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Performance Variability in Solid Rocket Motors

Manvith Amara

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Manvith Amara

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Honors Capstone Director: Dr. David Lineberry

Research Engineer, UAH Propulsion Research Center

Manvith Amara 04/28/2022

Student Date

04/28/2022

Director Date

04/28/2022

Department Chair Date

William Wilkerson Digitally signed by William Wilkerson
Date: 2022.04.29 09:34:07 -05'00'

Honors College Dean Date

HONORS COLLEGE
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Honors College
Frank Franz Hall
+1 (256) 824-6450 (voice)
+1 (256) 824-7339 (fax)
honors@uah.edu

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___Manvith Amara____________

Student Name (printed)

Manvith Amara

Student Signature

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Abstract

Static motor tests of four Aerotech G138 solid rocket motors were conducted to assess performance variability for commercial hobby rocket motor propellant. Four Aerotech G138 motors were purchased from two different vendors to ensure at least two batches of propellant could be analyzed. Motors were tested on a single axis thrust stand and were instrumented with a single static pressure transducer at the head end of the motor case. Calculated values for average thrust, total impulse, specific impulse, burn time, and average chamber pressure were used to compare the performance of the four motors. The test values were compared against baseline values provide from a common motor performance source, ThrustCurve.org. The five test average values for average thrust, max thrust, total impulse, specific impulse, and burn time were 26.38 lbf, 35.74 lbf, 32.59 lbf-sec, 208.94 sec, and 1.24 sec respectively. The variation of the performance parameters ranged from +/- 24%, however deviation between the test average values and the baseline values varied as much as 16% for some of the parameters. The results presented in this project provide insight into motor variability that will be of value for modeling rocket flight and determining uncertainty in rocket flight performance using motors of the same propellant formulation.

Introduction

When analyzing a rocket motor's potential flight performance, a trajectory analysis is conducted to ensure that the rocket motor can meet the desired apogee as well as fulfill any other necessary trajectory requirements. While simulation software such as OpenRocket can generate a trajectory model based on given inputs, it does not do well in anticipating potential variability of parameters during flight. One of those parameters is thrust. The motor manufacturers provide a thrust curve based on a single motor test but do not provide information about potential thrust variability from motor to motor. Thrust produced by a motor can be particularly variable, as it is dependent on the propellant batch from which the motor was cast, as well the geometric characteristics of the grain and nozzle. Variations in the propellant formulation from batch to batch, as well as variation in the geometric characteristics of the grain or nozzle will result in performance that deviates from the single test thrust curve provided by the manufacturer. This variation can impact the rocket's trajectory and lead to a failure to meet mission objectives.

In order to assess the impact of thrust variation on the rocket trajectory, a Monte Carlo analysis is conducted to ensure that for a provided deviation from the predicted parameter value, the rocket can still meet its target requirement. In order to produce accurate results from the Monte Carlo analysis, the variability of each parameter must be understood. These predicted deviations can be difficult to calculate as some of them require adequate experimental testing to produce a statistical dataset. In order to improve the accuracy of the predicted trajectory, a value for the predicted deviation in average thrust was be found by conducting a set of experiments to measure the variability between a sets of motors from

different propellant batches. Similarly, deviations in other performance parameters such as burn time, max thrust, average thrust, specific impulse, and total impulse had been evaluated.

The experimental design consisted of igniting 4 G-class 29 mm motors on a thrust stand at the Propulsion Research Center and collecting data from each motor. In order to prevent error, motors were purchased from 2 different sellers in quantities of 2. For each motor, measurements such as nozzle throat diameter, grain length, grain bore diameter, and propellant mass before and after the test had been collected for each motor. Measurements of thrust versus time and chamber pressure were collected during the experiment using a load cell on the thrust stand and a head end pressure transducer. These measurements were then analyzed to evaluate traditional rocket motor performance parameters: burn time, average thrust, peak thrust, and peak chamber pressure. Compilation of this data occurred in Excel, where figures were generated from the final derivation of the data from each of the 4 tests to show the statistical variation of the average thrust and other measured parameters. The results from this statistical analysis will help the current and future Charger Rocket Works teams in analyzing trajectory models for their rocket and making appropriate mass and motor choices to ensure success of the rocket launch even if certain parameters such as average thrust, burn time, max thrust, and peak pressure deviate from the estimated value. Rather than attempting to guess how much those parameters could deviate, this experiment will help ensure a successful launch by accounting for an estimated deviation range in those parameters.

Experimental Setup

In order to static test fire the motors, a test stand was set up in order to restrain the motors during firing. This was done on by constraining the motor through the use of aluminum blocks and bolting it onto an aluminum structure. This structure was connected to a load cell in order to measure thrust throughout the duration of the burn. In addition to the load cell, a pressure transducer was connected to the forward closure of the motor, to measure chamber pressure throughout the duration of the burn. Figure 1 depicts the experimental setup used to retain the motor for the static test fires. Figure 2 shows the physical test stand, in a front and top view.

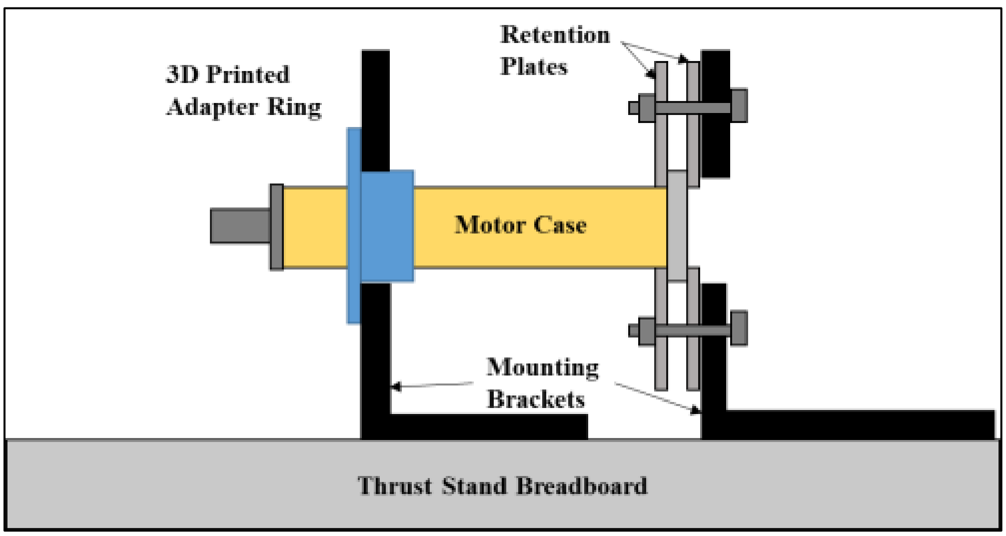

Figure 1: Motor Retention Configuration

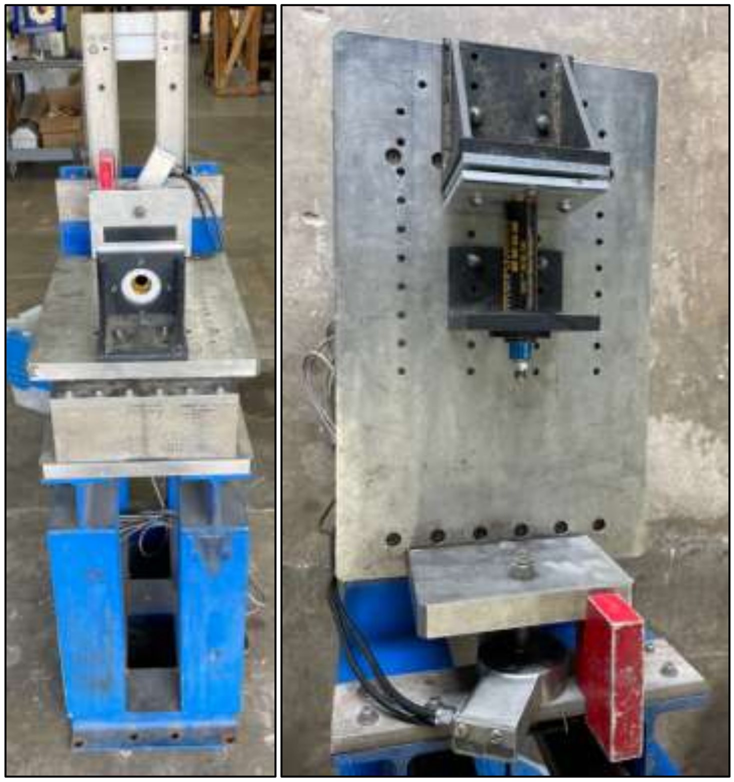

Figure 2: Test Stand Set-up [Left: Front View, Right: Top View]

Approach

Motor Characteristics

The motors used in this experiment are Aerotech G138T motors. Table 1 depicts motor characteristics provided by a third-party resource known as *ThrustCurve* that is generally used for basic motor information. The data found in this resource will be used as a baseline to compare with experimental results and measure variability. Figure 3 shows a thrust curve provided by the resource that shows a theoretical burn by the motor with thrust values over the burn time.

Table 1: Aerotech G138 Motor Baseline Characteristics[1]

Manufacturer	Aerotech
Designation	HP-G138T
Motor Type	Reload
Propellant	Blue Thunder
Diameter	29 mm
Length	124 mm
Total Weight	148 g
Propellant Weight	70 g
Average Thrust	31.02 lbf.
Max Thrust	42.74 lbf.
Burn Time	1.1 sec.
Total Impulse	35.32 lbf-sec
Specific Impulse	229.35 sec

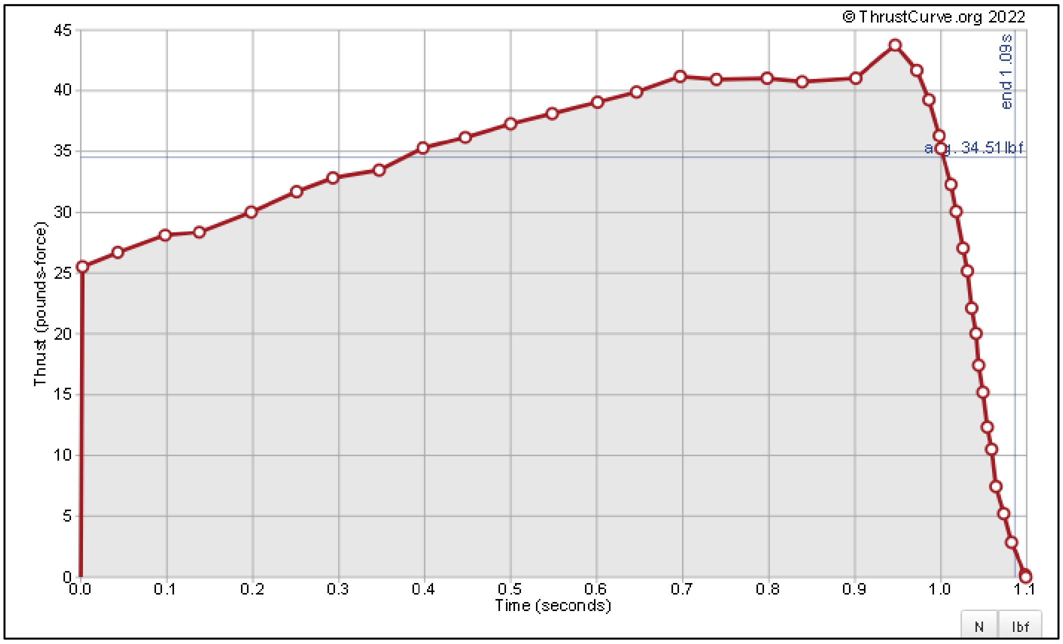

Figure 3: Thrust vs. Time provided by ThrustCurve.org[1]

Data Collection

Each day of testing required re-calibration of the load cell due to potential error from test to test and was done by loading various amounts of weight and determining the trendline from the load cell readings. After calibration of the load cell and other pre-test operations, a pre-load of around 20 lbs. was added to the load cell to remove slack from the load string. After confirmation that the load cell and pressure transducer were transmitting data, the motors were ignited, causing a brief burn. A visual is shown in Figure 4 of a motor fire on the test stand. The data was captured from the load cell and pressure transducer at 1000 Hz. was recorded into a system-design platform known as *LabView* where the data was written in a text file and then imported into an Excel file.

Figure 4: Static Fire of Motor on Test Stand

Results / Analysis

Data Analysis

Four motor tests were conducted, two motors from each hobby rocket motor vendor, CSRocketry and Balsa Machining. Using the Excel file exported from *LabView* for each of these motors, analysis was performed to find the variability in the average thrust, specific impulse, total impulse, max thrust, and burn time. In addition to this, batch variability can also be calculated based on the propellant and total weight of the motor, as these parameters were measured prior to the experiment for each motor. Motor dimensions prior to each test were measured in order to see variability in the hardware kits and are shown in Table 2. Post-test motor dimensions were measured and are shown in Table 3. Motor tests are classified by motor vendor, CS for CSRocketry and BM for Balsa Machining. A number is followed by the classification to signify the test number.

Table 2: Pre-Test Motor Measurements

	CS 1	CS 2	BM 1	BM 2
Nozzle Throat Diameter (in.)	0.176	0.18	0.18	0.172
Nozzle Mass (g.)	8	8	8	8
Propellant Mass (g.)	75	75	75	75
Propellant Bore Diameter (in.)	0.272	0.275	0.277	0.277
Propellant Length (in.)	3.917	3.913	3.911	3.903
Liner Diameter (in.)	1	1	1	0.96
Liner Wall Thickness (in.)	0.025	0.026	0.021	0.024
Total Assembled Weight (g.)	157	157	157	160

Table 3: Post-Test Motor Measurements

	CS 1	CS 2	BM 1	BM 2
Total Assembled Burnout Weight (g.)	86	86	85	93
Nozzle Burnout Mass (g.)	7	7	7	7
Liner Burnout Mass (g.)	5	4	4	4
Nozzle Burnout Throat Diameter (in.)	0.249	0.25	0.244	0.236

Based on the values derived from Table 2 and Table 3, the initial propellant mass and total weight of the motor can be compared with ThrustCurve data values, to see variability in mass from manufacturer. Equation 1 can be used to calculate the percent difference between the theoretical value and the experimental value.

$$\%\,Difference = \frac{Experimental - Theoretical}{Theoretical} * 100 \quad (1)$$

Using Equation 1, the percent difference between the experimental and theoretical propellant mass was found to be around 1.4 % for each motor when compared to the theoretical value of 75 g. provided by ThrustCurve. This calculation accounts for a liner mass of 4-5 grams. The percent difference in total weight before test can also be calculated and was found to be around 6.1% for each motor when compared to the theoretical value of 148 g. provided by ThrustCurve. The difference can be potentially shown through grease added to the motor during assembly, for which the ThrustCurve mass values may not account.

Similar to the calculations of percent difference for propellant weight and total weight variation, calculations can be performed to find variability in data derived parameters such as burn time, specific impulse, total impulse, max thrust, and average thrust variation. From the measurements collected during testing, the first step was to take an average value for thrust and pressure during pre-test, as data was measured every millisecond and data was recorded for over

a minute per test. This was done by averaging the thrust and pressure values before the test and subtracting it from the data to remove bias in the pressure measurement and the pre-load from the thrust measurement. Figure 5 shows a thrust curve of the four motor tests conducted versus time. Figure 6 shows a chamber pressure curve of the four motor tests conducted versus time.

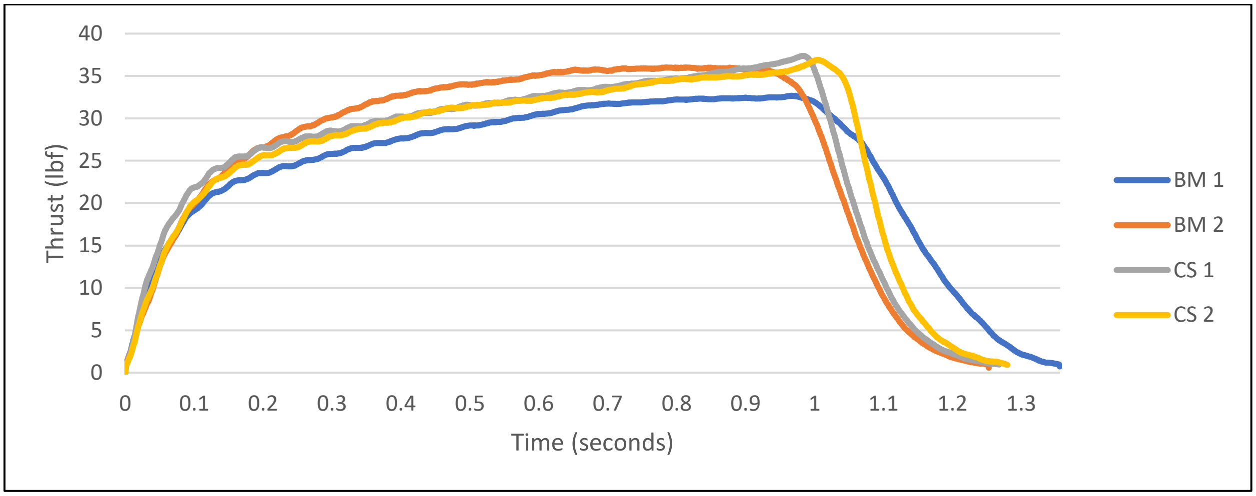

Figure 5: Thrust Curve of Motor Tests

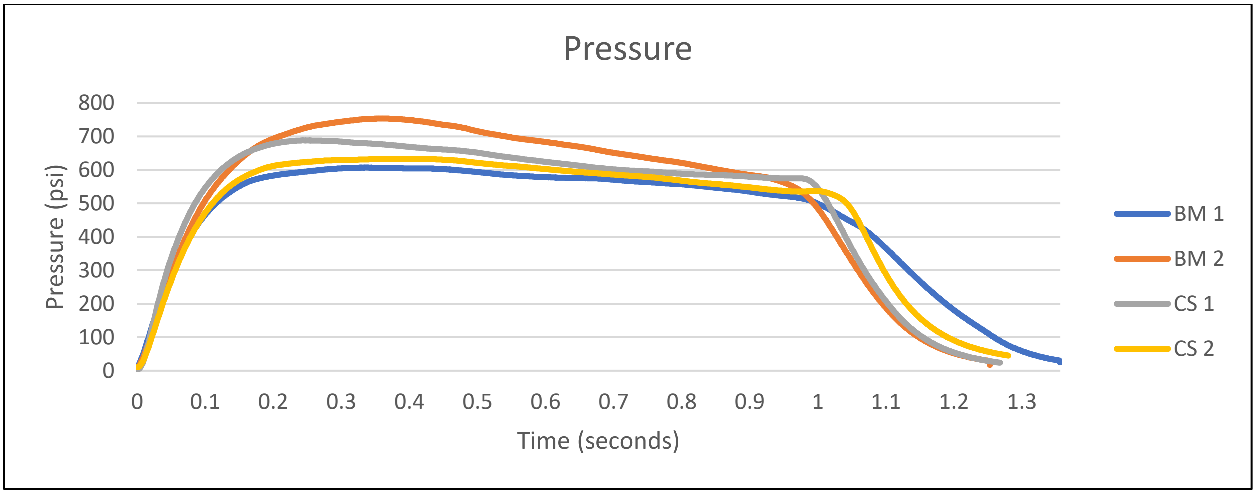

Figure 6: Pressure Curve of Motor Tests

From Figure 5 and Figure 6, key parameters can be determined for comparison against the presumed baseline values obtained from ThrustCurve.org. The primary parameters for comparison in this study were burn time, average thrust, max thrust, specific impulse, and total impulse. The burn time for each test was determined based on the initial increase in thrust above 5% of maximum thrust, the start of the burn, and the final decrease of the measured thrust below 5% of the maximum thrust as end of the burn at 5% of max thrust. The total impulse, average thrust, and specific impuse were then calculated based on this burntime. The total impulse for each motor test was calculated by numerically integrating the thrust over the burn time interval. Specific impulse was subsequently calculated by dividing the total impulse by the mass of the propellant consumed through the test. This mass was determined from the pre and post test mass measurements of the propellant. Finally, the average thrust was determined by dividing the total impulse by the burn time. The calculated parameters for each motor, along with the presumed baseline values are shown in Table 4.

Table 4: Key Parameters from Motor Tests

	Baseline	**BM 1**	**BM 2**	**CS 1**	**CS 2**
Burn Time (sec.)	1.1	1.3	1.2	1.2	1.2
Max Thrust (lbf.)	42.7	32.7	36.0	37.4	36.9
Average Thrust (lbf.)	31.0	24.3	27.5	26.9	26.7
Total Impulse (lbf-sec)	35.3	32.1	32.8	32.5	32.9
Specific Impulse (sec)	229	208	210	208	210

It is noticeable that most parameters differ greatly from the baseline values throughout each test. The estimated burntimes for each of the motors exceed the baseline value from 0.1 to 0.2 seconds (10% to 18%). For each of the other parameters of interest the calculated test values for

each motor were less than the baseline values. The maximum thrust from each the four tests were between 5.3 lbf and 10 lbf below the expected maximum thrust of 31 lbf. Average thrust values were between 6.7 lbf and 3.5 lbf below the expected value. The calculated specific impulse values were between 21 and 19 sec below the expected value of 219 sec. Total impulse was realtively closer to the expected values with the individual tests ranging from 3.2 lbf-sec to 2.4 lbf-sec, however these values were all below the expected total impulse of 35.3 lbf-sec. Although the sample size is relative small, the data does not indicate any significant parameter variation that could be attributed to batch variation between the two batches tested.

The four test average values for each of the calculated parameters was then calculated along with the standard deviation of each parameter. The average values are presented in Table 5. An assessment of the expected variability of the data was made by determining a 95% confidence interval. The 95% confidence interval was calculating by multiplying the standard deviation by the t-distribution value of 3.185, used for a sample size of 4 and a 95% confidence. Finally a percent variability was calculated. This value is the maximum percent difference between any of the four test values and the four test value, and represents the spread of the data around the mean value. Although burntime, maximum thrust, and average thrust had relatively large variation at 6.1%, 8.5%, and 7.8%, the variation in total impulse and specific impulse was relatively small at 1.5% and 0.5%. These smaller values provide an indication of the consistency in the data for these parameters.

Table 5: Test Average Values

	Thrust Curve	Average of Motor Tests	Standard Deviation	95% Confidence Interval	% Variability
Burn Time (sec.)	1.1	1.24	0.048	0.15	6.1%
Max Thrust (lbf.)	42.74	35.7	1.842	5.9	8.5%
Average Thrust (lbf.)	31.02	26.4	1.194	3.8	7.8%
Total Impulse (lbf-sec)	35.32	32.6	0.293	0.9	1.5%
Specific Impulse (sec)	229.35	209	1.180	3.8	0.5%

Utilizing Equation 1, the percent difference of each parameter, as well as the the four test average was calculated with its respective baseline value. These variations are shown in

Table **6**, depicting the percent difference from the expected value for each parameter. The percent differences in all values were greater than 7%, however, similar to the four test variation, burn time, maximum thrust, and averge thrust exhibited the largest percent differnce from baseline values. Total impulse and specific impulse had percent differences ranging from 7% to 9%. This percent difference is significantly larger than the 2% and 3% variations estimated for the four test averages. For all cases, the percent difference between any of the test values and the baseline value were greater than the percent difference between the four test mean values and any single test value. This result indicates that the four tests exhibited data that was very close to each other, but varied largely from the presumed baseline values obtained from ThrustCurve.org.

Table 6: Percent Difference in Key Parameters from ThrustCurve Value

	BM 1	BM 2	CS 1	CS 2	Average of Motor Tests
Burn Time	20%	9%	10%	12%	13%
Max Thrust	24%	16%	13%	14%	16%
Average Thrust	21%	11%	13%	14%	15%
Total Impulse	9%	7%	8%	7%	8%
Specific Impulse	9%	9%	9%	8%	9%

Some key inferences can be derived from the results presented in Tables 4, 5, and 6. The test to test variation in the key parameters that are used to simulate rocket flight was relatively small, compared to the variation between the values from a single test relative to baseline values obtained from a commonly used resource. The test to test variation presented in the tables provides a foundation for the expected performance variation of a given hobby rocket motor, however the deviation of the mean values from the baseline values was greater than the test to test variation. If the data collected from these tests is typical of other motors or similar or different popellant, then the data may indicate that relying on a single thrust curve, and specified parameters from ThrustCurve.org may not produce an accurate flight simulation. The amount of variation shown by these experimental results impact the credibility of data from ThrustCurve.org to be used in trajectory simulation studies. In most hobby rocket applications, the variations seen with this study are relatively insignificant unless the designed rocket is near limititations for safe flight, or if a highly accurate trajectory is required. In these scenarios, the data from this study imply that conducting ground tests of the motor selected for the design would be crutial to developing an accurate trajectory model.

Conclusion

The result of this experiment, provide a foundation for inclusion of rocket motor variability in flight simulations for future SLI teams at the University of Alabama in Huntsville. In these static fire tests of 4 motors, the performance variability due to batch variation was initially targeted by selecting 2 motors from 2 different hobby motor vendors, CSRocketry and Balsa Machining. Utilizing a load cell and pressure transducer to measure thrust and chamber pressure over time, thrust and pressure values were compared with baseline values obtained from a commonly used resource in the hobby rocket community, ThrustCurve.org. The data collected from the testing enabled for calculations of variation between each motor dataset and the baseline values and yielded an average variation of ± 13% for burn time, ± 16% for max thrust, ± 15 % for average thrust, ± 8 % for total impulse, and ± 9% for specific impulse. Comparison of the test values indicated that the batch-to-batch variation was small, although it should be noted that the sample set was also small and for a more conclusive study additional motors from additional propellant batches should be evaluated.

Although the batch-to-batch variation of motor performance parameters was small, the variation between the calculated performance parameters and the baseline data was larger than expected. For all calculated parameters, the variation derived from this experiment was greater than two standard deviations higher than the baseline values. All parameter baseline values other than the burn time fall outside of the 95% confidence interval, raising concern about the reliability of data from ThrustCurvel.org for design of rockets when highly accurate simulations are desired. Finally, it is recommended that future senior design teams to run their

own ground tests to normalize the variability based on the specific motor used in order to create more accurate flight simulations. .

References List

[1]ThrustCurve Data for Aerotech G138; https://www.thrustcurve.org/motors/AeroTech/HP-G138T/