XXVII Congresso Nacional de Estudantes de Engenharia Mecânica
08 a 12 de fevereiro de 2021, Curitiba, PR, Brasil

INHIBITION OF A SOLID ROCKET MOTOR PROPELLANT

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Abstract. *This work presents the casting process of solid propellants, called propellant grains, and how they were thermally protected in an amateur rocket called SELENE, from the Federal Fluminense University's LUFFT rocketry team. Thermal protection is very important for the safety of the solid rocket motor, preventing the occurrence of catastrophic failures. The BATES configuration is chosen for the propellant grains as it fits the team's expectations of the easiness in the casting process and performance. The casting process is made through a nylon cylindrical mold machined in a turning lathe machine and the chosen thermal inhibitor is a layer of Papel Vivaldi around the grain, which has proved to be a safe combination. Finally, according to the presented methods and the chosen thermal protection, the SELENE rocket did not suffer any structural damage in its experimental validations, obtaining a Thrust × Time curve within the expected and the most accurate apogee at ground level of the Latin American Space Challenge 2019.*

Keywords: *Solid Propulsion. Thermal Protection. Rocketry. Inhibition. Propulsion*

1. INTRODUCTION

In rocket literature, there is a distinction between rocket motor and rocket engine. The word motor is used for rockets propelled by solid propellants and the word engine is used for rockets propelled by liquid propellants. Rocket motors come in many different types and sizes, varying in thrust from about 2 to over 12 million Newtons (0.4 to over 3 million pound-force) (Sutton and Biblarz, 2017), where the classification for amateur rocketry varies between 0 and 655,360 N·s. In comparison to liquid rockets, solid rockets are typically much simpler, they are easy to attach, do not leak, are ready to ignite, require little servicing and the grain, that is the solid body of the hardened propellant, typically accounts for 82 to 94% of the total rocket motor mass. This is the reason why amateur rocketry teams start their studies in Solid Rocket Motors (SRM).

The propellant grain starts to burn on all its exposed inner surfaces. Many grains have slots, grooves, holes, or other geometric features that alter the initial burning surface and thus determine the initial mass flow rate and the initial thrust. Hot combustion gases flow along the perforation or port inside the cavity toward the nozzle, a component of the rocket motor responsible for the ejection of the hot gases. The motor body, also called casing, is either made of metal (such as steel, aluminum or titanium) or composite fiber-reinforced plastic material and it's responsible for maintaining the internal pressure of the rocket motor. Any inner surfaces of the casing, which are exposed directly to hot gases, must have thermal protection, that can be an inhibitor, or insulation layers to keep the casing from overheating, that is a condition when it would no longer be able to contain the internal pressure. The motors nozzle has the role of efficiently accelerating the hot gases issuing from the combustion chamber through its purposely shaped convergentdivergent passage. The majority of all solid rocket motors have a simple fixed nozzle Sutton and Biblarz (2017).

In this article, KNDX was chosen as the solid propellant. KNDX (Nakka, 2018) is a propellant with 65% of potassium nitrate and 35% of dextrose by mass, these were chosen due to the easiness to acquire dextrose in its pure form and this ratio of oxidizer to fuel mass represents a practical upper limit for "solids" loading of a sugar binder, while maintaining good performance and burn rate characteristic. The material and geometrical configuration of the grain govern motor performance characteristics, and in worksheets provided by Richard Nakka (Nakka, 2020a), a mechanical engineer who makes all his knowledge about amateur rockets available for free on the internet, there is a simplification of using grains with cylindrical perforations, both to maintain a constant thrust curve, neutral burn and and to ease the casting process. The solid propellants are usually heavier compared to liquids, they require more propellant (for continuous gas flow), thus its apogee at ground level will be negatively affected, but they are much cheaper and simpler to be designed and tested by amateur teams.

Inhibitor is a layer or coating of slow or nonburning material applied to a part of the grains propellant surface to prevent burning on that surface. By preventing burning on inhibited surfaces the initial burning area can be reduced and controlled. There are two methods of holding the grain in its casing. In case-bonded grains the casing is used as a mold and the propellant is cast directly into the casing and is bonded to the casing. Freestanding grains are manufactured separately from the casing (by extrusion or by casting into a cylindrical mold or cartridge) and then loaded into or assembled into the casing, because of that, the configuration chosen for the grain in this article was the freestanding one, because it often have a lower cost and gives freedom to exchange a non-functional grain for a functional one, and also allows the grain to be divided into smaller portions for easy fabrication and a better allocation in the combustion chamber. The inhibitor makes the contact of the grain surface with the casing in this freestanding model, serving as the cylindrical mold in the casting process and also of the thermal protection.

The SELENE mission used a SRAD (Student Researched and Developed) rocket motor, where the casing, that contains the combustion chamber, was made of stainless steel AISI 316, and the chosen propellant was KNDX (Potassium Nitrate and Dextrose). The design of the propulsion subsystem is done through Nakka's spreadsheets (Nakka, 2020a), that takes into account the rocket's external fuselage diameter and the mass of the rocket without propellant, delivering as a result the volume of the propellant, mass of the final rocket and the optimal dimensions for the combustion chamber. From the obtained dimensions of the combustion chamber it is possible to iterate through Schmidt's Method and Nakka's THERMCAS (THERMal CASing) software (Nakka, 2020b) the desirable thickness of the inhibitor, in order to ensure the safety of the project.

2. METHODOLOGY

In rockets that use solid propellants, after igniting a spark, the mixture of oxidant and fuel within the propellant grain causes an increase in temperature and pressure in the combustion chamber (the internal part of the casing) due to the burning of the propellant. As a result of this burning, there is a chance that the heat transfer in the combustion chamber is extremely harmful to the rocket motor structure, for this reason it is recommended to use an inhibitor. For the amateur rocket presented in this article, four cylindrical shaped grains were used to better fit the cylindrical combustion chamber, in addition, the type of grain is the BATES (BAllistic Test Evaluation System) format, which is recommended for providing a neutral burn. The inhibitor will act as thermal protection layer on the surface that surrounds the propellant grain, preventing it from burning in an uncontrolled way and damaging the rocket components, causing an accident. It will be discussed how the propellant grains were inhibited in the propulsion project of an amateur rocket called SELENE, from the Federal Fluminense University's LUFFT rocketry team, that competed in the Latin American Space Challenge 2019, reaching the most precise apogee, 913 of the aimed 1000 meters.

According to Sutton and Biblarz (2017), the process of defining the configuration of the propellant grains depends on what is expected from the burning of the propellant during the flight, the shape of the fuselage and the consequent space available to allocate the grain and its erosive burning process. The shape of the grain for amateur rockets is usually cylindrical for better use of the shape of the rocket and structural components of the propulsion, however, the shape of the grain core (a cylindrical perforation, in this article) is also important as it has a direct influence on the Thrust × Time curve.

Based on (Nakka, 2020a), the core and its shape interfere in the burning area during combustion, since the existence of the core gives greater initial exposure of the propellant's surface area for combustion and the shape of the core dictates how the burning of the propellant occurs between the inner and outer diameter of the grain. Given this information and taking into account the grain manufacturing process, which according to Sutton and Biblarz (2017) should be an easy to reproduce process, the team chose a grain of the format BATES, which is the acronym for Ballistic Test Evaluation System.

In Fig. 1, we can see the outer surface that will be the inhibited surface, as well as the core and the web of the grain, the web being the difference between the external and internal radius of the grain, it is the surface where the fuel is found, and the core is the constant internal section on the axis.

The advantages related to the choice of this grain format are found in the ease of manufacture, the cylindrical shape facilitates with respect to the manufacture of the mold and the neutral burn that the format provides for being a hollow cylinder which, according to (Nakka, 2020a), is ideal for maintaining a constant pressure in the chamber and allowing the nozzle to work efficiently. In terms of manufacturing, the team's choice was to use a mold made of nylon, this material was chosen due to its characteristics of low volume deformation at high temperatures, in order to avoid defects in the grains that would impair their homogeneity, such as bubbles or micro cracks. In addition, this material does not react chemically with the KNDX propellant.

Given the choice of the shape of the grain and the propellant, the dimensioning of the thermal protection must be addressed. The configuration chosen by the team as the most suitable for allocating the propellant in the combustion chamber is the freestanding, from that it is necessary to define the type of ideal inhibitor given the material of the grain

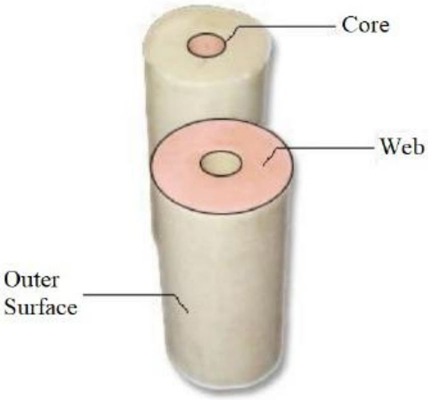


Figure 1. Web, core and outer surface of the grain

mold.

When the grain is in the freestanding configuration, at the moment of combustion it burns together with the internal wall of the combustion chamber, Fig. 2, and this occurs because the grain was manufactured separately from the chamber so that when burning begins, a mass flow is initiated, which results in a heat transfer to the combustion chamber walls. Thus, an external surface inhibitor is needed to stop the burning and prevent a direct mass flow between the propellant and the chamber.

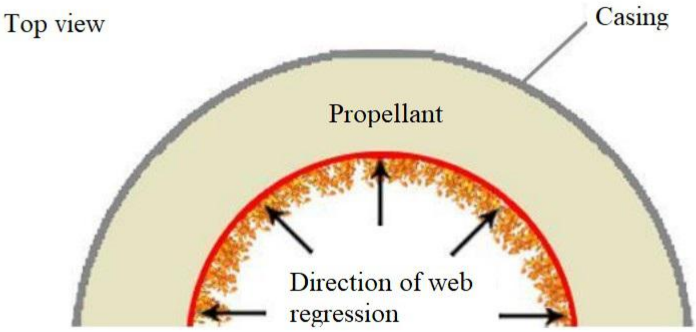


Figure 2. Cross section of a BATES grain

The grain fabrication procedure takes place from a molten mixture of potassium nitrate and dextrose. Those chemicals are purified from easily obtainable products in the market. The dextrose is obtained through direct purchase from stores, in anhydrous form (0.01% water), and is then dried further through heating, aiming to maximize purity. The potassium nitrate is purified from Krista-K fertilizer, a product with considerable concentration of this compound. The potassium nitrate is isolated by heating the fertilizer in water to 100 °C, which dissolves the desired chemical, and then filtrating the solution, transferring water and KNO3 ions through the filter, and leaving most impurities behind. This product is then recrystallized and refiltered three times, in order to maximize purity.

The crystals are then dried and thoroughly mixed and crushed alongside the dextrose, in the appropriate stoichiometric proportion to obtain the desired 65% potassium nitrate and 35% dextrose, forming a very fine powder, which will then be melted and poured into the mold. Before receiving the mixture, the mold is prepared in such a way that vaseline is applied to top and bottom parts of the nylon mold, and then the inhibitor is inserted into the bottom part, already with the projected dimensions. Subsequently, a steel plate is placed, external to the inhibitor, in the shape of a sectioned cylinder with a steel clamp in order to contain the deformation and keep the dimensions of the final product as faithful as possible to those projected. With this, the mixture, when reaching its melting temperature, is poured into its mold and adhered to the inhibitor during the curing process.

The inhibitors must be chemically compatible with the propellant, in addition to having good adhesion so that they remain attached to the propellant grains and must also be low density materials in order to reduce the inert mass (Sutton and Biblarz, 2017). In the SELENE mission, the inhibitor chosen was Vivaldi paper, which in addition to having the characteristics mentioned above, also has a low cost.

According to Trubiene (2015), it is possible to define the inhibitor's thickness ($t_{inhibitor}$) from an equation that relates the grain's web thickness (t_{web}) and a safety factor (SF), which varies between 3 and 5%:

Figure 3. Components of the mold where the grain is fabricated

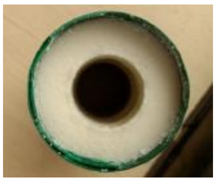


Figure 4. Grain after the casting process, with a visible green inhibitor

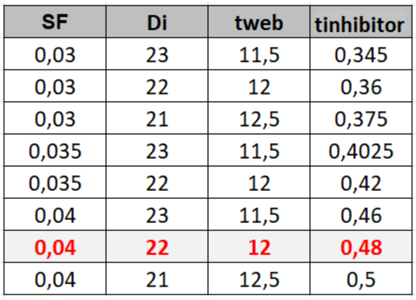
$$t_{inhibitor} = SF * t_{web} \quad (1)$$

To calculate the outer diameter (D_o) of an inhibited grain segment, the combustion chamber's thickness (t_{casing}) is utilized. For reasons outside of the scope of this article, the combustion chamber's defined outer diameter is 50.8 mm with 1.5 mm of thickness; that is:

$$\begin{aligned} D_{o\,(inhibited\ grain)} &= D_{o\,(casing)} - 2t_{casing} \\ D_{o\,(inhibited\ grain)} &= 50.8mm - 2(1.5mm) \\ D_{o\,(inhibited\ grain)} &= 47.8mm \end{aligned}$$

Therefore, the outer diameter of the inhibited grain segment has a limit of 47.8 mm, and adding dimensional tolerance, 47.5 mm is defined as the target outer diameter for an inhibited grain.

From these informations and considering a range for the inhibitor thickness' safety factor (from 3% to 5% of the web thickness), the following results for the inhibitor thickness of an unhibited grain with 46 mm of diameter are obtained, that can be seen in the Fig. 5.



SF	Di	tweb	tinhibitor
0,03	23	11,5	0,345
0,03	22	12	0,36
0,03	21	12,5	0,375
0,035	23	11,5	0,4025
0,035	22	12	0,42
0,04	23	11,5	0,46
0,04	22	12	0,48
0,04	21	12,5	0,5

Figure 5. Table containing coordinates for choosing the inhibition thickness from the safety factor thickness

In Fig. 5, the thicknesses are in millimeters. The chosen internal diameter of the grain was of 22 mm, given that it is a normalized size and easily found for production of a mold. Therefore, working with a safety factor of 4%, according to the table above, the inhibitor would need at least 0.48 mm of thickness. The inhibition employed at the SELENE mission was done from two complete revolutions of Vivaldi paper (Canson), characterizing an inhibitor thickness of 0.55 mm.

Based on the chosen values for the outer and internal diameter of the grain, and from equation (1):

$$t_{inhibitor} = SF * t_{web}$$

$$SF = \frac{t_{inhibitor}}{t_{web}}$$

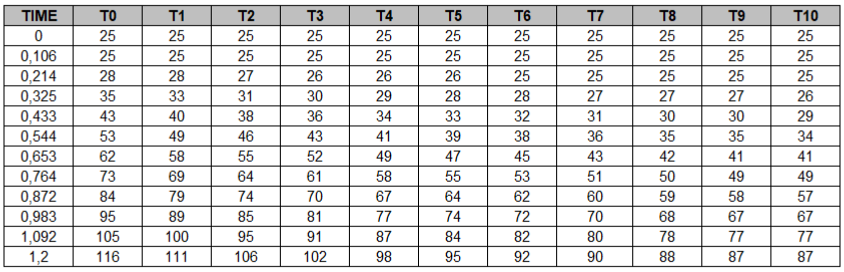
$$SF = \frac{(2 * 0.55)}{(46 - 22)}$$

$$SF \approx 0.0458 = 4.58\%$$

Therefore, a safety factor of 4.58% was obtained, which indicates reasonable choices for the grain's and inhibitor's geometry.

3. RESULTS

The thickness of the inhibitor was validated through the THERMCAS software, Fig. 6, where information about the casing material were added, as well as about the inhibitor, in addition to the combustion and wall temperatures and the convection coefficient of heat transfer. The mathematical model that was used by the THERMCAS software to numerically calculate the temperature distribution in the rocket's combustion chamber is called the Schmidt Method (For a better understanding of the method, it is necessary to consult the bibliography listed in the References), then THERMCAS gives an output that can be seen in the Fig. 6.



TIME	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
0	25	25	25	25	25	25	25	25	25	25	25
0,106	25	25	25	25	25	25	25	25	25	25	25
0,214	28	28	27	26	26	26	25	25	25	25	25
0,325	35	33	31	30	29	28	28	27	27	27	26
0,433	43	40	38	36	34	33	32	31	30	30	29
0,544	53	49	46	43	41	39	38	36	35	35	34
0,653	62	58	55	52	49	47	45	43	42	41	41
0,764	73	69	64	61	58	55	53	51	50	49	49
0,872	84	79	74	70	67	64	62	60	59	58	57
0,983	95	89	85	81	77	74	72	70	68	67	67
1,092	105	100	95	91	87	84	82	80	78	77	77
1,2	116	111	106	102	98	95	92	90	88	87	87

Figure 6. Table containing the temperature in wall sections of the combustion chamber

In Fig. 6, the time is in seconds and the temperature of T_0 to T_{10} are degrees Celsius. With this information it was possible to generate a graph of the temperature × position along the thickness.

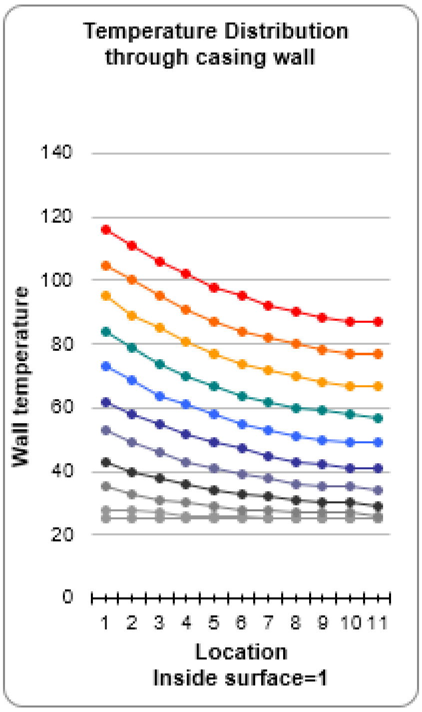
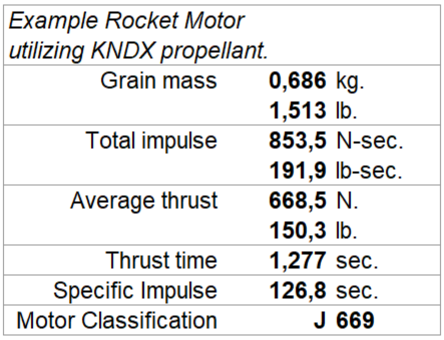


Figure 7. Temperature in wall sections of the combustion chamber

Analyzing the Temperature × Position graph, it is noted that the highest possible temperature for the thickness of the chamber would be around 120 °C. Knowing the yield limit stress of AISI 316 steel, the crystalline structure in the casing will not undergo major changes, and Fig. 7 confirms this. It is also noted that the temperature variation shown by THERMCAS does not present great risks to the rocket motor structure.

The validation of the thermal protection operation was performed by computer simulations, static fire tests and one flight test in the Latin American Space Challenge 2019. The computer simulations were performed in the SRM (Solid Rocket Motor) spreadsheets provided by Richard Nakka, that address much information of the propulsion subsystem such as type of solid propellant, mass of the rocket without propellant and the rocket motor diameter, in order to obtain the informations contained in the Fig. 8. In addition, the Thrust × Time, Fig. 9, was also an output.



Example Rocket Motor utilizing KNDX propellant.		
Grain mass	**0,686**	kg.
	1,513	lb.
Total impulse	**853,5**	N-sec.
	191,9	lb-sec.
Average thrust	**668,5**	N.
	150,3	lb.
Thrust time	**1,277**	sec.
Specific Impulse	**126,8**	sec.
Motor Classification	**J 669**	

Figure 8. Rocket motor data from Nakka's software

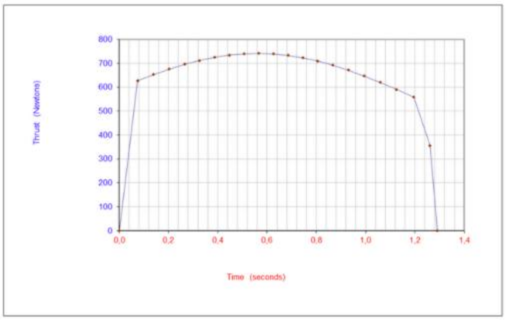


Figure 9. Rocket motor Thrust Curve from Nakka's software

From the Thrust × Time curve it is possible to see that there is only a small variation in thrust, which confirms the efficiency of the geometry of the BATES grain and of the selected inhibitor for the project in maintaining a neutral burn, so as not to cause any pressure spike or any other unusual event.

Some static fire tests and one flight test were performed on the SELENE mission. The static fire test of a rocket motor is carried out on the ground, so that the rocket motor is ignited and from a data acquisition system, measurements of the thrust provided by the rocket motor is collected.

In the static fire tests, a structure made of metalon was used as platform, with an analog scale attached, as can be seen in the Fig. 10.

Figure 10. SELENE's rocket motor static fire test platform

Even without a precise measurement of the burning time, it was possible to notice that it was short, up to 3 seconds, which indicates that there were no major problems with relation to the mixture of propellant and nozzle geometry, indicating reasonable pressurization of combustion chamber.

In the static fire tests, a system composed of 4 load cells (each one with a maximum reading capacity of 50 kgf), a signal amplifier, and a ARDUINO NANO board, connected to a computer for reading the data through an ARDUINO code was made by the LUFFT team. After the assembling of the rocket motor and the data acquisition system, the ignition of the rocket motor can be seen in the Fig. 11.

Figure 11. Static Fire Test in the beginning of the combustion

By the end of it, it was observed that the burning time was too long, which indicates a lack of pressurization. Also, an analysis was made of the images captured during the burning, and there is deposition of viscous material seeping out of the nozzle in one of the images, that can be seen in the Fig. 12.

Figure 12. Static Fire Test with bad combustion

The hypothesis accepted by the team is that dextrose was not well mixed with potassium nitrate. Given the flaws, the team concentrated on modifying and improving the chemical manufacturing process of the propellant, whose discussion was previously addressed, where reducing grain size, cristallization of nitrate potassium, heating the beans to remove the water before the casting process, among other things, were crucial to improve the other static fire tests and are one of the most important results that the authors share.

It was also built a new support structure, where team members could see mechanical fabrication processes such as welding and machining, and the data acquisition system was remade, this time with a single load cell with a maximum reading capacity of 200 kgf, that can be seen in the Fig. 13.

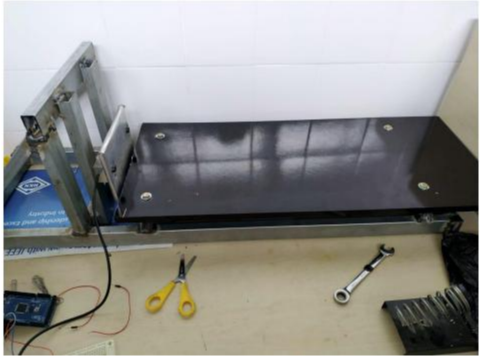


Figure 13. Static fire test platform made by the LUFFT team

Given the new testing structure and the modifications to the chemical manufacturing process of the propellant grain mentioned other static fire test was performed, as illustrated in the Fig. 14.

In the flight test, the rocket is prepared for the flight to obtain the desired data, which in this case would be the altitude, Fig. 15. In both cases the performance of the rocket motor is evaluated in relation to being consistent with the projected data and, mainly, if there was no failure or no explosion that caused any damage to the rocket components.

Figure 14. Static fire test of the rocket motor of SELENE

The authors reinforce the prioritization of experimentation, where through the learnings of other static tests, the rocket motor of SELENE reached the safety conditions of the project to carry out a flight test, integrated with the other parts of the rocket.

Figure 15. Flight test of the rocket motor of SELENE

The inhibition is of fundamental importance so that the casing do not suffer thermal or mechanical structural damage, due to the increase in temperature and pressure during the propellant combustion process, addressed throughout this article. As a result, it was possible to reuse the same casing for all static fire tests and the flight test, due to the iterations supported in the THERMCAS software tables to obtain the thickness of the inhibitor.

4. CONCLUSIONS

With the obtained results, this paper offers assistance in the manufacture of propellant grains of a rocket, as well as discusses the necessary thermal protection to keep the activity safe, demonstrating the importance of inhibition to solid propellant rocket motors and how it applies in the design of a real rocket. The authors and LUFFT amateur rocketry team hope that other amateur rocketry teams will achieve reproducibility through what was discussed in the article.

The importance of a multidisciplinary team in a mechanical engineering project is clear, since the project addresses numerous themes and subjects, so a team with a plurality of knowledge only makes us achieve greater goals.

The contribution of this article is to guide the current bibliographic reference on model rockets, which, as discussed exhaustively throughout the text, are (Nakka, 2020a) and Sutton and Biblarz (2017). In addition to the subjects covered in this article, lessons learned in manufacturing processes such as welding, machining, laminating polymeric materials in the outer fuselage of the rocket were incorporated into the team members.

The New Space scenario in Brazil is still very recent and student teams play an extremely important role in the development of this scenario, because they are constantly studying and improving the engineering applied to their rockets in order for their members to continue expanding their knowledge even after they graduate, either through the academic or corporate areas. Therefore, it is of utmost importance that there is the transfer of knowledge between the teams so that they increasingly push their limits and that Brazil becomes a reference in the aerospace area in the near future.

5. ACKNOWLEDGMENTS

The authors are grateful for the collaboration of the LUFFT rocketry team, the IEEE UFF Student Branch and Federal Fluminense University.

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7. RESPONSIBILITY FOR INFORMATION

The authors are solely responsible for the information included in this work.