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Potassium Nitrate Based Rocket Propulsion

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Abstract:

We built and tested rocket engines, varying the ratios of two main parts of the propellant – the fuel and the oxidizer. The oxidizer used was Potassium Nitrate, and the fuel was Sorbitol. We aimed to determine how changing the ratios of the Potassium Nitrate to Sorbitol in rocket propellant affect engine performance. The engines were made completely from scratch, with PVC casings, handmade propellant, and concrete-based nozzles. The experiments were carried out via tests in which the rocket engine was mounted nozzle-end-up in a test stand, so that when the engine was ignited it pressed down against a force plate, used to produce a graph of thrust versus time. At the same time, strain gauges and temperature sensors were placed along the rocket casing body to measure chamber stress, case stress, and case temperature.

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Introduction

Research Question:

Does changing the ratios of the components of potassium nitrate-based rocket propellant impact the thrust, case stress, case temperature, burn time and internal pressure of a rocket engine during ignition?

Hypothesis:

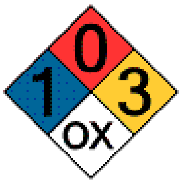
Changing these ratios will affect thrust, case stress, case temperature, and internal pressure.
In particular:

- The ratio of Potassium Nitrate to Sorbitol that yields the most products is 2:1. Since the 2:1 ratio produces the most products, we predict that this ratio also produces the greatest nozzle exhaust velocity, case temperature, case stress, and internal pressure.
- Having a large imbalance in the ratio of propellant components will decrease the burn rate because the chemical reaction will differ from the 2:1 ratio reaction.
- As the ratio between the two reactants becomes larger and larger, we predict that burn rate continues to decrease further and further. We also believe that there is a point at which the engine produces only minimal thrust/does not ignite at all.

Literature Review:

The following is the chemical equation for the combustion of Potassium Nitrate and Sorbitol.

$$5O_2 + 4KNO_3 + 2C_6H_4O_6 \rightarrow 12CO_2 + 4H_2O + 2N_2 + 2K_2CO_3$$



Potassium nitrate has a low health rating and is not flammable at all. It has a rating of three in instability but that is to be expected since we want it to be explosive to be able to propel our engines. It will be contained in small quantities to minimize the effects of a rare explosion.

Potassium carbonate is released by the combustion reaction and is neither flammable nor explosive. It has a rating of two for health but since it is hygroscopic, it absorbs water soon after it is created and is therefore diluted. All of the other chemicals have ratings of zero in every category.

The safest, cheapest, most reliable, and easiest to apply system of propulsion is the one in which only solid fuels are used. In particular, the nitrate based propellant is very popular. When preparing a nitrate-based fuel, the components must be dissolved to ensure thorough mixing and a uniform texture throughout the fuel. One of the most efficient nitrate-based propellants is a mixture of potassium nitrate and sugar, commonly referred to as "Rocket Candy." This fuel is commonly used by amateurs.

Our rocket engines are comparable to commercial model rocket engines. They are between F-class and I-class engines, no larger. The F, G, H, and I class engines are defined as having a total impulse anywhere from 40.01N·s to 640.00N·s. Impulse is the integral of the rocket’s thrust over time. (Nakka 2007) **(Figure 1)**

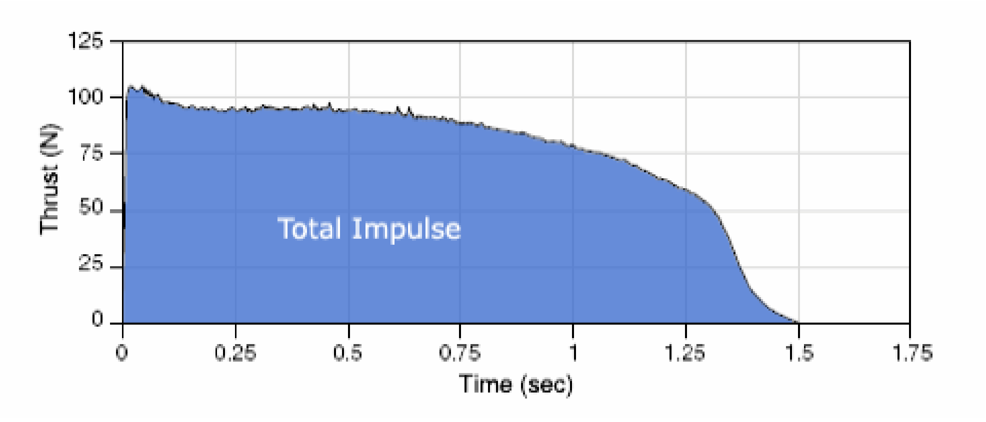


Figure 1 – A “G” Class rocket engine’s thrust/time curve. http://thrustcurve.org/enginestats.shtml

Impulse is a classification technique which is applied to rocketry, being the most important indicator of a rocket’s performance. Specific impulse is the thrust-seconds (impulse) per unit of propellant; it is measured in seconds. Impulse is defined as the integral of a force (in this case, thrust) with respect to time, and is measured in Newton-seconds.

$$\mathbf{I} = \int \mathbf{F}\, dt$$

Using the impulse-momentum theorem, this simplifies to:

$$\mathbf{I} = \int \frac{d\mathbf{p}}{dt}\, dt$$

$$\mathbf{I} = \int d\mathbf{p}$$

$$\mathbf{I} = \mathbf{F}\Delta t = \Delta\ p$$

Where: **I** is impulse,
F is force,
t is time,
m is mass,
v is velocity,
and **p** is momentum. (Sutton 28)

Using a known value for impulse, Specific Impulse is:

$$\mathbf{I}_{sp} = \frac{\mathbf{v_e}}{\mathbf{g}_0}$$

Where:
$\mathbf{v_e}$ is the exhaust velocity at the nozzle exit (m/s)
g_o is gravitational acceleration at sea level on Earth (9.807 m/s^2)
(Tajmar 8)

Thrust is defined as the flow rate of the exhaust gas multiplied by the effective velocity of gases coming out of the nozzle, or:

$$\begin{aligned} F &= \dot{m}\,V_e + (P_e - P_o)\,A_e \\ &= \dot{m}\left[V_e + \left(\frac{P_e - P_o}{\dot{m}}\right)A_e\right] \\ &= \dot{m}\,V_{eq} \end{aligned}$$

Where:
F is the gross rocket engine thrust (N)
$\dot{m}$ is the mass flow rate of the exhaust (kg/s)
V_e is the exhaust velocity at the nozzle exit (m/s)
P_e is the exhaust pressure at the nozzle exit (Pa)
P_o is the external ambient pressure (Pa)
A_e is the cross-sectional area of the nozzle exit (m^2)
V_{eq} is the effective exhaust gas velocity at the nozzle exit (m/s)
I_{sp} is the specific impulse (s)
g_o is gravitational acceleration at sea level on Earth (9.807 m/s^2)

Thrust is measured in Newtons, and tells us how many Newtons of pushing power are being exerted by a rocket's exhaust. An interesting thing to note about the above equation is that it takes into account the difference between pressure of the gases exiting the nozzle and the ambient pressure, which fits with the information given by **Figure 3**. (Turcotte 5) (Sutton 63) (Nakka 2007)

Taking a rocket similar to ours into consideration, we can set:

$\dot{m}$: .0304 kg/s
V_e: 2999 m/s
P_e: 3.695×10^6 Pa
P_o: 1.013×10^5 Pa
A_e: 1.27×10^{-4} m^2

Thus, theoretically, F = 547.6 N. The values above have been experimentally produced by Richard Nakka.

Materials and Methods

Method: Preparing the rocket

The following instructions are for making the equivalent to a commercially-produced 'G' size engine. Only the instructions on preparing the propellant are included in detail, since that is the only hazardous part of the entire process.

The engine casing was made from a 8-1/4" long 1" Schedule 40 PVC pipe. One end was covered with an end cap, with the nozzle fixture inside of it.

The length and width of the PVC pipe were chosen specifically because the diameter of 1" is small enough to be safe, but still large enough to work with. If we were to halve the amount of propellant used by the engine, we would have two options. The first would be to decrease the diameter of the PVC pipe so as to maintain the length of the grain. This would make building the engine extremely hard, not only because of the fact that everything is so much smaller, but because of parts availability issues, such as finding the correct size washers. Another option would be to keep the same width, but use a much shorter PVC pipe. This would dramatically decrease burn time and thrust, meaning that any errors in any of the measuring equipment will be amplified greatly. Approximately 150 grams of propellant will be used inside of one engine.

We used 120 grit sandpaper to rough the inside surface at one end of the PVC pipe to a depth of about 1-1/2". We painted this surface with latex house paint and allow it to dry over night. This paint served the function of a primer so that the cement used for the nozzle adhered better to the PVC plastic.

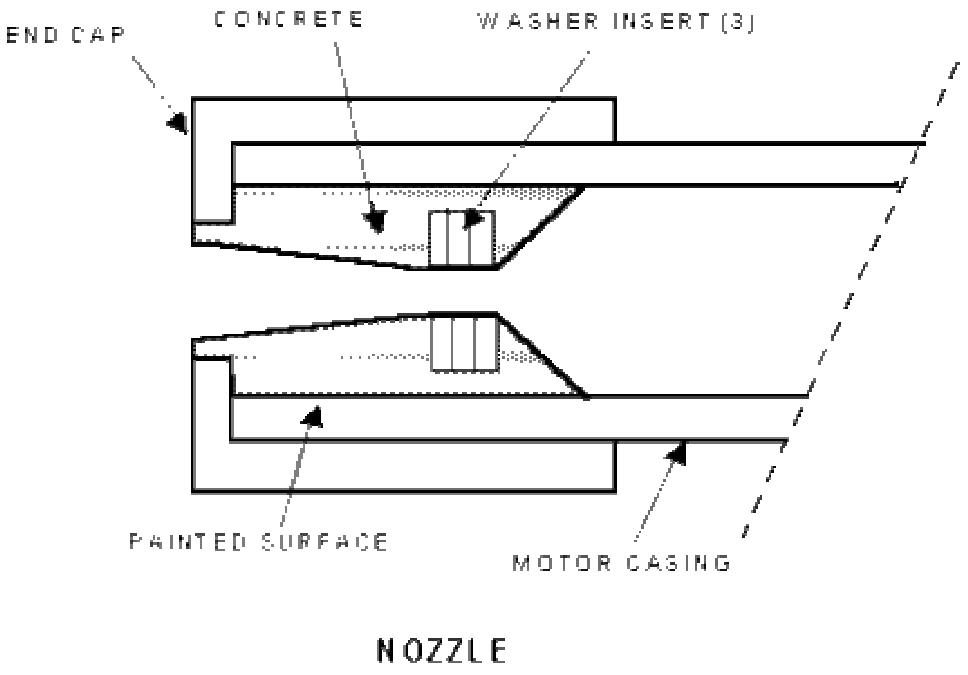


Figure 2 – http://nakka-rocketry.net/pvcmot5.html

After this, we drilled a 1/8" starter hole into the center of an end cap with a drill press to ensure the drill bit stays centered. Then, we used a 3/4" Speedbor drill bit to make a larger hole in the end cap while using the starter hole as a guide. This is the process of making the end cap **(Figure 2)**.

The nozzle is a convergent-divergent de Laval nozzle cast inside of the engine casing and held into position by a PVC end cap. A hole was drilled through this entire fixture to form the opening for the nozzle.

Cement was used to make the de Laval nozzle. The bushing served as a mold for the cement to be poured around. It was be taken out as the cement began to dry. The washers helped guide us when we were drilling the nozzle hole, and to help prevent too much erosion on the nozzle while the engine was burning. Figure 4 demonstrates the entire nozzle assembly.

Directions for making the propellant:

1. Ensure that the sorbitol and KNO_3 are grounded to fine powders. Put them into a container and shake them.
2. Use a double pan arrangement to melt the KNO_3 and sorbitol, with canning wax used in the bottom pan as the heat transfer medium. The reason for this is that wax does not change temperature too easily, thus eliminating a quick spike in temperature which could ignite the propellant. Throughout the melting process, the wax will remain steady at 250°F. The mixture is stirred with a wooden dowel until it is completely molten and has a homogeneous consistency.
3. The molten mixture will be transferred to a casting stand made from PVC identical to that of the

actual engine casing and lined with paper. Within this stand, the propellant will cool and form a solid block that we can then transfer into the actual engine.

4. Transfer the molten mixture to the casting stand by first actually pouring it into the casting stand straight from the pan, and then by ladling the rest in using a flexible spatula.
5. After all of the propellant has been ladled into the casting stand, push a metal rod through the center of the molten propellant to form the core of the grain. This is basically a spindle hole in the propellant which allows for a large amount of propellant surface area burning at once.
6. The coring rod cannot be removed while the propellant is still very viscous because the spindle that it creates would get filled up again. If the propellant is only partially viscous when the coring rod is removed, then a lot of the propellant will be pulled up with the coring rod, since the propellant has a tendency to dry from the inside out. If an attempt is made to remove the coring rod after the propellant has dried, it will be completely impossible to remove, unless the coring rod has been previously lubricated. The best lubrication to use is cooking spray, and the best removal method is by putting the protruding coring rod in a vice and gently twisting the hardened propellant off.

The grain was cast separately from the pipe containing the nozzle so that it could be loaded into this pipe with a paper sleeve surrounding it. This allowed exhaust gasses to surround the grain and distribute pressure throughout the entire grain equally. However, the outside of the grain was not allowed to burn since it was surrounded by a sleeve.

The propellant is hygroscopic, and thus was either used within around two days or put in a desiccator grain storage case.

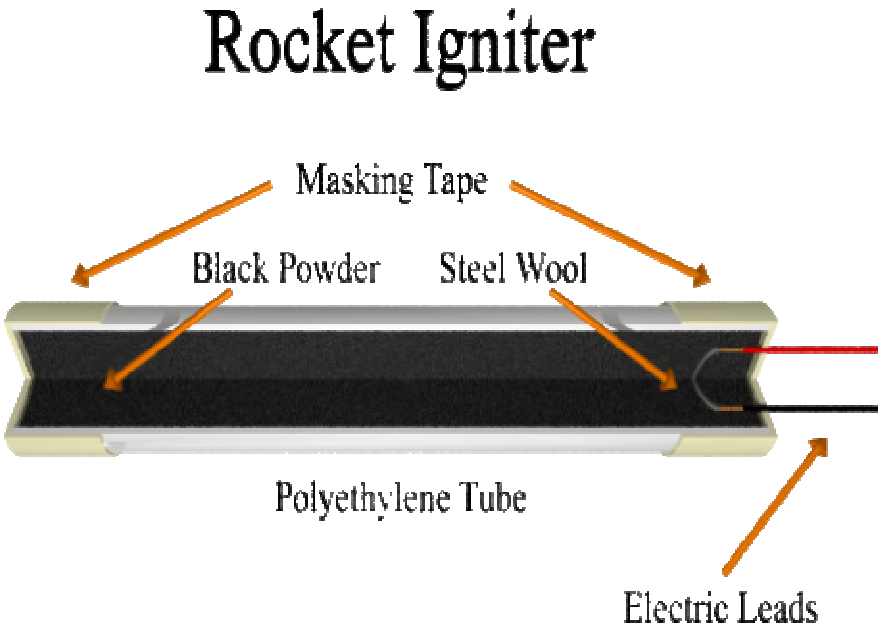


Figure 3: Rocket Ignition Device

Figure 3 shows our ignition device. The entire device is made inside a small length of straw which is pushed past the nozzle and into the vicinity of the propellant. The electric leads are connected to a lantern battery. The ‘polyethylene tube’ is a cut length of straw. It is filled almost completely with black powder, which is 80% organic charcoal and 20% potassium nitrate by weight. At either end it is sealed with masking tape. A thin wire of wound together steel wool is made and poked through the upper end of the straw using a paper clip. When current is passed through these leads, the wool will become red-hot, hot enough to ignite the black powder. The black powder ignites very quickly, and the straw bursts, causing a large flame and buildup of pressure near the propellant. The combination of pressure and heat ignites all of the exposed surface area of propellant almost instantly, allowing the nozzle to assume a choked state quicker. (Steeler 456) (Nakka 2007)

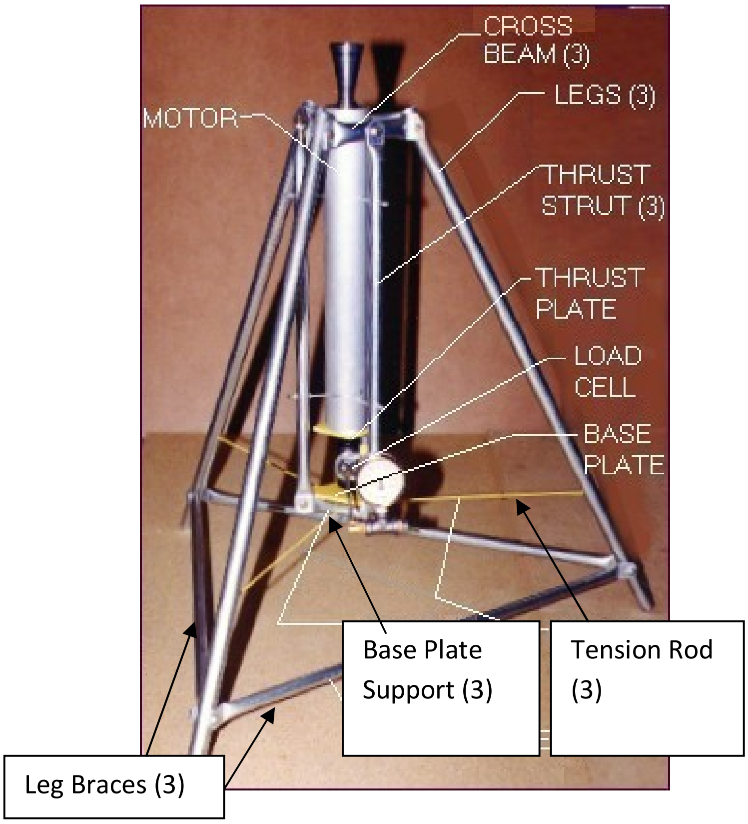


Figure 4 - http://www.nakka-rocketry.net/sts5000f.html

A test stand **(Figure 4)** was also used. The design was tested to withstand an excess of 5000 Newtons. (Nakka 2007) It was made of Electrical Metallic Tubing. A slight modification of the design allowed us to use the force plate instead of the hydraulic load cell pictured. As the engine fired, it pressed downwards on the *base plate* which was connected to the *cross beams* and *legs* by the three *thrust struts*. A slight modification allowed us to use the force plate instead of the hydraulic load cell. The design was modified to use a combination of extrusion and conduit hangers to secure the engine’s PVC casing to the test stand. (Pollino 44

METHOD: Sensors

- Temperature is measured using a thermocouple connected to a Labpro interface. A thermocouple uses the Seebeck effect to measure temperature. The Seebeck effect states that a conductor will produce a voltage when exposed to a thermal gradient. Our thermocouple has an accuracy of ±5°C in the range of 0°C to 900°C, our expected operating temperature. (Moyer 2003)

- Force is measured by using a Vernier Force Plate connected to a Labpro interface. The force plate has a strain gauge within it. When force is applied, the strain gauge becomes deformed. The resulting resistance change is translated into force by factory calibration. Thus, force is converted into an electrical signal.

METHOD: Set Up

The different scenarios will be carried out via static tests in which the rocket engine is mounted nozzle end up in a test stand, so that when the engine is ignited it presses down and does not fly into the air. **Figures 6, 7, and 8** give details about this set up.

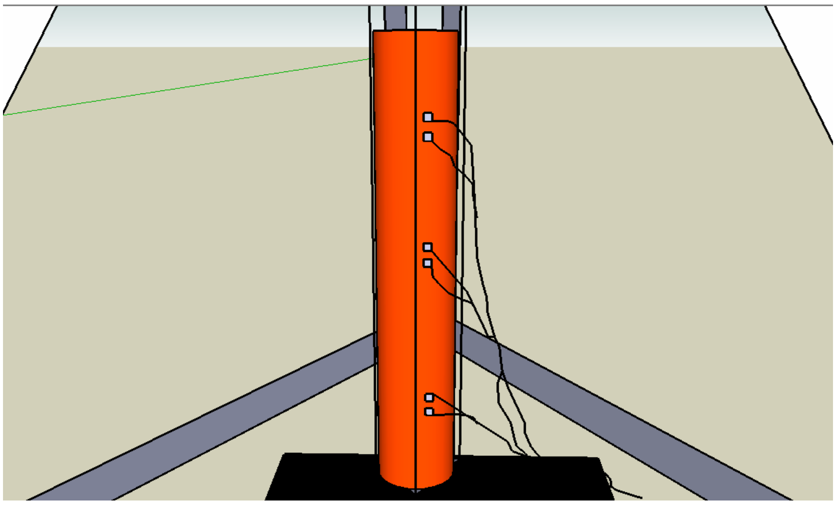


Figure 6: Temperature and stress sensors at intervals along the outer casing of the engine (orange) and a force plate beneath the rocket (black) to measure force.

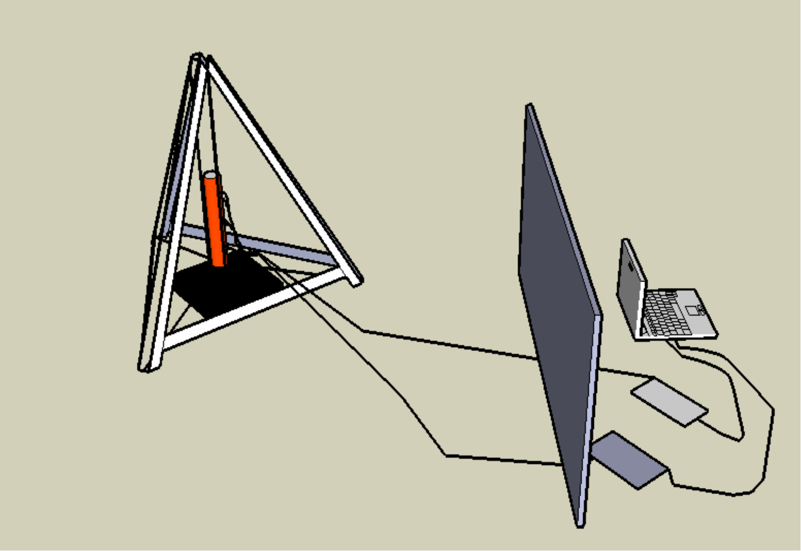


Figure 7: A laptop collecting data from the sensors via Labpro and a protection shield to protect the laptop from debris from a potential rocket failure.

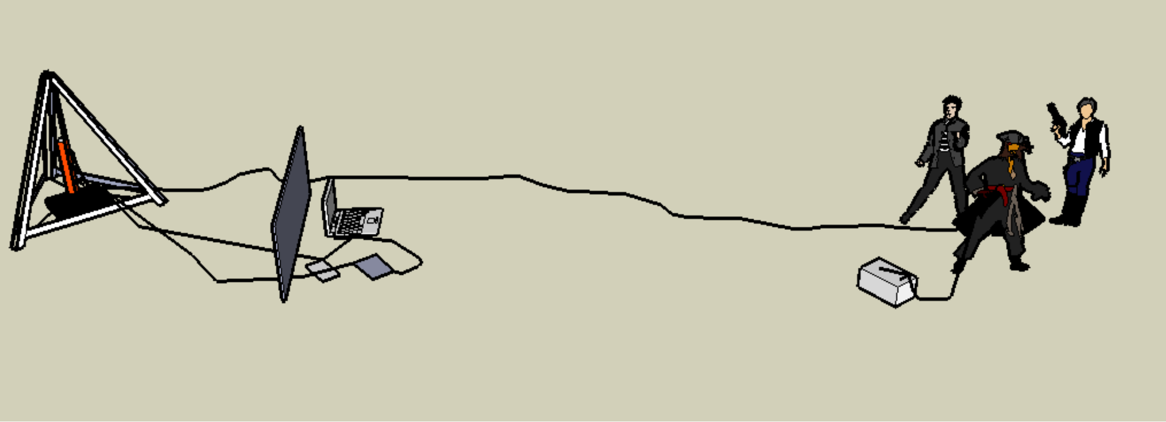


Figure 8: A distance of at least thirty feet between the experimenters and the rocket is shown, as is the ignition device.

METHODS: Testing the rocket engine:

- Ensure that the area in which the test is to be performed is free of obstructions and unwary people. The best area on NCSSM's campus seems to be one of the athletic fields.
- Transfer the force plate, thermocouple, computer, and barrier, and camera to the testing site.
- Ensure that everything is set up and completely ready minus the engine.
- Test the force plate and the computer equipment to ensure that it is working properly.
- Transfer the finished engine from its storage place to its testing place on the force plate, using all safety precautions necessary such as not exposing it to open flame. Zero the force plate after the engine has been placed on the stand. Attach the thermocouple to the engine casing using duct tape.

- Attach the wires from the ignition device to the engine while wearing safety equipment (but do not connect any power source to it yet).
- Slowly back away from the test stand to the shielded user interface, taking care not to trip on any wires.
- Begin recording with the camera and with the force plate's computer interface.
- Connect the battery so as to pass current through the igniter. The engine will soon begin burning. Let it burn until there is no visual flame, smoke, or any other kind of particle exiting the engine. As a secondary precaution, ensure that there is no thrust being recorded by the force plate.
- Record any purely visual observations that deviated from the expected burn characteristics. (Did we notice an uneven burn? Was there a particular color to the exhaust gases that we did not predict?).
- Detach the power source from the ignition mechanism.
- Record any observations of damage done to any part of the test stand.
- Retrieve the rocket from the test stand.
- Clean any soot and deposits from the test stand, pack up all of the equipment, and return it to its proper location.
- Analyze the data collected by the computer and the data collected by the video camera.

UNCERTAINTIES:

- Potential Errors:
    - Proportions of the components in the propellant could be skewed
    - Setting the nozzle
    - Calibration errors in the electronic measuring equipment
    - Uneven distribution of propellant in the rocket engine

Results, Discussion, and Conclusions

Until this point, most of our efforts have been focused on perfecting methods of building various parts of the rocket engine and testing apparatus. This included successfully constructing a concrete-based nozzle, gaining a familiarity with working with the propellant that we are using, creating a working ignition system, gathering and calibrating the sensors, and successfully creating 'G' class rocket engines.

So far, we have manufactured multiple propellant grains. In the beginning, there were usually errors in their making (i.e. the coring rod could not be removed or the grain could not be removed from the casting stand) and they could not be used for actual data collecting purposes. Several weeks ago, we solved the problem with the coring rod, as outlined in step 6 in the instructions for using a coring rod to make a core.

Our first engine test was one of a grain without the core produced by a coring rod. Not using a coring rod decreases the amount of surface area which could burn at any given moment. (Sleeter 292) This has the effect of increasing burn time. This grain had a burn time of around two minutes and the maximum thrust was only approximately 2N. We also noticed that the PVC engine casing had very pronounced deformations, which we hypothesized was a result of the long burn time. We predicted that building an engine with a core will increase the burning surface area, thus increasing thrust and decreasing the burn time. In addition, we predicted that a shorter burn time would mean that the PVC would be exposed to the high combustion temperatures for a shorter period of time, possibly helping it keep its integrity throughout the duration of the burn.

Several weeks ago, building a grain with a core was made possible by using cooking spray to lubricate the coring rod, so that it would not get stuck in the engine after the propellant had hardened. Once we managed to do this, we tested it and collected force plate and thermocouple data during the test, which is shown in **Figure 9**. The thermocouple was attached to the outside of the casing. The data, shown in the top graph of **Figure 9**, shows that the PVC itself did not begin to get significantly heated to the point that it could deform until the main reaction had died off, showing that PVC does not conduct heat very well. This is evidence supporting the notion that PVC is a very good engine casing for short burn duration engines. The differences between this test and the last one, without the core, are as follows: the duration of the burn was much less, being under a minute, the amount of deformation of the PVC pipe was similarly less, and there was an unprecedented spike in pressure when the rocket reached its full thrust at around 40 seconds after data collection began. This spike in pressure never occurred in any earlier tests, which demonstrates that the increased burning surface area has a lot to do with pressurizing the reaction chamber enough such that the exhaust gases reach the velocity at which the nozzle reaches its choked state.

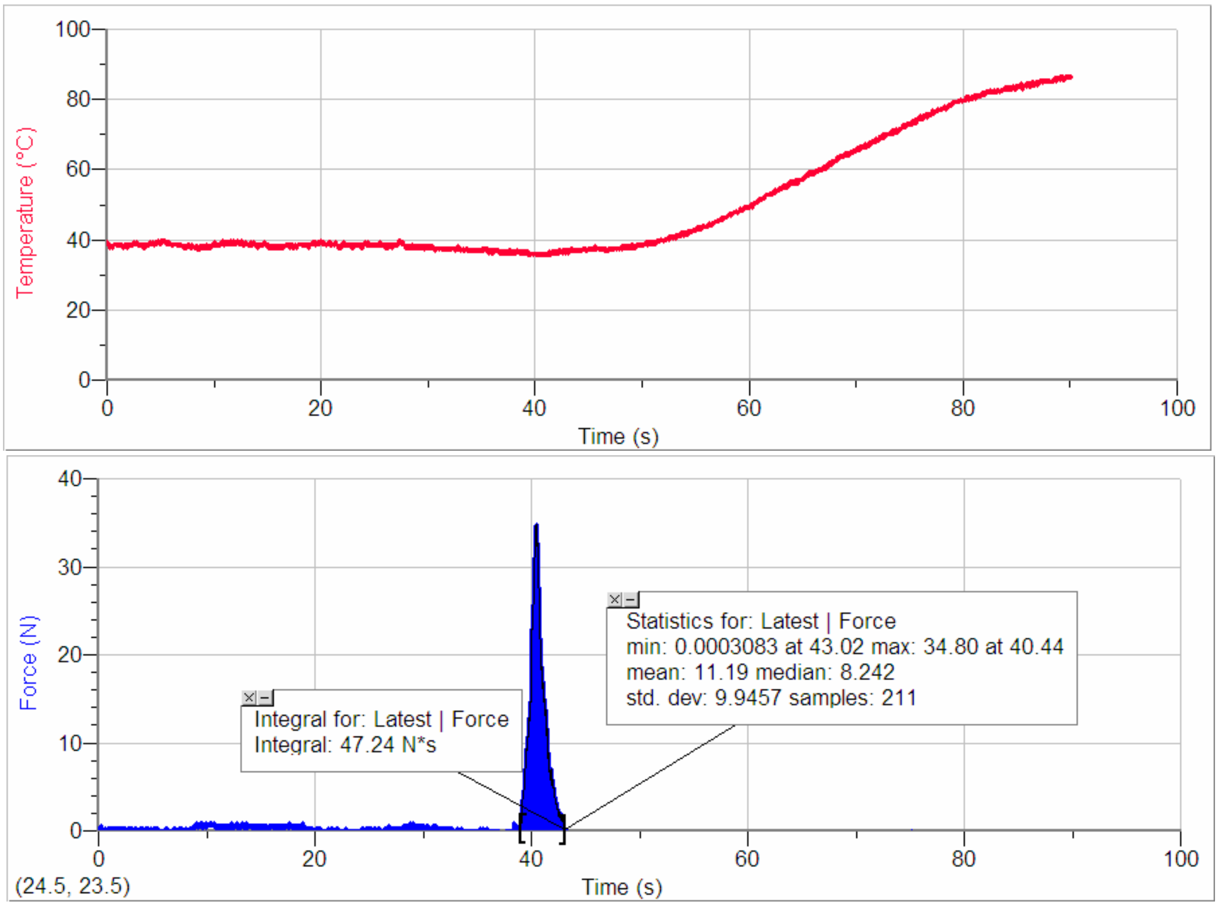
Many other subsequent tests were performed to establish a relative constant of expected results from the 65/35 propellant, including tests to determine what the effects of powdering the potassium nitrate would be. As of yet, no tests have been performed of varied ratios.The combined results are shown in the following table.

Test Number	**Measured Total Impulse**	**Notes**
1	47.24 N*s	Relatively small igniter used
2	86.11 N*s	Larger Igniter, unsteady burn, Non powdered Potassium Nitrate
3	152.4 N*s	Powdered Potassium Nitrate
4	162.9 N*s	Powdered Potassium Nitrate
5	149.1 N*s	Non Powdered Potassium Nitrate

Temperature readings for all of these tests stayed relatively constant, remaining at ambient temperature until after the propellant had finished burning, and eventually peaking between 65 to 80 degrees Celsius. Also, as the experience of the engine builder increases, the quality and strength of the engines also increase. Tests 2-5 resulted in absolutely no PVC deformation.

One potential performance boost that was researched was the use of powdered potassium nitrate. This entailed reducing the granule size of the potassium nitrate to a mere powder before mixing it with the sorbitol and melting it. This ensured that more potassium nitrate would be in contact with each atom of sorbitol, thus theoretically decreasing burn time and increasing reaction temperature. Contrary to the hypothesis, the burn times for all of these tests (with the exception being Test 1) each had a burn time of approximately 1.4-1.5 seconds. In addition, the eventual case temperatures for all of the tests but test 5 were approximately 85 degrees Celsius. Test 5 showed a remarkable eventual temperature of around 65 degrees Celsius, showing that *not* powdering the propellant held the chance of a lower reaction temperature. Further tests on Non-Powdered potassium nitrate based propellant may be needed in order to justify this claim, since the only other engine test using this configuration resulted in an unsteady burn, which can be most likely attributed to defects in workmanship. If the difference in impulse between the two propellant types is shown to be marginal or nonexistent, then not powdering the potassium nitrate may be a very easy way to lower the reaction temperature. The impulse differences cannot be currently calculated to significant accuracy, because of the lack of significant amounts of data to back either claim.

Problems that must be addressed in the future include finding a way to allow PVC to sustain long burn times while keeping deformation at a minimum, though this may be achieved as a side effect of optimizing a propellant ratio. Deformation occurs as combination of pressure being exerted on the casing as a byproduct of the internal combustion reaction and the soft qualities that PVC exhibits as it is heated. The amount of deformation depends on the temperature of the casing, which only increases after the engine has been heated for quite some time, unless external cooling methods are incorporated.



Integral for: Latest | Force
Integral: 47.24 N*s

Statistics for: Latest | Force
min: 0.0003083 at 43.02 max: 34.80 at 40.44
mean: 11.19 median: 8.242
std. dev: 9.9457 samples: 211

Figure 9: The engine's peak thrust was approximately 34.8 N, and the outside of the case reached approximately 86.2°C at the peak of the temperature graph. The total impulse that this rocket produced was 47.24 N*s.

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