Experimental PVC Rocket XR-1

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I. Introduction

This report is intended to analyze the development, testing process, and results of our experimental PVC rocket and identify potential root sources of failure. The goal of this experiment was to achieve lift off at the very least. Ultimately the system failed and instead of getting off the ground, there was a structural failure that caused the system to explode after ignition. Upon inspection of the post-mortem system, we cannot determine the specific reasons for the failure; however, we have plausibly developed several potential modes of failure.

II. Design Summary

The goal of this project was to construct a rocket in a household settings without advanced equipment, materials, sensors, etc. This includes the overall structure, nozzle, and fuel. The structure of the rocket was schedule 40 2" PVC pipe with a PVC 2:1 inch coupling nozzle molded with quick-set cement, and a potassium nitrate-sucrose fuel. A more in depth description of the rocket can be found in the Final Model section.

III. Design Process

Overall, our time was mostly spent developing the propellant of this system. The real reason for this is because it was easiest to make and test compared to making and testing the structure. There was an assumption that the structure would hold regardless of the other components due to our experience with using PVC. In retrospect, this may have been a detrimental flaw; we will discuss more in the Conclusion section. Preliminary analysis of the structure could have been done using our knowledge from structures classes and the material allowables given; however, due to our limited amount of time to carry out this experiment we neglected this analysis.

The remainder of this section discusses the materials/tools used during the design process and our findings from intermediary tests.

A. Materials

1. Potassium Nitrate (stump remover)
2. Sucrose (powdered sugar)
3. Sch 40 PVC pipe
    a) 2" dia.
    b) 1.5" dia
    c) 2"-1" Coupler
    d) Screw on Cap
4. Durham's water putty
5. PVC primer/cement

B. Phase 1: Propellant

The propellant used was a combination of powdered sugar (sucrose) and stump remover (potassium nitrate) commonly known as Rocket Candy. After preliminary experimentation with arbitrary combinations and cooking methods, we tested 6 specific methods and ratio of ingredients. The rocket candy was made with a skillet on an electric stove top set at medium-high temperature and a constant mass was used for each sample. The powder fuels were poured into the pan and cooked for a set amount of time on the stovetop, with occasional folding/stirring to optimize exposed surface area. The mixtures became solutions as they melted, turning from a pure white to a dark orange-ish brown color. We noted that the smell resembled caramelizing sugar (for obvious reasons) and something of burning cleaning solutions. For each sample we extracted the hot liquid and let cool until it hardened. Once they were cool and rigid, they were ignited with a barbeque lighter and observed. The observations are listed in Table 1, along with the specifics of each sample.

Table 1 - Varying Ratios of Ingredients in Propellant

Fuel Type	KNO_3	Sugar	Water	Cook Time	Observations
1	65%	35%	0%	1:10	Harder to light, burns longer.
2	55%	45%	10%	1:30	More intense than 5, still slow and overall better flame
3	75%	25%	10%	1:30	Extremely strong flame, very fast crumb-life fuel, soft enough to pack - maybe cook longer.
4	75%	25%	0%	1:10	Spews more excess, left behind lots of hard white substance. Looks hotter and more uncontrolled.
5	55%	45%	0%	1:10	Very slow big flame, more controlled. No white residue, left black ash behind. Campfire-like flame.
6	65%	35%	10%	1:30	Extremely volatile, very fast burn spewed even more than 4, no residual left over.

It is important to note that our observations and test results for the propellant trials are not overly scientific. We were sure to be precise with our measurements and methods of making the fuel because our available tools and skills allowed for it; however, for testing we were unable to quantitatively analyze the results. Our qualitative observations were taken in comparison to our initial batch of propellant, which was used as a baseline. Videos are available for reference and can be sent upon request.

C. Phase 2: Structure Trials

The structural considerations for the rocket were less than that of the propellant. In terms of structure, most of our time was spent on developing the nozzle. Few options were considered and the final decision was to mold a converging-diverging nozzle with the PVC coupler and water cement. The divergent section of the nozzle was molded using a funnel and the converging section was molded using a 1” PVC cap depressed into the wet cement. However, due to our assumption of incompressible flow, the diverging section can be regarded as insignificant.

Figure 1: Nozzle

Note that the throat of the nozzle does not flow smoothly into the diffuser. This was not how the nozzle was at the time of launch. Unfortunately, there is no documentation of the nozzle at the time of launch, but a pocket knife was used to carve out the throat from both ends such that the contour flowed smoothly into the converging and diverging section.

IV. Final Model

Considering the propellant and structural preparations, we created our final model. The PVC tube (listed in the “Materials” section) made up the fairing, while we attached a threaded PVC cap for the nose. The nozzle was a 2:1” coupling with a quick-set cement converging and diverging section molded into it. All the PVC connections were primed and cemented using standard PVC primer and cement. Regarding the propellant, the fuel was split up and stored in 3 individual grains. A grain was a 4” piece of 1.5” PVC filled completely with the fuel. Assuming that the “first” grain is the grain at the bottom (closest to the nozzle), the first grain was Fuel Type 3. This was deemed the best out of the volatile fuel types. The second and third grains were Fuel Type 2; 2 was the best of the slow burning fuels. The rationale for this decision that the rocket needs a high impulse to initially achieve liftoff, then a slow burning yet consistent fuel is best for sustained flight. We did not attach the grains together, nor did we fix them securely inside of the fairing. No holes were drilled through the grains, nor was a fuse set inside of any grain. The fuse was inserted through the nozzle and pressed against the bottom face of the first grain. There was a small amount of “wiggle” room for the grains to slightly shift around, but this was assumed to be insignificant. The grains sat directly atop each other when the rocket was vertical, as in the orientation when ignition occurred. Attached via tape to the outer surface of the fairing was a 1” cardboard tube. This tube slid around a rebar section that was impaled into the ground. The entire apparatus weighed 1.542 kg.

V. Launch Results and Summary

Preparations for the launch were not taken with much consideration. The time of launch was a cool and wet spring morning. The launching apparatus consisted of steel reinforcement bar embedded vertically into wet soil. The rocket was fastened to a cardboard tube that loosely enveloped the RE bar. A large sheet of plywood was set underneath to prevent significant erosion to the ground below the diffuser. Several inches of space were provided by 2 planks of wood. A firework fuse was inserted through the nozzle touching the surface of the bottom (first) fuel grain. The apparatus can be seen in Figure 1. Lit with a barbeque lighter, we had ample time to evacuate the area and begin recording a video as well as observing visually.

Figure 2 - Launch Apparatus

The video documentation captures the launch very well. It is observed that a large amount of smoke began pouring out of the nozzle once the fuse ignited the fuel. After a considerable amount of time, we began to approach the rocket’s vicinity as it was not lifting off despite large amounts of smoke and sounds of rushing air from the nozzle. It is important to note that approaching a flammable, pressurized, and volatile system like this is unsafe and not recommended despite the actions that took place while testing. Once the rocket is approached, things turn south very quickly. The sounds of rushing air out of the nozzle increase in volume and pitch extremely dramatically only a split second before the entire rocket explodes. Pieces of the rocket flew in every direction and some even up to 30+ feet in the air. They scattered across the field and we attempted to collect all of them. The following images are of the pieces we were able to collect.

Figure 3: Nozzle

Figure 4: Nozzle Underside

Figure 5: Outer Casing

Figure 6: Fuel Grain

Figure 7: Fuel Grain

Figure 8: Outer Casing

Figure 9: Outer Casing

Figure 10: Outer Casing

It can be seen in the photos above that the fuel grains in particular were greatly deformed and blackened. All the inside surface of the other pieces also reflect the same coloration, implying that extreme temperatures were experienced.

VI. Test Analysis

The following is a summary of our mathematical analysis of the system including a force balance and conservation of momentum to see whether our knowledge of the system is consistent with the events that took place. The goal of the force balance is to calculate the flow exit velocity, which will be used along with the pressure to analyze momentum conservation. Conservation of momentum can provide a calculated velocity of the control volume, which should be approximately 0. These calculations are merely to mathematically verify the experiment and determine where we have inaccuracies in both our measurements and our theory.

Stress Analysis

$\sigma = \frac{PR}{t}; P = 230psir = 2.375int = 0.154in \Rightarrow \sigma = \frac{230*2.375}{0.154} = 3.547ksi$

Force Balance Analysis

The basic premise of this analysis was to say that in order to lift off (which did not occur) thrust must overpower gravity. From the data we do have, we can then estimate what a necessary flow exit velocity would be. Then we can use some educated reasoning to determine whether this makes sense and what implications it makes about our system and why it did not lift off.

$\Sigma F = m * a,\ a > 0\ \Rightarrow \Sigma F > 0 = T - mg$

$T = \dot{m} * v_e + (p_e - p_0)A_e\ ; m = m_i - (\int_0^t \dot{m} * dt)$

$\dot{m} * v_e + (p_e - p_0)A_e\ >\ (m_i - \dot{m} * t) * g$ Assume the flow is perfectly expanded so pressure term is negligible

$\dot{m} = \frac{\Delta m}{\Delta t}$

$v_e > \frac{(m_i - \dot{m}*t)g}{\dot{m}}$

$m_i = 1.5422kg,\ m_f = 0.5727kg,\ \Delta t = 50s,\ g = 9.81m/s/s$

$v_e = 289.75m/s$

This calculation shows that in order for our rocket to take off, the flow exit velocity must be approximately 290m/s, which is 0.84 Mach. All things considered, such as our very high takeoff weight, low fuel mass ratio, etc. this number does seem to make sense (from the limited experience we have).

Conservation of Momentum in an Accelerating Reference Frame.

The purpose of this analysis is that we think the exit area of the nozzle is important to include in the analysis, and this was not taken into consideration in the force balance analysis.
Global conservation of momentum with a rectilinear acceleration is given by:

$$\frac{\partial}{\partial t}\oiiint_V \rho \vec{u}^{rel} dV + \vec{a}^{rf} M_{CV} = -\oiint_S \rho \vec{u}^{rel}(\vec{u}^{rel}\cdot\vec{n})dS - \oiint_S p\vec{n}\,dS + \vec{F}_{visc} + \oiiint_V \rho \vec{f}_{body} dV + \vec{F}_{ext}$$

We can say that aerodynamic forces are neglected and reduce this equation to the reduced local form:

$M\frac{dv}{dt} = \dot{m} * v_e - P * A_e + M * g$ where the mass, M is given as: $M\ =\ m_i - \dot{m} * t$

This equation can be rearranged to solve for dv/dt of the system, and then integrated to achieve the velocity. Substituting in the known values for mass flow rate, g, exit area, initial mass, and pressure, as well as the calculated exit velocity, we reach an estimated velocity of 297 m/s after integration. This value is obviously ridiculous. Considering the rocket did not even lift off, it is comical to say that in theory it should have been traveling at 0.84 Mach. I am skeptical that this velocity calculated is the same value as given by the force balance for flow exit velocity. There very well could be a theoretical error that is causing these values to come out the same despite the fact that they are completely separate values.

Matlab code below was used to calculate the velocity.

```
t = 50;
mi = 1.542;
mf = 0.5727;
mdot = (mi-mf)/t;
p = 1586000;
Ae = pi*(.00635)^2;
ve = 289.75;
g = 9.81;

V = ((mdot*ve)-(p*Ae))*log(mi/mf) + g*t
        =297.068
```

Ideal Rocket Equation

Out of curiosity, we wanted to see what sort of a velocity the ideal rocket equation would give. We have a decent bit of experience using and manipulating this equation for various systems from a sophomore year class, AAE251.

$$\Delta V = g_0 I_{sp} ln(\frac{m_t}{m_i})$$

Here, g0 is the gravitational acceleration on earth, initial and final mass are self-explanatory, and Isp represents the specific impulse of the fuel used. This value was pulled from an online source that estimates the specific impulse of the rocket candy at 115.

Plugging these values into the equation gives a velocity of 1117.4 m/s. Of course, this is even more preposterous than the result of momentum conservation.

VII. Conclusion

Regarding the results of the launch attempt, we have compiled a non-exhaustive list of potential failure modes. First of all, it is obvious that the PVC experienced structure failure. This is most likely because the internal pressure, due to the chemical reaction, exceeded the allowable pressure of the PVC pipe. There are two channels of failure from here: the internal pressure rose above the allowable for schedule 40 PVC, and/or the structural integrity of the PVC was diminished to the high temperature. We believe that the system experienced the first scenario. To get at the root cause of the issue, we deduced that the most probable source of a drastic pressure buildup in lieu of a much faster flow exit velocity is the rate of convergence in the nozzle. That is, we believe that the rate of convergence was too abrupt.

The angle for the converging section is estimated at 80 degrees with the surface of the fairing. This was essentially a wall, and did not allow for a smooth flow of fluid to and through the throat. Regarding the throat, it is also possible that it was too constrictive. A sort of "bottlenecking" could have occurred, drastically increasing the internal pressure of the system. We also observed that the throat expanded during the burn. The throat started at roughly ¼" and finished at ⅜". While we highly doubt the problem stemmed from the diffuser, we acknowledge that the diffuser we created was short and may have led to an increase in internal pressure. However, we believe this possibility is not as likely as those prior.

Another possible drastic pressure increase likely was an effect of the volatility of the propellant. We stationed our fuel in 3 grains, from least volatile at the start to most volatile at the end. The assumed "first" grain is the grain closest to the nozzle, and the last grain is the farthest from the nozzle. Also assumed is that the grains ignite in the preset order. This assumption may be incorrect, although we have no way to verify this phenomena. The extreme increase in pressure may have arose from the last grain of fuel being ignited. We had no way of measuring quantitative data of any fuel type, so there is little concrete analysis available.

While these scenarios are our perceived most likely modes of failure, as aforementioned, we also believe that the structural integrity of the PVC may have been compromised by the chemical reaction. Due to our lack of chemical knowledge, we again have no quantitative values to associate with the reaction of the propellant in terms of temperature. We surmised that there is a possibility of the temperature exceeding the capability of the PVC pipe to perform to specifications. While the pipe was not melted, it was charred black with apparent fractures. We are not aware of the chemical composition of the plastic, nor the critical temperature of schedule 40 PVC, nor are we aware of how such a plastic would react to extreme heat. However, this may have led to the PVC compromising before the rocket could achieve lift off. Another possible product of the chemical reaction could have been the components reacting with the chemicals within the PVC. We are again surmising that either the reactants/reagents of the Rocket Candy reaction may have reacted with some chemical within the PVC plastic. While we have no scientific or academic rationale behind this mode of failure, we again acknowledge this as a potential source of failure.

To summarize, we assume that the structural failure was caused by some combination of the internal pressure increasing, and the structural integrity of the PVC decreasing. An abrupt converging section, the over-constrictive nozzle, and the short diverging section are all possible modes of failure regarding the increase of internal pressure. The increase of temperature and chemical composition alteration via chemical reaction are potential sources of failure regarding the decrease of the structural integrity of the PVC pipe. While we do not have much quantitative data, through analysis of the video evidence, post-mortem remains, and various academic concepts, we believe that the reason for structural failure can be found within the aforementioned modes.

VIII. Future Designs

Despite the outcome of this experiment, there are plans to do another. The process a second time around will be much smoother as well as (hopefully) much more successful. The experiment we conducted previously was done with very limited knowledge, experience, and time. After much research, we have several different ideas for a future model. The majority of these ideas include using a different nozzle and construction completely. As discussed, the overarching source of failure was the rocket was just too heavy and the majority of the mass came from the nozzle construction and excess material used. Future designs of a nozzle include forming PVC into a nozzle by boiling sections to make the pipe malleable as well as manufacturing a metal nozzle using various different techniques found online. The best source of inspiration for us is this website, http://www.nakka-rocketry.net/ where there are loads of ideas for nozzles, propellants, etc. We plan on doing a larger number of static tests prior to attempting a launch as well.