5-2016

The Effect of Axial Spacing of Constant and Variable Blockages on the Deflagration-to-Detonation Transition in a Pulse Detonation Engine

Nicole Gagnon

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THE EFFECT OF AXIAL SPACING OF CONSTANT AND VARIABLE
BLOCKAGES ON THE DEFLAGRATION-TO-DETONATION TRANSITION IN A
PULSE DETONATION ENGINE

A Thesis

Submitted to the Faculty

of

Embry-Riddle Aeronautical University

by

Nicole Gagnon

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Aerospace Engineering

May 2016

Embry-Riddle Aeronautical University

Daytona Beach, Florida

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Nicole Gagnon

A Thesis prepared under the direction of the candidate's committee chairman, Dr. Magdy Attia, Department of Aerospace Engineering, and has been approved by the members of the thesis committee. It was submitted to the School of Graduate Studies and Research and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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ACKNOWLEDGMENTS

Firstly, I would like to thank Dr. Magdy Attia for all the support, guidance, and education provided through our interactions. I would like to thank Darrell Stevens for his assistance, insights and support. Additionally, I would like to thank my committee members Dr. Mark Ricklick and Dr. Lakshmanan Narayanaswami for the knowledge they have provided me.

My sincere thanks goes to my fellow Gas Turbine Lab labmates for the stimulating discussions, sleepless nights spent working together in the lab, countless coffee trips, and all of their support.

Last but not least, I would like to thank my family for all of their patience, support and encouragement. I would sincerely like to thank my father for inspiring me to pursue aerospace engineering.

ABSTRACT

Author: Gagnon, Nicole E.

Title: The Effect of Axial Spacing of Constant and Variable Blockages on the Deflagration-to-detonation Transition in a Pulse Detonation Engine

Institution: Embry-Riddle Aeronautical University

Degree: Master of Science in Aerospace Engineering

Year: 2016

An investigation was conducted into the effects of obstacle spacing on the deflagration-to-detonation transition section length in a pulse detonation engine. Testing was conducted with one hundred and ninety-five different obstacle, and spacing configurations. The configurations included constant, as well as variable spacing between obstacles. The goal of this investigation was to correlate the spacing between obstacles and the blockage ratio of the obstacles with the detonation success and the shortening of the DDT section. The ten cases that achieved the highest percentage of detonations were investigated further to determine the distance needed for the deflagration-to-detonation transition. A 33% blockage ratio was the most successful to induce turbulence and not quench the detonation wave. With these conditions, DDT was achievable with 100% success in a section whose length was 31 times the inner diameter of the DDT section. Detonation was unachievable in 82 times the inner diameter in a “smooth” tube. This is a greater than 63% decrease in detonation transition length. This decrease in length will further facilitate the integration of pulse detonation engines into gas turbine engines.

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SYMBOLS

D	Diameter
p	Pressure
V	Volume
v	Velocity
x	Axial Measurement
r	Radial Measurement

ABBREVIATIONS

BR	Blockage Ratio
CD	Converging-Diverging
Con	Converging
CSCB	Constant Spacing & Constant Blockage Ratio
CSVB	Constant Spacing & Variable Blockage Ratio
DDT	Deflagration-to-Detonation Transition
Div	Diverging
DW	Downwind
ID	Inner Diameter
kpsi	Kilo – Pounds per Square Inch
nondim	Non-dimensional
PDE	Pulse Detonation Engine
p-V	Pressure vs. Volume
T-s	Temperature vs. Entropy
UW	Upwind
VSCB	Variable Spacing & Constant Blockage Ratio
VSVB	Variable Spacing & Variable Blockage Ratio

1. INTRODUCTION

1.1. Gas Turbine Engines

December 17th 1903 marked the beginning of powered flight by the Wright Brothers. In January 1930, Frank Whittle was issued the first patent for a gas turbine engine, the Whittle engine. The combustion in the Whittle engine took place in a large reverse flow burner since stable combustion proved difficult inside a straight-flow burner. In 1936, von Ohain received a patent for the first engine that utilized a straight-flow combustor, the Jumo 004B. Since then, a better understanding of combustion has led to more efficient combustion chambers with smaller lengths and volumes (Farokhi, 2014). In an effort to further increase the efficiency and increase range of flight Mach number flight, pulse detonation combustion is being looked at as a replacement for the current combustion process.

1.2. Pulse Detonation

Pulse detonation is an unsteady combustion process which utilizes a detonation wave to propel the combustion region through an unburned fuel-oxidizer mixture. Detonation waves are favorable due to the large pressures produced by the shock wave. These high pressures translate into high thrust for pure pulse detonation engines and a reduced compression requirement for pulse detonation engines integrated into gas turbine engines. Therefore, in a gas turbine engine, the size of the compressor can be decreased, or in some cases even eliminated (Bussing & Pappas, 1994). Pure pulse detonation engines or PDEs are being looked at for up to Mach 3 to Mach 4 flight applications since current turbojet and turbofan engines become increasingly expensive for applications greater than

Mach 3 (Roy, Frolov, Borisov, & Netzer, 2004). Pulse detonation engines have a greater specific impulse than turbojet engines and the Mach number range of a PDE is greater than that of a turbojet engine. Specific impulse is equivalent to the thrust per unit weight flow rate of fuel, therefore PDEs are more fuel efficient than turbojet engines especially at Mach 3 to Mach 4 applications. Another advantage of PDEs is their capacity to generate static thrust (unlike a ramjet) (Ciccarelli & Dorofeev, 2008). Figure 1.1 shows a comparison of specific impulse at varying Mach numbers for multiple engine types for both hydrogen and hydrocarbon fuels with PDEs highlighted.

Figure 1.1 Specific Impulse (Bussing, Bratkovich, & Hinkey Jr., 1997)

The integration of pulse detonation combustors into gas turbine engines poses many challenges including unsteady combustion, turbine wear, heating and noise (Frolov, Pulse Detonation Propulsion, 2010). Pulse detonation engines are being researched to replace the

high pressure core of a gas turbine engine, which is made up of the high pressure compressor, combustion chamber and high pressure turbine. See Section 1.9. Gas-Turbine Engine Integration for more on integration of pulse detonation combustors into gas-turbine engines.

1.3. Combustion

Combustion transforms chemical energy into thermal and kinetic energy. A combustion wave propagates through a reactant fuel-air mixture and releases potential energy which is stored in the chemical bonds of the reactants. The propagation of the combustion wave can occur subsonically as a deflagration wave or supersonically as a detonation wave (Lee, 2008). The detonative combustion process can be approximated as a constant volume process which has a greater efficiency than deflagration combustion which is modeled as a constant pressure process (Bussing & Pappas, 1994).

1.3.1. Efficiencies and Engine Cycles

Deflagrations can be modeled as a part of the constant pressure process, the Brayton Cycle, because the decrease in pressure across the reaction front is small. Detonation can be roughly modeled as a part of the constant volume process, the Humphrey Cycle, which is a more efficient cycle than the Brayton cycle used to model deflagration combustion (Bussing & Pappas, 1994). The issue with using the Humphrey cycle is the assumptions of thermodynamic equilibrium and replacing chemical reactions with heat addition without mass addition (Heiser & Pratt, 2002). In Figure 1.2, a p-V (Pressure-Volume) Diagram and a T-s (Temperature-Entropy) Diagram of both the Brayton Cycle and the Humphrey Cycle are shown. On both diagrams, the Brayton cycle is depicted as 1-2-5-6 whereas the

Humphrey cycle is depicted as 1-2-3-4. The deflagration combustion process is depicted on Figure 1.2 going from point 2 to point 5 and the detonation combustion process is depicted going from point 2 to 3 (Farokhi, 2014, p. 13).

Figure 1.2 Brayton and Humphrey Cycles (Farokhi, 2014, p. 13)

The efficiency of the Brayton Cycle is dependent only on the temperature change of the isentropic compression process whereas the efficiency of the Humphrey Cycle depends also on the ratio of specific heats and the temperature change associated with the constant volume combustion process (Farokhi, 2014, p. 13).

$$\eta_{th,Brayton} = 1 - \frac{T_1}{T_2}$$

$$\eta_{th,Humphrey} = 1 - \gamma \frac{T_1}{T_2} \left[\frac{\left(\frac{T_3}{T_2}\right)^{\frac{1}{\gamma}} - 1}{\frac{T_3}{T_2} - 1} \right]$$

Equation 1.1 Humphrey and Brayton Cycle Efficiencies (Farokhi, 2014, p. 13)

In Equation 1.1, γ is the ratio of specific heats. For a diatomic gas, such as air, this value is approximately 1.4 (Farokhi, 2014).

1.4. Deflagration

Deflagration is the “self-sustaining propagation of a localized combustion zone at subsonic velocities” (Turns, 2000). This propagation velocity is on the order of one meter per second to several hundred meters per second in a pipe (Bussing & Pappas, 1994). These flames propagate by diffusive transport of mass and energy (Ciccarelli & Dorofeev, 2008). The majority of current gas turbine engines utilize deflagration combustion.

1.5. Detonation

Detonation waves are combustion waves which propagate at supersonic velocities; on the order of a thousand meters per second depending on the fuel. Detonation waves create large increases in pressure, density and temperature. The pressure increases by a factor varying between ten and thirty across a detonation (Ragland & Bryden, 2011). In detonations, a shock wave travels at a distance of a few millimeters in front of the reaction zone, therefore the detonation wave is often modeled as a shock wave followed by a reaction (James, 2001).

1.5.1. Detonation Wave Model

Zel’dovich, von Neumann, and Doering (ZND) developed a one-dimensional model for detonation waves where a leading shock wave is closely followed by a reaction front. This gap between the leading shock wave and the reaction front is called the “induction delay” (Roy, Frolov, Borisov, & Netzer, 2004). The region directly behind the shock wave is a region of stable high pressure which is known as the von Neumann spike. The spike is typically on the order of nanometers long. The ZND model uses detailed chemical kinetics which are unable to be solved analytically, but this theory can be used to

calculate parameters based on the detonation wave structure (James, 2001).

Figure 1.3 Detonation Wave (Bussing & Pappas, 1994)

The Chapman-Jouguet (CJ) theory is based on conservation of mass, momentum and energy as well as thermodynamics. It uses a one-dimensional model to relate equilibrium properties before and after the combustion region. The von Neumann spike is neglected in this model and the CJ theory cannot be used to calculate parameters that are based on the detonation wave structure (James, 2001).

The strong deflagration, weak deflagration, weak detonation, and strong detonation solutions are points of intersections of the Hugoniot curve and the Rayleigh line, see Figure 1.4. The Hugoniot equations relate upstream and downstream thermodynamic properties of the combustion zone and the Rayleigh line is a rearrangement of the continuity and momentum equations. The Chapman-Jouguet points are tangency points between the Hugoniot curve and a line through (P_I, v_I) or (initial pressure, initial specific volume). The upper CJ point corresponds to the minimum wave speed needed to achieve self-sustaining detonation (Bussing & Pappas, 1994). At the Chapman-Jouguet condition, the flow velocity at the end of the reaction zone is sonic (Ciccarelli & Dorofeev, 2008). The peak detonation velocity is achieved with an equivalence ratio of about 1.2 in saturated

hydrocarbon-air mixtures and about 1.3 in unsaturated hydrocarbon-air mixtures (Roy, Frolov, Borisov, & Netzer, 2004). Ethylene, which will be used for this investigation, is an unsaturated hydrocarbon due to its chemical structure.

Figure 1.4 Rayleigh Line & Hugoniot Curve (Bussing & Pappas, 1994)

To calculate the detonation parameters at the upper CJ point for a 1.3 equivalence ratio ethylene-air mixture, the NASA Chemical Equilibrium with Applications (CEA) calculator was used (NASA Glenn Research Center, 2015). The pressure (P), temperature (T), Mach number (M), density (ρ) and detonation velocity are shown in Table 1.1. The subscript 1 represents initial or upstream conditions. See Appendix A for complete calculations.

Table 1.1 Calculated Upper-CJ Point (NASA Glenn Research Center, 2015)

Parameter	Value
P/P_1	17.524
T/T_1	9.477
M/M_1	0.9772
ρ/ρ_1	1.8070
Det Mach Number	5.1711
Det Velocity, m/s	1787.0

The detonation pressure is calculated to be 17.5 times the initial conditions. The detonation temperature and density are 9.5 and 1.8 times the initial conditions, respectively. The detonation wave Mach number is 5.2 and the detonation wave velocity is 1787 m/s.

1.5.2. Detonation Wave Structure

The detonation wave has a “fish scale” like cell structure created by shock wave interactions. “The cellular nature of the detonation front is caused by the rapid heat release that warps the flame front, thus causing curved shocks, which interact by means of triple shock interactions” (Ragland & Bryden, 2011). The shocks that make up the triple-shock points are an incident shock, a transmitted or Mach-stem shock and a reflected shock. The incident shock reflects obliquely toward the intersection. The transmitted shock, also known as a Mach-stem, is normal to the flow and intersects with the incident shock. Since this shock is normal to the flow it is the strongest shock wave. The reflected shock handles pressure discrepancies in the flow (Ragland & Bryden, 2011). The minimum diameter for self sustaining detonation waves to propagate is approximately twice the detonation cell width. For an ethylene-air mixture, the cell width is approximately 20 to 31 mm (0.787 to 1.22 inches) (James, 2001). Figure 1.5 depicts the cellular structure of a detonation wave with points A, B, C and D as triple points.

Figure 1.5 Detonation Wave Cell Structure (Turns, 2000, p. 617)

1.6. The Pulse Detonation Engine Cycle

The pulse detonation engine cycle is a multistep process. First, the combustion chamber is filled with a fuel-oxidizer mixture. For the experiments conducted, Ethylene and air were used as the fuel and oxidizer, respectively. Then, the detonation wave is initiated. This can be achieved by either direct initiation or a transition from deflagration. For hydrocarbon fuels, the energy required for direct initiation renders it cost-prohibitive in an air-breathing PDE although hydrocarbon fuels are preferable due to their high energy density (Frolov, Pulse Detonation Propulsion, 2010). The experiments conducted achieve detonation by transitioning from deflagration. See Section 1.7 for more on the deflagration-to-detonation transition. Next, the detonation wave propagates through the combustion chamber propelled by the pressure difference between the chamber pressure and the external pressure. Behind the detonation wave, an expansion wave, known as the Taylor expansion fan, propagates in order to satisfy the zero velocity closed-end boundary condition (Ciccarelli & Dorofeev, 2008). Then, the burned gases are expelled from the combustion chamber in a blowdown process (Bussing & Pappas, 1994). This process is shown in Figure 1.6. Due to the lengthy deflagration-to-detonation transition (DDT) length in an unobstructed pulse detonation engine, obstacle use has been widely investigated to shorten this transition. The filling process and the exhausting process are typically the longest-duration processes (Bussing & Pappas, 1995).

Figure 1.6 Pulse Detonation Cycle (Bussing & Pappas, 1995)

1.7. Deflagration-to-Detonation Transition

According to Frolov, in a gaseous propane-air mixture, no less than 260 tube diameters are needed to achieve DDT in a straight, smooth tube and no less than 60 diameters for a straight tube with regular obstacle turbulence promoters (Frolov, Pulse Detonation Propulsion, 2010). Regular orifice plate obstacles are a popular turbulence promoter and have been used for multiple studies. Orifice plates are annular in shape and are referred to by their blockage ratio. The blockage ratio is the percentage of the cross sectional area of the obstacle with respect to the cross sectional area of the PDE and can be calculated using Equation 1.2.

$$BR = \frac{\text{Cross Sectional Area of PDE} - \text{Cross Sectional Area of Obstacle}}{\text{Cross Sectional Area of PDE}}$$

$$BR = \frac{\frac{1}{2} \pi r_{PDE}^2 - \frac{1}{2} \pi r_{ObsID}^2}{\frac{1}{2} \pi r_{PDE}^2} = \frac{r_{PDE}^2 - r_{ObsID}^2}{r_{PDE}^2}$$

Equation 1.2. Blockage Ratio

The DDT process starts with the weak ignition of a combustible material which then propagates subsonically as a deflagration by transport of mass and energy through diffusion. As the laminar flame, which initially has a smooth surface, propagates, the flame front becomes wrinkled due to Landau-Darrieus instability (Ciccarelli & Dorofeev, 2008). Darrieus (1938) and Landau (1944) independently discovered that planar deflagrations are unconditionally unstable (Matalon, 2007). This instability results in turbulence, which results in an increased flame surface area which increases the reaction rate and the flame velocity. Acoustic waves, such as those generated by obstacles and walls, can also further increase the flame surface area. Obstacles in the path of the flow cause a swift increase in

the surface area of the flame (Ciccarelli & Dorofeev, 2008). See Figure 1.7 for an example of flame propagation through obstacles.

Figure 1.7 Flame Propagation with BR=0.6 Obstacles in 70% H₂-Air Mixture (Ciccarelli & Dorofeev, 2008)

Although turbulence can increase the area of the flame front which increases the flame velocity, too much turbulence can cause quenching which is the phenomenon where the flame is accelerated and is then extinguished. This decreases the energy release rate. This phenomenon is often seen when higher blockage ratio orifice plates are used (Ciccarelli & Dorofeev, 2008).

As the flame accelerates, compression waves are formed ahead of the deflagration reaction zone and then a leading shock wave forms. The detonation wave initiates the chemical reaction, and therefore, the detonation wave and its associated chemical reaction zone are coupled. Due to the coupled detonation wave and reaction zone, the leading shock wave and deflagration do not merge to form a detonation wave, rather a localized explosion occurs in the region between the leading shock and the combustion zone which produces a detonation wave front. This is referred to as the “explosion in the explosion” phenomenon. Detonations can also be triggered by shock waves reflecting off of obstacles or the pulse detonation tube walls (Ciccarelli & Dorofeev, 2008).

1.8. Literature Survey and Experiments Conducted

There have been many experiments conducted in the area of pulse detonation with the goal of decreasing the deflagration-to-detonation transition (DDT) length.

The first to utilize orifice plate obstacles was Chapman and Wheeler. A methane-air mixture was used in a 5 cm inner diameter (ID) tube with one diameter spacing between obstacles. Without obstacles, the flame velocity reached 10 m/s but with obstacles over 400 m/s was achieved. Transition to detonation was not observed (Ciccarelli & Dorofeev, 2008).

To increase the turbulence, Shchelkin placed a wire coil helix in the tube to artificially roughen the tube. Shchelkin spirals are commonly used to reduce DDT distance in PDEs. Shchelkin, Salamandra and Soloukhin demonstrated that flame acceleration depends on the roughness of the wall. For obstacles with blockage ratios of less than 10%, the flame acceleration and flame structure are similar to those in a smooth walled tube (Ciccarelli & Dorofeev, 2008).

The effect of obstacle shape was studied by Frolov. Research was conducted to develop an “efficient means for reducing the deflagration-to-detonation transition run-up distance and time” (Frolov, Detonation Initiation Techniques for Pulse Detonation Propulsion, 2009). Both constant blockage ratio orifice plates and “saw-tooth” shaped obstacles were considered. The height of the saw-tooth and the orifice plates were held constant as well as the number of obstacles. See Figure 1.8 for a depiction of the obstacles used. With the orifice plates, detonation was only achieved with fuel-oxidizer mixture, kerosene TS-1 (JetA) and air, entering with Mach numbers greater than 4.5 but no “fast DDT” was detected, whereas detonation could be achieved with an initial Mach number of

A study was conducted using a detonation tube with two turbulizing chambers at the ignition section, chambers incorporated throughout the entire length of the tube and two chambers at the far end of the detonation tube. The chambers were 100mm in diameter by 100mm long and the tube was 20mm in diameter by 2.95m long. The distance between

chambers was 50mm. Results showed that increasing the number of turbulizing chambers prevented the onset of detonation due to the “sharp variations in cross-section area in the chamber and periodic flame slowing down due to its expansion” (Smirnov, Nikitin, Shevtsova, & Legros, 2006).

Figure 1.10 Turbulizing Chambers (Smirnov, Nikitin, Shevtsova, & Legros, 2006)

At the Naval Postgraduate Research School, research was conducted on the effects of swept ramp obstacles. It was found that the most favorable swept ramp configuration produced a 50% lower pressure loss than wall-spiral (Shchelkin spirals) approaches. These pressure loss reductions can decrease the time for the refresh portion of the engine cycle which accounts for approximately 60% of the total engine cycle time. The swept ramp obstacles also resulted in 25% greater refresh Mach numbers and thrust than spiral counterparts. This was attributed to more favorable turbulence and mixing flow direction. The testing was conducted using an ethylene-air mixture (Brophy, Dvorak, Dausen, & Myers, 2010).

Figure 1.11 Swept Ramp Obstacles (Brophy, Dvorak, Dausen, & Myers, 2010)

Experimental research with a valve-less PDE, operated using a stoichiometric ethylene and air mixture, was conducted with hybrid DDT enhancement devices. The DDT enhancement devices used were orifice plate obstacles, vortex generators, vortex generators with ignition spark plugs, and Shchelkin spirals. The study used ten hybrid obstacle configurations comprised of the above mentioned devices. It was concluded that the DDT transition takes place following the obstacle termination more frequently than within the obstacles and that the effectiveness of DDT enhancement devices is dependent on the operating frequency of the PDE (Li, Teo, Lim, Wen, & Khoo, 2013).

Figure 1.12 Vortex Generators used by Li et al.

Computational research performed by Gamezo shows that small spacing between obstacles initially accelerated the flame faster but the spacing must then be large enough for Mach stems to form. It was also found that for blockage ratios from 0.31 to 0.56, the distance to DDT did not change significantly but there were significant increases in DDT length outside of the previously mentioned range. Larger obstacles promoted flame acceleration but weaken diffracting shocks. A two-dimensional channel with evenly spaced obstacles of varying height were used in this investigation (Gamezo, Ogawa, & Oran, 2007).

1.9. Gas-Turbine Engine Integration

Much of the pulse detonation research is focused on the impulse thrust of a PDE which exhausts into the atmosphere, whereas the goal of this investigation is working toward the integration of pulse detonation engines into gas turbine engines. By decreasing the length of the pulse detonation engine, integration into a gas turbine engine becomes more feasible. There are still many challenges associated with implementation, including the unsteadiness of the pulse detonation cycle since current turbines are designed for steady-state operation (Caldwell, Glaser, & Gutmark, 2006).

Experimental research was conducted by GE Global Research on the effects of a multi-tube pulsed detonation combustion system on an axial turbine. The investigation was conducted with an eight tube can-annular array integrated with a single stage axial turbine. The high pressure core of a gas turbine engine was replaced by an array of pulse detonation chambers. The Numerical Propulsion System Simulation (NPSS) tool was used to model the hybrid PDE-Gas Turbine Engine which produced a 2% greater thrust with an 8-10% lower TSFC than conventional gas-turbine engines. See Figure 1.13 for a depiction of the Hybrid (PDE) Engine analyzed (Rasheed, Furman, & Dean, 2005).

Figure 1.13 Pulse Detonation Combustor Integration

Also at General Electric, experimental testing was conducted using a 2D turbine blade cascade. High speed shadowgraph images were taken of the detonation wave propagating through the 2D blade cascade. It was seen that the reaction front and the shock wave were decoupling, which was attributed to the area increase of the duct leading up to the blade cascade. In Figure 1.14 (d) the shock wave is exiting the blade cascade as the reaction zone interacts with the leading edge. The strong compression waves reflecting off of the turbine blades affected the mass flow rate of the PDE but did not prevent the PDE from operating continuously for seven cycles of operation. Quasi-steady pressure values were achieved after 5-6 cycles and quasi-steady temperature values were achieved after 2-3 cycles (Haubert, Rasheed, Tangirala, Vandervort, & Dean, 2004).

Figure 1.14 (a) 2.91ms (b) 3.05ms (c) 3.14ms (d) 3.32ms (Haubert, Rasheed, Tangirala, Vandervort, & Dean, 2004)

An investigation at Brigham Young University was done with a full annular pulsed, compressed air flow into a turbine in an effort to compare the steady flow of a traditional gas turbine engine with the pulsating flow of a hybrid-PDE engine. It was found that the operation curves of the pulsating flow were similar to the steady flow but with decreased

turbine performance. At higher operating frequencies, the drop in efficiency and specific power between the pulsed flow and steady flow decreases. Frequencies tested included 40 Hz, 20 Hz and 10 Hz (Fernelius, 2013).

It has been shown that pulse detonation engines can be integrated with a turbine but with many significant challenges that must be overcome. Challenges include a drop in turbine efficiency and a decrease in the PDE mass flow as well as unsteady combustion, turbine wear, heating and noise (Frolov, Pulse Detonation Propulsion, 2010).

2. EXPERIMENTAL SET-UP

2.1. The Pulse Detonation Engine

The pulse detonation engine (PDE) used consists of three main sections; an ignition section, a detonation transition section, and a measurement section. The majority of fuel and air are injected into the PDE in the ignition section. The fuel-air mixture is then ignited and the flame propagates through the detonation transition section. The detonation transition section has a circular cross section with a 1.705-inch inner diameter. This was determined by the detonation wave cell width for a stoichiometric ethylene-air mixture, which is approximately 0.8 inches wide. For self-sustaining detonation waves to propagate, the inner diameter should be at least twice the detonation cell width. Therefore, the minimum inner diameter is approximately 1.6 inches (James, 2001). Once the combustion region has traversed the detonation transition section, it enters the measurement section where pressure measurements and flame passage times are collected.

Figure 2.1 Pulse Detonation Engine (Tate, 2015)

2.1.1. PDE Tube

The PDE tube was constructed from schedule 80 Stainless Steel 304. It has a nominal inner diameter of 2". The nominal wall thickness is 0.216" with a minimum wall thickness of 0.189". It has a maximum working pressure (at ambient temperature) of 3,411

psi and a burst pressure of 13,642 psi.

2.1.2. Flanges and Components

Flanges are used to bolt multiple tube sections and/or fuel injectors together. Flanges are socket-welded, Class 300, which conform to MSS SP-6, MSS SP-25, ASTM A182 and ANSI/ASME B16.5 standards. Flange gaskets, depicted between flanges in Figure 2.2, are Full Face Gaskets conforming to ASME B16.20, Class 300, NOVATEC 925F Engineered Graphite which are able to withstand 925°F temperatures. Bolts are Grade 2 Stainless Steel bolts with a maximum tensile strength of 70 ksi.

Figure 2.2 Flange Assembly

2.2. The Ignition Section

The ignition section tube is approximately 13” long and the spark plug is located approximately 6” prior to the beginning of the obstacle section. As part of the ignition section, air and fuel are input at the head of the ignition section and between the ignition section and the detonation transition section.

Figure 2.3 Ignition Section

2.2.1. Ignition Coil, Igniter and Power Supply

The ignition module is manufactured by BOSCH and is powered by a B&K 1692 Switching Mode DC Power Supply. The power supply was used to power the injection driver box, ignition coil and igniter. The 13.8V direct-current mode with 40A continuous output was used. It is connected to an Autolite 26 spark plug.

2.2.2. Fuel and Air Input

At the head of the ignition section there is one fuel and two air injection points. The first is an air injector that is parallel to the flow. Directly following that, there is an injection plate with swirled fuel and air injection. There are additional injection plates between the ignition section and the detonation transition section and between the detonation transition section and the measurement section to fill the entire PDE with the ethylene-air mixture. The design of the injector plates swirls the fuel and air to promote mixing. See Figure 2.4 for a depiction of the fuel and air injector plates.

Figure 2.4 Injector Plate

An issue encountered previously by graduate students with the PDE used is fuel and air mixing (Tate, 2015). Ideally the fuel and air would be pre-mixed for a more consistent mixture but due to the laboratory environment, pre-mixing the fuel and air could create a safety hazard. Early investigations led to the restructuring of the fuel and air injection pulses to optimize detonation. Initially the fuel was input in two pulses in the center of the two air pulses respectively (see Figure 2.5) but investigations revealed that that fuel-air mixing was not sufficient to achieve repeatable detonations. For the testing conducted, the air is input in one pulse with the fuel input in six short pulses divided across the duration of the air pulse (Figure 2.6) to fill the PDE with a 1.3 equivalence ratio ethylene-air mixture. To inject the fuel and air into the PDE, Alternative Fuel Systems, Inc. Gs Series fuel injectors were used.

Figure 2.5 Firing Cycle 2 (Tate, 2015)

0 - Off 1 - On

Figure 2.6 New Fuel and Air Firing Cycle

There were no injection curves for ethylene but, since the molecular weight of air is 28.97 and the molecular weight of ethylene is 28.05, the air injection curves were used for the ethylene injection calculations since, of the given curves, air most closely correlated with ethylene's physical properties. A curve fit was done to calculate the duration of the pulse needed to inject the correct mass of air and fuel into the PDE. See Appendix B for the fuel curves used and Appendix C for mass calculations.

A study was done to determine the ideal fuel and air supply pressures to achieve the most repeatable detonations. It was found that the ideal air supply pressure was 57 psi and that the ideal fuel supply pressure was 25 psi. The air-line was connected to an

accumulator tank prior to the injector to decrease the pressure loss in the system during pulses.

2.3. Detonation Transition Section

Two different detonation transition section configurations were utilized for the two phases of testing. The first phase was an exploratory phase, and the second phase looked at the most successful configurations from the first phase and used additional sensors to gather more data about the deflagration-to-detonation transition. The first phase utilized a single 61-inch-long tube for the detonation transition section whereas, the second phase used two 31-inch-long tube sections bolted together to make up the detonation transition section. The second tube section, used for the second phase of testing, had 14 additional sensors spaced at 4" intervals along its length. At each location, a pressure transducer and an ion probe were axially co-located but clocked at 90 degrees to each other. In Figure 2.7, the configuration on the left was utilized for phase one and the configuration on the right was utilized for the second phase of testing. See Section 2.4 for more information on the sensors used.

Figure 2.7 Phase 1 (left) and Phase 2 (right) PDE Configurations

2.4. Measurement Section

The measurement section contained two ion probes and four pressure transducers. The pressure transducers were used to determine the peak pressure which corresponds to the pressure when the detonation or deflagration wave passes the probe. The ion probes register a voltage spike when the flame front passes. A virtual instrument (VI) was developed in LabVIEWTM to control the fuel and air input timing, spark timing and record data from all six sensors. The pressure readings were compared to the calculated upper Chapman-Jouguet pressure for self-sustaining detonation waves. The wave velocity was calculated using the flame passage measurements from the ion probes and compared to the calculated upper CJ velocity. These measurements were used to determine the detonation success rate. The detonation success rate is the percentage of successful detonations for a given configuration. The sensors on the measurement section were only used for the first phase of testing.

2.4.1. Pressure Transducers

PCB Piezoronics, Inc. Model 111A24 pressure transducers were used to record pressure measurements. The pressure transducer had approximately a 5 mV/psi sensitivity with a NIST calibration certificate. They are limited to a steady state operating temperature range from -100°F to 275°F but are able to withstand flash temperatures of 3000°F.

2.4.2. Ion Probes

The ion probes used were Autolite brand number 26 spark plugs connected to a signal conditioner. The ion probes were aligned axially with pressure transducers and mounted at ninety degrees counter-clockwise from the pressure transducers. Coincident

pressure spikes and flame fronts (as measured by the ion probes) would further indicate a successful detonation, since the detonation wave and combustion region are coupled.

2.4.3. Data Acquisition

A National InstrumentsTM USB-6351 X Series Multifunction Data Acquisition (DAQ) device was used to log data from pressure transducers and ion probes. For multi-channel analog inputs, a sampling rate of up to 1.25 MHz (aggregate) with 16-bit resolution was achievable. The range of the device was ± 10 V. The DAQ was also used to trigger the fuel and air injection solenoids and the igniter.

2.4.4. Signal Conditioner

A PCB Piezotronics, Inc. Model 482C15 signal conditioner was used to provide current to the pressure transducers and ion probes. The signal conditioner supported up to four channels.

2.5. LabVIEWTM Interface

Two LabVIEWTM virtual instruments were utilized for testing. The first interface was used for the first phase of testing and the second was used for the second phase of testing which incorporated the use of additional sensors. With the virtual instruments, the air injection, fuel injection, ignition was executed and data logging was controlled. See Figure 2.8 for the interface used for the first phase of testing and Figure 2.9 for the interface used for the second phase of testing.

Figure 2.8 LabVIEW™ Interface Phase 1

The user interface and block diagram were modified from the LabVIEW™ virtual instrument utilized by Tate who was a previous graduate student researcher in the ERAU Gas Turbine Lab using the same PDE configuration as phase one (Tate, 2015).

With the sensor tube, there were 7 sensor locations with pressure transducers and ion probes co-located. The hardware was only able to support a total of 6 sensors, therefore, the second interface was created to include additional information about the serial numbers of the pressure transducers and the locations of the sensors in use. Phase two used three ion probes and three pressure transducers whereas, phase one used four pressure transducers and two ion probes. The remainder of the interface and coding remained the same between the two interfaces for the two phases of testing.

Figure 2.9 LabVIEW™ Interface Phase 2

The parameters used for both phases of testing are tabulated in Table 2.1. The PDE was run for single pulses operating at 4 Hz. There were 6 fuel pulses spread across a singular air injection pulse. Air and fuel were input at 4 and 3 locations along the PDE, respectively to create a 1.3 equivalence ratio fuel-air mixture. This mixture was injected to fill 100% of the 97 inch long PDE. The gauge pressure of the air and fuel were set to 57 psi and 25 psi, respectively. This was determined to be optimal from initial testing. There was a 0.05 second start delay for fuel and air injection. The spark is delayed 100 milliseconds and the spark duration is 20 milliseconds. The sampling rate is 233,333 Hz which is limited by the sampling rate of the DAQ.

Table 2.1 LabVIEW™ Input Parameters

Parameter	Input Value
Number of Pulses	1
System Pulse Frequency (Hz)	4
Fuel Pulses	6
Air Injectors	4
Fuel Injectors	3
Fuel Pressure (psig)	25
Oxidizer Pressure (psig)	57
Equivalence Ratio	1.3
Start Delay (s)	0.05
Fill Percentage (%)	100
Tube Length (in)	97
Spark Delay (ms)	100
Spark Time (ms)	20
Sample Rate (Hz)	233333

LabVIEW™ uses a graphical programming structure. The front panel or user interface is coded via block diagram coding. The block diagram code for the second phase of testing is shown in Figure 2.10 and Figure 2.11. The left-hand side of the block diagram code is identical for the first and second phases of testing. The variation between the virtual instruments is additional blocks representing information about the sensor locations and the pressure transducer serial numbers in the phase two interface which is shown in the box on the right hand side of the block diagram coding. The serial numbers are important to convert the signal in mV to psi. The block diagram took the fuel and air input parameters given in the LabVIEW™ interface and calculated the length of the fuel and oxidizer pulses needed to fill the PDE based on the selected fuel and oxidizer types, specified equivalence ratio, number of fuel injectors, number of air injectors, tube length, percentage of PDE tube to be filled, the overall number of pulses and the number of fuel pulses for each air pulse. Then based on the start delay, spark delay, and spark time the timing of inputs and spark was determined. See Appendix C for the methodology used to program the user interfaces.

When the air, fuel, and ignition were turned on, the code can be executed by pushing the run button. This will calculate filling parameters and send a signal to the PDE to execute firing and return data from sensors through the DAQ. The calculations, and data from the sensors is then displayed on the front panel.

Figure 2.10 LabVIEW Block Diagram LHS

Figure 2.11 LabVIEW™ Block Diagram RHS

The data collected was then analyzed in MATLAB to determine the maximum pressure of each pressure transducer and the flame velocity from the ion probe voltage spikes for both phases of testing.

2.6. PDE Improvements

Issues were encountered replicating Tate's results (Tate, 2015). Initial testing was done with Tate's configuration 2 which used 44% blockage ratio orifice plates with 2" spacing between each obstacle. Firing cycle 2 was used for injection of fuel, injection of air and spark time. See Figure 2.5 for firing cycle 2 timing. This cycle used two air and fuel pulses with the fuel pulse centered within the air pulses (See Figure 2.6). Replication of a 90% detonation success rate was not achieved. Peak pressures achieved ranged from approximately 75psi to 90psi with an air supply pressure of 87 psig and a fuel supply pressure of 29 psig.

Tate encountered issues with fuel and air mixing. In an attempt to improve fuel and air mixing, the fuel and air injector plate between the detonation transition section and the measurement section was moved adjacent to the injector plate at the head of the injection section but with the orientation of opposing swirl. It was determined that the initial configuration which is mentioned in Section 2.2.2 yielded the greatest success.

Multiple improvements were made to the PDE. An air accumulator tank was added to decrease pressure loss during air injection, supply lines were replaced and maintenance was performed on injectors. The LabVIEW™ block diagram was modified to change the firing cycle to a single air pulse with multiple fuel pulses within (See Figure 2.5). Testing was conducted on the optimal number of fuel pulses per air pulse, which was deemed to be 6 pulses. The calculations for pulse length were driven by the injection curves in Appendix

B and methodology in Appendix C.

When trials were complete, fuel is shut off at the source and the PDE is run to eliminate excess fuel in the line. While the PDE was being run with fuel off at the supply, detonation was achieved with a fuel pressure of approximately 20 psi where it previously was not with 29 psi. This led to a study of fuel and air supply pressures. The fuel and air were tested at a wide range of supply pressures. An air supply pressure of 57 psi with a fuel pressure of 25 psi was found to be the optimal. This study was done coincidentally with the optimization of the number of fuel pulses.

3. EXPERIMENTAL PROCEDURE

There have been multiple experiments conducted with orifice plates, but the blockage ratio of the orifice plates was held constant throughout the tube as spacing was varied. Tate (Tate, 2015) conducted experiments where variable blockage ratio orifice plates were investigated but the spacing between obstacles remained at approximately one diameter. This study investigates the effect of both varied spacing and varied blockage ratios including test configurations where the spacing between obstacles varies from obstacle to obstacle in the same configuration.

3.1.Obstacles

In the detonation transition section, various configurations of regular orifice plate blockages and spacers were investigated. All obstacles used are annular in shape with the outer diameter equal to the inner diameter of the detonation transition section and varying inner diameters. There were five different blockage ratios of obstacles used in testing. The five obstacles employed had blockage ratios varying from 29% to 59%. See Table 3.1 for the inner diameter of the five different obstacles used and their respective blockage ratios.

Figure 3.1 Orifice Plates

Table 3.1 Diameter and Blockage Ratios

Number Obstacle	Inner Diameter	Blockage Ratio
1	1.438"	29%
2	1.391"	33%
3	1.277"	44%
4	1.154"	54%
5	1.090"	59%

Spacers were used to separate the obstacles. The spacers had a 1.705" inner diameter and were 2" long which is equivalent to 1.173 times the inner diameter (D). All obstacle and spacing configurations were tested in the detonation transition section. Due to the length of the stoppers, at the beginning and end of the detonation transition section, used to hold the obstacles in place during operation of the PDE, the obstacle configuration made up 54" of the detonation transition section.

3.2. Benchmark from Tate (Tate, 2015)

Tate performed experiments on the effect of variable blockage ratio obstacles on the deflagration-to-detonation transition in the ERAU Gas Turbine Lab. The experiments were conducted on the same PDE test rig. Thirteen different configurations were tested, all with two-inch spacing between obstacles. The configurations included three constant blockage ratio configurations, shallow and steep converging, shallow and steep diverging, shallow and steep converging-diverging, two alternating at $\frac{1}{2}$ PDE length (one decreasing and one increasing), one alternating at $\frac{1}{4}$ PDE length, and one alternating every other blockage. See Figure 3.2 for a depiction of the configurations tested by Tate and Table 3.2 for the detonation success rate for each of the respective configurations (Tate, 2015).

Figure 3.2 Tate's Configurations (Tate, 2015)

Table 3.2 Tate's Detonation Success (Tate, 2015)

<i>Configuration</i>	Detonation Success
<i>1</i>	55 %
<i>2</i>	90 %
<i>3</i>	0 %
<i>4</i>	0 %
<i>5</i>	100 %
<i>6</i>	70 %
<i>7</i>	100 %
<i>8</i>	100 %
<i>9</i>	100 %
<i>10</i>	25 %
<i>11</i>	45 %
<i>12</i>	85 %
<i>13</i>	70 %

Tate found that shallow converging, shallow diverging and both converging-diverging orifice plate blockage ratios yielded the highest detonation success rates. All tests were performed with a two-inch space between each orifice plate. The PDE used by Tate is the same engine that is being used for the first phase of this investigation (Tate, 2015).

3.3. Phase 1: Test for Detonation Success

One-hundred and ninety-five different obstacle and spacing configurations were tested. These configurations were grouped into four categories. The first category contained configurations where the blockage ratio of the obstacles and the spacing between obstacles were held constant (CSCB). The second configuration contained configurations where the blockage ratio of the obstacles was held constant but the spacing between obstacles varied (VSCB). The third category contained configurations where the blockage ratio of the obstacles varied but the spacing between obstacles was held constant (CSVb). The fourth category contained configurations where both the blockage ratio of the obstacles and the spacing between the obstacles varied (VSVB).

The axial and radial dimensions given have been nondimensionalized by the diameter, and the orifice plate sizes have been nondimensionalized as a blockage ratio percentage. See Equation 3.1 for nondimensionalization used and Equation 1.2 for blockage ratio calculations.

<i>Measurement</i>	Non-Dimensionalization
<i>Axial Measurements</i>	$x_{nondim} = \frac{x_{actual}}{ID_{DDT\ Section}} = \frac{x_{actual}}{1.705}$
<i>Radial Measurements</i>	$r_{nondim} = \frac{r_{actual}}{ID_{DDT\ Section}} = \frac{r_{actual}}{1.705}$

Equation 3.1 Non-Dimensionalized Parameters

3.3.1. Constant Spacing & Constant Blockage Ratio (CSCB)

The constant blockage ratio (BR) and constant spacing category contained 54 configurations and was split into six groups. The first group, group A, contained 10 configurations where 33% blockage ratio orifice plates were used with a constant spacing between each obstacle. Alternating obstacle and spacing was used until the entire detonation transition section was filled. The configurations with lower spacing between obstacles contained more obstacles for this group. The configurations had spacing ranging from 1.173 times the inner diameter of the detonation transition section (D) (2") spacing to 11.72 D (20") between obstacles. In addition, the configurations with 4.69 D (8"), 5.87 D (10"), and 7.04 D (12") were tested with 29%, 44%, 54%, and 59% blockage ratio obstacles. See Figure 3.3 for three of the configurations that were contained in the CSCB group A. All three configurations shown have a different number of blockages, 27, 6 and 3 respectively which is dependant on the spacing.

Figure 3.3 Constant Blockage Ratio – Constant Spacing (Alt Obstacle and Spacing)

The second group, group B, contained 8 configurations where 33% blockage ratio orifice plates were used with constant spacing between each obstacle. The obstacle and spacing configuration was repeated until 3 orifice plates were used. Then, the remainder of the detonation transition section was then held at the 1.705" inner diameter (ID). The configurations had spacing ranging from 1.173 times the diameter (D) (2") spacing to 9.38 D (16") between obstacles. In group A, the 10.56 D (18") and 11.72 D (20") spacing both used 3 orifice plates, therefore the configurations were not re-tested. Groups C and D used a similar configuration to group B, but the obstacle and spacing configurations were repeated until 5 orifice plates and 7 orifice plates were used, respectively. See Figure 3.4 for an example of configurations that used a constant number of obstacles within the group and constant spacing between obstacles with varying spacing between configurations. The

configurations shown used 3, 5 and 7 obstacles representing configurations from group B, C, and D respectively with $3.52 D$ (6") between obstacles. The configurations with a set number of obstacles were conducted to eliminate number of obstacles as a variable. In group A, the obstacles and spacing was repeated until the end of the detonation transition section. This led to a larger number of obstacles in the configurations where small spacing was used and very few obstacles where the spacing was large. For example, the first configuration with $1.17 D$ (2") between obstacles used 27 obstacles, whereas the configurations with $10.56 D$ (18") and $11.73 D$ (20") only used 3 obstacles.

Figure 3.4 Constant Blockage Ratio – Constant Spacing (Set # Obstacles)

For groups E and F, $1.17 D$ (2") and $2.35 D$ (4") spacing between obstacles was used respectively. Each group contained 8 configurations. Prior to the first obstacle in the

obstacle and spacing configuration was a “run-up” distance ranging from 2.35 D (4”) to 18.77 D (32”) in increments of 2.35 D (4”). The obstacle and spacing configurations were repeated until 5 orifice plates were used. An example with a 7.04 D (12”) run-up distance and 1.17 D (2”), from group F, is shown in Figure 3.5. The run-up distance was to allow the flame front to develop and instabilities to begin to form before turbulence was induced by the obstacles.

Figure 3.5 Constant Blockage Ratio – Constant Spacing (Run-Up Distance)

3.3.1. Variable Spacing & Constant Blockage Ratio (VSCB)

The next group of configurations contained 16 configurations with constant blockage ratio orifice plates with variable spacing between obstacles. It was theorized that as the flame accelerated and the shock waves which interact to create triple points formed, specifically Mach stem shock waves, that greater spacing would promote DDT. Gamezo found that obstacle spacing must be great enough for Mach stems to form or else DDT would not occur (Gamezo, Ogawa, & Oran, 2007). Decreased spacing at the beginning of DDT would induce turbulence then the increase would allow Mach stems to form.

The first group, group A, contained configurations where the spacing between obstacles increased as the axial location along the detonation transition section increased. The spacing between obstacles increased by a constant value after each obstacle or after

every two obstacles. All four groups in the VSCB category used a set number of obstacles within the group. Groups A, B, and C used 5 obstacles and group D used 6 obstacles.

Group B contained configurations where the spacing between obstacles decreased as the axial location along the detonation transition section increased. The spacing mirrored the group A increasing spacing configuration but with decreasing spacing. See Figure 3.6 for a depiction of the increasing and decreasing spacing obstacle configurations from groups A and B, respectively. The spacing between the first two obstacles in Figure 3.6 on the increasing spacing graph is the same spacing as the spacing between the last two obstacles on the decreasing spacing graph.

Figure 3.6 Variable Spacing – Constant BR (Increasing and Decreasing)

The third group, group C, contained configurations where the spacing increased but the increase in spacing between obstacles was not constant. For example, the spacing between each obstacle doubled as the axial location along the detonation transition section increased or the spacing increased following the Fibonacci sequence.

The fourth and final group, group D, contained configurations where the spacing

between obstacles decreased then increased or increased then decreased. This group used 6 obstacles. The spacing increase and decrease were mirror image; the spacing between the first two obstacles was equivalent to the spacing between the last two obstacles. See Figure 3.7 for an example of group D configurations.

Figure 3.7 Constant BR – Variable Spacing (Inc-Dec and Dec-Inc)

3.3.2. Constant Spacing & Variable Blockage Ratio (CSVB)

The third category of configurations contained 85 configurations where the spacing between obstacles was held constant but the blockage ratio varied. The variable blockage ratio configurations were achieved with either 5 or 9 orifice plates. They were arranged in converging blockage ratios, diverging blockage ratios, centered throat converging-diverging (CD) blockage ratios, upwind (UW) throat converging-diverging blockage ratios and downwind (DW) throat converging-diverging blockage ratios configurations. Odd numbers of obstacles were used in order to have a defined throat for the converging-diverging configurations. See Figure 3.8 for an example with $5.87 D$ (10”) between each obstacle for all 5 of the variable blockage ratio orifice plate configurations. The

configurations shown utilized 5 orifice plates.

Figure 3.8 Variable BR – Constant Spacing Configurations

The first CSVB group, group A, utilized the same spacing configuration as the CSCB group C configurations which used five constant blockage ratio orifice plates. The

configurations had spacing ranging from $1.173 D$ (2") spacing to $7.04 D$ (12").

The second and fourth groups, group B and group D, mirror the constant blockage ratio with constant spacing configurations in group E and group F where $1.17 D$ and $2.35 D$ spacing between obstacles was used respectively. Prior to the first obstacle in the arrangement was a "run-up" distance ranging from $4.69 D$ (8") to $18.77 D$ (32") in increments of $4.69 D$ (8"). The obstacle and spacing configurations were repeated until 5 orifice plates were used. Group C used 9 obstacles in the same 5 blockage ratio configurations as the other 3 CSVB groups. See Table 3.3 for the orifice plates used in both the 5 and 9 orifice plate configurations. Group C contained 2 configurations, one with $1.17 D$ (2") between obstacles and the other with $2.35 D$ (4") between obstacles.

Table 3.3 Variable Blockage Ratio Configurations

<i>Configuration</i>	5 Orifice Plates	9 Orifice Plates
<i>Diverging</i>	5 – 4 – 3 – 2 – 1	5 – 5 – 4 – 4 – 3 – 2 – 2 – 1 – 1
<i>Upwind Con-Div</i>	3 – 5 – 3 – 1 – 1	3 – 4 – 5 – 4 – 3 – 3 – 2 – 2 – 1
<i>Con-Div</i>	1 – 3 – 5 – 3 – 1	1 – 2 – 3 – 4 – 5 – 4 – 3 – 2 – 1
<i>Downwind Con-Div</i>	1 – 1 – 3 – 5 – 3	1 – 2 – 2 – 3 – 3 – 4 – 5 – 4 – 3
<i>Converging</i>	1 – 2 – 3 – 4 – 5	1 – 1 – 2 – 2 – 3 – 4 – 4 – 5 – 5

3.3.3. Variable Spacing & Variable Blockage Ratio (VSVB)

The last category of contained 40 configurations where both the blockage ratio and the spacing between obstacles varied. All of the configurations were achieved with 5 blockages. The spacing between obstacles for groups A, B and C are the same as for the CSVB configurations, groups A, B and C respectively. All 5 blockage ratio schemes from the constant spacing with variable blockage ratio were used with each spacing configuration.

For all 195 configurations tested, see Appendix D.

3.3.4. Detonation Success

For each configuration, single pulse firings were used. Data from four pressure transducers and two ion probes was taken for twenty iterations of each configuration. Using MATLAB, the maximum pressure for each pressure transducer was determined, the flame velocity was calculated from the ion probes, and the detonation success was determined.

If an iteration achieved detonation by the measurement section, the iteration was considered successful. The percentage of successful iterations for each configuration determined the detonation success rate of its respective configuration. Detonation was considered to be achieved if the pressure met 95% of the upper CJ pressure for self-sustaining detonations and if the flame passage and pressure spike were aligned. The flame front and the combustion region are only a few millimeters apart and the detonation wave is moving at approximately 1787 meters per second therefore the time delay between the combustion region and the pressure spike is on the order of microseconds. Pressure transducer 3 and ion probe 1 were axially coincident as were pressure transducer 4 and ion probe 2. Figure 3.9 shows an iteration that successfully achieved detonation. It can be seen that the pressure spike and the flame passage for the coincident ion probe and pressure transducer pairs are nearly simultaneous and the detonation pressure is greater than the CJ detonation pressure.

Figure 3.9 Pressure Transducer and Ion Probe Data – Detonation

In many configurations, detonation was not achieved. The deflagration signal response has pressure spikes that were less than the upper CJ pressure and the ion probe spike was a longer, more gradual signal increase than the detonation response. Figure 3.10 depicts a configuration where DDT did not occur.

Figure 3.10 Pressure Transducer and Ion Probe Data – Deflagration

3.4.Phase 2 Testing: Test for DDT Length

The second phase of testing utilized the ten configurations from phase 1 that yielded the greatest detonation success rate. See Appendix D for details of the configurations listed in Table 3.4.

Table 3.4 Ten Most Successful Configurations

#	Case	Configuration Description	Detonation Success Rate
1	CSCB.A.5	33% BR – 5.87 <i>D</i> (10") Spacing	100%
2	VSVB.B.ii.4	5 Obstacles – Diverging – Decreasing Spacing	100%
3	CSCB.C.6	5 Obstacles – 33% BR – 7.04 <i>D</i> (12") Spacing	100%
4	CSCB.C.5	5 Obstacles – 33% BR – 5.87 <i>D</i> (10") Spacing	100%
5	CSCB.A.4	33% BR – 4.69 <i>D</i> (8") Spacing	95%
6	CSVB.A.iv.6	5 Obstacles – UW CD – 7.04 <i>D</i> (12") Spacing	95%
7	CSVB.A.v.5	5 Obstacles – DW CD – 5.87 <i>D</i> (10") Spacing	90%
8	VSCB.D.4	6 OP – 33% BR – Dec-Inc Spacing (16-8-4-8-16")	90%
9	CSVB.A.v.6	5 Obstacles – DW CD – 7.04 <i>D</i> (12") Spacing	85%
10	VSCB.D.1	6 OP – 33% BR – Inc-Dec Spacing (6-10-14-10-6")	80%

For each configuration, 100 iterations of pressure transducer and ion probe data were taken at sensor locations 2-7. These tests were also conducted as single pulse iterations. Since the sampling rate of the system can only handle six sensors at a time, testing was conducted with paired ion probes and pressure transducers at sensor locations 2, 3 and 4 then at sensor locations 5, 6 and 7. These location designations can be seen in Figure 3.11, along with the axial distance from the start of the detonation transition section.

Figure 3.11 Sensor Locations

4. RESULTS

4.1.Phase 1 Testing Results

Parameters associated with the obstacle configuration were compared to the detonation success of the configurations. These parameters include, the average spacing between obstacles as a function of the inner diameter of the detonation transition section, the number of obstacles in the configuration and the average blockage ratio of the obstacles. From these correlations, it is concluded that the optimal average spacing between obstacles is between 5.9 and 7.0 times the inner diameter of the detonation transition section.

Figure 4.1 Detonation Success as a Function of Blockage Parameters

For constant spacing with constant blockage ratio configurations, the variable between configurations within groups was spacing. Therefore, the spacing between obstacles versus the detonation success rate was compared and it was found that for the 33% blockage ratio orifice plates, the greatest success occurred with a spacing of $\sim 5.87 D$

(10") between obstacles. Configurations where the detonation transition section was filled with alternating obstacle-spacer arrangements and configuration with a set 5 obstacles, 100% detonation success was achieved with 5.87 D (10") spacing. With only 3 obstacles, detonation was not achieved with any spacing distance between obstacles. Using 7 obstacles, detonation was achieved with a 95 % success rate with 4.69 D (8") between obstacles which is identical to the configuration with alternating obstacle-spacer arrangements filling the detonation transition section of identical spacing. See Figure 4.2 for alternating obstacle-spacer arrangements to fill the detonation transition section (group A) and 5 obstacles (group C) spacing versus detonation success.

Figure 4.2 Detonation Success vs. Spacing Between CSCB Configurations

The standard deviation of the pressure measurements was examined. For configurations with high detonation success rates (greater than or equal to 80% success) the standard deviation between peak pressure measurements for a given pressure transducer

was approximately 100 psi with an average pressure of approximately 380 psi. Configurations where detonation success was low (less than or equal to 20% success) the standard deviation between peak pressure measurements for a given pressure transducer was approximately 18 psi with an average pressure of approximately 85 psi. For configurations with both high and low detonation success rates, the standard deviation was approximately 21 to 27% of the average pressure. See Figure 4.3 for an example of the standard deviation for a detonation successful case. The circular markers represent individual pressure readings and the bars represent two standard deviations from the mean which encompasses approximately 95% of the data.

Figure 4.3 All Peak Pressure Transducer Readings for CSCB.A.5

The configurations with downwind throat converging-diverging blockage ratios had the greatest detonation success for the variable blockage ratio configurations tested. This includes both the 5 and 9 blockage ratio configurations and constant spacing from $1.17 D$ (2") to $7.04 D$ (12"). In Figure 4.4, the detonation success rate for 4 different spacing

configurations was plotted cumulatively versus the obstacle blockage ratio configuration. Only spacings that achieved detonation success greater than 0% in at least one of the variable blockage ratio configurations is shown.

Figure 4.4 Cumulative Detonation Success for Variable BR Obstacle Configurations

All of the configuration where spacing preceded the obstacle configuration yielded a 0% detonation success rate. These tests were only conducted with 1.17 D (2") and 2.35 D (4") which yielded 0% detonation success without preceding obstacles in both the alternating obstacle-spacer arrangements and set number of obstacle configurations.

The 10 configurations with the greatest detonation success rate that were identified for additional testing are tabulated in Table 4.1. Of the cases identified, the detonation success rate was 80% or greater. The average velocity was 1730 m/s or greater with a calculated detonation velocity 1787 m/s. There were only 2 configurations, #9 and #10, where the average velocity fell below the calculated value. The average pressure was 337 psi or greater with a calculated detonation pressure of 258 psi. The pressure rise from the

detonation wave ranged from 23 to 28 times the initial pressure. See Figure 4.5 for the average pressures and velocities for the 10 cases with the greatest detonation success rate compared to the upper Chapman-Jouguet calculated values. The average spacing between obstacles for the ten most detonation successful configurations was 10 inches or 6.1 times the inner diameter of the PDE. The configuration group with the greatest number of detonation successful cases came from the constant spacing between obstacles with constant blockage ratios with 4 out of 10 of the cases. Next was the constant spacing variable blockage ratio cases with 3 out of 10. The variable blockage ratio cases only made up 3 of the 10 cases. Therefore, it can be concluded that constant blockage ratio orifice plate configurations have a greater detonation success rate.

Table 4.1 Ten Most Successful Phase 1 Cases

#	Case	Avg Blockage Ratio	Avg Spacing (in)	Avg Pressure (psi)	Avg Velocity (m/s)	Det Success Rate (%)
1	CSCB.A.5	33%	10.00	415	1956	100%
2	VSVB.B.ii.4	45%	11.00	411	1858	100%
3	CSCB.C.6	33%	12.00	391	2093	100%
4	CSCB.C.5	33%	10.00	377	1840	100%
5	CSCB.A.4	33%	8.00	407	1829	95%
6	CSV.B.A.iv.6	42%	12.00	389	2037	95%
7	CSV.B.A.v.5	42%	10.00	375	1932	90%
8	VSCB.D.4	33%	10.40	346	1861	90%
9	CSV.B.A.v.6	42%	12.00	337	1732	85%
10	VSCB.D.1	33%	9.20	385	1777	80%

Figure 4.5 Average Pressure and Velocity for Top 10 Configurations

4.2. Phase 2 Testing Results

Of the 10 configurations that were subjected to additional testing, 30% of the configurations achieved 100% detonation success in less than 30.8 diameter lengths which is equivalent to approximately 50 inches. The shortest length in which detonation was achieved with 100% success was 30.8 D . 40% of configurations achieved detonation with a 100% success rate in 33 inches and 80% of cases achieved detonation with a 90% success rate in 33 inches. Detonation was unachievable without obstacles in 82 diameters. With obstacles, a greater than 63% decrease in DDT length was achievable. See Table 4.2 for the detonation success at each sensor location for the ten most detonation successful configurations. The axial dimensions are given in terms of the number of diameters.

Table 4.2 Detonation Success Rate at Varying Axial Locations

<i>Config/Distance</i>	21.41	23.75	26.10	28.45	30.79	33.14
1	0%	4%	72%	89%	100%	100%
2	0%	0%	16%	66%	55%	96%
3	0%	0%	22%	80%	81%	96%
4	0%	15%	74%	75%	84%	100%
5	0%	11%	85%	53%	100%	100%
6	16%	62%	35%	64%	100%	100%
7	0%	3%	7%	43%	60%	94%
8	0%	0%	3%	22%	58%	72%
9	0%	0%	3%	39%	43%	88%
10	0%	0%	0%	21%	72%	98%

The average pressures for each configuration by axial location are depicted in Figure 4.6. As the axial distance increases, pressure also increases. In Figure 4.7, the average velocity is displayed. As with pressure, average velocity increases as the axial distance increases. The black line represents the calculated CJ values.

Figure 4.6 Average Pressure by Axial Location

Figure 4.7 Average Velocity by Axial Location

5. CONCLUSION

The optimal obstacle spacing is between 5.9 and 7 times the inner diameter of the PDE. The spacing is deemed to be large enough for Mach stems to form but not so large as to inhibit turbulence generation. Spacing held constant between obstacles yielded greater success than configurations where spacing varied from obstacle to obstacle. With the PDE configuration used in this investigation, a 33% blockage ratio was the most successful to induce turbulence and not quench the detonation wave. Three obstacles were not sufficient to achieve detonation even with favorable spacing. With five or more obstacles and favorable spacing, detonation was achievable with great success. Spacing preceding the obstacle configuration was deemed to be inconclusive because spacing between obstacles was not great enough for success in order to accommodate the preceding spacing. With these conditions, DDT was achievable with 100% success in 31 times the inner diameter of the detonation transition section where detonation was unachievable in 82 times the inner diameter in a “smooth” tube. This is a greater than 63% decrease in detonation transition length. This decrease in length will allow for the integration of pulse detonation engines into gas turbine engines.

6. RECOMMENDATIONS

Based on the results of this investigation, the following suggestions are provided as guidance for further study. The suggestions have been separated by the different physical features associated with them.

7.1. Verify Scaling

Test configuration with blockage ratio and spacing in terms of the inner diameter of the detonation transition section with a smaller or larger inner diameter. Determine if detonation cell size has an effect on the DDT length or if the measurements can be scaled as long as the minimum diameter for self-sustaining detonation waves to propagate has been met.

7.2. Obstacles

Use different shaped obstacles and determine their effect on obstacle spacing for minimum DDT length. Also, look in to more durable alternatives. Many obstacles, especially those with higher blockage ratios were deformed due to the high pressures achieved during operation.

7.3. Increase Frequency of Operation

In order for pulse detonations to produce quasi-steady thrust, the frequency of operation must be around 100 Hz. Currently the PDE is operating at 4 Hz. Improvements to the pulse detonation engine need to be made in order to improve the operating frequency prior to integration with a turbine.

7.4. Visual Representation

Use a visual method such as Computational Fluid Dynamics (CFD) or Schlieren Photography to see how the flow is interacting with the obstacles and how the flame accelerates due to these obstacle interactions to gain greater insight into designing PDEs.

7.5. Gas Turbine Integration

The goal of the research is to integrate PDEs into gas turbine engines. Once challenges with obstacle durability, operation frequency and continuous operation have been resolved in a single PDE, create amulet-tube array and work toward integration with an axial turbine.

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A. NASA CHEMICAL EQUILIBRIUM WITH APPLICATIONS UPPER-CJ POINT CALCULATION

11/16/2015

prob3772.html

NASA-GLENN CHEMICAL EQUILIBRIUM PROGRAM CEA2, FEBRUARY 5, 2004
BY BONNIE MCBRIDE AND SANFORD GORDON
REFS: NASA RP-1311, PART I, 1994 AND NASA RP-1311, PART II, 1996

```

prob case=prob3772 det
p,atm 1
t,k 298.15
phi 1 1.3
output short
output trans
output trace=1e-5
output transport
reac
fuel C2H4 wt%= 100.
oxid N2 wt%= 79.00
oxid O2 wt%= 21.00
end

```

DETONATION PROPERTIES OF AN IDEAL REACTING GAS

CASE = prob3772

	REACTANT	WT FRACTION (SEE NOTE)	ENERGY KJ/KG-MOL	TEMP K
FUEL	C2H4	1.0000000	0.000	0.000
OXIDANT	N2	0.7900000	0.000	0.000
OXIDANT	O2	0.2100000	0.000	0.000

O/F= 16.29498 %FUEL= 5.782024 R,EQ.RATIO= 1.000000 PHI,EQ.RATIO= 1.000000

UNBURNED GAS

```

P1, BAR      1.0132
T1, K        298.15
H1, KJ/KG    108.21
M1, (1/n)    28.724
GAMMA1       1.3837
SON VEL1,M/SEC 345.6

```

BURNED GAS

```

P, BAR      17.756
T, K        2825.58
RHO, KG/CU M 2.1215 0
H, KJ/KG     1215.88
U, KJ/KG     378.89
G, KJ/KG    -24571.0
S, KJ/(KG)(K) 9.1262

```

```

M, (1/n)    28.069
(dLV/dLP)t -1.00697
(dLV/dLT)p  1.1653
Cp, KJ/(KG)(K) 2.6612
GAMMA5      1.1685
SON VEL,M/SEC 988.9

```


11/16/2015

prob3772.html

TRANSPORT PROPERTIES (GASES ONLY)
 CONDUCTIVITY IN UNITS OF MILLIWATTS/(CM)(K)

VISC,MILLIPOISE 0.87687

WITH EQUILIBRIUM REACTIONS

Cp, KJ/(KG)(K) 2.6612
 CONDUCTIVITY 3.9322
 PRANDTL NUMBER 0.5934

WITH FROZEN REACTIONS

Cp, KJ/(KG)(K) 1.4614
 CONDUCTIVITY 1.8034
 PRANDTL NUMBER 0.7106

DETONATION PARAMETERS

P/P1 17.524
 T/T1 9.477
 M/M1 0.9772
 RHO/RHO1 1.8070
 DET MACH NUMBER 5.1711
 DET VEL,M/SEC 1787.0

MOLE FRACTIONS

*CO 3.1449-2
 *CO2 8.4257-2
 *H 1.5861-3
 *H2 5.5636-3
 H2O 1.0467-1
 *NO 8.6424-3
 *N2 7.4147-1
 *O 1.5241-3
 *OH 9.3432-3
 *O2 1.1471-2

* THERMODYNAMIC PROPERTIES FITTED TO 20000.K

NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS

DETONATION PROPERTIES OF AN IDEAL REACTING GAS

CASE = prob3772

	REACTANT	WT FRACTION (SEE NOTE)	ENERGY KJ/KG-MOL	TEMP K
FUEL	C2H4	1.0000000	0.000	0.000
OXIDANT	N2	0.7900000	0.000	0.000
OXIDANT	O2	0.2100000	0.000	0.000

O/F= 12.53460 %FUEL= 7.388471 R,EQ.RATIO= 1.300000 PHI,EQ.RATIO= 1.300000

UNBURNED GAS

P1, BAR 1.0132
 T1, K 298.15
 H1, KJ/KG 138.27
 M1, (1/n) 28.712
 GAMMA1 1.3797

<https://cearun.grc.nasa.gov/OFILES/prob3772.html>

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11/16/2015

prob3772.html

SON VEL,M/SEC 345.1

BURNED GAS

P, BAR 18.447
 T, K 2857.95
 RHO, KG/CU M 2.1021 0
 H, KJ/KG 1295.72
 U, KJ/KG 418.16
 G, KJ/KG -25550.3
 S, KJ/(KG)(K) 9.3935

M, (1/n) 27.078
 (dLV/dLP)t -1.00415
 (dLV/dLT)p 1.0969
 Cp, KJ/(KG)(K) 2.2127
 GAMMAS 1.1945
 SON VEL,M/SEC 1023.8

TRANSPORT PROPERTIES (GASES ONLY)

CONDUCTIVITY IN UNITS OF MILLIWATTS/(CM)(K)

VISC,MILLIPOISE 0.87784

WITH EQUILIBRIUM REACTIONS

Cp, KJ/(KG)(K) 2.2127
 CONDUCTIVITY 3.4479
 PRANDTL NUMBER 0.5634

WITH FROZEN REACTIONS

Cp, KJ/(KG)(K) 1.5000
 CONDUCTIVITY 1.9008
 PRANDTL NUMBER 0.6928

DETONATION PARAMETERS

P/P1 18.206
 T/T1 9.586
 M/M1 0.9431
 RHO/RHO1 1.7912
 DET MACH NUMBER 5.3133
 DET VEL,M/SEC 1833.9

MOLE FRACTIONS

*CO 8.2704-2
 *CO2 5.9928-2
 *H 3.4928-3
 *H2 2.2469-2
 H2O 1.1553-1
 *NO 2.6673-3
 *N2 7.0587-1
 *O 5.1226-4
 *OH 5.7779-3
 *O2 1.0513-3

* THERMODYNAMIC PROPERTIES FITTED TO 20000.K

NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS

<https://cearun.grc.nasa.gov/OFILES/prob3772.html>

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B. AIR AND FUEL CALCULATIONS

There were no injection curves for ethylene. Since MW_{air} is approximately 28.97 and MW_{ethylene} is approximately 28.05, the air injection curves were used for the ethylene injection calculations.

Figure B.7.1 Mass vs. Pulse Width for Air

C. LABVIEW™ CALCULATIONS

Fuel: Ethylene (C₂H₄)

Density ($\rho_{C_2H_4}$):	1.173 kg/m ³
Molecular Weight ($mw_{C_2H_4}$):	28.05 kg/kmol

Oxidizer: Air

Density (ρ_{air}):	1.275 kg/m ³
Molecular Weight (mw_{air}):	28.96 kg/kmol

Stoichiometric Chemical Equation:

Air-Fuel Ratio:

$$\left(\frac{A}{F}\right)_{stoic} = \frac{3 * 4.76 * mw_{air}}{1 mw_{C_2H_4}} = 3 * 4.76 * \frac{28.96}{28.05} = 14.74$$

Using Input Values:

Equivalence Ratio (ϕ):	1.3
Air Fuel Ratio:	

$$\left(\frac{A}{F}\right)_{actual} = \frac{\left(\frac{A}{F}\right)_{stoic}}{\phi} = 11.34$$

Determine Volume of Fuel and Oxidizer Needed to Fill PDE:

PDE Tube Length (L):	97 in
PDE Inner Diameter (D):	2 in
PDE Volume (V_{PDE}):	

$$V_{PDE} = \pi * \left(\frac{D}{2}\right)^2 * L = 304 \text{ in}^3 = 0.00499 \text{ m}^3$$

Mixture Molecular Weight (mw_{mix}):	28.89 kg/mol
--	--------------

Mixture Mass (m_{mix}):

$$m_{mix} = m_{air} + m_{C_2H_4}$$

Using the ethylene and air supply pressures and the manufacturer's curves for the injectors, appropriate volumes of air and fuel were input into the PDE. See Appendix B for the fuel and air injection curves.

Num	Case	Configuration (1-5 represents obstacles and “-” represents a 2” spacer)
53	CSCB.F.7	-----2- -2- -2- -2- -2- -2
54	CSCB.F.8	-----2- -2- -2- -2- -2- -2
55	CSV.B.A.i.1	1-2-3-4-5
56	CSV.B.A.i.2	1- -2- -3- -4- -5
57	CSV.B.A.i.3	1- - -2- - -3- - -4- - -5
58	CSV.B.A.i.4	1- - - -2- - - -3- - - -4- - - -5
59	CSV.B.A.i.5	1- - - - -2- - - - -3- - - - -4- - - - -5
60	CSV.B.A.i.6	1- - - - - -2- - - - - -3- - - - - -4- - - - - -5
61	CSV.B.A.ii.1	5-4-3-2-1
62	CSV.B.A.ii.2	5- -4- -3- -2- -1
63	CSV.B.A.ii.3	5- - -4- - -3- - -2- - -1
64	CSV.B.A.ii.4	5- - - -4- - - -3- - - -2- - - -1
65	CSV.B.A.ii.5	5- - - - -4- - - - -3- - - - -2- - - - -1
66	CSV.B.A.ii.6	5- - - - - -4- - - - - -3- - - - - -2- - - - - -1
67	CSV.B.A.iii.1	1-3-5-3-1
68	CSV.B.A.iii.2	1- -3- -5- -3- -1
69	CSV.B.A.iii.3	1- - -3- - -5- - -3- - -1
70	CSV.B.A.iii.4	1- - - -3- - - -5- - - -3- - - -1
71	CSV.B.A.iii.5	1- - - - -3- - - - -5- - - - -3- - - - -1
72	CSV.B.A.iii.6	1- - - - - -3- - - - - -5- - - - - -3- - - - - -1
73	CSV.B.A.iv.1	3-5-3-1-1
74	CSV.B.A.iv.2	3- -5- -3- -1- -1
75	CSV.B.A.iv.3	3- - -5- - -3- - -1- - -1
76	CSV.B.A.iv.4	3- - - -5- - - -3- - - -1- - - -1
77	CSV.B.A.iv.5	3- - - - -5- - - - -3- - - - -1- - - - -1
78	CSV.B.A.iv.6	3- - - - - -5- - - - - -3- - - - - -1- - - - - -1
79	CSV.B.A.v.1	1-1-3-5-3
80	CSV.B.A.v.2	1- -1- -3- -5- -3
81	CSV.B.A.v.3	1- - -1- - -3- - -5- - -3
82	CSV.B.A.v.4	1- - - -1- - - -3- - - -5- - - -3
83	CSV.B.A.v.5	1- - - - -1- - - - -3- - - - -5- - - - -3
84	CSV.B.A.v.6	1- - - - - -1- - - - - -3- - - - - -5- - - - - -3
85	CSV.B.B.i.1	---1-2-3-4-5
86	CSV.B.B.i.2	-----1-2-3-4-5
87	CSV.B.B.i.3	-----1-2-3-4-5
88	CSV.B.B.i.4	-----1-2-3-4-5
89	CSV.B.B.ii.1	---5-4-3-2-1
90	CSV.B.B.ii.2	-----5-4-3-2-1
91	CSV.B.B.ii.3	-----5-4-3-2-1
92	CSV.B.B.ii.4	-----5-4-3-2-1
93	CSV.B.B.iii.1	---1-3-5-3-1
94	CSV.B.B.iii.2	-----1-3-5-3-1
95	CSV.B.B.iii.3	-----1-3-5-3-1
96	CSV.B.B.iii.4	-----1-3-5-3-1
97	CSV.B.B.iv.1	---3-5-3-1-1
98	CSV.B.B.iv.2	-----3-5-3-1-1
99	CSV.B.B.iv.3	-----3-5-3-1-1
100	CSV.B.B.iv.4	-----3-5-3-1-1
101	CSV.B.B.v.1	---1-1-3-5-3
102	CSV.B.B.v.2	-----1-1-3-5-3
103	CSV.B.B.v.3	-----1-1-3-5-3
104	CSV.B.B.v.4	-----1-1-3-5-3
105	CSV.B.C.i.1	1-1-2-2-3-4-4-5-5
106	CSV.B.C.i.2	1- -1- -2- -2- -3- -4- -4- -5- -5
107	CSV.B.C.i.3	1- - -1- - -2- - -2- - -3- - -4- - -4- - -5- - -5

Num	Case	Configuration (1-5 represents obstacles and “-” represents a 2” spacer)
108	CSVB.C.ii.1	5-5-4-4-3-2-2-1-1
109	CSVB.C.ii.2	5- -5- -4- -4- -3- -2- -2- -1- -1
110	CSVB.C.ii.3	5- - -5- - -4- - -4- - -3- - -2- - -2- - -1- - -1
111	CSVB.C.iii.1	1-2-3-4-5-4-3-2-1
112	CSVB.C.iii.2	1- -2- -3- -4- -5- -4- -3- -2- -1
113	CSVB.C.iii.3	1- - -2- - -3- - -4- - -5- - -4- - -3- - -2- - -1
114	CSVB.C.iv.1	3-4-5-4-3-2-2-1-1
115	CSVB.C.iv.2	3- -4- -5- -4- -3- -2- -2- -1- -1
116	CSVB.C.iv.3	3- - -4- - -5- - -4- - -3- - -2- - -1- - -
117	CSVB.C.v.1	1-1-2-2-3-4-5-4-3
118	CSVB.C.v.2	1- -1- -2- -2- -3- -4- -5- -4- -3
119	CSVB.C.v.3	1- - -1- - -2- - -2- - -3- - -4- - -5- - -4- - -3
120	CSVB.D.i.1	- - -1- -2- -3- -4- -5
121	CSVB.D.i.2	- - - - -1- -2- -3- -4- -5
122	CSVB.D.i.3	- - - - - -1- -2- -3- -4- -5
123	CSVB.D.i.4	- - - - - - -1- -2- -3- -4- -5
124	CSVB.D.ii.1	- - -5- -4- -3- -2- -1- -
125	CSVB.D.ii.2	- - - - -5- -4- -3- -2- -1
126	CSVB.D.ii.3	- - - - - -5- -4- -3- -2- -1
127	CSVB.D.ii.4	- - - - - - -5- -4- -3- -2- -1
128	CSVB.D.iii.1	- - -1- -3- -5- -3- -1
129	CSVB.D.iii.2	- - - - -1- -3- -5- -3- -1
130	CSVB.D.iii.3	- - - - - -1- -3- -5- -3- -1
131	CSVB.D.iii.4	- - - - - - -1- -3- -5- -3- -1
132	CSVB.D.iv.1	- - -3- -5- -3- -1- -1- -
133	CSVB.D.iv.2	- - - - -3- -5- -3- -1- -1
134	CSVB.D.iv.3	- - - - - -3- -5- -3- -1- -1
135	CSVB.D.iv.4	- - - - - - -3- -5- -3- -1- -1
136	CSVB.D.v.1	- - -1- -1- -3- -5- -3
137	CSVB.D.v.2	- - - - -1- -1- -3- -5- -3
138	CSVB.D.v.3	- - - - - -1- -1- -3- -5- -3
139	CSVB.D.v.4	- - - - - - -1- -1- -3- -5- -3
140	VSCB.A.1	2-2-2- -2- -2
141	VSCB.A.2	2-2- -2- - -2- - - -2
142	VSCB.A.3	2-2- - -2- - - -2- - - - -2
143	VSCB.A.4	2-2- - - -2- - - - -2- - - - -2
144	VSCB.B.1	2- -2- -2-2-2
145	VSCB.B.2	2- - -2- - -2- -2-2
146	VSCB.B.3	2- - - - -2- - - -2- -2-2
147	VSCB.B.4	2- - - - - -2- - - - -2- - -2-2
148	VSCB.C.1	2-2- -2- - -2- - - -2
149	VSCB.C.2	2-2- -2- - -2- - - - -2
150	VSCB.C.3	2-2- -2- - - -2- - - - -2
151	VSCB.C.4	2-2- -2- - -2- - - - -2
152	VSCB.D.1	2- - -2- - - -2- - - -2- - -2- -2
153	VSCB.D.2	2- - - - -2- - - -2- -2- - -2- - - -2
154	VSCB.D.3	2- -2- - -2- - - - -2- - -2- -2
155	VSCB.D.4	2- - - - -2- - -2- -2- - -2- - - -2
156	VSVB.A.i.1	1-2-3- -4- -5
157	VSVB.A.i.2	1-2- -3- - -4- - -5
158	VSVB.A.i.3	1-2- - -3- - - -4- - - -5
159	VSVB.A.i.4	1-2- - - -3- - - - -4- - - - -5
160	VSVB.A.ii.1	5-4-3- -2- -1
161	VSVB.A.ii.2	5-4- -3- - -2- - -1
162	VSVB.A.ii.3	5-4- - -3- - - -2- - - - -1

Num	Case	Configuration (1-5 represents obstacles and "-" represents a 2" spacer)
163	VSVB.A.ii.4	5-4- - -3- - - - -2- - - - -1
164	VSVB.A.iii.1	1-3-5- -3- -1
165	VSVB.A.iii.2	1-3- -5- -3- - -1
166	VSVB.A.iii.3	1-3- -5- - -3- - - -1
167	VSVB.A.iii.4	1-3- - -5- - - -3- - - - -1
168	VSVB.A.iv.1	3-5-3- -1- -1
169	VSVB.A.iv.2	3-5- -3- - -1- - -1
170	VSVB.A.iv.3	3-5- - -3- - - -1- - - -1
171	VSVB.A.iv.4	3-5- - -3- - - - -1- - - - -1
172	VSVB.A.v.1	1-1-3- -5- -3
173	VSVB.A.v.2	1-1- -3- - -5- - -3
174	VSVB.A.v.3	1-1- -3- - - -5- - - -3
175	VSVB.A.v.4	1-1- - -3- - - - -5- - - - -3
176	VSVB.B.i.1	1- -2- -3-4-5
177	VSVB.B.i.2	1- - -2- - -3- -4-5
178	VSVB.B.i.3	1- - - -2- - - -3- - -4-5
179	VSVB.B.i.4	1- - - - -2- - - - -3- - -4-5
180	VSVB.B.ii.1	5- -4- -3-2-1
181	VSVB.B.ii.2	5- - -4- - -3- -2-1
182	VSVB.B.ii.3	5- - - -4- - - -3- -2-1
183	VSVB.B.ii.4	5- - - - -4- - - - -3- -2-1
184	VSVB.B.iii.1	1- -3- -5-3-1
185	VSVB.B.iii.2	1- - -3- - -5- -3-1
186	VSVB.B.iii.3	1- - - -3- - - -5- -3-1
187	VSVB.B.iii.4	1- - - - -3- - - - -5- -3-1
188	VSVB.B.iv.1	3- -5- -3-1-1
189	VSVB.B.iv.2	3- - -5- - -3- -1-1
190	VSVB.B.iv.3	3- - - -5- - - -3- -1-1
191	VSVB.B.iv.4	3- - - - -5- - - - -3- -1-1
192	VSVB.B.v.1	1- -1- -3-5-3
193	VSVB.B.v.2	1- - -1- - -3- -5-3
194	VSVB.B.v.3	1- - - -1- - - -3- -5-3
195	VSVB.B.v.4	1- - - - -1- - - - -3- -5-3

E. PHASE 1 DATA SUMMARY

Num	Case	Average P1 (psi)	Average P2 (psi)	Average P3 (psi)	Average P4 (psi)	Average Pressure (psi)	Average Velocity (m/s)	Detonation Success Rate (%)
1	CSCB.A.1	100.30	115.60	108.91	100.78	106.40	313.27	0%
2	CSCB.A.2	124.01	125.81	135.93	142.69	132.11	413.67	0%
3	CSCB.A.3	223.07	185.43	223.00	280.50	228.00	674.67	15%
4	CSCB.A.4	463.93	332.50	404.43	428.80	407.42	1828.70	95%
5	CSCB.A.5	389.95	421.49	446.67	402.39	415.13	1955.58	100%
6	CSCB.A.6	365.08	348.36	398.51	348.36	365.08	1873.89	95%
7	CSCB.A.7	158.82	133.87	159.11	160.01	152.95	1122.11	0%
8	CSCB.A.8	203.49	158.17	187.22	156.81	176.42	961.51	0%
9	CSCB.A.9	125.35	99.40	106.90	99.00	107.66	859.58	0%
10	CSCB.A.10	138.76	90.40	96.92	83.59	102.42	835.87	0%
11	CSCB.A.a.4	247.23	233.06	237.25	235.84	238.35	995.98	20%
12	CSCB.A.a.5	217.67	390.02	218.03	193.68	304.46	555.80	0%
13	CSCB.A.a.6	201.24	172.25	189.76	156.55	179.95	692.83	0%
14	CSCB.A.b.4	143.40	139.53	145.75	159.40	147.02	316.42	0%
15	CSCB.A.b.5	174.99	145.73	189.82	165.17	178.82	436.58	0%
16	CSCB.A.b.6	313.41	437.27	311.31	287.85	375.85	1121.65	25%
17	CSCB.A.c.4	111.76	112.45	116.71	122.66	115.90	304.82	0%
18	CSCB.A.c.5	123.53	119.75	133.28	145.76	130.58	388.37	0%
19	CSCB.A.c.6	148.53	134.15	143.53	153.51	144.93	421.36	0%
20	CSCB.A.d.4	85.88	85.33	100.72	90.91	90.71	236.70	0%
21	CSCB.A.d.5	107.39	106.53	112.25	105.79	107.99	236.18	0%
22	CSCB.A.d.6	127.36	152.56	143.35	155.50	144.69	305.34	0%
23	CSCB.B.1	48.16	36.71	35.79	31.16	37.96	703.68	0%
24	CSCB.B.2	60.80	46.65	45.47	43.32	49.06	765.08	0%
25	CSCB.B.3	48.64	40.75	41.69	38.75	42.46	706.28	0%
26	CSCB.B.4	35.44	31.90	34.31	31.37	33.26	453.39	0%
27	CSCB.B.5	47.64	44.92	52.29	44.38	47.31	474.81	0%
28	CSCB.B.6	103.27	93.82	103.66	88.74	97.37	674.64	0%
29	CSCB.B.7	100.28	99.48	125.68	109.07	108.63	694.67	0%
30	CSCB.B.8	112.87	98.93	114.93	97.12	105.96	888.51	0%
31	CSCB.C.1	100.90	79.24	74.92	70.81	81.47	788.89	0%
32	CSCB.C.2	57.61	51.31	56.21	48.99	53.53	664.56	0%
33	CSCB.C.3	52.97	48.61	55.73	53.23	52.63	389.07	0%
34	CSCB.C.4	88.71	83.00	96.26	83.84	87.95	568.66	0%
35	CSCB.C.5	365.35	351.39	413.54	378.56	377.21	1840.15	100%
36	CSCB.D.1	75.35	62.57	66.66	60.05	66.16	591.48	0%
37	CSCB.D.2	40.33	36.67	40.85	38.09	38.99	506.24	0%
38	CSCB.D.3	160.40	161.41	172.90	163.74	164.61	569.60	0%
39	CSCB.E.1	56.31	47.22	48.25	46.38	49.54	680.64	0%
40	CSCB.E.2	41.44	36.06	39.49	34.04	37.76	499.13	0%
41	CSCB.E.3	51.76	48.17	47.71	39.99	46.91	514.31	0%
42	CSCB.E.4	58.81	52.63	51.16	42.82	51.36	558.64	0%
43	CSCB.E.5	86.31	78.86	86.40	66.49	79.52	739.09	0%
44	CSCB.E.6	96.97	88.24	97.75	82.64	91.40	1073.45	0%
45	CSCB.E.7	97.32	82.47	98.12	83.53	90.36	730.93	0%
46	CSCB.E.8	103.17	83.39	102.27	81.88	92.68	903.46	0%
47	CSCB.F.1	44.75	40.76	44.13	38.25	41.97	567.95	0%
48	CSCB.F.2	63.94	62.63	71.05	64.04	65.41	377.05	0%
49	CSCB.F.3	94.49	81.36	87.95	72.69	84.12	727.36	0%
50	CSCB.F.4	107.66	96.06	114.20	85.25	100.79	736.23	0%
51	CSCB.F.5	129.99	106.85	125.77	118.37	120.25	940.97	0%
52	CSCB.F.6	130.82	103.09	142.75	117.75	123.60	911.14	0%
53	CSCB.F.7	115.01	102.44	119.83	101.35	109.66	842.92	0%
54	CSCB.F.8	122.38	112.53	114.70	111.23	115.21	929.95	0%
55	CSVB.A.i.1	71.74	60.55	65.80	57.46	63.89	734.82	0%
56	CSVB.A.i.2	58.20	51.94	60.97	50.64	55.44	502.86	0%
57	CSVB.A.i.3	99.17	85.94	91.46	80.49	89.27	416.40	0%

Num	Case	Average P1 (psi)	Average P2 (psi)	Average P3 (psi)	Average P4 (psi)	Average Pressure (psi)	Average Velocity (m/s)	Detonation Success Rate (%)
58	CSV.B.A.i.4	201.31	182.69	220.84	191.33	199.05	785.24	15%
59	CSV.B.A.i.5	404.99	358.22	384.09	451.48	399.70	1738.57	70%
60	CSV.B.A.i.6	394.33	304.82	315.74	331.30	336.55	1371.30	45%
61	CSV.B.A.ii.1	68.39	53.45	51.18	50.71	55.93	599.46	0%
62	CSV.B.A.ii.2	67.50	56.39	58.95	54.00	59.21	613.25	0%
63	CSV.B.A.ii.3	46.88	42.61	48.29	41.80	44.90	523.83	0%
64	CSV.B.A.ii.4	61.77	57.96	65.01	59.97	61.18	441.96	0%
65	CSV.B.A.ii.5	138.70	116.65	155.14	121.89	133.10	667.41	0%
66	CSV.B.A.ii.6	341.29	299.33	412.47	371.22	356.08	1881.86	80%
67	CSV.B.A.iii.1	76.82	59.82	58.66	55.36	62.67	600.49	0%
68	CSV.B.A.iii.2	41.76	38.30	42.90	39.73	40.67	519.30	0%
69	CSV.B.A.iii.3	46.00	43.35	46.78	43.07	44.80	448.70	0%
70	CSV.B.A.iii.4	72.02	65.95	70.49	60.07	67.13	437.35	0%
71	CSV.B.A.iii.5	291.94	302.81	366.75	295.41	314.23	1494.35	65%
72	CSV.B.A.iii.6	377.30	347.44	385.63	299.54	352.48	1779.09	70%
73	CSV.B.A.iv.1	69.98	55.64	51.00	48.99	56.40	687.34	0%
74	CSV.B.A.iv.2	51.57	45.81	49.44	44.84	47.91	585.52	0%
75	CSV.B.A.iv.3	39.86	38.73	45.64	39.31	40.88	404.58	0%
76	CSV.B.A.iv.4	80.65	72.14	82.34	68.47	75.90	531.51	0%
77	CSV.B.A.iv.5	194.57	173.17	207.99	187.49	190.81	981.01	15%
78	CSV.B.A.iv.6	402.08	366.33	435.82	353.77	389.50	2037.04	95%
79	CSV.B.A.v.1	72.55	59.09	59.40	57.79	62.21	817.85	0%
80	CSV.B.A.v.2	41.21	37.16	41.93	38.51	39.70	549.58	0%
81	CSV.B.A.v.3	72.56	66.78	72.28	59.82	67.86	528.77	0%
82	CSV.B.A.v.4	142.70	127.70	139.68	129.27	134.84	845.06	0%
83	CSV.B.A.v.5	374.74	386.93	432.78	304.83	374.82	1931.58	90%
84	CSV.B.A.v.6	372.44	347.21	339.61	288.16	336.86	1731.64	85%
85	CSV.B.B.i.1	44.98	40.45	45.22	38.10	42.19	684.87	0%
86	CSV.B.B.i.2	61.00	55.41	55.74	44.89	54.26	532.39	0%
87	CSV.B.B.i.3	65.42	64.62	71.53	68.68	67.56	586.78	0%
88	CSV.B.B.i.4	63.21	56.13	60.50	51.00	57.71	552.54	0%
89	CSV.B.B.ii.1	39.35	35.19	37.69	32.68	36.23	617.49	0%
90	CSV.B.B.ii.2	55.42	48.90	48.75	40.67	48.43	589.82	0%
91	CSV.B.B.ii.3	67.61	63.35	64.42	57.20	63.14	514.93	0%
92	CSV.B.B.ii.4	61.74	58.06	63.11	52.50	58.85	483.64	0%
93	CSV.B.B.iii.1	43.40	36.01	36.61	33.08	37.28	621.69	0%
94	CSV.B.B.iii.2	53.67	44.97	46.91	40.78	46.58	460.56	0%
95	CSV.B.B.iii.3	47.31	44.89	45.68	40.55	44.60	536.06	0%
96	CSV.B.B.iii.4	58.84	52.93	55.27	50.21	54.31	504.94	0%
97	CSV.B.B.iv.1	42.42	37.07	39.60	35.01	38.52	642.21	0%
98	CSV.B.B.iv.2	51.39	46.36	47.99	39.83	46.39	445.96	0%
99	CSV.B.B.iv.3	71.98	66.74	67.61	54.31	65.16	457.56	0%
100	CSV.B.B.iv.4	58.49	53.41	55.44	49.52	54.22	468.23	0%
101	CSV.B.B.v.1	47.88	40.63	42.51	37.80	42.20	605.59	0%
102	CSV.B.B.v.2	54.21	45.36	49.64	41.30	47.63	367.10	0%
103	CSV.B.B.v.3	69.15	64.77	75.42	62.21	67.89	557.39	0%
104	CSV.B.B.v.4	74.78	67.93	82.41	70.31	73.86	694.01	0%
105	CSV.B.C.i.1	48.37	41.92	46.69	42.31	44.82	669.02	0%
106	CSV.B.C.i.2	78.52	69.37	70.41	65.52	70.95	518.41	0%
107	CSV.B.C.i.3	136.70	120.64	140.45	121.85	129.91	433.18	0%
108	CSV.B.C.ii.1	50.63	46.21	51.22	45.22	48.32	625.88	0%
109	CSV.B.C.ii.2	68.11	62.32	72.17	62.39	66.25	413.63	0%
110	CSV.B.C.ii.3	256.57	238.31	267.69	220.28	245.71	1155.70	55%
111	CSV.B.C.iii.1	48.33	44.49	49.06	44.68	46.64	656.21	0%
112	CSV.B.C.iii.2	74.40	70.61	73.11	67.90	71.50	429.50	0%
113	CSV.B.C.iii.3	123.32	121.58	139.17	158.06	135.54	349.21	0%
114	CSV.B.C.iv.1	61.52	54.76	57.88	52.30	56.62	569.02	0%
115	CSV.B.C.iv.2	83.07	77.08	79.14	69.53	77.20	587.16	0%
116	CSV.B.C.iv.3	158.92	151.56	173.70	165.40	162.40	428.87	10%
117	CSV.B.C.v.1	44.70	39.86	44.98	41.84	42.85	537.90	0%

Num	Case	Average P1 (psi)	Average P2 (psi)	Average P3 (psi)	Average P4 (psi)	Average Pressure (psi)	Average Velocity (m/s)	Detonation Success Rate (%)
118	CSV.B.C.v.2	95.40	85.53	87.10	75.03	85.77	774.77	0%
119	CSV.B.C.v.3	238.67	206.13	235.28	232.83	228.23	867.84	25%
120	CSV.B.D.i.1	68.61	60.24	63.56	53.84	61.56	691.75	0%
121	CSV.B.D.i.2	73.87	72.07	82.24	70.03	74.55	724.56	0%
122	CSV.B.D.i.3	100.00	83.45	100.43	84.19	92.02	729.13	0%
123	CSV.B.D.i.4	99.44	76.09	90.04	83.31	87.22	646.17	0%
124	CSV.B.D.ii.1	57.27	50.90	55.45	47.41	52.76	450.55	0%
125	CSV.B.D.ii.2	73.78	67.72	76.64	62.83	70.24	637.26	0%
126	CSV.B.D.ii.3	79.76	71.72	83.50	67.90	75.72	598.82	0%
127	CSV.B.D.ii.4	84.80	74.49	84.30	75.44	79.76	765.73	0%
128	CSV.B.D.iii.1	56.81	48.83	51.76	43.27	50.17	445.49	0%
129	CSV.B.D.iii.2	56.70	51.38	53.68	48.31	52.52	537.76	0%
130	CSV.B.D.iii.3	79.59	70.79	83.11	71.40	76.22	501.58	0%
131	CSV.B.D.iii.4	84.75	73.35	89.21	72.99	80.07	640.41	0%
132	CSV.B.D.iv.1	64.70	60.64	62.15	52.21	59.93	508.83	0%
133	CSV.B.D.iv.2	85.13	74.62	83.13	65.34	77.05	638.11	0%
134	CSV.B.D.iv.3	84.12	70.55	86.60	69.12	77.60	574.08	0%
135	CSV.B.D.iv.4	97.03	87.50	104.09	81.90	92.63	679.90	0%
136	CSV.B.D.v.1	71.30	64.29	67.02	56.84	64.86	645.28	0%
137	CSV.B.D.v.2	69.49	68.27	69.71	59.65	66.78	903.63	0%
138	CSV.B.D.v.3	74.08	66.20	77.36	69.97	71.90	444.29	0%
139	CSV.B.D.v.4	90.01	86.60	92.48	73.89	85.75	638.50	0%
140	VSC.B.A.1	96.37	75.28	70.04	65.79	76.87	906.56	0%
141	VSC.B.A.2	43.83	40.23	44.62	39.60	42.07	500.24	0%
142	VSC.B.A.3	130.81	117.37	134.51	119.41	125.52	577.41	0%
143	VSC.B.A.4	181.23	145.50	158.38	134.25	154.84	825.45	0%
144	VSC.B.B.1	69.16	55.92	55.00	52.34	58.10	630.60	0%
145	VSC.B.B.2	44.40	40.23	45.85	46.25	44.18	439.49	0%
146	VSC.B.B.3	276.57	250.43	383.05	243.47	288.38	1446.11	45%
147	VSC.B.B.4	195.62	146.33	171.38	164.42	169.44	1167.26	5%
148	VSC.B.C.1	127.04	107.59	116.55	93.42	111.15	630.77	0%
149	VSC.B.C.2	130.04	113.72	130.72	104.83	119.83	843.45	0%
150	VSC.B.C.3	155.81	129.60	136.51	114.11	134.01	1133.15	0%
151	VSC.B.C.4	47.02	43.40	48.22	42.10	45.18	444.78	0%
152	VSC.B.D.1	371.96	370.61	439.23	357.56	384.84	1776.56	80%
153	VSC.B.D.2	276.45	256.97	309.33	265.03	276.95	1446.18	25%
154	VSC.B.D.3	338.14	367.44	434.99	348.34	372.23	1536.71	60%
155	VSC.B.D.4	483.65	289.24	296.03	314.19	345.78	1861.00	90%
156	VSV.B.A.i.1	46.98	43.47	49.19	44.05	45.92	652.42	0%
157	VSV.B.A.i.2	45.79	42.48	51.13	46.22	46.41	432.81	0%
158	VSV.B.A.i.3	87.50	78.10	90.38	78.21	83.55	614.49	0%
159	VSV.B.A.i.4	171.83	158.30	194.31	161.32	171.44	752.44	10%
160	VSV.B.A.ii.1	81.47	67.53	65.37	58.93	68.32	786.35	0%
161	VSV.B.A.ii.2	56.19	54.39	61.11	50.56	55.56	572.55	0%
162	VSV.B.A.ii.3	121.74	111.98	119.74	103.71	114.29	642.18	0%
163	VSV.B.A.ii.4	127.86	108.58	113.81	93.58	110.96	550.35	0%
164	VSV.B.A.iii.1	84.94	70.28	71.38	63.73	72.58	688.94	0%
165	VSV.B.A.iii.2	51.50	49.11	53.84	46.89	50.33	589.62	0%
166	VSV.B.A.iii.3	75.69	67.75	75.43	63.13	70.50	485.99	0%
167	VSV.B.A.iii.4	147.73	130.91	164.68	142.85	146.54	719.20	0%
168	VSV.B.A.iv.1	83.50	67.74	63.66	62.27	69.29	655.46	0%
169	VSV.B.A.iv.2	54.60	51.04	55.72	47.21	52.14	460.56	0%
170	VSV.B.A.iv.3	116.71	97.69	98.29	82.64	98.83	641.26	0%
171	VSV.B.A.iv.4	212.87	161.65	168.45	150.16	173.28	733.21	0%
172	VSV.B.A.v.1	53.72	48.91	53.40	47.80	50.96	536.49	0%
173	VSV.B.A.v.2	50.05	44.68	49.35	44.38	47.12	535.35	0%
174	VSV.B.A.v.3	75.59	70.65	76.96	70.32	73.38	360.22	0%
175	VSV.B.A.v.4	290.59	277.94	307.95	279.76	289.06	1469.52	65%
176	VSV.B.B.i.1	46.99	40.27	44.02	40.73	43.00	603.14	0%
177	VSV.B.B.i.2	56.19	49.49	56.55	51.79	53.51	438.34	0%

Num	Case	Average P1 (psi)	Average P2 (psi)	Average P3 (psi)	Average P4 (psi)	Average Pressure (psi)	Average Velocity (m/s)	Detonation Success Rate (%)
178	VSVB.B.i.3	109.51	89.88	102.12	91.46	98.25	574.69	0%
179	VSVB.B.i.4	146.46	120.31	132.73	121.70	130.30	904.00	10%
180	VSVB.B.ii.1	84.63	69.59	69.60	60.86	71.17	602.49	0%
181	VSVB.B.ii.2	47.57	44.30	49.72	46.25	46.96	485.10	0%
182	VSVB.B.ii.3	82.58	77.72	91.24	77.73	82.32	475.96	0%
183	VSVB.B.ii.4	388.90	480.27	441.93	333.13	411.06	1858.43	100%
184	VSVB.B.iii.1	46.37	40.22	46.59	43.34	44.13	561.33	0%
185	VSVB.B.iii.2	43.49	41.76	47.99	43.09	44.08	447.27	0%
186	VSVB.B.iii.3	83.97	80.96	81.45	68.15	78.63	587.75	0%
187	VSVB.B.iii.4	108.74	88.89	109.53	85.61	98.19	591.07	0%
188	VSVB.B.iv.1	70.35	58.35	59.90	56.53	61.28	462.61	0%
189	VSVB.B.iv.2	39.07	35.09	40.02	36.10	37.57	408.63	0%
190	VSVB.B.iv.3	115.71	98.80	124.77	96.83	109.03	605.61	0%
191	VSVB.B.iv.4	255.61	218.40	265.20	242.65	245.46	1376.69	40%
192	VSVB.B.v.1	35.29	32.10	35.28	32.20	33.72	493.84	0%
193	VSVB.B.v.2	47.23	42.87	46.38	43.09	44.89	428.39	0%
194	VSVB.B.v.3	85.80	76.90	90.79	70.15	80.91	812.77	0%
195	VSVB.B.v.4	86.80	74.40	90.55	70.95	80.68	599.32	0%