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Using an Ultrasonic Technique to Determine Burning Rate Law

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by

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1 Abstract

A sample of Aerotech Blue Thunder propellant was burned in a closed combustion bomb to assess the propellant burning rate. The cylindrical sample was inhibited on one end, in the bore, and around the outer face to ensure burning from only one end of the propellant. The sample was ignited and the length of the propellant was measured during the burn using an ultrasonic technique. The 0.55 in propellant sample burned in approximately 1 second and the combustion bomb reached a peak pressure of 2676 psig. The collected data was assessed using a Matlab Script to determine the instantaneous length of the propellant as a function of burn time. Attempts to assess the burning rate were made but were ultimately unsuccessful.

2 Introduction

For the Rocket Design senior design course at UAH, many students are thrust into a project the likes of which they've never taken part of. Not having relevant experience is intimidating, and many decisions are made without knowing better from worse. The overarching goal of this Honors Capstone was to provide future teams with data relevant to motor selection for their rockets, specifically about burning rate. The propellant grain chosen to be used this year is called Blue Thunder, so this project deals with experimentation on this type of propellant. Every propellant burns at a specific rate, which is determined by pressure and two coefficients, a and n, that are dependent upon the propellant. However, as with all things in actuality, burning rate coefficients are not truly constant. Manufacturers may list the expected values of these coefficients, but variables such as the batch a propellant is made in can alter these values. It is thus beneficial to provide testing and experimental data on something such as this, as that can help determine the accuracy of the predicted values.

2.1 Theory

The process for determining burning rate coefficients involves several equations. First and foremost, it is important to note the relation between the length of the propellant, E, and the propagation time for the ultrasonic waves, τ. At any instant in time ,i, the instantaneous length can be determined based on the initial length, E_o, the initial propagation time, τ_o, and the propagation time at that instance, τ_i. As shown in Equation 1, the ratio of length over the propagation time is equivalent no matter the time of sampling.

$$\frac{E_o}{\tau_o} = \frac{E_i}{\tau_i} \tag{1}$$

Unfortunately, this account for variable speed of sound in the medium through which the ultrasonic waves propagate. For the test setup the ultrasonic waves travel through an epoxy coupling material and through the propellant. The speed of sound in both of these

materials will change with changing pressure in the combustion bomb. A correction factor for the propagation times can be included in Equation 1. The revised equation is given as:

$$E_{P_i}(\tau_i) = \frac{E_{P_o}}{\tau_P(P_i)}[\tau_i - \tau_c(P_i)] \tag{2}$$

Here, it is important to note that τ_p and τ_c are not values found by testing and are rather found in constant situations, such as before or after a test, making it essential to sample values at three separate instances: a pretest, a test, and a post test. The τ_p and τ_c equations are below.

$$\tau_p = a_p * P + b_p \tag{3}$$

$$\tau_c = a_c * P + b_c \tag{4}$$

Equation 2 can then be plotted against time. The derivative of this relation is the change in length with respect to time, which is also the burning rate.

$$\frac{dE}{dt} = \dot{r} = aP^n \tag{5}$$

Finally, the coefficients can be determined by plotting a logarithmic graph of $\dot{r}$ versus pressure. The linear fit is given by Equation 6, where n is the slope and $ln(a)$ is the y-intercept, making calculations for the coefficients fairly simple after this point.

$$ln(\dot{r}) = n * ln(P) + ln(a) \tag{6}$$

3 Experimental Procedure

To go about determining the burning rate coefficients of the selected propellant, the Propulsion Research Center's High Pressure Laboratory was utilized. An ultrasonic transducer was fit onto a closed combustion bomb, which had a sample of propellant epoxied to a base. This was then pressurized in a controlled environment, and the propellant was ignited. The transducer and the data acquisition unit in the lab output both oscilloscope and pressure data throughout the tests. A description of the procedure is below.

3.1 Preparation

The first thing done was to prepare the epoxy. The intended outcome of the epoxy was to have it contain the least amount of air possible. Once the epoxy was mixed with a hardener, it was placed into a vacuum chamber. The vacuum pump was active for ten minutes, and during this, the epoxy bubbled up. To combat this, air was let back into the chamber in small amounts, putting pressure back on the epoxy and settling it down. This was done because, if the epoxy were to overflow, some would be lost to the experiment and could not be used.

Figure 1: Epoxy Bubbling up in Vacuum Chamber

Once the epoxy had spent ten minutes in the chamber, it was pulled out and poured onto the top of the base of the propellant sample holder. The sample holder had been put into a container with walls that prevented the epoxy from spilling over the sides of the sample holder. The sample holder was then put into the vacuum chamber, and the pump was run for ten minutes again to draw air out of the epoxy that had been poured. The same caution was taken from the previous use of the pump to ensure that the epoxy did not overflow.

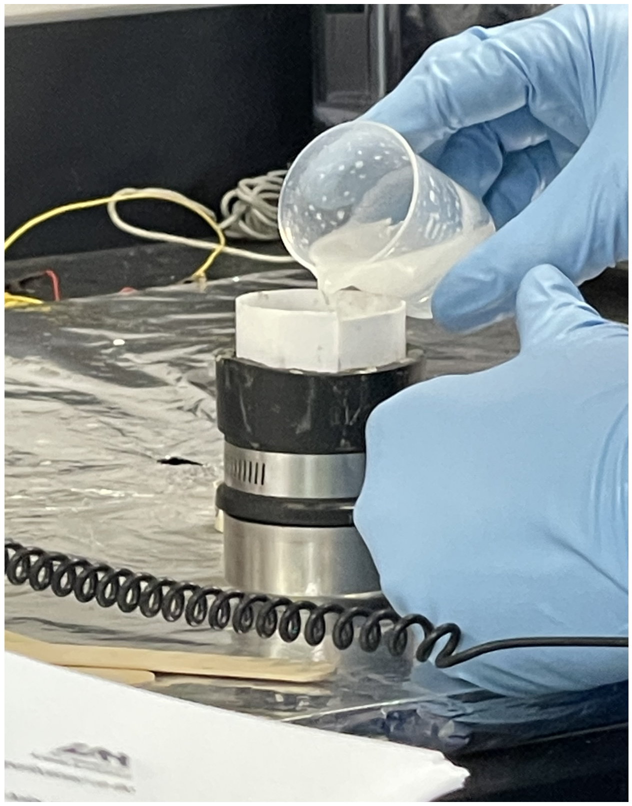

Figure 2: Pouring Epoxy in Base Contraption

After the sample holder had been removed from the vacuum chamber, the propellant sample was measured to prepare for calculations. The mass and initial length of the sample were taken. When measuring the length of the propellant, the surface was found to be uneven. Because of this, an average was taken from the highest and lowest points on the surface of the sample, and this was the value used for the burning rate calculations. The sample was then taken and placed on top of the epoxy on the base with care to ensure that it was centered. More epoxy was poured around and into the middle of the sample so that the propellant would be fully cast to the base. Care was also taken to ensure that epoxy was not poured onto the top of the sample, as that would inhibit the burning of the propellant during the test.

Figure 3: Propellant Sample and Epoxy Before Vacuum Chamber

The assembly was then placed into the vacuum chamber for three more minutes in order to draw more air out of the epoxy. A weight was also placed on top of the sample so that it could be set more firmly into the epoxy. Unfortunately, while caution was taken to prevent the epoxy from overflowing in the chamber again, some of it bubbled up from the center of the sample and covered its top. However, after the three minutes while the pump was active, the assembly was left in the closed chamber to allow the epoxy to fully cure.

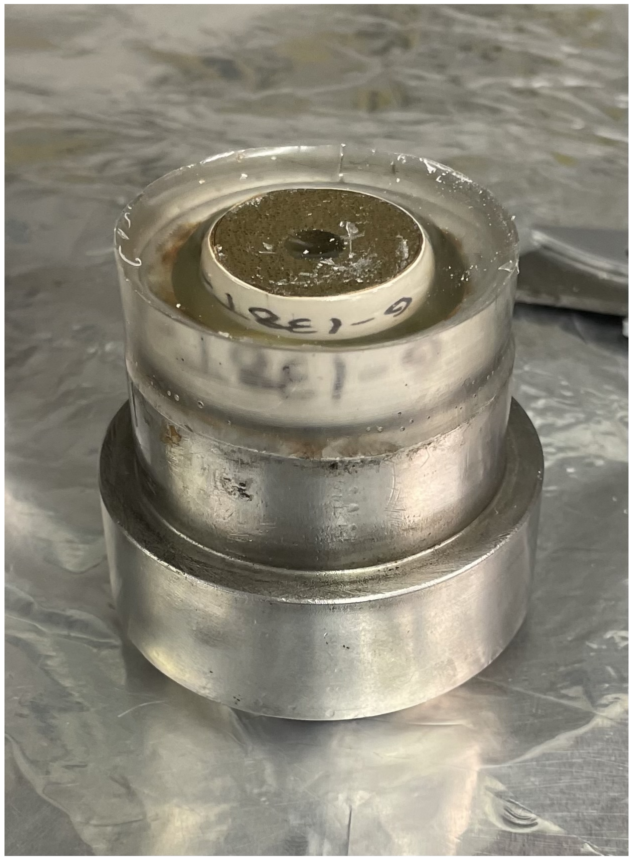

Figure 4: Base with Propellant and Sample After Casting

3.2 Testing

The epoxy was only required to set for twenty-four hours, but due to scheduling conflicts, the test was not conducted until a week after the epoxy was cast. When the team returned to the lab, the sample holder was removed from the vacuum chamber and disassembled. At this point, the propellant sample was completely cast in the epoxy, and it was evident that some epoxy was also covering the very top of the sample. To help ensure the propellant would ignite on the top surface, a scalpel was used to scrape as much epoxy off the propellant as possible. After this was done, the base was ready to be assembled in the closed combustion bomb. There were several components needed to seal the sample into the bomb, as shown below.

Figure 5: Combustion Bomb Pieces

O-rings were also put in between these separate pieces. Once all the pieces were assembled with an igniter connected to the combustion bomb, a multimeter was used to ensure continuity where appropriate. After confirmation that the bomb was assembled correctly, it was transferred to the test chamber. It was connected to pressurization, vent, and sense ports and the leads to the igniter were connected to the bomb. Additionally, the ultrasonic transducer was connected to the very bottom of the bomb. The test chamber was then shut and the systems check commenced.

Figure 6: Assembled Combustion Bomb in Test Chamber

Before ignition of the sample, it was crucial that the pressure system was known to be working properly. This required pressurizing and depressurizing the test chamber as well as the bomb itself to ensure that the data acquisition unit and the LabVIEW software were performing as intended. At first, there were some issues with the DAQ and the and the software, but after some resets, they ran fine. The next step was testing. However, when the test was initialized, the software was not recording any changes to the data like one would expect when a propellant is ignited. It was discovered that the igniter circuit had an electrical short, so it was repaired. After this, there were three total tests that were performed: a pretest, the actual test, and a post test. All three of these recorded oscilloscope and pressure data and were used in the analysis of the data after the experiment was concluded.

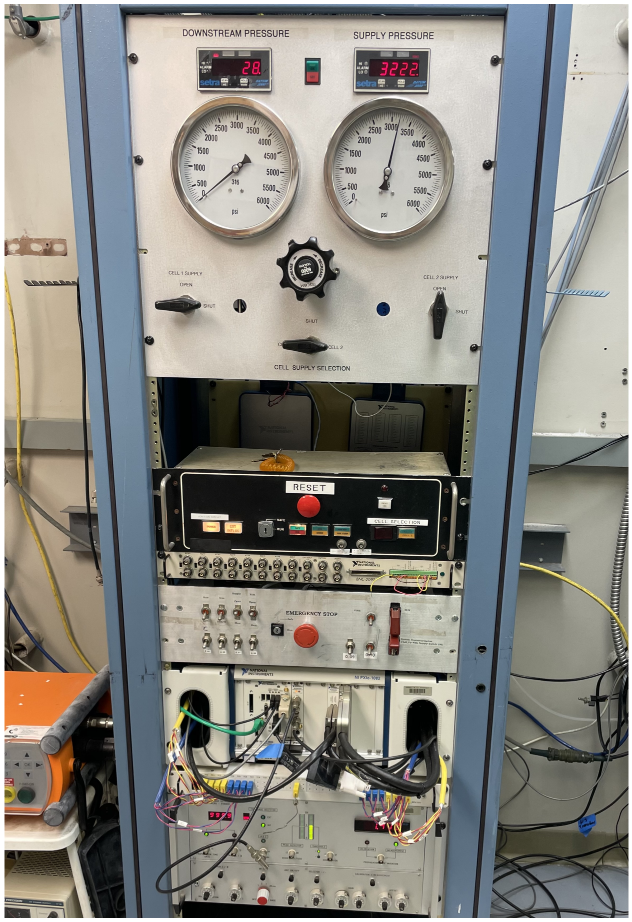

Figure 7: Data Acquisition Unit (DAQ)

4 Data Analysis

As mentioned above, both oscilloscope and pressure data were collected during the tests. However, it is also important as to how the oscilloscope data is to be read. Below is an image of the LabVIEW window before the tests. The y-axis of the graph displays an amplitude of voltage, while the x-axis displays time.

Figure 8: Oscilloscope Reading Prior to Testing

The ultrasonic transducer works by sending out sonic pulses cooresponding to a clock signal of 1 kHz. When the rising edge of the clock signal is detected, the ultrasonic transducer sends out a sonic pulse the pressure transducers record a single measurement value, and the oscilloscope card begins a waveform capture at 10 MHz. As the sonic waves go through the materials in the combustion bomb, some are reflected and travel back the opposite way. When they come in contact with the transducer, they create a voltage. The stronger the wave, the higher the amplitude of the voltage. This means that closer interfaces register as stronger voltages; additionally, since sound waves travel and are not instantaneous, the peaks that are further to the right on the chart represent interfaces that are farther away from the transducer, allowing for a relation between the time axis and distance from the transducer.

The raw data from the experiment was imported into a MATLAB script for analysis. The first objective was to trim the data. Because there was data sampled at distances too close or too far from the transducer to matter, each test's oscilloscope data was truncated to

get rid of this unneeded data. This was not entirely necessary, but it did help make the data easier to work with. Next, a time was defined based upon the frequency of the transducer, allowing each data point to correspond to a point in time. The next requirement was to remove bad data, since there was occasionally a bad waveform, and having bad data can impact the entire outcome of the data set. At first, this was done by manually sifting through the data and selecting waveforms that misconstrued the set. However, it was quickly found that there were many more bad waveforms than initially anticipated, so a more automated approach was taken. This involved having the code sift through the data and remove waveforms that had amplitude values that were too high for certain distances from the transducer.

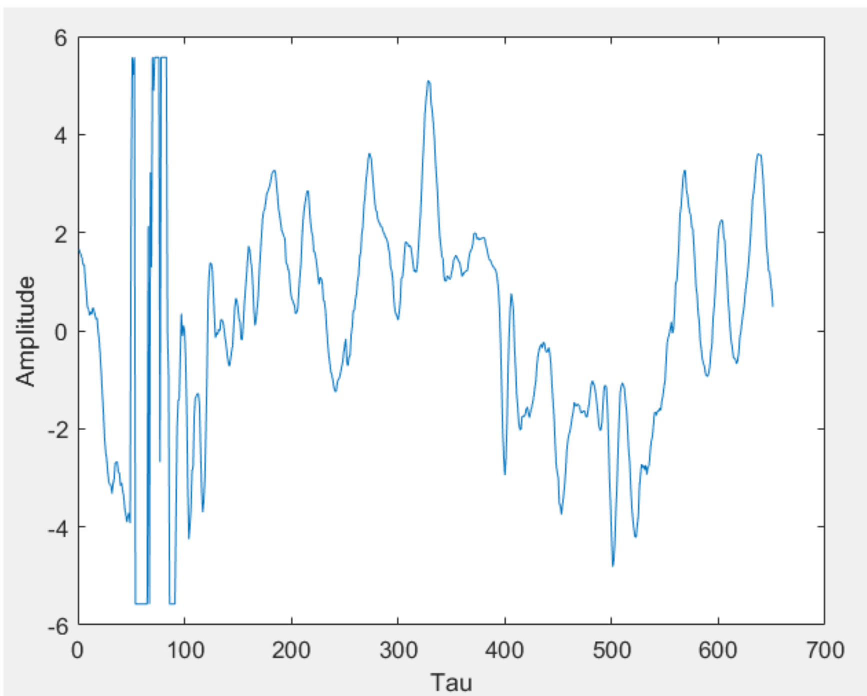

Figure 9: Example of Bad Waveform

Once the data had been refined, it was then used to track the surface of the propellant as it burned. As is shown in the figure below, there are three major peaks in the oscilloscope data. The first and largest peak corresponds to the base of the contraption that the propellant sample was epoxied to. The second peak corresponds to the interface between the

bottom of the propellant sample and the epoxy in the middle of the base. The third and final peak corresponds to the end of the sample.

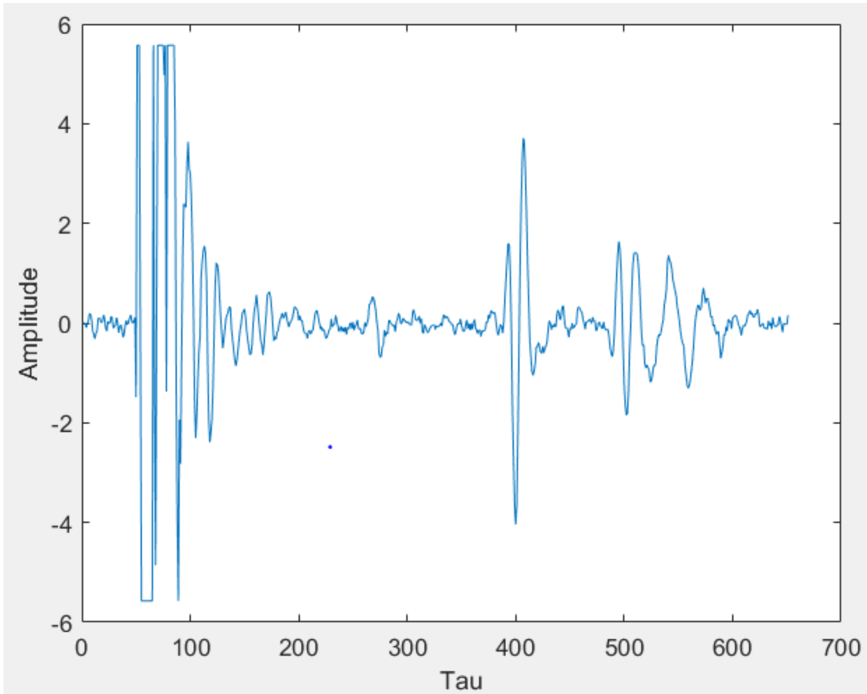

Figure 10: Example of Good Waveform

As the propellant burned, the end of the sample got closer two transducer, and thus it took less time for the waves to reach the end. Another figure below shows the regression of the sample end over time.

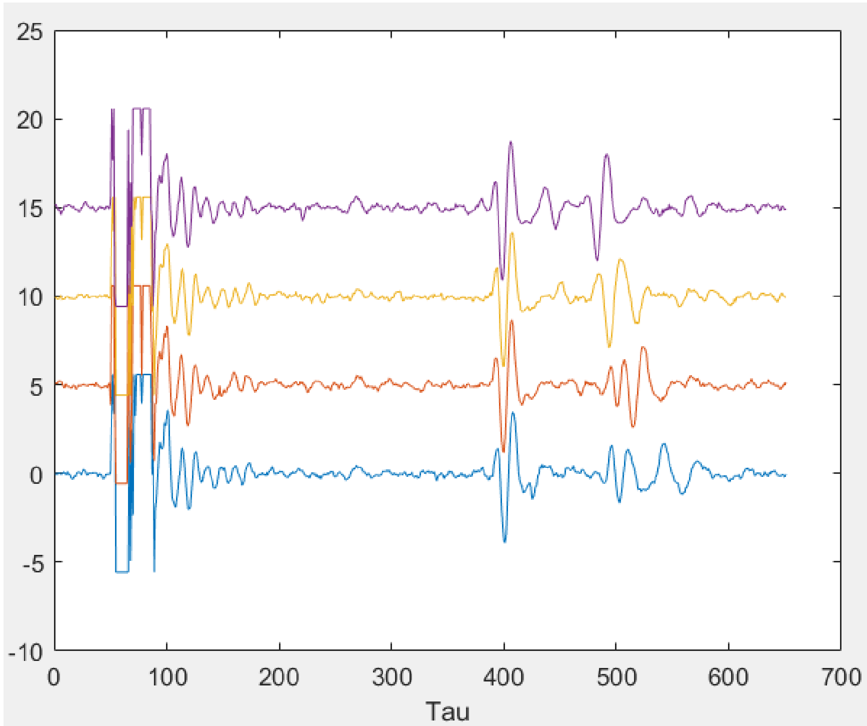

Figure 11: Wave Samples Over Time

The code was written to identify and track the propellant surface (the third location) for both the pretest and the full test. Finally, the method discussed in the introduction was utilized. The location of the surface of the sample during the pretest was plotted versus the pressure, and a linear fit was used to calculate a regression line. This determined the variable τ_p. Then, the location of the interface between the sample and the base was plotted against the pressure. A linear fit was used again to find the variable τ_c. These were applied to Equation 2 along with the initial length of the sample and the length of the sample throughout the test to determine E_{P_i}, which is the instantaneous length of the propellant. A plot of the instantaneous length of the propellant during the test is shown below.

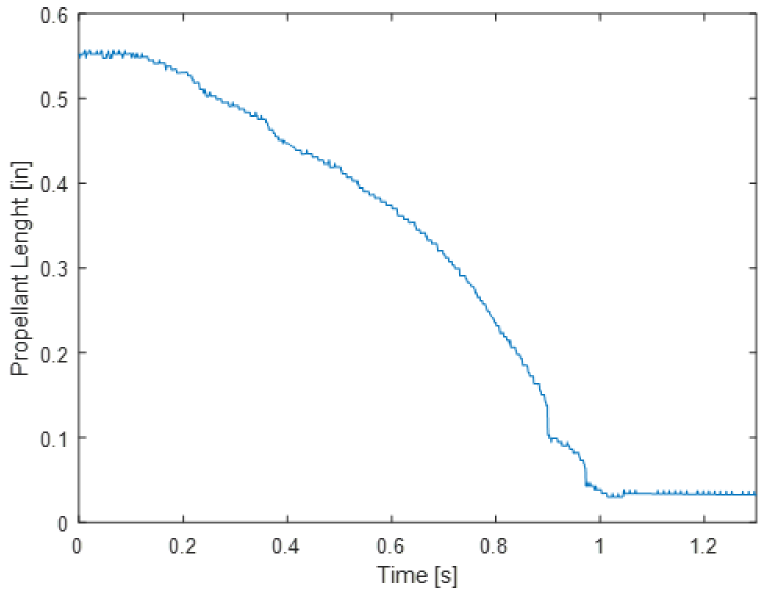

Figure 12: Instantaneous Length of Propellant Through the Test

Due to the relation between instantaneous length and time, the change in E_{P_i} with respect to time is $\dot{r}$, or the burning rate. As shown in Equation 5, the burning rate is dependent on pressure, so the time rate of change of the propellant length must be correlated with the pressure measurements from the experiments to determine the coefficient and exponent in the burning rate equation. To determine these parameters, a linear fit of the natural logarithm of $\dot{r}$ versus the natural logarithm of pressure is performed. A linear regression from this plot provides both burning rate coefficients, n and a, using the knowledge from Equation 6. To check accuracy of this experiment, a prediction for r was calculated using the pressure values from the test. Below is a graphical comparison of the predicted and actual plots for $ln(\dot{r})$ and $ln(P)$.

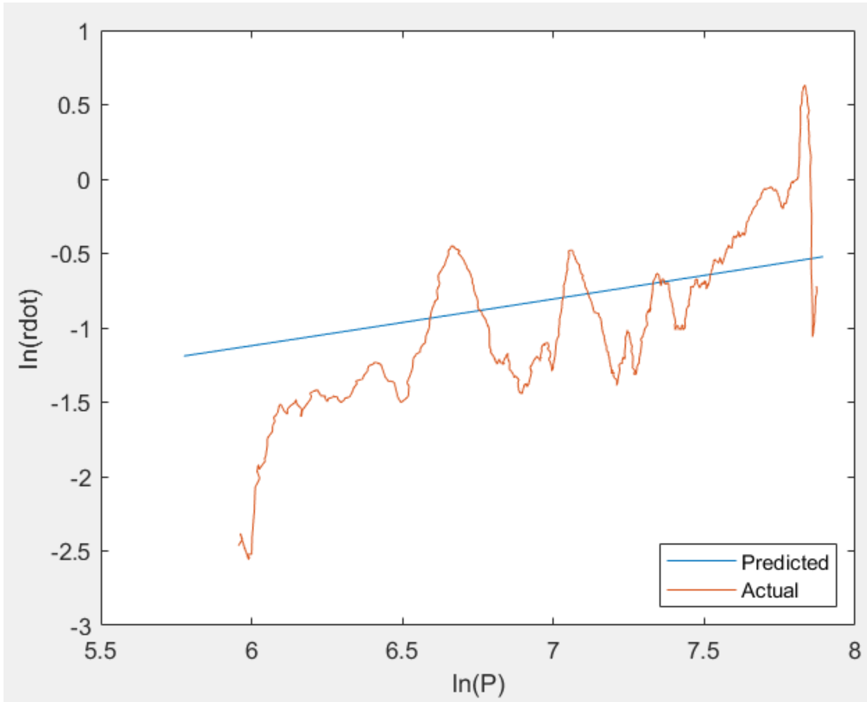

Figure 13: Natural Log of $\dot{r}$ versus Natural Log of P

There were attempts made to smooth the actual plot, but none of them came to fruition. The predicted coefficients are $n = 0.32$ and $a = 0.049$, which are very close to the values published by the manufacturer of $n = 0.32$ and $a = 0.047$. While the current calculation outputs coefficient values of $n = 0.88$ and $a = 0.0008$, there is a way to sift through the data to potentially produce more accurate coefficients. If only the points in the middle of the test are considered, a regression comes about that is much closer to the predicted values. When only samples 200 through 700 are considered, the plot appears as below, and the coefficient values become $n = 0.44$ and $a = 0.0176$. While these values are not exact, they may account for potential error in ignition or some other unknown variable.

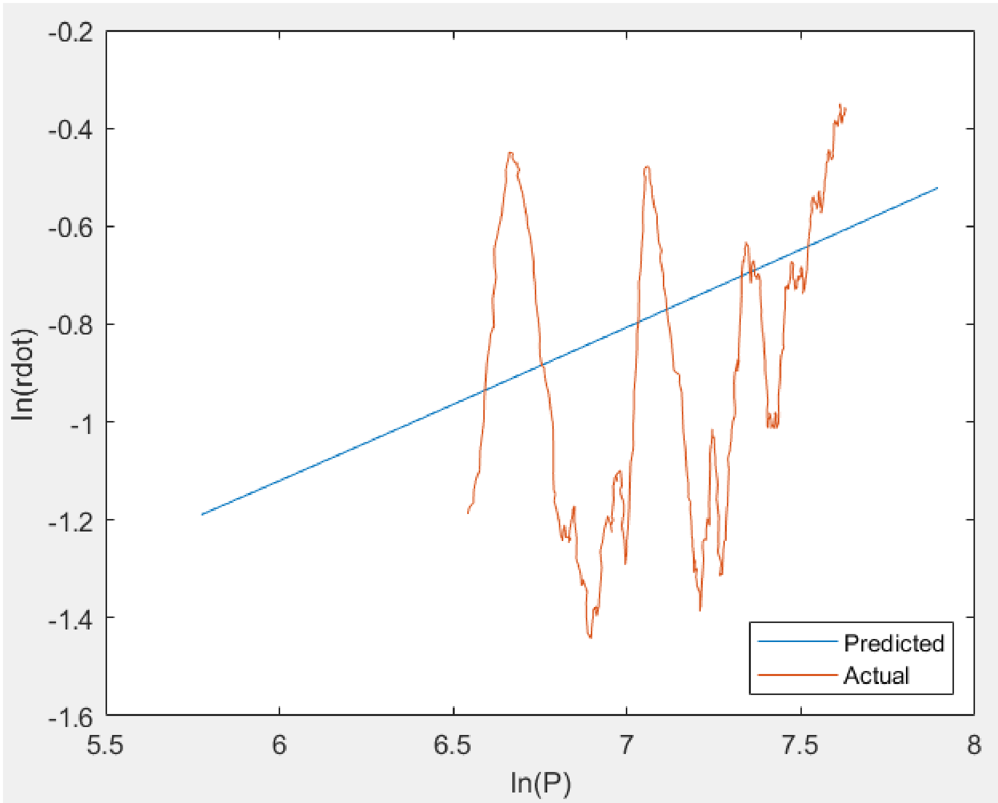

Figure 14: Correction for Natural Log of $\dot{r}$ versus Natural Log of P

5 Conclusion

A sample of Aerotech Blue Thunder propellant was tested to assess the burning rate of the propellant. During the test, the propellant sample ignited and burned to completion in approximately 1 second and resulted in a combustion bomb pressure increase from 300 psig to 2700 psig. Data analysis was performed to attempt to quantify the burning rate of the propellant. Unfortunately, attempts to establish the burning rate law from the data were unsuccessful, however the estimated burning rate versus pressure curve was compared against a curve generated from a manufacturer provided burning rate law. The slope of the data natrual log of burning rate versus the natrual log of pressure appeared to be slightly steeper than the manufacturer data indicating a higher exponent would have been determined from the test data had analysis methods been successful. Bad data caused many issues and was the focus of much of the coding developed for this analysis. The elimination of this data proved fruitful, with the code being written to where it should work on other sets of data as well. The only drawback seems to be the linear regression of the natural log of $\dot{r}$ versus the natural log of P. Due to the "jumpy" nature of the data, the fit is very poor. Despite this, a reasonable fit was found when only considering the middle and end of the test. There is a likelihood that the burning rate was most stable and accurate at this time, providing coefficients that are closer to the published values. More experimentation would be helpful in determining if the gathered data is indicative of Blue Thunder propellant or if this sample was somewhat of an outlier.