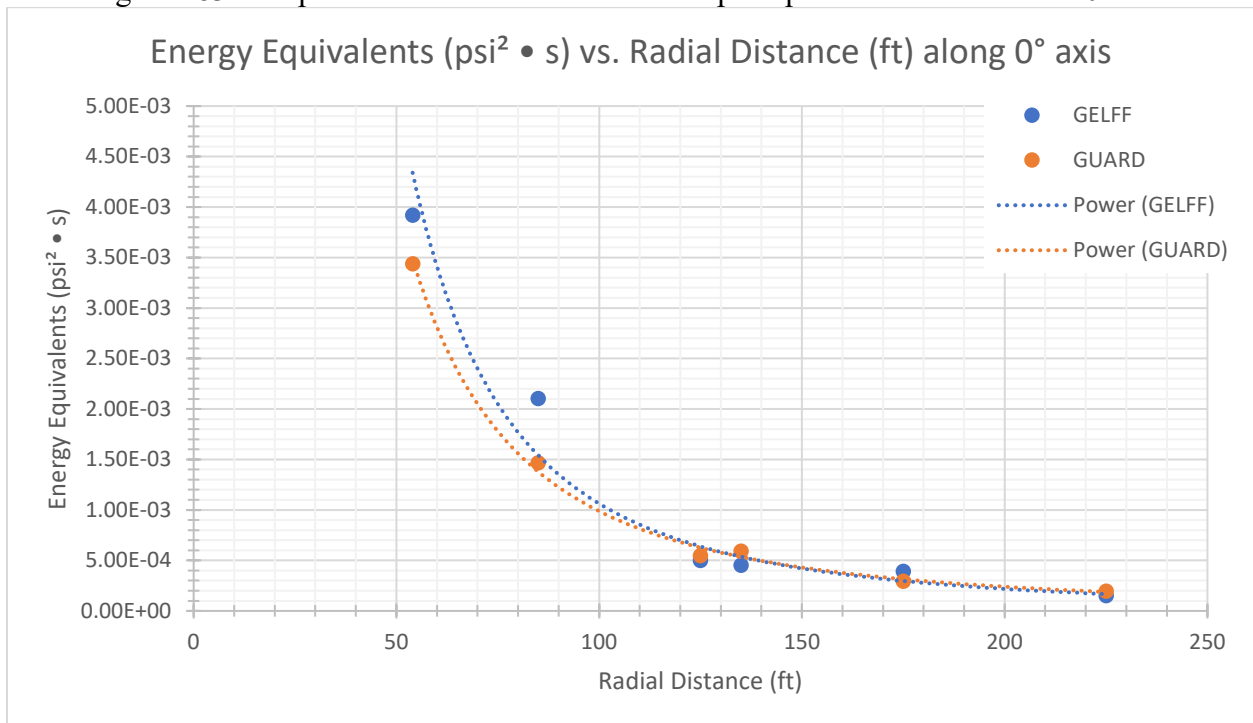


Figure 284 Comparison of GUARD and GELFF energy equivalent results for the 0° axis

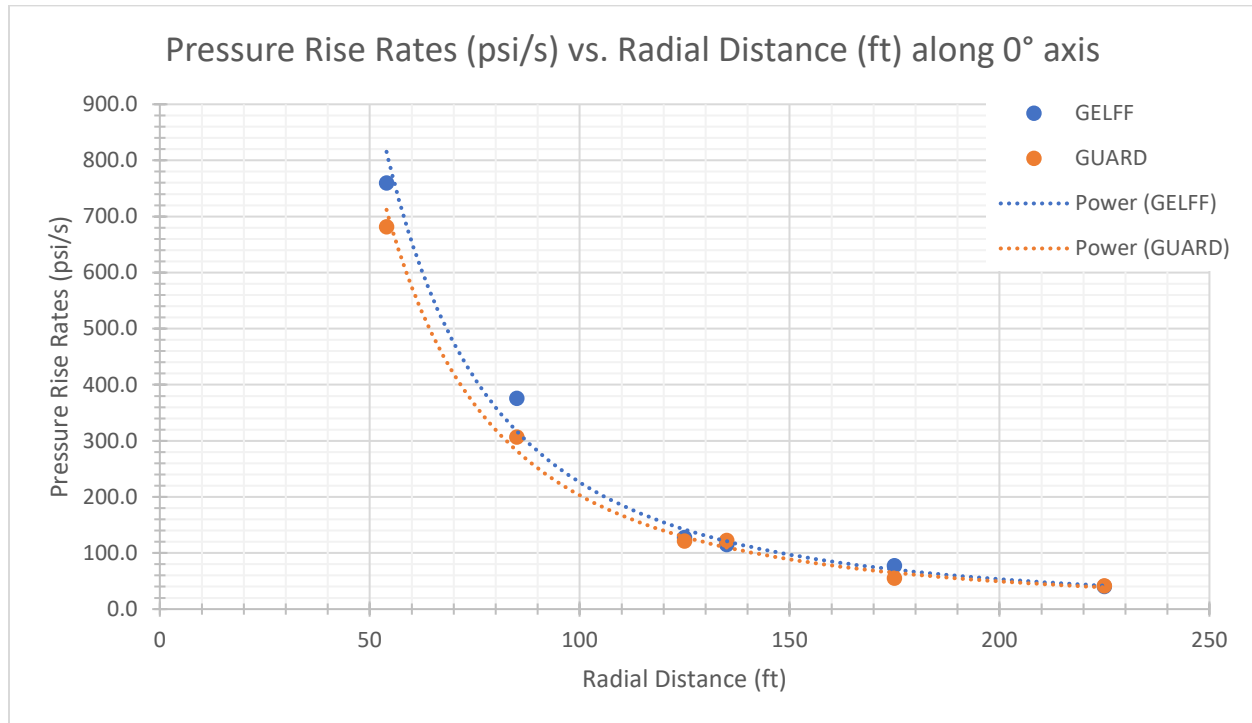


Figure 285 Comparison of GUARD and GELFF pressure rise rate results for the 0° axis

4.3 Phase 3

The focus of Phase 3 of the testing plan was to obtain pressure data from locations where unique terrain features were present. This pressure data was then compared against the Phase 2 results of similar explosives and testing arrangements to better understand the influence of the chosen terrain features. Although it is not feasible to investigate all possible terrain conditions, and the results obtained are inherently limited to the specific locations tested, the results and associated observations were largely successful in providing insight into the effects of three common terrain features – a cliff, a ridge, and a gully. The specific conclusions and observations made for each terrain feature will be discussed in greater detail in the following sections, but a brief summary is presented here.

In all cases, the limited testing that was performed and limited data collected made it challenging to adequately characterize the three terrain features. Accordingly, in order to obtain a more thorough understanding of each of these terrain features, a more extensive testing plan with multiple locations, additional microphone locations, and similar terrain features is strongly recommended. Nonetheless, the initial results obtained in the present work did indicate some level of difference between the terrain testing and the comparable testing performed in Phase 2 – implying that the terrain features do result in a measurable difference to system performance. For the cliff and gully terrain features, a decrease in the radial decay of the peak pressure was observed along the 0° axis. For the ridge terrain feature, peak pressures and energy equivalent magnitudes were decreased overall and the radial decay of the peak pressure was also decreased.

4.3.1 Cliff Terrain Feature

The results of the cliff terrain feature testing showed a moderate increase in the directionality of the blast wave over the flat-field testing and operational Wyssen Tower testing. The results of cliff terrain test showed peak pressures were lower than the flat-field and operational tests across all measured axes and radii except for distances greater than about 200 ft along the 0° axis (Figure 286, Figure 289, and Figure 292). The energy equivalent results of the cliff terrain test indicated that the radial decay of the energy equivalent was less than flat-field or operational tests along the 0° axis, but greater along the 45° and 90° axes. Similarly, it was found that the energy equivalent magnitudes of the cliff test were higher at all measured radii than the flat-field or operational tests on the 0° axis (Figure 287), about equal on the 45° axis (Figure 290), and smaller along the 90° axis (Figure 293). Lastly, for the pressure rise rate, it was determined that the pressure rise rate for the cliff shot was 2 to 4 times lower than the pressure

rise rates of the operational and flat-field Pentolite testing for all measured axes and radii (Figure 288, Figure 291, and Figure 294).

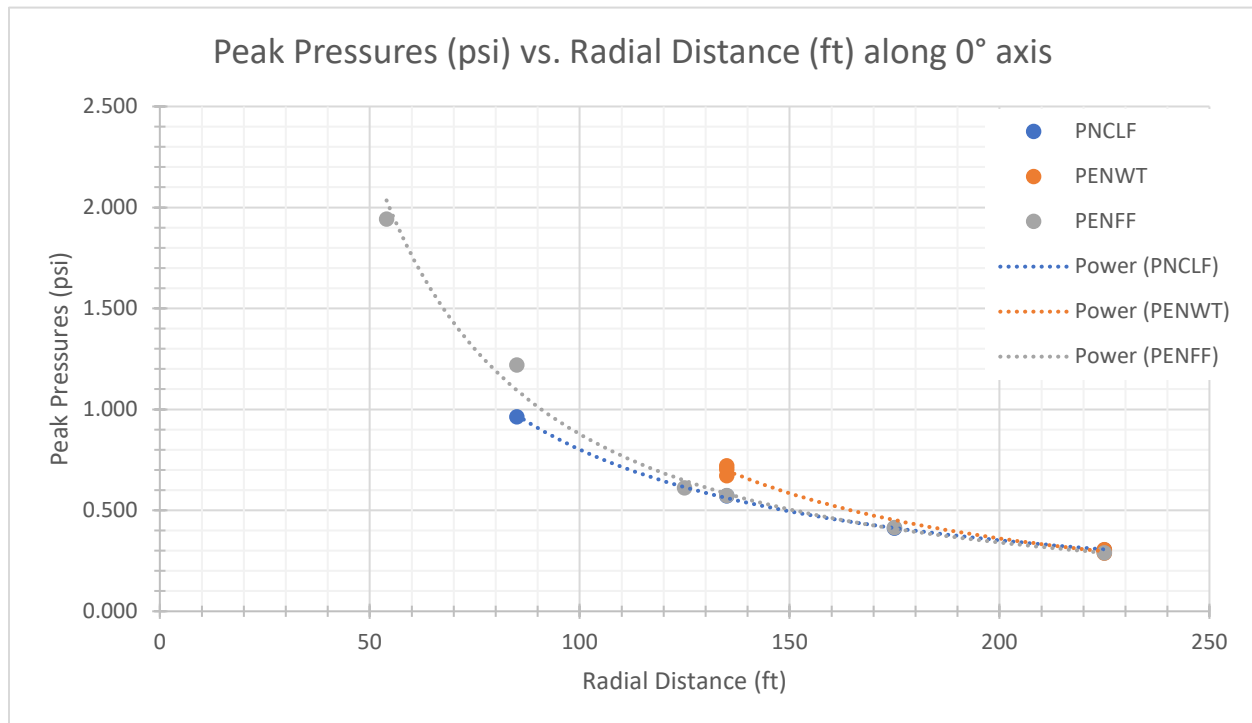


Figure 286 Comparison of PNCLF, PENWT, and PENFF peak pressure results for the 0° axis

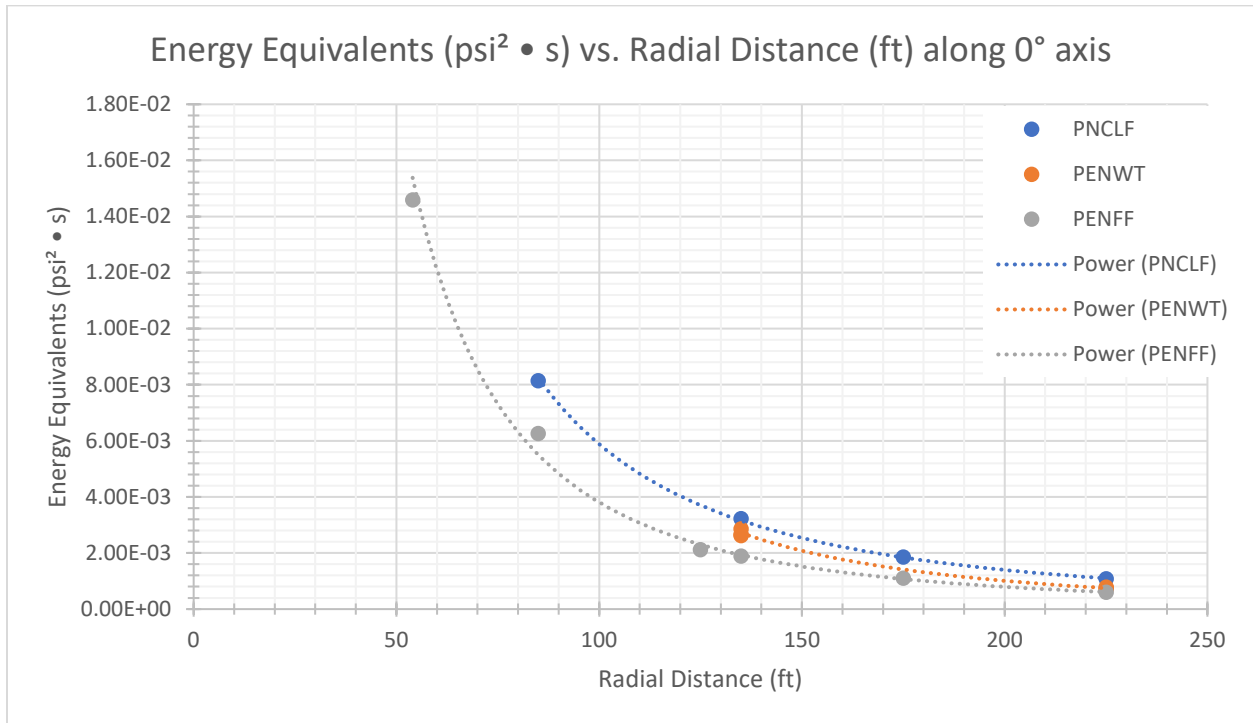


Figure 287 Comparison of PNCLF, PENWT, and PENFF energy equivalents for the 0° axis

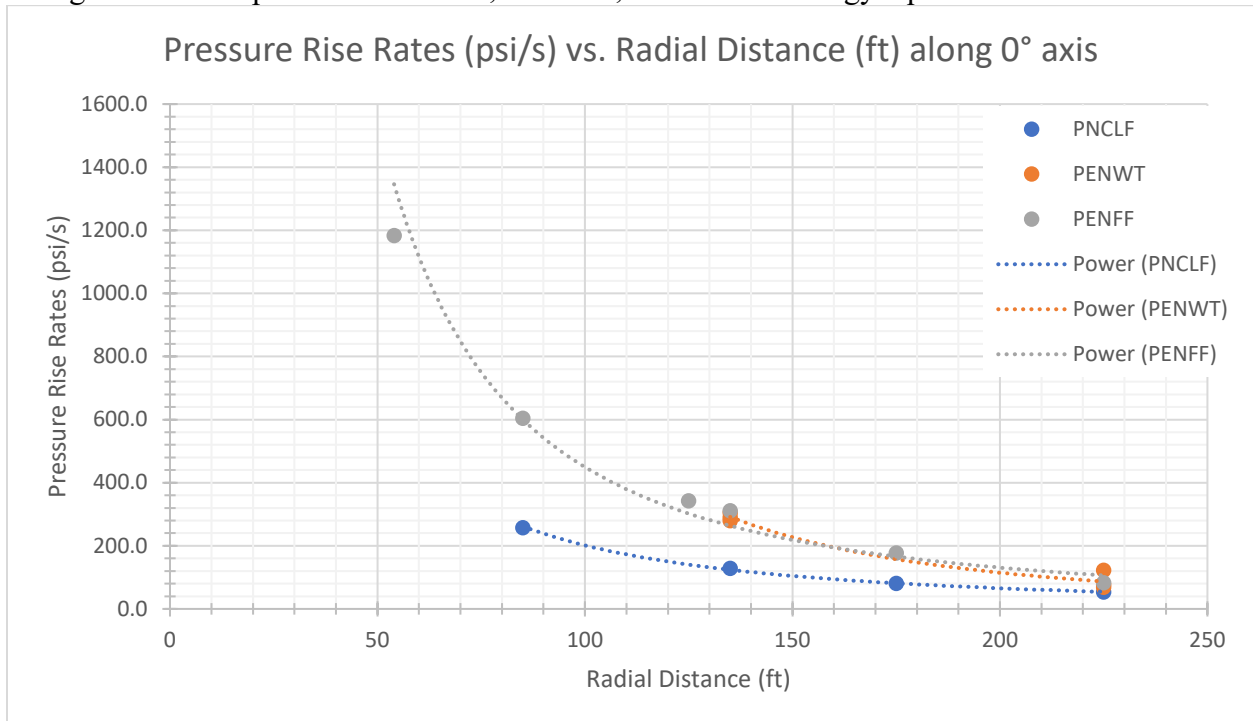


Figure 288 Comparison of PNCLF, PENWT, and PENFF pressure rise rate results for the 0° axis

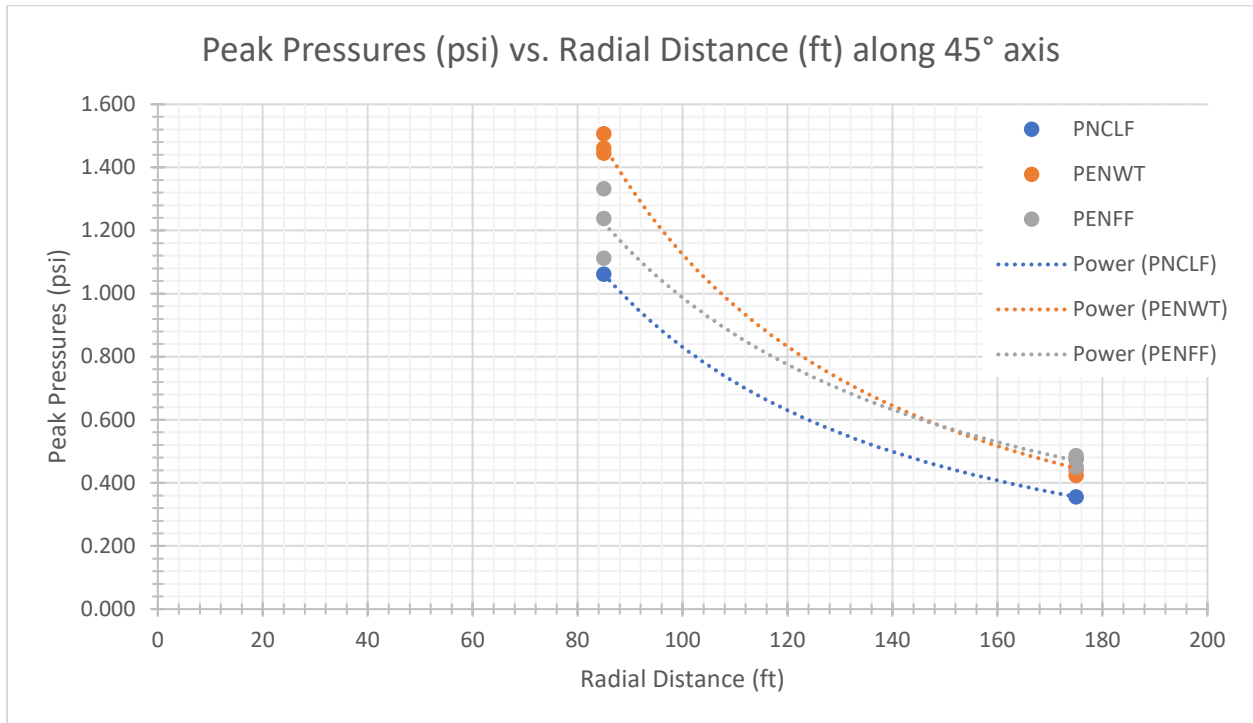


Figure 289 Comparison of PNCLF, PENWT, and PENFF peak pressure results for the 45° axis

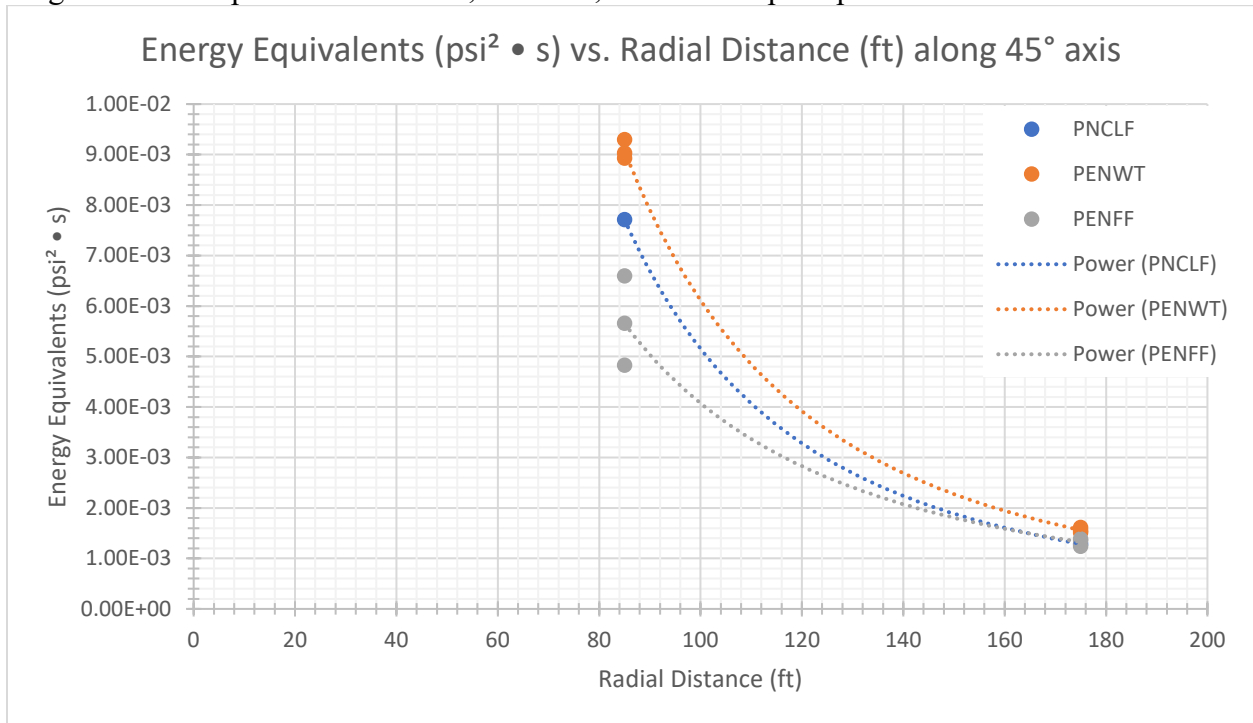


Figure 290 Comparison of PNCLF, PENWT, and PENFF energy equivalents for the 45° axis

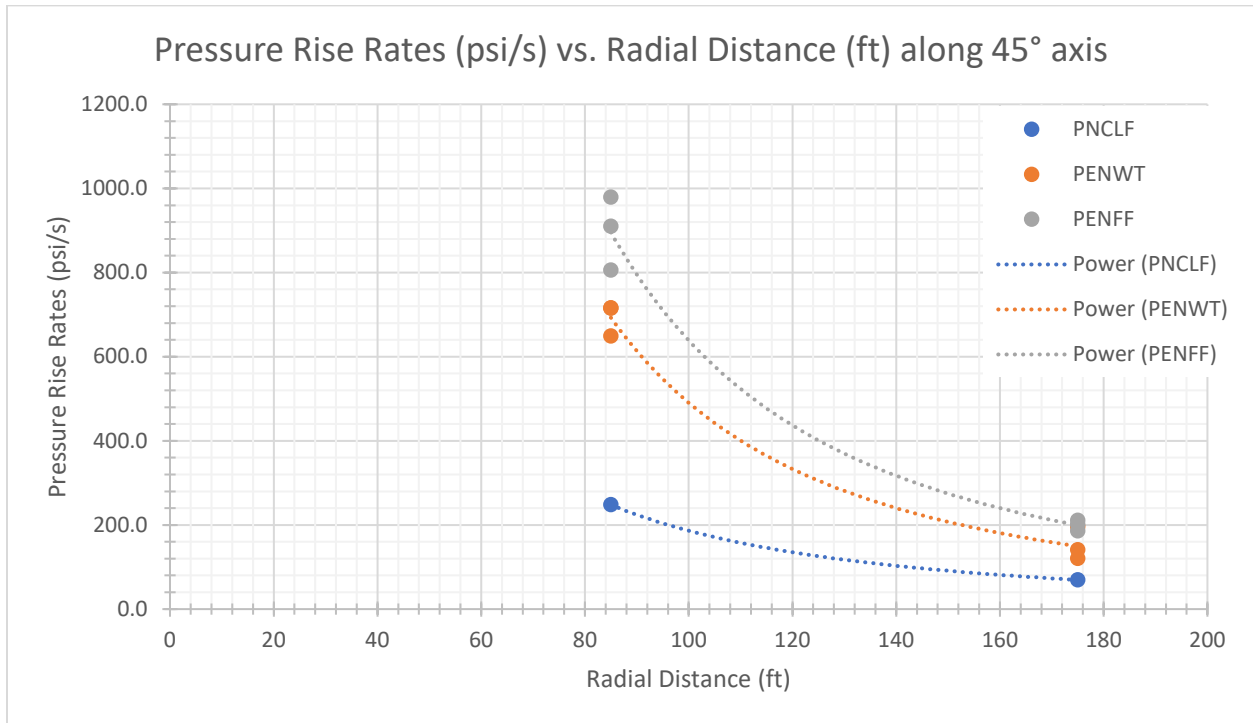


Figure 291 Comparison of PNCLF, PENWT, and PENFF pressure rise rates for the 45° axis

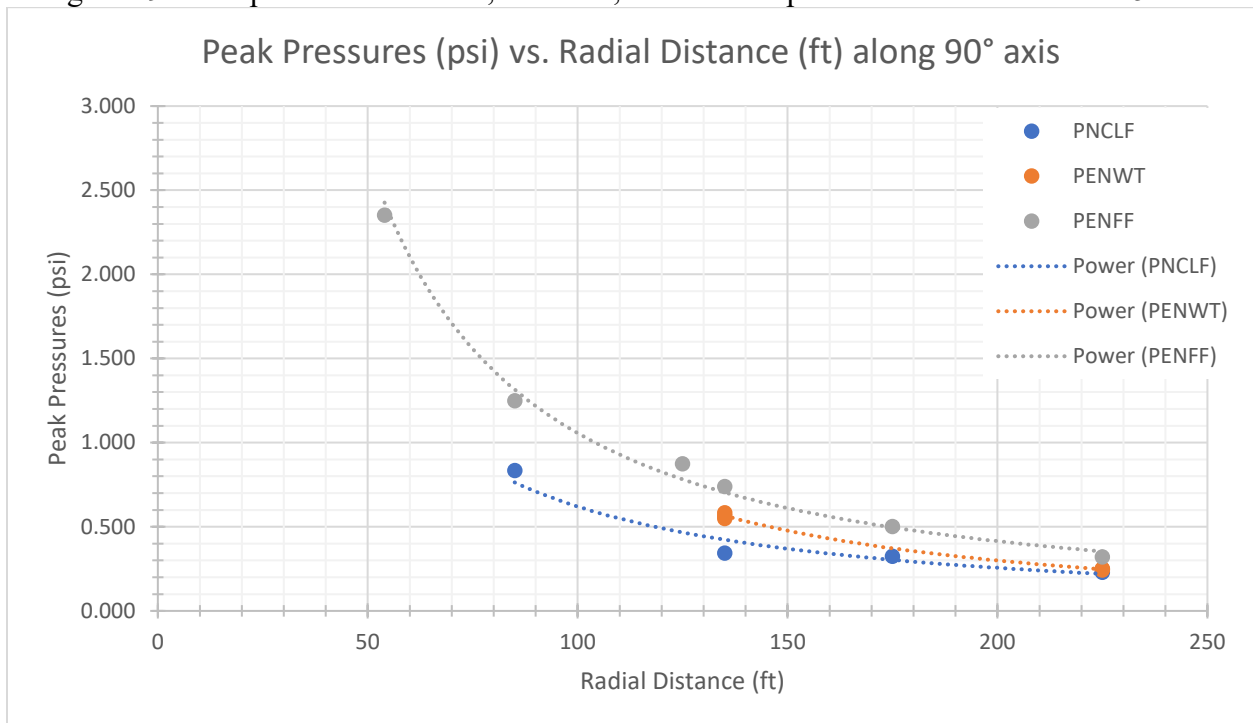


Figure 292 Comparison of PNCLF, PENWT, and PENFF peak pressure results for the 90° axis

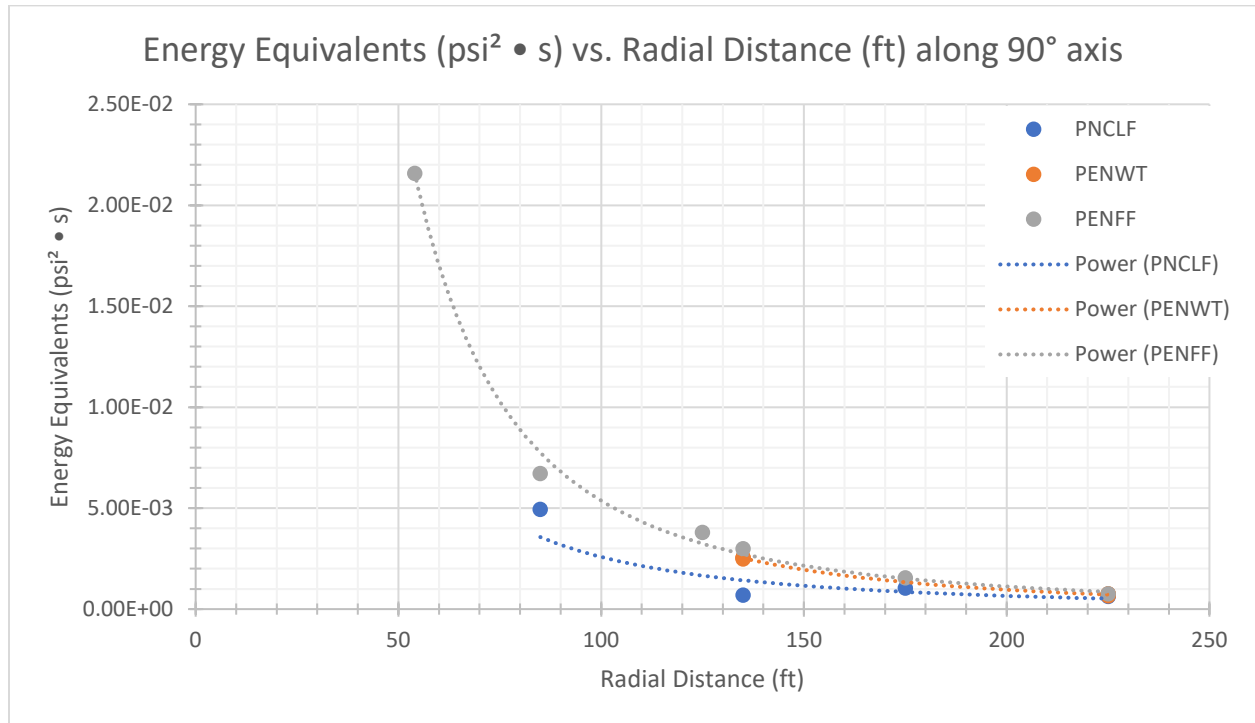


Figure 293 Comparison of PNCLF, PENWT, and PENFF energy equivalents for the 90° axis

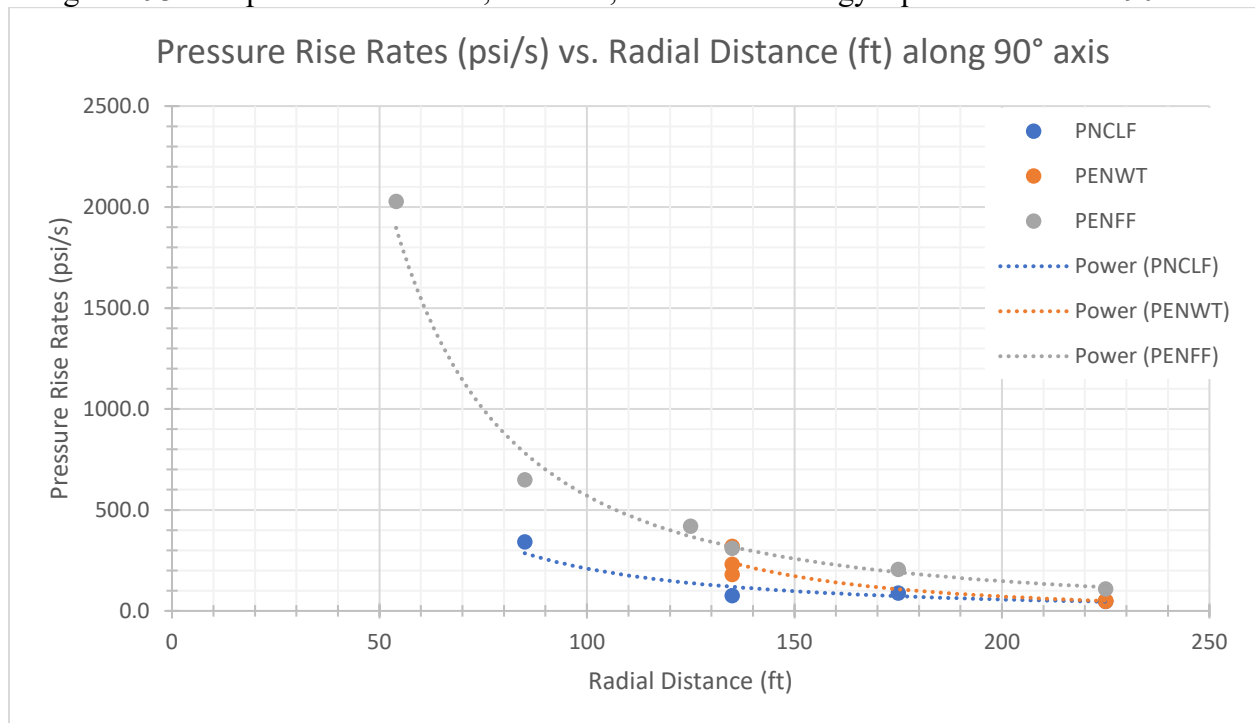


Figure 294 Comparison of PNCLF, PENWT, and PENFF pressure rise rates for the 90° axis

These initial findings seem to indicate that the cliff does reflect some of the explosive energy downslope of the cliff, reducing the radial decay of peak pressure in this direction, increasing peak pressures at larger radial distances, and increasing energy equivalent along the 0° axis as well. However, it seems that this moderate increase along the 0° axis comes at the cost of reducing near-field peak pressure magnitudes, reducing energy equivalent along the 45° and 90° axes, and reducing the pressure rise rates overall. Nonetheless, additional testing at similar terrain features (and with additional microphone locations) is still recommended to provide a more complete understanding of the effects of a large cliff on an explosive blast wave.

It should also be mentioned that the measurement and results challenges faced for the 60° and 90° axes of the Phase 2 O'Bellx testing, shown in Sections 4.2.2 and 3.2.2, may also be an unintended example of these cliff terrain effects.

4.3.2 Ridge Terrain Feature

As described in Sections 4.2.2 and 3.3.2, challenges were faced for both the 60° and 90° axes of the Phase 2 O'Bellx testing and for the 90° axis of the Phase 3 O'Bellx testing. As a result, the ability to compare the ridge terrain feature results to comparable baseline results was limited. However, despite these challenges and the significant differences in the two O'Bellx installations, a surprising degree of similarity in the peak pressure results was observed for the 0° axis, 30° axis, and even the 60° axis. For peak pressure, the ridgeline O'Bellx had similar, albeit slightly smaller, magnitudes over the measured radii on the 0° , 30° , and 60° axes and a similar, but weaker, radial decay (Figure 295, Figure 297, and Figure 299). As for energy equivalent, a greater difference between the two O'Bellx installations was observed. While the radial decay of energy equivalent was relatively similar between the two, the magnitude of the ridgeline O'Bellx

was shown to be about half of the energy equivalent of the Phase 2 O’Bellx at the measured radii and angles (Figure 296, Figure 298, and Figure 300). Lastly, for pressure rise rate no clear trend was observed – with the ridgeline O’Bellx and Phase 2 O’Bellx differing significantly in terms of magnitude and radial decay along each axis.

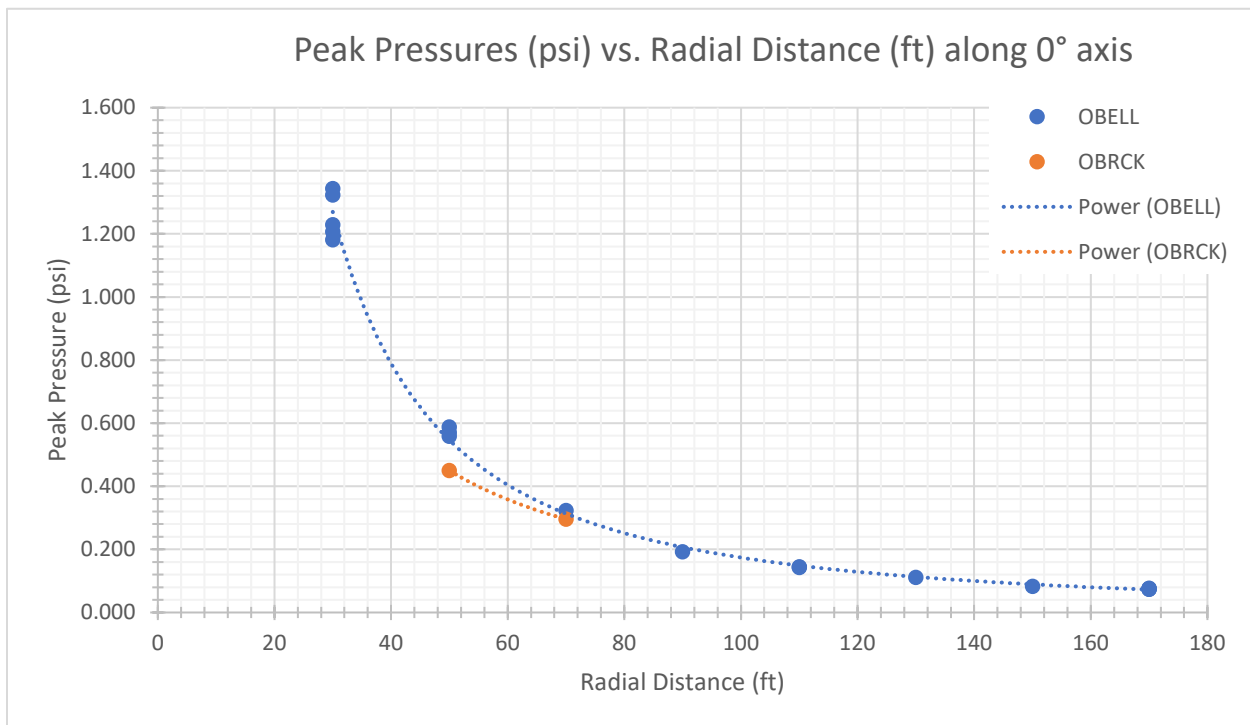
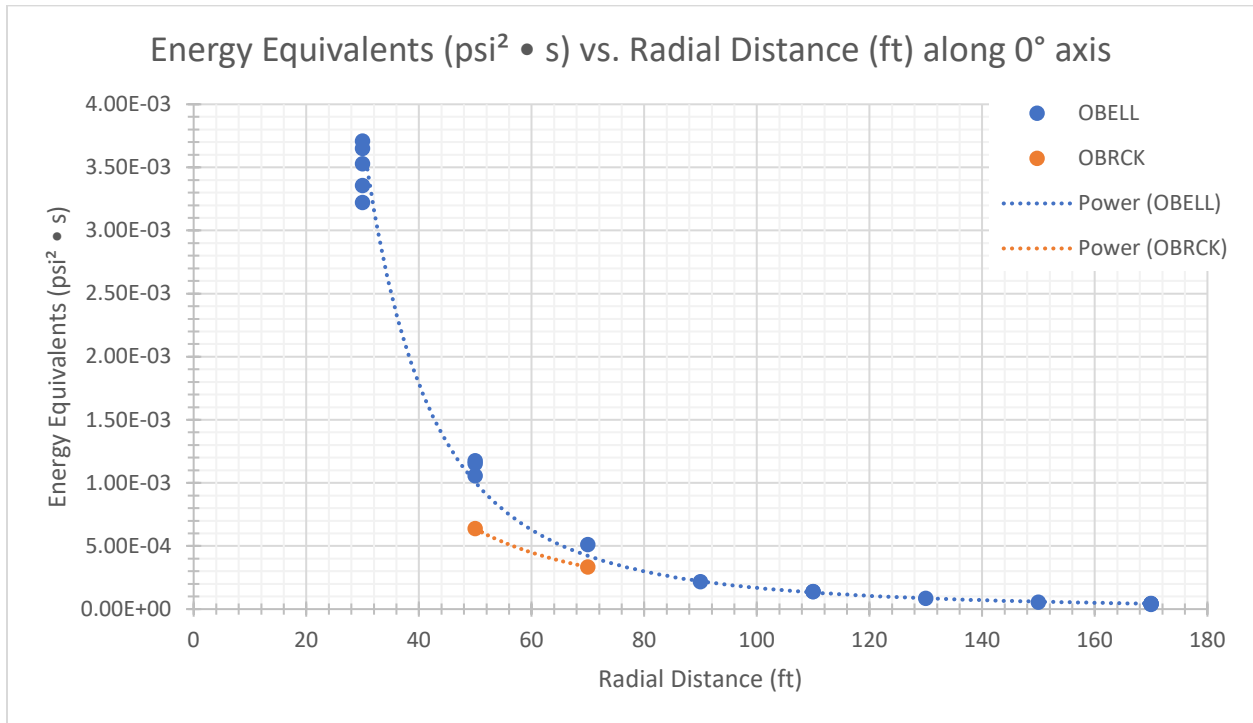
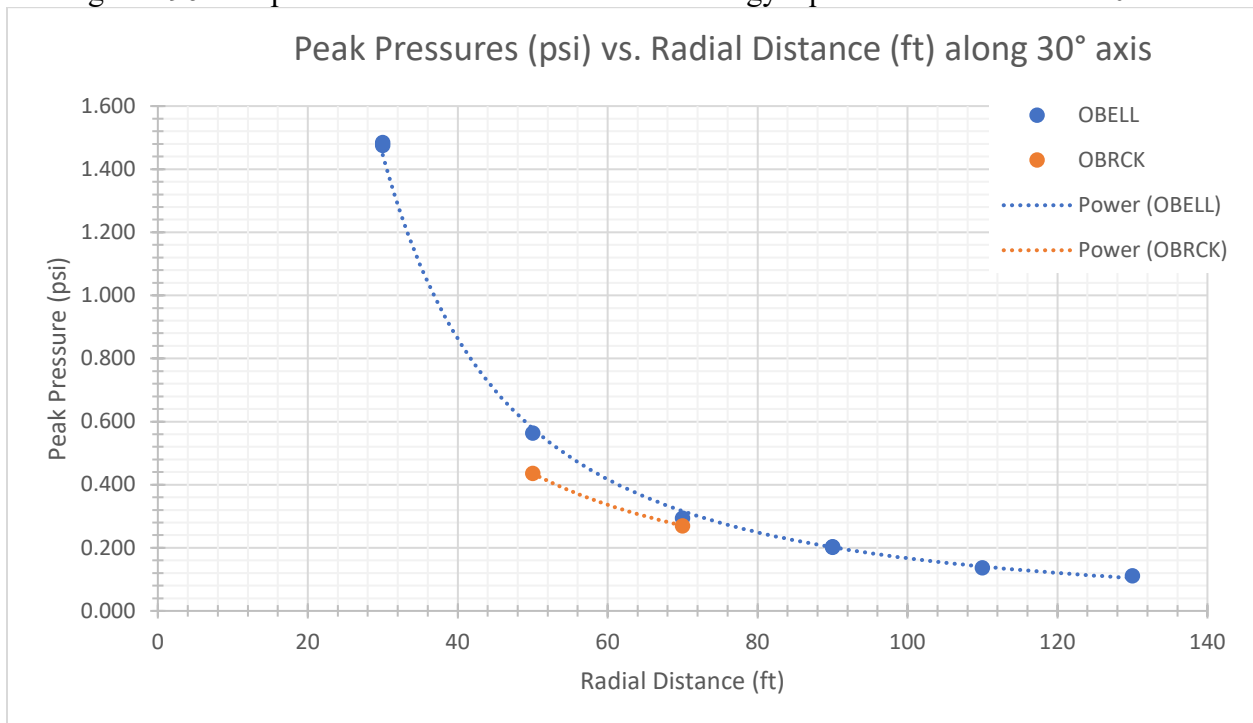


Figure 295 Comparison of OBRCK and OBELL peak pressure results for the 0° axis

Figure 296 Comparison of OBRCK and OBELL energy equivalent results for the 0° axisFigure 297 Comparison of OBRCK and OBELL peak pressure results for the 30° axis

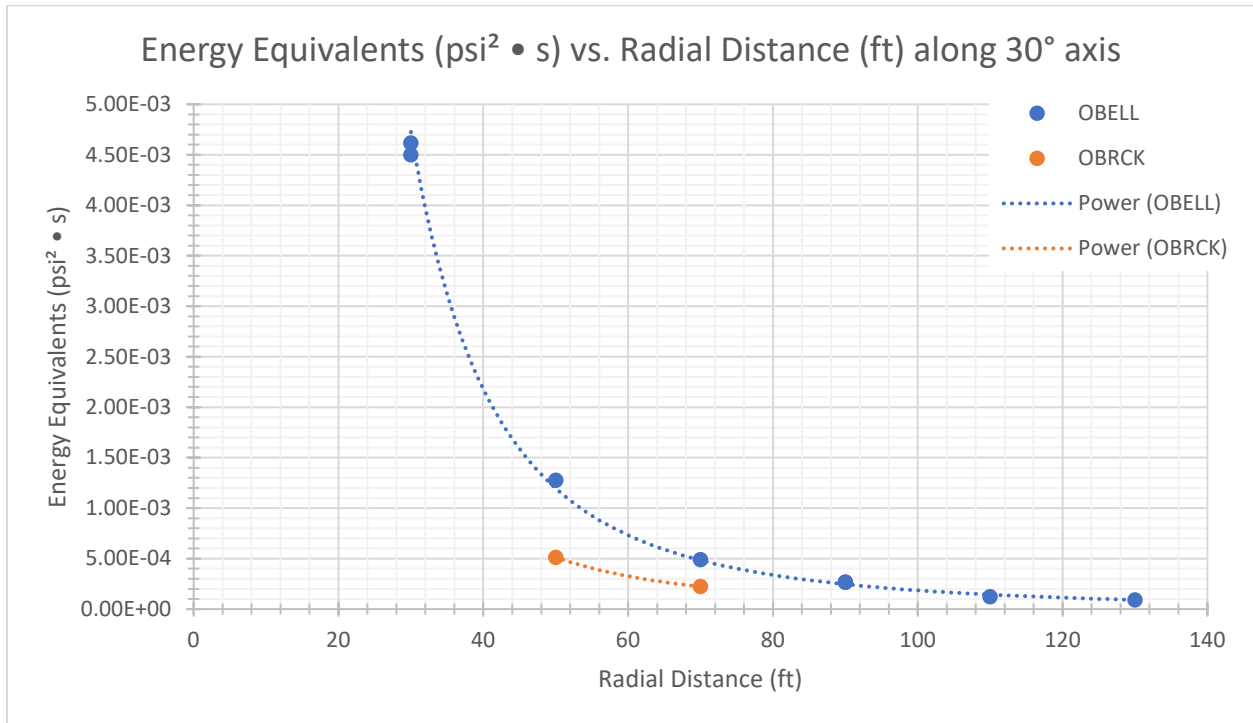


Figure 298 Comparison of OBRCK and OBELL energy equivalent results for the 30° axis

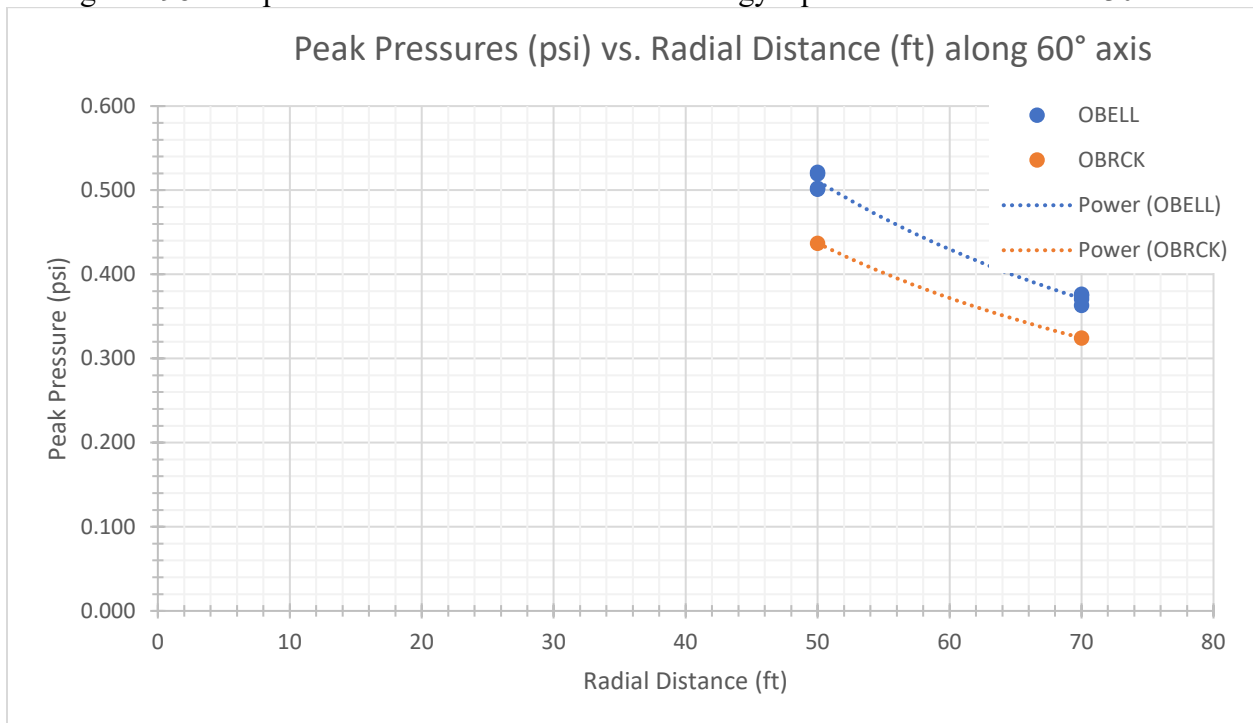


Figure 299 Comparison of OBRCK and OBELL peak pressure results for the 60° axis

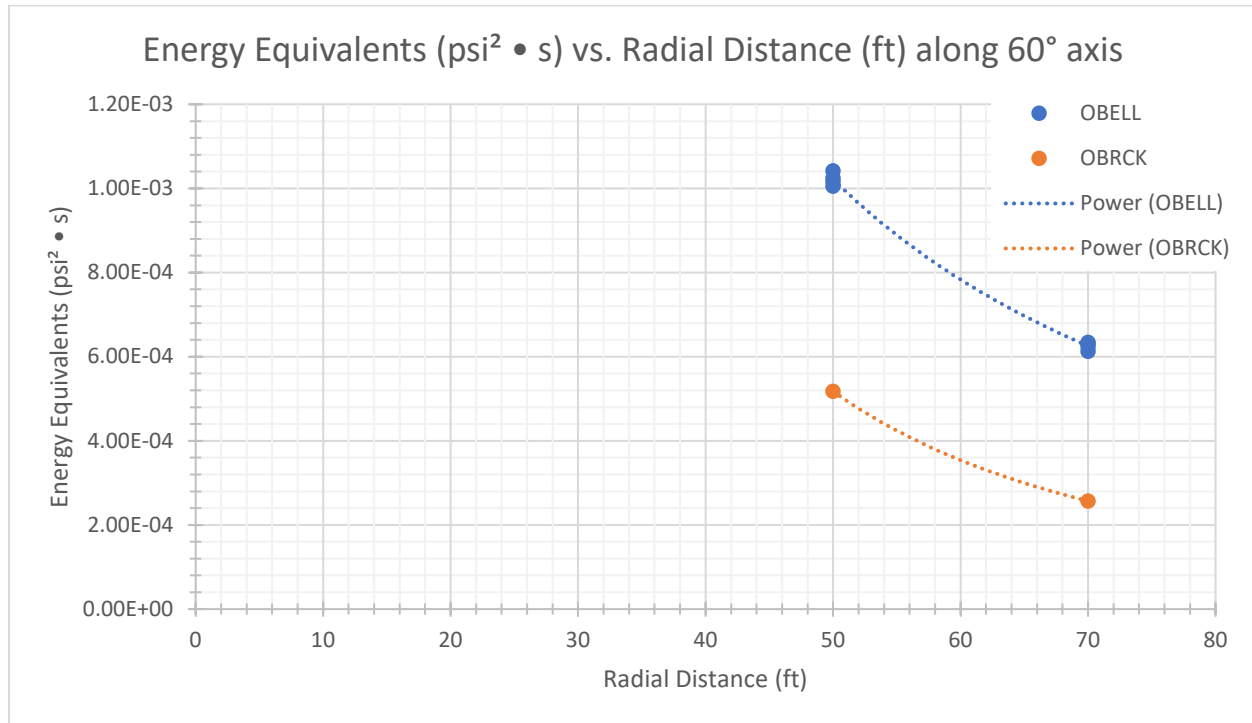


Figure 300 Comparison of OBRCK and OBELL energy equivalent results for the 60° axis

In summary, the present work does not enable a complete understanding of the effect of the rock ridge on the performance of the O'Belx system, or an avalanche control explosive in general. Further work and the placement of additional microphones is recommended to better capture data for the ridge terrain feature. Additionally, testing at a more suitable Phase 2 O'Belx installation is recommended to obtain a better understanding of the true baseline performance of the RAC system so that the results of ridge terrain feature testing can be more effectively and reliably compared. Nonetheless, the initial findings obtained in this work suggest that the ridgeline may be producing a similar response as was observed for the cliff terrain feature testing described in Section 4.3.1 – reducing near-field peak pressures while also decreasing the radial decay of the peak pressure (i.e., increasing peak pressures at larger radial distances) and decreasing the magnitude of the energy equivalent.

4.3.3 Gully and Foliage Terrain Feature

The final terrain feature, a gully with foliage, was also investigated over two tests: PGLY2 (the full Pentolite charge used at the operational Wyssen Tower testing), and PGLY1 (a half-sized charge due to a malfunction). The results of these tests revealed differences from the flat-field or operational testing of the Pentolite charges, as well as several differences from the cliff terrain feature testing.

To begin, the radial decay of all parameters along all axes was much weaker than for both the flat-field and operational testing – with the exception of the radial decay of the pressure rise rate along the 0° axis which was stronger than for flat-field testing and very similar to operational system testing. As for the magnitudes of these parameters, it was found that the peak pressure of the PGLY2 test was lower than found in both the flat-field and operational results for distances less than about 200 ft, but was higher at greater radial distances (Figure 301 and Figure 304). Similarly, energy equivalent magnitudes for the PGLY2 test were found to be as much as 2 to 3 times lower than the flat-field or operational testing results at radial distances less than 175 ft, and were very similar for radial distances greater than or equal to 175 ft (Figure 302 and Figure 305). Finally, pressure rise rates of the PGLY2 test were shown to be as much as 2 times higher than the flat-field or operational tests on the 0° axis (Figure 303), but as much as 2 times lower for the 45° axis (Figure 306). Additionally, for completeness, it was also found that the half-sized PGLY1 charge resulted in lower magnitudes for peak pressure (1 to 1.5 times lower) and energy equivalent (1 to 2 times lower) than the PGLY2 test, but yielded similar pressure rise rate magnitudes (excluding the 85 ft location on the 0° axis) and fairly similar radial decays of all parameters (Figure 301 - Figure 306).

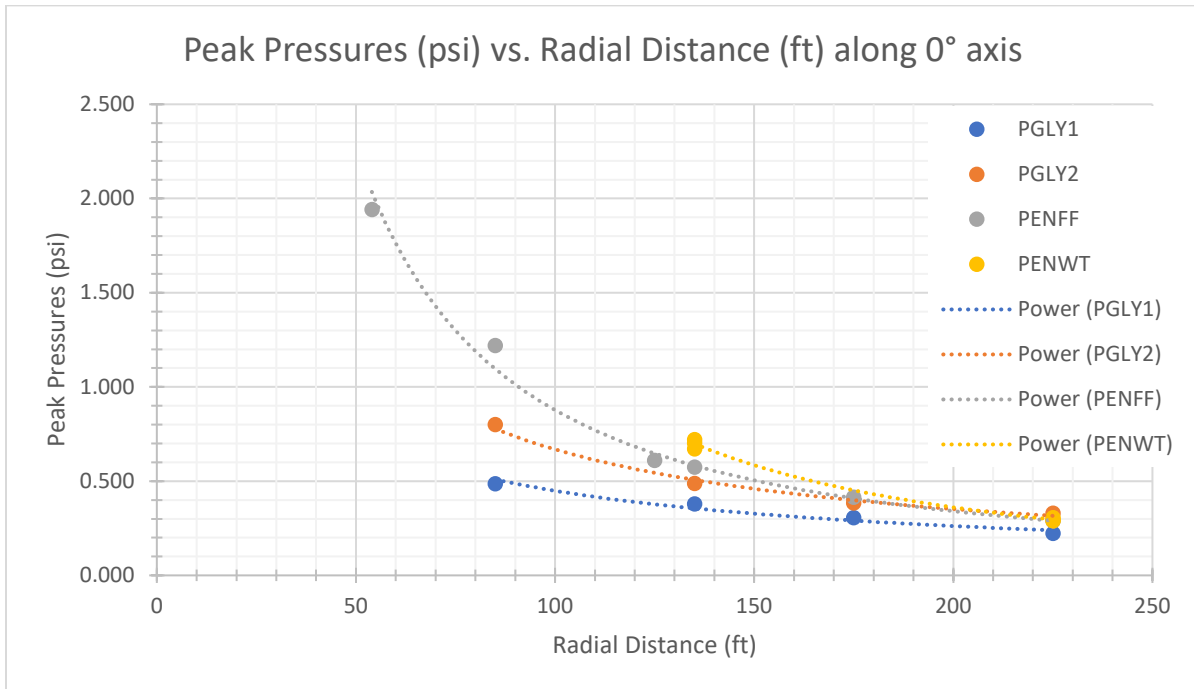


Figure 301 Comparison of PGLY1, PGLY2, PENWT, and PENFF peak pressure results for the 0° axis

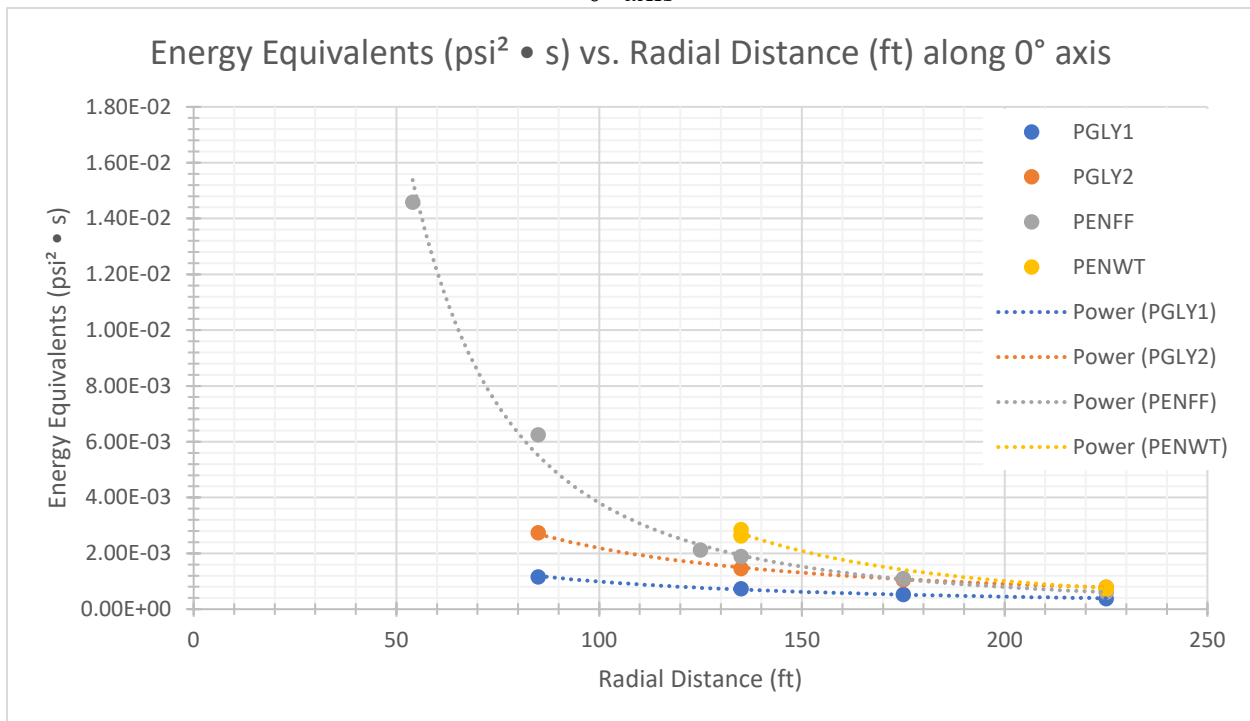


Figure 302 Comparison of PGLY1, PGLY2, PENWT, and PENFF energy equivalents for the 0° axis

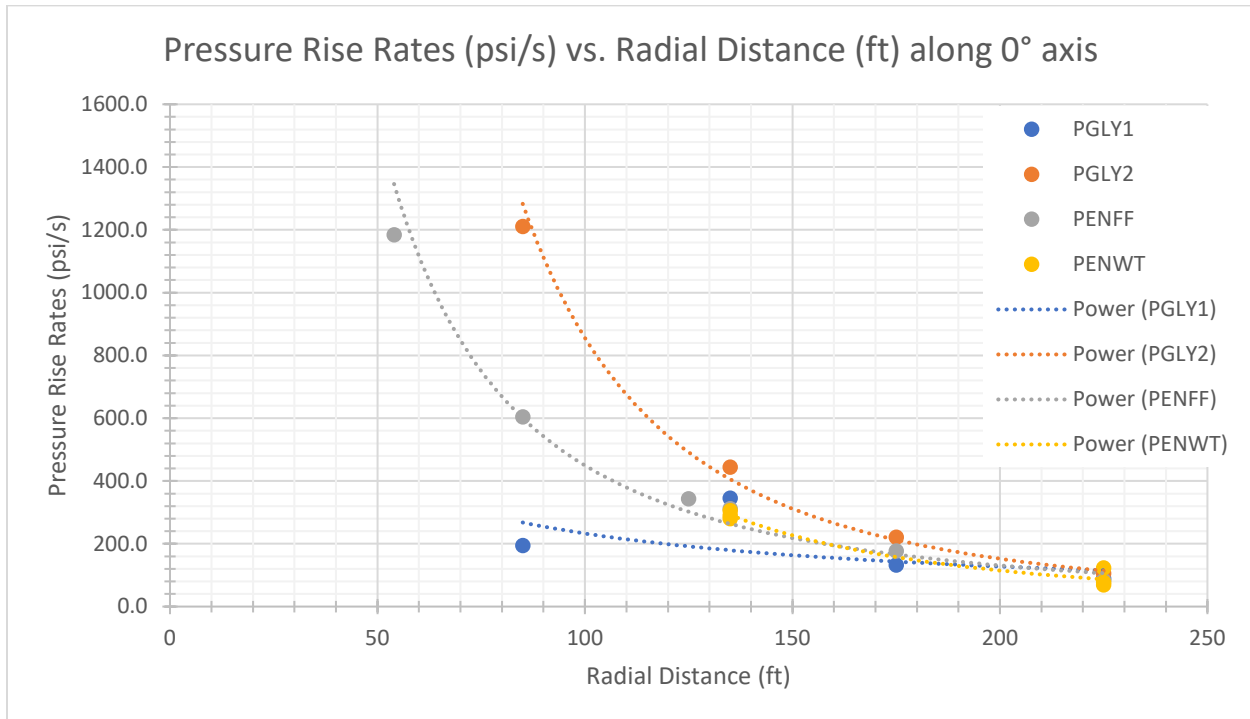


Figure 303 Comparison of PGLY1, PGLY2, PENWT, and PENFF pressure rise rate results for the 0° axis

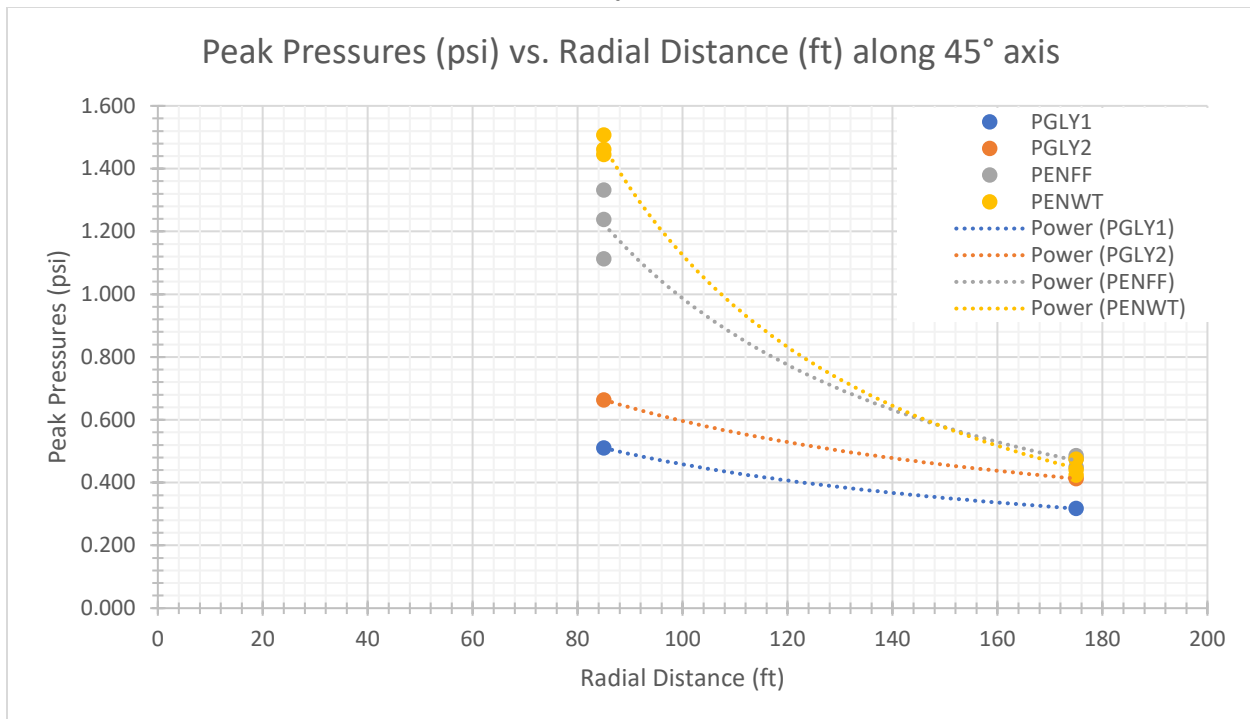


Figure 304 Comparison of PGLY1, PGLY2, PENWT, and PENFF peak pressure results for the 45° axis

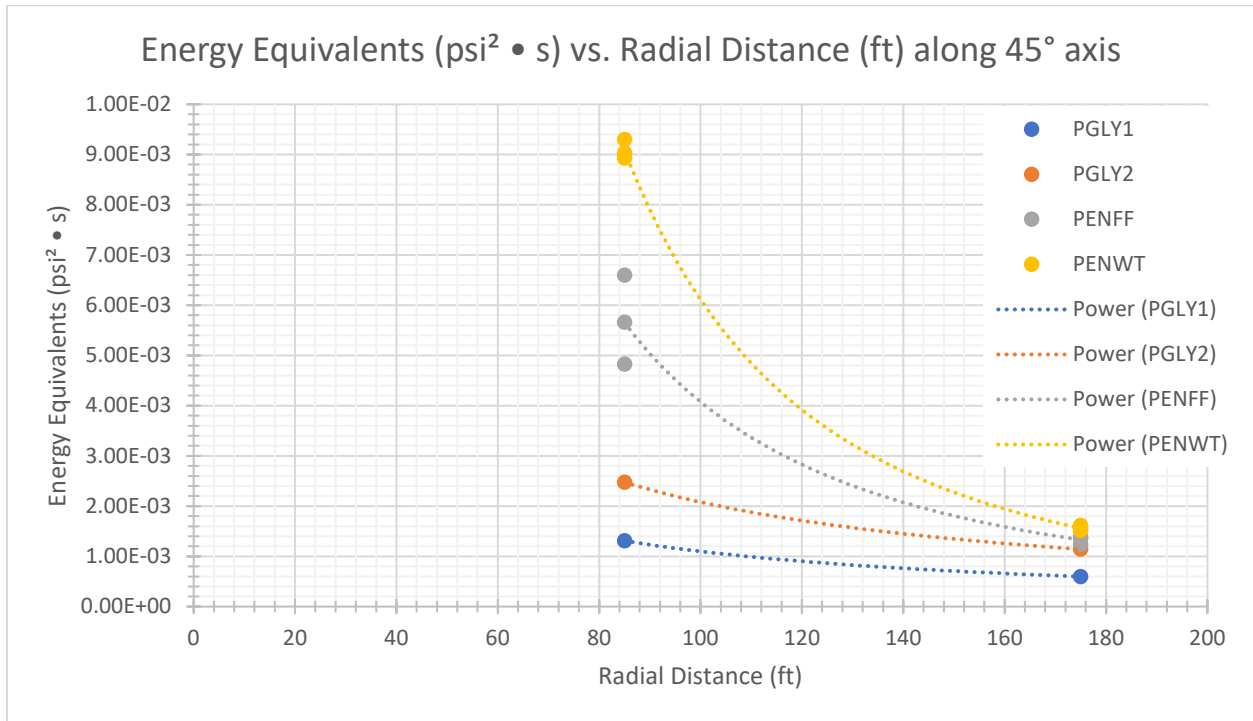


Figure 305 Comparison of PGLY1, PGLY2, PENWT, and PENFF energy equivalents for the 45° axis

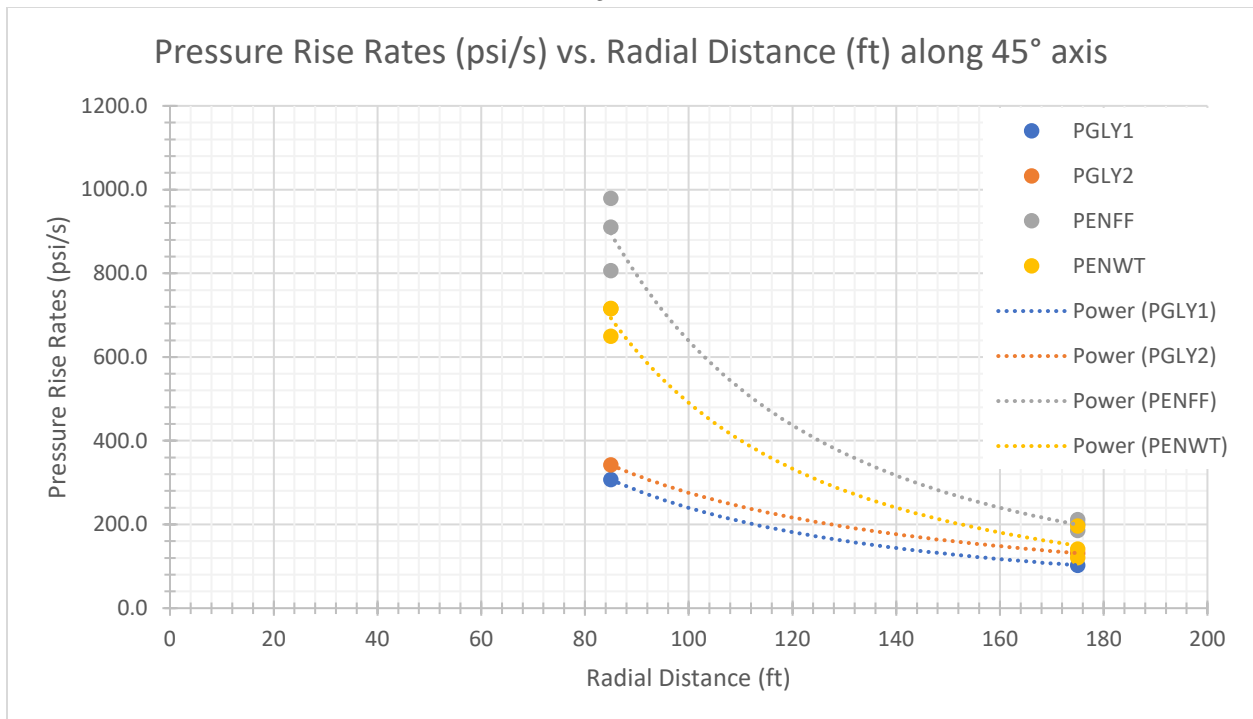


Figure 306 Comparison of PGLY1, PGLY2, PENWT, and PENFF pressure rise rates for the 45° axis

The gully terrain feature testing also produced different observations than the cliff terrain feature testing. Although, in both cases, the radial decay of peak pressure was reduced (and peak pressures at radial distances beyond about 200 ft were increased) along the 0° axis, the two terrain testing sequences had several key dissimilarities. For instance, while the energy equivalent of the cliff terrain testing was shown to also increase on the 0° axis and remain the same or decrease on other axes, the gully terrain testing indicated that the energy equivalent decreased on both the 0° and 45° axes. Furthermore, the cliff terrain testing revealed that the pressure rise rates were measurably lower on all axes, but the gully terrain testing showed an increase in pressure rise rates on the 0° axis and a decrease on the 45° axis.

Despite the differences between the cliff and gully terrain feature testing sequences, the initial findings from both seem to indicate that the observed behavior and increased directionality of the blast waves are, at least partly, due to the unique terrain features themselves. In both cases, the terrain feature testing revealed more dissimilarity between measured axes (i.e., less circular isolines) than was found in the flat-field or operational tower testing of the Pentolite charges. Regardless, it is highly recommended to conduct additional testing at similar gully terrain features and include additional microphone locations along the 45° and 90° axes to better understand the potential effects of a gully on explosive blast waves.

4.4 Observations, Trends, and Comparisons

Having now presented and discussed the results obtained from all testing sequences and explosive devices, there were several observations, similarities, and trends observed across many or most devices and test results which can also be commented on.

The first commonality observed in nearly all cases was the relationship between the radial decay of the peak pressure, energy equivalent, and pressure rise rate results. By looking at the summary tables of all power law coefficients calculated in this work (APPENDIX A), it can be seen that, in most cases, the energy equivalent decayed most strongly with radial distance, followed then by the radial decay of the pressure rise rate, and lastly by the radial decay of the peak pressure. As discussed in Section 4.2.1, this finding is consistent with the results of Simioni et al. (2016) and the knowledge that the energy of a spherical wave decays with the square of its amplitude decay (Simioni et al., 2016), and implies that the duration of the blast wave attenuated more with distance than the magnitude or steepness of the wavefront pressure.

Another trend observed for all tests was the sensitivity of the pressure rise rate calculations to electronic noise or other unusual artifacts. As mentioned above, this challenge was also seemingly faced by Simioni & Schweizer (2018) based on the increased scatter in their figures showing the power law fitting of the pressure rise rate results. For future work, an improved method for determining the pressure rise rate is recommended (one possibility will be discussed in Section 5.1) and a reduction of any electronic noise is also suggested.

Another common theme shared by the above results is the choice not to use a charge-mass scaling as has been done in much of the prior work in this subject area. In short, a charge-mass scaling law was not practical for the operational gas-based devices tested since the gas-based RAC systems are calibrated for each specific installation (Simioni, 2017) and thus utilize an unknown, and likely variable, volume of gas.

Lastly, despite the above commonalities, another overall trend identified was the distinct differences in peak pressure, energy equivalent, and pressure rise rate magnitudes across the

explosive types tested. These differences will be discussed below, can be viewed graphically in Figure 307 to Figure 312, and are summarized through a comparison of the locations of the 1 kPa or (0.145 psi) peak pressure reference for each testing sequence of this work (Table 38). Phase 2 testing indicated that the peak pressures, energy equivalents, and pressure rise rates at the measured locations were highest for the Pentolite-based explosives in all directions, followed then by the gel emulsion charge, 1.5 m³ Gazex system, and lastly the O'Bellx system. More specifically, the peak pressures and pressure rise rates of the Pentolite charges were approximately 1.5-2 times higher than the gel emulsion charge, and the energy equivalents of the Pentolite charge were 3-4 times greater than those of the gel emulsion charge. However, it is important to note that pressure rise rates and energy equivalents at distances beyond about 150 ft were shown to be quite small for all devices in comparison to the magnitudes of these parameters at more proximal distances. It was also shown that the performance of the 1.5 m³ Gazex system very closely resembled the peak pressures, energy equivalents, and pressure rise rates of the gel emulsion charge along the 0° axis, but was significantly weaker in lateral or uphill directions due to the observed highly directional nature of the gas exploder. More exactly, along the 90° axis the Gazex systems was shown to have approximately 1/3rd of the peak pressure of the gel emulsion charge, approximately 1/4th of the energy equivalent of the gel emulsion charge, and approximately 1/5th of the pressure rise rate of the gel emulsion charge. As expected, the O'Bellx system was also shown to have a directional effect like the Gazex, though the directionality of this system was not quite as strong as the Gazex system (i.e., the O'Bellx had more circular peak pressure, energy equivalent, and pressure rise rate isolines). Furthermore, the O'Bellx was shown to have a much more localized effect than any of the other devices tested – though this was an

expected result given the smaller volume of the gas charge of the O'Bellx system and thus smaller explosive energy content.

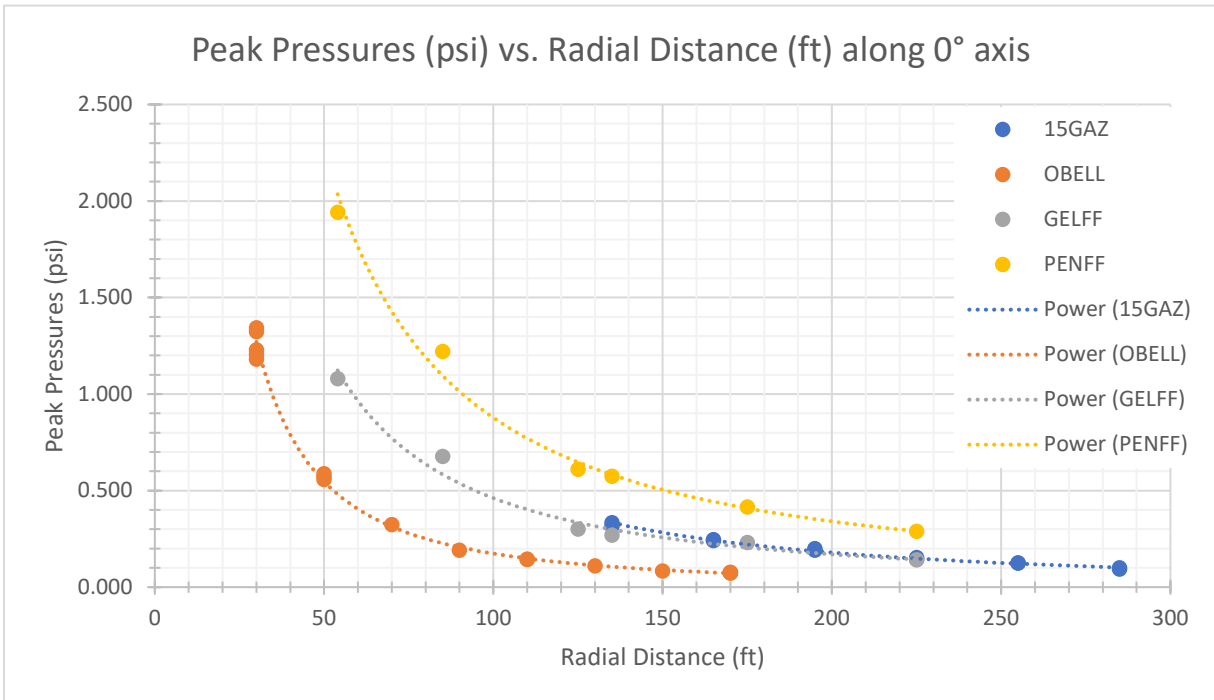


Figure 307 Comparison of peak pressure results along the 0° axis for the major explosive types considered in this work

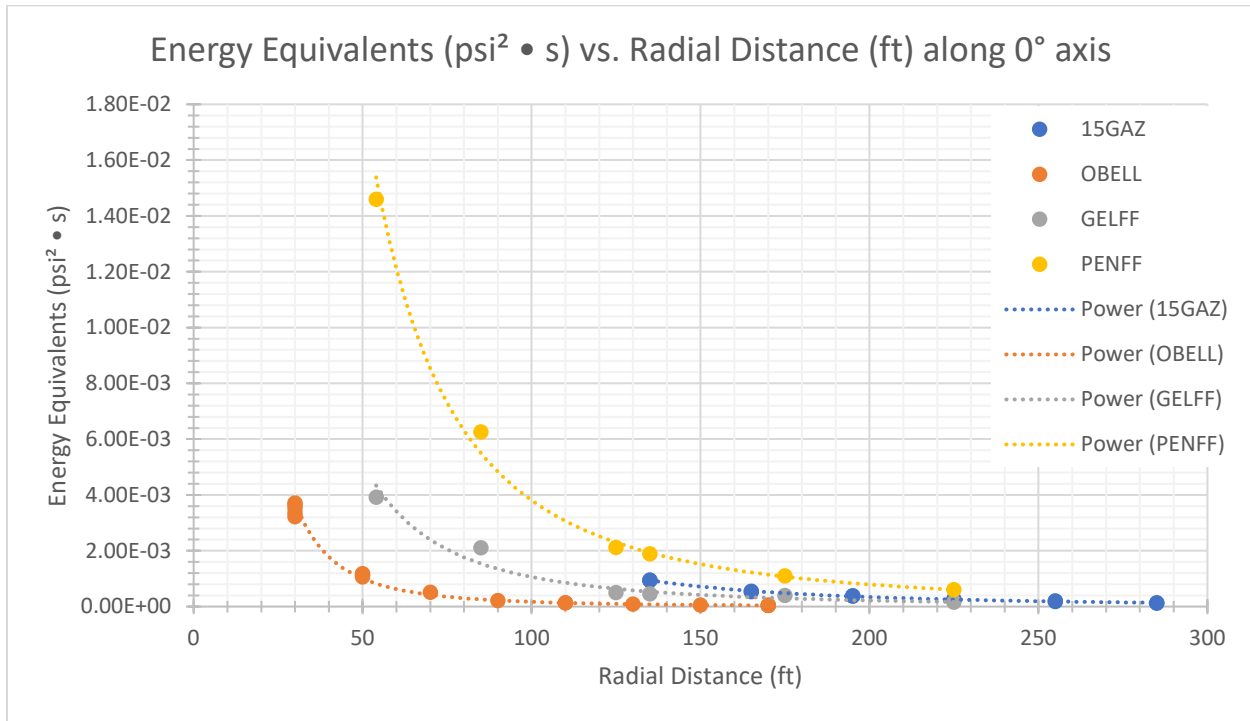


Figure 308 Comparison of energy equivalent results along the 0° axis for the major explosive types considered in this work

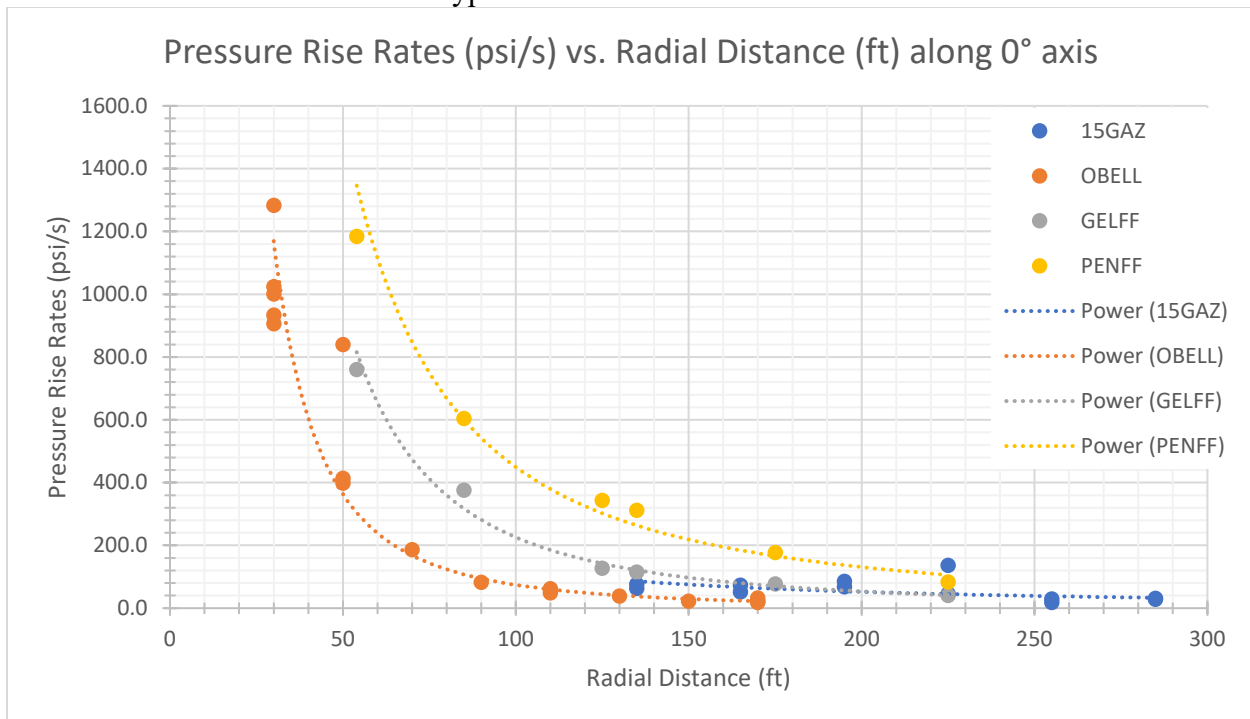


Figure 309 Comparison of pressure rise rates along the 0° axis for the major explosive types considered in this work

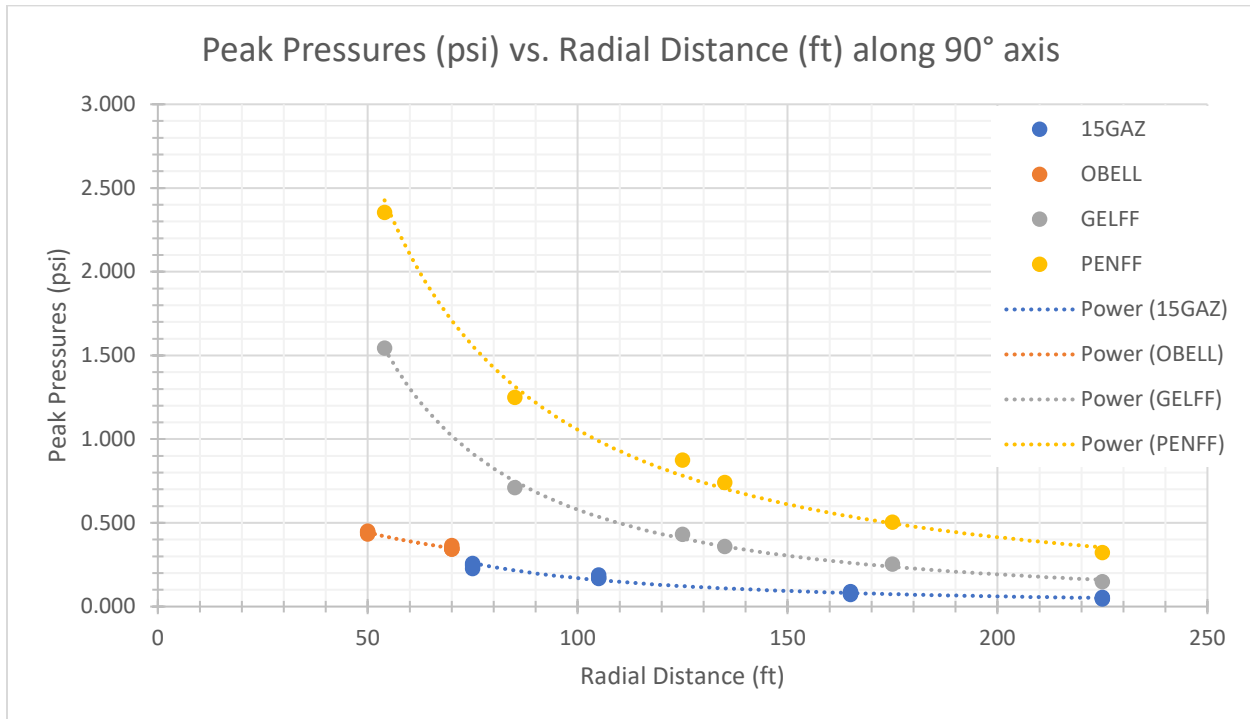


Figure 310 Comparison of peak pressure results along the 90° axis for the major explosive types considered in this work

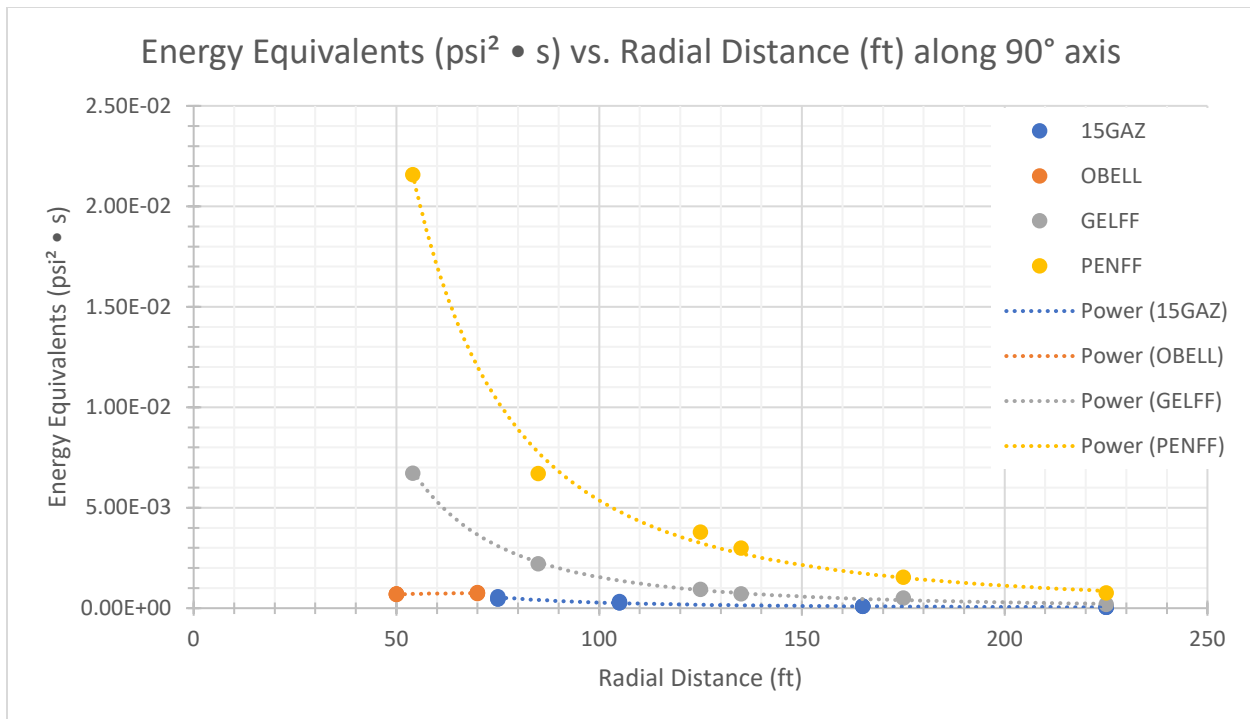


Figure 311 Comparison of energy equivalent results along the 90° axis for the major explosive types considered in this work

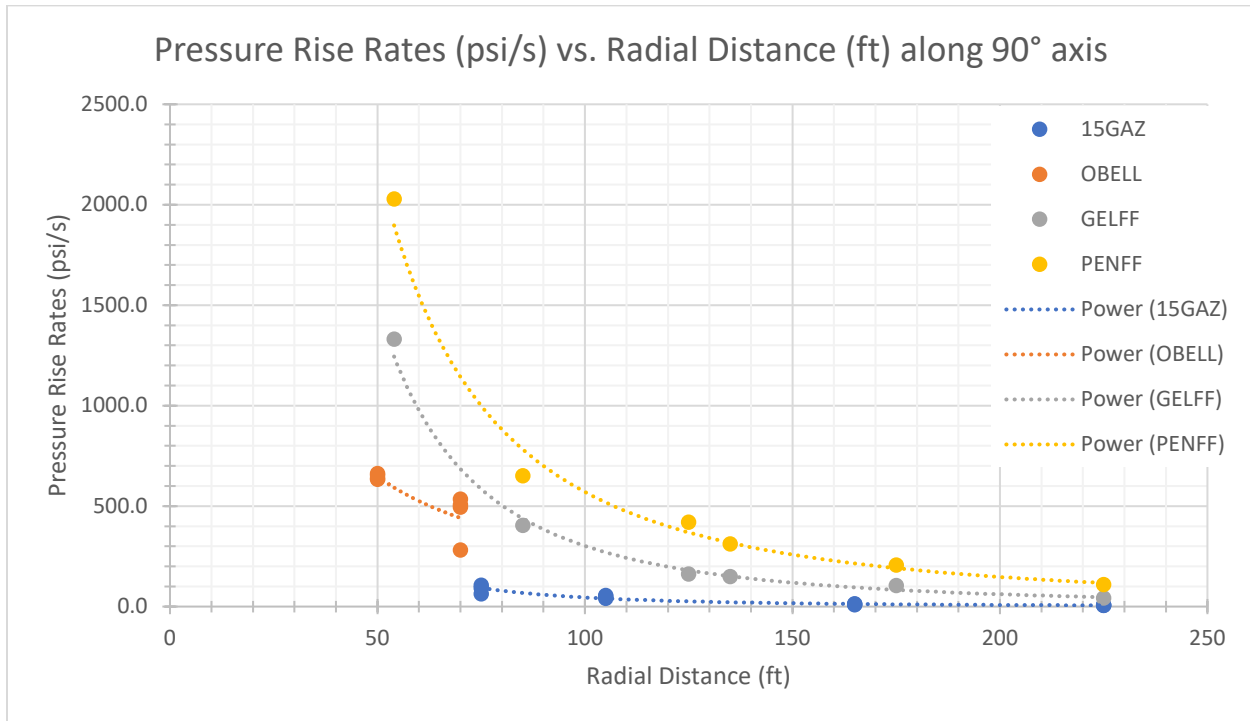


Figure 312 Comparison of pressure rise rates along the 90° axis for the major explosive types considered in this work

Table 38 Comparison of the radial locations of the 1 kPa (0.145 psi) peak pressure for all testing.

Radial Location of 1 kPa (0.145 psi) Peak Pressure Reference (ft)												
Angle (°)	2#PEN	15GAZ	OBELL	GELFF	GELWT	PENFF	PENWT	GUARD	PNCLF	OBRCK	PGLY1	PGLY2
0	138	230	115	234	239	404	345	222	429	124	477	490
30	X	X	105	X	X	X	X	X	X	109	X	X
45	141	X	X	246	238	425	346	237	317	X	576	859
60	X	155	188	X	X	X	X	X	X	174	X	X
90	128	113	245	238	215	467	313	227	280	X	X	X
120	X	82	97	X	X	X	X	X	X	X	X	X
135	X	X	X	257	212	466	300	232	X	X	X	X
150	X	X	110	X	X	X	X	X	X	X	X	X
180	X	X	96	242	198	466	319	214	X	X	X	X

5.CONCLUSION

In review, this research project was established to provide practical comparisons of the operational performance of modern avalanche control methods. The current body of work in this area was investigated and summarized in Chapter 1, and was found to be limited in quantity, and somewhat limited in descriptions of test methods and results. This has left avalanche control practitioners with a limited amount of information to make informed decisions about the evaluation, selection, installation, and operation of modern avalanche control systems such as RACS.

The present work helps to meet this need in two ways. First, in areas where the present work overlapped with existing research, a good agreement of results was generally found which helps to validate and reinforce the existing work. Secondly, this research expands on the current body of work on RACS by: offering detailed air pressure data and corresponding performance metrics for a variety of previously untested, or undertested, avalanche control systems in operational, flat-field, and unique terrain settings (Chapters 3 and 4); developing and providing the design for a modern measurement system well-suited for in-situ testing of avalanche explosives; providing a detailed record of the testing methods, testing challenges, and limitations of the present work (Chapter 2); and suggesting improvements and methodologies to help guide future work in this area (Section 5.1).

Due to the fieldwork-based nature of this research, the results obtained are inherently limited in applicability to the specific devices, locations, and conditions tested. While an effort was made to select RAC devices and testing locations that would generalize results to the greatest extent possible, it is important to reiterate this inherent limitation of fieldwork-based

research. Moreover, the differences in design, size, operation, and intended applications of the various explosives and explosive systems selected in this work make it very challenging to provide a definitive and succinct “apples-to-apples” comparison of the devices tested. As such, the comparisons provided in Chapter 4 and the following summaries are only meant to describe the principal results obtained in this work and should not be considered as a conclusive account of the performance of the explosives and explosive systems under all conditions.

The baseline performance data collected in Phase 2 on the explosives and RAC types revealed several surprisingly clear and easily described trends.

First, the radial decay of energy equivalent was generally found to be the strongest, followed by pressure rise rate, and then peak pressure.

Secondly, it was observed that the respective radial decay rates for peak pressure, energy equivalent, and pressure rise rate were very similar across all explosives. For instance, most explosives had peak pressure power law exponents of 1.2-1.7, energy equivalent power law exponents in the range of 1.9-2.5, and pressure rise rate power law exponents of 1.5-2.2. In fact, more similarity in these decay rates was observed for tests at the same *location* than for tests of the same *explosive* at different locations – indicating that the radial decay of these parameters is likely more dependent on environmental and snow conditions than the explosives themselves. One example of this is the radial decay of the gel emulsion parameters. In general, the radial decays of the peak pressure, energy equivalent, and pressure rise rate for the flat-field testing of the gel emulsion charge were more similar to the flat-field testing of the Pentolite charge or simulated Avalanche Guard charge than to the operational Wyssen Tower testing of the gel emulsion charge itself (APPENDIX A).

The third overall trend identified was the distinct differences in peak pressure, energy equivalent, and pressure rise rate magnitudes across the explosive types tested. Phase 2 testing indicated that the peak pressures, energy equivalents, and pressure rise rates were highest for the Pentolite-based explosives, followed then by the gel emulsion charge, 1.5 m³ Gazex system, and lastly the O'Bellx system. However, it was also noted that pressure rise rates and energy equivalents at distances beyond about 150 ft were shown to be quite small for all devices in comparison to the magnitudes of those parameters at more proximal distances.

Based on the results presented in this work and the abovementioned general trends, the question could be asked: How might an avalanche control practitioner utilize the Phase 2 findings of this work? This question returns to the original motivation for this work which was to provide avalanche control experts with additional information on operational RAC systems so they can make more informed decisions on how to best utilize these modern technologies to mitigate avalanche risk in their area. To address this question, and as an additional method to summarize the Phase 2 findings, the following *possible* applications for each of the major RACS is now offered. Due to its large charge mass and mostly symmetric blast wave profile, the Wyssen Tower with either the gel emulsion or a Pentolite-based charge, may be best suited for covering (i.e., triggering or controlling) the largest areas of avalanche terrain where the downslope, across-slope, and upslope directions are all equally important for avalanche initiation. Due to their directionality, Gazex systems are perhaps best suited for locations where the potential avalanche starting zones are relatively narrow and elongated downslope of the installation site, and the uphill direction is not an important starting zone. Lastly, due to its

relatively small combustion chamber volume, the O'Bellx system might be best used in a relatively small area where a localized and reliable weak spot or trigger point is known.

Lastly, although limited testing was able to be performed in Phase 3, there are still some meaningful conclusions to be discussed. In general, Phase 3 testing provided some initial support of the ability of terrain effects to meaningfully alter the blast wave effects of an explosive. In this way, these results indicate that current avalanche control practices making use of unique terrain features do have some merit. For instance, when compared against Phase 2 testing, the cliff and gully terrain feature testing showed a moderate increase in blast wave range (i.e., reduction in radial decay) along the 0° axis. In addition, when compared against Phase 2 results, the ridge terrain feature testing showed a comparable, but slightly attenuated, response along the 0°, 30°, and 60° axes – indicating that the explosive device may be able to affect both sides of the ridge with some detriment to blast wave strength on either side. However, to be able to properly understand and exploit terrain features to improve avalanche control efforts, a much more extensive testing sequence with additional microphone locations is necessary. This would allow for a better spatial resolution of pressure data which would provide a better indication of the overall effects of a terrain feature, but even then it is expected that the results would be quite sensitive to the specific site conditions and terrain feature geometry such that the results would be difficult to recreate and generalize to similar terrain features.

5.1 Suggestions for Future Work

Throughout this document several challenges and limitations of the current work have been described alongside discussions of potential suggestions and remedies for future work.

For instance, many of the challenges faced during the processing and analysis of results could have been alleviated by the presence of more than two microphone measurements on a given axis. For future work, it is strongly recommended to include at least 3, and ideally a minimum of 4, microphones along each axis. This enables a more reliable power law to be fit to the data and may clear up any uncertainties regarding the radial decay of a parameter along a given axis.

It is also recommended to utilize a method for calculating pressure rise rate that is less sensitive to electronic noise and the shape of the pressure vs. time profile of the blast wave. The present work used both a numerical method and a direct linear approximation method (see Sections 2.5.2.3 and 2.2.1.2). It was found that the numerical method was sensitive to electronic noise and the direct linear approximation was sensitive to the location of the peak pressure on the pressure vs. time profile. The direct method was sensitive to the shape of the pressure vs. time profile because the linear approximation was performed from the onset of the pressure impulse to the apex of the pressure vs. time profile (i.e., peak pressure). In some tests, this apex would occur directly after the initial pressure increase – in which case the direct linear approximate would provide a reasonable estimate of the initial pressure rise rate. However, other times this apex would occur at a later point in the pressure vs. time profile – as with a rounded and long-duration pressure vs. time profile or with a pressure vs. time profile that included a secondary (reflected) peak (Figure 249) – in which case the linear approximation would underestimate the pressure rise rate. One possible solution would be to utilize a linear approximation that begins at the onset of the pressure impulse and ends when the rate begins to decrease by a specified amount (even if the peak pressure has not yet been reached).

Along these lines, another potential improvement for future work would be to mitigate electronic noise at the hardware level. Although filtering methods proved to be highly effective for this work, improvements to result quality could likely be made through the reduction of electronic noise in the measurement system. One possible method for accomplishing this would be to reduce microphone cabling – which was believed to be one of the primary sources of noise. This would also likely improve field-testing logistics since one of the biggest challenges during fieldwork was found to be managing and transporting the large amount of microphone cabling.

Finally, care should also be taken in future work to thoroughly consider each proposed field-testing location and the logistics of accessing the site and setting up measurement equipment. Optimization of the testing plan should be done to reduce equipment setup, movement, and takedown, and minimize the necessary on-site traversing of researchers.

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APPENDICES

APPENDIX A

MASTER SPREADSHEETS OF RESULTS AND POWER LAWS

MASTER SPREADSHEET																	
TEST AND MICROPHONE IDENTIFIER						MICROPHONE LOCATION		RESULTS						TIMING OF KEY EVENTS			
Testing Phase Number	RACS-Device Identifier	Testing Set Number	Test Number	DAQ Identifier	Channel #	Microphone Angle (°)	Microphone Radial Distance (ft)	Maximum Pressure (psi)	Minimum Pressure (psi)	Average Slope (Numeric Derivative Average) (psi/s)	Average Slope (Direct Calculation) (psi/s)	Energy Equivalent (psi ² •s)	Impulse (psi•s)	Start of Blast (Time Index)	Max. Pressure (Time Index)	Positive to Negative Pressure Transfer (Time Index)	Min. Pressure (Time Index)
1	2#PEN	2	1	A	0	0	16	4.600	-0.866	1235.5	1236.5	3.80E-02	-4.5E-05	104	290	490	588
1	2#PEN	2	1	A	7	0	23	2.576	-0.592	984.1	983.3	1.80E-02	-1.7E-04	445	576	769	1026
1	2#PEN	2	1	B	0	0	50	0.733	-0.261	402.9	393.9	2.85E-03	-1.7E-04	1265	1358	1678	1879
1	2#PEN	2	1	B	7	0	75	0.415	-0.183	138.6	132.3	1.09E-03	-5.5E-07	2405	2562	2868	3247
1	2#PEN	2	1	C	0	45	23	2.280	-0.757	1250.6	1252.7	1.67E-02	-1.5E-04	1014	1105	1347	1526
1	2#PEN	2	1	C	7	45	50	0.731	-0.283	351.4	341.6	2.73E-03	2.3E-04	2242	2349	2652	2870
1	2#PEN	2	1	D	0	90	10	7.404	-1.157	2711.4	2742.2	5.24E-02	9.6E-06	114	249	459	669
1	2#PEN	2	1	D	7	90	23	1.841	-0.688	1104.2	1095.6	1.17E-02	2.4E-05	627	711	962	1162
1	2#PEN	2	1	E	0	90	50	0.738	-0.381	303.4	290.5	2.89E-03	-2.5E-06	455	582	863	1115
1	2#PEN	2	1	E	7	90	75	0.362	-0.196	108.1	99.9	9.09E-04	-2.8E-05	1619	1800	2098	2353
1	2#PEN	2	2	A	0	0	16	4.898	-0.859	2570.3	2578.0	4.23E-02	1.7E-05	834	929	1112	1248
1	2#PEN	2	2	A	7	0	23	2.674	-0.682	1858.1	1910.0	1.94E-02	2.5E-05	1091	1161	1417	1604
1	2#PEN	2	2	B	0	0	120	0.220	-0.120	50.7	44.5	4.20E-04	1.8E-06	1608	1855	2186	2561
1	2#PEN	2	2	B	7	0	220	0.103	-0.072	40.7	31.4	1.05E-04	-1.9E-04	6353	6517	6876	7234
1	2#PEN	2	2	C	0	45	23	2.794	-0.820	1702.5	1703.7	1.97E-02	-1.9E-04	1090	1172	1416	1596
1	2#PEN	2	2	C	7	45	120	0.214	-0.133	48.2	42.0	3.88E-04	4.4E-05	5561	5816	6120	6458
1	2#PEN	2	2	D	0	90	10	7.637	-0.998	3220.5	3236.1	5.44E-02	-5.0E-05	1027	1145	1356	1425
1	2#PEN	2	2	D	7	90	23	2.209	-0.586	1317.3	1314.6	1.23E-02	1.5E-04	1507	1591	1845	2114
1	2#PEN	2	2	E	0	90	120	0.214	-0.142	58.2	50.3	4.23E-04	3.1E-06	2369	2582	2975	3173
1	2#PEN	2	2	E	7	90	220	0.099	-0.074	40.9	31.2	9.71E-05	-2.2E-04	6957	7115	7476	7832
2	GELFF	1	1	A	0	0	54	1.079	-0.349	732.2	759.8	3.92E-03	-5.0E-05	2657	2728	3035	3613
2	GELFF	1	1	A	7	0	125	0.301	-0.142	136.7	127.4	5.00E-04	-9.0E-05	5878	5996	6351	6955
2	GELFF	1	1	B	0	45	85	0.580	-0.282	354.5	345.1	1.58E-03	2.6E-05	2272	2356	2729	3174
2	GELFF	1	1	B	7	45	175	0.219	-0.146	81.1	73.9	3.72E-04	6.2E-06	6162	6310	6699	7219
2	GELFF	1	1	C	0	90	54	1.543	-0.453	1326.0	1330.3	6.71E-03	-3.1E-04	2303	2361	2658	3142
2	GELFF	1	1	C	7	90	125	0.432	-0.207	153.4	162.4	9.37E-04	-5.7E-05	5492	5625	5964	6518
2	GELFF	1	1	D	0	135	54	1.295	-0.455	909.0	938.1	5.56E-03	2.0E-05	2101	2170	2455	2882
2	GELFF	1	1	D	7	135	125	0.368	-0.201	161.0	150.7	7.03E-04	1.5E-06	5663	5785	6127	6578
2	GELFF	1	1	E	0	180	54	1.095	-0.306	788.3	816.8	3.73E-03	-3.7E-05	1631	1698	2001	2251
2	GELFF	1	1	E	7	180	125	0.365	-0.121	163.2	154.7	6.33E-04	-5.1E-05	4548	4666	5004	5326
2	GELFF	1	2	A	0	0	85	0.677	-0.291	386.9	375.9	2.10E-03	-1.9E-05	2497	2587	2995	3440
2	GELFF	1	2	A	7	0	175	0.231	-0.131	84.6	77.6	3.94E-04	-7.7E-05	6515	6664	7110	7507
2	GELFF	1	2	B	0	45	85	0.610	-0.270	375.8	363.3	1.63E-03	-3.4E-05	2471	2555	2965	3388
2	GELFF	1	2	B	7	45	175	0.243	-0.141	88.2	80.9	4.25E-04	-5.2E-05	6405	6555	6993	7419
2	GELFF	1	2	C	0	90	85	0.710	-0.294	411.9	403.6	2.22E-03	-7.9E-06	2282	2370	2776	3168
2	GELFF	1	2	C	7	90	175	0.254	-0.148	113.6	104.1	5.00E-04	-2.1E-05	6587	6709	7172	7598
2	GELFF	1	2	D	0	135	85	0.737	-0.272	428.7	418.8	2.12E-03	-4.4E-05	2226	2314	2687	3079
2	GELFF	1	2	D	7	135	175	0.267	-0.144	94.1	87.1	4.84E-04	-8.8E-05	6318	6471	6889	7294
2	GELFF	1	2	E	0	180	85	0.538	-0.241	299.1	289.5	1.54E-03	-2.1E-05	2411	2504	2905	3309
2	GELFF	1	2	E	7	180	175	0.276	-0.144	98.4	90.7	4.94E-04	-5.2E-05	6092	6244	6662	7134
2	GELFF	1	3	A	0	0	135	0.270	-0.129	124.3	115.2	4.52E-04	-6.8E-06	2141	2258	2656	3033
2	GELFF	1	3	A	7	0	225	0.142	-0.080	46.0	40.2	1.54E-04	-2.0E-05	6182	6358	6767	7210
2	GELFF	1	3	B	0	45	85	0.629	-0.253	385.8	374.4	1.62E-03	-1.5E-05	2407	2491	2841	3268
2	GELFF	1	3	B	7	45	175	0.226	-0.126	104.2	95.8	3.48E-04	-2.6E-05	6336	6454	6878	7294

2	GELFF	1	3	C	0	90	135	0.358	-0.167	157.9	149.1	7.15E-04	1.8E-05	2195	2315	2675	3145
2	GELFF	1	3	C	7	90	225	0.149	-0.096	48.8	42.9	1.84E-04	-3.9E-05	6151	6324	6745	7205
2	GELFF	1	3	D	0	135	135	0.344	-0.161	150.2	141.2	6.79E-04	6.8E-06	2008	2130	2499	2834
2	GELFF	1	3	D	7	135	225	0.158	-0.091	50.3	44.5	1.96E-04	-4.7E-06	6224	6401	6805	7233
2	GELFF	1	3	E	0	180	135	0.305	-0.147	138.9	129.1	5.48E-04	-3.5E-05	2502	2620	3005	3360
2	GELFF	1	3	E	7	180	225	0.155	-0.090	59.0	52.0	1.94E-04	-4.0E-05	6625	6774	7225	7662
2	PENFF	1	1	A	0	0	54	1.942	-0.437	1183.2	1184.1	1.46E-02	-1.2E-04	3035	3117	3573	4145
2	PENFF	1	1	A	7	0	125	0.611	-0.180	352.0	343.2	2.12E-03	-2.2E-04	6258	6347	6920	7526
2	PENFF	1	1	B	0	45	85	1.238	-0.287	880.2	910.1	5.66E-03	6.5E-06	2602	2670	3205	3547
2	PENFF	1	1	B	7	45	175	0.476	-0.147	209.6	201.5	1.35E-03	1.3E-04	6499	6617	7203	7588
2	PENFF	1	1	C	0	90	54	2.353	-0.494	2013.8	2028.7	2.16E-02	-2.4E-05	2125	2183	2648	2929
2	PENFF	1	1	C	7	90	125	0.874	-0.231	405.2	420.3	3.79E-03	-3.0E-04	5291	5395	5914	6233
2	PENFF	1	1	D	0	135	54	2.196	-0.646	1304.0	1307.1	1.87E-02	-1.7E-05	3216	3300	3727	4394
2	PENFF	1	1	D	7	135	125	0.721	-0.264	339.4	353.6	2.72E-03	-1.6E-04	6734	6836	7372	8096
2	PENFF	1	1	E	0	180	54	1.871	-0.470	1017.0	1016.8	1.45E-02	-9.3E-04	2489	2581	3164	3426
2	PENFF	1	1	E	7	180	125	0.723	-0.186	308.7	301.1	2.81E-03	6.6E-05	5424	5544	6138	6415
2	PENFF	1	2	A	0	0	85	1.220	-0.279	587.5	604.1	6.26E-03	1.2E-04	2928	3029	3510	4123
2	PENFF	1	2	A	7	0	175	0.415	-0.119	185.3	177.3	1.10E-03	4.9E-05	6900	7017	7642	8295
2	PENFF	1	2	B	0	45	85	1.112	-0.254	778.8	806.1	4.83E-03	2.1E-05	3030	3099	3649	4142
2	PENFF	1	2	B	7	45	175	0.450	-0.144	193.7	185.8	1.24E-03	1.7E-04	6939	7060	7642	8163
2	PENFF	1	2	C	0	90	85	1.249	-0.315	632.5	650.5	6.71E-03	-1.3E-04	3106	3202	3701	4202
2	PENFF	1	2	C	7	90	175	0.503	-0.168	214.0	206.2	1.54E-03	-3.2E-04	7398	7520	8107	8611
2	PENFF	1	2	D	0	135	85	1.293	-0.276	751.2	743.3	6.69E-03	-1.1E-03	4108	4195	4673	5602
2	PENFF	1	2	D	7	135	175	0.508	-0.140	216.2	208.1	1.52E-03	-4.3E-05	8174	8296	8864	9876
2	PENFF	1	2	E	0	180	85	0.911	-0.267	511.0	500.6	4.34E-03	-6.7E-04	2968	3059	3592	4093
2	PENFF	1	2	E	7	180	175	0.510	-0.180	218.8	209.0	1.49E-03	-3.0E-04	6635	6757	7363	7880
2	PENFF	1	3	A	0	0	135	0.574	-0.157	320.6	311.8	1.89E-03	-2.1E-04	3203	3295	3871	4366
2	PENFF	1	3	A	7	0	225	0.289	-0.093	90.0	83.6	6.05E-04	8.1E-05	7188	7361	7959	8453
2	PENFF	1	3	B	0	45	85	1.332	-0.295	950.1	979.5	6.60E-03	2.0E-05	3030	3098	3612	4137
2	PENFF	1	3	B	7	45	175	0.486	-0.132	220.5	211.4	1.39E-03	9.8E-05	6922	7037	7624	8147
2	PENFF	1	3	C	0	90	135	0.741	-0.213	320.1	311.1	2.99E-03	-2.7E-05	3126	3245	3762	4308
2	PENFF	1	3	C	7	90	225	0.323	-0.118	116.7	109.7	7.61E-04	-1.1E-04	7018	7165	7777	8258
2	PENFF	1	3	D	0	135	135	0.722	-0.175	308.3	300.9	2.71E-03	-1.4E-04	3004	3124	3635	4135
2	PENFF	1	3	D	7	135	225	0.324	-0.103	114.0	107.4	7.65E-04	-8.5E-05	7200	7351	7978	8430
2	PENFF	1	3	E	0	180	135	0.653	-0.173	369.6	358.6	2.39E-03	-3.0E-04	2971	3062	3624	4074
2	PENFF	1	3	E	7	180	225	0.352	-0.113	125.6	118.1	8.48E-04	-1.0E-04	7055	7204	7840	8312
2	GUARD	1	1	A	0	0	54	0.940	-0.335	656.5	681.5	3.44E-03	-6.3E-05	2345	2414	2774	3266
2	GUARD	1	1	A	7	0	125	0.284	-0.147	130.4	121.5	5.47E-04	-1.1E-04	5609	5726	6132	6590
2	GUARD	1	1	B	0	45	85	0.543	-0.187	329.2	319.3	1.27E-03	-1.5E-05	2052	2137	2510	2906
2	GUARD	1	1	B	7	45	175	0.216	-0.105	82.3	75.0	3.25E-04	-1.5E-05	5990	6134	6540	6914
2	GUARD	1	1	C	0	90	54	1.346	-0.457	944.3	975.5	6.17E-03	-6.7E-05	2343	2412	2724	3256
2	GUARD	1	1	C	7	90	125	0.444	-0.216	189.7	180.5	1.10E-03	-5.8E-05	5563	5686	6043	6572
2	GUARD	1	1	D	0	135	54	1.303	-0.484	913.2	944.4	6.04E-03	-5.3E-05	2138	2207	2523	2946
2	GUARD	1	1	D	7	135	125	0.400	-0.191	173.2	163.9	9.24E-04	-7.7E-05	5700	5822	6197	6610
2	GUARD	1	1	E	0	180	54	1.199	-0.430	865.0	895.1	5.38E-03	-2.1E-04	2555	2622	2947	3494
2	GUARD	1	1	E	7	180	125	0.419	-0.197	186.9	177.7	9.72E-04	-7.9E-05	5470	5588	5966	6504
2	GUARD	1	2	A	0	0	85	0.540	-0.217	319.2	306.9	1.47E-03	-3.7E-05	2277	2365	2730	3154
2	GUARD	1	2	A	7	0	175	0.194	-0.108	61.3	55.3	2.96E-04	-7.2E-05	6289	6464	6842	7308
2	GUARD	1	2	B	0	45	85	0.456	-0.182	282.4	271.5	1.06E-03	-4.8E-06	2156	2240	2617	2974
2	GUARD	1	2	B	7	45	175	0.199	-0.108	66.6	60.4	3.14E-04	-7.0E-05	6108	6273	6648	7040
2	GUARD	1	2	C	0	90	85	0.574	-0.224	336.9	326.0	1.63E-03	-2.2E-05	1848	1936	2290	2818
2	GUARD	1	2	C	7	90	175	0.227	-0.128	68.4	62.7	4.24E-04	-7.0E-05	6169	6350	6701	7111
2	GUARD	1	2	D	0	135	85	0.639	-0.277	378.6	367.1	1.88E-03	8.3E-06	2398	2485	2855	3301
2	GUARD	1	2	D	7	135	175	0.242	-0.154	86.6	79.0	4.62E-04	-2.8E-05	6489	6642	7015	7553

2	GUARD	1	2	E	0	180	85	0.472	-0.241	275.2	265.1	1.34E-03	-2.0E-05	2114	2203	2577	3064
2	GUARD	1	2	E	7	180	175	0.245	-0.150	88.9	81.5	4.61E-04	-5.2E-05	5814	5964	6348	6909
2	GUARD	1	3	A	0	0	135	0.287	-0.176	131.1	122.7	5.93E-04	-2.3E-07	2460	2577	2974	3436
2	GUARD	1	3	A	7	0	225	0.147	-0.107	47.4	41.6	1.97E-04	-1.4E-05	6490	6667	7076	7494
2	GUARD	1	3	B	0	45	85	0.633	-0.255	397.3	386.0	1.63E-03	9.7E-07	2027	2109	2451	2836
2	GUARD	1	3	B	7	45	175	0.227	-0.124	83.1	76.3	3.54E-04	-1.3E-05	5929	6078	6451	6820
2	GUARD	1	3	C	0	90	135	0.322	-0.163	140.7	132.0	6.40E-04	-9.4E-06	1937	2059	2409	2780
2	GUARD	1	3	C	7	90	225	0.141	-0.084	47.7	41.7	1.68E-04	-5.1E-05	5877	6046	6461	6952
2	GUARD	1	3	D	0	135	135	0.303	-0.137	132.7	124.1	5.59E-04	-2.3E-05	2332	2454	2825	3182
2	GUARD	1	3	D	7	135	225	0.143	-0.086	39.7	34.8	1.74E-04	-5.5E-05	6570	6775	7129	7540
2	GUARD	1	3	E	0	180	135	0.266	-0.123	124.3	114.6	4.46E-04	-1.4E-05	2367	2483	2852	3208
2	GUARD	1	3	E	7	180	225	0.145	-0.083	56.6	49.5	1.71E-04	-6.0E-05	6494	6640	7054	7515
2	OBELL	1	1	A	0	0	30	1.344	-0.529	935.8	933.1	3.71E-03	4.1E-05	994	1066	1246	1454
2	OBELL	1	1	A	7	0	50	0.571	-0.316	390.7	413.7	1.18E-03	4.3E-05	1763	1832	2060	2245
2	OBELL	1	1	B	0	0	110	0.145	-0.094	56.2	48.9	1.39E-04	-1.6E-05	1693	1841	2085	2284
2	OBELL	1	1	B	7	0	170	0.077	-0.051	28.4	22.2	4.36E-05	-1.5E-05	4441	4614	4911	5222
2	OBELL	1	1	C	0	30	30	1.485	-0.562	886.2	883.8	4.62E-03	-2.9E-05	1012	1096	1257	1453
2	OBELL	1	1	C	7	30	90	0.204	-0.146	92.5	84.1	2.69E-04	-4.0E-06	3616	3737	3981	4202
2	OBELL	1	1	D	0	60	50	0.521	-0.251	331.2	321.9	1.04E-03	1.2E-05	1231	1312	1525	1745
2	OBELL	1	1	D	7	60	70	0.371	-0.189	293.2	281.0	6.31E-04	9.7E-05	1963	2029	2279	2670
2	OBELL	1	1	E	0	90	50	0.444	-0.182	669.8	653.6	7.04E-04	1.6E-05	1240	1274	1516	1701
2	OBELL	1	1	E	7	90	70	0.364	-0.251	556.5	535.2	7.73E-04	2.0E-05	2010	2044	2393	2719
2	OBELL	1	2	A	0	0	30	1.323	-0.512	908.2	906.0	3.65E-03	5.1E-05	944	1017	1190	1375
2	OBELL	1	2	A	7	0	50	0.588	-0.312	786.8	839.6	1.15E-03	5.9E-05	1714	1749	2007	2201
2	OBELL	1	2	B	0	0	110	0.143	-0.097	71.3	61.5	1.37E-04	4.3E-06	1726	1842	2115	2354
2	OBELL	1	2	B	7	0	170	0.074	-0.052	27.6	21.6	4.15E-05	-5.1E-06	4469	4640	4921	5189
2	OBELL	1	2	C	0	30	30	1.476	-0.565	891.1	888.9	4.50E-03	1.3E-06	951	1034	1193	1413
2	OBELL	1	2	C	7	30	90	0.202	-0.143	94.0	85.4	2.64E-04	-2.1E-05	3560	3678	3925	4144
2	OBELL	1	2	D	0	60	50	0.519	-0.248	329.9	320.6	1.02E-03	-1.1E-05	1260	1341	1556	1772
2	OBELL	1	2	D	7	60	70	0.375	-0.185	301.5	288.1	6.24E-04	7.3E-05	1993	2058	2309	2527
2	OBELL	1	2	E	0	90	50	0.443	-0.182	646.8	632.9	6.99E-04	1.8E-05	1358	1393	1630	1796
2	OBELL	1	2	E	7	90	70	0.343	-0.245	295.5	281.5	7.58E-04	1.2E-05	2118	2179	2505	2843
2	OBELL	1	3	A	0	0	30	1.228	-0.528	1024.8	1023.6	3.53E-03	3.9E-06	1039	1099	1287	1473
2	OBELL	1	3	A	7	0	70	0.323	-0.200	200.4	185.8	5.11E-04	7.2E-05	2613	2700	2930	3101
2	OBELL	1	3	B	0	0	130	0.111	-0.072	45.5	38.2	8.46E-05	-1.7E-05	1594	1739	1992	2246
2	OBELL	1	3	B	7	0	170	0.073	-0.050	41.4	32.4	3.81E-05	-6.3E-05	3366	3479	3759	4002
2	OBELL	1	3	C	0	30	50	0.564	-0.328	259.6	273.6	1.28E-03	-2.2E-05	1393	1496	1682	1907
2	OBELL	1	3	C	7	30	110	0.137	-0.097	54.2	46.7	1.23E-04	-1.3E-06	4233	4380	4624	4868
2	OBELL	1	3	D	0	60	50	0.501	-0.253	318.9	309.4	1.01E-03	-4.1E-06	1422	1503	1716	1924
2	OBELL	1	3	D	7	60	70	0.363	-0.185	292.1	279.3	6.13E-04	9.1E-05	2157	2222	2474	2687
2	OBELL	1	3	E	0	90	50	0.433	-0.190	652.7	637.4	6.83E-04	8.9E-06	1299	1333	1577	1737
2	OBELL	1	3	E	7	90	70	0.347	-0.238	515.8	495.5	7.40E-04	3.4E-05	2068	2103	2456	2791
2	OBELL	1	4	A	0	0	30	1.206	-0.494	1231.4	1283.3	3.36E-03	3.3E-05	1050	1097	1285	1473
2	OBELL	1	4	A	7	0	90	0.192	-0.128	90.7	82.0	2.17E-04	6.4E-05	3572	3689	3944	4176
2	OBELL	1	4	B	0	0	150	0.083	-0.055	27.8	22.2	5.45E-05	-1.4E-05	1761	1948	2207	2530
2	OBELL	1	4	B	7	0	170	0.075	-0.051	23.0	18.0	4.15E-05	6.6E-07	2532	2742	2980	3276
2	OBELL	1	4	C	0	30	70	0.294	-0.189	132.9	122.7	4.91E-04	1.8E-06	1600	1720	1929	2140
2	OBELL	1	4	C	7	30	130	0.111	-0.084	35.9	30.2	8.99E-05	2.4E-05	4480	4664	4897	5101
2	OBELL	1	4	D	0	60	50	0.502	-0.252	320.2	310.2	1.02E-03	1.1E-05	1214	1295	1510	1716
2	OBELL	1	4	D	7	60	70	0.377	-0.197	297.9	285.2	6.34E-04	-1.1E-05	1951	2017	2268	2606
2	OBELL	1	4	E	0	90	50	0.450	-0.196	676.0	661.9	6.97E-04	-3.2E-06	1208	1242	1485	1628
2	OBELL	1	4	E	7	90	70	0.344	-0.232	528.2	506.4	7.35E-04	1.7E-05	1974	2008	2346	2631
2	OBELL	2	1	A	0	0	30	1.181	-0.501	1002.2	1000.8	3.22E-03	1.6E-05	1015	1074	1261	1457
2	OBELL	2	1	A	7	0	50	0.558	-0.292	377.2	398.6	1.06E-03	2.9E-05	1783	1853	2069	2236

2	OBELL	2	1	B	0	120	15	1.874	-0.590	701.8	715.3	5.61E-03	5.2E-05	745	876	1021	1231
2	OBELL	2	1	B	7	120	30	0.713	-0.271	907.6	963.0	1.33E-03	9.8E-06	1372	1409	1620	1760
2	OBELL	2	1	C	0	150	15	1.260	-0.513	640.8	636.6	3.57E-03	-9.5E-05	898	997	1132	1328
2	OBELL	2	1	C	7	150	30	0.565	-0.196	387.3	409.2	7.71E-04	1.1E-04	1592	1661	1847	2019
2	OBELL	2	1	D	0	120	50	0.370	-0.127	750.3	840.4	3.22E-04	9.0E-05	1426	1448	1723	1877
2	OBELL	2	1	D	7	150	50	0.370	-0.234	480.3	462.4	4.21E-04	-6.2E-05	1191	1231	1477	1639
2	OBELL	2	1	E	0	180	15	1.420	-0.502	858.2	855.2	3.69E-03	4.1E-06	789	872	1015	1152
2	OBELL	2	1	E	7	180	30	0.605	-0.218	827.1	889.1	7.95E-04	4.4E-05	1427	1461	1669	1846
2	GELWT	1	1	A	0	0	135	0.356	-0.148	128.4	120.2	8.06E-04	-4.7E-05	2441	2589	2960	3281
2	GELWT	1	1	A	7	0	225	0.154	-0.075	48.6	42.6	2.07E-04	-2.7E-06	6612	6793	7234	7611
2	GELWT	1	1	B	0	45	85	0.782	-0.278	283.8	293.9	2.82E-03	-8.8E-06	1380	1513	1830	2002
2	GELWT	1	1	B	7	45	175	0.238	-0.100	70.1	64.3	4.29E-04	-4.0E-05	5166	5351	5735	6370
2	GELWT	1	1	C	0	90	135	0.340	-0.178	116.2	109.8	7.79E-04	4.6E-06	3042	3197	3571	4100
2	GELWT	1	1	C	7	90	225	0.134	-0.083	42.8	37.1	1.80E-04	5.0E-06	7166	7347	7887	8322
2	GELWT	1	1	D	0	135	135	0.295	-0.164	107.0	100.2	6.21E-04	-3.4E-05	2638	2785	3182	3735
2	GELWT	1	1	D	7	135	225	0.137	-0.080	37.3	32.4	1.90E-04	-1.4E-04	6786	6997	7507	7945
2	GELWT	1	1	E	0	180	135	0.234	-0.123	72.2	66.6	4.67E-04	4.9E-05	2342	2518	2943	3535
2	GELWT	1	1	E	7	180	175	0.173	-0.097	45.6	40.8	2.72E-04	3.9E-05	4199	4411	4823	5270
2	GELWT	1	2	A	0	0	135	0.367	-0.169	127.9	120.8	8.43E-04	1.8E-05	2766	2918	3265	3716
2	GELWT	1	2	A	7	0	225	0.163	-0.097	41.9	36.9	2.29E-04	1.4E-06	6908	7128	7516	7960
2	GELWT	1	2	B	0	45	85	0.804	-0.365	355.6	368.9	3.00E-03	-3.4E-05	1820	1929	2260	2456
2	GELWT	1	2	B	7	45	175	0.232	-0.096	72.3	65.2	4.14E-04	-4.7E-05	5579	5757	6120	6539
2	GELWT	1	2	C	0	90	135	0.325	-0.150	113.8	105.4	7.22E-04	-3.2E-05	2800	2954	3349	3961
2	GELWT	1	2	C	7	90	225	0.134	-0.073	36.1	31.1	1.63E-04	-4.6E-05	6923	7138	7624	8168
2	GELWT	1	2	D	0	135	135	0.286	-0.128	108.4	101.5	5.58E-04	1.0E-05	2551	2692	3078	3621
2	GELWT	1	2	D	7	135	225	0.132	-0.066	35.4	30.6	1.64E-04	-6.9E-05	6697	6913	7386	7880
2	GELWT	1	2	E	0	180	135	0.232	-0.118	57.8	53.1	4.46E-04	4.3E-05	2154	2373	2738	3256
2	GELWT	1	2	E	7	180	175	0.168	-0.091	56.5	50.3	2.53E-04	3.3E-06	4006	4173	4627	5154
2	GELWT	1	3	A	0	0	135	0.383	-0.162	162.3	154.5	8.38E-04	-3.7E-06	1918	2042	2408	2577
2	GELWT	1	3	A	7	0	225	0.164	-0.077	49.5	43.7	2.14E-04	1.4E-05	6038	6225	6630	7009
2	GELWT	1	3	B	0	45	85	0.763	-0.258	283.0	293.4	2.69E-03	-1.2E-05	1426	1556	1877	2313
2	GELWT	1	3	B	7	45	175	0.250	-0.101	91.2	83.4	4.34E-04	1.5E-05	5271	5421	5830	6200
2	GELWT	1	3	C	0	90	135	0.334	-0.149	116.4	109.1	7.74E-04	-1.3E-06	2615	2768	3165	3735
2	GELWT	1	3	C	7	90	225	0.133	-0.084	42.2	36.4	1.85E-04	2.2E-06	6821	7004	7520	8088
2	GELWT	1	3	D	0	135	135	0.260	-0.138	78.7	73.0	5.32E-04	-5.7E-05	2549	2727	3124	3654
2	GELWT	1	3	D	7	135	225	0.131	-0.068	45.1	39.1	1.52E-04	-1.5E-04	6739	6906	7420	7995
2	GELWT	1	3	E	0	180	135	0.242	-0.119	84.7	78.1	4.58E-04	1.7E-05	2205	2360	2778	3232
2	GELWT	1	3	E	7	180	175	0.168	-0.089	49.0	43.6	2.54E-04	2.7E-05	4065	4258	4690	5212
2	PENWT	1	1	A	0	0	135	0.671	-0.267	287.7	279.7	2.62E-03	2.2E-05	4352	4472	5061	5924
2	PENWT	1	1	A	7	0	225	0.289	-0.151	83.7	77.6	7.27E-04	-4.1E-06	8461	8647	9301	10170
2	PENWT	1	1	B	0	45	85	1.445	-0.470	696.6	715.2	9.03E-03	-5.0E-05	3282	3383	4009	4400
2	PENWT	1	1	B	7	45	175	0.424	-0.183	148.1	141.2	1.51E-03	-2.3E-05	7063	7213	7935	8464
2	PENWT	1	1	C	0	90	135	0.565	-0.267	239.7	231.5	2.54E-03	-5.4E-05	3220	3342	4011	4454
2	PENWT	1	1	C	7	90	225	0.249	-0.134	52.1	48.2	7.32E-04	-2.1E-05	7395	7653	8366	8815
2	PENWT	1	1	D	0	135	135	0.489	-0.168	167.5	160.8	1.69E-03	1.0E-04	2990	3142	3807	4414
2	PENWT	1	1	D	7	135	225	0.211	-0.092	52.4	47.8	4.95E-04	-5.7E-05	7092	7313	8108	8679
2	PENWT	1	1	E	0	180	135	0.416	-0.154	147.3	140.5	1.46E-03	1.9E-06	3080	3228	3942	4498
2	PENWT	1	1	E	7	180	175	0.304	-0.137	78.7	73.7	8.79E-04	-1.6E-05	4903	5109	5794	6439
2	PENWT	1	2	A	0	0	135	0.720	-0.277	314.5	305.0	2.86E-03	-7.1E-05	4334	4452	4984	5937
2	PENWT	1	2	A	7	0	225	0.305	-0.157	132.3	123.2	7.86E-04	-6.5E-05	8480	8604	9258	10175
2	PENWT	1	2	B	0	45	85	1.461	-0.417	697.3	716.2	8.93E-03	3.7E-05	3249	3351	3869	4478
2	PENWT	1	2	B	7	45	175	0.441	-0.188	127.1	120.5	1.56E-03	-1.7E-05	7094	7277	8012	8554
2	PENWT	1	2	C	0	90	135	0.584	-0.235	331.5	320.7	2.48E-03	-1.4E-04	3420	3511	4244	4631
2	PENWT	1	2	C	7	90	225	0.243	-0.117	55.7	50.9	6.66E-04	1.1E-04	7599	7838	8590	9020

2	PENWT	1	2	D	0	135	135	0.496	-0.197	201.1	193.9	1.76E-03	4.9E-05	3304	3432	4155	4614
2	PENWT	1	2	D	7	135	225	0.228	-0.109	60.9	55.6	5.71E-04	-9.3E-05	7460	7665	8419	8987
2	PENWT	1	2	E	0	180	135	0.430	-0.160	146.7	139.6	1.48E-03	-7.5E-05	3249	3403	4092	4707
2	PENWT	1	2	E	7	180	175	0.308	-0.142	75.3	70.5	8.64E-04	-1.0E-04	5065	5283	5960	6574
2	PENWT	1	3	A	0	0	135	0.702	-0.241	299.0	290.2	2.67E-03	-1.5E-05	3968	4089	4646	5516
2	PENWT	1	3	A	7	0	225	0.296	-0.138	73.7	68.8	7.38E-04	-1.0E-05	8093	8308	8897	9754
2	PENWT	1	3	B	0	45	85	1.507	-0.446	653.1	649.5	9.30E-03	-2.5E-06	3172	3288	3800	4377
2	PENWT	1	3	B	7	45	175	0.475	-0.171	203.7	196.3	1.62E-03	1.4E-07	6998	7119	7831	8328
2	PENWT	1	3	C	0	90	135	0.549	-0.269	187.3	180.6	2.55E-03	-5.9E-05	3218	3370	4047	4521
2	PENWT	1	3	C	7	90	225	0.251	-0.156	55.4	50.6	7.59E-04	-2.6E-05	7381	7629	8342	8814
2	PENWT	1	3	D	0	135	135	0.488	-0.188	166.0	159.5	1.77E-03	4.5E-05	3202	3355	4072	4508
2	PENWT	1	3	D	7	135	225	0.237	-0.114	59.2	54.3	5.82E-04	-8.4E-05	7336	7554	8318	8908
2	PENWT	1	3	E	0	180	135	0.412	-0.158	144.6	137.5	1.45E-03	-7.7E-06	3069	3219	3930	4496
2	PENWT	1	3	E	7	180	175	0.301	-0.137	75.0	70.4	8.60E-04	-3.9E-06	4886	5100	5816	6445
2	15GAZ	1	1	A	0	60	75	0.366	-0.236	109.3	103.9	1.28E-03	-3.6E-06	2675	2851	3263	3582
2	15GAZ	1	1	A	7	60	105	0.246	-0.163	58.0	53.5	7.13E-04	-9.4E-06	3603	3833	4274	4553
2	15GAZ	1	1	B	0	60	165	0.131	-0.094	22.6	19.2	2.09E-04	3.6E-05	3262	3602	4076	4574
2	15GAZ	1	1	B	7	60	225	0.072	-0.049	31.3	24.3	6.59E-05	-1.4E-04	6400	6548	7088	7570
2	15GAZ	1	1	C	0	90	165	0.079	-0.057	11.4	10.4	9.17E-05	-2.0E-06	4208	4587	5030	5764
2	15GAZ	1	1	C	7	90	225	0.050	-0.040	7.9	6.8	3.81E-05	-3.9E-06	6968	7333	7901	8613
2	15GAZ	1	1	D	0	90	75	0.227	-0.127	102.3	92.1	4.56E-04	-2.6E-05	2669	2792	3291	3588
2	15GAZ	1	1	D	7	90	105	0.167	-0.090	57.7	51.3	2.68E-04	-4.3E-05	3929	4092	4595	4915
2	15GAZ	1	1	E	0	120	75	0.154	-0.083	50.6	48.5	1.66E-04	-3.4E-05	2424	2583	3001	3483
2	15GAZ	1	1	E	7	120	105	0.110	-0.060	41.8	39.2	8.84E-05	-3.5E-05	3407	3548	4117	4459
2	15GAZ	1	2	A	0	60	75	0.387	-0.241	150.1	142.4	1.44E-03	2.6E-05	2923	3059	3517	3880
2	15GAZ	1	2	A	7	60	105	0.293	-0.208	63.8	58.9	8.07E-04	-8.8E-06	3845	4094	4484	4893
2	15GAZ	1	2	B	0	60	165	0.135	-0.102	17.2	18.4	2.30E-04	2.5E-05	3366	3734	4185	4536
2	15GAZ	1	2	B	7	60	225	0.074	-0.049	11.8	10.6	7.76E-05	-4.7E-05	6311	6659	7228	7636
2	15GAZ	1	2	C	0	90	165	0.090	-0.063	15.2	13.9	1.11E-04	-2.0E-05	2739	3062	3589	4209
2	15GAZ	1	2	C	7	90	225	0.055	-0.039	7.1	6.2	4.55E-05	-2.6E-05	5477	5920	6396	7206
2	15GAZ	1	2	D	0	90	75	0.258	-0.149	68.9	62.8	5.62E-04	-2.3E-06	2756	2961	3397	3676
2	15GAZ	1	2	D	7	90	105	0.189	-0.114	46.5	41.4	3.31E-04	-1.0E-05	4002	4230	4665	4947
2	15GAZ	1	2	E	0	120	75	0.165	-0.100	35.7	34.0	2.08E-04	-7.3E-05	2885	3128	3594	3881
2	15GAZ	1	2	E	7	120	105	0.109	-0.068	18.6	17.3	1.12E-04	-3.9E-05	3827	4141	4560	4865
2	15GAZ	1	3	A	0	60	75	0.347	-0.259	105.9	100.3	1.29E-03	2.0E-05	2846	3019	3442	3769
2	15GAZ	1	3	A	7	60	105	0.240	-0.195	55.3	50.9	7.19E-04	-1.3E-05	3771	4007	4442	4757
2	15GAZ	1	3	B	0	60	165	0.136	-0.103	20.3	19.3	2.06E-04	2.0E-05	3188	3541	4044	4279
2	15GAZ	1	3	B	7	60	225	0.066	-0.050	11.5	10.3	6.89E-05	2.7E-07	6122	6443	6997	7433
2	15GAZ	1	3	C	0	90	165	0.071	-0.057	10.4	9.3	8.85E-05	-3.0E-06	3001	3386	3841	4515
2	15GAZ	1	3	C	7	90	225	0.046	-0.041	7.1	6.1	3.77E-05	8.8E-06	5728	6103	6652	7418
2	15GAZ	1	3	D	0	90	75	0.246	-0.148	114.8	106.2	4.53E-04	-1.7E-05	2983	3099	3625	3961
2	15GAZ	1	3	D	7	90	105	0.171	-0.092	61.5	54.8	2.64E-04	-3.5E-05	4227	4383	4901	5183
2	15GAZ	1	3	E	0	120	75	0.161	-0.076	57.0	54.8	1.56E-04	-3.2E-06	1959	2106	2522	3015
2	15GAZ	1	3	E	7	120	105	0.105	-0.061	37.2	34.7	8.38E-05	-8.3E-06	2933	3084	3537	3973
2	15GAZ	2	1	A	0	60	75	0.392	-0.280	105.6	99.5	1.46E-03	1.4E-05	2459	2656	3037	3368
2	15GAZ	2	1	A	7	60	105	0.273	-0.207	63.6	58.9	7.97E-04	8.8E-06	3375	3607	4035	4327
2	15GAZ	2	1	B	0	60	165	0.125	-0.100	14.8	15.8	2.23E-04	1.6E-05	3247	3643	4055	4335
2	15GAZ	2	1	B	7	60	225	0.067	-0.051	10.3	9.3	7.55E-05	1.0E-05	6184	6546	7076	7480
2	15GAZ	2	1	C	0	0	195	0.200	-0.118	75.0	67.5	3.74E-04	5.5E-05	2659	2807	3259	3566
2	15GAZ	2	1	C	7	0	225	0.153	-0.092	152.9	136.5	2.37E-04	9.8E-05	4127	4183	4757	5219
2	15GAZ	2	1	D	0	0	255	0.125	-0.087	35.1	29.5	1.84E-04	-3.5E-05	3140	3352	3814	4128
2	15GAZ	2	1	D	7	0	285	0.094	-0.066	38.3	31.4	1.21E-04	-3.0E-05	4871	5021	5558	5979
2	15GAZ	2	1	E	0	0	135	0.334	-0.228	77.7	76.4	9.39E-04	3.6E-05	2658	2877	3234	3566
2	15GAZ	2	1	E	7	0	165	0.246	-0.149	70.3	72.9	5.37E-04	9.2E-05	4011	4180	4652	5043

2	15GAZ	2	2	A	0	60	75	0.377	-0.264	110.7	104.6	1.39E-03	2.6E-05	2829	3009	3440	3788
2	15GAZ	2	2	A	7	60	105	0.271	-0.180	59.9	55.6	7.81E-04	-1.2E-05	3754	3998	4431	4746
2	15GAZ	2	2	B	0	60	165	0.138	-0.097	17.3	18.4	2.24E-04	6.8E-07	477	852	1297	1771
2	15GAZ	2	2	B	7	60	225	0.070	-0.054	11.0	9.8	7.66E-05	-3.0E-05	3431	3786	4359	4824
2	15GAZ	2	2	C	0	0	195	0.191	-0.126	95.8	85.5	3.82E-04	-1.6E-05	2657	2769	3324	3598
2	15GAZ	2	2	C	7	0	225	0.143	-0.103	51.6	45.1	2.60E-04	1.0E-05	4133	4291	4799	5245
2	15GAZ	2	2	D	0	0	255	0.125	-0.093	21.4	18.3	2.05E-04	2.1E-05	2937	3278	3657	4076
2	15GAZ	2	2	D	7	0	285	0.101	-0.074	33.6	28.0	1.37E-04	-4.9E-05	4674	4854	5395	5832
2	15GAZ	2	2	E	0	0	135	0.315	-0.220	63.9	62.5	9.46E-04	-1.1E-05	2709	2961	3329	3681
2	15GAZ	2	2	E	7	0	165	0.240	-0.155	49.8	51.6	5.49E-04	-1.5E-05	4084	4317	4737	5088
3	PNCLF	1	1	A	0	0	85	0.963	-0.501	258.2	257.6	8.14E-03	-8.0E-05	2730	2917	3536	4018
3	PNCLF	1	1	A	7	0	135	0.571	-0.329	129.7	128.6	3.22E-03	-1.3E-04	5121	5343	5946	6512
3	PNCLF	1	1	B	0	0	175	0.412	-0.257	82.3	81.1	1.85E-03	-5.0E-08	3332	3586	4190	4775
3	PNCLF	1	1	B	7	0	225	0.303	-0.194	54.5	53.4	1.08E-03	3.6E-05	5580	5864	6484	7071
3	PNCLF	1	1	C	0	45	85	1.062	-0.414	248.7	248.1	7.71E-03	-1.7E-04	2984	3198	3758	4223
3	PNCLF	1	1	C	7	45	175	0.356	-0.164	70.8	69.5	1.29E-03	1.7E-05	7158	7414	8020	8608
3	PNCLF	1	1	D	0	90	85	0.834	-0.376	342.3	341.9	4.94E-03	-3.4E-05	3867	3989	4533	5330
3	PNCLF	1	1	D	7	90	135	0.345	-0.025	75.0	76.9	6.95E-04	2.0E-03	6239	6463	7134	786
3	PNCLF	1	1	E	0	90	175	0.326	-0.192	90.7	88.6	1.04E-03	4.1E-05	4196	4380	5039	5804
3	PNCLF	1	1	E	7	90	225	0.230	-0.152	46.6	48.5	6.29E-04	1.6E-05	6572	6809	7478	8253
3	OBRCK	1	1	A	0	0	50	0.450	-0.238	457.1	432.4	6.37E-04	2.2E-05	1133	1185	1419	1569
3	OBRCK	1	1	A	7	0	70	0.296	-0.156	989.1	923.6	3.34E-04	5.9E-06	1781	1797	2099	2348
3	OBRCK	1	1	B	0	30	50	0.436	-0.181	1327.4	1282.2	5.14E-04	2.1E-05	1394	1411	1697	1885
3	OBRCK	1	1	B	7	30	70	0.270	-0.132	959.8	900.8	2.23E-04	1.4E-05	2298	2313	2629	2876
3	OBRCK	1	1	C	0	60	50	0.437	-0.190	306.3	316.7	5.18E-04	3.2E-06	1612	1681	1944	2241
3	OBRCK	1	1	C	7	60	70	0.324	-0.132	235.7	245.8	2.57E-04	4.0E-05	2268	2334	2614	2903
3	OBRCK	1	1	D	0	90	50	0.366	-0.194	263.8	273.5	4.95E-04	-2.6E-05	1938	2005	2303	2631
3	PGLY1	1	1	A	0	0	85	0.485	-0.088	201.5	194.1	1.16E-03	1.7E-03	3887	4012	4576	5461
3	PGLY1	1	1	A	7	0	135	0.380	-0.125	359.7	345.1	7.32E-04	7.6E-05	6163	6218	6704	7281
3	PGLY1	1	1	B	0	0	175	0.307	-0.114	142.4	132.2	5.30E-04	3.1E-06	2706	2822	3299	3786
3	PGLY1	1	1	B	7	0	225	0.223	-0.108	99.5	89.8	3.79E-04	-4.8E-05	5059	5183	5685	6227
3	PGLY1	1	1	C	0	45	85	0.510	-0.161	319.1	307.2	1.31E-03	5.9E-05	2455	2538	2997	3255
3	PGLY1	1	1	C	7	45	175	0.317	-0.112	109.1	102.3	5.98E-04	5.0E-05	5514	5669	6120	6378
3	PGLY2	1	1	A	0	0	85	0.799	-0.028	1210.5	1211.2	2.74E-03	7.6E-03	19575	19608	30989	18945
3	PGLY2	1	1	A	7	0	135	0.488	-0.137	456.3	444.0	1.46E-03	2.0E-04	21844	21899	22517	23348
3	PGLY2	1	1	B	0	0	175	0.385	-0.131	233.0	221.0	1.06E-03	-2.6E-05	3456	3543	4174	4662
3	PGLY2	1	1	B	7	0	225	0.330	-0.118	112.5	105.8	7.97E-04	-5.8E-05	5808	5964	6538	7121
3	PGLY2	1	1	C	0	45	85	0.663	-0.147	327.6	342.0	2.48E-03	1.3E-04	2076	2173	2727	3645
3	PGLY2	1	1	C	7	45	175	0.413	-0.095	138.4	131.4	1.14E-03	1.9E-04	5134	5291	5829	6808

[illegible][illegible][illegible]

APPENDIX B

DATA PROCESSING MATLAB CODES

RACS RESEARCH - DATA TRIMMING SCRIPT 08/31/2020

```
%{
    The purpose of this script is to take raw voltage data collected from
    the DAQs, convert it to psi, and allow the user to graphically trim,
    and edit then save the modified data and calculations
    for later processing.
%}

clear;
clc
```

Initialize variables

```
AdjustFlag = 1;
ReplotFlag = 0;
SensorDistance = {};

wavevelocity = NaN;

LeftBuffer = 3;
RightBuffer = 5;

CH0Color = 'red';
CH7Color = 'blue';
```

Select File for Trimming

```
[ReadFile, ReadFilePath] = uigetfile('C:\Users\brand\Box\School\Grad School\Research\Data\Raw
Data\ *.csv','Select .CSV File for Processing');
ReadPath = strcat(ReadFilePath,ReadFile);
ReadMatrix = readmatrix(ReadPath);

CH0_V = ReadMatrix(:,1);
CH7_V = ReadMatrix(:,2);

CH0_PSI = (2.504-CH0_V)*(10/2.5);
CH7_PSI = (2.504-CH7_V)*(10/2.5);
```

Create Time Matrix for Plotting

```
SampleRate = 50000;
dt = 1/SampleRate;
t0 = 0;
```

```
N = length(ReadMatrix);
t = t0 + (0:N-1)*dt;
```

Create a Default Guess for Event Location

```
[EventGuessPeak,EventGuess] = max(CH0_PSI);
```

Plot Raw Data

```
figure(1);
clf(1);
plot(t,CH0_PSI,CH0Color,t,CH7_PSI,CH7Color)
title(ReadFile,'Interpreter','none')
xlabel('Time (s)')
ylabel('Pressure (psi)')
legend('CH 0', 'CH 7')
grid on
grid minor
```

Identify Event for Processing

```
prompt = 'Enter approximate time of event (to the nearest 1/10th of a second): ';
dlgtitle = 'Select Event for Processing';
dims = [1 75];
definput = {num2str(t(EventGuess))};
EventTimeInput = inputdlg(prompt,dlgtitle,dims,definput);
EventTime = str2double(cell2mat(EventTimeInput));

% Defining initial window of 1 second
if rem(EventTime,1) == 0

    LowEventTime = EventTime-0.5;
    HighEventTime = EventTime+0.5;

else

    LowEventTime = round(EventTime,1)-.5;
    HighEventTime = round(EventTime,1)+.5;

end

[LowTime, LowTimeIndex] = min(abs(t-LowEventTime));
[HighTime, HighTimeIndex] = min(abs(t-HighEventTime));

% Finding max within 1 second window and finding min just after max
```

```

[CH0Peak,CH0PeakIndex] = max(CH0_PSI(LowTimeIndex:HighTimeIndex,:));
[CH0Trough,CH0Peak2Trough] = min(CH0_PSI((LowTimeIndex+CH0PeakIndex):HighTimeIndex,:));
[CH7Peak,CH7PeakIndex] = max(CH7_PSI(LowTimeIndex:HighTimeIndex,:));
[CH7Trough,CH7Peak2Trough] = min(CH7_PSI((LowTimeIndex+CH7PeakIndex):HighTimeIndex,:));

% Minimum and Maximum indices of trimmed window
TrimmedMin = min([(LowTimeIndex+CH0PeakIndex) -
(LeftBuffer*CH0Peak2Trough),(LowTimeIndex+CH7PeakIndex) - (LeftBuffer*CH7Peak2Trough)]);
TrimmedMax = max([(LowTimeIndex+CH0PeakIndex) +
(RightBuffer*CH0Peak2Trough),(LowTimeIndex+CH7PeakIndex) + (RightBuffer*CH7Peak2Trough)]);

```

Plot Trimmed Data

```

figure(2);
clf(2);
set(gcf,'Position',[300,300,1000,400])
plot(t(:,TrimmedMin:TrimmedMax),CH0_PSI(TrimmedMin:TrimmedMax,:),CH0Color,t(:,TrimmedMin:TrimmedM
ax),CH7_PSI(TrimmedMin:TrimmedMax,:),CH7Color)
title(ReadFile,'Interpreter','none')
xlabel('Time (s)')
ylabel('Pressure (psi)')
lgd = legend({'CH 0', 'CH 7'},'FontSize',8);
text([t(LowTimeIndex+CH0PeakIndex),t(LowTimeIndex+CH0PeakIndex+CH0Peak2Trough)], [CH0Peak,CH0Trough],{['\leftarrow CH0 Peak = ', num2str(CH0Peak), ' psi'], [' At t = ', num2str(t(LowTimeIndex+CH0PeakIndex)), ' s']},{'\leftarrow CH0 Trough = ', num2str(CH0Trough), ' psi'], [' At t = ', num2str(t(LowTimeIndex+CH0PeakIndex+CH0Peak2Trough)), ' s']}},'FontSize',8,'Color',CH0Color)
text([t(LowTimeIndex+CH7PeakIndex),t(LowTimeIndex+CH7PeakIndex+CH7Peak2Trough)], [CH7Peak,CH7Trough],{['\leftarrow CH7 Peak = ', num2str(CH7Peak), ' psi'], [' At t = ', num2str(t(LowTimeIndex+CH7PeakIndex)), ' s']},{'\leftarrow CH7 Trough = ', num2str(CH7Trough), ' psi'], [' At t = ', num2str(t(LowTimeIndex+CH7PeakIndex+CH7Peak2Trough)), ' s']}},'FontSize',8,'Color',CH7Color)
grid on
grid minor

```

Loop for Further Adjustments

```

while AdjustFlag == 1
    ANSWR = questdlg('Would you like to save this data or make further changes?', 'Continue Editing Data?','Save','Continue Editing','Save');
    switch ANSWR
        case ''
            AdjustFlag = 0;
            WriteMatrix = [CH0_PSI(TrimmedMin:TrimmedMax,:),CH7_PSI(TrimmedMin:TrimmedMax,:));

        case 'Save'
            AdjustFlag = 0;

```

```

WriteMatrix = [CH0_PSI(TrimmedMin:TrimmedMax,:),CH7_PSI(TrimmedMin:TrimmedMax,:)];

SaveList = {'Save Data to .CSV','Save Figure as .PNG','Save MATLAB Calculations (Peak
Pressures, Wave Velocity, etc.)','Save All'};
[SaveSelections,tf] = listdlg('PromptString',{'What would you like to
save?'},'SelectionMode','single','ListString',SaveList,'ListSize',[500,200]);

if isempty(SaveSelections) == 1
    AdjustFlag = 1;
    continue

elseif SaveSelections(1) == 1

    CSVSavewindow()
    [WriteDataFile, WriteDataFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Trimmed Data\','ReadFile(1:end-4)','.csv'],'Save .CSV File');
    WriteDataPath = strcat(WriteDataFilePath,WriteDataFile);
    writematrix(WriteMatrix,WriteDataPath);

elseif SaveSelections(1) == 2

    [WriteFigureFile, WriteFigureFilePath] =
uiputfile(['C:\Users\brand\Box\School\Grad School\Research\Data\MATLAB Figures\','ReadFile(1:end-
4)','.png'],'Save Figure as .PNG');
    FigureSavewindow()

    WriteFigurePath = strcat(WriteFigureFilePath,WriteFigureFile);
    saveas(gcf,WriteFigurePath)

elseif SaveSelections(1) == 3

    MATSavewindow()
    [WriteMATFile, WriteMATFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\MATLAB Calculations\','ReadFile(1:end-4)','.mat'],'Save .MAT File');
    WriteMATPath = strcat(WriteMATFilePath,WriteMATFile);
    save(WriteMATPath, 'WaveVelocity', 'CH0Peak', 'CH0Trough', 'CH7Peak',
'CH7Trough');

elseif SaveSelections(1) == 4

    CSVSavewindow()
    [WriteDataFile, WriteDataFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Trimmed Data\','ReadFile(1:end-4)','.csv'],'Save .CSV File');
    WriteDataPath = strcat(WriteDataFilePath,WriteDataFile);
    writematrix(WriteMatrix,WriteDataPath);

    FigureSavewindow()
    [WriteFigureFile, WriteFigureFilePath] =
uiputfile(['C:\Users\brand\Box\School\Grad School\Research\Data\MATLAB Figures\','ReadFile(1:end-
4)','.png'],'Save Figure as .PNG');

```

```

writeFigurePath = strcat(writeFigureFilePath,writeFigureFile);
saveas(gcf,writeFigurePath)

MATSaveWindow()
[writeMATFile, writeMATFilePath] = uinputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\MATLAB Calculations\',ReadFile(1:end-4),'.mat'],'Save .MAT File');
writeMATPath = strcat(writeMATFilePath,writeMATFile);
save(writeMATPath, 'WaveVelocity', 'CH0Peak', 'CH0Trough','CH7Peak',
'CH7Trough');

end

case 'Continue Editing'
    EditList = {'Lower Bound','Upper Bound','CH0 Peak','CH0 Trough','CH7 Peak','CH7
Trough','Calculate wave velocity'};
    [EditSelections,tf] = listdlg('PromptString',{'What would you like to
change?','Multiple selections can be made.'},'ListString',EditList,'ListSize',[500,200]);
    for a = 1:length(EditSelections)
        if EditSelections(a) == 1
            prompt = 'Enter approximate time for desired lower bound: ';
            dlgtitle = 'Select New Lower Bound';
            dims = [1 75];
            NewLowerTimeInput = inputdlg(prompt,dlgtitle,dims);
            if isempty(NewLowerTimeInput) == 1
                continue
            else
                LowEventTime = str2double(cell2mat(NewLowerTimeInput));
                [NewLowTime, TrimmedMin] = min(abs(t-LowEventTime));
                ReplotFlag = 1;
            end

        elseif EditSelections(a) == 2
            prompt = 'Enter approximate time for desired upper bound: ';
            dlgtitle = 'Select New Upper Bound';
            dims = [1 75];
            NewUpperTimeInput = inputdlg(prompt,dlgtitle,dims);
            if isempty(NewUpperTimeInput) == 1
                continue
            else
                HighEventTime = str2double(cell2mat(NewUpperTimeInput));
                [NewHighTime, TrimmedMax] = min(abs(t-HighEventTime));
                ReplotFlag = 1;
            end

        elseif EditSelections(a) == 3
            prompt = {'Enter a time slightly lower than the desired peak: ','Enter a time
slightly higher than the desired peak: '};
            dlgtitle = 'Relocate CH0 Peak';
            dims = [1 75];
            NewCH0PeakBounds = inputdlg(prompt,dlgtitle,dims);

```

```

        if isempty(NewCH0PeakBounds) == 1
            continue
        else
            LowEventTime = str2double(NewCH0PeakBounds(1));
            HighEventTime = str2double(NewCH0PeakBounds(2));
            [NewLowTime, NewLowTimeIndex] = min(abs(t-LowEventTime));
            [NewHighTime, NewHighTimeIndex] = min(abs(t-HighEventTime));
            [CH0Peak, NewCH0PeakIndex] =
max(CH0_PSI(NewLowTimeIndex:NewHighTimeIndex,:));
            NewCH0PeakIndex = NewCH0PeakIndex + (NewLowTimeIndex - LowTimeIndex);
            CH0Peak2Trough = CH0Peak2Trough - (NewCH0PeakIndex - CH0PeakIndex);
            CH0PeakIndex = NewCH0PeakIndex;
            ReplotFlag = 1;
        end

        elseif EditSelections(a) == 4
            prompt = {'Enter a time slightly lower than the desired trough: ', 'Enter a
time slightly higher than the desired trough: '};
            dlgtitle = 'Relocate CH0 Trough';
            dims = [1 75];
            NewCH0TroughBounds = inputdlg(prompt,dlgtitle,dims);
            if isempty(NewCH0TroughBounds) == 1
                continue
            else
                LowEventTime = str2double(NewCH0TroughBounds(1));
                HighEventTime = str2double(NewCH0TroughBounds(2));
                [NewLowTime, NewLowTimeIndex] = min(abs(t-LowEventTime));
                [NewHighTime, NewHighTimeIndex] = min(abs(t-HighEventTime));
                [CH0Trough, NewCH0Trough] =
min(CH0_PSI(NewLowTimeIndex:NewHighTimeIndex,:));
                NewCH0Trough = NewCH0Trough + (NewLowTimeIndex - LowTimeIndex);
                CH0Peak2Trough = (NewCH0Trough - CH0PeakIndex);
                ReplotFlag = 1;
            end

            elseif EditSelections(a) == 5
                prompt = {'Enter a time slightly lower than the desired peak: ', 'Enter a time
slightly higher than the desired peak: '};
                dlgtitle = 'Relocate CH7 Peak';
                dims = [1 75];
                NewCH7PeakBounds = inputdlg(prompt,dlgtitle,dims);
                if isempty(NewCH7PeakBounds) == 1
                    continue
                else
                    LowEventTime = str2double(NewCH7PeakBounds(1));
                    HighEventTime = str2double(NewCH7PeakBounds(2));
                    [NewLowTime, NewLowTimeIndex] = min(abs(t-LowEventTime));
                    [NewHighTime, NewHighTimeIndex] = min(abs(t-HighEventTime));
                    [CH7Peak, NewCH7PeakIndex] =
max(CH7_PSI(NewLowTimeIndex:NewHighTimeIndex,:));

```

```

        NewCH7PeakIndex = NewCH7PeakIndex + (NewLowTimeIndex - LowTimeIndex);
        CH7Peak2Trough = CH7Peak2Trough - (NewCH7PeakIndex - CH7PeakIndex);
        CH7PeakIndex = NewCH7PeakIndex;
        ReplotFlag = 1;
    end

    elseif EditSelections(a) == 6
        prompt = {'Enter a time slightly lower than the desired trough: ', 'Enter a
time slightly higher than the desired trough: '};
        dlgtitle = 'Relocate CH7 Trough';
        dims = [1 75];
        NewCH7TroughBounds = inputdlg(prompt,dlgtitle,dims);
        if isempty(NewCH7TroughBounds) == 1
            continue
        else
            LowEventTime = str2double(NewCH7TroughBounds(1));
            HighEventTime = str2double(NewCH7TroughBounds(2));
            [NewLowTime, NewLowTimeIndex] = min(abs(t-LowEventTime));
            [NewHighTime, NewHighTimeIndex] = min(abs(t-HighEventTime));
            [CH7Trough, NewCH7Trough] =
min(CH7_PSI(NewLowTimeIndex:NewHighTimeIndex,:));
            NewCH7Trough = NewCH7Trough + (NewLowTimeIndex - LowTimeIndex);
            CH7Peak2Trough = (NewCH7Trough - CH7PeakIndex);
            ReplotFlag = 1;
        end

        elseif EditSelections(a) == 7
            SensorDistance = inputdlg({'Input distance between CH0 and CH7 sensors:
','(Units)'},'wave velocity Calculation', [1 50; 1 12]);
            if isempty(SensorDistance) == 1
                continue
            else
                ReplotFlag = 1;
                continue
            end
        end
    end
    if ReplotFlag == 1
        figure(3);
        clf(3);
        set(gcf, 'Position', [400,400,1000,400])

        plot(t(:,TrimmedMin:TrimmedMax), CH0_PSI(TrimmedMin:TrimmedMax,:), CH0Color, t(:,TrimmedMin:TrimmedM
ax), CH7_PSI(TrimmedMin:TrimmedMax,:), CH7Color)
        title('Trimmed Pressure Data')
        xlabel('Time (s)')
        ylabel('Pressure (psi)')
        lgd = legend({'CH 0', 'CH 7'}, 'FontSize', 8);
        if isempty(SensorDistance) ~= 1
            wavevelocity = str2double(SensorDistance(1))/(t(LowTimeIndex+CH7PeakIndex) -

```

```

t(LowTimeIndex+CH0PeakIndex));
    title(lgd,{'Wavefront Velocity: ';cell2mat([num2str(waveVelocity),'
',SensorDistance(2),'/sec'])},'FontSize',8)
    end

text([t(LowTimeIndex+CH0PeakIndex),t(LowTimeIndex+CH0PeakIndex+CH0Peak2Trough)], [CH0Peak,CH0Trough],{'\leftarrow CH0 Peak = ', num2str(CH0Peak),' psi'},['          At t = ', num2str(t(LowTimeIndex+CH0PeakIndex)), ' s']},{'\leftarrow CH0 Trough = ', num2str(CH0Trough),' psi'},['          At t = ', num2str(t(LowTimeIndex+CH0PeakIndex+CH0Peak2Trough)), ' s']},'FontSize',8,'Color',CH0Color)

text([t(LowTimeIndex+CH7PeakIndex),t(LowTimeIndex+CH7PeakIndex+CH7Peak2Trough)], [CH7Peak,CH7Trough],{'\leftarrow CH7 Peak = ', num2str(CH7Peak),' psi'},['          At t = ', num2str(t(LowTimeIndex+CH7PeakIndex)), ' s']},{'\leftarrow CH7 Trough = ', num2str(CH7Trough),' psi'},['          At t = ', num2str(t(LowTimeIndex+CH7PeakIndex+CH7Peak2Trough)), ' s']},'FontSize',8,'Color',CH7Color)
    grid on
    grid minor
else
    continue
end
end
end

function CSVSavewindow

    CSVDIALOG = dialog('Position',[500 500 250 150],'Name','Save .CSV');

    uicontrol('Parent',CSVDIALOG,...
        'Style','text',...
        'Position',[20 80 210 40],...
        'String','You will now specify the file location for the .CSV file...');

    uicontrol('Parent',CSVDIALOG,...
        'Position',[85 20 70 25],...
        'String','OK',...
        'Callback','delete(gcf)');
    waitfor(CSVDIALOG)
end

function Figuresavewindow

    FigureDialog = dialog('Position',[500 500 250 150],'Name','Save Figure');

    uicontrol('Parent',FigureDialog,...
        'Style','text',...
        'Position',[20 80 210 40],...
        'String','You will now specify the file location for the figure file...');

    uicontrol('Parent',FigureDialog,...

```



```

        'Position',[85 20 70 25],...
        'String','OK',...
        'Callback','delete(gcf)');
    waitfor(FigureDialog)
end

function MATSavewindow

    FigureDialog = dialog('Position',[500 500 250 150],'Name','Save Calculations to .MAT File');

    uicontrol('Parent',FigureDialog,...
        'Style','text',...
        'Position',[20 80 210 40],...
        'String','You will now specify the file location for the .MAT file...');

    uicontrol('Parent',FigureDialog,...
        'Position',[85 20 70 25],...
        'String','OK',...
        'Callback','delete(gcf)');
    waitfor(FigureDialog)
end

```

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RACS RESEARCH - DATA PROCESSING SCRIPT 02/01/2021

```

%{
    The purpose of this script is to take the trimmed data from the
    DataTrimmer.m script, and apply necessary processing and calculations
    to data (filtering, integrations, derivatives, etc.)
    and save calculations and processed data for later analysis and graphing.
%}

clear;
clc
close all

SampleRate = 50000; % Samples/Second

CH0Color = 'red';
CH7Color = 'blue';

EditFilterFlag = 1;

PreBlastZeroLimit = 0.075; % PSI Limit to zero data before blast is received.

% Figure Locations and Sizes
x1 = 10;           % Left Column Left Edge
x2 = 825;          % Right Column Left Edge
y1 = 50;           % Bottom Row Bottom Edge
y2 = 510;          % Top Row Bottom Edge
w = 800;           % Width
H = 375;           % Height

UpperAxisBuffer = 1.25; % Graph Headroom
LowerAxisBuffer = 1.5;  % Graph Footroom

```

Select File for Processing

```

[ReadFile, ReadFilePath] = uigetfile('C:\Users\brand\Box\School\Grad School\Research\Data\Trimmed
Data\ *.csv','Select .CSV File for Processing');
ReadPath = strcat(ReadFilePath,ReadFile);
ReadMatrix = readmatrix(ReadPath);

% Ensures that the length of the data is divisible by two to allow use of
% fftshift() and inverse of fftshift()
if rem(length(ReadMatrix),2)~=0
    CH0_PSI = ReadMatrix(1:end-1,1);
    CH7_PSI = ReadMatrix(1:end-1,2);
    N = length(ReadMatrix)-1;
else

```

```

CH0_PSI = ReadMatrix(:,1);
CH7_PSI = ReadMatrix(:,2);
N = length(ReadMatrix);
end

```

Create Time Matrix for Plotting

```

dt = 1/SampleRate;
t0 = 0;
t = t0 + (0:N-1)*dt;

```

Plot Trimmed Data

```

figure(1);
clf(1);
set(gcf, 'Position', [x1,y2,w,H])
plot(t,CH0_PSI,CH0Color,t,CH7_PSI,CH7Color)
title(ReadFile, 'Interpreter', 'none')
xlabel('Time (s)')
ylabel('Pressure (psi)')
legend('CH 0', 'CH 7')
grid on
grid minor
hold on
axis([min(t) max(t) LowerAxisBuffer*min([min(CH0_PSI), min(CH7_PSI)])
UpperAxisBuffer*max([max(CH0_PSI), max(CH7_PSI)])]);

```

Apply Low Pass Filter

```

frq =(-N/2:N/2-1)*SampleRate/(N);

CH0DefaultLowPassStart = '0';           %Hz
CH0DefaultLowPassStop = '1500';         %Hz
CH7DefaultLowPassStart = '0';           %Hz
CH7DefaultLowPassStop = '1500';         %Hz

while EditFilterFlag == 1
    prompt = {'Channel 0: Low Pass/Band Pass Filter Start (Hz)', 'Channel 0: Low Pass/Band Pass Filter Stop (Hz)', 'Channel 7: Low Pass/Band Pass Filter Start (Hz)', 'Channel 7: Low Pass/Band Pass Filter Stop (Hz)'};
    dlgtitle = 'Define Filter Bounds';
    dims = [1 75];
    FilterBounds =
inputdlg(prompt,dlgtitle,dims,{CH0DefaultLowPassStart,CH0DefaultLowPassStop,CH7DefaultLowPassStart,CH7DefaultLowPassStop});

```

```

if isempty(FilterBounds)
    uiwait(warndlg('Please specify filter bounds.','warning'));
    continue
end
CH0DefaultLowPassStart = cell2mat(FilterBounds(1));
CH0DefaultLowPassStop = cell2mat(FilterBounds(2));
CH7DefaultLowPassStart = cell2mat(FilterBounds(3));
CH7DefaultLowPassStop = cell2mat(FilterBounds(4));

CH0LowPassStart = str2double(FilterBounds(1));
CH0LowPassStop = str2double(FilterBounds(2));
CH7LowPassStart = str2double(FilterBounds(3));
CH7LowPassStop = str2double(FilterBounds(4));

FCH0=fftshift(fft(CH0_PSI));
FCH0Filt = zeros(length(FCH0),1);
for a = 1:N
    if abs(frq(a))< CH0LowPassStop && abs(frq(a))> CH0LowPassStart
        FCH0Filt(a) = FCH0(a);
    end
end
CH0Filt = ifft(fftshift(FCH0Filt));

FCH7=fftshift(fft(CH7_PSI));
FCH7Filt = zeros(length(FCH7),1);
for a = 1:N
    if abs(frq(a))< CH7LowPassStop && abs(frq(a))> CH7LowPassStart
        FCH7Filt(a) = FCH7(a);
    end
end
CH7Filt = ifft(fftshift(FCH7Filt));

%Plot Raw Data
figure(2);
clf(2);
set(gcf,'Position',[x2,y2,w,h])
plot(t,CH0_PSI,CH0Color,t,CH7_PSI,CH7Color)
title(ReadFile,'Interpreter','none')
xlabel('Time (s)')
ylabel('Pressure (psi)')
legend('CH 0', 'CH 7')
grid on
grid minor
hold on
%Plot Filtered Data
plot(t,CH0Filt,'m',t,CH7Filt,'g')
title('Low-Pass Filter','Interpreter','none')
legend('CH 0', 'CH 7','CH 0 Filtered', 'CH 7 Filtered')
axis([min(t) max(t) LowerAxisBuffer*min([min(CH0_PSI), min(CH7_PSI), min(CH0Filt),
min(CH7Filt)]) UpperAxisBuffer*max([max(CH0_PSI), max(CH7_PSI), max(CH0Filt), max(CH7Filt)])]);

```

```

% Plot FFT and Filtered FFT in Frequency Domain
CH0FFTFig = figure(3);
clf(CH0FFTFig)
set(gcf, 'Position', [x1,y1,w,h])
subplot(2,1,1)
plot(frq,abs(FCH0)/N)
title("Ch. 0 Raw Data(Frequency Domain)")
xlabel('Frequency (Hz)')
ylabel('Amplitude')
grid on
grid minor

subplot(2,1,2)
plot(frq,abs(FCH0Filt)/N)
title("Ch. 0 Filtered Data(Frequency Domain)")
xlabel('Frequency (Hz)')
ylabel('Amplitude')
grid on
grid minor

CH7FFTFig = figure(4);
clf(CH7FFTFig)
set(gcf, 'Position', [x2,y1,w,h])
subplot(2,1,1)
plot(frq,abs(FCH7)/N)
title("Ch. 7 Raw Data(Frequency Domain)")
xlabel('Frequency (Hz)')
ylabel('Amplitude')
grid on
grid minor

subplot(2,1,2)
plot(frq,abs(FCH7Filt)/N)
title("Ch. 7 Filtered Data(Frequency Domain)")
xlabel('Frequency (Hz)')
ylabel('Amplitude')
grid on
grid minor

ANSWR = questdlg('would you like to edit the Filter?', 'Edit Filter?', 'YES','NO','NO');
switch ANSWR
    case 'YES'

    case 'NO'
        EditFilterFlag = 0;
    case ''
        pause(5)
end

```

```

end

close(1);
close(2);

%Plot Filtered Data
FiltFig = figure(1);
clf(FiltFig);
set(gcf, 'Position', [x1,y2,w,h])
plot(t, CH0Filt, CH0Color, t, CH7Filt, CH7Color)
xlabel('Time (s)')
ylabel('Pressure (psi)')
grid on
grid minor
title(ReadFile, 'Interpreter', 'none')
legend('CH 0 (Filtered)', 'CH 7 (Filtered)')
axis([min(t) max(t) LowerAxisBuffer*min([min(CH0Filt), min(CH7Filt)])
UpperAxisBuffer*max([max(CH0Filt), max(CH7Filt)])]);

```

Find Filtered Maxima and Minima and Times

```

[CH0Peak, CH0PeakIndex] = max(CH0Filt);
[CH0Trough, CH0TroughIndex] = min(CH0Filt);
[CH7Peak, CH7PeakIndex] = max(CH7Filt);
[CH7Trough, CH7TroughIndex] = min(CH7Filt);

```

Find Onset of Pressure Rise to Aid in Derivative and Integral Calculations

```

for a = CH0PeakIndex:-1:51
    if abs(CH0Filt(a:-1:a-50)) <= PreBlastZeroLimit
        CH0BlastStart = a;
        break
    end
end
for a = CH7PeakIndex:-1:51
    if abs(CH7Filt(a:-1:a-50)) <= PreBlastZeroLimit
        CH7BlastStart = a;
        break
    end
end

CH0Filt(1:CH0BlastStart) = 0;
CH7Filt(1:CH7BlastStart) = 0;

```

Find Location of Change from Positive to Negative Pressure

```

for a = CH0PeakIndex:N-51
    if CH0Filt(a:a+50) <= 0
        CH0P2N = a;
        break
    end
end
for a = CH7PeakIndex:N-51
    if CH7Filt(a:a+50) <= 0
        CH7P2N = a;
        break
    end
end
end

```

Plot Filtered Data with Annotations

```

AnnotFiltFig = figure(2);
clf(AnnotFiltFig);
set(gcf, 'Position', [x2,y2,w,H])
plot(t, CH0Filt, CH0Color, t, CH7Filt, CH7Color)
title(ReadFile, 'Interpreter', 'none')
xlabel('Time (s)')
ylabel('Pressure (psi)')
legend('CH 0 (Filtered)', 'CH 7 (Filtered)')
text([t(CH0PeakIndex), t(CH0TroughIndex)], [CH0Peak, CH0Trough], {[ 'CH0 Max = ',
num2str(round(CH0Peak,3)), ' psi', ' \rightarrow'], ['@ t = ', num2str(round(t(CH0PeakIndex),3)), ' s
']}, {[ 'CH0 Min = ', num2str(round(CH0Trough,3)), ' psi', ' \rightarrow'], ['@ t = ',
num2str(round(t(CH0TroughIndex),3)), ' s
']}, 'FontSize', 8, 'HorizontalAlignment', 'right', 'FontWeight', 'Bold', 'Color', 'black')
text([t(CH7PeakIndex), t(CH7TroughIndex)], [CH7Peak, CH7Trough], {[ 'CH7 Max = ',
num2str(round(CH7Peak,3)), ' psi', ' \rightarrow'], ['@ t = ', num2str(round(t(CH7PeakIndex),3)), ' s
']}, {[ 'CH7 Min = ', num2str(round(CH7Trough,3)), ' psi', ' \rightarrow'], ['@ t = ',
num2str(round(t(CH7TroughIndex),3)), ' s
']}, 'FontSize', 8, 'HorizontalAlignment', 'right', 'FontWeight', 'Bold', 'Color', 'black')
text(t(CH0BlastStart), CH0Filt(CH0BlastStart), ['t = ', num2str(round(t(CH0BlastStart),3)), ' s
\rightarrow'], '
', 'FontSize', 8, 'HorizontalAlignment', 'right', 'FontWeight', 'Bold', 'Color', 'black')
text(t(CH7BlastStart), CH7Filt(CH0BlastStart), ['t = ', num2str(round(t(CH7BlastStart),3)), ' s
\rightarrow'], '
', 'FontSize', 8, 'HorizontalAlignment', 'right', 'FontWeight', 'Bold', 'Color', 'black')
text(t(CH0P2N), CH0Filt(CH0P2N), ['\leftarrow t = ', num2str(round(t(CH0P2N),3)), ' s'], '
', 'FontSize', 8, 'HorizontalAlignment', 'left', 'FontWeight', 'Bold', 'Color', 'black')
text(t(CH7P2N), CH7Filt(CH7P2N), ['\leftarrow t = ', num2str(round(t(CH7P2N),3)), ' s'], '
', 'FontSize', 8, 'HorizontalAlignment', 'left', 'FontWeight', 'Bold', 'Color', 'black')
grid on
grid minor
axis([min(t) max(t) LowerAxisBuffer*min([min(CH0Filt), min(CH7Filt)])
UpperAxisBuffer*max([max(CH0Filt), max(CH7Filt)])]);

```

Calculate Derivatives of Initial Impulse

```

CH0Deriv = zeros(N,1);
CH7Deriv = zeros(N,1);

% Channel 0 Numerical Derivative
for i = CH0BlastStart:N
    if i == CH0BlastStart % If at first point, use forward-
difference
        CH0_p1 = CH0Filt(i+1);
        CH0_i = CH0Filt(i);

        CH0Deriv(i) = (CH0_p1 - CH0_i)/dt;

    elseif i == CH0BlastStart+1 || i == N-1 % If at second or second-to-last
point, use central-difference
        CH0_p1 = CH0Filt(i+1);
        CH0_m1 = CH0Filt(i-1);

        CH0Deriv(i) = (CH0_p1 - CH0_m1)/(2*dt);

    elseif i == N % If at last point, use backward-
difference
        CH0_i = CH0Filt(i);
        CH0_m1 = CH0Filt(i-1);

        CH0Deriv(i) = (CH0_i - CH0_m1)/dt;

    else % Use 4th order method for all
interior points
        CH0_p2 = CH0Filt(i+2);
        CH0_p1 = CH0Filt(i+1);
        CH0_m1 = CH0Filt(i-1);
        CH0_m2 = CH0Filt(i-2);

        CH0Deriv(i) = (CH0_m2 - (8*CH0_m1) + (8*CH0_p1) - CH0_p2)/(12*dt);

    end
end

CH0NumericDerivImpulseAve = mean(CH0Deriv(CH0BlastStart:CH0PeakIndex));
CH0DirectDeriv = (CH0Peak)/(t(CH0PeakIndex) - t(CH0BlastStart));

% Channel 7 Numerical Derivative
for i = CH7BlastStart:N
    if i == CH7BlastStart % If at first point, use forward-
difference
        CH7_p1 = CH7Filt(i+1);
        CH7_i = CH7Filt(i);

```



```

        CH7Deriv(i) = (CH7_p1 - CH7_i)/dt;

        elseif i == CH7BlastStart+1 || i == N-1                % If at second or second-to-last
point, use central-difference
            CH7_p1 = CH7Filt(i+1);
            CH7_m1 = CH7Filt(i-1);

            CH7Deriv(i) = (CH7_p1 - CH7_m1)/(2*dt);

        elseif i == N                                          % If at last point, use backward-
difference
            CH7_i = CH7Filt(i);
            CH7_m1 = CH7Filt(i-1);

            CH7Deriv(i) = (CH7_i - CH7_m1)/dt;

        else                                                    % Use 4th order method for all
interior points
            CH7_p2 = CH7Filt(i+2);
            CH7_p1 = CH7Filt(i+1);
            CH7_m1 = CH7Filt(i-1);
            CH7_m2 = CH7Filt(i-2);

            CH7Deriv(i) = (CH7_m2 - (8*CH7_m1) + (8*CH7_p1) - CH7_p2)/(12*dt);

        end
    end

    CH7NumericDerivImpulseAve = mean(CH7Deriv(CH7BlastStart:CH7PeakIndex));
    CH7DirectDeriv = (CH7Peak)/(t(CH7PeakIndex) - t(CH7BlastStart));

```

Calculate Integrals Using Trapezoidal Method

Channel 0 Energy Equivalent Integral

```

I_CH0P2 = cumtrapz(dt,CH0Filt.^2);
% Channel 0 Impulse Integral
I_CH0P = cumtrapz(dt,CH0Filt);

% Channel 7 Energy Equivalent Integral
I_CH7P2 = cumtrapz(dt,CH7Filt.^2);
% Channel 7 Impulse Integral
I_CH7P = cumtrapz(dt,CH7Filt);

CH0_Impulse = I_CH0P(end);
CH0_EE = I_CH0P2(end);

```

```
CH7_Impulse = I_CH7P(end);
CH7_EE = I_CH7P2(end);
```

Prepare Data and Calculations for Saving

```
clearvars -except FiltFig AnnotFiltFig ReadFile ReadFilePath ReadPath t ...
CH0FFTFig CH0Filt CH0Peak CH0Trough CH0_EE CH0_Impulse CH0BlastStart CH0PeakIndex CH0P2N
CH0TroughIndex CH0Deriv I_CH0P I_CH0P2 CH0DirectDeriv CH0NumericDerivImpulseAve CH0LowPassStart
CH0LowPassStop FCH0 FCH0Filt ...
CH7FFTFig CH7Filt CH7Peak CH7Trough CH7_EE CH7_Impulse CH7BlastStart CH7PeakIndex CH7P2N
CH7TroughIndex CH7Deriv I_CH7P I_CH7P2 CH7DirectDeriv CH7NumericDerivImpulseAve CH7LowPassStart
CH7LowPassStop FCH7 FCH7Filt
```

Save

```
ANSWR = questdlg('would you like to save data, figures, and/or calculations?',
'Save?', 'Save', 'Close', 'Save');
switch ANSWR
case ''

case 'Save'
    SaveList = {'Save Filtered Data, FFT Data, Derivatives, and Integrals to .XLS', 'Save
Figures as .PNG', 'Save MATLAB Calculations and Values (Peak Pressures, Filter Settings, Impulse
Slope, etc.)', 'Save All'};
    [SaveSelections, tf] = listdlg('PromptString', {'what would you like to
save?'}, 'SelectionMode', 'single', 'ListString', SaveList, 'ListSize', [500, 200]);

    if isempty(SaveSelections) == 1

        elseif SaveSelections(1) == 1

            T = table(t',
CH0Filt, CH7Filt, CH0Deriv, CH7Deriv, I_CH0P, I_CH7P, I_CH0P2, I_CH7P2, FCH0, FCH7, FCH0Filt, FCH7Filt, 'Vari
ableNames', {'Time (sec)' 'CH.0 Filtered Data (psi)' 'CH.7 Filtered Data (psi)' 'CH.0 Numerical
Derivative (psi/s)' 'CH.7 Numerical Derivative (psi/s)' 'CH.0 Int(P) (psi s)' 'CH.7 Int(P) (psi
s)' 'CH.0 Int(P^2) (psi s)' 'CH.7 Int(P^2) (psi s)' 'CH.0 FFT (freq. domain)' 'CH.7 FFT (freq.
domain)' 'CH.0 Filtered FFT (freq. domain)' 'CH.7 Filtered FFT (freq. domain)'});

            XLSSavewindow()
            [WriteXLSFile, WriteXLSFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Processed Data\', ReadFile(1:end-4), '.xls'], 'Save .XLS File');
            WriteXLSPath = strcat(WriteXLSFilePath, WriteXLSFile);
            writetable(T, WriteXLSPath);

        elseif SaveSelections(1) == 2

            FigureSavewindow()
```

```

[WriteFigureFile, WriteFigureFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Figures\',ReadFile(1:end-4),'.png'],'Save Figure as .PNG');

WriteFigurePath = strcat(WriteFigureFilePath,"Filtered ", WriteFigureFile);
saveas(FiltFig,WriteFigurePath)

WriteFigurePath = strcat(WriteFigureFilePath,"Filtered Annotated ", WriteFigureFile);
saveas(AnnotFiltFig,WriteFigurePath)

WriteFigurePath = strcat(WriteFigureFilePath,"CH.0 FFT ", WriteFigureFile);
saveas(CH0FFTFig,WriteFigurePath)

WriteFigurePath = strcat(WriteFigureFilePath,"CH.7 FFT ", WriteFigureFile);
saveas(CH7FFTFig,WriteFigurePath)

elseif SaveSelections(1) == 3

    MATSavewindow()
    [WriteMATFile, WriteMATFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Calculations\',ReadFile(1:end-4),'.mat'],'Save .MAT File');
    WriteMATPath = strcat(WriteMATFilePath,WriteMATFile);
    save(WriteMATPath,'CH0_EE', 'CH0_Impulse', 'CH0BlastStart', 'CH0DirectDeriv',
'CH0LowPassStart', 'CH0LowPassStop', 'CH0NumericDerivImpulseAve', 'CH0P2N', 'CH0Peak',
'CH0PeakIndex', 'CH0Trough', 'CH0TroughIndex', 'CH7_EE', 'CH7_Impulse', 'CH7BlastStart',
'CH7DirectDeriv', 'CH7LowPassStart', 'CH7LowPassStop', 'CH7NumericDerivImpulseAve', 'CH7P2N',
'CH7Peak', 'CH7PeakIndex', 'CH7Trough', 'CH7TroughIndex', 'ReadFile', 'ReadFilePath', 'ReadPath'
);

elseif SaveSelections(1) == 4

    % Data Save
    T = table(t',
CH0Filt,CH7Filt,CH0Deriv,CH7Deriv,I_CH0P,I_CH7P,I_CH0P2,I_CH7P2,FCH0,FCH7,FCH0Filt,FCH7Filt,'Vari
ableNames',{'Time (sec)' 'CH.0 Filtered Data (psi)' 'CH.7 Filtered Data (psi)' 'CH.0 Numerical
Derivative (psi/s)' 'CH.7 Numerical Derivative (psi/s)' 'CH.0 Int(P) (psi s)' 'CH.7 Int(P) (psi
s)' 'CH.0 Int(P^2) (psi s)' 'CH.7 Int(P^2) (psi s)' 'CH.0 FFT (freq. domain)' 'CH.7 FFT (freq.
domain)' 'CH.0 Filtered FFT (freq. domain)' 'CH.7 Filtered FFT (freq. domain)'});

    XLSSavewindow()
    [WriteXLSFile, WriteXLSFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Processed Data\',ReadFile(1:end-4),'.xls'],'Save .XLS File');
    WriteXLSPath = strcat(WriteXLSFilePath,WriteXLSFile);
    writetable(T,WriteXLSPath);

    % Figures Save
    FigureSavewindow()
    [WriteFigureFile, WriteFigureFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Figures\',ReadFile(1:end-4),'.png'],'Save Figure as .PNG');

    WriteFigurePath = strcat(WriteFigureFilePath,"Filtered ", WriteFigureFile);
    saveas(FiltFig,WriteFigurePath)

```

```

writeFigurePath = strcat(writeFigureFilePath,"Filtered Annotated ", writeFigureFile);
saveas(AnnotFiltFig,writeFigurePath)

writeFigurePath = strcat(writeFigureFilePath,"CH.0 FFT ", writeFigureFile);
saveas(CH0FFTFig,writeFigurePath)

writeFigurePath = strcat(writeFigureFilePath,"CH.7 FFT ", writeFigureFile);
saveas(CH7FFTFig,writeFigurePath)

% Calculations Save
MATSaveWindow()
[writeMATFile, writeMATFilePath] = uiputfile(['C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Calculations\'],ReadFile(1:end-4),'.mat'],'Save .MAT File');
writeMATPath = strcat(writeMATFilePath,writeMATFile);
save(writeMATPath,'CH0_EE', 'CH0_Impulse', 'CH0BlastStart', 'CH0DirectDeriv',
'CH0LowPassStart', 'CH0LowPassStop', 'CH0NumericDerivImpulseAve', 'CH0P2N', 'CH0Peak',
'CH0PeakIndex', 'CH0Trough', 'CH0TroughIndex', 'CH7_EE', 'CH7_Impulse', 'CH7BlastStart',
'CH7DirectDeriv', 'CH7LowPassStart', 'CH7LowPassStop', 'CH7NumericDerivImpulseAve', 'CH7P2N',
'CH7Peak', 'CH7PeakIndex', 'CH7Trough', 'CH7TroughIndex', 'ReadFile', 'ReadFilePath', 'ReadPath'
);

    end
close all
case 'Close'

end

```

Save Window Prompts

```

function XLSSaveWindow

CSVDialog = dialog('Position',[500 500 250 150],'Name','Save .xls');

uicontrol('Parent',CSVDialog,...
    'Style','text',...
    'Position',[20 80 210 40],...
    'String','You will now specify the file location for the .xls file...');

uicontrol('Parent',CSVDialog,...
    'Position',[85 20 70 25],...
    'String','OK',...
    'Callback','delete(gcf)');
waitfor(CSVDialog)
end

function FigureSaveWindow

```

```

FigureDialog = dialog('Position',[500 500 250 150],'Name','Save Figures');

uicontrol('Parent',FigureDialog,...
    'Style','text',...
    'Position',[20 80 210 40],...
    'String','You will now specify the file location for the figure files...');

uicontrol('Parent',FigureDialog,...
    'Position',[85 20 70 25],...
    'String','OK',...
    'Callback','delete(gcf)');
waitfor(FigureDialog)
end

function MATSavewindow

    FigureDialog = dialog('Position',[500 500 250 150],'Name','Save Calculations to .MAT File');

    uicontrol('Parent',FigureDialog,...
        'Style','text',...
        'Position',[20 80 210 40],...
        'String','You will now specify the file location for the .MAT file...');

    uicontrol('Parent',FigureDialog,...
        'Position',[85 20 70 25],...
        'String','OK',...
        'Callback','delete(gcf)');
    waitfor(FigureDialog)
end

```

RACS RESEARCH - DATA COMPILATION SCRIPT 02/10/2021

```
%{
    The purpose of this script is to take the processed data/calculations,
    test layout information, and additional field data/notes from an
    explosive device test and tabulate the results into a master list for
    later processing and graphing.
%}

close all
all_fig = findall(0, 'type', 'figure');
close(all_fig)
clear;
clc
```

Select and Plot Test Layout

```
uiwait(helpdlg('Please Select Desired Test Layout File (.xls)','Select Layout File'));
while 1
    close all
    [CHOMicLocations,CH7MicLocations,TestLayout,FileName] = ImportTestLayout;
    ANSWR = questdlg('Is this testing configuration correct?', 'Confirm Configuration','Yes','No
- Reselect','Yes');
    switch ANSWR
        case ''

            case 'Yes'
                break
            case 'No - Reselect'

    end
end
```

Open Master Spreadsheet for Data Appending

```
uiwait(helpdlg('Now Select the Master Spreadsheet for Appending Testing Data (.xls)','Select
Master Spreadsheet File'));
[MS, MSPath] = uigetfile('C:\Users\brand\Box\School\Grad School\Research\Data\ *.xlsx','Select
Master Spreadsheet File');
FullMSPath = strcat(MSPath,MS);
MasterTable = readtable(FullMSPath,'PreserveVariableNames',1);
OriginalTable = MasterTable;

uiwait(helpdlg('You Will Now Select the Data/Calculations File (.mat) for Each DAQ in the Testing
Sequence','Select Data Files'));
```

Loop through each DAQ and each test to select and add .mat files to Master Spreadsheet

```

for TestNum = 1:size(TestLayout,1)
    DAQCounter = 0;
    for DAQNum = 2:4:size(TestLayout,2)

        DAQCounter = DAQCounter + 1;

        % Highlight Current DAQ/Mics in Plots
        figure(TestNum)
        hold on
        P0 = text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{ '
<===','Color',[0.9294    0.6941
0.1255],'FontWeight','bold','FontSize',16,'VerticalAlignment','middle','HorizontalAlignment','left'
t');
        P7 = text(deg2rad(TestLayout{TestNum,DAQNum+2}),TestLayout{TestNum,DAQNum+3},{ '
<===','Color',[0.9294    0.6941
0.1255],'FontWeight','bold','FontSize',16,'VerticalAlignment','middle','HorizontalAlignment','left'
t');

        figure(size(TestLayout,1)+1)
        hold on
        S0 = text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{ '
<===','Color',[0.9294    0.6941
0.1255],'FontWeight','bold','FontSize',16,'VerticalAlignment','middle','HorizontalAlignment','left'
t');
        S7 = text(deg2rad(TestLayout{TestNum,DAQNum+2}),TestLayout{TestNum,DAQNum+3},{ '
<===','Color',[0.9294    0.6941
0.1255],'FontWeight','bold','FontSize',16,'VerticalAlignment','middle','HorizontalAlignment','left'
t');

        % Current DAQ and Test Message
        SetTestName = cell2mat(TestLayout{TestNum,1});
        opts.Interpreter = 'tex';
        opts.Default = 'Select File';

        % Tell User to Select File or Skip Entry
        ANSWR = questdlg({'\fontsize{10}          Select the .mat Data File for: ','
';['\fontsize{14}\bf          ',TestLayout.Properties.VariableNames{DAQNum}(1:5), ' in ',
SetTestName,'\fontsize{10}\rm'];' ';['e.g. "',TestLayout.Properties.VariableNames{DAQNum}(1:5),'
..... .mat" in ',FileName(1:7),'.',SetTestName(5),'.',SetTestName(end),' ']], 'Select or
Skip?','Select File','Skip',opts);
        switch ANSWR
            case 'Select File'
                SkipFlag = 0;
                % Select .mat File for Active DAQ and Test for Data Appending
                [MATFile, MATPath] = uigetfile('C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Calculations\ *.mat','Select Correct Data File');
                FullMATPath = strcat(MATPath,MATFile);

```

```

case 'skip'
    SkipFlag = 1;
    AddCH0Flag = -1;
    OverwriteCH0Flag = -1;
    SkipCH0Flag = 1;

    AddCH7Flag = -1;
    OverwriteCH7Flag = -1;
    SkipCH7Flag = 1;
end

```

Start loop to allow for reselecting .mat file if incorrect selection was made or if errors

occur

```

while 1

% Do not add data if skip flag is enabled
if SkipFlag == 1
    break
end

%Verification Flags
NonMatchFlag = 0;

AddCH0Flag = 0;
OverwriteCH0Flag = 0;
SkipCH0Flag = 0;

AddCH7Flag = 0;
OverwriteCH7Flag = 0;
SkipCH7Flag = 0;

```

Verify Selected .mat File Name and Path Corresponds to Current DAQ and Test

```

if TestLayout.Properties.VariableNames{DAQNum}(5) ~= MATFile(5)
    uiwait(warndlg({'    DAQ Names Do Not Match';' ';['\fontsize{14}\bfExpected DAQ:
',TestLayout.Properties.VariableNames{DAQNum}(5),'\fontsize{10}'];['\fontsize{14}Selected DAQ:
',MATFile(5)]}, 'Incorrect Selection?',opts));
    NonMatchFlag = 1;
end
if FileName(1) ~= MATPath(end-13)
    uiwait(warndlg({'    Phase #s Do Not Match';' ';['\fontsize{14}\bfExpected Phase:
',FileName(1),'\fontsize{10}'];['\fontsize{14}Selected Phase: ',MATPath(end-13)]}, 'Incorrect
Selection?',opts));
    NonMatchFlag = 1;
end

```



```

        if FileName(3:7) ~= MATPath((end-10):(end-6))
            uiwait(warndlg({' RACS-Identifiers Do Not Match'; ' '};['\fontsize{14}\bfExpected
RAC: ',FileName(3:7),'\fontsize{10}'];['\fontsize{14}Selected RAC: ',MATPath((end-10):(end-
6))]],'Incorrect Selection?',opts));
            NonMatchFlag = 1;
        end
        if SetTestName(5) ~= MATPath(end-3)
            uiwait(warndlg({' Set #s Do Not Match'; ' '};['\fontsize{14}\bfExpected Set:
',SetTestName(5),'\fontsize{10}'];['\fontsize{14}Selected Set: ',MATPath(end-4)]],'Incorrect
Selection?',opts));
            NonMatchFlag = 1;
        end
        if SetTestName(end) ~= MATPath(end-1)
            uiwait(warndlg({' Test #s Do Not Match'; ' '};['\fontsize{14}\bfExpected Test:
',SetTestName(end),'\fontsize{10}'];['\fontsize{14}Selected Set: ',MATPath(end-1)]],'Incorrect
Selection?',opts));
            NonMatchFlag = 1;
        end
        if NonMatchFlag == 1
            ANSWR = questdlg('Are you sure you selected the correct .mat File?', 'Confirm
File','Yes','No - Reselect','Yes');
            switch ANSWR
                case ''
                    % If User is sure the file is correct, continue to next verification
                case 'Yes'
                    % Select .mat File for Active DAQ and Test for Data Appending
                    [MATFile, MATPath] = uigetfile('C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Calculations\ *.mat','Select Correct Data File');
                    FullMATPath = strcat(MATPath,MATFile);
                case 'No - Reselect'
            end
        end
    end
end

```

Once File Name and Path Has Been Verified, Verify Desire to Add Data to Master

Spreadsheet

```

        ANSWR = questdlg(['Add ...\ ',FullMATPath(end-51:end)];'To Master Spreadsheet
for:':[TestLayout.Properties.VariableNames{DAQNum}(1:5), ' in ', SetTestName]], 'Add
Data?','Yes','No - Reselect','Yes');
        switch ANSWR
            case ''
                % Open .mat File for Active DAQ and Test for Data Appending
                [MATFile, MATPath] = uigetfile('C:\Users\brand\Box\School\Grad
School\Research\Data\Processed MATLAB Calculations\ *.mat','Select Correct Data File');
            case 'No - Reselect'
        end
    end
end

```

```

FullMATPath = strcat(MATPath,MATFile);

case 'Yes'

% Load .mat File
load(FullMATPath)

% Build New Ch.0 and Ch.7 Rows to Append to Master Spreadsheet
AppendingTable = [];

AppendingTable =
{str2double(FileName(1)),(FileName(3:7)),str2double(SetTestName(5)),str2double(SetTestName(end)),
(ReadFile(8:17)),(ReadFile(21:28)),(MATFile(5)),0,CH0MicLocations(1,DAQCounter,TestNum),CH0MicLocations(2,DAQCounter,TestNum),CH0Peak,CH0Trough,CH0NumericDerivImpulseAve,CH0DirectDeriv,CH0_EE,CH0_Impulse,CH0LowPassStart,CH0LowPassStop,CH0BlastStart,CH0PeakIndex,CH0P2N,CH0TroughIndex,'None'}
;

AppendingTable = [AppendingTable;
{str2double(FileName(1)),(FileName(3:7)),str2double(SetTestName(5)),str2double(SetTestName(end)),
(ReadFile(8:17)),(ReadFile(21:28)),(MATFile(5)),7,CH7MicLocations(1,DAQCounter,TestNum),CH7MicLocations(2,DAQCounter,TestNum),CH7Peak,CH7Trough,CH7NumericDerivImpulseAve,CH7DirectDeriv,CH7_EE,CH7_Impulse,CH7LowPassStart,CH7LowPassStop,CH7BlastStart,CH7PeakIndex,CH7P2N,CH7TroughIndex,'None'}
];

```

Verify Channel 0 and Channel 7 were not Inadvertantly Swapped During Testing

```

if CH7PeakIndex <= CH0PeakIndex
    ANSWR = questdlg('It appears that the the Channel 0 and Channel 7 Microphones may have accidentally been swapped during testing since the Ch.7 peak occurred before Ch.0. What would you like to do?', 'Channels Swapped!!!','Fix Before Saving','Nothing - Continue','Fix Before Saving');
    switch ANSWR
        case ''
            case 'Fix Before Saving'
                AppendingTable([1,2],11:end) = AppendingTable([2,1],11:end);
                AppendingTable{1,end} = 'Channels 0 & 7 were swapped during testing. Repaired During Processing.';
                AppendingTable{2,end} = 'Channels 0 & 7 were swapped during testing. Repaired During Processing.';
            case 'Nothing - Continue'
                AppendingTable{1,end} = 'Channels 0 & 7 may have been swapped during testing. Review Carefully!';
                AppendingTable{2,end} = 'Channels 0 & 7 may have been swapped during testing. Review Carefully!';
            end
        end

clearvars    ReadFile ReadFilePath ReadPath ...

```

```

CH0FFTfig CH0Filt CH0Peak CH0Trough CH0_EE CH0_Impulse
CH0BlastStart CH0PeakIndex CH0P2N CH0TroughIndex CH0Deriv I_CH0P I_CH0P2 CH0DirectDeriv
CH0NumericDerivImpulseAve CH0LowPassStart CH0LowPassStop FCH0 FCH0Filt ...
CH7FFTfig CH7Filt CH7Peak CH7Trough CH7_EE CH7_Impulse
CH7BlastStart CH7PeakIndex CH7P2N CH7TroughIndex CH7Deriv I_CH7P I_CH7P2 CH7DirectDeriv
CH7NumericDerivImpulseAve CH7LowPassStart CH7LowPassStop FCH7 FCH7Filt

```

Verify Data is not already in Master Spreadsheet (Same Phase #, Device Name, Set #, Test #, DAQ Name,& Channel #)

```

CH0Duplicates = [];
CH7Duplicates = [];
for a = 1:size(MasterTable,1)
    % Checks if new Ch.0 data has the same: Phase Device Set Test DAQ Channel
#
    if MasterTable{a,1} == str2double(FileName(1)) &&
convertCharstoStrings(MasterTable{a,2}) == convertCharstoStrings(FileName(3:7)) &&
MasterTable{a,3} == str2double(SetTestName(5)) && MasterTable{a,4} ==
str2double(SetTestName(end)) && convertCharstoStrings(MasterTable{a,7}) ==
convertCharstoStrings(MATFile(5)) && MasterTable{a,8} == 0
        CH0Duplicates = [CH0Duplicates a];
    end
    % Checks if new Ch.7 data has the same: Phase Device Set Test DAQ Channel
#
    if MasterTable{a,1} == str2double(FileName(1)) &&
convertCharstoStrings(MasterTable{a,2}) == convertCharstoStrings(FileName(3:7)) &&
MasterTable{a,3} == str2double(SetTestName(5)) && MasterTable{a,4} ==
str2double(SetTestName(end)) && convertCharstoStrings(MasterTable{a,7}) ==
convertCharstoStrings(MATFile(5)) && MasterTable{a,8} == 7
        CH7Duplicates = [CH7Duplicates a];
    end
end

% Handle Duplicate Ch.0 Data
if isempty(CH0Duplicates) == 0
    uiwait(helpdlg('It appears that the Channel 0 data may already be in the
Master Spreadsheet. Please Review Duplicate Data (Yellow) by Pressing OK.','Duplicate Data?'));
    CH0DuplicateIndices = zeros(length(CH0Duplicates),size(MasterTable,2));
    for a = 1:length(CH0Duplicates)
        for b = 1:size(MasterTable,2)
            CH0DuplicateIndices(a,b) =
isequal(AppendingTable{1,b},MasterTable{CH0Duplicates(a),b});
        end
        if
isequal(AppendingTable{1,2},cell2mat(MasterTable{CH0Duplicates(a),2}))
            CH0DuplicateIndices(a,2) = 1;
        end
    end
end

```

```

        if
isequal(AppendingTable{1,5},cell2mat(MasterTable{CH0Duplicates(a),5}))
            CH0DuplicateIndices(a,5) = 1;
        end
        if
isequal(AppendingTable{1,6},cell2mat(MasterTable{CH0Duplicates(a),6}))
            CH0DuplicateIndices(a,6) = 1;
        end
        if
isequal(AppendingTable{1,7},cell2mat(MasterTable{CH0Duplicates(a),7}))
            CH0DuplicateIndices(a,7) = 1;
        end
        if
isequal(AppendingTable{1,end},cell2mat(MasterTable{CH0Duplicates(a),end}))
            CH0DuplicateIndices(a,end) = 1;
        end
    end

    [row,col] = find(CH0DuplicateIndices);
    if size(CH0DuplicateIndices,1) == 1
        CH0HighlightIndices = [row,col];
    else
        CH0HighlightIndices = [row,col];
    end
    s = uistyle('BackgroundColor','yellow','Fontweight','bold');

    CH0DuplicateFig = uifigure(1,'Name','Duplicate(s) of Ch. 0 Data');
    clf(CH0DuplicateFig);
    Tablewidth = 1500;
    TableHeight = (length(CH0Duplicates)+1.5)*25;
    Columnwidth = 'auto';%(Tablewidth-150)/23;
    Buttonwidth = 300;
    ButtonHeight = 25;

    set(CH0DuplicateFig,'Position',[10,50,Tablewidth+10,(TableHeight*2.25)+65])
    ExistingDataPanel = uipanel(CH0DuplicateFig,'Title','Existing Data in
Master Spreadsheet (Duplicate Values Highlighted in
Yellow):','Fontweight','bold','FontSize',12,'BackgroundColor',[0.9290 0.6940
0.1250],'Position',[0,(TableHeight*1.25) + 35,Tablewidth+10,(TableHeight)+30]);
    CH0DuplicateFigTable = uitable(CH0DuplicateFig,'RowName',{'Data in
Spreadsheet:','Columnwidth',{Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnw
idth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth},'Data',MasterTable(CH0Duplicates(:),:));
    CH0DuplicateFigTable.Position = [5,(TableHeight*1.25) +
45,Tablewidth,(TableHeight)];
    CH0DuplicateFigTable.FontSize = 10;
    addStyle(CH0DuplicateFigTable,s,'cell',CH0HighlightIndices);
    NewDataPanel = uipanel(CH0DuplicateFig,'Title','Data to be Added to
Master Spreadsheet:', 'Fontweight','bold','FontSize',12,'BackgroundColor',[0.3010 0.7450

```

```

0.9330], 'Position', [0,5,Tablewidth+10,(TableHeight)+30]);
    CH0ImportTable = uitable(CH0DuplicateFig,'RowName',{'Data to be Imported:
'}, 'Columnwidth', {Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnw
idth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwid
th,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwid
th}, 'ColumnName', MasterTable.Properties.VariableNames, 'Data', AppendingTable(1,:));
    CH0ImportTable.Position = [5,15,Tablewidth,(TableHeight)];
    CH0ImportTable.FontSize = 10;
    AddButton = uibutton(CH0DuplicateFig,'Text','Add Data to Spreadsheet as
New Entry','ButtonPushedFcn','AddCH0Flag =
1;;uiresume(CH0DuplicateFig)','Position',[((Tablewidth/2)-(Buttonwidth*2)) ((TableHeight) + 35)
Buttonwidth ButtonHeight]);
    OverwriteButton = uibutton(CH0DuplicateFig,'Text','Overwrite Existing
Data','ButtonPushedFcn','OverwriteCH0Flag =
1;;uiresume(CH0DuplicateFig);','Position',[((Tablewidth/2)-(Buttonwidth/2)) ((TableHeight) + 35)
Buttonwidth ButtonHeight]);
    NothingButton = uibutton(CH0DuplicateFig,'Text','Do Not Add Data to
Spreadsheet','ButtonPushedFcn','SkipCH0Flag =
1;;uiresume(CH0DuplicateFig);','Position',[((Tablewidth/2)+(Buttonwidth)) ((TableHeight) + 35)
Buttonwidth ButtonHeight]);
    uiwait(CH0DuplicateFig)

    close(CH0DuplicateFig);
end

% Handle Duplicate Ch.7 Data
if isempty(CH7Duplications) == 0
    uiwait(helpdlg('It appears that the Channel 7 data may already be in the
Master Spreadsheet. Please Review Duplicate Data (Yellow) by Pressing OK.','Duplicate Data?'));
    CH7DuplicateIndices = zeros(length(CH7Duplications),size(MasterTable,2));
    for a = 1:length(CH7Duplications)
        for b = 1:size(MasterTable,2)
            CH7DuplicateIndices(a,b) =
isequal(AppendingTable{2,b},MasterTable{CH7Duplications(a),b});
        end
    end
    if
isequal(AppendingTable{2,2},cell2mat(MasterTable{CH7Duplications(a),2}))
        CH7DuplicateIndices(a,2) = 1;
    end
    if
isequal(AppendingTable{2,5},cell2mat(MasterTable{CH7Duplications(a),5}))
        CH7DuplicateIndices(a,5) = 1;
    end
    if
isequal(AppendingTable{2,6},cell2mat(MasterTable{CH7Duplications(a),6}))
        CH7DuplicateIndices(a,6) = 1;
    end
    if
isequal(AppendingTable{2,7},cell2mat(MasterTable{CH7Duplications(a),7}))
        CH7DuplicateIndices(a,7) = 1;
    end
end

```

```

        end
        if
isequal(AppendingTable{2,end},cell2mat(MasterTable{CH7Duplicates(a),end}))
            CH7DuplicateIndices(a,end) = 1;
        end
    end

    [row,col] = find(CH7DuplicateIndices);
    if size(CH7DuplicateIndices,1) == 1
        CH7HighlightIndices = [row,col];
    else
        CH7HighlightIndices = [row,col];
    end
    s = uistyle('BackgroundColor','yellow','Fontweight','bold');

    CH7DuplicateFig = uifigure(1,'Name','Duplicate(s) of Ch. 7 Data');
    clf(CH7DuplicateFig);
    Tablewidth = 1500;
    TableHeight = (length(CH7Duplicates)+1.5)*25;
    Columnwidth = 'auto';%(Tablewidth-150)/23;
    Buttonwidth = 300;
    ButtonHeight = 25;

    set(CH7DuplicateFig,'Position',[10,50,Tablewidth+10,(TableHeight*2.25)+65])
    ExistingDataPanel = uipanel(CH7DuplicateFig,'Title','Existing Data in
Master Spreadsheet (Duplicate Values Highlighted in
Yellow):','Fontweight','bold','FontSize',12,'BackgroundColor',[0.9290 0.6940
0.1250],'Position',[0,(TableHeight*1.25) + 35,Tablewidth+10,(TableHeight)+30]);
    CH7DuplicateFigTable = uitable(CH7DuplicateFig,'RowName',{'Data in
Spreadsheet:','Columnwidth',{Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnw
idth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth},'Data',MasterTable(CH7Duplicates(:),:));
    CH7DuplicateFigTable.Position = [5,(TableHeight*1.25) +
45,Tablewidth,(TableHeight)];
    CH7DuplicateFigTable.FontSize = 10;
    addStyle(CH7DuplicateFigTable,s,'cell',CH7HighlightIndices);
    NewDataPanel = uipanel(CH7DuplicateFig,'Title','Data to be Added to
Master Spreadsheet:','Fontweight','bold','FontSize',12,'BackgroundColor',[0.3010 0.7450
0.9330],'Position',[0,5,Tablewidth+10,(TableHeight)+30]);
    CH7ImportTable = uitable(CH7DuplicateFig,'RowName',{'Data to be Imported:
','Columnwidth',{Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnw
idth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth},'ColumnName',MasterTable.Properties.VariableNames,'Data',AppendingTable(2,:));
    CH7ImportTable.Position = [5,15,Tablewidth,(TableHeight)];
    CH7ImportTable.FontSize = 10;
    AddButton = uibutton(CH7DuplicateFig,'Text','Add Data to Spreadsheet as
New Entry','ButtonPushedFcn','AddCH7Flag =
1;;uiresume(CH7DuplicateFig)','Position',[((Tablewidth/2)-(Buttonwidth*2)) ((TableHeight) + 35)

```

```

Buttonwidth ButtonHeight]);
    OverwriteButton = uibutton(CH7DuplicateFig,'Text','Overwrite Existing
Data','ButtonPushedFcn','OverwriteCH7Flag =
1;uiresume(CH7DuplicateFig);','Position',[((Tablewidth/2)-(Buttonwidth/2)) ((TableHeight) + 35)
Buttonwidth ButtonHeight]);
    NothingButton = uibutton(CH7DuplicateFig,'Text','Do Not Add Data to
Spreadsheet','ButtonPushedFcn','SkipCH7Flag =
1;uiresume(CH7DuplicateFig);','Position',[((Tablewidth/2)+(Buttonwidth)) ((TableHeight) + 35)
Buttonwidth ButtonHeight]);
    uiwait(CH7DuplicateFig)

    close(CH7DuplicateFig);
end

```

Once all verifications are complete, break from While loop to actually add data to spreadsheet

```

break
end
end

```

Actually Add/Overwrite/Skip and Save New Spreadsheet

```

% Add/Overwrite/Skip Channel 0 Data
if AddCH0Flag == 1 || (AddCH0Flag+OverwriteCH0Flag+SkipCH0Flag) == 0
    MasterTable = [MasterTable;AppendingTable(1,:)];

    % Cross-off new entries in plots
    figure(TestNum)
    hold on
    set(P0,'visible','off')
    P0 = text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{'\surd';'
'},'Color',[0.4667 0.6745
0.1882],'FontWeight','bold','FontSize',20,'VerticalAlignment','middle','HorizontalAlignment','cen
ter');

    figure(size(TestLayout,1)+1)
    hold on
    set(S0,'visible','off')
    S0 = text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{'\surd';'
'},'Color',[0.4667 0.6745
0.1882],'FontWeight','bold','FontSize',20,'VerticalAlignment','middle','HorizontalAlignment','cen
ter');

```

```

elseif OverwriteCH0Flag == 1
    if length(CH0Duplications) == 1
        MasterTable(CH0Duplications(1,1),:) = AppendingTable(1,:);
    else
        uiwait(helpdlg('There are Multiple Duplicates of Ch.0 in the Master Spreadsheet.
Please Select Existing Entry (or Entries) to Delete from Master Spreadsheet and replace with a
Single Entry of New Data'));

        CH0DuplicateFig = uifigure(1,'Name','Duplicate(s) of Ch. 0 Data');
        clf(CH0DuplicateFig);
        Tablewidth = 1500;
        TableHeight = (length(CH0Duplications)+1.5)*25;
        Buttonwidth = 300;
        ButtonHeight = 25;
        Columnwidth = 'auto';%(Tablewidth-150)/23;

        set(CH0DuplicateFig,'Position',[10,(TableHeight*6),Tablewidth+10,(TableHeight*2.25)+65])
        ExistingDataPanel = uipanel(CH0DuplicateFig,'Title','Existing Data in Master
Spreadsheet (Duplicate values Highlighted in
Yellow):','FontWeight','bold','FontSize',12,'BackgroundColor',[0.9290 0.6940
0.1250],'Position',[0,(TableHeight*1.25) + 35,Tablewidth+10,(TableHeight)+30]);
        IsEditable=[true false(1,23)];
        CH0DuplicateFigTable = uitable(CH0DuplicateFig,'RowName',{'Data in
Spreadsheet:','ColumnName',[ 'Select Rows to Remove' }
MasterTable.Properties.VariableNames'],'ColumnEditable',IsEditable,'Columnwidth',{Columnwidth,Colu
mnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Column
width,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth},'Data',[num2cell(false(length(
CH0Duplications),1)) MasterTable(CH0Duplications(:,:))]);
        CH0DuplicateFigTable.Position = [5,(TableHeight*1.25) +
45,Tablewidth,(TableHeight)];
        CH0DuplicateFigTable.FontSize = 10;
        CH0HighlightIndices(:,2) = CH0HighlightIndices(:,2) + 1;
        addStyle(CH0DuplicateFigTable,s,'cell',CH0HighlightIndices);
        NewDataPanel = uipanel(CH0DuplicateFig,'Title','Data to be Added to Master
Spreadsheet:','FontWeight','bold','FontSize',12,'BackgroundColor',[0.3010 0.7450
0.9330],'Position',[0,5,Tablewidth+10,(TableHeight)+30]);
        CH0ImportTable = uitable(CH0DuplicateFig,'RowName',{'Data to be Imported:
'},'Columnwidth',{Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnw
idth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwidth,Columnwi
dth},'ColumnName',MasterTable.Properties.VariableNames,'Data',AppendingTable(1,:));
        CH0ImportTable.Position = [5,15,Tablewidth,(TableHeight)];
        CH0ImportTable.FontSize = 10;
        DelCH0Button = uibutton(CH0DuplicateFig,'Text','Delete Selected
Entries','ButtonPushedFcn','uiresume(CH0DuplicateFig)','Position',[((Tablewidth/2)-
(Buttonwidth/2)) ((TableHeight) + 35) Buttonwidth ButtonHeight]);
        uiwait(CH0DuplicateFig)

        CH0DeleteSelections = get(CH0DuplicateFigTable,'data');

```



```

        MasterTable(find(CH0DeleteSelections{:,1}),:) = AppendingTable(1,:);
        close(CH0DuplicateFig);

    end

    % Cross-off new entries in plots
    figure(TestNum)
    hold on
    set(P0,'Visible','off')
    P0 = text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{'\surd';'
'},'Color',[0.4667    0.6745
0.1882],'FontWeight','bold','FontSize',20,'VerticalAlignment','middle','HorizontalAlignment','center');

    figure(size(TestLayout,1)+1)
    hold on
    set(S0,'Visible','off')
    S0 = text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{'\surd';'
'},'Color',[0.4667    0.6745
0.1882],'FontWeight','bold','FontSize',20,'VerticalAlignment','middle','HorizontalAlignment','center');

elseif skipCH0Flag == 1
    % Cross-off skipped entries in plots
    figure(TestNum)
    hold on
    set(P0,'Visible','off')
    P0 =
text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{'X'},'Color',[1    0
0],'FontWeight','bold','FontSize',16,'VerticalAlignment','middle','HorizontalAlignment','center')
;

    figure(size(TestLayout,1)+1)
    hold on
    set(S0,'Visible','off')
    S0 =
text(deg2rad(TestLayout{TestNum,DAQNum}),TestLayout{TestNum,DAQNum+1},{'X'},'Color',[1    0
0],'FontWeight','bold','FontSize',16,'VerticalAlignment','middle','HorizontalAlignment','center')
;

end

% Add/Overwrite/Skip Channel 7 Data
if AddCH7Flag == 1 || (AddCH7Flag+OverwriteCH7Flag+skipCH7Flag) == 0
    MasterTable = [MasterTable;AppendingTable(2,:)];

    % Cross-off new entries in plots
    figure(TestNum)
    hold on
    set(P7,'Visible','off')

```

```

P7 =
text(deg2rad(TestLayout{TestNum,DAQNum+2}),TestLayout{TestNum,DAQNum+3},{'\surd';'
'}, 'Color',[0.4667 0.6745
0.1882], 'FontWeight', 'bold', 'FontSize',20, 'VerticalAlignment', 'middle', 'HorizontalAlignment', 'center');

figure(size(TestLayout,1)+1)
hold on
set(S7, 'Visible', 'off')
S7 =
text(deg2rad(TestLayout{TestNum,DAQNum+2}),TestLayout{TestNum,DAQNum+3},{'\surd';'
'}, 'Color',[0.4667 0.6745
0.1882], 'FontWeight', 'bold', 'FontSize',20, 'VerticalAlignment', 'middle', 'HorizontalAlignment', 'center');

elseif OverwriteCH7Flag == 1
if length(CH7Duplicates) == 1
MasterTable(CH7Duplicates(1,1),:) = AppendingTable(2,:);
else
uiwait(helpdlg('There are Multiple Duplicates of Ch.7 in the Master Spreadsheet.
Please Select Existing Entry (or Entries) to Delete from Master Spreadsheet and replace with a
Single Entry of New Data')));

CH7DuplicateFig = uifigure(1,'Name','Duplicate(s) of Ch. 7 Data');
clf(CH7DuplicateFig);
Tablewidth = 1500;
TableHeight = (length(CH7Duplicates)+1.5)*25;
Buttonwidth = 300;
ButtonHeight = 25;
Columnwidth = 'auto';%(Tablewidth-150)/23;

set(CH7DuplicateFig, 'Position', [10, (TableHeight*6), Tablewidth+10, (TableHeight*2.25)+65])
ExistingDataPanel = uipanel(CH7DuplicateFig, 'Title', 'Existing Data in Master
Spreadsheet (Duplicate Values Highlighted in
Yellow):', 'FontWeight', 'bold', 'FontSize', 12, 'BackgroundColor', [0.9290 0.6940
0.1250], 'Position', [0, (TableHeight*1.25) + 35, Tablewidth+10, (TableHeight)+30]);
IsEditable=[true false(1,23)];
CH7DuplicateFigTable = uitable(CH7DuplicateFig, 'RowName', {'Data in
Spreadsheet:'}, 'ColumnName', [{'Select Rows to Remove'}
MasterTable.Properties.VariableNames], 'ColumnEditable', IsEditable, 'ColumnWidth', {Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth}, 'Data', [num2cell(false(length(CH7Duplicates),1)) MasterTable(CH7Duplicates(:),:)]);
CH7DuplicateFigTable.Position = [5, (TableHeight*1.25) +
45, Tablewidth, (TableHeight)];
CH7DuplicateFigTable.FontSize = 10;
CH7HighlightIndices(:,2) = CH7HighlightIndices(:,2) + 1;
addStyle(CH7DuplicateFigTable, s, 'cell', CH7HighlightIndices);
NewDataPanel = uipanel(CH7DuplicateFig, 'Title', 'Data to be Added to Master

```

```

Spreadsheet:', 'FontWeight', 'bold', 'FontSize', 12, 'BackgroundColor', [0.3010 0.7450
0.9330], 'Position', [0, 5, Tablewidth+10, (TableHeight)+30]);
    CH7ImportTable = uitable(CH7DuplicateFig, 'RowName', {'Data to be Imported:
'}, 'ColumnWidth', {Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth, Columnwidth}, 'ColumnName', MasterTable.Properties.VariableNames, 'Data', AppendingTable(2,:));
    CH7ImportTable.Position = [5, 15, Tablewidth, (TableHeight)];
    CH7ImportTable.FontSize = 10;
    DelCH7Button = uibutton(CH7DuplicateFig, 'Text', 'Delete Selected
Entries', 'ButtonPushedFcn', 'uiresume(CH7DuplicateFig)', 'Position', [((Tablewidth/2)-(
(Buttonwidth/2))) ((TableHeight) + 35) Buttonwidth ButtonHeight]);
    uiwait(CH7DuplicateFig)

    CH7DeleteSelections = get(CH7DuplicateFigTable, 'data');
    MasterTable(find(CH7DeleteSelections{:,1}), :) = [];
    close(CH7DuplicateFig);
    MasterTable = [MasterTable; AppendingTable(2,:)];

end

% Cross-off new entries in plots
figure(TestNum)
hold on
set(P7, 'Visible', 'off')
P7 =
text(deg2rad(TestLayout{TestNum, DAQNum+2}), TestLayout{TestNum, DAQNum+3}, {'\surd'; '
'}, 'Color', [0.4667 0.6745
0.1882], 'FontWeight', 'bold', 'FontSize', 20, 'VerticalAlignment', 'middle', 'HorizontalAlignment', 'center');

figure(size(TestLayout, 1)+1)
hold on
set(S7, 'Visible', 'off')
S7 =
text(deg2rad(TestLayout{TestNum, DAQNum+2}), TestLayout{TestNum, DAQNum+3}, {'\surd'; '
'}, 'Color', [0.4667 0.6745
0.1882], 'FontWeight', 'bold', 'FontSize', 20, 'VerticalAlignment', 'middle', 'HorizontalAlignment', 'center');

elseif skipCH7Flag == 1
    % Cross-off skipped entries in plots
    figure(TestNum)
    hold on
    set(P7, 'Visible', 'off')
    P7 =
text(deg2rad(TestLayout{TestNum, DAQNum+2}), TestLayout{TestNum, DAQNum+3}, {'X'}, 'Color', [1 0
0], 'FontWeight', 'bold', 'FontSize', 16, 'VerticalAlignment', 'middle', 'HorizontalAlignment', 'center')
;

```

```

        figure(size(TestLayout,1)+1)
        hold on
        set(S7,'Visible','off')
        S7 =
text(deg2rad(TestLayout{TestNum,DAQNum+2}),TestLayout{TestNum,DAQNum+3},{ 'X'}, 'Color',[1      0
0], 'FontWeight','bold', 'FontSize',16, 'VerticalAlignment','middle', 'HorizontalAlignment','center')
;

        end

end
end

```

Review Entries, Add Notes, and Save Updated Master Spreadsheet

```

SaveSuccessfulFlag = 0;

while SaveSuccessfulFlag == 0
    try
        s = uistyle('BackgroundColor',[0.9412      0.8039      0.2627], 'FontWeight','bold');

        ReviewFig = uifigure(2, 'Name', 'Updated Master Spreadsheet');
        clf(ReviewFig);
        ReviewFig.WindowState = 'maximized';
        drawnow
        ButtonWidth = 300;
        ButtonHeight = 25;
        ColumnWidth = 'auto'; % (TableWidth-150)/23;
        IsEditable=[false(1,22) true];
        [NewRows, NewRowIndex] = setdiff(MasterTable,OriginalTable);
        ReviewPanel = uipanel(ReviewFig, 'Title', 'Master Spreadsheet (New Entries
Highlighted)', 'FontWeight','bold', 'FontSize',12, 'BackgroundColor',[0.9020      0.9020
0.9020], 'Position',[0,0,ReviewFig.Position(3),ReviewFig.Position(4)]);
        ReviewFigTable =
uitable(ReviewFig, 'RowName', 'numbered', 'ColumnName', [MasterTable.Properties.VariableNames], 'Column
nEditable', IsEditable, 'ColumnWidth', {ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,
ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth,ColumnWidth}, 'Data', MasterTable);
        addStyle(ReviewFigTable,s, 'row', NewRowIndex);
        ReviewFigPosition = [5 5 ReviewFig.Position(3)-10 ReviewFig.Position(4)-60];
        ReviewFigTable.Position = ReviewFigPosition;
        ReviewFigTable.FontSize = 10;
        SaveButton = uibutton(ReviewFig, 'Text', 'Save New Master
Spreadsheet', 'ButtonPushedFcn', 'uiresume(ReviewFig)', 'Position', [((ReviewFig.Position(3)/2) -
(ButtonWidth/2)) ReviewFig.Position(4)-50 ButtonWidth ButtonHeight]);
        uiwait(helpdlg('Please Review Entries, Add Notes (Far Right Column), and Press Save When
Ready to Upload Data to Master Spreadsheet.'));
        uiwait(ReviewFig)
    end
end

```

```

MasterTable = get(ReviewFigTable,'data');
close(ReviewFig);

% Save
writetable(MasterTable,FullMSPath);
SaveSuccessfulFlag = 1;
catch
    uiwait(warndlg('It seems that the Master Spreadsheet may be open in another application.
Please close Master Spreadsheet and then Press OK.'));
    try
        % Save
        writetable(MasterTable,FullMSPath);
        SaveSuccessfulFlag = 1;
    catch
        continue
    end
end
end
close all

```

Functions

```

function [CH0MicLocations,CH7MicLocations,ImportedLayout,ReadFile] = ImportTestLayout()
% Select File for Processing
[ReadFile, ReadFilePath] = uigetfile('C:\Users\brand\Box\School\Grad School\Research\written
work\Test Plan Spreadsheets\*.xls','Select .xls File for Importing');
ReadPath = strcat(ReadFilePath,ReadFile);
ImportedLayout = readtable(ReadPath,'PreserveVariableNames',1);
TestCount = size(ImportedLayout,1);
DAQCount = (size(ImportedLayout,2)-1)/4;

% Initialize matrix to record angles and distances for each test
CH0MicLocations = zeros(2,DAQCount,TestCount);
CH7MicLocations = zeros(2,DAQCount,TestCount);
%
%           ^      ^      ^
%           |      |      |
%           |      |      ---- 1 "Layer" for each Test
%           |      ---- 1 Column for each DAQ in Test
%           ---- Row 1 = Angles; Row 2 = Radii

for a = 1:TestCount
    for b = 1:DAQCount

        CH0MicLocations(1,b,a) = ImportedLayout{a,(2+(4*(b-1)))}; % Angles
        CH0MicLocations(2,b,a) = ImportedLayout{a,(3+(4*(b-1)))}; % Radii
    end
end

```

```

        CH7MicLocations(1,b,a) = ImportedLayout{a,(4+(4*(b-1)))};           % Angles
        CH7MicLocations(2,b,a) = ImportedLayout{a,(5+(4*(b-1)))};           % Radii

    end

    PlotTestLayout(a,[ReadFile(1:end-4),
    table2cell(ImportedLayout(a,1))],DAQCount,CH0MicLocations(:, :,a),CH7MicLocations(:, :,a),ImportedL
    ayout)
    end
    PlotSummaryLayout(a+1,ReadFile,DAQCount,TestCount,ImportedLayout)
end

function [] =
PlotTestLayout(fig,name,DAQCount,CH0MicLocations,CH7MicLocations,MicLocationSummary)
    % Display Inputted Test Layout
    figure(fig);
    clf(fig);
    set(gcf,'Position',[100+(350*(fig-1)),200,300,600])
    for b = 1:DAQCount
        polarscatter(deg2rad(CH0MicLocations(1,b)),CH0MicLocations(2,b),nan)
        text(deg2rad(CH0MicLocations(1,b)),CH0MicLocations(2,b),[char('A'+b-1)
'0'],'Color','red','FontWeight','bold','FontSize',8,'VerticalAlignment','middle','HorizontalAlign
ment','center');
        hold on
        polarscatter(deg2rad(CH7MicLocations(1,b)),CH7MicLocations(2,b),nan)
        text(deg2rad(CH7MicLocations(1,b)),CH7MicLocations(2,b),[char('A'+b-1)
'7'],'Color','blue','FontWeight','bold','FontSize',8,'VerticalAlignment','middle','HorizontalAlign
ment','center');
    end
    polaraxes = gca;
    polaraxes.ThetaTick = unique(MicLocationSummary{:,2:2:end});
    polaraxes.ThetaZeroLocation = 'bottom';
    polaraxes.FontWeight = 'bold';
    polaraxes.ThetaLim =
[min(unique(MicLocationSummary{:,2:2:end})),max(unique(MicLocationSummary{:,2:2:end})]);
    thetatickformat('degrees')

    UniqueRadii = unique(MicLocationSummary{:,3:2:end});
    polaraxes.RTick = UniqueRadii;
    polaraxes.RAxisLocation = (UniqueRadii(2) - UniqueRadii(1))/ 2;
    polaraxes.GridAlpha = .3;
    polaraxes.RLim = [0, max(UniqueRadii)];
    rtickformat('%g ft')

    polaraxes.FontSize = 8;

    title(name,'FontSize',14);
end

function [] = PlotSummaryLayout(fig,name,DAQCount,TestCount,MicLocationSummary)
    MicCount = DAQCount*2;

```

```

% Display Inputted Test Layout
figure(fig);
clf(fig);
set(gcf,'Position',[100+(350*(fig-1)),200,300,600])
for a = 1:TestCount
    for b = 1:MicCount
        polarscatter(deg2rad(MicLocationSummary{a,(2+(2*(b-
1))))},MicLocationSummary{a,(3+(2*(b-1)))},'m*')
        hold on
        MeasurementCount = length(find(MicLocationSummary{:(2+(2*(b-1)))} ==
MicLocationSummary{a,(2+(2*(b-1)))} & MicLocationSummary{:(3+(2*(b-1)))} ==
MicLocationSummary{a,(3+(2*(b-1)))}));
        text(deg2rad(MicLocationSummary{a,(2+(2*(b-1)))}),MicLocationSummary{a,(3+(2*(b-
1)))},[num2str(MeasurementCount)
'x'],'Color','black','FontWeight','bold','FontSize',8,'VerticalAlignment','middle','HorizontalAli
gnment','right');
    end
end

polaraxes = gca;
polaraxes.ThetaTick = unique(MicLocationSummary{:,2:2:end});
polaraxes.ThetaZeroLocation = 'bottom';
polaraxes.FontWeight = 'bold';
polaraxes.ThetaLim =
[min(unique(MicLocationSummary{:,2:2:end})),max(unique(MicLocationSummary{:,2:2:end}))];
thetatickformat('degrees')

UniqueRadii = unique(MicLocationSummary{:,3:2:end});
polaraxes.RTick = UniqueRadii;
polaraxes.RAxisLocation = (UniqueRadii(2) - UniqueRadii(1))/2;
polaraxes.GridAlpha = .3;
polaraxes.RLim = [0, max(UniqueRadii)];
rtickformat('%g ft')

polaraxes.FontSize = 8;

title([name(3:end-4) ' Summary'],'FontSize',14);
end

```

RACS RESEARCH - DEVICE PROCESSOR/GRAPHER SCRIPT 05/03/2021

```
%{
    The purpose of this script is to take data contained in the Master Spreadsheet
    and produce summarized data, equations, and graphs for a selected device.
%}
```

Initialization

```
close all
all_fig = findall(0, 'type', 'figure');
close(all_fig)
clear;
clc
```

Figure Settings

```
Angleslices = [0,30,45,60,90,120,135,150,180];

SS = get(0,'screensize');
FigNR1 = 4;
FigNR2 = 9;
widthR1 = 550;
widthR2 = 450;
heightR1 = 450;
heightR2 = 350;
xmin = 10;
yminR1 = 5;
yminR2 = SS(4) - heightR2 - 75;
xstepR1 = (SS(3)-widthR1-(2*xmin))/(FigNR1-1);
xstepR2 = (SS(3)-widthR1-(2*xmin))/(FigNR2-1);
IsoView = [125,60];
TopView = [90,90];
CountourLineCount = 15;
PlotCounter = 0;
VOIFlag = 0;
```

User Selects Master Spreadsheet

```
uiwait(helpdlg('Select the Master Spreadsheet File (.xlsx)','Select Master Spreadsheet File'));
[MS, MSPath] = uigetfile('C:\Users\brand\Box\School\Grad School\Research\Data\ *.xlsx','Select
Master Spreadsheet File');
```



```
FullMSPath = strcat(MSPath,MS);
MasterTable = readtable(FullMSPath,'PreserveVariableNames',1);
```

User Selects Desired Device

```
DeviceList = unique(MasterTable{:,2});
[DeviceSelection,DIndx] = listdlg('PromptString',{'Which Device Would You Like to Process?'},'SelectionMode','single','ListString',DeviceList,'ListSize',[500,200]);
SelectedDevice = DeviceList{DeviceSelection};

% Remove all entries that aren't selected device
MasterTable(convertCharsToStrings(MasterTable{:,2}) ~=
convertCharsToStrings(SelectedDevice),:)=[];
```

User Selects Desired Tests

```
DeviceTests =
unique([num2str(MasterTable{:,1}),cell2mat(MasterTable{:,2}),num2str(MasterTable{:,3}),num2str(MasterTable{:,4})], 'rows');
DeviceTests =
string(strcat(DeviceTests(:,1),'.(',DeviceTests(:,2:6),')',DeviceTests(:,7),'.',DeviceTests(:,8)));
[TestSelection,TIndx] = listdlg('PromptString',{'Which Tests Would You Like to Include in the Analysis?'},'SelectionMode','multiple','ListString',DeviceTests,'ListSize',[500,200]);
TestSelections = char(DeviceTests(TestSelection));

Phases = (str2num(TestSelections(:,1)));
Sets = (str2num(TestSelections(:,11)));
Tests = (str2num(TestSelections(:,13)));

% Remove all entries that aren't selected tests
MasterTable(~ismember([MasterTable{:,1},MasterTable{:,3},MasterTable{:,4}], [Phases,Sets,Tests], 'rows'),:)=[];
```

User Selects Desired Data

```
DataList = MasterTable.Properties.VariableNames(11:16);
[DataSelection,tf] = listdlg('PromptString',{'Which Data Would You Like to Process?'},'SelectionMode','single','ListString',DataList,'ListSize',[500,200]);
SelectedData = DataList(1,DataSelection);
```

Define Data and Locations in Polar and Cartesian

Values of selected data field

```

ZData = MasterTable{:,SelectedData};

% X and Y locations in feet
[XData,YData] = pol2cart(deg2rad(MasterTable{:,9}),MasterTable{:,10});

% Radii in feet
RData = MasterTable{:,10};

% Angles in radians
TData = deg2rad(MasterTable{:,9});

% Record of angles and radii measured
MeasuredAnglesDeg = unique(MasterTable{:,9});
MeasuredAnglesRad = unique(TData);
MeasuredRadii = unique(RData);

```

Creating a refined mesh (1° resolution and 1' resolution)

```

[TMesh,RMesh] = meshgrid(min(TData):(pi/180):max(TData),min(RData):1:max(RData));

```

Bilinearly interpolating and extrapolating (where necessary) to fill in refined mesh

```

BilinearInterpolantFunction = scatteredInterpolant(TData,RData,ZData,'linear','linear');
BilinearInterpolatedData = BilinearInterpolantFunction({TMesh(1,:),RMesh(:,1)});

% Reflecting interpolated data across the 0-180 axis
ReflectedBilinearInterpolatedData = [BilinearInterpolatedData,
BilinearInterpolatedData(:,(size(BilinearInterpolatedData,2)-1):-1:1)];
ReflectedTMesh = [TMesh (TMesh(:,(size(TMesh,2)-1):-1:1)-(2.*TMesh(:,(size(TMesh,2)-1):-
1:1))+(2*pi))];
ReflectedRMesh = [RMesh, RMesh(:,(size(BilinearInterpolatedData,2)-1):-1:1)];

```

Surface plot from bilinearly interpolated data

```

SurfBilinearInterpPlot = figure(PlotCounter + 1);
clf(SurfBilinearInterpPlot)
set(gcf,'Position',[xmin+(xstepR1*(PlotCounter)),yminR1,widthR1,heightR1])
PlotCounter = PlotCounter + 1;
polarplot3d(ReflectedBilinearInterpolatedData,'PlotType','surfn',...
'AngularRange',ReflectedTMesh(1,:), 'RadialRange',ReflectedRMesh(:,1),...
'InterpMethod','linear','ContourLines',CountourLineCount,'MeshScale',[1
1],'PolarGrid',{MeasuredRadii(:,1),MeasuredAnglesRad(:)});
view(IsoView)
hold on

```

```

MeasuredData = stem3(XData,YData,ZData,'rx','Markersize',12);
title([cell2mat(SelectedData),' (Bilinear Interp.) for ',SelectedDevice];' ','FontSize',8)
legend(MeasuredData,'Measured Data','Location','southoutside')
colormap(jet)
colorbar

```

Contour Plot from bilinearly interpolated data

```

ContBilinearInterpPlot = figure(PlotCounter + 1);
clf(ContBilinearInterpPlot)
set(gcf,'Position',[xmin+(xstepR1*(PlotCounter)),yminR1,widthR1,heightR1])
PlotCounter = PlotCounter + 1;
polarplot3d(ReflectedBilinearInterpolatedData,'PlotType','contour',...
    'AngularRange',ReflectedTMesh(1,:), 'RadialRange',ReflectedRMesh(:,1),...
    'InterpMethod','linear','RadLabels',MeasuredRadii(:,1),'RadLabelLocation',{310
    'top'}, 'ContourLines',CountourLineCount,'MeshScale',[1
    1], 'PolarGrid',{MeasuredRadii(:,1),MeasuredAnglesRad(:)}));
view(TopView)
hold on
MeasuredData = plot(XData,YData,'rx','Markersize',12);
title([cell2mat(SelectedData),' (Bilinear Interp.) for ',SelectedDevice];' ','FontSize',8)
legend(MeasuredData,'Measured Data','Location','southoutside')
colormap(jet)
colorbar

```

Power Law Fitting to Measured Data Only (with extrapolation)

Only perform power law fitting to data types that should follow a power law (max pressure, min pressure, energy equivalent)

```

if DataSelection>=1 || DataSelection<=5

    % Preallocate Power Law Fit and Goodness Values
    RowNames = string(strcat(num2str(MeasuredAnglesDeg),'^'));
    PowerFit =
    table('Size',[length(MeasuredAnglesDeg),7],'VariableTypes',{'double','double','double','double','double','double','double'},
        'VariableNames',{'a','b','SSE','R^2','dfe','R^2 - Adjusted','RMSE'},'RowNames',RowNames);

    % Iterate over measured angles and perform a Power Law fit to the data at each angle
    for A=1:length(MeasuredAnglesDeg)
        [Fit,FitGoodness] =
        fit(RData(TData(:)==MeasuredAnglesRad(A)),ZData(TData(:)==MeasuredAnglesRad(A)),'power1');
        PowerFit{A,1} = Fit.a;
        PowerFit{A,2} = Fit.b;
    end
end

```

```

PowerFit{A,3} = FitGoodness.sse;
PowerFit{A,4} = FitGoodness.rsquare;
PowerFit{A,5} = FitGoodness.dfe;
PowerFit{A,6} = FitGoodness.adjrsquare;
PowerFit{A,7} = FitGoodness.rmse;
end

```

Using Power Law Fitting to Extrapolate

Preallocating vector of radii where the Value of Interest is reached along each measured angle

```

Rad_VOI = zeros(length(MeasuredAnglesDeg),1);

% Ask user for extrapolation preference
ANSWR = questdlg('would you like to extrapolate to a specific value or radius?',
'Extrapolate?','Specify Radius','Specify Value','No','No');
switch ANSWR
case 'Specify Radius'
    VOIFlag = 0;
    prompt = 'Specify Radius (ft) for Extrapolating: ';
    dlgtitle = 'Specify Radius';
    dims = [1 75];
    SelExtrapRadius = inputdlg(prompt,dlgtitle,dims,{num2str(max(RMesh(:,1)))});

    ExtrapRadius = max([RMesh(:,1);ceil(str2double(SelExtrapRadius{1}))]);
    Rad_VOI = Rad_VOI + ExtrapRadius;

case 'Specify Value'
    VOIFlag = 1;
    prompt = 'Specify value for Extrapolating: ';
    dlgtitle = 'Specify Value';
    dims = [1 75];
    SelValue = inputdlg(prompt,dlgtitle,dims,{ '0.145' });
    VOI = (str2double(SelValue{1}));

    for A=1:length(MeasuredAnglesDeg)
        % Find the radii at which the Value of Interest is reached
        Rad_VOI(A,1) = (VOI/PowerFit{A,1})^(1/PowerFit{A,2});
    end

    ExtrapRadius = max([RData(:,1);ceil(max(Rad_VOI))]);

case 'No'
    VOIFlag = 0;
    ExtrapRadius = max(RData(:,1));
    Rad_VOI = Rad_VOI + ExtrapRadius;

```

```

end

% Creating a new refined mesh that extends to extrapolation radius (1° resolution and 1'
resolution)
[TMesh,RMesh] = meshgrid(TMesh(1,:),min(RData):1:ExtrapRadius);

```

Interpolating from Power Laws to fill in mesh (in between measured angles)

```

% Preallocate Power Law Data Matrix - Increasing angles across a row (increasing columns) and
increasing radii down a column (increasing rows)
PowerFitDataMeasuredAngles = zeros(size(RMesh,1),length(MeasuredAnglesDeg));

% Calculating Power Law values at each Angle and across all Radii
for A=1:size(PowerFitDataMeasuredAngles,2)
    PowerFitDataMeasuredAngles(:,A) = (PowerFit{A,1}).*((RMesh(:,1)).^(PowerFit{A,2}));
end

% Reformatting angle matrix for use in scatteredInterpolant()
AnglesRearranged = repmat(MeasuredAnglesRad(:)',size(RMesh,1),1);

% Interpolation using scatteredInterpolant() method
PowerInterpolantFunction =
scatteredInterpolant(AnglesRearranged(:),reshape(RMesh(:,1:length(MeasuredAnglesDeg)),[size(Power
FitDataMeasuredAngles,1)*size(PowerFitDataMeasuredAngles,2),1]),PowerFitDataMeasuredAngles(:),'li
near','linear');
PowerInterpolatedData = PowerInterpolantFunction({TMesh(1,:),RMesh(:,1)});

% Reflecting Data across the 0-180 axis
ReflectedPowerInterpolatedData = [PowerInterpolatedData,
PowerInterpolatedData(:,(size(PowerInterpolatedData,2)-1):-1:1)];
ReflectedTMesh = [TMesh (TMesh(:,(size(TMesh,2)-1):-1:1)-(2.*TMesh(:,(size(TMesh,2)-1):-
1:1))+(2*pi))];
ReflectedRMesh = [RMesh, RMesh(:,(size(PowerInterpolatedData,2)-1):-1:1)];

```

Surface Plot from power law interpolated data

```

SurfPowerInterpPlot = figure(PlotCounter + 1);
clf(SurfPowerInterpPlot)
set(gcf,'Position',[xmin+(xstepR1*(PlotCounter)),yminR1,widthR1,heightR1])
PlotCounter = PlotCounter + 1;
polarplot3d(ReflectedPowerInterpolatedData,'PlotType','surfn',...
    'AngularRange',ReflectedTMesh(1,:), 'RadialRange',ReflectedRMesh(:,1),...
    'InterpMethod','linear', 'ContourLines',ContourLineCount, 'MeshScale',[1
1], 'PolarGrid',{sort(unique([MeasuredRadii(:,1);ceil(max(Rad_VOI));floor(min(Rad_VOI))])),Measure
dAnglesRad(:)'});
view(IsoView)

```

```

hold on
MeasuredData = stem3(XData,YData,ZData,'rx','MarkerSize',12);
title([cell2mat(SelectedData),' (Power Law Interp.) for ',SelectedDevice];' ','FontSize',8)
legend(MeasuredData,'Measured Data','Location','southoutside')
colormap(jet)
colorbar

```

Contour Plot from power law interpolated data

```

ContPowerInterpPlot = figure(PlotCounter + 1);
clf(ContPowerInterpPlot)
set(gcf,'Position',[xmin+(xstepR1*(PlotCounter)),yminR1,widthR1,heightR1])
PlotCounter = PlotCounter + 1;
[xx,yy,zz] = polarplot3d(ReflectedPowerInterpolatedData,'PlotType','contour',...
    'AngularRange',ReflectedTMesh(1,:), 'RadialRange',ReflectedRMesh(:,1),...
    'InterpMethod','linear','RadLabels',sort(unique([MeasuredRadii(:,1);ceil(max(Rad_VOI));floor(min(
Rad_VOI))])), 'RadLabelLocation',{310 'top'}, 'ContourLines',CountourLineCount, 'MeshScale',[1
1], 'PolarGrid',{sort(unique([MeasuredRadii(:,1);ceil(max(Rad_VOI));floor(min(Rad_VOI))])),Measure
dAnglesRad(:)}));
view(TopView)
hold on
MeasuredData = plot(XData,YData,'rx','MarkerSize',12);
title([cell2mat(SelectedData),' (Power Law Interp.) for ',SelectedDevice];' ','FontSize',8)
legend(MeasuredData,'Measured Data','Location','southoutside')
colormap(jet)
colorbar

if VOIFlag == 1
    [C,h] = contour(xx,yy,zz,[VOI VOI],'k-','Linewidth',1.5);
    legend([MeasuredData,h],'Measured Data',SelValue{1},'Location','southoutside')
else
    legend(MeasuredData,'Measured Data','Location','southoutside')
end
end

```

Create Axial "Slice" Plots

Remove Slice Plots beyond data range

```

AnglesSlices(AnglesSlices(:)>max(MeasuredAnglesDeg)) = [];
AnglesSlices(AnglesSlices(:)<min(MeasuredAnglesDeg)) = [];
SlicePlots = cell(1,length(AnglesSlices));

% Loop and create slice plots
for Aslice = 1:length(AnglesSlices)

```

```

SlicePlots{Aslice} = figure(PlotCounter+1);
clf(SlicePlots{Aslice})
set(gcf,'Position',[xmin+(xstepR2*(Aslice-1)),yminR2,widthR2,heightR2])
PlotCounter = PlotCounter + 1;

% Different slice plots depending on data selection
if DataSelection>=1 || DataSelection<=5
    BilinearInterpSliceData =
plot(RMesh(1:size(BilinearInterpolatedData,1),1),BilinearInterpolatedData(:,AnglesSlices(Aslice)-
min(AnglesSlices)+1),'m:');
    hold on
    if ismember(AnglesSlices(Aslice)*(pi/180),TData)
        PowerInterpSliceData = plot(RMesh(:,1),PowerInterpolatedData(:,AnglesSlices(Aslice)-
min(AnglesSlices)+1),'blue');
        hold on
        SliceData = ismember(TData,AnglesSlices(Aslice)*(pi/180));
        StemSliceData = stem(RData(SliceData),ZData(SliceData),'rx','MarkerSize',12);
        legend([PowerInterpSliceData,BilinearInterpSliceData,StemSliceData],['Power Law Fit
(Y=',num2str(round(PowerFit{AnglesSlices(Aslice))==MeasuredAnglesDeg(:,1},2)), '*r^{' ,num2str(rou
nd(PowerFit{AnglesSlices(Aslice))==MeasuredAnglesDeg(:,2},3)), '}' ) R^2 =
',num2str(round(PowerFit{AnglesSlices(Aslice))==MeasuredAnglesDeg(:,4},3))], 'Linearly
Interpolated Data', 'Measured Data', 'Location', 'northeast', 'AutoUpdate', 'off', 'FontSize', 7)
    else
        PowerInterpSliceData =
plot(RMesh(:,1),PowerInterpolatedData(:,AnglesSlices(Aslice)+1),'k-.');
        legend([PowerInterpSliceData,BilinearInterpSliceData], 'Power Law Interpolated
Data', 'Linearlly Interpolated Data', 'Location', 'northeast', 'AutoUpdate', 'off', 'FontSize', 7)
    end

    xlim([0 max(ReflectedRMesh(:,1))]);
    if DataSelection == 2
        ylim([min([min(ReflectedPowerInterpolatedData,[], 'all'),
min(ReflectedPowerInterpolatedData,[], 'all'), min(ZData,[], 'all')]) 0]);
    else
        ylim([0 max([max(ReflectedPowerInterpolatedData,[], 'all'),
max(ReflectedPowerInterpolatedData,[], 'all'), max(ZData,[], 'all')])]);
    end

    xbounds = xlim;
    ybounds = ylim;

else
    if ismember(AnglesSlices(Aslice)*(pi/180),TData)
        BilinearInterpSliceData =
plot(RMesh(:,1),BilinearInterpolatedData(:,AnglesSlices(Aslice)-min(AnglesSlices)+1),'blue');
        hold on
        SliceData = ismember(TData,AnglesSlices(Aslice)*(pi/180));
        StemSliceData = stem(RData(SliceData),ZData(SliceData),'rx','MarkerSize',12);

```

```

    legend('Linearly Interpolated Data','Measured
Data','Location','northeast','AutoUpdate','off','FontSize',7)

    else
        BilinearInterpSliceData =
plot(RMesh(:,1),BilinearInterpolatedData(:,AnglesSlices(Aslice)-min(AnglesSlices)+1),'k-.');
        legend('Linearly Interpolated
Data','Location','northeast','AutoUpdate','off','FontSize',7)
    end

    xlim([0 max(ReflectedRMesh(:,1))]);
    ylim([0 max([max(ReflectedBilinearInterpolatedData,[],'all'),
max(ReflectedBilinearInterpolatedData,[],'all'), max(ZData,[],'all')])]);
    xbounds = xlim;
    ybounds = ylim;

end

xlabel('Radius (ft)','FontSize',7,'FontWeight','bold')
ylabel(SelectedData{1},'FontSize',7,'FontWeight','bold')
title([SelectedData{1},' on the ', num2str(AnglesSlices(Aslice)) , '° Axis for
',SelectedDevice'],'FontSize',7)

ax = gca;
ax.XMinorTick = 1;
ax.YMinorTick = 1;
ax.XGrid = 1;
ax.YGrid = 1;
ax.XMinorGrid = 1;
ax.YMinorGrid = 1;

if ismember(AnglesSlices(Aslice)*(pi/180),TData)
    if VOIFlag == 1
        line([0,Rad_VOI((AnglesSlices(Aslice))==MeasuredAnglesDeg(:),1)], [VOI
VOI], 'Color', '#77AC30', 'LineStyle', '--', 'Linewidth', 1)
        %text((Rad_VOI((AnglesSlices(Aslice))==MeasuredAnglesDeg(:),1))/2, VOI, ['y=
', num2str(VOI)], 'Color', '#77AC30', 'FontSize', 11, 'FontWeight', 'bold', 'HorizontalAlignment', 'center
', 'VerticalAlignment', 'top')
        text(0, VOI, [num2str(VOI), '
psi'], 'Color', '#77AC30', 'FontSize', 10, 'FontWeight', 'bold', 'HorizontalAlignment', 'right', 'Vertical
Alignment', 'bottom')

        line([Rad_VOI((AnglesSlices(Aslice))==MeasuredAnglesDeg(:),1), Rad_VOI((AnglesSlices(Aslice))==Measu
redAnglesDeg(:),1)], [ybounds(1) VOI], 'Color', '#77AC30', 'LineStyle', '--', 'Linewidth', 1)
        %text((Rad_VOI((AnglesSlices(Aslice))==MeasuredAnglesDeg(:),1)), VOI/2, ['r=
', num2str(round(Rad_VOI((AnglesSlices(Aslice))==MeasuredAnglesDeg(:),1),1)), ' ft
'], 'Color', '#77AC30', 'FontSize', 11, 'FontWeight', 'bold', 'HorizontalAlignment', 'right', 'VerticalAli
gnment', 'mid')

        text((Rad_VOI((AnglesSlices(Aslice))==MeasuredAnglesDeg(:),1)), VOI, [num2str(round(Rad_VOI((AnglesI
ces(Aslice))==MeasuredAnglesDeg(:),1),1)), ' ft

```



```

'], 'Color', '#77AC30', 'FontSize', 10, 'FontWeight', 'bold', 'HorizontalAlignment', 'left', 'VerticalAlign', 'bottom')

plot(Rad_VOI((Angleslices(Aslice))==MeasuredAnglesDeg(:),1), VOI, '*', 'Color', '#77AC30')
    end
end
end

```

Save Figures and Save Power Fits

```

ANSWER = questdlg('would you like to save the Figures and Power Law Fits?', 'Save?', 'Save', 'No', 'Save');
switch ANSWER
    case 'Save'
        uiwait(helpdlg('Select the "Device Summaries" folder', 'Select Summary Folder'));
        MasterSummaryFolderPath = uigetdir('C:\Users\brand\Box\School\Grad School\Research\Data\','Select Summary Folder');

        % Create Directories
        DeviceFolderName = SelectedDevice;
        TestSelList = 'Summaries for {';
        for a = 1:size(TestSelections,1)
            TestSelList = [TestSelList '(' TestSelections(a,1) '_' TestSelections(a,4:8) '_' TestSelections(a,11) '_' TestSelections(a,13) ')'];
        end
        TestsListFolderName = [TestSelList '}'];
        [row,col] = ismember('(', DataList{DataSelection});
        DataSelectionFolderName = [DataList{DataSelection}(1:col-2) ' Summary'];

        FigFolder = [DeviceFolderName '\ TestsListFolderName \ DataSelectionFolderName '\ Figures' ];

        if ~exist([MasterSummaryFolderPath, '\ FigFolder'], 'dir')
            mkdir(MasterSummaryFolderPath, FigFolder)
        end

        % Save figures
        writeFigurePath = [MasterSummaryFolderPath, '\ FigFolder, \', 'Bilinearly Interpolated Surface Plot'];
        savefig(SurfBilinearInterpPlot, writeFigurePath)
        saveas(SurfBilinearInterpPlot, writeFigurePath, 'png')
        writeFigurePath = [MasterSummaryFolderPath, '\ FigFolder, \', 'Bilinearly Interpolated Contour Plot'];
        savefig(ContBilinearInterpPlot, writeFigurePath)
        saveas(ContBilinearInterpPlot, writeFigurePath, 'png')
        if DataSelection>=1 || DataSelection<=5

```

```

        WriteFigurePath = [MasterSummaryFolderPath, '\', FigFolder, '\', 'Power Law Fit Surface
Plot'];
        savefig(SurfPowerInterpPlot, WriteFigurePath)
        saveas(SurfPowerInterpPlot, WriteFigurePath, 'png')
        WriteFigurePath = [MasterSummaryFolderPath, '\', FigFolder, '\', 'Power Law Fit Contour
Plot'];
        savefig(ContPowerInterpPlot, WriteFigurePath)
        saveas(ContPowerInterpPlot, WriteFigurePath, 'png')
    end
    for FIG = 1:length(SlicePlots)
        WriteFigurePath =
[MasterSummaryFolderPath, '\', FigFolder, '\', num2str(AnglesSlices(FIG)), ' Axis'];
        savefig(SlicePlots{FIG}, WriteFigurePath)
        saveas(SlicePlots{FIG}, WriteFigurePath, 'png')
    end

    if DataSelection >= 1 || DataSelection <= 5
        PWRFolder = [DeviceFolderName '\ TestsListFolderName '\ DataSelectionFolderName
'\Power Law Fits' ];

        if ~exist([MasterSummaryFolderPath, '\', PWRFolder], 'dir')
            mkdir(MasterSummaryFolderPath, PWRFolder)
        end
        % Save power law fit table
        WriteTablePath = [MasterSummaryFolderPath, '\', PWRFolder, '\', 'Power Law Fits.xlsx'];
        writetable(PowerFit, WriteTablePath);
    end

    close all

    case 'no'

end

```

PolarPlot3D

```

function [Xi,Yi,Zi] = polarplot3d(Zp,varargin)
% POLARPLOT3D Plot a 3D surface from polar coordinate data
% [Xi,Yi,Zi] = polarplot3d(Zp,varargin)
%
% Input
% Zp          A two dimensional matrix of input magnitudes or intensities.
%             Each column of Zp contains information along a single meridian. Each row
%             of Zp contains information at a single radius. The direction sense of the
%             rows and columns is determined by the relative order of the angular and
%             radial range vectors. By default Zp is increasing in radius down each
%             column and increasing in angle along each row in the counter-clockwise
%             direction. The default plot is a full 360 degree surface plot with unit
%             radius.
%
% varargin 'property',value pairs that modify plot characteristics.
%          Property names must be specified as quoted strings. Property names and
%          their values are not case sensitive. For each property the default value
%          is given below. All properties are optional. They may be given in any
%          order.
%
% 'PlotType'      'surfn'    surface plot,                no mesh (default)
%                  'surfcn'  surface plot with contours, no mesh
%                  'surfc'   surface plot with contours
%                  'surf'    surface plot
%                  'mesh'    mesh plot
%                  'meshc'   mesh plot with contours
%                  'contour'  2D contour plot
%                      Use 'ContourLines' to set the number of contours.
%                  'contourf' 2D filled contour plot
%                      Use 'ContourLines' to set the number of contours.
%                  'wire'     wireframe polar grid plot only, no surface plot
%                      A wireframe polar grid is plotted without a surface.
%                  'off'      no surface plot
%                      The data is interpolated to a new grid according to
%                      the 'MeshScale' property and transformed to Cartesian
%                      coordinates.
%
% 'AngularRange'  scalar or vector, radians (default = [0 2*pi])
% 'RadialRange'   scalar or vector          (default = [0 1])
%               If a scalar is given for either range it is used as the maximum value and
%               zero is used for the minimum. If a two element vector is given, columns
%               (or rows) are evenly spaced between these values. Otherwise the number
%               of elements must match the size of the corresponding dimension of Zp and
%               specifies the location of each column (or row). If the vector values are
%               decreasing the corresponding dimension of Zp is reversed.
%
% 'ColorData'     Matrix of color values, size must be equal to size(Zp)

```

```

% The default coloring is according to the magnitude of Zp. For example
% specifying gradient(Zp) colors the plot according to slope in the radial
% direction. Similarly gradient(Zp.').' colors the surface according to
% slope in the azimuthal direction.
%
% 'CartOrigin' Cartesian axis origin, 3 element vector (default = [0 0 0])
% The center of the polar plot is translated to this location.
%
% 'MeshScale' Mesh scale factors, 2 element vector (default = [1 1])
% The data is interpolated to a new mesh size. Values > 1 increase mesh
% element size and values < 1 decrease mesh element size.
%
% 'TickSpacing' Spacing of polar tick marks in degrees (default = 10)
% Every other tick mark is labeled. To suppress tick marks specify zero,
% an empty vector or an increment value greater than 180.
%
% 'PolarGrid' Polar grid density (2 element cell array) (default = {10 8})
% Number of grid sections in the radial and azimuthal directions. A value
% of 1 eliminates a grid direction from the plot. If a vector is specified
% for a direction, gridlines are drawn at the specified locations.
%
% 'GridScale' Smoothness of contoured grid lines (default = [40 40])
% Larger values make the grid lines smoother.
%
% 'GridStyle' Style of polar grid lines (default = ':' dotted line)
% Plotting style for the radial and azimuthal grid lines. Any format
% supported by the plot function can be used: '-' solid, ':' dotted,
% '-.' dashdot or '--' dashed.
%
% 'ContourLines' Scalar (number of contours) or a vector (contour locations)
% Either the number of contours or the location of contour lines is specified.
% The default is auto selection by the contour function.
%
% 'AxisLocation' 'surf' polar axis along edge of surface (default)
% 'min' polar axis at minimum Zp for largest radius
% 'max' polar axis at maximum Zp for largest radius
% 'mean' polar axis at mean Zp for largest radius
% 'top' polar axis at top of plot box
% 'bottom' polar axis at bottom of plot box
% value polar axis is drawn at specified height
% 'off' no polar axis
%
% 'RadLabels' Number of radial labels (default = 0)
% The inner and outer most radii are not labeled. Labels are equally spaced
% within the radial range of the data.
%
% 'RadLabelLocation' Radial label location (2 element cell array) (default = {0 'max'})
% The first element is the azimuthal location of the radial labels in
% degrees. The second element is the sagittal location of the labels. The
% following values are allowed. If a value is given it can be a scalar or

```

```

%      a vector the same length as the value of the 'RadLabels' property.
%
%      'surf'    above the surface at each theta,R
%      'min'     at minimum value of Zp
%      'max'     at maximum value of Zp (default)
%      'mean'    at mean    value of Zp
%      'top'     at the top    of the plot box
%      'bottom'  at the bottom of the plot box
%      value     at the specified height(s)
%      'off'     no radial labels
%
%      'PolarDirection' 'ccw'    0 degs along +x axis, angles increase ccw (default)
%                        'cw'    0 degs along +y axis, angles increase cw
%                        This makes a compass-style polar grid.
%
%      'InterpMethod'  'cubic'  bicubic          interpolation on Zp (default)
%                        'linear' bilinear        interpolation on Zp
%                        'spline' spline          interpolation on Zp
%                        'nearest' nearest neighbor interpolation on Zp
%
%      'PolarAxisColor' color of the polar axis    (default = 'black')
%      'GridColor'      color of polar grid lines  (default = 'black')
%      'TickColor'      color of polar tick marks  (default = 'black')
%      'TickLabelColor' color of polar tick labels (default = 'black')
%      'RadLabelColor'  color of radial labels     (default = 'black')
%
%      Additional 'property',value pairs are applied to the current
%      axis using the set() command after the polar plot is drawn.
%
% Output
%      Xi,Yi,Zi  Cartesian locations corresponding to polar coordinates (T,R,Zp)
%                T and R are created from AngularRange and RadialRange arguments
%                using meshgrid and converted to Cartesian coordinates with
%                pol2cart. Xi,Yi,Zi are square matrices with size equal to the
%                dimensions of Zp after interpolation. Matrix sizes are reduced
%                or enlarged by the MeshScale property.
%
% Notes
%      Zp is the only required input argument
%      If no input arguments are given an example plot is produced
%      and this help text is displayed in the command window.
%
% ----
% Example
%      [t,r] = meshgrid(linspace(0,2*pi,361),linspace(-4,4,101));
%      [x,y] = pol2cart(t,r);
%      P = peaks(x,y); % peaks function on a polar grid
%
%                        % draw 3d polar plot
%      figure('Color','white','NumberTitle','off','Name','PolarPlot3d v4.3');
%      polarplot3d(P,'PlotType','surfn','PolarGrid',{4 24},'TickSpacing',8,...

```

```

%             'AngularRange',[30 270]*pi/180,'RadialRange',[.8 4],...
%             'RadLabels',3,'RadLabelLocation',{180 'max'},'RadLabelColor','red');
%
%                                     % set plot attributes
%     set(gca,'DataAspectRatio',[1 1 10],'View',[-12,38],...
%           'xlim',[-4.5 4.5],'xtick',[-4 -2 0 2 4],...
%           'ylim',[-4.5 4.5],'ytick',[-4 -2 0 2 4]);
%     title('polarplot3d example');
%
% ----
% Versions
% 1   Original function based on POLAR3D by J De Freitas
% 2   Changed argument method to 'property',value pairs using PARSE_PV_PAIRS by J. D'Errico
% 2.1 Added 'ColorData' property
% 2.2 Updated contour plot implementation for meshc, surf and surfn plot types
% 2.3 Added radial and azimuthal mesh scale factors
% 2.4 Added 'CartOrigin' property
% 2.5 Added 'PolarAxisColor', 'GridColor', 'TickColor' and 'TickLabelColor' properties
% 2.6 Added 'PolarDirection' and 'GridScale' properties
% 3   Removed PARSE_PV_PAIRS dependency
% 4   Support for non-uniform grid spacing. Removed redundant 'MeshL' plot type
% 4.1 Replaced optional 'PlotProps' cell argument with 'property',value list
% 4.2 Added 'RadLabels', 'RadLabelLocation' and 'RadLabelColor' properties

% -- Help

% polarplot3d was called without arguments
% Draw an example in a new figure and display help text
if nargin < 1
    [t,r] = meshgrid(linspace(0,2*pi,361),linspace(-4,4,101));
    [x,y] = pol2cart(t,r);
    P = peaks(x,y);                                     % peaks function on a polar grid

                                     % draw 3d polar plot
    figure('Color','white','NumberTitle','off','Name','PolarPlot3d v4.3');
    polarplot3d(P,'PlotType','surfn','PolarGrid',{4 24},'TickSpacing',8,...
               'AngularRange',[30 270]*pi/180,'RadialRange',[.8 4],...
               'RadLabels',3,'RadLabelLocation',{180 'max'},'RadLabelColor','red');

                                     % set plot attributes
    set(gca,'DataAspectRatio',[1 1 10],'view',[-12,38],...
          'xlim',[-4.5 4.5],'xtick',[-4 -2 0 2 4],...
          'ylim',[-4.5 4.5],'ytick',[-4 -2 0 2 4]);
    title('polarplot3d example');

                                     % display help text
    error(['No input arguments given\n'...
          'Please consult the help text and the example plot\n'...
          '-----\n%s'],help(mfilename));
end

```

```

%-- Parse and validate input arguments

% Allowed argument string for property values
plst = {'mesh','meshc','wire',...
        'surf','surfc','surfn','surfcn','contour','contourf','off'};
alst = {'off','const','min','max','mean','surf','top','bottom'};
rlst = {'off','const','min','max','mean','surf','top','bottom'};
mlst = {'cubic','linear','spline','nearest'};
dlst = {'ccw','cw'};
glst = {'-',':','-','--'};

% Set up property structure with default values
p.angularrange = [0 2*pi]; % angular range
p.radialrange = [0 1]; % radial range
p.plottype = 'surfn'; % surface plot, no rectangular grid
p.meshscale = [1 1]; % no mesh scaling
p.polargrid = {10 8}; % number of radial and azimuthal sections
p.gridscale = [40 40]; % 40x scaling for smooth grid interpolation
p.cartorigin = [0 0 0]; % Cartesian origin
p.tickspacing = 10; % ten degree tick mark spacing
p.radlabels = 0; % number of radial grid labels
p.axislocation = ''; % polar axis location
p.radlabellocation = ''; % radial label location
p.polaraxisdirection = 'ccw'; % default polar axis direction
p.interpmethod = 'cubic'; % bicubic interpolation
p.colordata = []; % default coloring according to Zp values
p.contourlines = ''; % default contour specification
p.gridcolor = 'black'; % default overlay grid line color
p.gridstyle = ''; % style of grid lines: '-' ':' '-.' '---'
p.polaraxiscolor = 'black'; % default polar axis color
p.tickcolor = 'black'; % default polar tick color
p.ticklabelcolor = 'black'; % default polar tick label color
p.radlabelcolor = 'black'; % default radial label color
p.plotprops = {}; % no additional plot properties

% Parse property value pairs, replace defaults with values specified by caller
try
    [p,leftovers] = structrecon(pv2struct(varargin{:}),p);
    p.plotprops = struct2pv(leftovers);
catch ERR
    error('Error parsing varargin list\n??? %s',ERR.message);
end

% Check input data size
[Zrows,Zcols] = size(Zp);
if (Zrows < 5) || (Zcols < 5)
    error('Input matrix size must be greater than 4 x 4');
end

```

```

% Check plot type specification
if ~ischar(p.plottype) || isempty(matchstr2lst(lower(p.plottype),plst))
    error('Invalid ''PlotType'' property value');
end
p.plottype = lower(p.plottype);

% Choose default polar axis location
if isequal(p.axislocation,'')
    if ~isempty(matchstr2lst(p.plottype,{'meshc','surfc','surfcn'}))
        p.axislocation = 'bottom'; % plot box bottom for contour plots
    else p.axislocation = 'surf'; % along perimeter of surface otherwise
    end
end

% User specified polar axis location as a numeric value
if isnumeric(p.axislocation)
    [r,c] = size(p.axislocation);
    if (((r ~= 1) || (c ~= 1)) || ~isnumeric(p.axislocation))
        error('''AxisLocation'' property value must be scalar, positive and real');
    end
    polax = p.axislocation;
    p.axislocation = 'const';
end

% Check polar axis location specification
if ~ischar(p.axislocation) || isempty(matchstr2lst(lower(p.axislocation),alst))
    error('Invalid ''AxisLocation'' property value');
end
p.axislocation = lower(p.axislocation);

% Check polar axis direction specification
if ~ischar(p.polardirection) || isempty(matchstr2lst(lower(p.polardirection),dlst))
    error('Invalid ''PolarDirection'' property value');
end
p.polardirection = lower(p.polardirection);

% Check grid scaling specification
p.gridscale = p.gridscale(:)';
if ~isnumeric(p.gridscale) || any(p.gridscale <= 0)
    error('Non-numeric or non-positive grid scale parameter');
end
if length(p.gridscale) ~= 2
    error('''GridScale'' property must be a two element numeric vector');
end

% Check angular range vector
p.angularrange = p.angularrange(:);
if ~isnumeric(p.angularrange)
    error('''AngularRange'' property value must be numeric');
end

```



```

if isscalar(p.angularrange), p.angularrange = [0; p.angularrange]; end
if length(p.angularrange) == 2
    p.angularrange = linspace(p.angularrange(1),p.angularrange(2),Zcols).';
end
if ~ismono(p.angularrange)
    error('''AngularRange'' vector must be monotonic');
end
if length(p.angularrange) ~= Zcols
    error('''AngularRange'' size must match number of columns in input matrix');
end

% Check radial range vector
p.radialrange = p.radialrange(:);
if ~isnumeric(p.radialrange)
    error('''RadialRange'' property value must be numeric');
end
if isscalar(p.radialrange), p.radialrange = [0; p.radialrange]; end
if length(p.radialrange) == 2
    p.radialrange = linspace(p.radialrange(1),p.radialrange(2),Zrows).';
end
if ~ismono(p.radialrange)
    error('''RadialRange'' vector must be monotonic');
end
if length(p.radialrange) ~= Zrows
    error('''RadialRange'' size must match number of rows in input matrix');
end

% Angular and radial range vectors define data order
[Tmin,Tmax] = deal(min(p.angularrange),max(p.angularrange)); % Tmin < Tmax
[Rmin,Rmax] = deal(min(p.radialrange ),max(p.radialrange )); % Rmin < Rmax

% Reflect Zp left-right and/or up-down depending on angular and radial ranges
if p.angularrange(1) > p.angularrange(end), Zp = fliplr(Zp); end
if p.radialrange (1) > p.radialrange (end), Zp = flipud(Zp); end

% Angular range cannot be more than one full circumference
if abs(Tmax - Tmin) > 2*pi
    error('Angular range cannot be greater than 2*pi');
end

% Check radial and azimuthal polar grid density
p.polargrid = p.polargrid(:);
if length(p.polargrid) ~= 2 || ~iscell(p.polargrid)
    error('''PolarGrid'' property value must be a two element numeric cell array');
end
[radgrid,azmgrid] = deal(p.polargrid{1},p.polargrid{2});

% Check azimuthal grid density
if ~isnumeric(azmgrid)
    error('Non-numeric azimuthal grid parameter');
end

```

```

end
if isempty(azmgrid) || (length(azmgrid)==1 && azmgrid == 0)
    azmgrid = 1;
end
if length(azmgrid) == 1
    azmgrid = linspace(Tmin,Tmax,azmgrid+1).';
end

% Check radial grid density
if ~isnumeric(radgrid)
    error('Non-numeric radial grid parameter');
end
if isempty(radgrid) || (length(radgrid)==1 && radgrid==0)
    radgrid = 1;
end
if length(radgrid) == 1
    radgrid = linspace(Rmin,Rmax,radgrid+1).';
end

% Check radial label location, {azimuthal, sagittal}
if isempty(p.radlabellocation)
    p.radlabellocation = {0 'surf'};
end
if ~iscell(p.radlabellocation) || numel(p.radlabellocation) ~= 2
    error('''RadLabelLocation'' property must be a 2 element cell array');
end
azimuth_radax = p.radlabellocation{1};
if ~isnumeric(azimuth_radax) || azimuth_radax < 0 || azimuth_radax > 360
    error('azimuthal radial location must be between 0 and 360 degrees');
end
p.radlabellocation = p.radlabellocation{2};
if isnumeric(p.radlabellocation)
    sagittal_radax = p.radlabellocation;
    p.radlabellocation = 'const';
end
if ~ischar(p.radlabellocation) || isempty(matchstr2lst(lower(p.radlabellocation),r1st))
    error('Invalid ''RadLabelLocation'' property value');
end
p.radlabellocation = lower(p.radlabellocation);

% Check mesh scale factor property value
if isscalar(p.meshscale), p.meshscale = [p.meshscale p.meshscale]; end
if ~isnumeric(p.meshscale) || any(p.meshscale <= 0)
    error('''MeshScale'' property values must be positive and real');
end

% Check tick spacing property value
if ~isempty(p.tickspacing) && (~isscalar(p.tickspacing) || ~isnumeric(p.tickspacing))

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    error('''TickSpacing'' property value must be a scalar numeric value or empty');
end

% Check contour lines property value
if ~isnumeric(p.contourlines) && ~isequal(p.contourlines,'')
    error('''ContourLines'' property value must be numeric');
end
p.contourlines = p.contourlines(:);

% Check grid line style property value, default depends on plottype
if isempty(p.gridstyle)
    if isequal(p.plottype,'contour'), p.gridstyle = ':';    % dotted line
    elseif isequal(p.plottype,'contourf'), p.gridstyle = ':';    % dotted line
    else
        p.gridstyle = '-';    % solid line
    end
end
if ~ischar(p.gridstyle) || isempty(matchstr2lst(lower(p.gridstyle),glst))
    error('Invalid ''GridStyle'' property value');
end

% Check interpolation method
p.interpmethod = lower(p.interpmethod);
if ~ischar(p.interpmethod) || isempty(matchstr2lst(p.interpmethod,m1st))
    error('Invalid ''InterpMethod'' property value');
end

% Check if mesh scale factor is compatible with input data dimension
if round(min([Zrows Zcols]./p.meshscale)) < 4
    error('Mesh scale factor is too large, not enough data remaining to plot');
end

% Choose default color matrix
if isempty(p.colordata), p.colordata = Zp; end    % surface height coloring

% Check color matrix
if ~isnumeric(p.colordata) || ~isequal(size(p.colordata),[Zrows,Zcols])
    error('Color matrix must be numeric and the same size as Zp');
end

% Polar axis z location is a constant for contour plots
if isequal(p.plottype,'contour') && ~isequal(p.axislocation,'off')
    polax = 0;
    p.axislocation = 'const';
elseif isequal(p.plottype,'contourf') && ~isequal(p.axislocation,'off')
    polax = 0;
    p.axislocation = 'const';
end

% Check Cartesian origin
if isempty(p.cartorigin) || ~isnumeric(p.cartorigin)

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    error('Cartesian origin must be numeric');
end
if length(p.cartorigin)<3, p.cartorigin(3) = 0; end

%-- Create polar grid and interpolate data

% Create radius and angle vectors and polar grid for input data matrix
rho = p.radialrange; % radius vector
angl = p.angularrange; % angle vector
[xx,yy] = meshgrid(angl,rho); % mesh matrices
Zi = Zp; % z's == input data
Ci = p.colordata; % colormap

% No interpolation for uniform scaling
if isequal(p.meshscale,[1 1]) % uniform scaling
    Xi = rho * cos(angl. '); % matrix of x's
    Yi = rho * sin(angl. '); % matrix of y's
end

% Create a new grid and interpolation data
else
    q = fix([Zrows Zcols]/p.meshscale); % new mesh size
    rho = linspace(Rmin,Rmax,q(1)); % radius vector
    angl = linspace(Tmin,Tmax,q(2)); % angle vector
    [theta,rad] = meshgrid(angl,rho); % create polar grid
    T = interp2(xx,yy,Zp,theta,rad,p.interpmethod); % interpolate Zp to grid
    Ci = interp2(xx,yy,Ci,theta,rad,p.interpmethod); % interpolate color
    [Xi,Yi,Zi] = pol2cart(theta,rad,T); % convert to Cartesian
end

% Swap x,y for clockwise polar plot
if isequal(p.polardirection,'cw')
    [Xi,Yi] = deal(Yi,Xi);
end

% Offset grid data to Cartesian origin
Xi = Xi + p.cartorigin(1);
Yi = Yi + p.cartorigin(2);
Zi = Zi + p.cartorigin(3);

%-- Plot the surface

switch p.plotttype
case 'wire', grid on;
case 'meshc', mesh(Xi,Yi,Zi,Ci);
               addcontours(Xi,Yi,Zi,p.contourlines);
case 'mesh', mesh (Xi,Yi,Zi,Ci);
case 'surf', surf (Xi,Yi,Zi,Ci);
case 'surfc', surf (Xi,Yi,Zi,Ci);

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        addcontours(Xi,Yi,Zi,p.contourlines);
    case 'surfn', surf (Xi,Yi,Zi,Ci,'LineStyle','none');
    case 'surfcn', surf (Xi,Yi,Zi,Ci,'LineStyle','none');
        addcontours(Xi,Yi,Zi,p.contourlines);
    case 'contour', contour(Xi,Yi,Zi,p.contourlines);
        axis equal; xlim(xlim*1.1); ylim(ylim*1.1);
        set(gca,'visible','off');
        set(get(gca,'xlabel'),'visible','on');
        set(get(gca,'ylabel'),'visible','on');
        set(get(gca,'title'),'visible','on');
    case 'contourf', contourf(Xi,Yi,Zi,p.contourlines);
        axis equal; xlim(xlim*1.1); ylim(ylim*1.1);
        set(gca,'visible','off');
        set(get(gca,'xlabel'),'visible','on');
        set(get(gca,'ylabel'),'visible','on');
        set(get(gca,'title'),'visible','on');
end

%-- Plot the polar axis

% Axis and tick label attributes
fontargs = {'FontName','Arial','FontSize',10,'FontWeight','bold'};

if ~isequal(p.axislocation,'off')

    % Create polar axis data just outside the largest radius
    xa = Rmax * 1.005 .* cos(angl) + p.cartorigin(1);
    ya = Rmax * 1.005 .* sin(angl) + p.cartorigin(2);

    % Set polax to z location of polar axis
    switch p.axislocation
        case 'min', polax = min (Zi(end,:));
        case 'max', polax = max (Zi(end,:));
        case 'mean', polax = mean(Zi(end,:));
        case 'top', zlim = get(gca,'zlim'); polax = zlim(2);
        case 'bottom', zlim = get(gca,'zlim'); polax = zlim(1);
    end

    % Z values for polar axis
    if isequal(p.axislocation,'surf')
        za = Zi(end,:); % vary along edge of surface
    else za = zeros(size(xa)) + polax; % constant location
    end

    % Swap x,y for clockwise polar plot
    if isequal(p.poldirection,'cw'), [xa,ya] = deal(ya,xa); end

    % Plot the polar axis
    hold on;

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line(xa,ya,za,'color',p.polaraxiscolor,'Linewidth',1);

% Add tick marks and labels
if ~isempty(p.tickspacing) && p.tickspacing > 0 && p.tickspacing <= 180

    % Create polar axis tic marks at p.tickspacing intervals
    ts = 180/p.tickspacing;
    ta = pi/ts * (round(Tmin*ts/pi):1:round(Tmax*ts/pi));
    tr = Rmax * [1.005; 1.03; 1.1];
    xt = tr * cos(ta) + p.cartorigin(1);
    yt = tr * sin(ta) + p.cartorigin(2);

    % Z values for polar tick marks
    if isequal(p.axislocation,'surf')
        zt = interp1(angl,za,ta,'linear'); % vary along edge of surface
    else zt = zeros(1,length(ta)) + polax; % constant location
    end

    % Label every other tick mark
    n1 = round(length(ta)/2);

    % Beginning and end of a full polar axis are identical, label once
    if abs(Tmin-Tmax) == 2*pi, n1 = n1-1; end

    % Swap x,y for clockwise polar plot
    if isequal(p.polardirection,'cw'), [xt,yt] = deal(yt,xt); end

    % Draw the tick marks
    line(xt(1:2,:),yt(1:2,:),[zt; zt],'color',p.tickcolor);

    % Add tick labels
    for k = 2 * (1:n1) - 1
        text(xt(3,k),yt(3,k),zt(k),[num2str(ta(k)*180/pi),'°'],...
            'HorizontalAlignment','Center',fontargs{:},'color',p.ticklabelcolor);
    end
end
hold off;
end

% -- Add radial labels
if isnumeric(p.radlabels)
    % Find x,y locations of radial labels
    tr = p.radlabels;
    ta = zeros(length(tr),1);
    ta(1:2:end,1) = (azimuth_radax-10)*pi/180;
    ta(2:2:end,1) = (azimuth_radax+10)*pi/180;

    % tr(1) = []; tr(end) = []; % delete inner,outer labels
    xt = tr .* cos(ta) + p.cartorigin(1);
    yt = tr .* sin(ta) + p.cartorigin(2);

```

```

% Swap x,y for clockwise polar plot
if isequal(p.polardirection,'cw'), [xt,yt] = deal(yt,xt); end

% Set sagittal_radax to z location of radial labels
switch p.radlabellocation
    case 'min',    sagittal_radax = min (Zi(:));
    case 'max',    sagittal_radax = max (Zi(:));
    case 'mean',   sagittal_radax = mean(Zi(:));
    case 'top',    zlim = get(gca,'zlim'); sagittal_radax = zlim(2);
    case 'bottom', zlim = get(gca,'zlim'); sagittal_radax = zlim(1);
end

% Z values for radial labels
if isequal(p.radlabellocation,'surf')
    zt = interp2(xx,yy,Zp,ta,tr,p.interpmethod);    % vary with surface
else
    sagittal_radax(length(tr)+1:end) = [];
    sagittal_radax(end+1:length(tr)) = sagittal_radax(end);
    zt = zeros(1,length(tr)) + sagittal_radax;    % constant location
end

% Add radial labels to the plot
hold on;
for k = 1:length(tr)
    text(xt(k),yt(k),zt(k),[num2str(tr(k))',''],[],...
        'HorizontalAlignment','Left','FontWeight','normal',fontargs{:},'Color',p.radlabelcolor);
end
hold off;
else
    if p.radlabels > 0 && ~isequal(p.radlabellocation,'off')

        % Find x,y locations of radial labels
        tr = linspace(Rmin,Rmax,p.radlabels+2);
        ta = zeros(length(tr),1);
        ta(1:2:end,1) = (azimuth_radax-10)*pi/180;
        ta(2:2:end,1) = (azimuth_radax+10)*pi/180;
        xt = tr .* cos(ta) + p.cartorigin(1);
        yt = tr .* sin(ta) + p.cartorigin(2);

        % Swap x,y for clockwise polar plot
        if isequal(p.polardirection,'cw'), [xt,yt] = deal(yt,xt); end

        % Set sagittal_radax to z location of radial labels
        switch p.radlabellocation
            case 'min',    sagittal_radax = min (Zi(:));
            case 'max',    sagittal_radax = max (Zi(:));
            case 'mean',   sagittal_radax = mean(Zi(:));
            case 'top',    zlim = get(gca,'zlim'); sagittal_radax = zlim(2);
            case 'bottom', zlim = get(gca,'zlim'); sagittal_radax = zlim(1);

```

```

end

% Z values for radial labels
if isequal(p.radlabellocation,'surf')
    zt = interp2(xx,yy,Zp,ta,tr,p.interpmethod); % vary with surface
else
    sagittal_radax(length(tr)+1:end) = [];
    sagittal_radax(end+1:length(tr)) = sagittal_radax(end);
    zt = zeros(1,length(tr)) + sagittal_radax; % constant location
end

% Add radial labels to the plot
hold on;
for k = 1:length(tr)
    text(xt(k),yt(k),zt(k),num2str(tr(k)),...
        'HorizontalAlignment','Center',fontargs{:},'Color',p.radlabelcolor);
end
hold off;
end
end

%-- Draw polar grid lines

r = length(radgrid);
m = length(azmgrid);

% Is there more than one radial or azimuthal section?
if r > 1 || m > 1

    % Allocate space for grid lines
    u = p.gridscale(1);
    v = p.gridscale(2);
    rho = zeros(1,(r-1)*u+1);
    angl = zeros(1,(m-1)*v+1);

    % Fill in grid vectors between points so the interpolated grid follows
    % surface contours smoothly and the azimuthal grid lines are circular.
    for k = 1:r-1
        rho((k-1)*u+1:(k*u)+1) = linspace(radgrid(k),radgrid(k+1),u+1);
    end
    for k = 1:m-1
        angl((k-1)*v+1:(k*v)+1) = linspace(azmgrid(k),azmgrid(k+1),v+1);
    end

    % Interpolate data to a fine mesh to produce smooth grid lines
    [theta,rad] = meshgrid(angl,rho); % create polar grid
    T = interp2(xx,yy,Zp,theta,rad,p.interpmethod); % interpolate to grid
    [xi,yi,zi] = pol2cart(theta,rad,T); % convert to Cartesian
    xi = xi + p.cartorigin(1); % translate center, x

```



```

yi = yi + p.cartorigin(2);          % y
zi = zi + p.cartorigin(3);          % z

% Swap x,y for clockwise polar plot
if isequal(p.poldirection,'cw')
    [xi,yi] = deal(yi,xi);
end

% In-plane grid lines for contour plots
if isequal(p.plotttype,'contour'), zi = zeros(size(zi));
elseif isequal(p.plotttype,'contourf'), zi = zeros(size(zi)); end

% draw radial grid lines in azimuthal direction (meridians)
hold on;
if length(azmgrid) > 2
    xr = xi(:,1:u:end);
    yr = yi(:,1:u:end);
    zr = zi(:,1:u:end);
    plot3(xr,yr,zr,p.gridstyle,'color',p.gridcolor,'Linewidth',1);
end

% Draw azimuthal grid lines in radial direction (concentric arcs)
if length(radgrid) > 2
    xm = xi(1:v:end,:);
    ym = yi(1:v:end,:);
    zm = zi(1:v:end,:);
    plot3(xm',ym',zm',p.gridstyle,'color',p.gridcolor,'Linewidth',1);
end
hold off;
end

%-- Set axis font
if ~isequal(p.plotttype,'off'), set(gca,fontargs{:}); end

%-- Apply additional properties to the plot
if ~isempty(p.plotprops), set(gca,p.plotprops{:}); end
end

%-- Local functions

% Add a contour plot to the current surface or mesh plot
function addcontours(x,y,z,levels)

if isempty(levels), levels = 16; end
hold on;
a = get(gca,'zlim');
zpos = a(1);          % find smallest z value in 3d plot

% Add contours

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[~,hh] = contour3(x,y,z,levels);

% Change all contour group positions to bottom of plot
for j = 1:length(hh)
    zz = get(hh(j),'zdata');
    set(hh(j),'zdata',zpos*ones(size(zz)));
end
end

% Structure reconciliation with a template
function [T,S] = structrecon(S,D)

% Check arguments, must have two structures
if ~(isstruct(S) && isstruct(D))
    error('input arguments must be structures');
end

T = D; % copy the template
fname = fields(T); % make a list of field names

% Loop over all fields in the template, copy matching values from S
for k = 1:length(fname)
    % Process matching field names in S
    if isfield(S,fname{k})
        % Is this a substructure ?
        if isstruct(T.(fname{k})) && isstruct(S.(fname{k}))
            % Recursively process the substructure
            T.(fname{k}) = structrecon(S.(fname{k}),T.(fname{k}));
        % Not a substructure, copy field value from S
        else T.(fname{k}) = S.(fname{k});
        end
        S = rmfield(S,fname{k});
    end
end
end

% Convert an argument pairs cell array to a structure
function S = pv2struct(varargin)

% No inputs, return empty structure
if isempty(varargin), S = struct(); return; end

% Need pairs of inputs
if mod(length(varargin),2)~=1
    error('number of arguments must be even');
end

% Odd elements of varargin are fields, even ones are values
% Store all field names in lower case
for k = 1:2:length(varargin)

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    S.(lower(varargin{k})) = varargin{k+1};
end
end

% Convert a structure to an argument pairs cell array
function P = struct2pv(S)

% Check input argument
if ~isstruct(S), P = {}; return; end

% Get field names
n = fieldnames(S);

% Convert structure values to cell array
v = struct2cell(S);

% Combine names and values, return a 1xN cell array
P = {n{:}; v{:}};
P = P(:).';
end

% Match a string with a list of strings
function idx = matchstr2lst(str,strarray,opt)

if nargin < 2, return; end
idx = find(strncmpi(str,strarray,length(str))==1);
idx = idx(:);

if nargin > 2
    if strcmpi(opt,'first'), idx = idx(1);
    elseif strcmpi(opt,'last'), idx = idx(end);
    end
end
end

% Test monotonicity of a vector
function m = ismono(v)

[r,c] = size(v);      % size of input
if r == 1,            % row vector
    v = v';           % transpose
    r = c; c = 1;      % size
end

sgn = sum(sign(diff(v,1,1)),1); % sgn is r+1 or -(r+1) for monotonic columns
up   = sgn - repmat(r,1,c);    % subtract r to detect increasing (-1)
down = sgn + repmat(r,1,c);    % add      r to detect decreasing (+1)
up   (up < -1) = 0;             % force non-monotonic entries to zero
down(down > 1) = 0;

```

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m = -(up + down);           % flip sense of output so +1 is increasing  
end
```

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