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ITA Candy rocket motor design and solid propellant manufacture challenges

Daniel Bontorin[1] Susane R Gomes[2], Roberta J. Rocha[2] Leopoldo Rocco Jr[3], José Atílio F. F. Rocco[5] and Koshun Iha[4]

Instituto Tecnológico de Aeronáutica - ITA, São José dos Campos, São Paulo, 12228000, Brazil

The ITA Candy Rocket Program is a student program of undergraduate students to develop and fly a sounding rocket motor and compete at the Intercollegiate Rocket Engineering Competition. The program was kicked off in August 2011 and every year the design is altered for improvements. This paper shows the solid propellant preparation from easily available raw ingredients. The propellants are potassium nitrate and sorbitol. The potassium nitrate was purified, sieved, and recrystallized. A ground test program with small and real scale tests was conducted to evaluate the motor design and development.

I. Introduction

THE ITA Candy Rocket Motor Program was conceived in late-2011 with the mission of developing a sounding rocket to compete at the Intercollegiate Rocket Engineering Competition. There are many undergraduate sounding rocket projects[1,2] this particular initiative's goal was to develop a vehicle capable of an apogee of 10,000 ft. and, in the process, learn the engineering aspects of a space vehicle design, especially the propulsion system. The project team consists of undergraduate students of aerospace and electrical engineering with guidance from multidepartment professors.

The team competes annually at the IREC (Intercollegiate Rocket Engineering Competition) in the basic category and has won several awards such for best project and ranked second in its category. the basic category competition rules, are:

i. The rocket must get as close as possible to an apogee of 10,000 ft. Any apogee out of the range of 5,000 ft to 12,000 ft is declassified. ii. The rocket motor must not release any toxic gases; iii. The rocket motor case and other components must be reflyable; thus it must be recovered.

One of the greatest challenges that the team has to outcome is the logistics. Everything that is tested and made in Brazil must be made in the US, so every part and equipment must be as compact as to fly in a commercial international flight or it must be easy and cheap to bought in the US. The candy rocket suits very well this requirement since all of its components are easily found and bought in both Brazil and the US and its manufacture is easy to do in one week (time the team has to prepare their rocket in the United States).

II. Rocket Motor Design

The rocket motor design is constrained by the competition rules and by component logistics. The propellants that suit all the constraints are potassium nitrate, obtained from fertilizer, and sorbitol, an over the counter type of sugar, this combination is a candy motor. This session will show the project of an M class KNSB (potassium nitrate and sorbitol) motor, from development of the propellant to the static test.

[1] Undergraduate Student, aerospace engineering, danielbontorin152@gmail.com
[2] Professor, Aerospace Dept., susane@ita.br, AIAA Member.
[2] , Postdoctoral Researcher, Chemistry Dept., robertajr@gmail.com
[3] Postdoctoral Researcher, Chemistry Dept., leopoldorocco@gmail.com, AIAA Member [5]
Professor, Chemistry Dept., friz@ita.br, and AIAA Senior Member.
[4] Professor, Chemistry Dept., koshun@ita.br, AIAA Member

III. Propellant

The propellant is composed of a mixture of 65% in mass of potassium nitrate and 35% in mass of sorbitol, a type of sugar. From now on, this mixture is going to be refereed as KNSB. All components must be accessible to students in both countries. The potassium nitrate in the fertilizer must be purified and it is a important energetic material that can be combined with other chemical raw materials like boron to produce pyrothechnics components[3,4].

A. Purification

The process of purification is needed due to the nature of the potassium nitrate that the students have access to. The solubilization of potassium nitrate is endothermic, so the solution must be heated for complete solubilization of the salt.

The main steps of the purification process are:

1) Solubilization of the salt in water (1kg of nitrate for every 500 g of water);
2) Filtration on regular coffee filters to retain most impurities at 93 º C/194 º F;
3) Recrystallization

Shortly after the passing through the filters, the solution of nitrate sits for about half an hour under constant agitation until the salt decants. The agitation from the helix, which is connected to an electric motor, is used to break the crystals on the process of recrystallization, making its edges rounder and, thus, with more contact surface. The increase in the salt's surface area gives the propellant more power, since it increases the burning reaction. Another gain that this agitation process provides is that the break of the crystals is not homogeneous; therefore, there is a broader variety of crystals diameters that will fill in the empty spaces on the final mixture of KNSB, improving the oxidizer-fuel rate.

The decanted salt is then removed from the solution, which is still warm, and taken to a vacuum filtration system with an electric pump. The salt that remained on the Buchner funnel is still humid and needs to be completed dried, so it is putted in a pan and heated with a stove. Although the temperature control isn't precise, the nitrate needs to be carefully dried so it doesn't degrade on the hot surface of the pan. Whenever a hard thin yellowish crust forms, the pan is taken off the stove and the crust is removed and, at the same time, the pan surface cools down. This procedure of removing wet salt from the solution and then drying it lasts until the solution hits the room temperature. It is possible to immerge the Becker in an ice bath to increase the process efficiency, as more slat will decant.

After all this process, the potassium nitrate from the fertilizer is purified. There are some leftovers of the salt at the bottom of the kitset used on the vacuum filtration but in an undesired crystal form, since it hasn't been recrystallized under agitation. The natural form of the potassium nitrate crystal is in a needle shape with sharp edges and low contact surface. These leftovers are purified and can be dissolved and recrystallized again for efficiency sake.

The efficiency of this process varies on 60% to 70% depending on the quality of the initial compound; therefore, the team needs to do this process several times. Since this purification process takes up to four hours to be completed, this becomes the slowest step on the manufacturing of the propellant and a crucial mater when analyzing the time needed to prepare the rocket on the US.

B. Microscopic analysis

Figure 1 Needle shape of natural potassium nitrate crystals.

To assess the quality of potassium nitrate crystals, a microscopic analysis of the material was made. As seen in figure 1, the natural crystal form of the potassium nitrate is a needle shape crystal with sharp edges and low contact surface. If this large crystal is broken manually with a spoon the crystals obtained are such as found in figure 2 left, that still have low contact surface. These characteristics are found in the crystals marked with a black circle.

It is visible in figure 2 right that the procedure of constantly breaking the crystals while they are still in the recrystallization process gives a much rounder crystal. It is also noticeable the broader variety of crystals sizes. This characteristic improves the propellant performance because there are less empty spaces in the propellant.

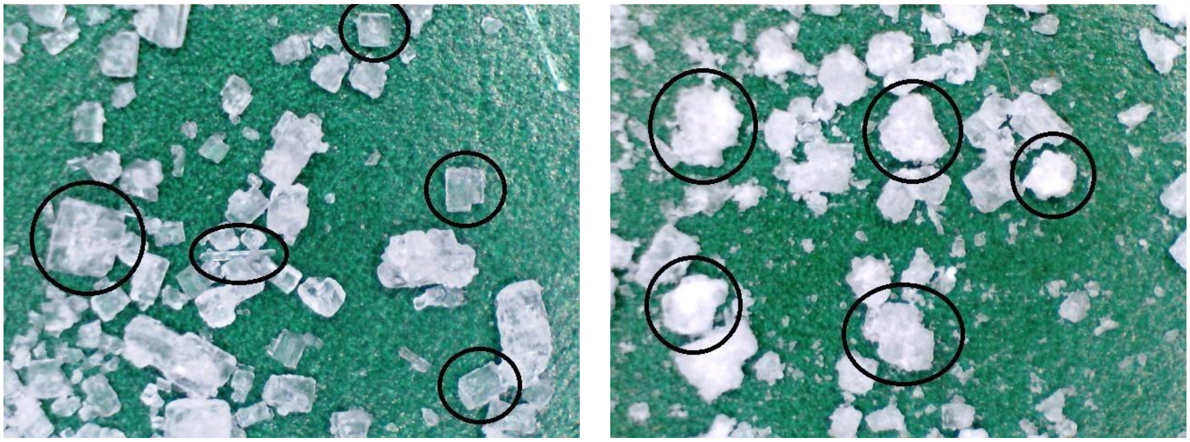

Figure 2. Left: Microscopic image of sharp edge crystals. Right: Microscopic image of round edge crystals.

C. Grain Manufacturing

After purifying of the oxidizer, it is mixed with the fuel, sorbitol. The sugar does not have to be purified for it is already bought in a high purity grade. The components are pre-mixed at the room temperature in a large bowl with simple stir with a large spoon. Then, the mixture is heated so that the sugar can melt and act as a binder on the propellant. This stage can be done by a normal pan and stove (the same used on the drying process of the nitrate), although it is not recommended due to the high temperature of the stove and its irregularity. If some of the mixture spills out of the pan and hits the stove is certain ignition, the flame can even spread to the pan and light all the propellant up, as it happened once to the Brazilian team.

To fix this problem, it is used a fryer that, no only gives the pan surface a more homogeneous distribution of temperature, but also provides a cooler surrounding to the pan, avoiding the accidental ignition problem. It's poured some kitchen oil on the fryer so that the bottom of the pan gets "wet", because when it heats up it will expand and can overflow. The oil temperature varies from around 120 ºC up to 180ºC and the pan bottom from 100ºC to 150ºC. The melting temperature of each sugar is different; having the team worked with sucrose, dextrose and sorbitol, being the sorbitol's the smaller temperature, around 80ºC. This cooler melting point is an advantage not only because it makes the process faster, but also makes it more safe, for it is needed a cooler working temperature.

Figure 3 KNSB propellant process

Another advantage of the sorbitol over the other two sugars is its larger gap between the melting point and the caramelization point. If the sugar caramelizes, it loses efficiency and the lack of precision on the pan temperature makes it crucial. Both components, sugar and potassium nitrate, are white and remain white on the melting process, unless the sugar caramelizes, which gives the mixture a yellowish coloring. Figure 3 shows the mixture of KNSB propellant process immediately before the injection in the rocket motor case.

The manufacturing of the propellant has many details and due to that, it can have several outcomes. For reducing the probability of an undesired outcome, the team works to reduce the human presence on the process so, the mixing of the propellant while it melts is made by the helix that stirred the potassium nitrate. This makes the procedure more reproducible and easier, since the exhausting task of stirring is made by a machine. The powder is poured slowly, when all the content on the pan melts, its added a little more. Usually is added the same amount that already is in the pan, with the initial being around 200g.

D. Casting and solidification

After all sugar has melted and the mixture is homogeneous, the propellant is casted into a fiberglass tube that is inside a metallic tube. The grain conformation is cylindrical with a cylindrical internal shape. All dimensions are fixed because of the metallic mold with the exception of the height of the grain that can go up to 160mm. The melted mix is poured until it covers the fiberglass tube and then it's putted a cover on top that is smaller than the metallic mold but bigger than the fiber tube.

Figure 4 shows all the parts of the mold. On the left, the metallic tube with the fiberglass tube inside it. On the middle top is the cover and at the bottom the cover cup, that allows to press the cover without hitting the mandrill, which is found to the right.

Figure 4 Metallic tube, cover, cover cup and mandrill

Next, the cover is pressed with a hydraulic press until it touches the fiber tube and it is locked this way with some steel boards, threaded rods and nuts. This configuration is called compressing tower. Some hot propellant flows out of the casting due to the pressure and must be removed while still hot unless it will solidify which will make its removal more difficult. The mixture inside the mold sits for at least 17 hours for complete solidification of the sugar. Figure 5 shows the compressing tower before the propellant casting on the left, and after casting to the right.

Figure 5 Compressing tower before and after the propellant casting

Next to the solidification, the grain is removed from the mold and is visually analyzed for bubbles and cracks. Then, its dimensions and mass are taken and its density calculated for comparison with the ideal that is taken from [5]Nakka (Nakka, s.d.). From earlier experiences with KNSB, it was acquired that the method described above yields grains with densities around 90% ± 2% of the ideal, so, the grains are acceptable for the x-ray analysis if they do not show any cracks or discontinuities on the surface and their densities fall on the given interval. Then, are chosen some grains that are acceptable and is made x-ray analysis on them. The x-rays show that, as expected due to the relative density below 100%, there are some discontinuities on the propellant. These discontinuities can be seen in both sides of figure 6. Voids and a crack are circled for improved visualization.

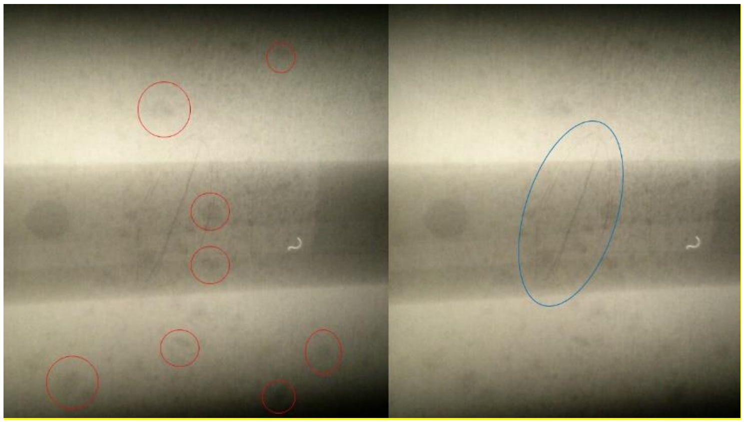

Figure 6. X-ray images of the grain with voids, fissures and discontinuities.

Although the voids were expected, the crack is a result of poor quality control over the propellant manufacturing process. This can lead to increase in the burning area and over pressurization of the combustion chamber, not only changing the thrust and pressure curves, but also increasing the probability of an explosion of the motor.

In order to improve the quality control of the grains, there is an interest in automating as many steps of the processing as possible. The team is developing a vacuum casting chamber, to be operated over a vibrating table. This vibration will favor the removal of the voids, providing more reliability and reproducibility of the grains.

IV. Motor Hardware

A. Inhibition and Thermal Protection

After the removal of the grains from the molds, a layer of fiberglass is applied to unite all of them. The inner and outer fiberglass layers serve as inhibitors so that the outer face of the grain isn't exposed to the flame. Therefore, the burn profile is a Bate's form, implying that the core, the top and the bottom surfaces are the only ones that burn. The composition of the cigar and the expanding radial burns gives the thrust and the pressure curves a table shape, or something close to it.

Figure 7. Grains united by fiberglass.

The thermal protection is set between the case and the propellant with a nitrile rubber blanket of 0.8mm thick.

B. Motor components

The motor, which is showed in Figure 8, casing is made in aeronautic aluminum and the nozzle and bulkhead are made in steel. The motor considered in this article was projected considering a fixed throat diameter and varying the grains length to obtain different thrust curves. It was made this way because the total mass of the rocket was uncertain and it was necessary to project a motor that could fulfill every mass requirement (so the rocket would get to 10,000 ft.). The motors simulated were the following.

Motor A:
Grain height = 130mm;
Total propellant mass = 6.158 kg;
Maximum pressure = 2.64 MPa;
Burn time = 4.6 s;
Average thrust = 1,576 N.

Motor B:
Grain height = 140mm;
Total propellant mass = 6.632 kg;
Maximum pressure = 2.79 MPa;
Burn time = 4.6 s;
Average thrust = 1,706 N.

Motor C:
Grain height = 150mm;
Total propellant mass = 7.105 kg;
Maximum pressure = 2.94 MPa;
Burn time = 4.6 s;
Average thrust = 1,839 N.

Motor D:
Grain height = 160mm;
Total propellant mass = 7.579 kg;
Maximum pressure = 3.11 MPa;
Burn time = 4.6 s;
Average thrust = 1,972 N.


Figure 8. Motor

V. Experimental Results

A. Small scale firing tests

The tests consist on casting the propellant into an empty shotgun shell and drilling the core. Figure 8 shows the small propellant samples. These samples undergo firing testes, the thrust and pressure profiles are obtained.

Figure 9. Samples of propellant in shotgun shells

Figure 9 shows the pattern of pressure and thrust curves obtained from these tests.

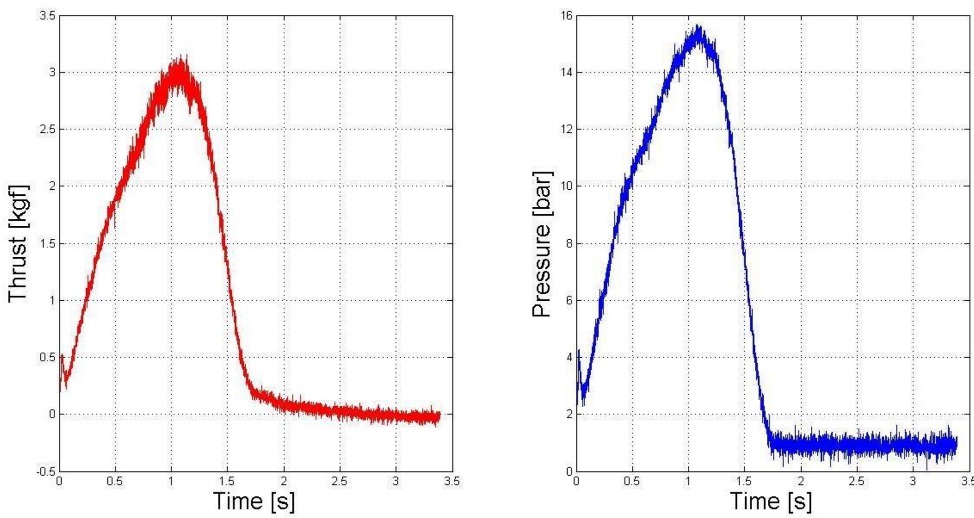

Figure 10. Thrust and pressure vs time curves pattern for the small motor tests

The main characteristics calculated are the specific impulse and characteristic velocity, which have means and standard deviation according to table 2.

Table 1 – Means and standard deviation for characteristics calculated

	Mean value	Std. deviation
Specific impulse (s)	117.8	10.5
Characteristic velocity (m/s)	1,240.6	40.2

These results are close to Nakka's reference. (Nakka, s.d.)

B. Real size firing tests

There were two real size firing tests. The only instruments on both were a student-built load cell to measure the thrust curve. For the first test, since the motor was projected to have a maximum thrust of 1.8 kN, the load cell had a saturation point of 2.6 kN. Although, the trust curve of the first test saturated for most of the curve, but showing a triangular shape for it, different from the theoretical, as show in the upper graphic in figure 11. For the second test, the upper limit of the load cell was raised to 4.3 kN, but the thrust curve still saturated, for a small part of the curve this time, but still having the triangular shape. The first test was made using compounds from Brazil and the second from the US. These tests showed that sorbitol deviate from the theoretical thrust curve and, by similarity, the pressure curve also, giving a triangular shaped curve instead of the almost constant theoretical curve.

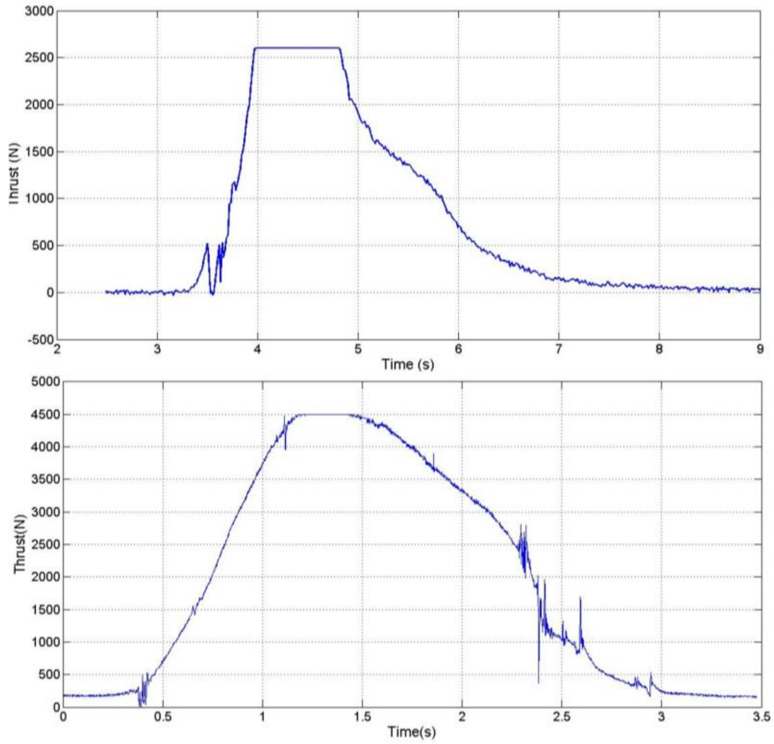

Figure 11. Thrust versus time results of firing test.

VI. Conclusion

The process of designing this motor in the way presented in this article differs a lot from the industrial design of motors, but that is the point of this project, to do something accessible to college students. From the compounds used in the formulation of the propellant, to its manufacturing process and the motor loading, the process is outdated and have less reliability than the professional method, but it works on some level and can fly a relatively large rocket. Since this project is always in a development stage, there were and there will still be many changes on it, but until the making of this article, this is the safest, most reliable, most powerful and easiest way the team has ever made a motor.

VII. Acknowledgments

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