

COB-2023-2313

COMPARATIVE STUDY OF THE TECHNICAL AND ECONOMIC FEASIBILITY BETWEEN ABLATIVE MATERIALS AND SPECIAL ALLOYS APPLIED IN THE ROCKET ENGINE.

Willem Vieira Nascimento

Luiz Cláudio Pardini

Instituto Tecnológico de Aeronáutica, Praça Marechal Eduardo Gomes, 50 – Vila das Acácias 12228-900 – São José dos Campos, SP - Brasil.

e-mails: willem.vieira@hotmail.com, luizpardini@gmail.com

Abstract. *The aerospace sector is of fundamental importance for the development of humanity, such as the telecommunication sector etc. This was possible due to the development of new materials that resist there are various phenomena: physical, chemical, aerodynamic, thermodynamic among others, with emphasis on the extremely high temperature to which the rocket is subjected. Mainly the nozzles of rocket propulsion engines, the gases from burning of propellant and the drag make it necessary a thermal protection system due the erosion caused by the flow of gases. Therefore, a thermal protection system (TPS) is necessary. At the moment, are also using special alloys together with the regenerative cooling system. The present study investigated, based on the literature and normative parameters, the main materials for this type of application, and comparing the advantages and disadvantages of traditional ablative materials and the special metallic alloys currently employed by SpaceX e NASA. The Therefore, it is concluded that the special metal alloy has the advantage of being reused differently ablative materials. In addition to that, it presents a cost reduction in space exploration.*

Keywords: *ablative materials, nozzles, nickel super alloy, regenerative cooling*

1. INTRODUCTION

The aerospace sector has been essential to humankind's progress, and this relationship is growing at an exponential rate. Several technologies are now present in society's existence as a result of space exploration and the knowledge acquired from it, such as the internet via satellite, the telecommunications industry, climate monitoring, autonomous navigation, and transport, among other diverse uses. With the space race between the United States and the Soviet Union in the early 1960s, the space sector rose to prominence. Currently, numerous other countries, including the European Union, Japan, China, and India, stand out in this category. Brazilian research in this field began in the 1960s, with the development of sounding rockets with solid propulsion. The mastery of this technology served as the foundation for the construction of the Satellite Launch Vehicle (VLS) in the 1980s, as it is shown in Figures 1 (Gomes et al, 2010).

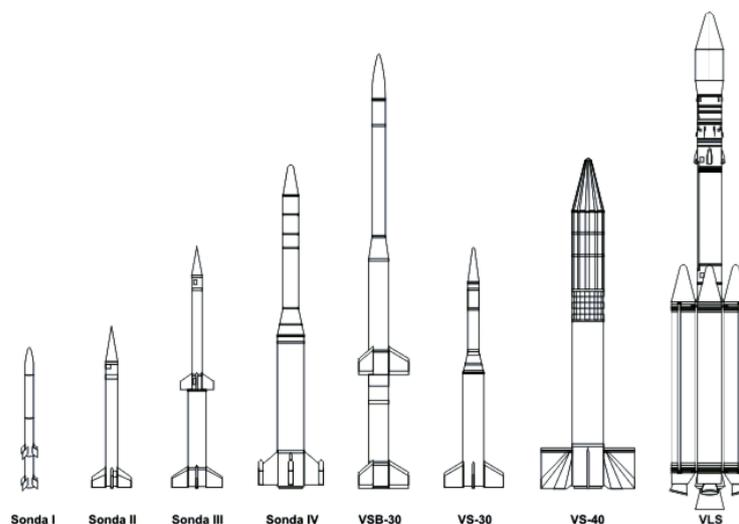


Figure 1: Evolution of launch vehicles of the Brazilian aerospace industry.

Space exploration's success is the result of improvements in study in a wide range of domains of knowledge, which include the development of novel materials that match project standards. Among these design requirements for aerospace systems, high thermal and chemical resistance, low specific mass and high mechanical strength and stiffness stand out. Composite materials are a type of materials that have been meeting these requirements for a long time. Among composite materials, ablative materials meet these requirements satisfactorily, especially when the requirements are more stringent, such as high temperatures and erosion in the combustion chamber, nozzle of rocket engines, for example, induced by the flow of gases from fuel combustion. For these applications, conventional materials could not be used until then, since thermal degradation could generate catastrophic failures. Therefore, a Thermal Protection System (TPS) based on ablative materials is necessary (Silva, 2015).

The National Aeronautics and Space Administration (NASA) of the United States has consistently been and continues to be a major participant in the development of rockets and space exploration. However, private businesses have lately entered this area, with particular emphasis on SpaceX, which arose in the early 2000s intending to build reusable space vehicles with lower prices and higher reliability. SpaceX has built a family of launch vehicles to accomplish this goal, as illustrated in Figure 2. It has also developed the Dragon capsule, which will deliver supplies and crew to the International Space Station (ISS). The Starship is a reused second stage vehicle (Ashutosh and Bhowmik, 2021).

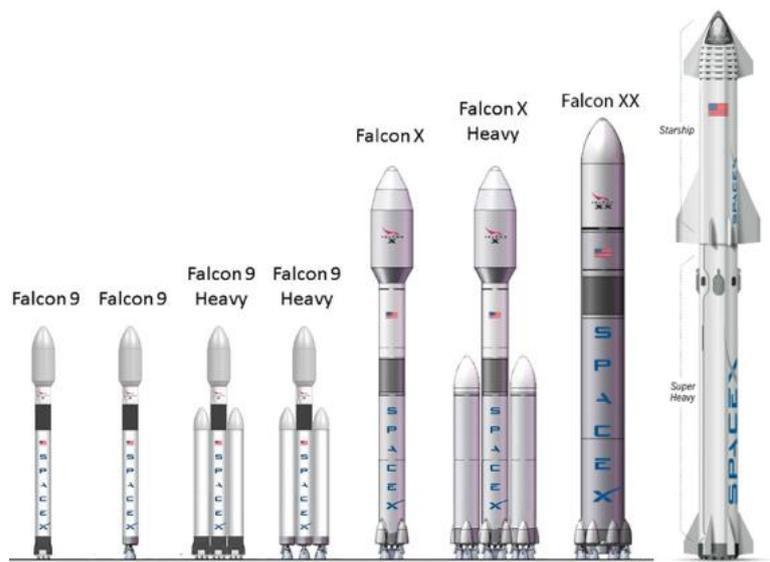


Figure 2: Rockets developed by SpaceX from 2002 up to present day.

Ablative materials are challenging to manufacture, have significant costs, and are often not reusable. Both NASA and SpaceX have begun to build engines in metallic materials in recent decades, to reuse the launch vehicle. SpaceX succeeded in 2015 by bringing back to Earth the Falcon 9 launch systems that previously had been abandoned. As a result, the company was capable of using the same platform for several launches, which led to significant cost savings, shorter time between launches, increased engine availability, and reduced manufacturing time. One reason that enabled this advancement was the use of metallic alloys in various areas of the rocket engine, including the nozzles and combustion chamber. Among the alloys employed, Inconel alloys such as the N06625 and N07718 family stand out (Kumar and Bhowmik, 2021).

2. OBJECTIVE

Based on literature documents and technical standards such as ASME and ASTM, compare the ablative materials and metallic alloys currently used by SpaceX and NASA in their rockets, exemplifying the main physical phenomena applied to the ablation process and the mechanical behavior of metallic alloys at high temperatures, along with the advantages and disadvantages of using metallic materials.

3. PRESENTATION OF ABLATIVE PHENOMENON

In the aerospace industry, ablation is described as a simultaneous heat and mass transfer process that consumes thermal energy owing to mass loss from the material's surface. This incident heat flow can be absorbed, dissipated, or inhibited. Melting, sublimation, vaporization, chemical changes, and decomposition are all examples of endothermic events that occur during the ablation process. Ablative materials are distinguished by the partial and progressive

destruction of the material caused by strong heat fluxes, as seen in Figure 3, which depicts an example of the ablation of a phenolic matrix composite reinforced with quartz fibers. This occurrence of extreme thermal fluxes occurs during the atmospheric re-entry of space spacecraft or when gases at high speeds and temperatures pass through the region of rocket nozzles. When talking about rockets, ablation also occurs inside de propellant combustion chamber. In this case, the elastomer, EPDM or nitrile rubber, which insulates the motor case from the burning of the propellant suffer the effects of ablation by creating a protective layer of carbon char during the propellant burning time. This mechanism of ablation in this case is the same as that which occurs during re-entry on external surfaces of launch vehicles (Natali. et al, 2016).

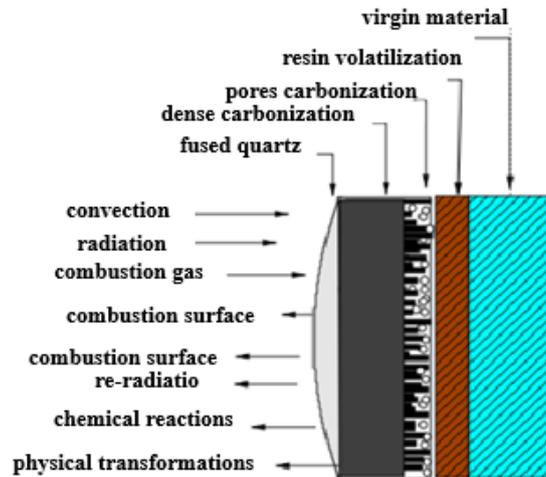


Figure 3: Scheme of the ablation mechanism, quartz fiber reinforced phenolic resin, for instance.

Thermal protection material that undergoes pyrolysis of organic material (carbonization) is often composed of a phenolic resin composite reinforced with reinforcing fibers, typically carbon fibers or silica fibers. The initially undecomposed substance is subjected to the flow of heat via aerothermodynamic heating, which raises its temperature until decomposition occurs. This causes the polymer to pyrolyze, resulting in the formation of a carbonized coating (char), held together by the fibers, that progresses towards the interior of the protection. Pyrolysis gases cross the carbonized layer (flow in porous media), absorbing energy through sensible heat and undergoing molecular cracking. Finally, they are injected into the boundary layer, causing the thickening of the boundary layer to restrict the passage of heat from aerodynamic heating. The carbonized surface region is often constituted primarily of insulating porous carbonaceous material that can resist high temperatures, resulting in significant heat rejection via radiation. Figure 9 (a) shows the reactions and different sections of the material, whereas (b) shows the temperature profile from the outermost layer to the protected material (Silva, 2015).

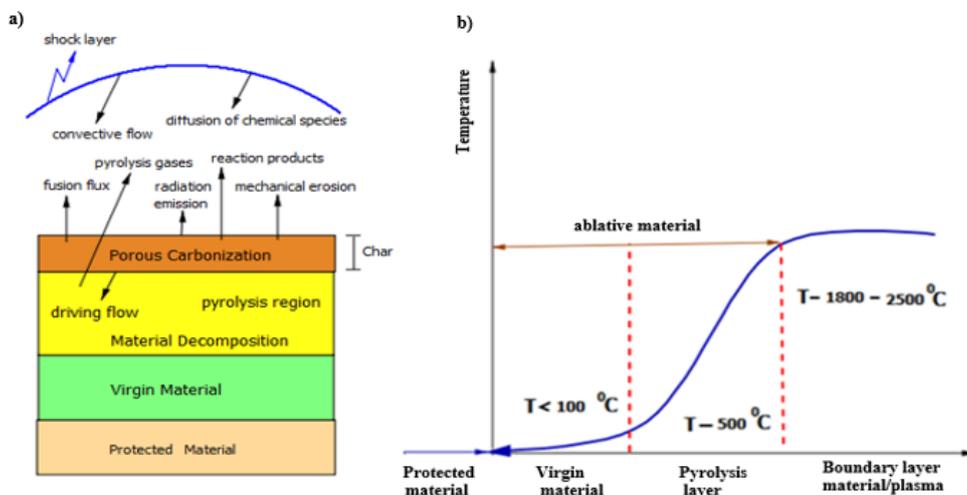


Figure 4: (a) Schematic section of a material under ablation; (b) Distribution of temperature throughout the body.

One of the major advantages of this sort of thermal protection is its low weight when compared to metallic materials. Ablative materials have shown to be useful since they have been utilized from the beginning of the space race to the current day, including vehicle coatings for thermal protection of the space shuttle and atmospheric reentry capsules. Polymers based on phenolic resins, elastomers, and carbon stand out among a variety of materials. When it comes to reinforcements, carbon, boron, quartz, and even asbestos fibers provide the designer with the potential for flexibility in structural designs while satisfying performance requirements. The selection of the phenolic matrix is because, when subjected to high temperatures, it manages to maintain 50% by mass of carbon, mainly due to the high degree of crosslinks, the carbon-hydrogen ratio in the phenolic, and the tendency for more bonds during heating, i.e. high energy of dissociation. Thermal stability of phenolic resin: new insights based on bond dissociation energy and reactivity of functional groups. (Bian, C. et al, 2016). This carbonaceous residue can absorb the heat generated during the ablation process, acting as a heat sink.

It is important to emphasize that for ablative applications elastomers can also be used, some of which are EPDM (Ethylene-Propylene-Diene elastomer), polysiloxanes (Q), styrene-butadiene elastomer (SBR), polychloroprene elastomer (CR), polybutadiene (BR), butyric rubber elastomers (IIR), polyurethane elastomers (AU), fluorinated elastomers (FPM, FKM), polyacrylate elastomers (ACM), acrylonitrile butadiene elastomers (NBR). For ablative applications, thermoplastics such as polytetrafluoroethylene (PTFE) might also be mentioned. Ethylene-propylene-diene elastomers (EPDM) are thermopolymers with a low specific mass that have high thermal and mechanical properties. EPDM's ability to integrate loads at higher levels than other elastomers without loss of its properties is one of its major benefits (Silva, F. S). EPDM has been utilized as a thermal coating in rocket engines due to these properties and the ability to incorporate enormous amounts of charges. The IAE/DCTA VLS (satellite launch vehicle) is coated with ablative materials of carbon/phenolic and carbon/carbon, as shown in Figure 5. (Da Costa,1996 and Silva, 2015)

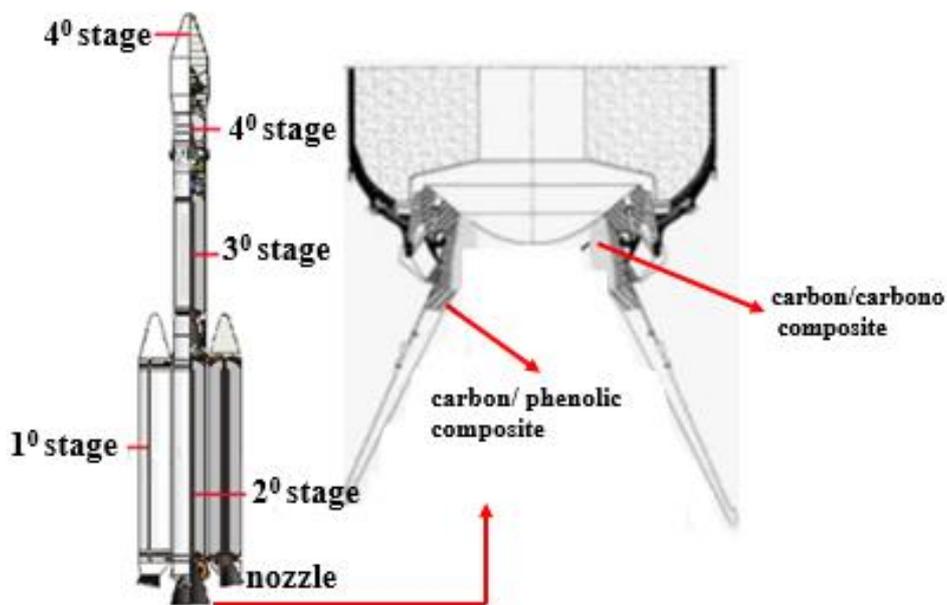


Figure 5: Diagram of a VLS composite nozzle, carbon/carbon and carbon/phenolic.

4. ANALYSIS OF THE METALLIC MATERIALS IN CRITICAL PARTS OF ROCKET ENGINE

The expansion of the space exploration market and the entry of new companies and countries into this sector encourages them to develop new products and improve on existing ones, as is the case with the various engines for space exploration, such as the AR-1, RS-25, Aerojet Rocketdyne's RL-10, SpaceX's Merlin and Raptor, Blue Origin's BE4 and BE3/BE3U, among others. Each of these systems has its own set of design requirements. In recent years, the control and landing of the primary stage on SpaceX rockets were considered a significant innovation, which was possible by the use of metallic materials, specifically nickel superalloys and Niobium base alloys used in the combustion chamber, nozzle and injectors, as shown in Figure 6, which depicts the corresponding rocket engines, of RS-25 engine that will take the crew to the moon, Artemis 2.

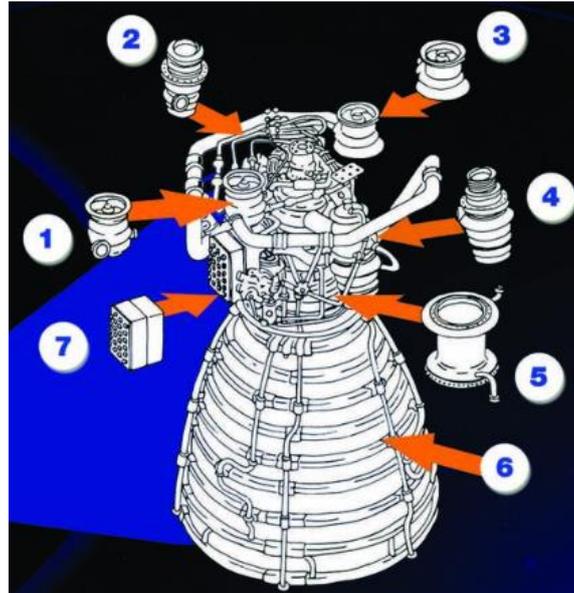


Figure 6: Illustration of the RS-25 engine and the use of metallic materials in place of ablative ones, and show the main parts of the engine: 1-4 - Turbo Pumps, 5 - Main Combustion Chamber, 6 - Nozzle, 7 - Engine Controller.

4.1 FACTORS THAT CONTRIBUTED TO THE APPLICATION OF METALLIC MATERIALS IN THE FACE OF ABLATIVES.

As previously mentioned the regions such as the combustion chamber and the Nozzle were made of ablative materials in rocket engines from various space agencies around of the world. However, the NASA and SpaceX have started employ metallic alloys in these components. The high temperatures and velocities of gases resulting from combustion are higher than the melting temperature of alloys in general. The internal energy of the propellants was used in a high pressure chamber (most combustion chambers operate between 240 to 360 Bar) to heat the reaction gases to temperatures of up to 4000 °C. These gases are then expanded in a nozzle and accelerated to high speeds (1800-4300 m/s), giving impulse the vehicle. These nozzles consist of a converging section to accelerate the gas until desired Mach number and a diverging section for continue accelerating of the fluid when it hits that spot. Figure 7, show the gas flow velocity regions (Urbano, 2012).

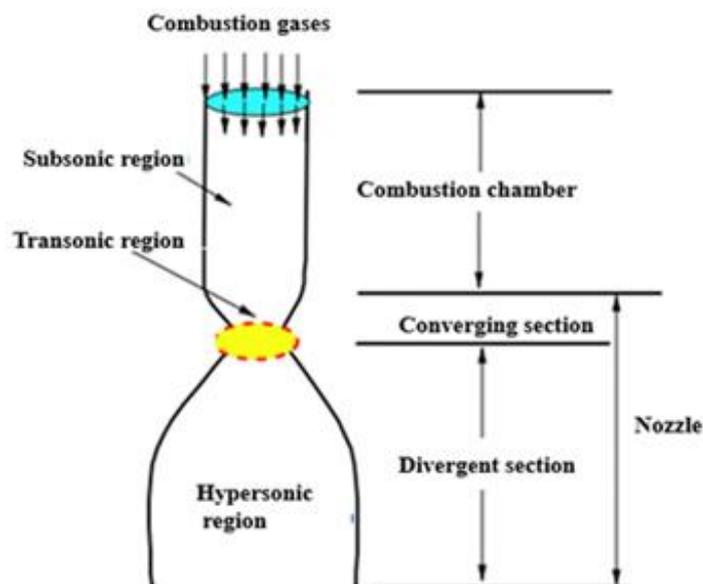


Figure 7. Show the velocities of fluid in different regions of the rocket engine.

To get around this problem was used a Regenerative Cooling System, which uses the liquid propellant itself at low temperatures as coolant, this enters through the cooling channel of the Nozzle. It is important to note that these channels have a few millimeters in diameter and meters long, and are manufactured by milling machine or welding. And Then the heated fuel enters the combustion chamber (Sutton, 2017). Figure 8 show an overview of the entire engine part and Nozzle's Regenerative Cooling System. It is important to note that the use of tubepumps in current engines makes the pressure level at the entrance of the cooling channel adequate, considering the high pressure losses that occur along these channels (Jules, 2018). That's why regenerative cooling systems are applied with systems powered by turbopumps. Pressure losses along of the channels are caused by shear stress and loss of hot (Dodd, 2019).

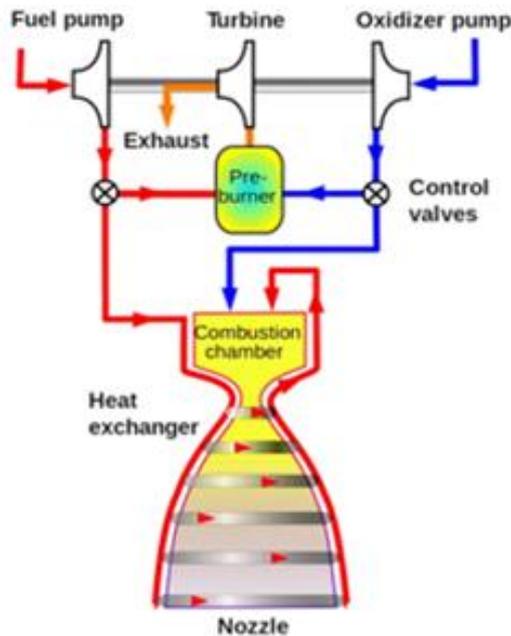


Figure 8: Overview of the Regenerative Cooling System used in the SpaceX raptor engine.

To model a refrigeration system of this complexity with several parameters and interactions involved, it must be considered a problem of coupled between the refrigerant flow, the heat transfer in the wall and the hot gas flows into the chamber. That's why one-dimensional numerical approaches are often used to describe the evolution of refrigerant flow in channels through semi-empirical correlations to relate the variables one-dimensional, which represent the behavior of the mass flow, and the variables of wall. More precisely, the body (T_b) and wall (T_w) temperatures are correlated with the heat flux (q_w) by the coefficient of heat transfer defined by Newton's law E(1) (Sutton, 2017).

$$q_w = h_c (T_w - T_b) \quad (1)$$

Nusselt number Nu and h_c are related by Eq(2):

$$Nu = hc$$

$$Nu = \frac{h_c D}{k_b} \quad (2)$$

which can be correlated with the Prandtl (Pr) and Reynolds (Re) numbers by correlations that are modifications of the Dittus-Bolter equation as demonstrated Eq(3):

$$Nu = K Re^a Pr^b \left(\frac{T_b}{T_w}\right)^c \left(\frac{\mu_b}{\mu_w}\right)^d \left(\frac{k_b}{k_w}\right)^e \left(\frac{c_{p,b}}{c_{p,w}}\right)^f \left(\frac{p_c}{p_b}\right)^g \left(1 + 2\frac{L}{D}\right)^m \quad (3)$$

where $c_p = (h_w - h_b)/(T_w - T_b)$. The coefficients K, a, b, d, e, f, g and m are related to one particular fluid and are determined from a least squares fit of the experimental data. To correlate the shear stress with the pressure losses in the momentum equation the cooling passage is considered as a hydraulic pipe and hence the friction loss can be calculated according with Eq(4) valid for a straight channel:

$$\frac{\Delta p}{\rho_b} = \frac{1}{2} f u_b^2 \left(\frac{L}{D}\right) \quad (4)$$

Where Δp is the pressure drop. Semi-empirical correlations permit to relate the friction loss coefficient f to the Reynolds number. To account for further local losses that occur when the flow direction is changed (like in bends) or the cross section changes, further pressure losses are added. These systems of pump consist of two pre-burners that use non-stoichiometric ratios of fuel and oxygen for produce controlled combustions that drive fuel and liquid oxygen inside of the combustion chamber at extremely high pressures – resulting in increased thrust and efficiency. The greater pressure in the Raptor's chamber is possible thanks to its pumping system, although it does not produce the maximum thrust, the Raptor has greater efficiency, how show the Table 1 that comparative variables between some rocket engines.

Table 1. Compares some variables for different engines.

Engines	Potential Cost (per flight per kN (\$))	Chamber Pressure (bar)	Reusability
Raptor	20	300	Yes
Merlin	117	250	Yes
RD-180	6527	257	No
F-1	4431	263	No
BE-4	133	310	Yes
RS-25	1414	366	Yes

It is important to underline that the new engines like the Raptor, Merlin, RS-25 are designed to be able to operate several times with little maintenance, whereas the older engines were designed to last a specific mission (Marí, 2021). This reduced the cost per kN of thrust from \$4,431 for the F-1 to just \$20 for the Raptor, which equates to a 99.5% reduction in price per unit of thrust. The propellants used in modern engines are liquid, as is the case of Merlin and Raptor, which uses kerosene and methane respectively, or hydrogen, as is the case with RS-25. Methane, used with oxygen, gives a higher specific impulse. Methane is less cryogenic than hydrogen, since it is stored at a temperature of 111 K in the tanks, while hydrogen at 20 K, influencing production and operating costs. Furthermore, methane is a safer fluid than hydrogen because the risk of explosion is lower (Gradl and Protz, 2020).

5. MATERIALS USED IN THE PROJECT AND WITH POTENTIAL APPLICATIONS.

The manufacturing processes, as well as the materials used in making the Nozzles, compression chamber, among others, are not disclosed in the literature in an objective and precise way due to industrial secrets. Metallic materials of public knowledge will be presented, some already used in the manufacture of nozzles. The chemical composition, mechanical properties, heat treatments will be determined in accordance with the following ASTM 2010 standards: Chemical analysis ASTM E 1473, Tension ASTM E8 and Rounding procedure E29. The metallic alloys presented in this study are N06625 and mainly N07718, both nickel-based. The Table 2 illustrates the chemical composition of nickel alloy N06625 and N07718 respectively (ASME, 2010).

Table 2. Chemical composition of inconel alloys.

Mechanical properties	Chemical composition, %, N06625 Inconel Alloy	Chemical composition, %, 718 Inconel Alloy
Carbon	0,10 max	0,08 max
Manganese	0,50 max	0,35
Silicon	0,50max	0,35
Phosphorus	0,015max	0,015
Sulfur	0,015max	0,015
Chromium	20,0 min – 23,0 max	17,0 21,0
Columbium (nióbio) + tantalum	3,15 min – 4,15 máx	4,75 -5,5
Cobalt (if determined)	1,0 max	1,0 max
Molybdenium	8,0 min – 10,0 max	2,8 – 3,3 max
Iron	5,0 max	Balance
Aluminum	0.40 max	0,2 – 0,8
Titanium	0.40 max	0,65 – 1,115
Copper	0,3
Nicker ^A	58,0 min	50,0 – 55,0

^(A)Elemento shall be determined arthmetically by difference.

It's a nickel superalloy, in which the alloying elements play important function of improving the properties of the alloy. Several mechanisms of resistance increase occur simultaneously, such as: substitutional solid solution, interstitial, intermetallic compounds and precipitation of different types of carbides. For example, tantalum is a strong former of carbide, however, it is very expensive and for this reason are used in special situations. Besides that, it has hot deoxidation power. In the alloy, niobium is a grain refiner of austenite when it is in solution or in large precipitates of undissolved carbide. The solubility of niobium in austenite matrix only occurs at high temperatures 1300 °C. Titanium, in addition to carbide formation, is also an excellent refiner of austenitic grains, especially when it acts together with aluminum, improving creep resistance.

The Most nickel superalloys have increased mechanical property values as a result of heat treatments such as annealing, solubilization and aging. The addition of chromium makes this material improve its resistance to corrosion, the presence of carbon in the alloy favors the formation of carbides such as titanium, vanadium, niobium, tantalum, silicon and molybdenum are excellent carbide formers, which serve as barrier to dislocation and consequently generating greater mechanical strength and thermal stability.

The alloy widely used in the aerospace sector in general is 718 Inconel, this alloy also has several alloying elements that contribute to the stabilization of the alloy at higher temperatures. The increase in mechanical resistance is due to precipitation hardening of Ni₃X-type phases (X = Ti, Nb, etc.), in addition to that presents the same hardening mechanism for increasing mechanical resistance mentioned previously. Generally the time the alloy passes when heat treated at elevated temperatures is several hours, as specified in the (ASME, 2010) for precipitation hardening treatment is 23 hours. In general, when the temperature increases, the resistance drops, however, in the case of these alloys, it drops to a stress level that is higher than the pressure specified in the chamber on the nozzle. The following Table 3 shows the mechanical properties of the Inconel 718 alloy, it can be seen that are practically the same chemical elements as the previous one, varying the composition of the main alloying elements such as niobium, aluminum and titanium that together with the thermal treatment, it significantly increases the mechanical resistance (ASME, 2010).

Table 3: presents values of mechanical properties for the inconel alloys.

Mechanical properties	N06625 Inconel Alloy	718 Inconel Alloy
Tensile Strenght, MPa	827	1162
Yield Strenght (0,2 % offset)	414	998
Elongation in 2in (50.8 mm) min, %	30	30

As soon, the combination of the efficient regenerative cooling system as used in current rocket engine concepts, with special alloys that withstand working temperatures around 1000 °C and pressure to 300 bar, means that these alloys can be used in the manufacture of combustion chamber, nozzle among others. Several nickel alloys and stainless steels can be studied and used in the aerospace sector.

6. CONCLUSION

Both ablative and metallic materials are of significant importance in the aerospace sector. In the last years, the ablative materials are employed in atmospheric re-entry capsule and the metallic materials in launch vehicle.

The rockets can be reused due to the regenerative cooling system, provided by the high pressures applied by the turbopumps in the cooling channels, which are made of metallic materials.

Modern engines such as Raptors have several advantages when compared to older ones, especially costs and efficiency. The substitution of ablative materials for metallic alloys in the nozzles allows the reuse of the primary system of the rockets. This made it possible to carry out several launches, thus reducing costs.

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