Performance Analysis of an Estes Rocket Engine Experimentally

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Cover Letter

This report is entitled the ‘performance analysis of an Estes rocket engine experimentally’. The primary testing occurred on December 3rd, 2019 and it was dated for agreement on December 5th, 2019.

This report dives into the performance of standard Estes engines that any rocket hobbyist can buy at a local hobby shop, the B6, C6 and D12. A hot-fire test of each are performed measuring force and pressure of the engine to analytically calculate the main performance characteristics of the engine. That information can be compared to more of the larger engines that people can buy, and even the engines we see in today’s orbital rockets.

Hobby rocket engines are used for many grade schools’ classes. Discovering performance parameters of the common engines yourself and relating that to industry standards can be impactful to the experimentalist. We hope that the testing, analysis, and conclusions can help you perform this test yourself, and help to make the same conclusions we did on how a small little hobby engine can be related to the big engines we see on today’s rockets.

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Objectives

The Estes engine is the most-used rocket engine for hobby rocketeers and physics class' worldwide. It can be hard to relate the activities of rocket building to a real-world job like working at NASA, SpaceX, Blue Origin, etc. The objective of this lab is to develop a well-designed testing procedure and full-proof analysis to determine primary performance characteristics of rocket engines that nearly anyone can get their hands on. These performance characteristics can then be compared to other engines in industry and understand why there is such a difference in overall efficiency and power. The test will be done using the standard B, C and D engines and a simple hot-fire test stand that can support the engine during ignition and firing. A load cell and pressure transducer will be attached to the test system to get real-time data of the engine during test for future us in the analysis to determine mass flow rate, exit velocity, specific impulse and thrust-to-weight ratio. This paper can then be distributed to the online community to replicate and improve for future use for students and hobbyists.

Executive Summary

The most significant parameters and take-aways to come from this experiment is the performance parameters of the engine that are commonly reported with rocket engines in industry through the decades. The following table, described in more detail later in the report, are the primary characteristics of the 3 Estes engines tested in house as well as other commercial engines well known in the industry.

Table 1 - Key performance parameters of tested and reported commercial engines

	Specific Impulse (s)	Thrust to Weight Ratio ()	Exit Velocity (m/s)
B6 Engine	58.1	23.2	565
C6 Engine	43.4	18.8	413
D12 Engine	71.7	19.7	662
F1	263	94.1	2580
RS-25	366	73.1	3590
Merlin 1D	282	179.8	2770

Not only does this compare the Estes engines (each nearly doubling in overall power by definition of size), but it allows the experimentalist and the reader to understand how industry compares to the small engines you can buy at any hobby store and test with a relatively small amount of material/cost. This also shows that the C engine has the lowest overall performance parameters even though being bigger than the B engine. This is because the engine is made to pack more fuel and burn longer while imparting a smaller force then the D engine, even though it has almost the same amount of total propellant. They did this in the design to lower its overall parameters causing a lower specific impulse and gas exit velocity. It is also obvious that large commercial engines like the F1 and the Merlin 1D outperform the small hobby rockets by a great amount, which was predicted. It is also surprising to see that the Merlin 1D has such a larger thrust to weight ratio as the other large legacy engines, mostly due to the fact that it is a more modern engine and could be optimized for total engine weight much more than during the Apollo era.

Theory and Experimental Methods

A rocket engine uses a solid fuel-oxidizer propellant that combusts to produce hot gas bi-products that pressurize and heat up within the chamber. The hot, pressurized gases travel down through the nozzle and converts its thermal energy into a high kinetic energy that creates a momentum differential that accelerates the entire engine in the opposite direction. The two factors that determine the force of an engine is its outgoing gas momentum, and the differential pressure of the engine environment to the atmosphere. The equation below illustrates this and is the most famous equation in rocketry.

$$F_T = \dot{m}v_e + A_e\,(p_e - p_{amb})$$

The thrust F_T is the force the engine imparts on the system. The engine exit pressure, p_e, is the pressure at the throat of the engine that contributes to the second half of the equation above. p_{amb} is the ambient atmosphere pressure, which for our case is 1 atmosphere, or 101,300 pascals. A_e is the area of the throat and the mass flow rate, $\dot{m}$, is the amount of propellant exiting the engine per second. Lastly, the effective exhaust velocity, v_e, is the speed at which the gas leaves the nozzle during a hot-fire test. Each of these fundamental parameters define the output of the engine and is used even in industry as it shows what values need to be changed in order to get the most thrust out of an engine in a specific operating condition.

The specific impulse, which defines the overall efficiency of the engine I_{sp}, can then be calculated directly two different ways with the parameters described above and g_0 , which is the force of gravity at sea level.

$$I_{sp} = \frac{F_T}{\dot{m} * g_0}$$

$$I_{sp} = \frac{v_e}{g_0}$$

The specific impulse, which is in the units of seconds, can be thought of as how many seconds the engine could produce 9.8 N of consistent force using only 1kg of propellant, if it could. It is the most standard reported parameter of industry engines and is the main objective to maximize for most rockets.

The last parameter that is commonly reported with engines and is nearly just as important as the specific impulse is the thrust-to-weight ratio. Although you can make some amazing engines, if the engine is heavier than the overall thrust it produces, it is not adding any value to the rocket itself. This parameter challenges design and manufacturing engineers to not only improve the performance of the engine, but to make it in a way to conserve the amount of parts/material used. This relation for r, the thrust to weight ratio, can be seen in the equation below where W is the total weight of the rocket engine.

$$r = \frac{F_T}{W}$$

To obtain the necessary information to analyze the engine, an experimental setup was created to physically hold the engine during fire, which is commonly called a static test fire stand. It utilizes wooden planks to place each subsystem and sensor needed. There are many options on how to fix the engine, but clamps were easily accessible to fix onto pieces of wood.

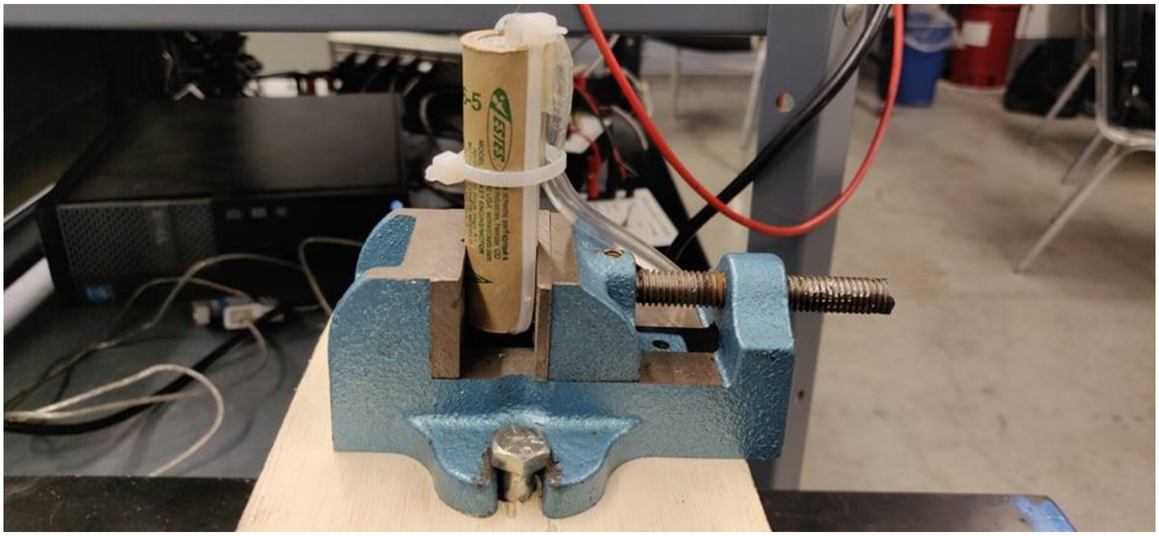


Figure 1 - An Estes engine attached to a clamp

An electronic system was also assembled to provide the necessary voltage to start the engine from an electrical spark. This includes a 12-volt car battery and a pair of alligator clips and wire to provide the voltage potential to the igniter.

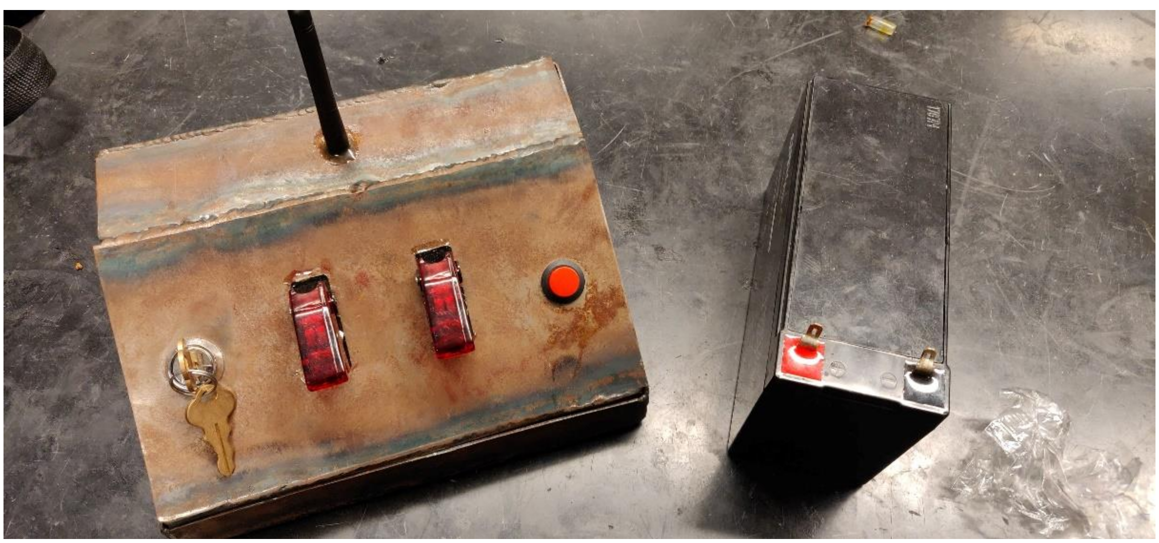


Figure 2 - A part of our electrical ignition system responsible for creating a spark for engine start-up

The simplest parameters to measure directly during the test with the equipment most classrooms and universities have on hand are thrust and exit pressure. The thrust, which is a force pointing in the opposite direction of the thrust stream, will be measured using a 100lb load cell attached to under the static test fire stand. This will equip us to obtain a thrust vs. time curve that can be used for further analysis.

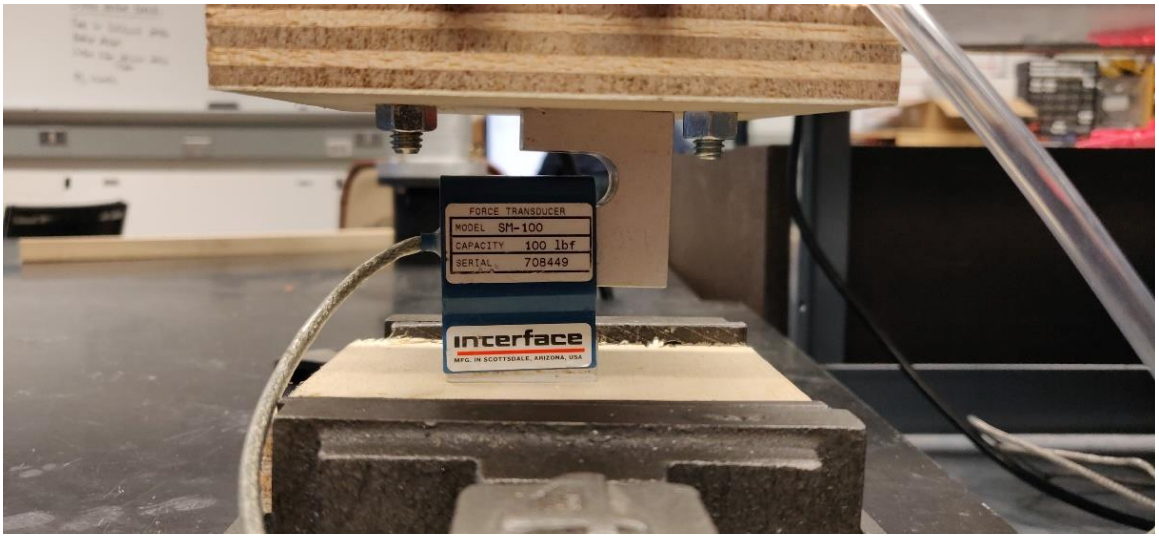


Figure 3 - A 100lbf load cell by Interface place below the clamp/engine assembly to collect the force the engine produces over the test

The exit pressure of the engine, which is located at the throat, will be measured with a 300psig capable pressure transducer with a pressure tap tube being attached directly off the throat of the engine. Although we will not be able to get the pressure readings exactly at the throat for obvious reasons, we will know it will be reported slightly smaller than what is occurring at the throat.

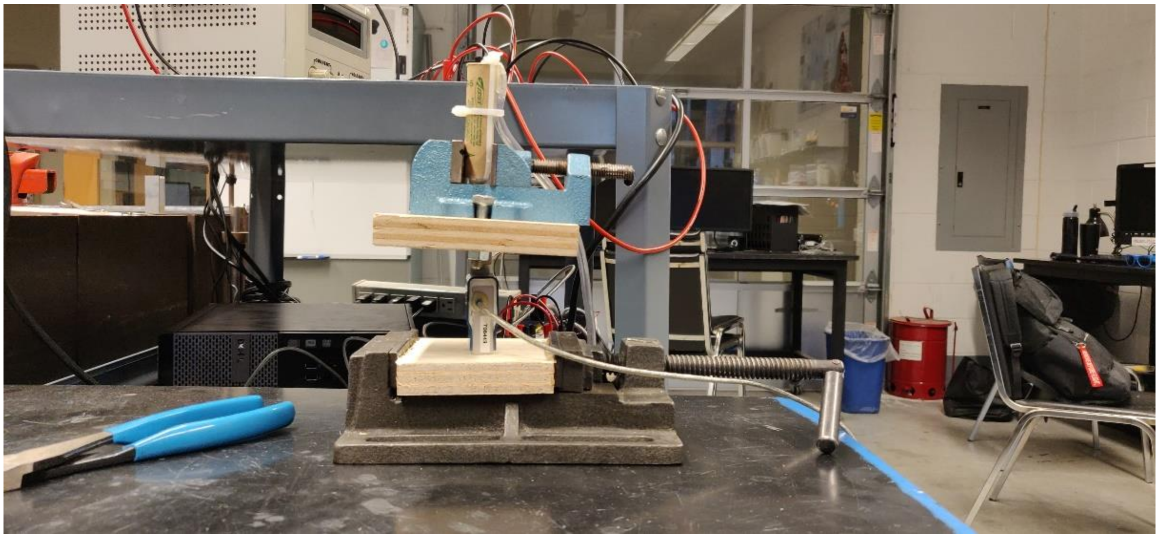


Figure 4 - A full assembly picture of the hot-fire test stand that includes the engine, clamp, pressure tap and the load cell

The entire test will take in the order of a second, as that is the burn time of the Estes engines, so the rate at which data should be taken should be at least 20 points/second to collect the significant events of the test. Data acquisition equipment is utilized to obtain this with correct amplification of the load cell. If the equipment can go faster, there is no downside to increasing the amount of samples per second.

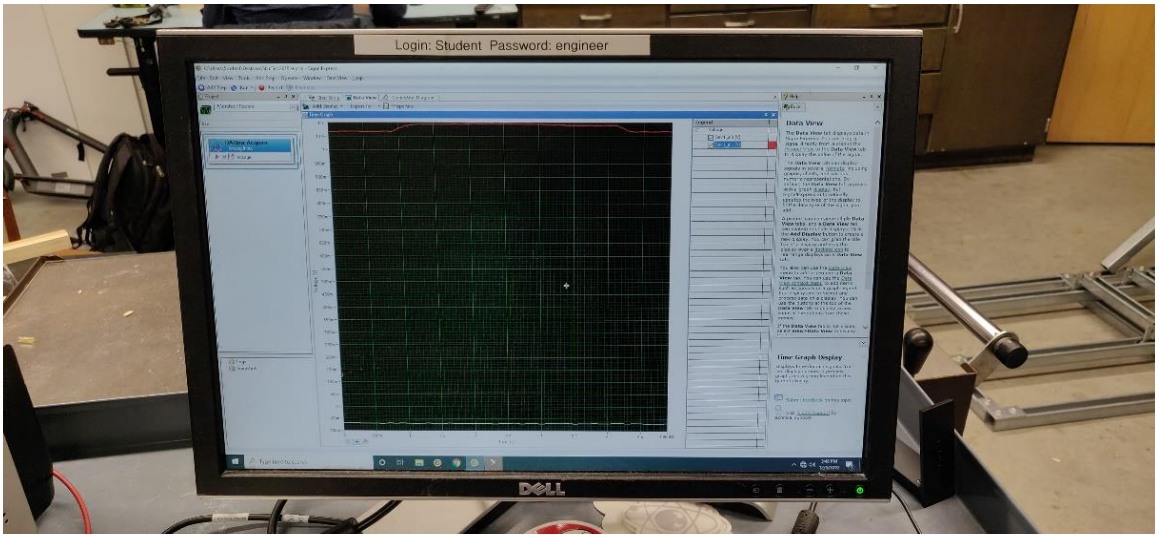


Figure 5 - Data cart with monitor showcasing data collection

Pictured above is raw data from our two sensors being displayed on the monitor of our data collection cart. This is used to export the recorded data for further analysis.

Results and Discussion

Three tests were completed on the most common rocket engines used in the hobby: the B6, C6 and D12 engines. Each test was done one after the other with the same configuration and procedure as described previously in the report and the appendix. The primary data that was achieved was the thrust curve of the engine. The second parameter of the engine that was measured during the test was the outlet pressure, with the steady state pressure being the important value. Figures 6, 7 and 8 are the force vs. time curves of each engine.

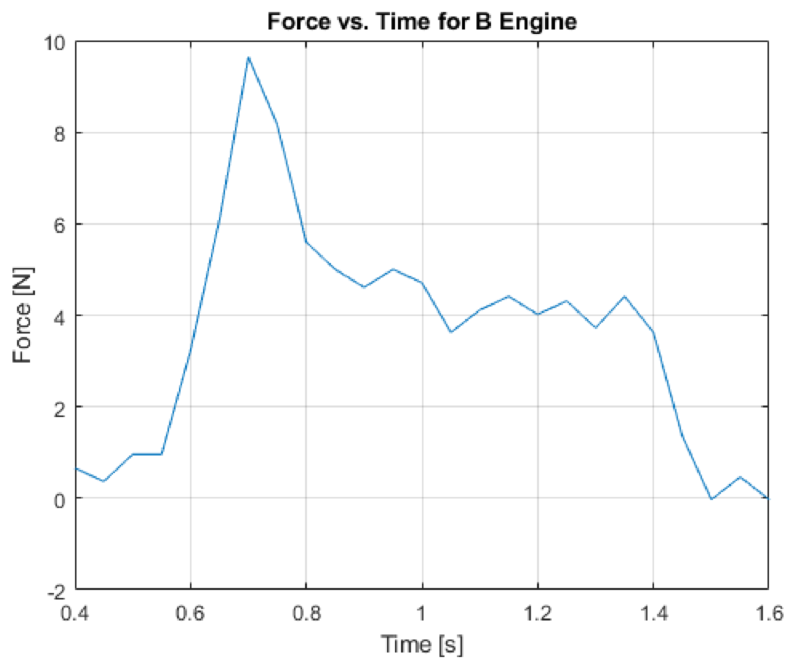


Figure 6 - The B-Engine thrust curve with a 0.9 second total burn time and a steady state force of 4N

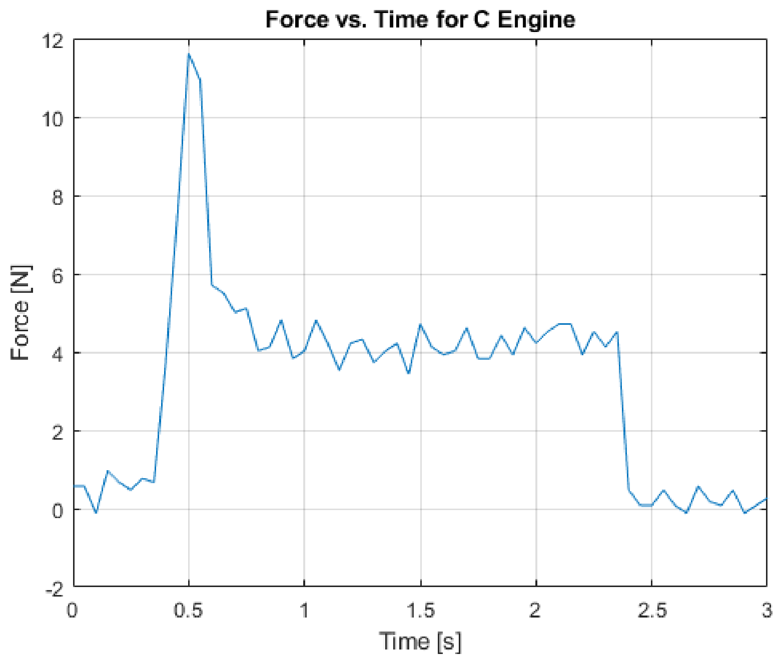


Figure 7 - The C-Engine thrust curve with a 1.9 second total burn time and a steady state force of 4N

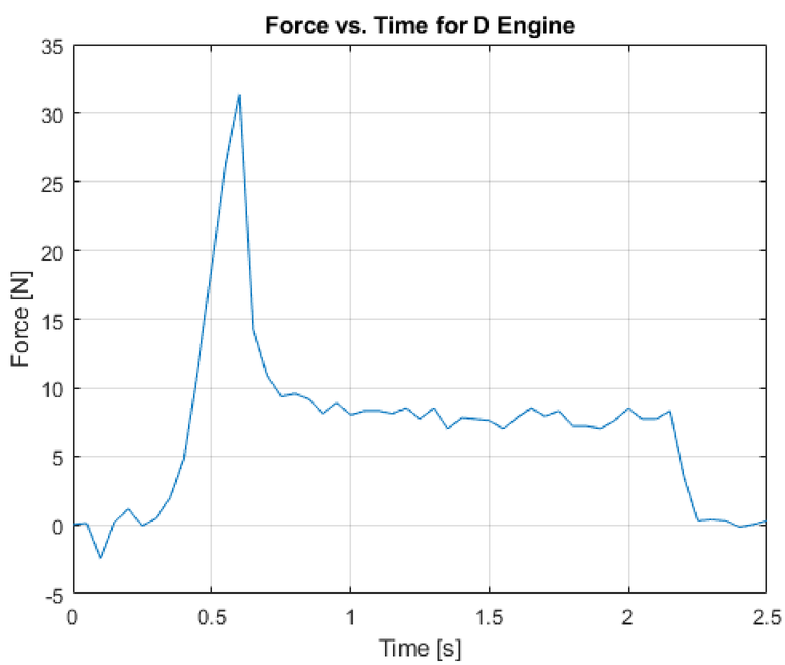


Figure 8 - The D-Engine thrust curve with a 1.7 second total burn time and a steady state force of 8N

The following table compiles the other physical parameters of the engine that are needed to calculate the primary engine characteristics wanted. The propellant mass is a trusted, given value from the manufacturer. The throat diameters were measured with a digital caliper and varied slightly with each engine. The burn time was determined from the experimental data and was cross-checked with the reported burn time and lined up perfectly.

Table 2 - Physically measured engine values and reported values of each Estes engine

	Propellant Mass (g)	Throat Diameter (in)	Burn Time (s)
B6 Engine	5.6	0.125	0.9
C6 Engine	19.8	0.138	1.9
D12 Engine	21.1	0.150	1.7

Once the basic parameters of an engine are measured and determined, we can dive deeper into the base data we got from the test and calculating some other primary factors needed for the fundamental rocket equation,

$$F_T = \dot{m}v_e + A_e\,(p_e - p_{amb})$$

to determine specific impulse and its thrust to weight ratio. The average steady-state force was calculated using the experimental data over the test and is reported below. Also, within the table is the measured average pressure of the test during its steady state performance. This is an under-estimate as it does not factor in the initial startup pressure of the engine and the power that comes from that but is needed as the data collected during that period is unreliable. This is due to using a pressure tap that should have been made of a more rigid material and not so easily affected by bursts of energy. The mass flow rate was calculated under the assumption that the grain of the fuel burns steady (which is a well-established concept for Estes engines) and was simply its propellant mass over its burn time. This will be an over-estimate from its steady state burn as initially, it burns quicker releasing more propellant. The exit velocity could then be calculated using the equation from above, solving for the average exit velocity of the engine over its steady burn. The three tested engines are compared below.

Table 3 - Primary measured and calculated values needed for key performance parameters of the Estes engines

	Average Force (N)	Average Pressure (Pa, Gauge)	Mass Flow Rate (g/s)	Exit Velocity (m/s)
B6 Engine	3.54	3,832	6.2	565
C6 Engine	4.43	13,128	10.4	413
D12 Engine	8.72	43,853	12.4	662

Finally, once the core parameters of the engine have been calculated, it is now simple to input those values into the specific impulse and thrust-to-weight ratio equations described in the previous portion of this report.

Table 4 - Key performance parameters of the Estes engines

	Specific Impulse using Exit Velocity (s)	Specific Impulse using Force (s)	Thrust to Weight Ratio ()
B6 Engine	57.6	58.1	23.2
C6 Engine	42.2	43.4	18.8
D12 Engine	67.6	71.7	19.7

The specific impulse was calculated using two different methods from the data collected. The two methods returned similar specific impulse results for all three engines, this leads us to believe that the methods and data obtained are accurate. The final thing that is important is to understand how these engines relate to the engines seen in the past and today on orbital rockets. The following engines have been chosen to be presented with the Estes engine tested and can be seen in the table below.

Table 5 - Key performance parameters of tested and reported commercial engines

	Specific Impulse (s)	**Thrust to Weight Ratio ()**	**Exit Velocity (m/s)**
B6 Engine	58.1	23.2	565
C6 Engine	43.4	18.8	413
D12 Engine	71.7	19.7	662
F1	263	94.1	2580
RS-25	366	73.1	3590
Merlin 1D	282	179.8	2770

From the table, it is obvious that the bigger and more advance rocket engines we have seen in our past are much more efficient then the hobby engines. They have larger specific impulses, meaning they use their fuel more efficiently, and they have higher gas exit velocity due to that. It is also important to note the thrust to weight ratios of the Estes, old space engines, and the newer Merlin. The thrust to weight ratio doesn't only play on its total force it can impart onto the launch vehicle, but also the engineering feats done to minimize mass and still perform to their wants and dreams. These engines are also different in nature than the ones tested in this report. The commercial engines mentioned above are all liquid propellant engines whereas the hobby rocket engines that were tested are purely solid fuel, which can have different affects on how much an engine can be optimized and tested.

Conclusions

Charlie Nitschelm

The data collected from this engine experiment allowed us to peer into the fundamentals of engine design and performance characteristics. The overall thrust to weight ratio of each Estes engine tested were similar, all around 20. The exit velocity, though, surprised us with the C6 engine, the one slightly bigger than the B6 engine, outputting a slower overall gas exit stream, and in turn, a smaller specific impulse. With a deeper look into the engines fundamental purpose, it was noticed that the C6 engine, although the same diameter as the B6 engine, was made to produce a longer burn and same average force as the smaller B6 engine. To do so, it must be designed to burn and exit the engine differently to ensure that average force is like the B6. This causes it to use its propellant resources less efficiently causing an overall lower performance, even though it has a larger total impulse. The D12 engine, the biggest of the engines tested, performed the most efficiently compared to the other engines with a specific impulse of 71.7 seconds, but due to its extra weight, it has a lower overall thrust to weight ratio than the B6 engine. It would be worth testing the engines with upgraded pressure taps to ensure a more accurate exit pressure reading while not affecting the stream of hot gas, possibly using copper tubing. It would also be beneficial to do multiple tests of the same engine to do an analysis on the variation that is seen engine to engine and set-up to set-up.

Lucas Simmonds

A procedure to test the performance of amateur rocket engines has been outlined in this report. Three solid fuel engines were tested, and their performance characteristics were calculated. The three engines tested were B6, C6, and D12 Estes engines, each increasing in thrust. The instrumentation stands and methods used to calculate these parameters were successful due to their similarity to the values provided by the manufacturers. The thrust-to-weight ratio for all three of these engines were around 20. The B6 was the smallest engine of the three, however it did have the highest thrust-to-weight ratio. It also had the second highest specific impulse at 58.1 seconds. The D12 engine had a specific impulse of 71.7 seconds, which was the highest specific impulse and the second highest thrust-to-weight ratio of 19.7. It was noticed through evaluating these parameters that the C6 engine, the middle-sized engine, had what seems like the worst engine performance characteristics, despite having more thrust than the B6. This can be traced back to the intent of use for each engine. The C6 engine was designed to burn longer than the C6 while maintain the same thrust capabilities. In order to do this the nozzle geometry was altered to reduce efficiency. This was seen in the exit velocity and mass flow rate data. The C6 engine had the slowest exit velocity, but its mass flow rate was 4.2 kg/s higher than the B6 engine. To improve this experiment, upgraded copper tubing to measure pressure could be used and the sampling rate could be increased to improve the resolution of the data.

Zachary Raboin

The results of this experiment provide a means for amateur rocketeers to investigate engine performance parameters experimentally. The thrust curves measured by the load cell for each engine match closely to the thrust curves presented in engine specification documents. With this, one can use the collection of data instead of fitting points to the curve on the specification sheet. Pressure at the engine outlet was also measured for use in basic rocket thrust equations. The engines investigated in this experiment were the Estes, B6, C6, and D12; these are some of the most common choices for rocketeers. The thrust from the B6 and C6 engines were both about 4 newtons while the D12 engine produced nearly 9 newtons. Through visual inspection of the thrust curve, the burn time was approximated, and the C engine had about double the burn time of engine B. This engine was created to produce similar thrust but over a longer duration. The D engine had a comparable burn time to the C engine but produced significantly more thrust. Using the pressure and thrust data as well as dimensional measurements made on the engine, exhaust velocities are estimated and used to calculate specific impulse. The specific impulses, in table 4, were calculated with velocity and again by thrust, producing very similar results. The C6 engine had the lowest specific impulse while the D12 engine had the highest specific impulse. These values are presented along with the specific impulses of historic engines made by the leaders in rocket design. The rudimentary and mass-produced Estes engine is, understandably, significantly lower than the engines produced by industry leaders. The Estes engine is not intended for multi-billion dollar missions carrying priceless instrumentation to orbit. In order to improve the procedure for experimental determination of commercial off-the-shelf hobby rocket engines, the pressure data acquisition setup should be improved. There was noticeable damage to the pressure tap entrance following testing. This should be addressed by use of high temperature metal fittings connected at the ends of the tube to shield the plastic from the flame.

Reference

[1] Ogata, Katsuhiko. *System Dynamics*. Pearson/Prentice Hall, 2004.

[2] "Solid Rocket Engine." *NASA*, NASA, www.grc.nasa.gov/www/k-12/airplane/srockth.html.

[3] "Solid-Propellant Rocket." *Wikipedia*, Wikimedia Foundation, 12 Oct. 2019, en.wikipedia.org/wiki/Solid-propellant_rocket.

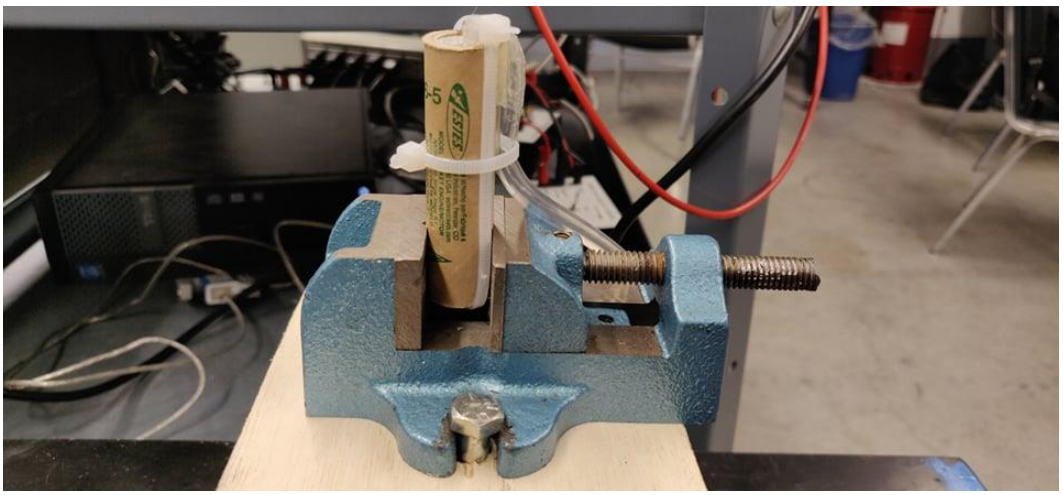
[4] "Rocket Engine." *Wikipedia*, Wikimedia Foundation, 26 Nov. 2019, en.wikipedia.org/wiki/Rocket_engine.

Appendix

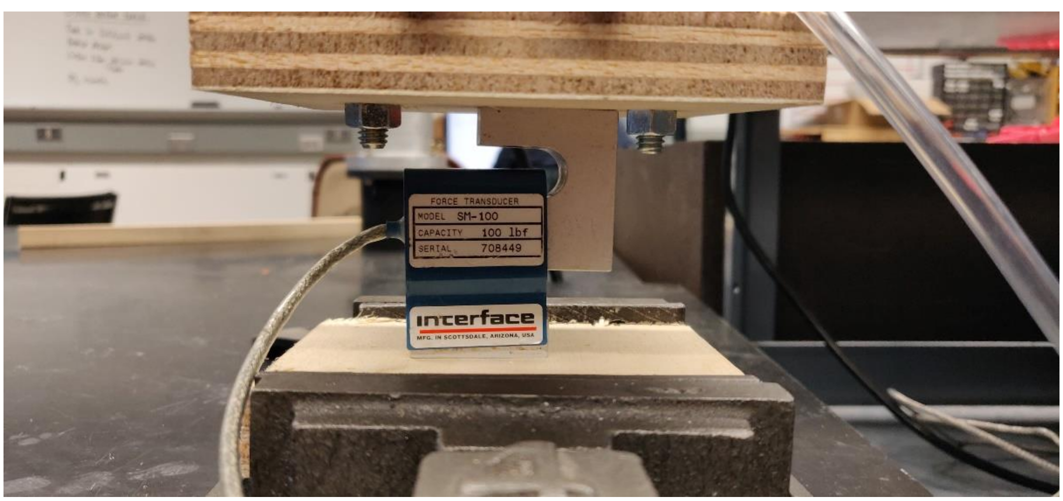
Procedure

A procedure has been outlined below for others to replicate this test and gain their own data to assess the properties of their own engines.

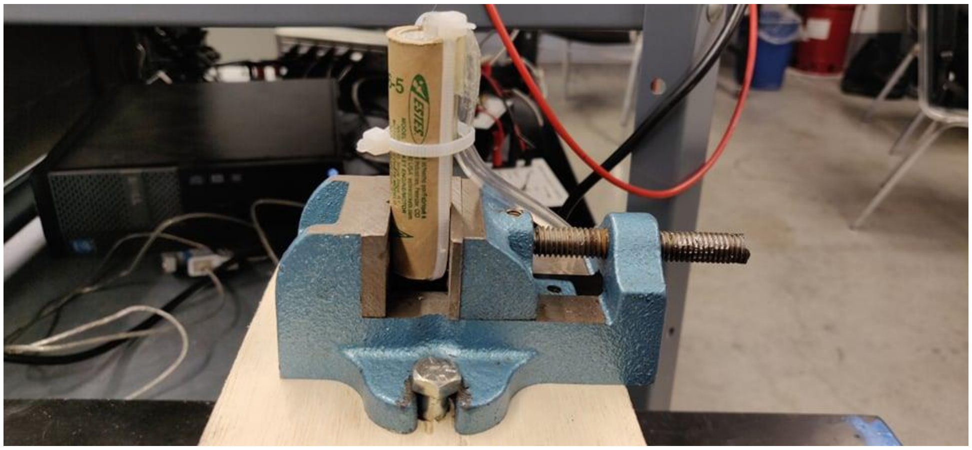
1.) To prepare an engine for testing, the first step is to use super glue and fix high temperature soft rubber tubing perpendicular to the nozzle of the engine. Wait for the glue to dry and then use zip ties to hold down the tubing. This can be seen in the figure below. Do not block the engine throat, but directly next to it. High temperature epoxy also works great for this as well as zip ties to hold it during transportation.



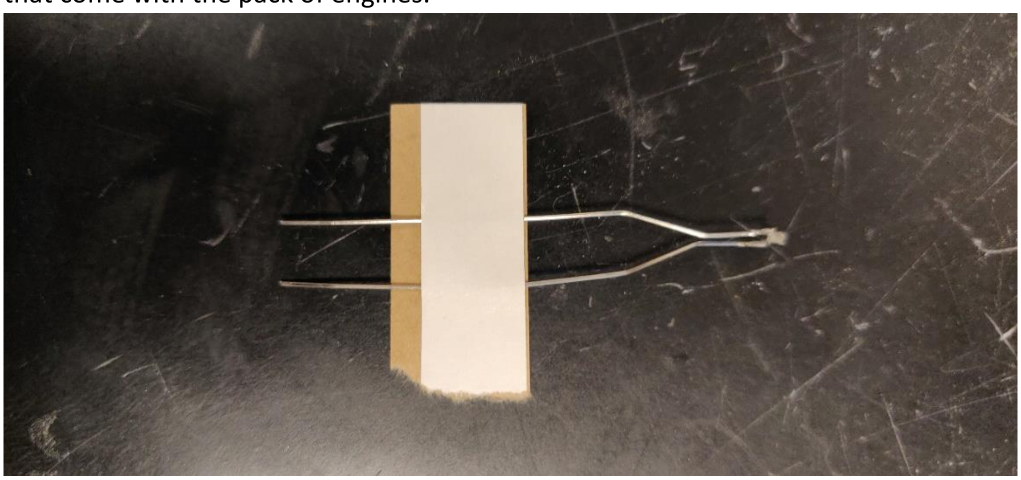
2.) To provide a secure base for the test to happen on, use a wooden platform to bolt the load cell on to. This wooden platform is then secured by grips to make the testing stand sturdier. This can be seen in the image below.



3.) Place a second wooden platform on top of the load cell as seen in the image above, this will be used to provide protection to the load cell and ensure that the thrust being produced is centered over the load cell for more accurate data.
4.) Next use grips on top of the second wooden platform to secure the estes or other COTS rocket engine directly over the load cell, this can be seen in the figure below.



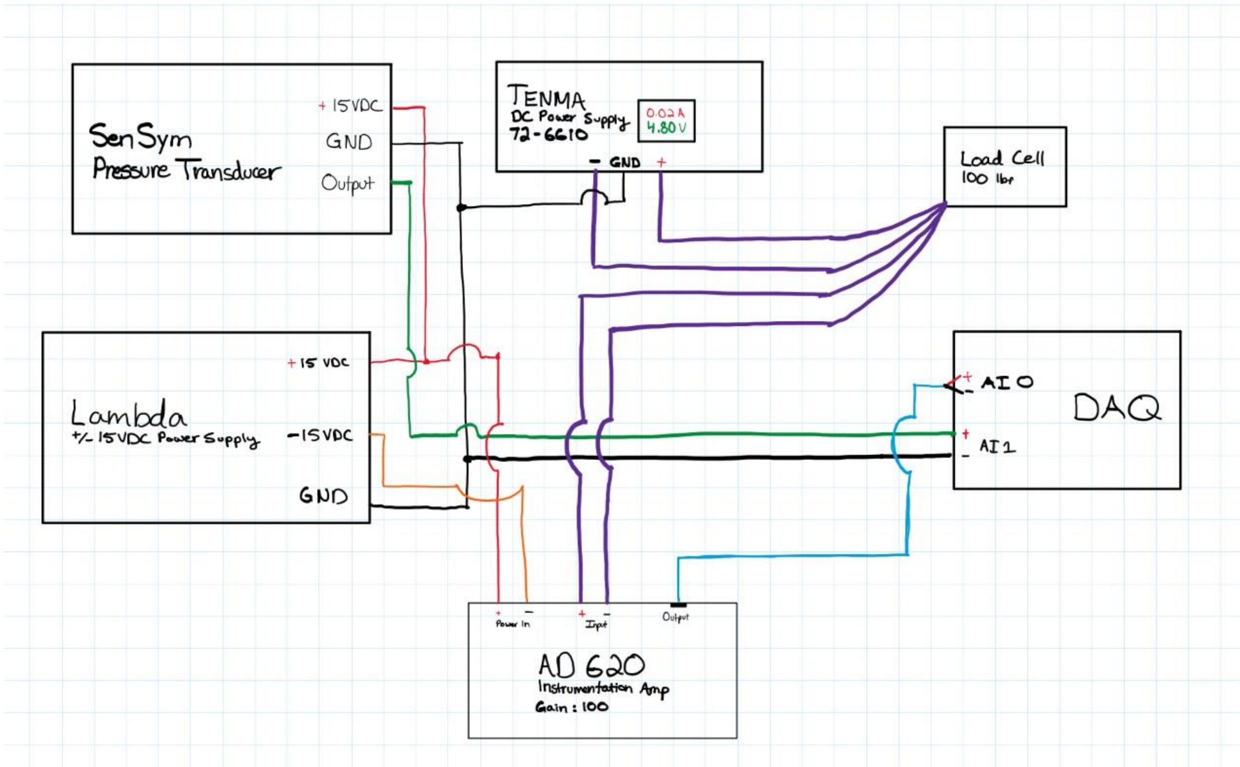
5.) Once the test stand has been created and the sensors are all secure and attached correctly, it is time to use a 12 volt battery and two electrical leads to ignite the engine using the made igniters that come with the pack of engines.



6.) Depending on your data collection system, it is ready to run the test. Start data collection for greater then 15 seconds, and shortly after starting collection, start the engine. Allow for a full burn and wait an additional 10 seconds for safety. Once the stand is inactive, save your data and repeat for any other engines wanted to analyze.
7.) To setup the sensors needed for appropriate data collection, the following equipment is required…
    a. SenSym 300 psi Pressure Transducer
    b. TENMA 72-6610 DC Power Supply
    c. Interface 100lbf Load Cell
    d. DAQ w/ at least 2 Input Locations
    e. AD 620 Instrumentation Amplifier
    f. Lambda +/- 15 Volt DC Power Supply

g. Computer Monitor

8.) The data collection equipment was connected as shown in the following wiring diagram.



9.) The TENMA Power Supply supplies 5 volts to the load cell and the load cell should connected to the AD 620 Instrumentation Amplifier with a gain of 100. The output from the AD 620 should be fed to the DAQ input AI0.

10.) The SenSym Pressure Transducer requires a 15 volt input from the Lambda Power Supply. The output of the transducer is then fed to the DAQ input AI1.

Given Thrust Curves

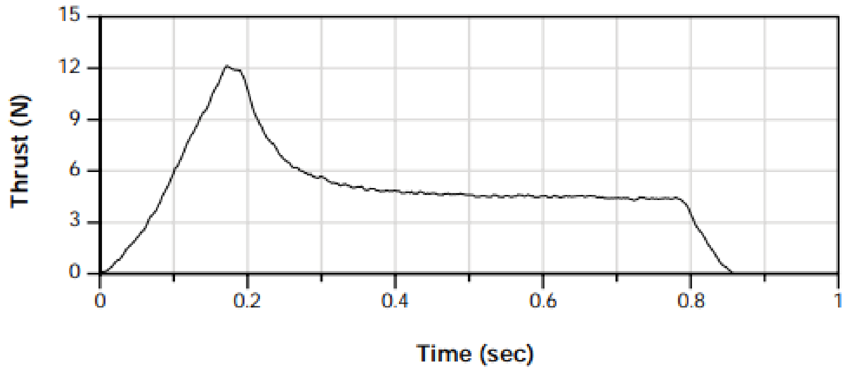


Figure 9 - The B engine thrust curve from Estes

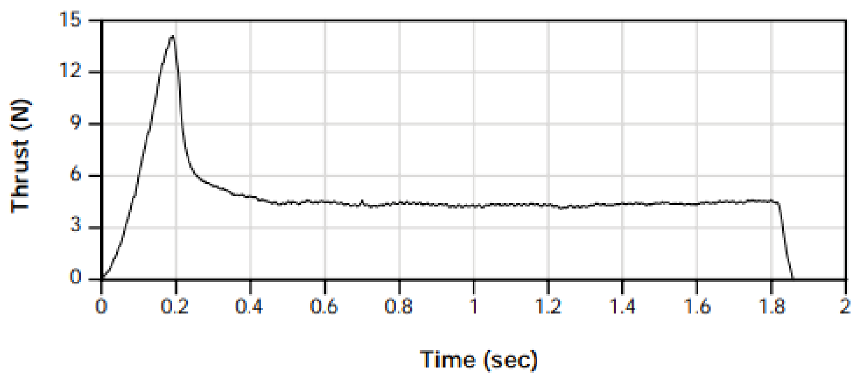


Figure 10 - The C engine thrust curve from Estes

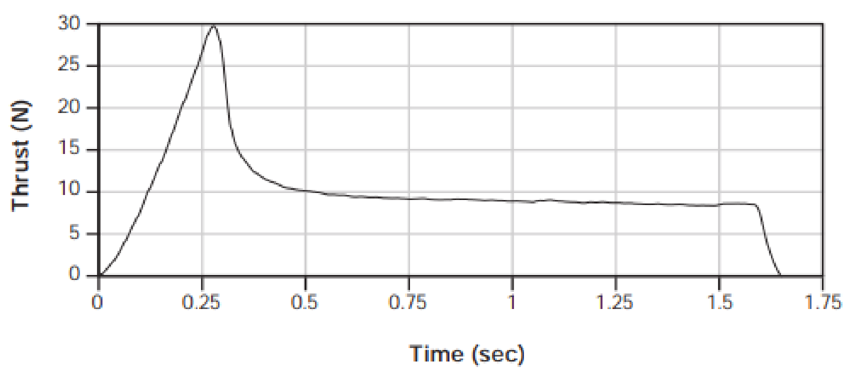


Figure 11 -The D engine thrust curve from Estes

MATLAB Analysis Code

```
clear all; close all; clc;

addpath('C:\Users\User\Desktop\Rocket Data');

bTime    = xlsread('bengine.xlsx', 'Voltage - Dev1_ai0', 'A9:A209');
bForce   = xlsread('bengine.xlsx', 'Voltage - Dev1_ai0', 'B9:B209');
bPressur = xlsread('bengine.xlsx', 'Voltage - Dev1_ai1', 'B9:B209');



cTime    = xlsread('Cengine.xlsx', 'Voltage - Dev1_ai0', 'A9:A209');
cForce   = xlsread('Cengine.xlsx', 'Voltage - Dev1_ai0', 'B9:B209');
cPressur = xlsread('Cengine.xlsx', 'Voltage - Dev1_ai1', 'B9:B209');

dTime    = xlsread('d engine.xlsx', 'Voltage - Dev1_ai0', 'A9:A209');
dForce   = xlsread('d engine.xlsx', 'Voltage - Dev1_ai0', 'B9:B209');
dPressur = xlsread('d engine.xlsx', 'Voltage - Dev1_ai1', 'B9:B209');

% Sensitivity Conversion for Pressures
bPressur = (bPressur - mean(bPressur(end - 50:end))).*20;
bPressur = bPressur.*6894.757;

cPressur = (cPressur - mean(cPressur(end - 50:end))).*20;
cPressur = cPressur.*6894.757;

dPressur = (dPressur - mean(dPressur(end - 50:end))).*20;
dPressur = dPressur.*6894.757;

bForce = ((bForce - mean(bForce(end - 10:end)))./.015).*4.5;
cForce = ((cForce - mean(cForce(end - 10:end)))./.015).*4.5;
dForce = ((dForce - mean(dForce(end - 10:end)))./.015).*4.5;


%measured values
d_throatd = .150*.0254;
c_throatd  = .1375*.0254;
b_throatd = .125*.0254;
% B Engine
figure()
plot(bTime - 1.5, bForce);
xlabel('Time [s]'); ylabel('Force [N]'); grid on;
title('Force vs. Time for B Engine')
xlim([0.4 1.6])

figure()
plot(bTime - 1.7, bPressur);
xlabel('Time [s]'); ylabel('Pressure [Pa]'); grid on;
title('Pressure vs. Time for B Engine')
xlim([0 1])
```

```
% C Engine
figure()
plot(cTime - 2, cForce);
xlabel('Time [s]'); ylabel('Force [N]'); grid on;
title('Force vs. Time for C Engine')
xlim([0 3])

figure()
plot(cTime - 2, cPressur);
xlabel('Time [s]'); ylabel('Pressure [Pa]'); grid on;
title('Pressure vs. Time for C Engine')
xlim([0 1.5])

% D Engine
figure()
plot(dTime - 1.7, dForce);
xlabel('Time [s]'); ylabel('Force [N]'); grid on;
title('Force vs. Time for D Engine')
xlim([0 2.5])

figure()
plot(dTime - 1.8, dPressur);
xlabel('Time [s]'); ylabel('Pressure [Pa]'); grid on;
title('Pressure vs. Time for D Engine')
xlim([0 1])
```

Key Performance Calculations

```
bForce = bForce(37:61);

cForce = cForce(48:90);

dForce = dForce(40:80);



bMean = mean(bForce);

cMean = mean(cForce);

dMean = mean(dForce);



%given values
tot_thrustd  = 20; % N sec
tot_thrustc  = 10; % N sec
```

```
tot_thrustb  = 5;  % N sec

max_Pb = max(bPressur);
max_Pc = max(cPressur);
max_Pd = max(dPressur);

d_throatA = ((d_throatd/2)^2)*pi;
c_throatA  = ((c_throatd/2)^2)*pi;
b_throatA = ((b_throatd/2)^2)*pi;

m_dotb = (.0056/.9);
m_dotc = (.0198/1.9); %kg/s
m_dotd = (.0211/1.7);

ve_b = (bMean-(b_throatA*(max_Pb)))/m_dotb;
ve_c = (cMean-(c_throatA*(max_Pc)))/m_dotc;
ve_d = (dMean-(d_throatA*(max_Pd)))/m_dotd;


Ispb1 = bMean/(m_dotb*9.81);
Ispc1 = cMean/(m_dotc*9.81);
Ispd1 = dMean/(m_dotd*9.81);

Ispb2 = ve_b/9.81;
Ispc2 = ve_c/9.81;
Ispd2 = ve_d/9.81;


rd = 1/(((45.2/1000)*9.81)/dMean);
rc = 1/(((24.0/1000)*9.81)/cMean);
rb = 1/(((15.6/1000)*9.81)/bMean);
```