Investigation of the Effect of Increasing Grain Internal Diameter (cm) of Potassium Nitrate - Sucrose (KNSU) Solid-Propellant on Peak Thrust Measured in Newtons.

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Abstract

This study investigates the effect of varying internal grain diameter in Potassium Nitrate-Sucrose (KNSU) solid-propellant rocket motors on peak thrust production. Rocket motor performance is significantly influenced by propellant grain geometry, with important implications for amateur rocketry and small-scale space launch attempts. Using a controlled experimental design, KNSU propellant grains with three different internal grain diameters (0.25", 0.50", and 0.75") were systematically tested on a calibrated load cell apparatus. Results demonstrated a consistent inverse relationship between internal grain diameter and peak thrust, with the 0.25" diameter configuration producing significantly higher peak thrust values compared to larger diameters. This finding contradicts some theoretical predictions that suggest increased burning surface area from larger internal diameters should increase peak thrust. The optimized 0.25" internal diameter design provides amateur rocketry teams with valuable data for developing self-manufactured solid propellants when commercial options are unavailable. Future research incorporating additional intermediate diameter values and varied propellant formulations could further refine our understanding of optimal grain geometry for maximum thrust production in small-scale solid rocket motors.

I. Introduction

1. Background and Rationale

1.1 Introduction

The idea and application of solid-propellant rocket motors has been around for centuries, from the first ever solid propellant rocket being accidentally created and fired in 1232[1] by the Chinese during the battle of Kai-Keng in the form of flying fire arrows, attached to tubes of gunpowder with a clay plug and an open nozzle. In the 1920's soviet research and development of solid-propellant rockets with the first launch in 1928, which flew approximately 1300 meters[1].

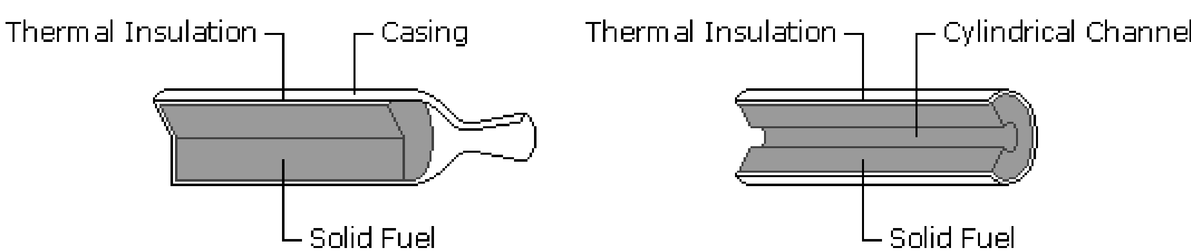

Figure 1. A standard grain cross-section for a solid-propellant rocket motor[2]. (Braeunig)

[1] Green, Becky, and Christy Hales. "History of Solid Rockets." NASA Technical Reports Server, NASA, Nov. 2017, ntrs.nasa.gov/api/citations/20170012460/downloads/20170012460.pdf. Accessed 12 Oct. 2024.

[2] Braeunig, Robert A. "Rocket Propulsion." Rocket and Space Technology, 2008, www.braeunig.us/space/propuls.htm. Accessed 12 Oct. 2024.

Referring to Fig. 1, note that in this paper, thermal-insulation/casing will be in the form of poly-vinyl chloride (PVC). In the official trials, we will be using the model on the right with the cylindrical channel/perforation varying in diameter, directly correlating to burning surface area.

Solid propellants have some important properties, such as the ability to sustain the burning process without any external force, once the reaction starts. Some solid-propellants are able to begin the burning process without any external initiation. This creates the propellant quite dangerous due to unwanted ignitions, but the removal of an ignition source, the total weight is reduced[3]. Solid propellant motors aren't the only type of rocket motors that are used in spaceflight and aerospace applications.

On large scales mostly liquid engines are used with LOX (liquid oxygen) as the strong oxidizing agent and liquid hydrogen or RP-1 (refined petroleum-1) as the fuel source. Even though liquid engines are significantly more efficient in terms of specific impulse, easier thrust vector control, and the ability to easily change throttle, liquid engines are extremely complicated at a smaller scale, requiring hard-to-acquire chemicals and a complicated design process. Additionally, solid propellant motors are more due to develop cracks and voids in their grain leading to increased local temperature, systematic pressure, and heat instability to the casing. In conclusion, solid propellants and systems for rocket propulsion are significantly more inflexible, but they produce good performance at a reduced cost and complexity.

The main aim of this research paper is to investigate and hopefully identify, through analytical methods, the relationship of inner diameter of Potassium Nitrate - Sucrose (KNSU) solid propellant grain as it relates to the peak thrust measured in Newtons. This research is important for smaller student-led projects that are being conducted at facilities such as Georgia Institute of Technology and Virginia Polytechnic institute and State University for future space launch attempts. Hopefully, with the conclusions drawn from the experimental trials in this paper, we will be able to fully understand and reinforce the relationship between grain internal diameter and peak thrust measured in Newtons.

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[3] Navarrete-Martin, Laura, and Petter Krus. "Sounding Rockets: Analysis, Simulation and Optimization of a Solid Propellant Motor Using Hopsan." *Transportation Research Procedia*, vol. 29, 2018, pp. 255–267, https://doi.org/10.1016/j.trpro.2018.02.023. Accessed 28 Oct. 2024.

2. Theoretical Assumptions

Nomenclature	
ϱ - Fuel density (g • cm^{-3})	C_t - Case thickness (cm)
L - Grain length (cm)	M_p - Mass of propellant (g)
d - Grain internal diameter (cm)	M_r - Molecular mass (g * mol^{-1})
r_i - Grain internal radius (cm)	V_p - Volume of propellant (cm^3)
I_{sp} - Specific impulse (N·s/g)	S - Grain (internal lateral) surface area (cm^2)
M_w or M_p - Wet mass of motor or Propellant mass (g)	V_c - Volume of cylinder (cm^3)
M_d - Dry mass of motor (g)	V_i - Volume using internal diameter (cm^3)
f - Fractional value of ingredient	V_e - Volume using external diameter (cm^3)
t - Time (s)	*I* - Total impulse (N • s)

2.1 Functional aspects of solid propellant motors

Components of a simple rocket motor:

1) Nozzle - The nozzle is made out of heat resistant materials such as graphite, which is usually in the shape of a "convergent-divergent hourglass", which has the role of accelerating compressible gas in the axial/thrust direction[4](Jayaprakash, P.). In this research paper we will be creating a 0.3-inch ⌀, PVC cap hole that is controlled across all trials.
2) Thermal Insulation - The thermal insulation is usually composed of phenolic resin which protects and shields the casing from the heat produced in the channel. This thermal insulation is mainly used in bigger-scaled rocket motors which will not be tested in this paper. Thermal insulation is not needed at the scale of testing that will be done in this paper, therefore we will not include any thermal insulation in the building process.

[4] Jayaprakash, P., D. Dhinarakaran, and D. Das. "Design and Analysis of a Rocket C-D Nozzle". International Journal of Health Sciences, vol. 6, no. S5, June 2022, pp. 3545-59, doi:10.53730/ijhs.v6nS5.9404.

3) Casing - The casing is constructed from a variety of materials. Cardboard is used in smaller black-powder motors, whereas aluminum is used in significantly larger and more powerful composite-fuel hobby motors. In this research paper, PVC tubing will be used as the casing, with proper safety precautions.
4) Solid Propellant - The finished solid propellant is also called the propellant grain. The propellant contains both a solid form of fuel, and a solid form of oxidizer. In this paper I will be using granulated sucrose as the fuel source, and potassium nitrate as the oxidizer in a melted down-65:35 oxidizer to fuel ratio[6]. It is important to note that the solid rocket propellant deflagrates from the surface of the channel grain in the chamber to the casing. We will refer to this propellant mixture by the acronym KNSU henceforward.

2.2 Fuel density and specifications

The solid propellant that will be used in the trials is the KNSU: 65% Potassium Nitrate: 35% Sucrose. Fuel density can be calculated with the weighted average of the density of both fuel components. In our case, KNO_3 has a density of $2.109\ g/cm^3$ (ρ_{KN}) at 19 degrees celsius. And $C_{12}H_{22}O_{11}$ has a density of $1.587\ g/cm^3$ (ρ_{SU}) while solid. In all trials the fuel will be mixed in a 65:35 oxidizer to fuel ratio (65 KNO_3 : 35 $C_{12}H_{22}O_{11}$). Therefore we can conclude that our fuel density at the given temperature can be given by:

$$Equation\ for\ density:\ \rho = \frac{1}{\frac{f_{KN}}{\rho_{KN}} + \frac{f_{SU}}{\rho_{SU}}}\ where\ \boldsymbol{f}_{KN} = 0.65,\ \boldsymbol{f}_{SU} = 0.35,$$

$$Theoretical\ ideal\ density\ at\ 25^{o}C:\ \rho = \frac{1}{\frac{0.65}{2.109} + \frac{0.35}{1.587}} = 1.891\ g/cm^3$$

$$Typical\ accepted\ density\ as\ cast^{6}:\ \rho = 1.80\ g/cm^3$$

Looking at the values, we can see little difference between the theoretically calculated density, and the typically accepted ideal density as calculated by ProPEP (Propellant Evaluation Program)[6]. Moving ahead in this paper, all computed values that use any density values will be the typical accepted value of 1.80 g/cm³.

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[6] Nakka, Richard . "Richard Nakka's Experimental Rocketry Site." Www.nakka-Rocketry.net, www.nakka-rocketry.net/succhem.html. Accessed 16 Oct. 2024.

[7] Reilley, Andrew. "OpenMotor." GitHub, 8 Apr. 2023, github.com/reilleya/openMotor. Accessed 16 Oct. 2024.

This value has been gathered through experimentation from Richard Nakka, a rocket scientist that has extremely valuable and extensive testing done on KNSU propellant, and giving us a realistic value that can be used to compute and derive values.

This value is invaluable to theoretically estimating the specific impulse, chamber pressure, and fuel composition using software programs such as *OpenMotor*[7]. Similarly we can use this number for the calculation of mass flow rates, allowing us to understand the amount of fuel that is lost throughout the burning process.

2.3 Pre-experimental calculations and definitions

M_r of KNO_3:

$$39.098\,(K) + 14.007\,(N) + 3 * 15.999\,(O_3) = 101.102\,g/mol$$

M_r of $C_{12}H_{22}O_{11}$:

$$12 * 12.011\,(C_{12}) + 22 * 1.008\,(H_{22}) + 11 * 15.999\,(O_{11}) = 342.297\,g/mol$$

For the ideal propellant mass varying from different IV's:

Equation 1:

$$M_p = M_w - M_d$$

Equation 2:

$$V_p = \frac{M_p}{\rho} = \frac{M_p}{1.80}$$

Equation 3:

$$V_c = \pi(r_i^2)L$$

Equation 1 defines that the mass of the propellant can be measured by the rocket motors wet weight (with solid-propellant grain) minus the rocket motors dry weight (without solid-propellant grain). This will vary per trial due to the fact that as the radius/diameter decreases the volume of the cylinder directly varies and therefore decreases, lessening the total mass of the propellant.

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[7] Reilley, Andrew. "OpenMotor." GitHub, 8 Apr. 2023, github.com/reilleya/openMotor. Accessed 16 Oct. 2024.

Equation 2 defines that the volume of the propellant can be given by Equation 1 knowing the density of the KNSU propellant as defined earlier and using the definition of volume = mass/density. Now using Equation 1 with the density of the propellant the volume can be calculated.

Equation 3 gives the definition of the volume of a cylinder. Specifically will be used to calculate the volume of cylindrical full grain, and perforation volume.

Using Equation 1, 2, and 3:

For any level of IV:

$$V_p = V_e - V_i$$

$$\therefore \; V_p = V_e - V_i = \frac{M_w - M_d}{\rho} = \frac{M_p}{\rho} = \frac{M_p}{1.80}$$

$$\therefore \; M_p = M_w - M_d = V_p \cdot \rho$$

$$\therefore \; M_p = V_p \cdot 1.80$$

Using the above set of calculations, we can conclude that the mass of the propellant at any level of IV can be given by the volume of the propellant times the density of the propellant, which is a constant. And the volume of the propellant can be calculated as the volume of the external cylinder using the nominal PVC internal radius, minus, the volume of the perforation: in other words, the volume of the internal cylinder using the radius of the internal perforation of the propellant. Using all of the above steps will produce a value, in grams, of the mass of propellant. Ideally this value should be constant throughout all trials of a specific IV-level.

Applying the set of equations and derivations above to IV-Level 1; 0.3175 cm inner radius. 1.27 cm external radius, L = 13 cm.

$$V_p = \pi(1.27)^2(13) - \pi(0.3175)^2(13)$$

$$V_p = 61.755\, cm^3$$

$$\therefore \; M_p = 61.755\, cm^3 \cdot 1.80\, g/cm^3$$

$$\therefore \; M_p = 111.16\, g$$

With the knowledge available to us, we can define that for the first levels of IV the difference between the wet mass of the motor and the dry mass of the motor should be 111.16 g, meaning that the propellant mass would weigh 111.16 g which would be used for the amount of propellant needs to be cast.

Using the exact same steps as the exemplar for the first level of IV we get:

$M_p = 88.93\ g$ for the second level of IV (1.27 cm diameter)

$M_p = 51.87\ g$ for the third level of IV (1.905 cm diameter)

One observation can be made from these values, as the radius expands, the mass of the propellant decreases, which aligns with simple reasoning, as the radius expands outwards towards the casing, creating a larger volume of perforation and decreasing the overall volume of the difference between the external and internal volumes. These values will be cross-referenced later in the paper to verify the mass of propellant per level of IV.

3. Methodology and Apparatus:

3.1 Considerations of safety

Potassium Nitrate is a strong oxidizing agent and it is imperative that proper PPE and glasses are worn while dealing with the chemical[8]. Potassium Nitrate is acutely toxic, odorless and looks like a granulated white powder. When mixing the chemical with the sucrose in the blender, allow the blending vessel to air out after blending, while wearing proper protective equipment as outlined previously. The final mixture of Sucrose + Potassium Nitrate (KNSU) propellant should not be brought near a flame or any heat source. Spontaneous combustion is possible if material/propellant is handled under warm conditions, source of heat is applied, electrical current is supplied, and/or sparks are induced upon the surface of the material. Sucrose is a safe and nonhazardous chemical, but should be treated as any other chemical in a laboratory[9]. Wearing proper PPE as outlined previously with Potassium Nitrate will be standard throughout the trials.

Throughout all of the trials, the measuring apparatus will be within an enclosed polycarbonate (PC) box. The box is made out of PC sheets that are roughly 0.3-0.5" in thickness and sealed together with epoxy resin. This box is then placed into a deep fire pit, and the main motor/testing module is covered in 4 bricks to weigh the module down and help with containment in case of an explosion. The opening of the PC box, from which the gas will be expelled out of, is promptly sealed with a metal mesh and grate ensuring nozzle failures do not pose harm to the surrounding environment. This rigorous safety step reassured that any type of failure that is caused by the shearing/shattering or breaking apart of the PVC casing, will be fully contained within the box, not causing any harm to the surrounding environment. One case that must be considered is the possibility of a forward closure failure (end-cap), but due to the nature of the rocket motor, if such a failure occurs, the motor will not travel far, due to the absence of any force in one axial direction and due to the fact that the motor is in an enclosed environment which prevents any surrounding damage.

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[8] Flinn Scientific. "Potassium Nitrate SDS (Safety Data Sheet) | Flinn Scientific." *www.flinnsci.com*, www.flinnsci.com/sds_640-potassium-nitrate/sds_640/. Accessed 15 Oct. 2024.

[9] Flinn Scientific. "Sucrose SDS (Safety Data Sheet) | Flinn Scientific." www.flinnsci.com, www.flinnsci.com/sds_789-sucrose/sds_789/. Accessed 15 Oct. 2024

Several potential failure scenarios were considered:

1. Casing Failure: PVC casing are prone and have been known to shear or shatter under high pressure or heat. In such cases, the polycarbonate containment box would absorb the impact and contain debris along with the bricks and fire pit walls (the module also had a small containment chamber with around 35% infill allowing for the slowing down of PVC debris)
2. Nozzle Failure: A nozzle failure could result in uncontrolled gas burning. The metal mesh/grate at the PC box opening mitigates this risk by preventing debris from escaping.
3. Forward Closure Failure: If the end cap fails, the motor may release force unevenly but will remain contained within the enclosure due to the design and placement in a fire pit.

These measures ensured that even in word-case scenarios, no harm would come to personnel or the surrounding environment.

Both Potassium Nitrate and Sucrose should be stored in airtight containers away from heat sources and direct sunlight[8]. Storage areas should be generally dry and cool to prevent degradation. After trials, any remaining propellant or chemical residues was burned off in the fire pit and disposed of according to local hazardous waste disposal regulations.

In case of an accident, a water hose was readily available to extinguish any possible fires associated with the motor burn. By adhering to these comprehensive and strict safety protocols, risks associated with handling, creating and firing these chemicals were significantly minimized.

3.2 Variables

Variables		
Variable	Levels of Variable	Description
IV: Increase of internal diameter of KNSU solid-propellant grain.	1) 0.635cm (0.25”) 2) 1.27cm (0.5”) 3) 1.905cm (0.75”)	The internal grain diameter of the propellant will be increased to observe the change in peak thrust measured in Newtons. The increase of the diameter varies directly with the internal lateral surface area of the propellant.
DV: Peak thrust measured in Newtons.	[Dependant of IV]	The peak thrust, according to my hypothesis, will be varying directly with the increase of the grain diameter and internal lateral surface area of propellant. Will be measured using a 20 kg load cell and processed with an Arduino REV3 board.

Controlled Variables	
Controlled Variable	How is it controlled?
PVC Casing Diameter and Length	The same PVC casing and type will be used through all trials. The nominal internal diameter, as described by the manufacturer, is held constant at 1”/2.54 cm and is SCH-40. The length of the PVC segments/casings will all be 15cm.
Testing Conditions	The testing conditions will be kept within a reasonable range of temperature, atmospheric pressure, and humidity. Although variance in the testing geographic area is quite constant, all trials would have to be done within a week in the same time-frame of day, and ideally with constant conditions.
Measuring Device	The measuring device will be a custom built: thrust-measuring rig that includes a 20kg load cell, HX711 amplifier, firing relay, and a Arduino REV3 board doing most of the processing. All of these electronic components are situated inside a plastic enclosure and are connected to my laptop through a printer cable, which writes the data received at a rate of ~80 sps (samples per second) to a csv file, which is later pasted into an excel file, and interpreted from there. The measuring device will be used throughout all of the trials, and if anything is to happen to one of the electronics in the device, an exact replacement of the electronic component will be done

	to allow the measuring device to operate normally.
Nozzle Diameter and Material*	The nozzle diameter and material will be held constant throughout all trials. The nozzle diameter will be a 0.3 inch (0.762 cm) hole made out of SCH 40 PVC end-cap.
Mandrel Coating	The mandrel coating will always be the same WD-40 silicone spray (mould release), but it will vary with the different diameter per trial, as its main purpose is to create the perforation in the grain depending on the diameter of solid propellant grain selected.
Polycarbonate Enclosing	The polycarbonate shield will be held constant throughout all trials, ensuring complete safety of people and property. The polycarbonate is in a square configuration and goes on top of the measuring apparatus as seen in Fig 2.
Solid-Propellant Composition	The same ratio of KNO_3 to $C_{12}H_{22}O_{11}$, 65:35 will be held throughout all trials. This will be first measured out in grams (65g KN, 35g SU), then poured into a blender and lastly decomposed down in a pan allowing for better bonding.
Grain Length (L)	The grain length will be kept constant to the greatest degree possible at 13cm. This will ensure that the same amount of fuel is being cast into the motor. This value will further be verified through the calculations done earlier for the mass of propellant for all trials.
Forward Closure Length and Material	The forward closure will consist of the material "bentonite clay". This material has an extremely high melting point at over 1200ºC, and can be easily blended and compressed into a strong forward closure for the motor, which will be kept constant to the greatest degree possible at 2 cm. An avid amount to retain all fuel and prevent any blowout.

3.3 Materials

- ~650 g. KNO_3 (Stump Remover)
- ~350 g. $C_{12}H_{22}O_{11}$ (Powder Sucrose)
- 12x - 15 cm. x 1 in. (nominal inner diameter) Poly-vinyl chloride. SCH 40 (PVC) tubing.
- 12x - 1 in. PVC SCH-40 End-caps
- 1x - Electric blender
- 1x - Electric/Gas stove top
- 1x of each: 0.25" (0.635cm)⌀ , 0.50" (1.27cm)⌀, 0.75" (1.905cm)⌀ Aluminum rod.
- 4x - 1"⌀ Hardwood Ram Rod
- 1x - Square-Polycarbonate enclosure
- 1x - Prebuilt load cell test stand apparatus ($\pm\ 0.01\ N$)
- 1x - Lab scale
- 12x - Mixing cups
- 1x - Non-Stick Heating pan
- 1x - N95 Mask
- 1x - Box of Nitrile Gloves
- 1x - WD-40 Silicone Spray
- 1x - Ballistic rated-goggles/glasses
- 1x - Wooden spatula/spoon
- ~500 g. Bentonite Clay

3.4 Apparatus

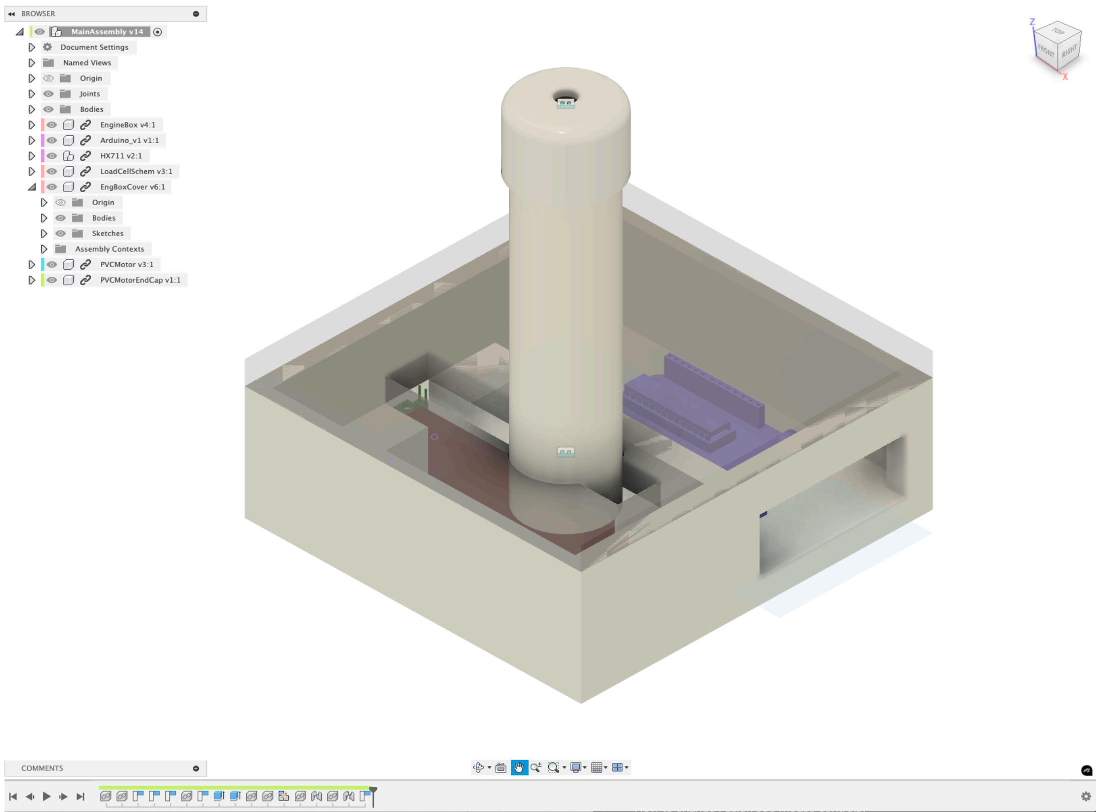
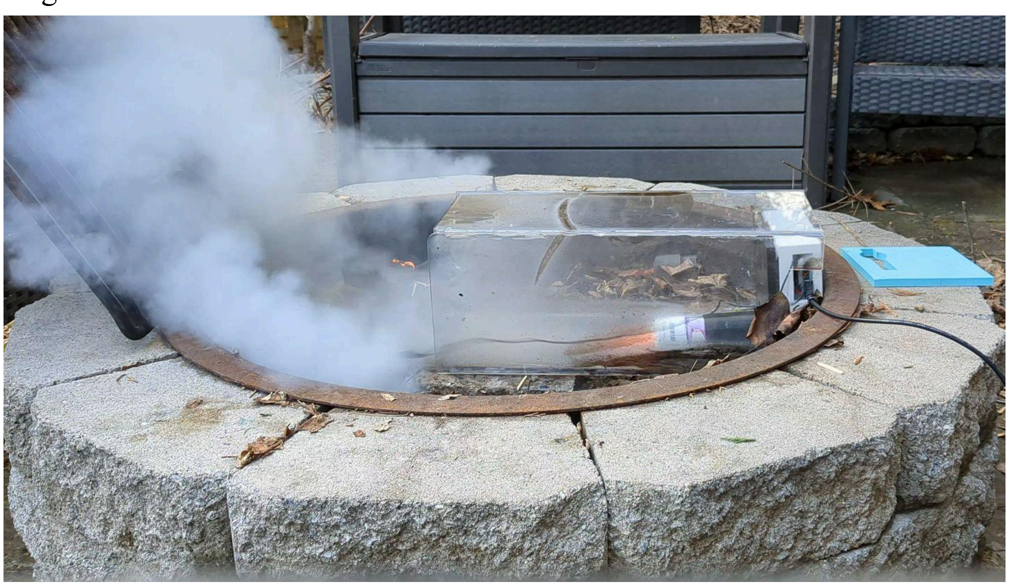


Figure 2. The fully assembled measuring apparatus in orthographic view. Modeled and assembled digitally using the software: "Fusion 360".

As seen in Fig. 2 Load cell in red, arduino microprocessing board in purple, and HX711 amplifier in green. All trials will be set in the same configuration as the assembly as seen in the figure. Note, polycarbonate shielding is not included in this assembly, but it will be a necessity during testing.



Picture 1. Above apparatus put in practice.

3.5 Method and Steps

Note: All steps were done outdoors while wearing proper PPE.

Preparation and Precautions:

1) The experiment begins by acquiring an N95 mask, nitrile gloves, and ballistic rated goggles/glasses. Before opening any containers and/or exposing to any chemicals, ensure PPE is already put on. Additionally, acquiring any and all chemicals/materials that will be needed for the casting and preparation phase of the solid-propellant is imperative for a speedy trial.
2) Next the mixing cup was placed on a lab scale and the weight tared. Continuing by pouring in Potassium Nitrate into the mixing cup until a mass of 65 grams was achieved.
3) Similarly, adding Sucrose powder to the same mixing cup until the scale reads 100 g for the 0.50" and 0.75" trial. Due to theoretical calculations, a 150 gram batch for the 0.25" trial, as per the calculations, would require 111.2 g, but continuously making sure to maintain the ratio of oxidizer to fuel.
4) Next, the mixing cup was removed with the chemicals from the scale. While at this step 50 grams of bentonite clay is measured out to use as the forward closure.

Binding of propellant and casting:

5) Next an electric blender was acquired. Carefully dumped all of the mixing cup contents into the blending vessel and began blending at a low speed constantly moving the blender around in all axes, to prevent any heating up at one spot. Wearing a mask was essential for this step: removing the vessel for mixing and letting it air out until no more fine-powder smoke was visible. Keeping the vessel upright and beside for the next steps. Repeat the steps above with the bentonite clay, except: make sure the blending speed is on HIGH, and blend for ~ 1:00.

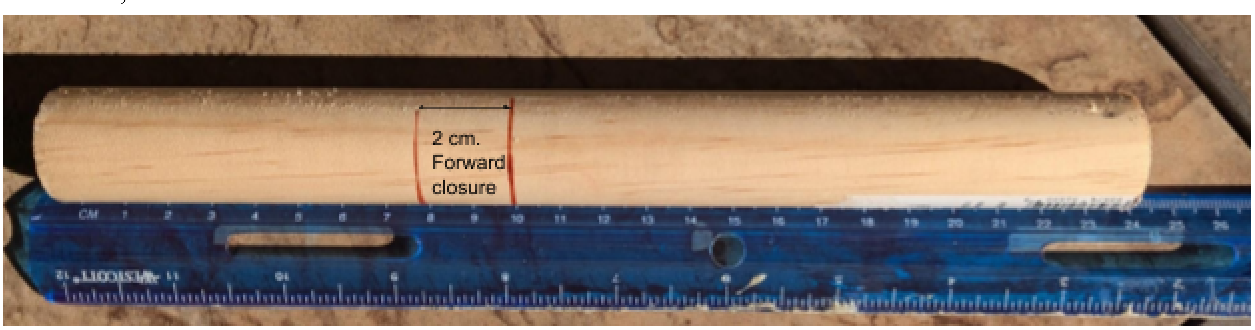


Figure 3. Hardwood ram rod used to create the forward closure.

6) Getting a wooden dowel and marking it as seen in Fig 3. Marking appropriately helps with proper forward closure sealing.
7) Next, plugging in the electric stove top and allowing for ample heating (1-2 minutes). Placing the frying pan on top of the electric stove top and allowing the frying pan to heat up slowly for 1 minute. Next, pouring all of the contents of the blending vessel into the frying pan and starting consistent mixing with a wooden spatula.

8) Consistently stir the propellant until a homogenous mixture consistency is achieved. The sucrose should be completely decomposed and bonded with the oxidizer. The color should be a light-golden-brown when the heat is turned off.
9) *These further steps were done in quick succession*. An aluminum rod with a certain diameter depending on the trial was coated with a copious amount of WD-40 silicone spray mold-release. Positioning it through the hole of the mandrel-3d-printed center-holder. Pouring the propellant into the unfilled cavity, that will be the propellant grain. Keep pouring until propellant is at the top (top edge of PVC pipe), if propellant did not flow, heating up slightly to re-enable the flowing of the propellant was ample. Allow this mixture to rest for ~5 minutes.
10) Repeating all steps depending on trial, changing the aluminum rod and 3d-printer mandrel holding diameter. It should be noted that with a 100 (65 KN: 35 SU) gram mix, the propellant in the pan will only fully cast 1 motor.

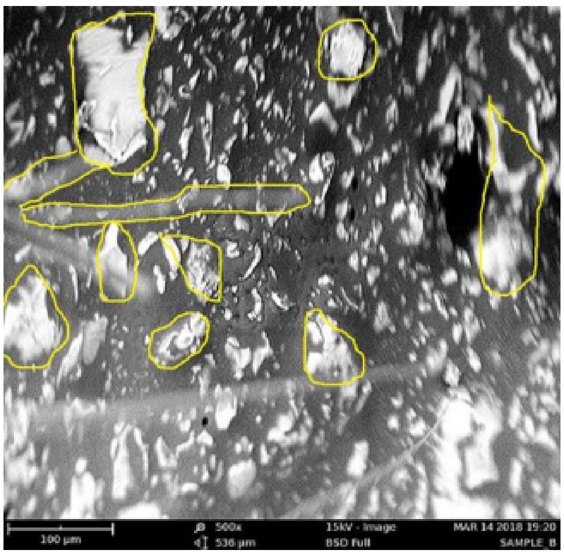


Figure 4. Melted complex of Sucrose (SU) + Potassium Nitrate (KN). (Iguniwei et al.)[10]

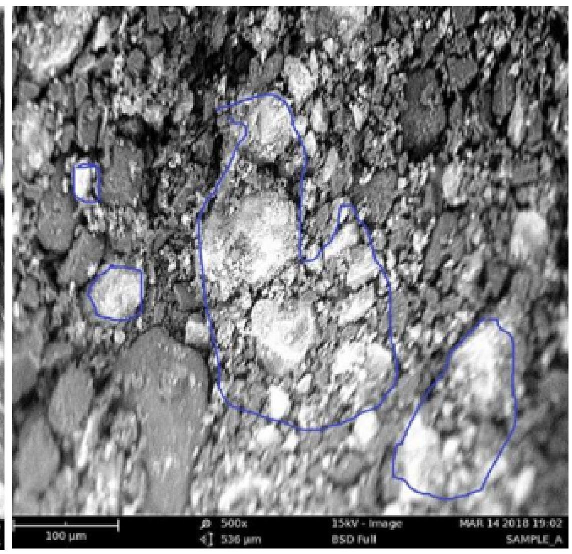


Figure 5. Dry complex of Sucrose (SU) + Potassium Nitrate (KN). (Iguniwei et al.)[10]

As seen in Figures 4 and 5. A melted complex of sucrose will significantly better bind the sucrose with the potassium nitrate. A dry complex will leave chunks of fuel or oxidizer not properly bonded together, leading to inconsistencies. Decomposing the SU and therefore binding it to the KN, allows a more even, homogenous, mixture throughout, providing more consistent burning.

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[10] Paul, Iguniwei, et al. *Scanning Electron Microscopic Analysis of a Sucrose Composite Propellant*. ijsrch.com/paper/IJSRCH18354.pdf. Accessed 17 Oct. 2024.

Testing and Data Collection:

11) With the motors ready, the assembled apparatus was prepared as seen in Figure 2. Positioning the rocket motor nozzle parallel to the horizontal would ensure mass changes in propellant would not affect readings. Prepare the firing operation by inserting the igniter through the throat of the rocket nozzle, making sure no power and electricity is being supplied to the igniter, to avoid accidental ignition.
12) Connect the arduino to the laptop and ensure all systems are nominal. Continue with covering the full apparatus including the rocket motor, with the polycarbonate enclosure. Continue with connecting the firing leads to the igniter leads, making sure you're still wearing the ballistic goggles. The system is now ready to fire.
13) By running the code now we get a 15 second timer to move away from the initiation system. Moving away at least 100 feet from the firing enclosure and elevating, ensured full safety. Everything should be done automatically and firing will be conceded without any external output after running code. After the motor has fired and the last flame is seen, wait at least 20 seconds before approaching, still wearing ballistic goggles. Begin by cutting power to the apparatus, by disconnecting the laptop from the arduino. Cleaning up all instruments to be used for next time, and allow motors to cool before trashing.
14) With the data collected in the form of a CSV file. Copy and paste into *Excel* and use the scatter plot graph option to present final data. Only include thrust data to ~2-3 seconds, to allow the thrust curve to be easily readable.

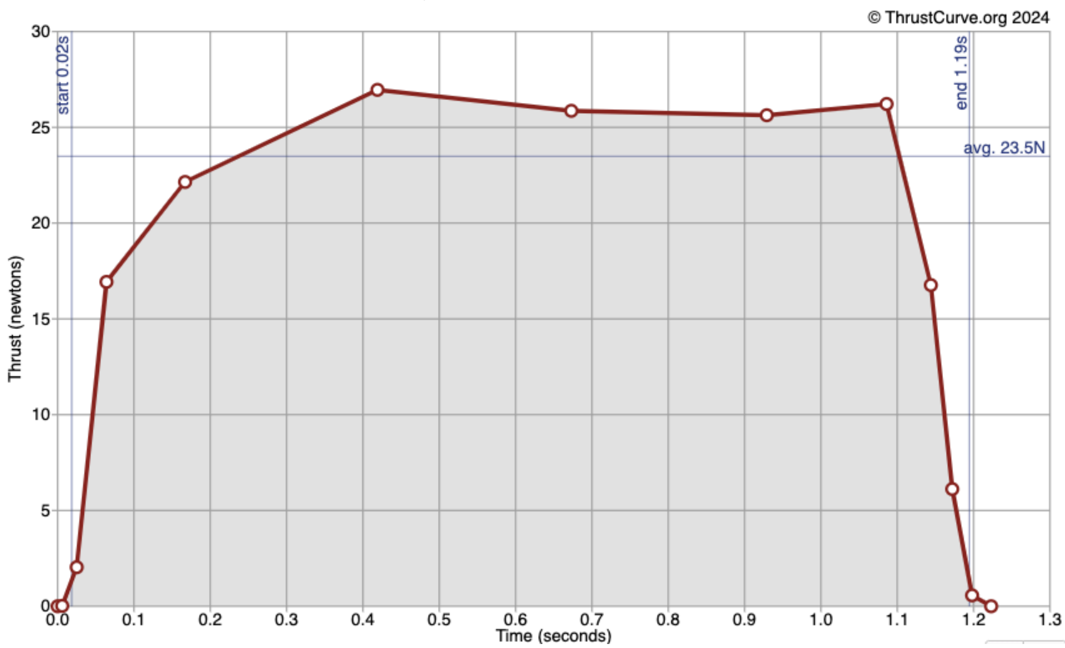

Figure 6. An example of a thrust curve from "ThrustCurve.org" of the AeroTech solid propellant motor: E26W

The specific method of data collection in the form of code can be found in APPENDIX A.

Data Collection and Results

Table 1. Data table for peak thrusts achieved throughout burn time.

IV (Perforation Dia.) ± 0.01 in.	Trials (Peak Thrust Measured, N)			
	Trial 1	Trial 2	Trial 3 (Simulated)	Average (Non-Simulated)
0.25 in.	204.53	211.04	250.51N	207.79
0.50 in.	102.68	94.39	268.75N	98.54
0.75 in.	68.30	38.51	290.84N	53.41

Table 2. Data table for total impulse achieved throughout burn time.

IV (Perforation Dia.) ± 0.01 in.	Trials (Total Impulse, N•s)			
	Trial 1	Trial 2	Trial 3 (Simulated)	Average (Non-Simulated)
0.25 in.	97.61	31.48	87.96	64.55
0.50 in.	37.18	21.98	70.63	29.58
0.75 in.	9.93	6.80	39.55	8.37

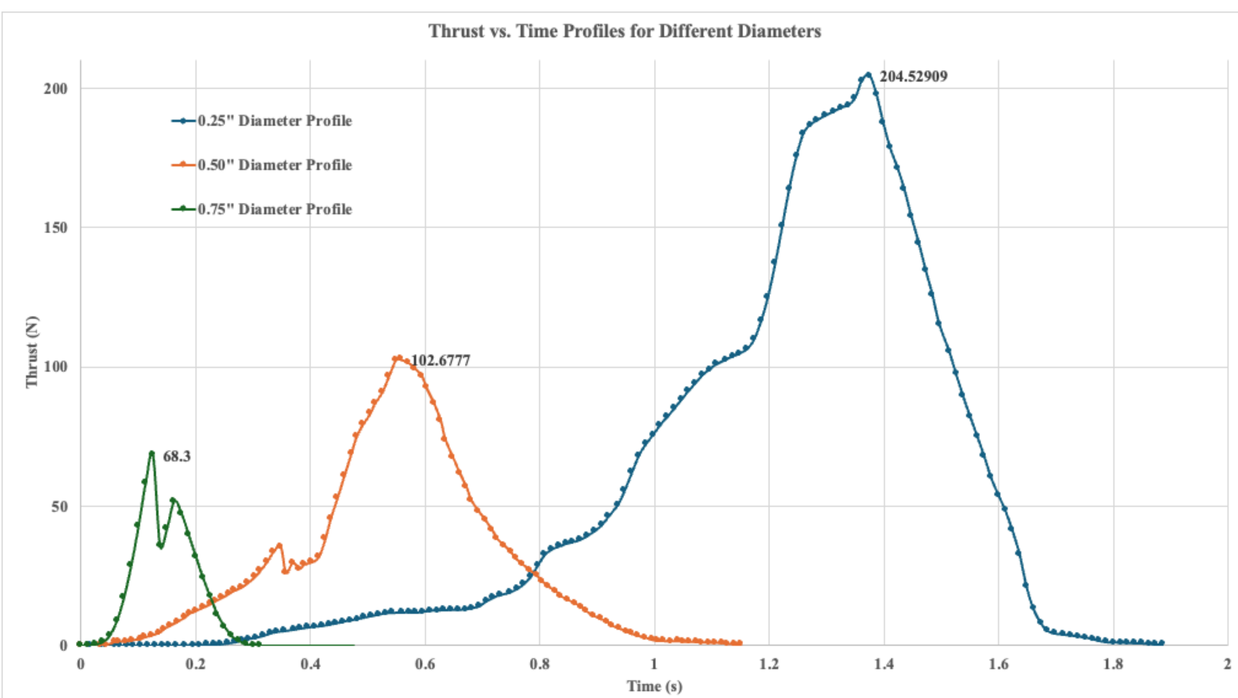

Figure 7. The graph overlays the thrust-time profiles of the trial 1 rocket motors raw-data.

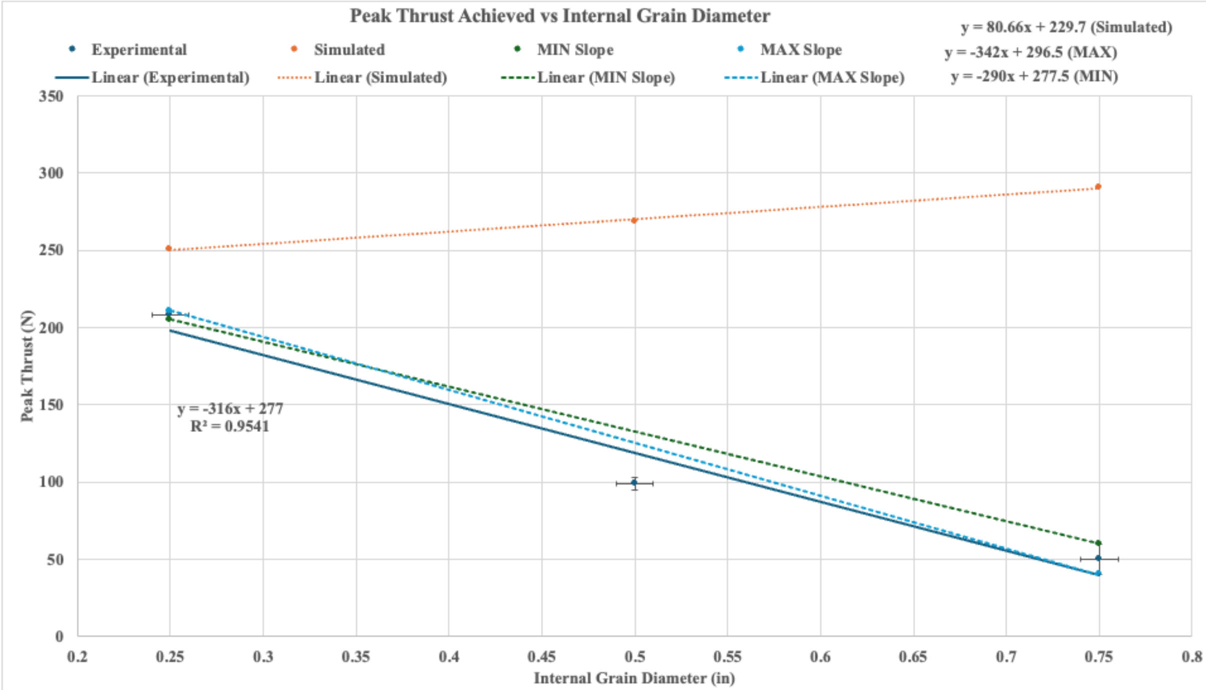

Figure 8. The graph relates peak thrust achieved vs the internal grain diameter of the rocket motor.

Calculations for Total Impulse

By summing the areas under the thrust-curve (referring to Fig. 2) for Trial 1, IV 0.25" yields:

$$\int_0^t f(t)\,dt = 7809 \text{ N}$$

Now, multiplying by time interval between measurements 0.0125 (80 sps):

$$I = 7809 * 0.0125 = 97.61\ N \bullet s$$

The result for the other calculations follows.

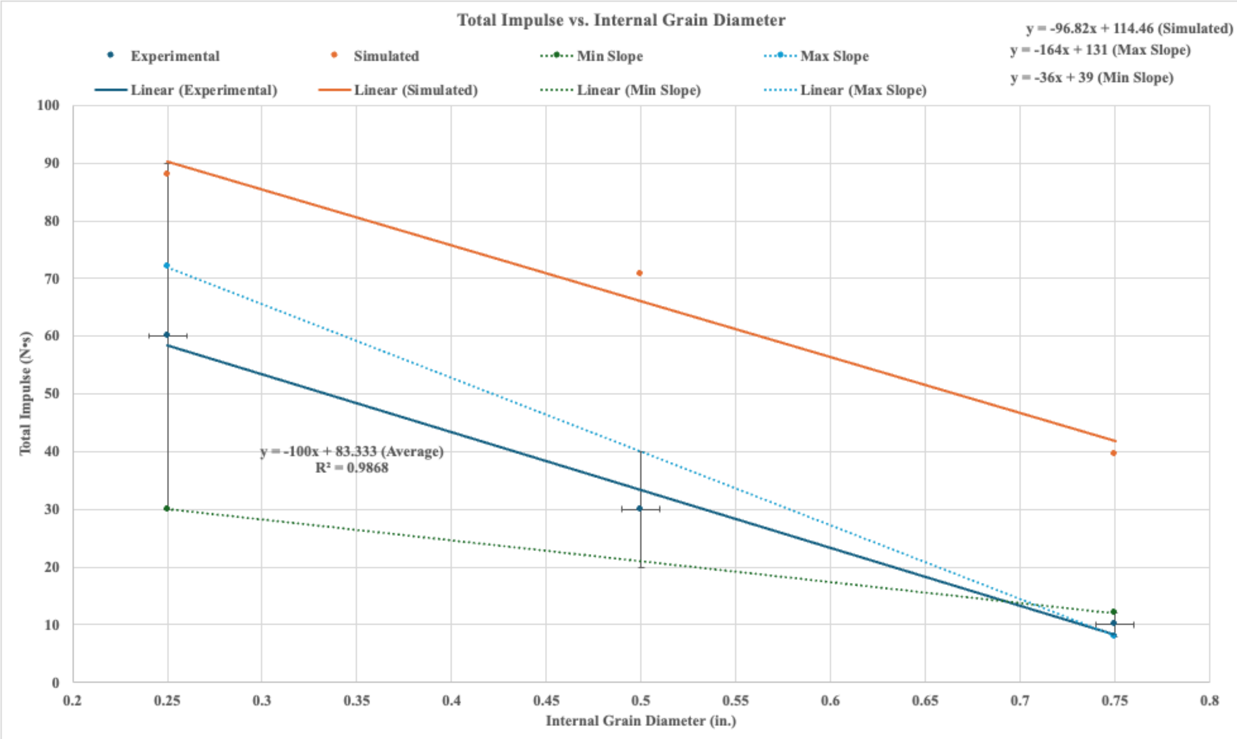

Figure 9. The graph relates total impulse vs. the internal grain diameter of the rocket motor.

4. Conclusion and Evaluation

4.1 Conclusion

This research investigated the effect of varying the internal grain diameter of a Potassium Nitrate - Sucrose solid propellant rocket motors on peak thrust measured in newtons. The experimental results consistently demonstrate that a smaller internal grain diameter yielded the greatest peak thrust compared to larger diameters. Therefore we can conclude, based on the diameters that were tested, that a 0.635 cm internal grain diameter is optimal for maximizing peak thrust and impulse.

Both graphs's uncertainty values were calculated using $\frac{(Max_{trials} - Min_{trials})}{2}$. Figure 8 had surprisingly small error bars considering the number of systematic random errors throughout the experiment. However, Figure 9 shows significantly bigger error bars signifying much different burn profiles/thrust curves.

Simulated data for both Figures was plotted with an orange line, this data was taken from *OpenMotor* as a way to compare my experimental results with the theoretical simulated ones. The percent difference in the experimental slope for peak thrust and the theoretical peak thrust cant even be calculated since the trend is oppositely correlated. The experimental slope being $-320 \pm 30 \quad N/in.$ while the theoretical slope was $80.66\ N/in.$. This shows significant differences most likely attributed to the limited capabilities of *OpenMotor* with the inability to model ambient temperature and other real-world conditions, paired with the high rate of systematic and random error in the experiment. The R^2 value, however, shows decent correlation of experimental results indicating some realized trend in the data. Figure 9 had a experimental slope of $-100 \pm 60\ N{\bullet}s{\bullet}in^{-1}$ while the simulated slope was $-97\ N{\bullet}s{\bullet}in^{-1}$. This shows slope agreement and a percent difference of $3.09\ \%$, significantly better than the previous results. The R^2 value was 0.9868, showing great correlation between data points on the graph, providing significance to the results.

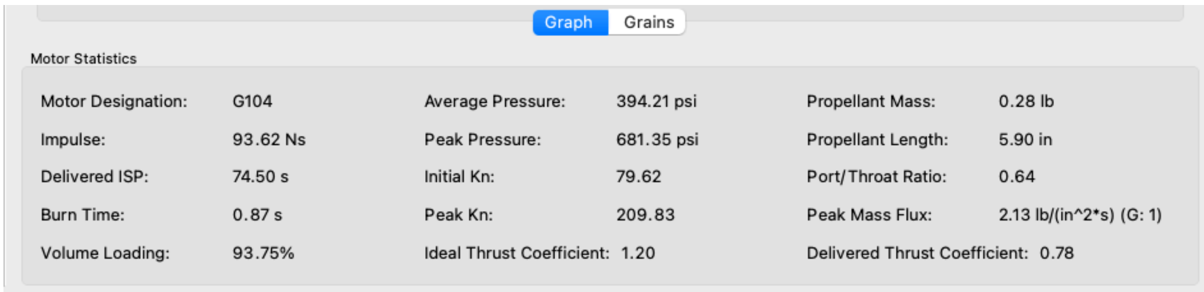

Figure 10. Example dashboard for a rocket motor simulated by OpenMotor.

To quantify the impact of different internal grain diameters on motor performance, we can calculate the specific impulse (I_{sp}). Specific impulse is a measure of how efficiently a rocket uses propellant, quantifying the thrust generated per unit weight of propellant consumed per unit time. The formula to determine specific impulse is as such: $I_{sp} = \frac{I}{W_p}$ where the specific impulse has units of $N \bullet s \bullet g^{-1}$.

IV Level 1 (0.25 in. 0.635 cm. ø), AVG Total Impulse: 64.55 N • s

$$I_{sp1} = \frac{64.55 \pm 33.07}{111.16} = 0.6 \pm 0.3\ N{\bullet}s{\bullet}g^{-1}$$

IV Level 2 (0.50 in. 1.27 cm. ø), AVG Total Impulse: 29.58 N • s

$$I_{sp2} = \frac{29.58 \pm 7.6}{88.93} = 0.33 \pm 0.09\ N{\bullet}s{\bullet}g^{-1}$$

IV Level 3 (0.75 in. 1.905 cm. ø), AVG Total Impulse: 8.37 N • s

$$I_{sp3} = \frac{8.37 \pm 1.565}{51.87} = 0.16 \pm 0.03\ N{\bullet}s{\bullet}g^{-1}$$

These numbers show a decreasing trend with increasing core/internal-grain diameter. The highest of the numbers would place the motor at around an ‘E12-4’ motor which has an I_{sp} of around $\sim 0.5\ N\ {\bullet}s{\bullet}g^{-1}$. Knowing these specific impulse values, we then can use many other formulas to find other characteristics of the burn. For example, using the $I_{sp} = \frac{v_e}{g}$, can provide the average exhaust velocity, from there the relation of thrust to exhaust velocity and mass flow rate through this identity: $F_{thrust} = v_e \bullet \dot{m}$. Using all of these values adequately characterizes the rocket motor.

4.2 Evaluation

To note, these trials were conducted under significantly colder weather than when rocket launches typically occur and such this must be considered prior to drawing any strong conclusions, as there is no effective way to alter these conditions:

"*Temperature affects the rate of chemical reactions and thus the initial temperature of the propellant grain influences the burning rate. If a particular propellant shows significant sensitivity to initial grain temperature, operation at temperature extremes will affect the time-thrust profile of the motor. This is a factor to consider for winter launches, for example, when the grain temperature may be lower than "normal" launch conditions.*"[2] (Braeunig)

Source of Error	**Type of Error**	**Effect on Data**	**Improvements**
Weighing of Reagents	Systematic and Random	Inaccurate fuel mixture ratios could lead to inconsistent burn rates and thrust values skewing results due to non-consistent formulations	Use higher calibrated scales and measuring tools. Implement multiple measurements to minimize random error.
Fuel Mixing Inconsistencies	Systematic and Random	Uneven distribution of oxidizer and fuel within the propellant grain can cause unpredictable burning and thrust profiles, leading to variability in the data.	Use a longer and more rigorous mixing procure with better equipment, longer time and better speed. Something such as ball milling to ensure better homogeneity of reagents.
Grain Casting Imperfections (Voids/Cracks)	Random	Voids and cracks increase the burning surface area erratically, leading to pressure spikes and inconsistent thrust	Use compressing methods or use a vacuum for degassing, removing air bubbles and videos during casting. Consistently control the cooling process to prevent cracking.
Nozzle Erosion	Systematic	Nozzle erosion can change the exhaust velocity and chamber pressure over the burn time, affecting the peak thrust measurements negatively.	Use more heat-resistant nozzle materials such as graphite. Consider ablative nozzle designs, and measuring the nozzle dimensions before and after each test to determine best nozzle material.
Load Cell Calibration Drift	Systematic	Load cell drift can lead to inaccurate thrust measurements over time.	Calibrate the load cell before and after each test to ensure minimal dirt and use a higher quality load

			cell with better stability.
Ambient Temperature Variations	Systematic	Temperature after the burning rate of the propellant (as stated in the beginning of the paper), influencing thrust.	Conduct experiments at a consistent outside temperature. Record the ambient temperature outside for each test and correct the data accordingly.
Hydrogrospic Properties of KNSU	Systematic	Due to KNSU's hydrogrospic properties, meaning that KNSU readily absorbs moisture from the air, the propellant burn rate will be decreased, negatively affecting results and peak thrust.	Store motors in a low-humidity environment and ensure little to no exposure to high moisture areas.
Mold Release Absorption by Propellant during Casting	Systematic	The KNSU most likely absorbed some WD-40, and while the amount used per trial was kept as consistent as possible, inaccuracies were present which would impair the burning of the propellant leaving a negative effect on the data.	Use different mold releases or use mandrel materials that do not require mold release with the propellant. Some more research on the effect of mold release could aid in the understanding of the effect on results and burn profiles.

Category	**Weaknesses**	**Future Improvements**
Propellant Composition	KNSU Propellant is highly sensitive to manufacturing inconsistencies and environmental conditions.	Experiment with other fuels such as Ammonium Perchlorate based fuel.
Motor Casing	PVC casing is extremely dangerous and may deform or fail under high pressure and temperature.	Use stronger casing materials such as aluminum or composite materials, and cast in grain batches.
Nozzle Design	Simple convergent nozzle design may not be optimal for thrust efficiency.	Optimize the nozzle geometry using CFD simulations and design in CAD, to later machines using CNC.
Data Acquisition	Limited data on chamber pressure and burn rate	Integrate pressure transducers into the motor to measure chamber pressure in real-time, in tandem with the use of the revised motor casing to get further information on burn characteristics.
Number of Trials	Number of trials done was quite underwhelming making it hard to draw conclusions, especially with the intermediary diameters	Allocate more time and test at least 5 levels of IV with 5 trials per level, using intermediary diameters to create and reinforce a more consistent trend.

4.3 Future Improvements and Next Steps

There are many things could be considered for future attempts of this experimentation, firstly being the ability to create larger range of sizes of core diameters including the extremes and the intermediate diameters that were not done in this experiment, this could provide even more insight, and be compared to theoretical and computational results. On the other hand a different approach to an experiment can be made in the form of differing grain geometry in the form of star-shaped and moon-burner grains, another can be in the form of nozzle characteristics and see how that may affect the performance of a solid-propellant motor. There were other aspects of this research that could be continued like measuring the K_n value to get the full performance characteristics, but time was limited.

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APPENDIX A

LoadCellPlotter.ino - Used for the main data collection and communication with the arduino module and the laptop.

```
C/C++
#include "HX711.h"

HX711 scale;

uint8_t dataPin = 3;
uint8_t clockPin = 2;
int relay = 7;
//bool firesent = false;

void setup() {
  pinMode(relay, OUTPUT);
  digitalWrite(relay, LOW);


  Serial.begin(115200);

  scale.begin(dataPin, clockPin);
  scale.set_scale(100.319198);  // Calibrate this value for your setup
  scale.tare();


  digitalWrite(relay, HIGH);
  delay(600);  // Keep firing relay on for 500 ms
  digitalWrite(relay, LOW);
}

void loop() {

  float weight = scale.get_units();
  if (abs(weight) > 0.8) {               // Adjust this threshold as needed
    weight = (weight / 1000) * 9.80665;  // Converting grams to Newtons
    Serial.println(weight, 5);
  } else {
    Serial.println(0.00000, 5);
  }

  // No delay here to allow for rapid measurements
}
```

LoadCellCalibration.ino - Used for calibration of the load cell prior to any firings.

```
C/C++
//
//    FILE: HX_calibration.ino
//  AUTHOR: Rob Tillaart
// PURPOSE: HX711 demo
//     URL: https://github.com/RobTillaart/HX711


#include "HX711.h"

HX711 myScale;

uint8_t dataPin = 3;
uint8_t clockPin = 2;

uint32_t start, stop;
volatile float f;


void setup() {
  Serial.begin(115200);
  Serial.println(__FILE__);
  Serial.print("LIBRARY VERSION: ");
  Serial.println(HX711_LIB_VERSION);
  Serial.println();

  myScale.begin(dataPin, clockPin);
}

void loop() {
  calibrate();
}



void calibrate() {
  Serial.println("\n\nCALIBRATION\n===========");
  Serial.println("remove all weight from the loadcell");
  //  flush Serial input
  while (Serial.available()) Serial.read();

  Serial.println("and press enter\n");
  while (Serial.available() == 0)
    ;

  Serial.println("Determine zero weight offset");
  myScale.tare(20);  // average 20 measurements.
```

```
  uint32_t offset = myScale.get_offset();

  Serial.print("OFFSET: ");
  Serial.println(offset);
  Serial.println();


  Serial.println("place a weight on the loadcell");
  //  flush Serial input
  while (Serial.available()) Serial.read();

  Serial.println("enter the weight in (whole) grams and press enter");
  uint32_t weight = 0;
  while (Serial.peek() != '\n') {
    if (Serial.available()) {
      char ch = Serial.read();
      if (isdigit(ch)) {
        weight *= 10;
        weight = weight + (ch - '0');
      }
    }
  }
  Serial.print("WEIGHT: ");
  Serial.println(weight);
  myScale.calibrate_scale(weight, 20);
  float scale = myScale.get_scale();

  Serial.print("SCALE:  ");
  Serial.println(scale, 6);

  Serial.print("\nuse scale.set_offset(");
  Serial.print(offset);
  Serial.print("); and scale.set_scale(");
  Serial.print(scale, 6);
  Serial.print(");\n");
  Serial.println("in the setup of your project");

  Serial.println("\n\n");
}


//  -- END OF FILE --
```

LoadCSVLogger.py - Used for final raw data collection and provides CSV file. Communicates through serial port with the arduino.

Python

```
import serial
import csv
import time
from datetime import datetime
from time import sleep
#from CountdownTester import loading_bar
import glob

#scanning for usb modem ports on laptop'''


ports = glob.glob("/dev/cu.*")
for port in ports:
    if "/dev/cu.usbmodem" in port:
        res = True
        SERIAL_PORT = port
        print(port.replace("/dev/cu.", ""))
    else:
        res = False

BAUD_RATE = 115200  # Make sure this matches your Arduino's baud rate

# CSV file configuration
CSV_FILENAME = f"load_cell_data_{datetime.now().strftime('%Y%m%d_%H%M%S')}.csv"

grain_dia = "What is the internal grain dia.?"
cont = input("Are you ready to start y/n?")
if cont == "n":
    exit()


def countdown_func():
    seconds = 15
    while seconds > 0:
        sleep(1)
        print(f"Starting data recording in {seconds} seconds")
        seconds -= 1
    print("Data recording has started: ")


def main():
    #record both time and thrust as a return for the main function
    thrust = []
    time = []

    try:
```

```
        # Open serial port
        with serial.Serial(SERIAL_PORT, BAUD_RATE, timeout=1) as ser:
            print(f"Connected to {SERIAL_PORT}")

            # Open CSV file
            with open(CSV_FILENAME, 'w', newline='') as csvfile:
                csv_writer = csv.writer(csvfile)
                csv_writer.writerow(['Time (s)', 'Thrust'])  # Write header

                print(f"Saving data to {CSV_FILENAME}")
                print("Press Ctrl+C to stop...")

                ser.write(b"S")
                print("Start signal sent to Arduino")

                start_time = time.time()  # Record the start time

                while True:
                    # Read a line from the serial port
                    line = ser.readline().decode('utf-8').strip()

                    if line:
                        current_time = time.time()
                        elapsed_time = current_time - start_time - 2.242


                        weight = float(line)

                        thrust.append(weight)
                        time.append(elapsed_time)

                        # Write to CSV
                        csv_writer.writerow([f"{elapsed_time:.3f}", weight])

                        # Print to console
                        print(f"{elapsed_time:.3f}: {weight}")

    except serial.SerialException as e:
        print(f"Error opening serial port: {e}")
    except KeyboardInterrupt:
        print("\nData collection stopped by user.")
    except Exception as e:
        print(f"An error occurred: {e}")

    results = [thrust, time]
    return results

if __name__ == "__main__":
```

```
countdown_func()
main()
print(CSV_FILENAME)
print("done")
print(main())
```

This code was the main function of collecting data but a more exhaustive list of the small things can be found in the following github repository: https://github.com/evankroz/RTEM.