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Design and Optimization of a Deflagration to Detonation Transition (DDT) Section

Francisco X. Romo
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Design and Optimization of a Deflagration to Detonation Transition (DDT) Section

Francisco X. Romo

A Thesis submitted to the Graduate Studies Office in Partial Fulfillment of the Requirements for the Degree of Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Spring 2012
Design and Optimization of a Deflagration to Detonation Transition (DDT) Section

Francisco X. Romo

This thesis was prepared under the direction of the candidates' thesis 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 Aerospace Engineering Department and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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Abstract

Throughout the previous century, hydrocarbon-fueled engines have used and optimized the ‘traditional’ combustion process called deflagration (subsonic combustion). An alternative form of combustion, detonation (supersonic combustion), can increase the thermal efficiency of the process by anywhere from 20 - 50%. Even though several authors have studied detonation waves since the 1890’s and a plethora of papers and books have been published, it was not until 2008 that the first detonation-powered flight took place. It lasted for 10 seconds at 100 ft. altitude.

Achieving detonation presents its own challenges: some fuels are not prone to detonate, severe vibrations caused by the cyclic nature of the engine and its intense noise are some of the key areas that need further research. Also, to directly achieve detonation either a high-energy, bulky, ignition system is required, or the combustion chamber must be fairly long (5 ft. or more in some cases). In the latter method, a subsonic flame front accelerates within the combustion chamber until it reaches supersonic speeds, thus detonation is attained. This is called deflagration-to-detonation transition (DDT).

Previous papers and experiments have shown that obstacles, such as discs with an orifice, located inside the combustion chamber can shorten the distance required to achieve detonation. This paper describes a hands-on implementation of a DDT device. Different disc geometries inside the chamber alter the wave characteristics at the exit of the tube. Although detonation was reached only when using pure oxygen, testing identified an obstacle configuration for LPG and air mixtures that increased pressure and wave speed significantly when compared to baseline or other obstacle configurations. Mixtures of LPG and air were accelerated to Mach 0.96 in the downstream frame of reference, which would indicate a transition to detonation was close. Reasons for not achieving detonation may include poor fuel and oxidizer mixing, and/or the need for a longer DDT section.
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## Nomenclature

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<th>Definition</th>
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<td>DDT</td>
<td>Deflagration to Detonation Transition</td>
</tr>
<tr>
<td>PDE</td>
<td>Pulse detonation engine</td>
</tr>
<tr>
<td>DAQ</td>
<td>Digital acquisition system</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical user interface</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied petroleum gas</td>
</tr>
<tr>
<td>d</td>
<td>Number of discs in cartridge</td>
</tr>
<tr>
<td>s</td>
<td>Disc spacing, inches</td>
</tr>
<tr>
<td>λ</td>
<td>Lambda – Detonation cell height</td>
</tr>
<tr>
<td>v</td>
<td>Specific volume</td>
</tr>
<tr>
<td>q</td>
<td>Heat</td>
</tr>
<tr>
<td>η</td>
<td>Efficiency</td>
</tr>
<tr>
<td>γ</td>
<td>Specific heats ratio</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
</tr>
<tr>
<td>m</td>
<td>Mass flux – mass flow by area</td>
</tr>
<tr>
<td>π</td>
<td>Compression ratio</td>
</tr>
<tr>
<td>BR</td>
<td>Blockage ratio – blocked area by total area</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>Φ</td>
<td>Equivalence ratio</td>
</tr>
<tr>
<td>L</td>
<td>Inverse of Φ</td>
</tr>
<tr>
<td>TR</td>
<td>Signal rise time</td>
</tr>
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</table>
1. Introduction

Pulse-detonation engines (or PDE) have received increased attention in the past decade due to their potential for higher overall thermal efficiency. A PDE has fewer moving parts than a gas turbine or internal combustion engine, making it also attractive from a reliability and mechanical standpoint. PDE’s operate in a similar intermittent-manner as pulse-jet engines, but with a different combustion process: detonation. Entropy is maximized during deflagration [1] (i.e. ‘normal’ combustion), thus making it the least efficient way of burning fuel. Detonation is an alternate, supersonic type of combustion which in addition to (chemically) releasing heat, also increases the burning gas pressure. To date, no PDE has been put into production. Most of the existing PDE prototypes (from Caltech, University of Texas, and USAF) focus on thrust production.

The author previously performed testing of a privately-funded Pulse Detonation Engine prototype at Embry-Riddle’s Gas Turbine Lab. This prototype differs because it claims to employ detonation to spin a shaft rather than producing thrust. Almost every motor and engine, whether used for transportation, industrial or power generation, has a rotating axle as the de-facto power transfer mechanism. The observations and experiences learned from testing the aforementioned prototype finally helped the development of this paper.

1.1 Problem statement

From a theoretical standpoint, detonation has been shown to be more thermally efficient than low-speed, normal deflagration. In an oil-dependent world, it shouldn’t be a surprise to hear that detonation is receiving renewed interest from the scientific community. Yet a practical detonation device, industrial or commercial, seems to be a few years (if not decades) away. Previous research has been focused on using highly detonable fuels, such as hydrogen, or pure oxygen instead of air. These two conditions effectively limit detonation to laboratory-only situations.
Although the first detonation models were developed over a century ago, between 1899 and 1905 by Chapman and Jouguet, detonation still remains an unpractical, theoretical concept described in combustion books. The problem lies in achieving detonation in a practical, controlled, consistent and repeatable manner. To achieve detonation, either direct detonation or deflagration to detonation transition (DDT) methods have been used.

Direct detonation entails releasing sufficient energy into a combustible mixture so that a detonation wave is directly formed. Energy levels vary up to millions of Joules, depending on the fuel and oxidizer being used. The methods used to deliver such energy are numerous, including plasma or corona-type electrical discharges, lasers, and perhaps the most obvious: explosives. Any of these methods remain clearly impractical outside research facilities.

DDT on the other hand, employs a much less drastic approach. Using a conventional consumer-grade ignition system, the resulting flame accelerates inside a chamber with obstacles until it transitions into detonation speeds. The main drawback with this approach is that the required distance for the wave to reach the CJ velocity (the supersonic speed at which detonation is stable) can be substantial. Depending on the fuel and oxidizer used, this distance can vary from a few inches to several feet.

Several authors have previously studied the effects of obstacles inside detonation tubes and their effects on DDT length [8] [10] [11]. All studies have used specific geometries, either by using Shchelkin spirals (coil springs) or fixed discs with a small orifice located inside the tube. Wire-wound spirals cannot withstand the high pressures and temperatures of detonation, and previous experiments showed they tend to disintegrate after a few cycles [8]. Most studies have been performed using small diameter tubes (less than 2 inches) with spirals inside them. This severely limits the mass flow through the device, thus limiting the amount of thrust and/or power generated by detonation. Other studies [10] [11] have used highly detonable mixtures (such as hydrogen...
and pure oxygen) with discs inside the tube. However, the use of pure oxygen limits the implementation and operation of such devices to laboratory conditions.

This paper explores the experimental results aimed to achieve detonation by DDT in a 4-inch ID, 6-foot long tube. In order to keep the experiment conditions as practical as possible, pure oxygen will be avoided, if only used to verify theoretical results. Therefore, consumer-grade LPG and air will be used. The selection of a 4-inch tube was made in order to allow one full detonation cell to pass through (see the following section), and to increase mass flow which would increase thrust and/or power on a PDE. Obstacles used inside the tube will be assembled using discs with different size orifices, limited by the length of the tube. The ideal disc stack will achieve the fastest flame speed within the tube.

The findings from this project will help develop easier, economical and more effective methods for building the next Pulse Detonation Engine prototypes. It will also provide a better understanding of detonation requirements regarding overall device dimensions as well as ignition systems. However, in order to better understand the nature and difficulty of detonation, a quick review of some combustion basics is warranted.

1.2 Combustion and Detonation

Combustion can be either subsonic (deflagration) or supersonic (detonation). During deflagration, heat is released due to the chemical reaction between fuel and oxidizer: a slight expansion lowers the final pressure of the gas (unless the reaction is carried out in a closed chamber) [2]. Gas downstream the flame front moves away from the flame. Deflagration can be modeled as an isobaric heat addition process.

Detonation is the combustion of a fuel and oxidizer mixture, where the combustion wave travels at supersonic speeds relative to the upstream gas mixture [2]. Unlike deflagration, detonation compresses the gas due to the supersonic wave. During detonation, downstream gas follows the
flame front. Although simplified, a conservative assumption is that detonation can be modeled as an isochoric (constant volume) process.

Previous studies have shown that for unsteady combustion, total entropy gain is lower for detonation. However, when the same analysis is applied to a steady-state process, detonation is shown to have a greater entropy gain than deflagration. Therefore, detonation has potential when used on pulsed, unsteady, cyclical devices [1].

Chapman and Jouguet (CJ) independently developed the basic thermodynamic model behind detonation. The CJ model describes the interaction between Rayleigh and Rankine-Hugoniot curves, defining the physically possible states that a thermodynamic process is bound to. The CJ model shows that detonation reaches equilibrium speed as the combustion wave reaches the speed of sound in the local wave frame of reference. From here, pressure and density can be easily calculated.

By using the conservation of energy, mass, momentum, continuity and ideal gas relationships, the Rankine-Hugoniot equation (1.1) is easily derived:

\[
\frac{y}{y-1}(P_2v_2 - P_1v_1) - \frac{1}{2}(P_2 - P_1)(v_1 + v_2) - q = 0
\]  

(1.1)

In equation 1.1, if the upstream flow conditions \(P_1\) and \(v_1\) are known, as well as the heat addition term \(q\), then the Rankine-Hugoniot equation determines the possible combinations of downstream conditions \(P_2\) and \(v_2\) while imposing the conservation laws. This can be plotted on a P-v diagram, as in Figure 1.
On the other hand, the Rayleigh line equation (1.2) results from simultaneously solving the continuity and momentum conservation equations:

\[ \frac{P_2 - P_1}{v_2 - v_1} = -m^2 \]  

(1.2)

The mass flux term is defined as mass flow divided by area. Once again, if upstream conditions \(P_1\) and \(v_1\) are known, several Rayleigh lines can be plotted on a \(P-v\) diagram passing through point A. For different mass flux values, the slope of the Rayleigh line will change. Since the mass flux term can only be positive (or zero), the resulting line slope can only vary from zero to negative infinity. This means no positive slope lines can exist.

When both Rayleigh and Rankine-Hugoniot are plotted together, the resulting graph is Figure 1. Both curves have \(P_1\) and \(v_1\) (point A) as initial conditions. When solving both equations, the first solution region is defined by the Rayleigh lines A-D and A-B. Any Rayleigh line with lower negative slope would not intersect the Rankine-Hugoniot curve. Any line with a positive slope (i.e., right of A-B) wouldn’t be a real process. Using the same arguments, the second region is limited from A-C to A-E.
This divides the Rankine-Hugoniot curve into 5 sections. To the left of point D, a subsonic 'strong detonation' area is defined. From D to B, a supersonic 'weak detonation' area is defined. The section B-C is not a real process. From C to E, a subsonic 'weak deflagration' region is defined. Below E, a supersonic 'strong deflagration' zone exists. The strong detonation and strong deflagration areas are mathematically possible, but such phenomena rarely exist [15].

Typical values for detonation wave velocities are Mach 5-10. For comparison, air-hydrocarbon mixtures deflagrations rarely exceed 1 m/s [2] [15].

Zel'dovich, von Neumann and Doering (ZND) further developed in the early 1940’s a model for a one-dimensional detonation wave. The ZND model suggests that a detonation wave can be modeled as a coupled, mutually supporting normal shock wave and a thin combustion reaction zone behind the shock. As the normal shock compresses and thus heats the gas, the chemical reaction is initiated behind the shock. The chemically released energy drives in turn the normal shock propagation [3]. A pressure spike can be observed right after the shock (induction zone), called the von Neumann spike. As the wave travels further down the mixture, pressure drops and decays to a stable value. The detonation wave speed is dependent on the fuel and oxidizer used, as well as their initial conditions (pressure, and to a lesser extent temperature) and stoichiometric ratio [4]. Typical detonation wave thickness is on the order of 0.1mm. A typical diagram of the ZND 1-D wave model is shown in Figure 2.
Figure 2 - ZND 1D model detonation wave

Experimental results have shown that the ZND model, a simplified 1D approximation, isn’t truly capable of predicting 2D/3D waves, which are complex structures characterized by an oscillatory motion. The leading shocks create transverse waves, and when these transverse waves collide, localized high pressure points are formed. The reaction rate of the mixture is increased at these points, which in turn accelerates the shock. The resulting effect is the observed fishnet pattern, as seen in Figure 3.

Figure 3 - 2D Detonation wave propagation pattern [1]
An important wave parameter is the cell width, \( \lambda \), seen in Figure 3. The cell size is dependent on the fuel and oxidizer used, stoichiometric ratio, initial pressure and temperature. To ensure detonation propagation, any detonation tube must be large enough to accommodate at least one complete detonation cell.

Detonation cell size is also a measure of the sensitivity of the mixture to detonate [5]. Table 1 shows a comparison of select fuels and their cell size. Although mathematical models to predict cell size exist, their poor accuracy favors values obtained experimentally.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>( \lambda ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oxygen</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1.3</td>
</tr>
<tr>
<td>Acetylene C(_2)H(_2)</td>
<td>0.109</td>
</tr>
<tr>
<td>Methane CH(_4)</td>
<td>8</td>
</tr>
<tr>
<td>Ethane C(_2)H(_6)</td>
<td>-</td>
</tr>
<tr>
<td>Propane C(_3)H(_8)</td>
<td>2.5</td>
</tr>
<tr>
<td>Kerosene</td>
<td>30.0</td>
</tr>
</tbody>
</table>

### 1.3 Detonation Initiation – Direct and DDT

The two most frequent methods to start detonation are direct initiation or DDT. Studies have shown that direct initiation requires considerable amounts of energy. Different variations of electric arcs (such as corona) are common methods for imparting high-energy levels. Direct detonation energy requirements vary depending on fuel being used and its conditions (temperature, pressure, stoichiometric ratio, oxidizer, diluents). Typical initiation energy ranges from a few joules to millions of joules [5] [7]. To ensure direct detonation is achieved, the amount of energy must be above that of the critical initiation energy. Due to the large amount of energy required for direct initiation, DDT is considered an easier method to initiate detonation.
DDT starts with a low-energy spark, which initiates deflagration in the gas mixture. As the flame travels through the combustion chamber, heat, pressure, and turbulence accelerate the flame until it reaches the speed of sound in the flame frame of reference, thus transitioning into a detonation wave. Obstacles placed inside the chamber can help accelerate the flame in a shorter distance. The Shchelkin spiral is perhaps the most common method used to partially block the chamber and induce DDT. The most important parameter for the spiral is the blockage ratio (BR), as shown in Figure 4. A similar definition for BR is used for obstacles such as discs with an orifice. Previous studies have shown that the spiral can be worn down after only a few detonations [8]; see Figure 5. For DDT to occur, the chamber (or detonation tube) must be long enough to ensure deflagration has sufficient distance to transition into detonation.

![Figure 4 - Shchelkin spiral](image)

![Figure 5 - Shchelkin spiral degradation after testing](image)

An interesting study showing different regimes for flame acceleration using discs was presented by Lee et al. in 1984 [19]. In their experiment, flame acceleration was measured in different tubes ranging from 11 to 17 meters long. They identified four different regimes for flame acceleration:
quenching, choking, quasi-detonation and CJ. In quenching, the flame initially accelerates and then self-extinguishes after passing through a certain number of discs. In choking, the wall friction and heat addition balance out, thus the flame reaches an equilibrium speed below the local sonic conditions. The discs effectively ‘choke’ the flame speed. In quasi-detonation, detonation is the propagation mode of the flame, but the momentum loss of the gas due to the obstacles and friction losses prevents it from reaching the CJ conditions. It was found that in the quasi-detonation and choking regimes, wave speed was very similar (around ~1000m/s in both cases). Finally, when detonation is achieved and the obstacles do not interfere with the wave propagation, CJ velocities are reached.

1.4 Pulsed Detonation Engine (PDE)

Ultimately, PDEs will use detonation and extract work from the burning gases. PDE prototypes have an unsteady nature: after detonation takes place, burnt gases must be expelled and fresh mixture fed to the chamber before a new detonation cycle can take place. Therefore, engine total output power will be proportional to its operating frequency. Mechanical and flow considerations currently limit the frequency at which prototype PDEs can operate. Let’s compare PDE efficiency with a gas turbine engine by considering Figure 6.

![Figure 6 - Brayton and Humphrey cycles P-V and T-s diagrams](image)

Traditional gas turbines operate on the Brayton cycle (0-1-4-5-0). A PDE engine can be modeled by the Humphrey cycle (0-1-2-3-0), where combustion (1-2) is an isochoric heat addition process.
The T-s diagram in Figure 6 shows that during detonation (1-2), final entropy is lower and pressure is higher for the Humphrey cycle (points 2 vs. 4). Due to the additional pressure, the expansion process (2-3) can achieve a larger temperature drop, which results in additional work performed by the gas. It should not be surprising that cycle efficiency for a PDE could be much higher than an equivalent engine operating on the Brayton cycle. Assuming ideal gas, the efficiency for both cycles are given by the following equations [2]:

\[
\eta_{\text{Humphrey}} = 1 - \frac{T_0}{T_1}
\]

\[
\eta_{\text{Brayton}} = 1 - \frac{T_0}{T_1} \times \frac{T_2}{T_1} \frac{1}{y} - 1
\]

Comparing equations 1.3 and 1.4, the Humphrey cycle has an additional term which is always less than unity. The additional term makes the efficiency dependent not only on the temperature ratio across the compression process, but also on specific heats and temperature ratio across the combustion process. Since the additional term is less than unity, an engine based on the Humphrey cycle will have a greater efficiency than a Brayton one, provided compression (hence temperature) ratios are similar.

When comparing the CJ and isochoric model gas final conditions, one can observe that CJ conditions are even higher than that of an isochoric process (Humphrey). A more accurate thermodynamic cycle for an ideal PDE is the Fickett-Jacobs (FJ) cycle [6] [1]. The basics of FJ are a cylinder and piston forming a closed system. The system is considered adiabatic, and the mass inside the cylinder is also fixed. Detonation occurs within the cylinder and its contents are brought back to initial conditions. The FJ cycle efficiency also depends on gamma, so a specific fuel and initial conditions are needed. A more in-depth explanation of the FJ cycle is given in [1]. Figure 7 shows a comparison made between all three cycles, for stoichiometric propane-air mixtures at 300K and 1 bar initial conditions. All calculations are assumed to be ideal cases, no
losses, with isentropic compression and expansion. It is now clear to see the tremendous benefits of detonation when applied to a PDE.

Perhaps the most obvious difference is that even without compression (i.e. \( \pi = 1 \)), the efficiency of the FJ cycle can exceed 30% where it would be zero for Brayton. As compression ratio increases, the difference is reduced, yet still being significant.

![Figure 7 - Thermal Efficiency vs. Compression Ratio](image.jpg)

### 1.5 Literature survey

Detonation experiments have been well documented throughout the 20\textsuperscript{th} century. With the theory set by the CJ model around 1900, newer ideas began to develop during the early and mid-20\textsuperscript{th} century. Due to the nature of detonation, it shouldn’t be a surprise that most developments happened during times of war. Russians, Germans and Americans greatly contributed to what we know about detonation today.

Against popular belief, the German V-1 missile used during World War II had a pulse jet engine operating with deflagration, not detonation. The heavily used V-2, unlike the V-1, switched to liquid fuels instead.
In a similar way as with the CJ model, independently developed by Chapman and Jouguet, the
ZND model is named after Zeldovich (Russian), von Neumann (Hungarian-American) and Doring
(German), who each independently developed a one dimensional model to physically explain the
thermodynamics behind the CJ theory. They published their works in 1940, 1943 and 1960
respectively.

Earlier experiments by Kayushin [16], tried to explore the effects of wire mesh placed inside a tube
on flame speed. Although using hydrogen and oxygen—perhaps the most easily detonable
mixture—the author found, by using Schlieren devices, that immediately after the wire mesh flame
speed seemed to accelerate. Grids were characterized by a non-dimensional number, relating the
number of elements in a grid and the diameter of its elements. Kayushin also experimented with
what he called diaphragms: essentially similar to a disc with an orifice. He found that as BR
increased, the flame speed after the obstacles increased, initially exceeding CJ speeds, settling
to CJ speeds. Hydrogen and oxygen mixtures have a cell size of around 1.3mm. His experiments
were carried out in a tube only 17.5 cm long.

Perhaps the most renowned device known to obtain detonation is the Shchelkin spiral, named
after (Russian) Kirill Ivanovich Shchelkin. His earlier works (circa 1949) included studies about
wall surface roughness and its effect on the velocity of flames. He published his findings about
using a spiral as an obstacle and how it accelerated the flame velocity within the tube. The BR
parameter is again mentioned as one of the most important spiral characteristics [8].

A recent study using discs as obstacles was performed by Chapin [18]. Discs with orifices were
mounted inside a tube to help shorten the DDT length. Hydrogen-air and ethylene-air mixtures
were used in the study. Experiments were carried out in a 2” diameter, 40” long clear
polycarbonate tube and a high-speed camera. Detonation was achieved within the tube length.
Chapin concluded that BR, length of DDT section and spacing between obstacles all affected the
required distance for detonation. Consumer-grade LPG and air mixtures were not tested.
Throughout the last decade, the University of Texas at Arlington has conducted several experiments and published numerous papers. A description of most experiments and their results can be found in Panicker’s Ph.D. dissertation [17]. Testing was performed using propane and oxygen mixtures. Several setups have been tested, including 0.75” ID and 1” ID tubes, Shchelkin spirals, rotary valves, water-cooled assemblies, converging-diverging nozzles, liquid-fuel injectors, and also a turbocharger turbine on an attempt to extract power from the gas. Albeit detonation was present on all setups, they didn’t achieve it in a consistent manner. In one of their latest papers [18], they even conclude that a clean-tube configuration had the best detonation success-rate over multiple firings.

Caltech’s Explosion Dynamics Laboratory hosts a very useful detonation database on their website. They host data from over 130 different publications containing experimental detonation data. The website shows the data based on different parameters such as cell size, tube diameter, and critical energy, among others. It is interesting to note that for the proposed fuel (propane) and air mixture, \( \lambda \) lies between 50 and 130mm, with the smallest size corresponding to a stoichiometric mixture. The critical energy to achieve direct detonation lies in the 200 kJ range. If direct detonation were to occur inside an engine at, say 20 times per second, the required initiation energy would equal approximately 4MJ/s, which means four megawatts for the ignition system alone. It should become clear to the reader why direct detonation methods can be impractical, to say the least.

Throughout the published papers, it would seem that researchers have avoided the use of LPG/propane and air, perhaps due to its relatively larger cell size. Although this mixture lies somewhere in the low-end of detonation sensitivity, it may be the most easily obtainable fuel for a commercial application. The experiments described in this paper are, for practicality reasons, restricted to LPG and air mixtures.
2. Test equipment and methodology

2.1 Methodology

This project focuses on a larger diameter (~4 inch ID) detonation tube, using readily available LPG (liquefied petroleum gas) and air mixtures. The tube is split into three sections. The center tube section allows the installation of a ‘cartridge’ consisting of discs with an orifice. The discs are secured on threaded rods, allowing the cartridge to be easily installed and removed from the tube. Testing was performed with several cartridge configurations in order to determine an optimal geometry, where the final flame speed is maximized in the available tube length. Figure 8 shows a diagram of the detonation test tube.

In order to detect detonation, high speed pressure sensors were used. The easiest way to detect detonation waves is by measuring their speed. Since the distance between two adjacent pressure sensors is known, the wave speed can be calculated by measuring the time it takes for the pressure spike(s) to travel between sensors. From CJ theory (see section 1.2), a theoretical detonation wave velocity can be calculated and compared with the measurements.

Initial testing was ‘dry’ – i.e. without fuel. The proper operation of the gas injectors, igniter and pressure sensors was verified. After checking for fuel and/or air leaks, the initial fuel tests were performed. For safety reasons, the initial fuel tests were carried out progressively by filling the tube with stoichiometric mixture from 10% up to 120% (tube total volume) in 10% increments. This ensured early detection of any possible flaws in the mechanical and/or electro-mechanical parts. All tests were performed by initially purging the tube with at least 80% (total volume) pure oxidizer.
Fuel testing was initially performed on an empty tube, to determine a baseline case. This configuration should achieve deflagration speeds near the spark plug, with flow accelerating towards the open-end of the tube due to heat addition (gas expansion) and friction.

Once a disc cartridge was installed, different equivalence ratios for the air/fuel mixture were tested, ranging from lean to rich until the mixture failed to ignite using the available ignition system. All equivalence ratios were tested with different fill rates (80%, 100% and 120%). Cartridges with different disc spacing and BR were tested using the same procedure. Up to a maximum of 14 discs were installed on a single cartridge, with a corresponding minimum disc
spacing of 3 inches. Discs with a BR of 30, 45, 60 and 75 (as defined in Figure 4) with spacing of
3, 4.5 and 6 inches were tested. Full and half-cartridges (half the discs) were also tested. Figure 9
shows the different test configurations using a tree diagram; only one branch is fully expanded
with equivalence ratio $\left( \frac{1}{7} \right)$ and fill rates due to space limitations.

Overall, 479 firings were recorded using LPG and air mixtures, and an additional 3 using pure
oxygen. After all data was collected, the results were analyzed and discussed.
Figure 9 - Test configurations (abbreviated)
2.2 Equipment layout

The DDT tube was built with a modular design in mind: it is comprised of three sections. The first section contains the mixture injection ports together with an ignition spark plug. The use of standard flanges between sections allows quick and easy cartridge changes inside the center section. The third section contains sensors to measure pressure and wave speed, as shown in Figure 8.

The initial section held the fuel and oxidizer injection pipes and spark plug. In order to minimize injection time, pressurized LPG and oxidizer were used. This ensured the detonation tube was purged and filled in a relatively short time, keeping losses through the tube’s open-end to a minimum. Injection was controlled by electrically operated solenoid valves and high-pressure check valves. The solenoids were controlled and timed by the Data Acquisition Board (DAQ). The injector pipes were welded in a tangential pattern. This geometry helps maximize turbulence (hence mixing of fuel and oxidizer) and maintain gas velocity inside the tube. Three different tangential configurations were considered. In the first two cases both pipes were as close as possible to each other (around 45° from each other), with oxidizer being injected ahead of fuel and vice versa. The third case had opposing, staggered pipes. From CFD analysis, it was observed that the opposing pipes configuration maintained higher gas velocity and provided a more homogeneous mixture. Figure 10 contains a snapshot of the analysis showing fuel mass fraction after injection has taken place. A high pressure check valve was mounted at the end of each injection pipe to prevent any backflow or flame travelling back into the supply lines. The initial section also held the spark plug. The ignition system comprised an automotive-grade ignition module and matching coil connected to the spark plug. A modified spark plug was used to ignite the mixture in the chamber (see equipment description). The ignition system was also controlled by the DAQ. The injector valves and ignition system were both powered by a 13.8 VDC power supply. Figure 11 shows a top view of the injection section with check valves and spark plug installed. Figure 12 shows the injection ports and spark plug.
Figure 10 - Injector configuration comparison

Figure 11 - Injection section top view
The center section was mounted to a stand, hence supporting the ignition and measurement sections. The disc cartridges were mounted by sliding them into the center section, and secured with radial bolts at the cartridge ends, Figure 13.

The last section of the tube held equally-spaced pressure sensors (<1 µs rise time) connected to a signal conditioning unit, which ultimately sent a voltage to a digital acquisition system capable
of sampling at 1.25 MHz. The DAQ was connected to a computer running Labview. Water cooling adaptors for the pressure sensors were available but not required, as the tube had sufficient time between firings to cool-down. Figure 8 shows the four sensors spaced 3.000 inches from each other, used to measure wave speed. A block diagram of the entire setup is shown in Figure 14.

![Diagram of equipment setup](image)

Figure 14 - Equipment block diagram
2.3 Equipment description

Several aspects of the entire setup were considered. The most important being safety, as the tube should be able to withstand the pressure of detonation. To evaluate the mechanical requirements of the tube, the worst case scenario was calculated. Using NASA’s online Chemical Equilibrium Analysis (CEA) program, the following scenario was considered: for detonation using pure oxygen and propane from atmospheric starting conditions, the wave Mach number is 7.63. The pressure ratio is 31.22, which translates to 459 psia. The tube, flanges, gaskets and check valves were selected with this value (and an additional safety margin) in mind. Figure 15 shows the assembled test stand.

![Complete test setup](image)

Figure 15 - Complete test setup

The following is a brief description of the test setup, grouped by electrical, hardware and control systems.

2.3.1 Electrical equipment description

**Pressure sensors**

The sensors used were PCB pressure transducers model 111A24. Maximum measurement range is 2,000 psi. Maximum pressure is 10,000 psi. They can withstand flash temperatures up to 10,000 °F. Maximum continuous temperature is 275 °F. Each sensor had a NIST calibration certificate, showing its output voltage vs. pressure trend. They have a linear relationship of 5.0 mV per psi.
The sensors use a fairly complicated mounting scheme, requiring a custom multiple-section mounting boss. This mount was machined and later welded to the final section of the tube. A soft-metal (brass) sealing washer was used between the sensor and the mounting boss. The sensor chassis is not electrically-isolated. The sensors require a constant current source, making them insensitive to any resistance and / or voltage drop in the cables. The signal output is AC-coupled.

**Signal conditioner**

The signal conditioner is a PCB 482C15 unit. It supports up to 4-channels (sensors) with individually adjustable gains. The signal conditioner provides a constant current source as required by the sensors. The conditioner included a NIST calibration certificate. The default current is set to 4 mA. The conditioner output is also AC-coupled.

**Data Acquisition Board (DAQ)**

A National Instruments USB-6351 DAQ was used for the experiments, Figure 16. Out of all the unit’s features, only the analog inputs and timers were used for testing. The analog inputs are capable of sampling at a rate of up to 1.25 MHz (multichannel aggregate) with 16-bit resolution and range of ±10 V. They were used to record the pressure signals. The 32-bit counter/timers were used as control lines to trigger the injection solenoids and ignition system. The actual sampling throughput was slightly higher due to the short sampling periods of approximately 100 ms. A short wire harness using an AMP multi-pin connector was used to easily transport / separate the DAQ from the main wiring harness.
Power supply
An adjustable 3-15 VDC 40 A B&K Precision 1692 switching power supply was used to power the igniter, coil, and the injector driver box. The unit has a fixed-voltage mode (at 13.8 VDC), used for testing. A digital display on the unit’s front panel shows the output voltage and instant current draw.

Injector valves
The injector valves are manufactured by AFS, model Gs-series. They are ‘peak-and-hold’ type valves. In order for them to have a fast response (opening/closing time), a high current must be initially applied. Once the valve is open, a lower ‘hold’ current is sufficient to keep them open. This avoids overheating the units. The manufacturer published mass flow vs. time curves were obtained by using an AFS injector driver box. Therefore, to be able to properly correlate injector opening time with mass flow, an AFS injector driver box was used.

Injector driver
The injector driver box is an AFS 8-channel unit. It was powered by 13.8 VDC from the power supply. It automatically provided the peak-and-hold output needed to trigger the injectors, based on logic-level input signals from the DAQ.
Oscilloscope

A Tektronix DPO3032, 300MHz 2-channel oscilloscope was used to compare and verify the DAQ-acquired data. This unit is capable of sampling up to 2.5 GS/s, with an analog bandwidth of 300 MHz. The scope-supplied 10x probes were used during testing. The unit’s trigger line was connected to the DAQ igniter signal.

Wiring

Special care was taken to minimize electrical noise as much as possible. Grounding techniques were in accordance with the DAQ manual, which extensively warns about ground loops. Shielded wiring was used whenever possible, especially for the signal and control lines from and to the DAQ. All cable shields were connected to ground on one end only. In order to avoid any asymmetrical signal delays due to capacitance, inductance, or other wiring-induced effect, equal-length cables were used from the DAQ to the signal conditioner and to the pressure sensors. For safety reasons, wire length was sufficient to allow the DAQ and computer to be located in a separate room.

The cable running from the pressure-sensors to the signal conditioner was a low noise, PCB-brand shielded coaxial cable. The required BNC connectors were pre-installed on the cable. From the conditioner to the DAQ, individually-shielded twisted-pair BELDEN-brand stranded cable was used. Similar cable was used for the signal lines from the DAQ to igniter and injector driver box.

Oversized 3x10 AWG cable was used to connect the power supply to the igniter and injector driver box. Two lines carried the required 13.8 VDC to both devices, while the third line was used to ground the tube and its stand directly.

Ignition coil and igniter

The ignition module and coil were BOSCH units, fitted to several European cars. They were powered by the 13.8VDC power supply, using heavy wire as described before. The ignition
module is of the ‘dumb’ type: i.e. coil charge time was directly controlled by the DAQ. A wire-wound noise suppression cable was used to connect the coil to the spark plug.

**Spark plug**

The spark plug used for all experiments is a modified NGK JR10B unit, normally used on sport-bike engines, Figure 17. The ground electrode was removed to maximize its gap, thus exposing a larger amount of fuel/air mixture to the spark. This also increases the amount of energy released to the gas, provided the coil remains capable of creating a high enough voltage for the arc to occur. The spark plug temperature range is among the lowest manufactured by NGK. This means that heat conduction from the spark plug tip to the spark plug body is higher compared to a regular plug. A cooler plug prevents it from becoming an auto-ignition hotspot.

![Figure 17 - Modified spark plug](image)

**2.3.2 Hardware description**

**Tube**

The tube was of seamless construction, nominal size 4 inches, schedule 80, conforming to ASTM A106 Grade B (material properties) and ASME B31.1 pressure piping standards. The tube manufacturer is Zelziarne Podbrezova (Slovak Republic - http://www.zelpo.sk). The tube characteristics are shown in Table 2.
**Table 2 - Tube characteristics**

<table>
<thead>
<tr>
<th>Nom. ID, inches</th>
<th>4.0</th>
<th>Outer diameter, inches</th>
<th>4.500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness, min., inches</td>
<td>0.295</td>
<td>Wall thickness, nominal, inches</td>
<td>0.337</td>
</tr>
<tr>
<td>Working pressure PSI (ambient T)</td>
<td>2,300</td>
<td>Yield strength, min, PSI</td>
<td>35,000</td>
</tr>
<tr>
<td>Burst pressure PSI (ambient T)</td>
<td>9,000</td>
<td>Tensile strength, min, PSI</td>
<td>60,000</td>
</tr>
</tbody>
</table>

**Flanges**

The flanges were socket-weld, class 300, conforming to ASTM A105 (material properties) and ASME B16.5 flange and fittings standard. The strength characteristics are presented in Table 3.

**Table 3 - Flange characteristics**

<table>
<thead>
<tr>
<th>Tensile strength, min, PSI</th>
<th>70,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength, min, PSI</td>
<td>36,000</td>
</tr>
</tbody>
</table>

ASME B16.5 lists the working pressure for this flange as 740 psi at temperatures below 38°C, dropping to 635 psi at 200°C. No burst pressures are specified. The flanges have the lowest pressure rating in the whole assembly. A TIG machine was used to weld the flanges to the tube sections with the appropriate filler rod.

**Bolts and nuts**

Bolts were selected in accordance with ASTM A193 standards for class 300 flanges, which specify grade 5 bolts. Nuts were selected in accordance with the corresponding ASTM A194 standard. Flange bolts were torqued down to 257 ft-lbs, also in accordance with standard practices.
Flange gasket

The gasket had a stainless steel wire wound spiral with pure graphite filler construction. It’s able to withstand up to 850 °F. The gasket outer dimensions allowed it to self-center once located between two flanges.

Injection pipe and check valves

Tangentially-mounted pipes were used to inject the gas into the main tube. Each pipe was 1.25” OD x 0.5” ID x 6” long. Material is drawn-over-mandrel C 1020 steel. Tensile and yield strengths are 80,000 and 70,000 psi, better than the main tube and flanges. Each injection pipe had a check valve installed. Parker valves 8M-C8L-1-B capable of withstanding 3000psi backpressure were used. They open with only 1psi forward-pressure. The valve fluorocarbon seal is rated for up to 400°F continuous service.

DDT cartridge

Obstacle discs were laser-cut from 1018 mild steel plate in two thicknesses (1/2 and 1/4 inch thick) and with blockage ratios of 30, 45, 60 and 75 as defined in Figure 4. The discs had a sliding fit with the tube center section. The thicker discs were used at the ends of the cartridge for securing the cartridge to the tube. Six radially-mounted 1/4-inch grade 9 bolts were used on each end disc to fasten the cartridge to the tube. The thinner discs were used to assemble the rest (center) of the cartridge. Discs were mounted to high-strength grade B16 threaded rods using grade 8 nuts. The one-piece disc cartridge was able to withstand the effects of combustion much better compared to previous studies using wire-spirals.
Figure 18 - Cartridges and discs

Injector valves block

The injector valves were mounted to a block of aluminum bolted on top of the test stand. The aluminum block was previously machined so the proper ports required to mount the injectors were ready. Fuel and oxidizer supply lines were connected to the valve inlet ports, Figure 19

Figure 19 - Injector valves block
Test stand

The test stand was also fabricated for this project. Square-section tubing was cut, MIG-welded and then prepped and painted before securing all the equipment to it.

LPG/air supply

A commercial LPG gas tank was procured for testing. Since LPG composition varies depending on the origin, the manufacturer MSDS specifies a range of its composition. Table 4 shows the specified gas composition. In order to control gas pressure (for both oxidizer and LPG), an adjustable single-stage pressure regulator was used on each line feeding the injector valve block. A flame arrestor valve was used at the exit of the LPG pressure regulator for extra safety. Pressurized air was used from the test facility off-site compressor.

![Table 4 - LPG composition](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>87.5-100</td>
</tr>
<tr>
<td>Ethane</td>
<td>0-7.0</td>
</tr>
<tr>
<td>Propylene</td>
<td>0-5.0</td>
</tr>
<tr>
<td>Butanes</td>
<td>0-2.5</td>
</tr>
<tr>
<td>Ethyl Mercaptan</td>
<td>0-50 ppm</td>
</tr>
</tbody>
</table>

2.3.3 Control system description

The entire system is controlled by the DAQ. The written Labview software is a fully customizable code allowing the user to select and/or change all experiment parameters such as L, injector duty cycle, sampling period, pre and post injection delays, fill rate and others. The required constants are coded in the Labview routine, but they can be easily changed if needed. Constants include injector mass flow vs. inlet pressure vs. opening time equations, tube geometry (volume) and density and stoichiometric ratios for fuel and oxidizer.
For each run, specific parameters were selected using the program GUI. These include purge and fill percentage, L (inverse of equivalence ratio), pre- and post-injection delays, fuel valve injection period, igniter charge time and DAQ sampling frequency and period. Two ON/OFF buttons allow the user to independently control either igniter, fuel valve or both for troubleshooting or to carry out extended purge runs. Figure 20 shows the graphical interface.

When the program is executed, the DAQ triggers the different devices with the appropriate timing to achieve the desired L, mixing delay, and sampling period. The code has three separate subroutines; all of them run in parallel once the program starts. The first subroutine calculates the injection parameters and triggers the injection valves accordingly. The second subroutine controls the ignition system. The final subroutine contains the sampling code.
The first subroutine calculates timing for the injection valves. Based on the user inputs, the code starts by calculating the total mass of fuel and oxidizer to be injected to achieve the desired fill rate and L. Oxidizer total mass includes purging and fuel-mixing mass. Based on the oxidizer pressure line input, the required oxidizer mass is translated to an equivalent injection period. The fuel mass injected per fuel injection period (a user input) is calculated as well. The total fuel mass is divided by the mass injected per fuel injection, and the resultant is the number of pulses that the fuel injector must be triggered for. To calculate timing between each fuel injection pulse (low-time), the code divides the oxidizer valve time (minus purge time) by number of fuel pulses. The resultant specifies the total time pert fuel injection cycle (including high and low-time). Finally, timing for the initial fuel pulse is established so that both fuel and oxidizer valves close simultaneously after total mass has been injected.

After the pre-injection delay has elapsed, the oxidizer valve is opened for the calculated amount of time. The oxidizer valve initially purges the tube, yet remains open after purging for additional oxidizer to be mixed with fuel. After the purge period elapses, the fuel valve is pulsed with the previously calculated frequency and duty cycle. By closing both valves together, a lean-mixture gas pocket close to the spark plug is avoided.

The second subroutine controls the ignition system. Once the required fuel and oxidizer mass are injected, the DAQ waits for a specified amount of time (to promote mixing) before triggering the ignition system. The coil is charged for a specific period (usually 10 ms) in order to saturate its core, thus maximizing the discharge energy. Once the signal drops, the magnetic field collapses and the stored energy is discharged into the spark plug. Figure 21 shows a simplified sequence of the DAQ output lines, where the red line represents the oxidizer valve signal, pink the LPG valve signal, and blue the igniter output.
Figure 21 - DAQ output control lines, simplified

The last subroutine contains the code for sampling. The external oscilloscope and this subroutine are triggered with the rising edge of the coil signal. Once triggered, sampling occurs for the specified period and frequency. The computer records the data to the hard drive and plots it on the screen. The oscilloscope also samples for the specified time, and the screen output is saved to a graphics file for later analysis. Figure 22 shows the complete Labview program / routines.

Figure 23 shows the logic sequence that the routine follows, where the left branch shows the injection subroutine, the center branch represents ignition, and the right branch the sampling subroutine.
Figure 22 - Labview program
Figure 23 - Labview routine flowchart
3. Results and analysis

3.1 Data processing methodology

The tube was fired over 600 times: 482 of them being recorded. The recorded pressure signals represent over 280 MB of raw data. This required a significant amount of time to analyze. The last three recordings correspond to oxygen tests, which deserve further special attention. Data was processed using MATLAB. Two separate programs were written to analyze the data. The first code calculates basic signal parameters and plots the data for each run. The second code gathers all the calculated parameters from all runs and then plots overall results.

The first code uses a subroutine from National Instruments to read Labview data into Matlab. The code then calculates the time difference between each sensor signal, the wave speed for each sensor pair and its average, the signal rise-time, and each channel’s maximum pressure. Finally, it plots and displays the calculated values on the figure. The appendix contains all 482 graphs. Figure 24 shows a sample output from the first code.

Due to the nature of the ignition system, electrical noise is generated (and recorded) during the ignition coil charge and discharge. For each recorded dataset, the initial 14 ms corresponding to ignition system noise are deleted. The code then calculates pressure from the voltage data. The next step is to locate the maximum pressure point for each channel. The code zooms-in to 0.5 ms before and 1 ms after the earliest maximum pressure point. For each channel, the script then locates the point where pressure starts to rise. The criteria for locating the rise point is to search for either the first sample with a value of at least 25% of the channel’s maximum pressure value, or the first sample to exceed a pre-established pressure level. The time difference between the rise point and maximum pressure location is calculated and displayed as $T_R$ for each channel on the graph. This indicator is closely related to the pressure spike local first derivative. It is a numerical indicator of the pressure spike shape. To calculate wave speed, the code uses the time
difference between the (previously located) rise points. A speed average is finally calculated and displayed along with the other parameters on the graph.

**Figure 24 - Matlab sample output graphs**

Once all 482 datasets were analyzed, the second code gathered the calculated data from each run. It then plotted distribution graphs for average maximum pressure, speed and rise time values. It also produced 3-D contour maps for pressure, speed and rise time.

Visual inspection of the plots revealed two very distinctive groups. One group had a low rise time showing an abrupt pressure spike (Figure 24 – left), while a second group showed high rise times and a gradual, oscillating pressure increase (Figure 24 – right). A sharp spike can be associated with supersonic flow, while a gradual pressure increase corresponds to a subsonic perturbation.

The base line configuration (empty tube) pressure change, if any, was too small to be detected from the sensors background noise: a flat line was recorded by all four sensors.
3.2 Numerical results

This initial analysis identifies those runs with the best performance: maximum speed, pressure and lowest $T_R$. Table 5 presents the top three samples for each category.

<table>
<thead>
<tr>
<th>Cartridge config</th>
<th>Speed avg (m/s)</th>
<th>$T_R$ avg (µs)</th>
<th>$P$ avg (psig)</th>
<th>d</th>
<th>s</th>
<th>BR</th>
<th>L</th>
<th>Fill %</th>
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<tbody>
<tr>
<td>24</td>
<td>904.4</td>
<td>12.1</td>
<td>94.3</td>
<td>14</td>
<td>3</td>
<td>45</td>
<td>1.4</td>
<td>120</td>
</tr>
<tr>
<td>24</td>
<td>885.1</td>
<td>13.5</td>
<td>93.3</td>
<td>14</td>
<td>3</td>
<td>45</td>
<td>1.4</td>
<td>120</td>
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<tr>
<td>24</td>
<td>875.5</td>
<td>11.4</td>
<td>86.0</td>
<td>14</td>
<td>3</td>
<td>45</td>
<td>1.4</td>
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<table>
<thead>
<tr>
<th>Cartridge config</th>
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<td>45</td>
<td>1.4</td>
<td>120</td>
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<td>725.3</td>
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<td>60</td>
<td>1.3</td>
<td>150</td>
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<table>
<thead>
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<th>$P$ avg (psig)</th>
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<td>120</td>
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<tr>
<td>15</td>
<td>797.3</td>
<td>9.9</td>
<td>80.5</td>
<td>14</td>
<td>3</td>
<td>60</td>
<td>1.6</td>
<td>120</td>
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<tr>
<td>23</td>
<td>759.3</td>
<td>9.9</td>
<td>62.1</td>
<td>14</td>
<td>2</td>
<td>60</td>
<td>1.2</td>
<td>120</td>
</tr>
</tbody>
</table>

The highest speed and pressure were both obtained on the same run using cartridge 24: 14 discs with BR of 45, spacing of 3 inches and L equal 1.4. For the best (lowest) $T_R$, a slightly different combination is required: 14 discs at either 2 or 3 inches spacing, but with BR of 60. Equivalence ratio (L) does not appear to be closer to a single value, as the top two observations had L=1.6 and the third L=1.2. For pressure and speed, L=1.4 seems to be the optimum. Lean mixtures are known to have faster flame speeds, and the experiment results match accordingly. Higher fill volumes seem to support better performance overall. The pressure plot for best pressure and speed is shown in Figure 25 – left. The pressure plot for best $T_R$ is in Figure 25 – right.
Using CEA and LPG composition from Table 4, the calculated pressure ratio for detonation is 18.265 (254 psig) and wave speed is 1,798 m/s. The best experimental results were able to reach 50.3% detonation speed and 37.1% detonation pressure. The flame is supersonic in the upstream frame of reference at Mach 2.66, and high-subsonic (Mach 0.96) in the downstream frame of reference. When compared to isentropic normal shock relations a pressure ratio of 8.04 is calculated: within 8% of the 7.4 measured ratio.

These results correspond to the fast flame regime. It is known that the flame front can transition to detonation once the sonic downstream conditions are attained. Here, the flame reached 96% of said conditions. Several reasons for not achieving detonation are possible and will be discussed in the following sections.
3.3 Regression model

To statistically analyze the experiment data, a multi-variable second-degree regression model using the least-squares method was created. The model tries to explain average pressure, rise time or wave speed using the following input variables: total discs, disc spacing, BR, L and fill percentage. Due to the non-linear behavior of these variables, a second-degree polynomial was assumed for all five variables. This requires extra data for the model, namely the square of each variable input data. The resulting model is expressed by equation 3.1.

\[ y = a^2 + a + c^2 + c + d^2 + d + e^2 + e + F^2 + kF + \text{onct nt} \] (3.1)

Where:
- \(y\) Parameter to be estimated: pressure, \(T_R\) or wave speed
- \(d\) Total number of discs
- \(s\) Disc spacing
- \(BR\) Blockage ratio
- \(L\) Inverse of equivalence ratio
- \(F\) Fill percentage
- \(a,b,c,e,f,g,h,l,j,k\) Variable coefficients, to be determined by the regression model

Several models were created, but all of them have a low adjusted determination coefficient \(R^2\) and / or have variable coefficients that cannot reject the null hypothesis. The model with the highest \(R^2\) is shown in Table 6.
Table 6 - Pressure regression model results

<table>
<thead>
<tr>
<th>Average Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

**Regression Statistics**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple R</td>
<td>0.765</td>
</tr>
<tr>
<td>R Square</td>
<td>0.586</td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td>0.577</td>
</tr>
<tr>
<td>Standard Error</td>
<td>13.280</td>
</tr>
<tr>
<td>Observations</td>
<td>479</td>
</tr>
</tbody>
</table>

**ANOVA**

<table>
<thead>
<tr>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance F</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>116625.578</td>
<td>116625.558</td>
<td>66.125</td>
<td>0.000</td>
</tr>
<tr>
<td>468</td>
<td>82541.925</td>
<td>176.372</td>
<td></td>
<td></td>
</tr>
<tr>
<td>478</td>
<td>199167.503</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-238.733</td>
<td>-10.374</td>
<td>0.000%</td>
<td>-283.952</td>
<td>-193.513</td>
</tr>
<tr>
<td>d</td>
<td>4.157</td>
<td>3.479</td>
<td>0.055%</td>
<td>1.809</td>
<td>6.505</td>
</tr>
<tr>
<td>d²</td>
<td>-0.036</td>
<td>-0.539</td>
<td>59.031%</td>
<td>-0.166</td>
<td>0.095</td>
</tr>
<tr>
<td>s</td>
<td>1.419</td>
<td>0.517</td>
<td>60.520%</td>
<td>-3.971</td>
<td>6.809</td>
</tr>
<tr>
<td>s²</td>
<td>0.217</td>
<td>0.657</td>
<td>51.143%</td>
<td>-0.433</td>
<td>0.868</td>
</tr>
<tr>
<td>BR</td>
<td>0.257</td>
<td>1.113</td>
<td>26.614%</td>
<td>-0.197</td>
<td>0.710</td>
</tr>
<tr>
<td>BR²</td>
<td>0.000</td>
<td>-0.026</td>
<td>97.926%</td>
<td>-0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>L</td>
<td>230.829</td>
<td>7.872</td>
<td>0.000%</td>
<td>173.207</td>
<td>288.451</td>
</tr>
<tr>
<td>L²</td>
<td>-86.339</td>
<td>-8.622</td>
<td>0.000%</td>
<td>-106.016</td>
<td>-66.663</td>
</tr>
<tr>
<td>F</td>
<td>1.170</td>
<td>4.537</td>
<td>0.001%</td>
<td>0.663</td>
<td>1.676</td>
</tr>
<tr>
<td>F²</td>
<td>-0.004</td>
<td>-3.165</td>
<td>0.165%</td>
<td>-0.007</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

With an adjusted $R^2$ value of 0.577, this model can only explain 57.7% of pressure behavior.

Analyzing the p-values, the coefficients for $d^2$, $s$, $s^2$, BR and BR² cannot be statistically proven with a 95% confidence level to be different than zero. The corresponding optimum values are either negative or simply impossible (for example, BR of 2130%). Nevertheless, some useful data from the model can be extracted by calculating the suggested optimum values for L: 1.336 and for F: 140.9%. The calculated L-value matches the maximums observed during testing. Although
fill rates of 140% weren’t tested, better performance was attained at higher fill rates, which agrees qualitatively with the regression model.

Due to the low $R^2$ value, model predictions or extrapolations cannot be considered accurate. This mathematical model expresses the irregularity of collected data. Even though testing conditions were kept as constant as possible, pressure and speed values have a high degree of variability that is unaccounted for.

3.4 Analysis

Distribution plots were obtained to get an idea of data behavior. Three plots showing a histogram and cumulative distribution for each one of the main variables are shown in Figure 26, Figure 27 and Figure 28.

![Average pressure histogram](image)

Figure 26 - Average pressure histogram
The average pressure histogram shows a slightly right-skewed distribution. Mean value is 34.41 psig and median is 31.60 psig. The cumulative plot shows a smooth curve, in accordance with the distribution histogram. Changes to the cartridge configuration will affect average pressure gradually. As long as the cartridge configuration is near the ‘sweet spot’, slight cartridge deviations will not change pressure significantly.

![Average speed histogram](image)

**Figure 27 - Average speed histogram**

The average speed histogram shows a different pattern than the pressure histogram. Average speed calculations are set to zero if a valid rise point cannot be detected or if they happen at the same location. This occurred on slow deflagrations that don’t have a clear, sharp pressure spike. Therefore, a significant number of observations (~40%) fall within the first bin of speeds between zero and ~30 m/s. A clear gap exists between samples for which a valid average speed cannot
be calculated and the rest. The remaining 60% show a bell-shaped distribution, with a slight right-hand skewness. Median speed is 570.9 m/s; mean speed is 405.7 m/s. Looking at the bell-shaped distribution section, the right skewness (as in the pressure histogram) allows some flexibility regarding deviations from the ideal cartridge configuration.

![Rise time histogram](image)

**Figure 28 - Average $T_R$ histogram**

The rise time histogram shows two groups, one centered on the origin and another around 550 $\mu$s. Mean value is 326.2 $\mu$s, and median is 315.3 $\mu$s. The (ideal) first bin has 100 observations, while the second bin drops sharply to 30 events. The cumulative distribution show that roughly 20% of all samples fall into the first bin. The higher $T_R$ group represents slow-deflagrations. Unlike the previous two distributions, the cartridge needs to be close to the ideal configuration in
order to obtain a low $T_R$ value. The function becomes relatively insensitive between 100 and 400 µs, just below the point where most deflagrations start to occur.

After analyzing the histograms, contour plots can be used to determine what the optimum configuration(s) is (are). The following figures show different relationships between the main variables, by plotting pressure, speed or rise time vs. two other variables, holding everything else constant.

![Figure 29 - Average pressure vs. BR vs. L](image-url)
Figure 30 - Average pressure vs. BR vs. d

Figure 31 - Average pressure vs. L vs. disc spacing
Figure 32 - Average speed vs. BR vs. L

Figure 33 - Average speed vs. BR vs. number of discs
Figure 34 - Average speed vs. L vs. disc spacing

Figure 35 - Rise time vs. BR vs. L
Figure 36 - Rise time vs. BR vs. number of discs

Figure 37 - Rise time vs. L vs. disc spacing
From the previous nine figures, an optimum configuration for each main variable can be obtained. Table 7 summarizes the ideal configurations for each main variable.

<table>
<thead>
<tr>
<th>Main variable to be optimized</th>
<th>BR</th>
<th>L</th>
<th>s</th>
<th>Number of discs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg max pressure</td>
<td>45-60</td>
<td>1.4</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Avg max speed</td>
<td>45</td>
<td>1.4</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Avg T_R</td>
<td>45 to 70</td>
<td>1.4</td>
<td>3</td>
<td>14</td>
</tr>
</tbody>
</table>

For average maximum pressure, the function seems to be more sensitive to L variations than BR (Figure 29). At the same time, gradient is higher for BR than number of discs (Figure 30). From Figure 31, it can be observed that cartridges with a higher number of discs obtain the highest pressure levels, and are more sensitive to variations in L than cartridges with lower disc density.

For average maximum speed, the function seems much more sensitive to L changes than BR (Figure 32). Similar to the maximum pressure case, speed is more sensitive to number of discs than changes in BR (Figure 33). Note that a significant change occurs when discs drop below 8 (it should be noted that number of discs is also related to disc spacing). Looking at Figure 34, it is observed that high disc-density cartridges (with low disc spacing) obtain the highest speeds, and are more sensitive to L than disc spacing. Lower disc-density cartridges seem as sensitive to L as high-density configurations, but obtain much lower speeds.

From Figure 35, T_R appears to be largely insensitive to BR changes between 45 and 75 compared to L. However, it’s more sensitive to BR than number of discs, as long as 8 or more discs are used (Figure 36). Finally, Figure 37 shows that T_R seems to be most insensitive to disc spacing; a low-disc-density cartridge (d=5 s=4.5) obtained T_R’s comparable to two high-density cartridges (d=14 s=2 and d=10 s=4.5).
Although detonation was not achieved, there appears to be an optimum cartridge configuration able to obtain better readings when compared to other configurations. For average pressure and speed, the configuration can be considered the same. Rise time shows a slight variation regarding the ideal BR, although the other three parameters L, s and number of discs are consistent with the previous numerical results.

Overall, it can be said that in order of importance, the most significant parameter is gas mixture composition L, followed by BR, number of discs, and finally disc spacing. As long as all parameters are close to their optimum, small deviations in pressure, speed and rise time will occur. If one or more parameter deviate significantly, pressure, speed and/or $T_R$ performance will be severely degraded. For this paper, the ideal cartridge must have BR 60, using 8 or more discs with 3-inch spacing.

Reasons for not achieving detonation can be several, including incorrect cartridge configuration, incomplete fuel/oxidizer mixing, or a longer DDT section is required.

Analyzing the cartridge configuration, the unrestricted core diameter for a disc with the highest BR of 75 is 47.6 mm. For propane, $\lambda$ is close to 51 mm [9]. Although it's possible that BR 70 discs were restricting the propagation of a complete detonation cell, tests with lower BR’s showed better speed and pressure characteristics. At BR 60, the unrestricted core diameter is 61.0 mm, enough for detonation to propagate. The same argument is valid for discs with an even larger core diameter (i.e. lower BR).

The second reason involves the injection procedure. In order to achieve the appropriate equivalence ratio, fuel injection was pulsed into the tube while the oxidizer injector was held open. This creates alternating fuel-rich and lean pockets, where gas speed and turbulence is expected to help complete mixing. CFD-results show that with the given tube geometry and mass flow,
mixing should not be a concern. A risky alternative would be pre-mixing. Any connection mechanism between the main tube and pre-mixing chamber will need to be flame-proof.

The third reason is perhaps the most reasonable: the maximum obtained speed falls short of that required to transition within the tube length and cartridge configuration. With the modular design of the test setup, the center tube section could be easily replaced or a second DDT section added to verify this allegation.

3.5 Oxygen testing results

After testing all cartridges with fuel/air mixtures, pure oxygen was used to verify the equipment capabilities. Pressure levels were over 10 times higher when detonation was finally achieved, confirmed by the corresponding wave speed. Figure 38 shows the results for oxygen testing. On the right, the graphs correspond to a cartridge with BR 30, 6-inch disc spacing, 4 discs total. Results for an empty tube are shown on the left. The top figures were recorded by the DAQ while the bottom figures were recorded with an oscilloscope.
Figure 38 - Oxygen testing results

The use of pure oxygen resulted in much higher speeds (2799.6 m/s) compared to LPG/air (maximum reached of 904 m/s). A pressure increase of roughly tenfold was achieved with oxygen: a maximum of 970.9 psig was recorded vs. a peak of 98.3 psig with air.

Using CEA, LPG / pure oxygen detonation predicts a wave speed of 2,357 m/s and pressure ratio of 36.1. For the empty-tube case (left), a wave speed of 2,799.6 m/s was recorded. Average pressure ratio was 56.5. It’s interesting to note that the pressure region is very thin, as pressure drops almost to zero by the time it reaches the next pressure sensor. This may indicate a decoupled wave, as pressure downstream of the wave should remain higher than initial conditions. Experiments from other research facilities have observed transitioning initially
produces over-driven waves before reaching CJ conditions. An over-driven wave is not considered to be stable, so additional equipment is required to determine its behavior. Current equipment does not allow for additional measurements up- or downstream of the tube, which would help determine if the wave was stabilizing towards CJ conditions.

For the obstacle case (right), wave speed (2,090 m/s) was closer to CJ conditions (2,357 m/s). Pressure ratio was also closer at 29.77 (CJ 36.1). Deviations from CJ-values are small (11% lower speed and 17% lower pressure ratio), which would indicate a slightly under-driven wave was established. The variations are comparable to other detonation studies. Downstream of the wave, pressure levels of around 100 psig were recorded. Short rise times were also present; both are typical characteristics of detonation waves.

**DAQ verification**

To verify the DAQ measurement capabilities, a comparison with an oscilloscope was made. For the empty tube case, the oscilloscope shows a time difference between channels 1 and 4 of 82.24000μs. Using this value, a speed of 2779.7 m/s is calculated. The value obtained using the DAQ / Matlab routine is 0.7% higher. Using the same procedure for the empty tube case, the DAQ value is found to be within 3% of the oscilloscope value. The oscilloscope has a higher accuracy due to its sampling rate of 5 MHz per channel (vs. 352 KHz per channel for the DAQ). Although the DAQ is sampling at its maximum frequency, the values obtained are very close to those obtained by the higher-accuracy oscilloscope. Slower flames accuracy (LPG / air) shouldn’t be a concern either.

**3.6 Testing observations**

**Signal clipping / signal conditioner output impedance**

While testing with oxygen, the signal conditioner output voltage was found to be ‘clipping’ at roughly 5 volts (1,000 psi). Clipping means the pressure measurement reaches hardware limits. Further testing showed the pressure sensor output presented no signs of clipping, while clipping
existed at the signal conditioner output. Wave speed is calculated based on the time difference between pressure rise points (and not the peak values), so speed calculation is not affected.

PCB was contacted for advice, and the conditioner was sent back for diagnosis. PCB didn’t find any problems with the unit. They did notice the signal would clip when connected to a 50 ohm output impedance load. Some discrepancy exists as to the proper conditioner output impedance. The conditioner manual specifies 50-ohms output impedance, while emails from PCB suggested a high-impedance load should be used. The issue was never fully cleared by PCB. The test setup used a 50 ohm resistor in parallel with the DAQ (with an internal impedance greater than 1 Gohm – i.e. negligible) to comply with the unit’s manual specs. For this application, an impedance mismatch would result in pressure scaling being off. The recorded peak pressure values should be considered accordingly. Another undesirable result of impedance mismatch would be the introduction of a delay in the pressure signal. If any delay was introduced, it would be applied equally to all channels. This would effectively cancel out any influence on wave speed calculation.

As PCB was never completely clear regarding the output impedance of the signal conditioner, a comparison test with a known calibrated pressure sensor should be carried out. For the present study, an off-scale pressure reading will not affect the speed calculations. However, validated pressure data would allow verification beyond that of flame speed. A comparison of pressure ratio and isentropic normal shock characteristics would be the prime candidate. It was noted during testing that pressure values seemed to match normal shock characteristics.

If scaling is confirmed to be accurate without the 50-ohm impedance-matching resistor, an AC-coupled digitizer or multiple-channel oscilloscope should be used. Since the DAQ is DC-coupled, the resistor kept the conditioner signal not only within the DAQ voltage limits (+/- 10V), but it also stabilized the output signal at zero volts with respect to ground. The signal conditioner output voltage drifts considerably without a resistor.
A different measurement option would be to monitor the pressure sensor output directly. This would bypass the signal conditioner signal circuitry. The conditioner would then only operate as a power supply for the sensors. The signal conditioner gain feature would be lost. For this scenario, AC-coupled equipment would be a must.

**Air-fuel ratio accuracy**

When stoichiometric conditions were called for, the resulting mixture appeared to be ‘rich’, based on excessive gas smell and ignitability issues. Although a gas analyzer (or oxygen sensor) was not available during testing, troubleshooting showed that once the oxidizer injector opened, line pressure dropped. This indicates mass flow was restricted. Attempts were made to increase or keep pressure constant, but were unsuccessful. Bigger oxidizer lines may help with this issue, as the off-site air compressor should be able to deliver the required mass flow. For this reason, the mixture parameter L should be treated accordingly. Nevertheless, it remains an effective tool to alter the actual equivalence ratio.

**Oxygen cartridge deformation**

Oxygen-testing showed much higher pressures than LPG / air mixtures. After obstacle-testing with oxygen, discs were found to be bent. Discs with BR 30 were the only ones tested with oxygen. Figure 39 shows the discs after removal. Further testing with oxygen will require thicker discs, similar to the cartridge end-discs.

![Figure 39 - Discs after oxygen testing (bent)](image-url)
Others

During initial fuel tests (at 10% fill volume), a blue-colored swirling flame was clearly observed inside the tube. At higher fill levels flame magnitude and speed didn’t allow for visual identification. Most experiments were recorded with a camera at 24 frames per second. At such slow rate, only a single bright frame was obtained. High-speed cameras would allow identification and measurement of flame propagation (luminescence) characteristics.

The interaction of the chemically reactive gas with the threaded rods supporting the discs is unknown. Although testing with only 1 disc and all three rods mounted inside the tube showed no improvement versus any other case, the effect of the rods on the combusting gas inside the tube should be considered. CFD may be the only available tool to account for the threaded rods effects.

No significant difference was found between installing half-cartridges at the ignition or exhaust end. One of the studies from the University of Arlington at Texas (mentioned in section 1.5) tested whether ignition location was significant to pressure and speed levels. They concluded that no significant evidence was found when changing ignition location. The equivalent effect of reversing the half-cartridge inside the tube is that of moving the ignition within the tube. Therefore, the experiment results match those of the previous paper.
4. Conclusions and recommendations

The experiments were able to achieve the fast flame regimes for LPG and air mixtures. Although LPG and oxygen mixtures were the only ones able to achieve detonation, pure oxygen limits the practicality of any device. Continuous efforts should be made towards achieving detonation with ordinary-fuel and air mixtures.

It is interesting to note that for oxygen mixtures, obstacles hampered wave pressure and speed, while for air mixtures they greatly increased pressure and speed. This can be interpreted as supporting evidence that a DDT section depends on the gas mixture being ignited.

All three main variables: peak pressure, maximum speed, and rise time are found to be sensitive to cartridge configuration, as long as the proper equivalence ratio mixture is supplied.

Statistical evidence suggests the ideal cartridge configuration depends on whether high pressure, speed or the sharpest pressure spike is desired, see Table 7. A sharper spike was obtained by using a slightly higher BR.

Future testing should include different fuels and DDT mechanisms. Extending the test section and mixing different BR discs on a single cartridge could be tested with minimal effort.

The present work not only identifies the most favorable obstacle configuration for the test tube, but also presents a platform upon which future testing can be performed. Other research facilities have revealed their intent to explore different geometries such as toroidal or helical DDT sections. Different flame acceleration devices should be explored while keeping in mind the usefulness and practicality of them.
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Appendix

Figure 1 - 01 S3D12+2 BR75_20percL1

Figure 2 - 01 S3D12+2 BR75_40percL1

Figure 3 - 01 S3D12+2 BR75_60percL1

Figure 4 - 01 S3D12+2 BR75_80percL1

Figure 5 - 01 S3D12+2 BR75_100percL1

Figure 6 - 01 S3D12+2 BR75_120percL1
Figure 55 - 07 S45D4+2 BR75_80percL=1.0

Figure 56 - 07 S45D4+2 BR75_80percL=1.2

Figure 57 - 07 S45D4+2 BR75_80percL=1.4

Figure 58 - 07 S45D4+2 BR75_80percL=1.6

Figure 59 - 07 S45D4+2 BR75_120percL=1.2

Figure 60 - 07 S45D4+2 BR75_120percL=1.4
Figure 67 - 08 S45D4+2 BR75
INV_100percL=1.4

Figure 68 - 08 S45D4+2 BR75
INV_120percL=1.3

Figure 69 - 08 S45D4+2 BR75
INV_120percL=1.5

Figure 70 - 08 S45D4+2 BR75
INV_120percL=1.6

Figure 71 - 08 S45D4+2 BR75
INV_120percL=1.7

Figure 72 - 08 S45D4+2 BR75
INV_120percL=1.2
Figure 73 - 08 S45D4+2 BR75
INV_120percL1.4=

Figure 74 - 09 S6D6+2 BR75_80percL=1.0

Figure 75 - 09 S6D6+2 BR75_80percL=1.2

Figure 76 - 09 S6D6+2 BR75_80percL=1.4

Figure 77 - 09 S6D6+2 BR75_80percL=1.6

Figure 78 - 09 S6D6+2 BR75_100percL=1.0
Figure 85 - 09 S6D6+2 BR75_120percL=1.6

Figure 86 - 09 S6D6+2 BR75_120percL=1.8

Figure 87 - 10 S_D1 BR75_100percL=1.0

Figure 88 - 10 S_D1 BR75_100percL=1.2

Figure 89 - 10 S_D1 BR75_100percL=1.4

Figure 90 - 10 S_D1 BR75_100percL=1.6
Figure 91 - 10 S_D1 BR75_150percL=1.2

Figure 92 - 11 S6D3+2 BR75_80percL=1.0

Figure 93 - 11 S6D3+2 BR75_80percL=1.2

Figure 94 - 11 S6D3+2 BR75_80percL=1.4

Figure 95 - 11 S6D3+2 BR75_80percL=1.6

Figure 96 - 11 S6D3+2 BR75_100percL=1.0
Figure 115 - 12 S3D6+1
BR60_120percL=1.0

Figure 116 - 12 S3D6+1
BR60_120percL=1.2

Figure 117 - 12 S3D6+1
BR60_120percL=1.4

Figure 118 - 12 S3D6+1
BR60_120percL=1.6

Figure 119 - 12 S3D6+1
BR60_120percL=1.8

Figure 120 - 12 S3D6+1 BR60_120percL=1
Figure 151 - 15 S3D12+2
BR60_120percL=1.3

Figure 152 - 15 S3D12+2
BR60_120percL=1.4

Figure 153 - 15 S3D12+2
BR60_120percL=1.4v2

Figure 154 - 15 S3D12+2
BR60_120percL=1.4v3

Figure 155 - 15 S3D12+2
BR60_120percL=1.6

Figure 156 - 15 S3D12+2
BR60_120percL=1.6v2
Figure 175 - 17 S45D4+1  
BR60_100percL=1.2

Figure 176 - 17 S45D4+1  
BR60_100percL=1.4

Figure 177 - 17 S45D4+1  
BR60_100percL=1.6

Figure 178 - 17 S45D4+1  
BR60_100percL=1.8

Figure 179 - 17 S45D4+1  
BR60_120percL=1.2

Figure 180 - 17 S45D4+1  
BR60_120percL=1.4
Figure 193 - 18 S45D4+1 BR60_120percL=1.6

Figure 194 - 18 S45D4+1 BR60_120percL=1.8

Figure 195 - 19 S6D3+1 BR60_80percL=1.2

Figure 196 - 19 S6D3+1 BR60_80percL=1.4

Figure 197 - 19 S6D3+1 BR60_80percL=1.6

Figure 198 - 19 S6D3+1 BR60_80percL=1.8
Figure 199 - 19 S6D3+1  
BR60_100percL=1.2

Figure 200 - 19 S6D3+1  
BR60_100percL=1.4

Figure 201 - 19 S6D3+1  
BR60_100percL=1.6

Figure 202 - 19 S6D3+1  
BR60_120percL=1.2

Figure 203 - 19 S6D3+1  
BR60_120percL=1.4

Figure 204 - 19 S6D3+1  
BR60_120percL=1.4
Figure 205 - 19 S6D3+1
BR60_120percL=1.6

Figure 206 - 19 S6D3+1
BR60_120percL=1.8

Figure 207 - 20 S6D3+1 BR60
INV_80percL=1.2

Figure 208 - 20 S6D3+1 BR60
INV_80percL=1.4

Figure 209 - 20 S6D3+1 BR60
INV_80percL=1.6

Figure 210 - 20 S6D3+1 BR60
INV_80percL=1.8
Figure 271 - 24 S3D12+2
BR45_120percL=1.3

Figure 272 - 24 S3D12+2
BR45_120percL=1.4

Figure 273 - 24 S3D12+2
BR45_120percL=1.4v2

Figure 274 - 24 S3D12+2
BR45_120percL=1.6

Figure 275 - 24 S3D12+2
BR45_120percL=1.8

Figure 276 - 25 S3D12+1
BR30_80percL=1.2
Figure 277 - 25 S3D12+1
BR30_80percL=1.4

Figure 278 - 25 S3D12+1
BR30_80percL=1.6

Figure 279 - 25 S3D12+1
BR30_80percL=1.8

Figure 280 - 25 S3D12+1
BR30_100percL=1.2

Figure 281 - 25 S3D12+1
BR30_100percL=1.4

Figure 282 - 25 S3D12+1
BR30_100percL=1.6
Figure 283 - 25 S3D12+1
BR30_100percL=1.8

Figure 284 - 25 S3D12+1
BR30_120percL=1.2

Figure 285 - 25 S3D12+1
BR30_120percL=1.4

Figure 286 - 25 S3D12+1
BR30_120percL=1.6

Figure 287 - 25 S3D12+1
BR30_120percL=1.8

Figure 288 - 26 S45D8+2
BR45_80percL=1.2
Figure 289 - 26 S45D8+2
BR45_80percL=1.4

Figure 290 - 26 S45D8+2
BR45_80percL=1.6

Figure 291 - 26 S45D8+2
BR45_80percL=1.8

Figure 292 - 26 S45D8+2
BR45_100percL=1.2

Figure 293 - 26 S45D8+2
BR45_100percL=1.4

Figure 294 - 26 S45D8+2
BR45_100percL=1.6
Figure 301 - 27 S3D6+1 BR30_80percL=1.4

Figure 302 - 27 S3D6+1 BR30_80percL=1.6

Figure 303 - 27 S3D6+1 BR30_80percL=1.8

Figure 304 - 27 S3D6+1 BR30_100percL=1.2

Figure 305 - 27 S3D6+1 BR30_100percL=1.4

Figure 306 - 27 S3D6+1 BR30_100percL=1.6
Figure 337 - 30 S6D6+2 BR30_80percL=1.4

Figure 338 - 30 S6D6+2 BR30_80percL=1.6

Figure 339 - 30 S6D6+2 BR30_80percL=1.8

Figure 340 - 30 S6D6+2 BR30_100percL=1.2

Figure 341 - 30 S6D6+2 BR30_100percL=1.4

Figure 342 - 30 S6D6+2 BR30_100percL=1.6
Figure 379 - 33 S45D8+2
BR30_100percL=1.8

Figure 380 - 33 S45D8+2
BR30_120percL=1.2

Figure 381 - 33 S45D8+2
BR30_120percL=1.4

Figure 382 - 33 S45D8+2
BR30_120percL=1.6

Figure 383 - 33 S45D8+2
BR30_120percL=1.8

Figure 384 - 34 S45D4 BR45
@end_80percL=1.2
Figure 427 - 37 S45D4 BR30 @ign_100percL=1.8

Figure 428 - 37 S45D4 BR30 @ign_120percL=1.2

Figure 429 - 37 S45D4 BR30 @ign_120percL=1.4

Figure 430 - 37 S45D4 BR30 @ign_120percL=1.6

Figure 431 - 37 S45D4 BR30 @ign_120percL=1.8

Figure 432 - 38 S3D6 BR45 @end_80percL=1.2
Figure 481 - 42 oxygen_oxygen02

Figure 482 - 42 oxygen_oxygen03