Combustion Performance Comparison of Propellant Grain for Hybrid Rocket Motors Manufactured by Casting and Fused Deposition Modeling

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Abstract—**Two manufacturing processes were performed to obtain fuel grains for hybrid rocket engines. Experimental comparisons were made between paraffin grains obtained by traditional casting methods and Acrylonitrile Butadiene Styrene (ABS) grains obtained by Direct-Digital Manufacturing (DDM). The comparative process shows results that present significant advantages between the use of fuels obtained by casting and those obtained by DDM. Features such as dimensional tolerance control, structural strength, presence of cracks and micro combustion chambers are some of the improvements that DDM offers over traditional casting fuel grain manufacturing methods. This characterization was performed on a hybrid rocket engine, designed to inject 99.99% pure nitrous oxide into a combustion chamber with a capacity to withstand 1000 PSI of pressure, and an easy-to-exchange nozzle to avoid erosive behavior in the throat. Parameters such as chamber pressure and engine thrust were measured during the test procedure.**

Index Terms—**Hybrid Rocket Motor, Paraffin, Direct digital manufacturing, Castin, Acrylonitrile Butadiene Styrene, Fused deposition modeling.**

I. Introduction

In the last 20 years, aerospace propulsion technology has turned its attention to the exploration and investigation of hybrid-type propulsive systems. [1] The hybrid rocket motor mixes oxidants and fuels in different phases to obtain combustion processes of great performance and versatility. [1]

The hybrid propulsion systems have generated a special interest in researchers because of its attractive possibility of commercial uses and space applications, which are appropriately used in missions requiring long-duration combustion process, command shutdown and restart, throttling, storable non-toxic propellants or operations that require non-self-deflagrating propulsion systems. [2]

Different experimental hybrid rocket motors have been flown in experimental vehicles and ground tested from 2 to 250.000 lbf thrust. However, there is not sufficient information on larger production systems or larger production lines available. [3]

On the other hand, the growing boom of three-dimensional manufacturing technologies has opened up a number of possibilities for development and manufacture of parts, prototypes and mechanisms with geometries of significant complexity.

Access to this technology is becoming more widespread and the cost of implementation and application are diminishing, which makes these processes an attractive manufacturing alternative for research and technological activities. [4]

An experimental campaign used the FDM (Fused Deposition Modeling) methodology, which is a technology that belongs to one of the branches of computer-controlled manufacturing and takes advantage of melting a thermoplastic polymer to deposit it in layers to generate different geometries layer by layer. [5]

The versatility of this additive manufacturing process and the ease of acquiring and manipulating polymeric materials will be exploited to generate fuel grains. It has been found that manipulation of geometric aspects in fuel grains used in hybrid propulsion systems can increase up to three times the regression rate in combustion processes, which allows better performance in hybrid rocket motors. [6] The use of thermoplastic polymeric materials in hybrid propulsion systems is a concept that has been recently studied and can be used to take advantage of its manufacturing processes and thermodynamic properties. [3, 4]

The other type of fuel used was commercial grade microcrystalline paraffin [7], cast in molds with a traditional casting method, and adjusted to the geometry of the combustion chamber. The combustion port geometry of both type of grains used in this campaign was a cylinder with constant diameter through the grain length. This research seeks to generate a comparison of the variability of some performance parameters during combustion between fuel grains obtained by three-dimensional manufacturing technologies and traditional casting and molding processes, using ABS and microcrystalline paraffin respectively.

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The parameters to be compared between the fuel grains are thrust and chamber pressure, which are measured on a custom static test bench and connected to a nitrous oxide line as an oxidizer.

II. Methods

A. Overview of Hybrid Rocket Engines

Hybrid rocket engines have proven very useful features in four different aspects of aerospace development: 1) possibilities of re-ignition and controlled acceleration, 2) safety in manufacturing, storage and transport, offering a lower chance of explosion or detonation, 3) higher specific impulse than solid rocket engines and higher specific density-impulse than liquid engines, 4) lower operating and manufacturing costs compared to liquids. [2]

Inside the combustion processes in hybrid rocket engines, the gas-phase flow is restricted to the interior of the inner fuel grain surfaces, obtaining an internal tube flow. Parameters such as axial temperature, pressure, enthalpy and mixing ratios can be factors that affect the formation of the boundary layer inside the combustion port of the fuel grains [1], and the main flow of gases from the combustion process is accelerated axially along the combustion port and accumulates, generating pressure gradients inside the engine.

In general terms, the energy balance represents the most complex boundary condition since it includes both conductive and radiative thermal transfer phenomena as well as enthalpy changes that must be quantified. A general expression that can be used to make this energy flux balance is:

$$Q_{tot} = \rho_f c_s\, r(T_s - T_0) - \rho_f\, r\left[\Delta H^o_{f,poly} + c_s\,(T_s - T_{ref})\right] + \rho_f\, r \sum_i^n Y_{i+}\left[\Delta H^o_{f,i} + \int_{Tref}^{Ts} c_{p,i}\, dT\right] \quad (1)$$

Where

ρ_f: Fuel density
r: Regression rate
T_s; T_0; T_{ref} : Temperatures of surface; oxidizer; reference
$\Delta H^o_{f,poly}$: Heat of formation (polymer)
Y_{i+}: Mass fraction above surface
$c_{p,i}$: Gas isobaric specific heat
c_s: Fuel specific heat

In (1) Q_{tot} represents the total heat flux received by the fuel surface due to radiative and convective heat fluxes in the boundary layer. [1] The regression rate of hybrid rocket motors has been found to be highly dependent on the rate of oxidant flow rate supplied, unlike solid motors where the burn rate is a function of chamber pressure. One of the most influential theories for understanding the burning process of hybrid engines was proposed by Marxman and Gilbert [8], who proposed that the presence of a flame sheet inside the combustion port separates the boundary layer into two parts. These parts are the upper zone which is rich in oxidant and where the temperature and speed gradients have opposite directions, while in contrast, the lower zone that is rich in fuel presents both speed and temperature gradients that are in the same direction.

The heat transfer generated by this flame is the control mechanism of the combustion process inside a hybrid rocket engine and takes place in a location where the concentrations of fuel and oxidant are adequate to develop the combustion; however, these concentrations are not necessarily stoichiometric. Using these assumptions Marxman and Gilbert [1] proposed the local regression rate of a solid fuel given by:

$$\rho_f r = CGRe_x^{-0.2}\left(\frac{St}{St_o}\right)\left(\frac{u_e}{u_{fl}}\right)\left[\frac{(h_{fl}-h_w)}{\Delta H_{v\,eff}}\right] \quad (2)$$

C: Function of Mach number (about 0.03 for low Mach n. in hybrids)
G: Local mass flux due to oxidizer and fuel.
S_t: Stanton number.
S_{to}: Stanton number for turbulent flow over flat plate.
u_e: Velocity at the edge of boundary layer.
u_c: Velocity of flame.
h_{fl}: Stagnation enthalpy of at the flame temperature.
h_w: Enthalpy at the wall in gas phase.
$\Delta H_{v,eff}$: Total heat of gasification.

This equation allows the calculation of the regression rate which depends mainly on G, the total mass flux, (oxidant and fuel flux) at any axial position along the combustion port. Additionally, G decreases as the port area increases during burning. This may suggest that the regression rate increases with the axial position of the grain and decreases with time, but it has been found experimentally that there is a slight negative dependence on the regression rate as the axial position approaches the nozzle.

Marxman and Gilbert explained this behavior as a consequence of the thickening of the boundary layer and its adverse effects on the heat transfer processes. As the flow approaches the outlet, the boundary layer temperature and the normal velocity gradients to the fuel surface become less influential and the convective heat transfer rate decreases. [1, 9]

B. Acrylonitrile Butadiene Styrene as Hybrid Rocket Fuel

The most widely used fuel in hybrid rocket engines has been hydroxyl-terminated polybutadiene (HTPB), which is a thermoset polymer which is also used in areas other than rocket propulsion systems.

The properties of the HTPB fuel grain obtained may vary depending on factors such as the percentage of mixture, relative humidity, amount of gas retained inside during solidification, temperature and drying time. Typically, a grain of HTPB requires 10 to 15 days to dry completely, and its solidified geometry cannot be modified. This polymer is currently not recyclable or reusable. [10]

As an alternative material to HTPB, Acrylonitrile Butadiene Styrene (ABS) is proposed; its most relevant characteristic in this field is its ability to be manufactured by direct digital manufacturing (DDM), in addition to being a material of extensive production worldwide, it is low cost and recyclable multiple times. The worldwide ABS production rate reported 10.8 million tons in 2016. [11]

ABS, although classified as a material not used in rocket propulsion systems, exhibits attractive properties for this purpose. The possibility of being manufactured by DDM processes, specifically Fused Deposition Modeling (FDM) is an alternative that offers the possibility of manufacturing more geometrically and structurally consistent fuel grains, in addition this manufacturing process allows obtaining a wide range of geometries in the combustion ports, which constitutes a method of improving the burning processes in this type of engines. [10]

Karabeyoglu et al. [12] reported in experiments made with thermoplastic polymers, that the formation of liquid droplets separates them from the liquid fuel layer and mixes with the oxidant flow, which has an overall effect of increasing the regression rate in hybrids.

C. *Paraffin as a Fuel Grain Obtained by Casting for Hybrids*

Paraffin wax has been studied for more than ten years as an alternative fuel to HTPB in hybrid rocket engines. It has been shown to have superior advantages over HTPB in generating regression rates three to five times higher. This phenomenon is due to the formation of a hydro-dynamically unstable liquid layer on the fuel surfaces during the combustion process, which allows the above-mentioned liquid droplets to be released into the main oxidant flow within the combustion port. [12]

This material also has important advantages over HTPB and even other combustible materials, some of which are non-hazardous, non-toxic, transportable by cargo, recyclable and reusable. Paraffin has between 13 to 16% higher density than kerosene, and although it has the same energy density per unit mass, it is not explosive, and its physical properties allow manufacturing processes of low complexity and low cost.

The paraffin wax easily generates micro-cracks, casting defects and micro structural discontinuities, which is mainly due to the intrinsic fragility of the material and the high volumetric shrinkage, with ranges from 15 to 25% depending on the paraffin type. This last characteristic can even affect large-scale production conditions, since it presents thermal gradients inside the solid, generating geometric variations at the molding stage.

Similarly, the management of densities in the two co-existing phases at the time of grain manufacture presents a challenge for the grain producer. [13]

D. *Experimental Setup for ABS and Paraffin Fuel Grain Fire Test*

The objective of this research is to make an experimental comparison between fuel grains of ABS manufactured by the FDM method and fuel grains of microcrystalline paraffin manufactured by the traditional casting and molding method. Several tests were performed on ABS and paraffin grains of identical size on a static test bench developed at the Universidad de Los Andes and tested at the Universidad de San Buenaventura in Bogotá.

This section details the construction and assembly aspects of the test engine and the manufacturing processes of the test fuel grains.

Motor Case and Igniter Assembly.

A static experimental hybrid engine was developed for comparative testing of fuels. The Fig. 1 shows the internal distribution of the built hybrid rocket motor for the tests. To start the combustion, a 30 g solid magnesium-based propellant igniter was used. Nicrom-based electronic matches initiate the igniters with a 12V signal sent from the main control console. E-matches and igniters are replaced after each test.

For chamber pressure measurement, a connection port was located on one side of the case, and a check valve

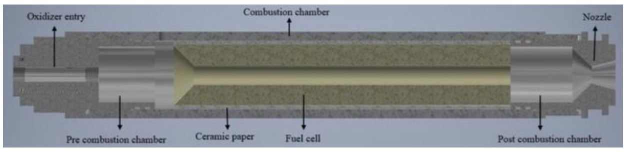

Figure 1. Cross section view of the hybrid rocket case. [14]

was connected between the pressure transducer and the combustion chamber. 10 ml of *Nuto H100-Mobil*® oil was poured into the check valve to reduce heat transfer between the combustion zone and the pressure transducer.

The Table I shows the main features of the hybrid rocket motor.

ABS fuel Grain Fabrication.

Several ABS fuel grains were manufactured with *Prusa Tayrona* FDM equipment, controlled by the *Repetier Host* software and commercial grade 1.75 mm diameter thermoplastic filament with an approximate monomer mole fraction of 50:47:3 (Butadiene: Acrylonitrile: Styrene), imported by *Shenzhen Esun Industrial Co*®.

The result of this manufacturing process was a grain with an approximate mean weight of 277.5 g, a volumetric shrinkage of approximately 4.1%, mass gain by absorption of ambient humidity of 0.12% and no apparent measurable deformation.

The fuel grains were designed with a 14.9 mm long conical inlet, which acts as a pre-combustion chamber to prevent erosive wear and chaotic combustion inside the combustion chamber. [5]

TABLE I. MOTOR CASE, NOZZLE, INJECTOR AND FUEL GRAIN FEATURES.

Motor case	365.02 mm Length	63.5 mm Diameter	--
Nozzle	21.5 mm Exit Diameter	12.5 mm Throat Diameter	2.95 Expansion ratio
Injector	0.094 in Orifice Dia. Nom.	0.094 in Max free Passage Dia.	BSJ Spiral Jet (Spraying Systems®)
Grain	248 mm Length	44.8 mm Diameter	7mm^2 Port area

The grains were coated with alumino-silicate ceramic fiber-based fabric (CeraTex®) to protect the case from the thermal damage. Some relevant features of the printer configuration are shown in Table II.

TABLE II. FDM EQUIPMENT CONFIGURATION FOR ABS FUEL GRAIN FABRICATION.

Software	Infill	Equipment general features
Slic3er Prusa Ed. 1.2.2 (Slicer)	Fill density: 100% Fill pattern: Concentric Top/bottom fill pattern: Concentric	Filament diameter: 1.75 mm Filament density: 975 kg/m^3
Repetier Host V2.0	Advance: Solid infill threshold area: 70 mm^2	Temp. Extruder First layer: 225 ℃ Other layers: 220 ℃ Hot-Bed First Layer: 95 ℃ Other layers: 95 ℃
RepRap Marlin/Sprinter (G-code flavour)	--	Nozzle diameter: 0.4 mm

Paraffin Fuel Grain Fabrication

The paraffin fuel grains were casted and molded using the product Sasolwax 0907® belonging to the microcrystalline paraffin type. The main manufacturer data are presented in Table III.

The manufacturing process of these grains consisted of a melting process of the raw material at 97 ℃ in a hotplate with temperature control and magnetic agitation, until a liquid consistency was obtained. Cylindrical molds of polyvinyl chloride with an internal diameter of 44.5 mm and a length of 248 mm were previously prepared.

The process of pouring the liquid paraffin into the molds was performed at 85 ℃ and cooling was allowed inside the mold, filling with additional liquid paraffin in the upper part due to the effect of volumetric retraction. Mineral oil applied in a layer on all the surfaces in contact with the paraffin was used to remove the mold. Once the grain was demolded, it was covered with the same CeraTex® fabric as mentioned in the manufacture process of the ABS grain.

Static Test Bench and Instrumentation.

A static test bench was designed and built for the development of this project. It is a device that allows the measurement of pressure in the combustion chamber and axial thrust of the engine.

TABLE III. SASOLWAX 0907, MICROCRYSTALLINE PARAFFIN WAX PROPERTIES. [7]

	Congealing Point (℃)	Oil Content (%)	Penetration 25 ℃ (mm/10)	Viscosity 100 ℃ (mm^2/s)
Sasolwax 0907®	83-94	0.0-2.0	4-10	8.5-12.5

This test stand supports a liquid nitrous oxide feed system that is regulated by a back pressure/regulating valve at 3447 kPa and passes through a flow control valve to finally enter the solenoid valve which is actuated from the instrumentation system.

Fig. 2 shows the piping diagram of the test bench. The axial load of this bench was measured with a Lexus® load cell type S model SA (500 N) located along the axial axis. The output response of this sensor is 2.0 ± 0.2% mV/V and excited with a 12 V DC source. The combustion chamber pressure was sensed with an EBCHQ PT258B® (0-60 MPa) pressure transmitter excited with 24 V DC and located next to the combustion chamber. The measuring systems were pre-calibrated with control inputs and are reported in Table IV with the installed calibration data.

TABLE IV. MANUFACTURER AND INSTALLED SPECIFICATIONS FOR STATIC TEST BENCH.

Instrument reference	Operating Range	Manufacturer accuracy	Installed accuracy
EBCHQ PT258B®	0-60 MPa	±0.25% FS	±13 kPa
Lexus® SA	500 N	±0.2% FS	±1.5 N

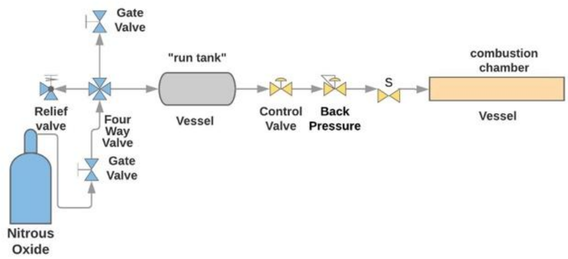

Figure 2. Hybrid rocket piping scheme used for fire-tests.

III. RESULTS

To analyze the manufacture behavior of ABS and paraffin as a fuel for hybrid rockets, a preliminary screening experiment was made with three replicates.

Measures of thrust and pressure were taken by sensors every hundred milliseconds in each run with each grain in each replicate. One block of ABS and one of microcrystalline paraffin wax were burning in each replicate in a randomized way.

The fire tests that were performed for seven-second thrust curves using each grain during each replicate are shown in Fig. 4. ABSB1E is for the first, ABSB2E for the second and ABSB3E for the third replicate made with ABS fuel grains. However, during the second replicate some adjustments to the oxidizer's control valve had to be made, affecting its performance. Similarly, the thrust behavior provided by paraffin is shown. Similarly, PB1E corresponds to the first replicate and so on.

The behavior of pressure is shown in Fig. 3 ABSB1Pr, ABSB2Pr and ABSB3Pr corresponds to replicate one to three respectively.

To statistically analyze the observed distributions obtained during the runs, adjusted box plots are used. Fig. 5 shows thrust behavior in each replicate with each grain.

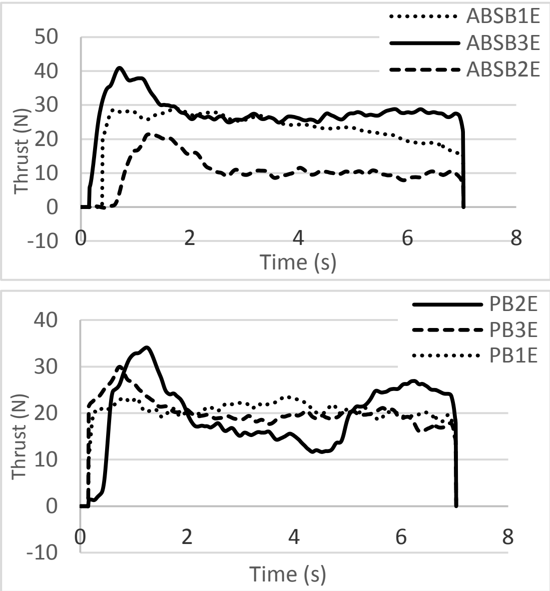

Figure 2. Pressure curves with ABS and paraffin fuel grains on each replicate. (ABS above, Paraffin wax below)

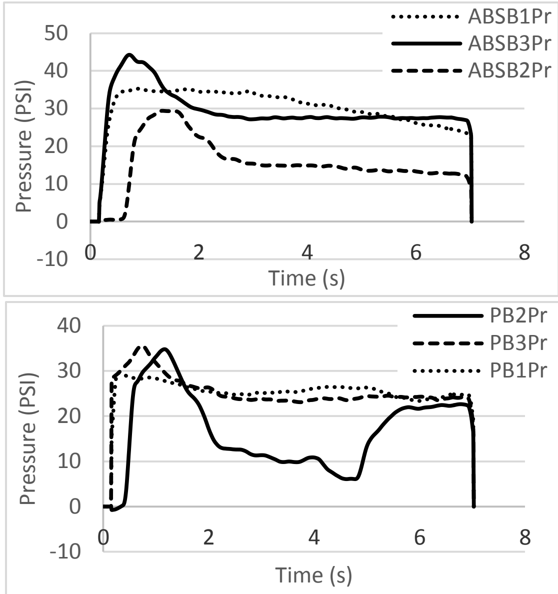

Figure 3. Thrust curves with ABS and paraffin fuel grains on each replicate (ABS above, Paraffin wax below).

The notches in the boxes correspond to median confidence intervals. Moreover, they are constructed to show evidence of significant differences in the median when the notches do not overlap at roughly 5% significance. However, when the notches of the boxes do overlap, this does not allow researchers to conclude that they are equal medians since it is not necessarily true. [15] Therefore, ABS fuel grain in replicate one (ABSB1E) has a significantly greater median thrust than paraffin grain in the same replicate (PB1E). ABS grain also produces significantly more thrust in the third replicate when compared to paraffin one, see (ABSB3E) and (PB3E).

The second replicate shows a different behavior since it is the only one that shows paraffin grain (PB2E) with a significantly greater median thrust than ABS fuel grain (ABS2E). In fact, during the second replicate an adjustment to oxidizer mass flux had to be made in order to optimize the rocket motor performance. This adjustment was made while the engine was running, hence the behavior observed in the respective graphs. As a result, Fig. 5 also shows that ABS fuel grain is more sensitive to changes in the oxidizer mass flux, since its median falls compared to paraffin grain.

Replicate two also has a symmetric distribution for PB2E and less skewed distribution for ABSB2E. It is interesting that when comparing ABS grain behavior replicate one to three (ABSB1E and ABSB3E) the distribution skew changes from negative to positive, and in the case of paraffin, (PB1E and PB3E) from a slightly positive skew to a more positively skewed distribution in replicate three. This could be caused by the adjustment made in the oxidizer during the second replicate.

Fig. 6 shows pressure-adjusted box plots where the notches on each replicate show enough evidence at roughly 5% of significance that median pressure is greater

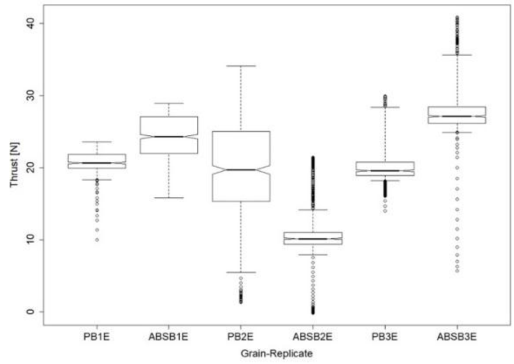

Figure 4. Adjusted box plot for thrust with ABS and paraffin fuel grains.

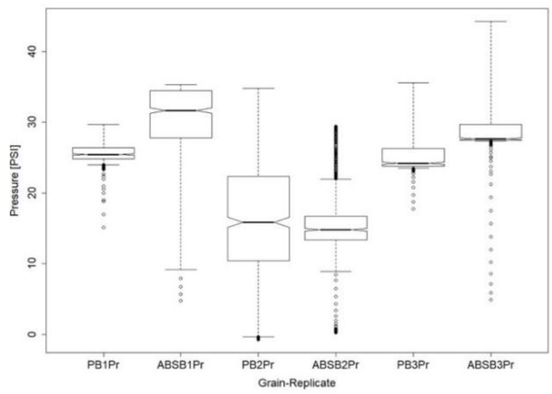

Figure 5. Adjusted box plot for pressure with ABS and paraffin fuel grains.

with ABS grain than with paraffin grain but replicate two where notches overlap give inconclusive information. In replicate two, also paraffin (PB2Pr) has more dispersion than paraffin in replica one and three (PB1Pr and PB3Pr). Similarly, the adjusted box plot for thrust,

Fig. 4, shows that there are skewed distributions especially in replicates one and three.

Replicate two has practically symmetric distribution for PB2Pr and ABS2Pr. On the other hand, ABS3Pr has positively skewed distribution in contrast to ABS2Pr that is negatively skewed, so pressure behaves similarly to thrust when using ABS; however, paraffin in both replicates (PB2Pr and PB3Pr) has positively skewed distributions with more variability in the third replicate that could be caused by the adjustment in the second replicate.

IV. Conclusions

With all data obtained during this screening experiment, we can see that the fuel grains obtained by FDM methodology (ABS fuel grain) generally performs better than the fuel grains obtained by traditional casting method (microcrystalline paraffin) in terms of parameters such as pressure and temperature. It can also be concluded that the grains of ABS fuel are more sensitive to oxidizer mass flow variations, which could make this fuel a very suitable candidate for hybrid rocket engines with acceleration capability and thrust control via oxidizer mass flow adjustment. This behavior, although also evident in paraffin grains, generates a lower consistency in pressure and temperature parameters. More experimentation is needed to confirm this preliminary analysis, especially oriented towards the variation of the O/F ratio of ABS-based fuels and microcrystalline paraffin waxes. Similarly, an in-depth study can be made of the relationship between the behavior of grains manufactured by FDM (ABS suggested as fuel) and hybrid engines, particularly regarding the ability to control the thrust and therefore the ability to control the acceleration of the vehicle carrying these engines.

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