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# DESIGN, MANUFACTURE, ASSEMBLY AND TESTING OF A LIQUID (LOX AND GASOLINE) ROCKET MOTOR FOR A VEHICLE WITH STRATOSPHERIC APOGEE IN COLOMBIA: THE *SUA II* ENGINE

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## Abstract

This work is about the process of design, manufacture, assembly and static test of a liquid engine developed by researchers of the *Proyecto Uniandino Aeroespacial (PUA)* at the *Universidad de los Andes*. The engine *SUA II* works with liquid oxygen (LOX) as oxidizer and gasoline as fuel. This engine has an expected (and demonstrated) thrust of almost 2 kN, a burn time of 25 seconds and it was designed to be used in a vehicle of two stages (*AINKAA VI* rocket). This rocket has the objective of reach an altitude of 14 Km above sea level or more, being the first stratospheric vehicle of his type at the near region. The *SUA II* could be classified as a low cost rocket engine due to its construction budget, inferior to USD 10.000, and it is expected to be the future engine base for other vehicles designed to reach higher altitudes.

## 1. Introduction

Propulsion can be defined as the action of increasing the movement of a body through the use of different mechanisms that generate a force with the objective of produce a speed change (acceleration) of it [1]. One of these mechanisms is the rocket propulsion, which supports its operation on the generation of thrust by the rapid expulsion of gases from a jet engine; the most used power sources are: chemical combustion, nuclear reactions and / or solar radiation [2].

This work is about the development and testing of a liquid rocket engine which will be part of a multi-stage mixed vehicle of solid and liquid propulsion, manufactured and assembled with a very limited budget and using local methods, resources and industries available in Colombia. This is a breakthrough in the area with regard to South American countries and emerging space powers, which up to date have done work on solid fuel rockets mainly [3]. This type of rockets are simpler, cheaper and safer than their liquid counterparts, but at the same time have greater restrictions and generally lower capacities [4]. Among the possible applications and benefits of small and medium scale rockets development (both solid and liquid fuel engines) are meteorological and scientific studies, as well as ballistic and space observation applications [5].

Specifically, the *SUA II*, object of study of this work, is a second generation liquid engine, designed to be part of the first stage of a chemical combustion rocket (The *AINKAA VI*), which consists of two stages with a solid propulsion and a liquid propulsion engine respectively, and which has been in process of development, study and construction since 2011 by the *Proyecto Uniandino Aeroespacial (PUA)* of the *Universidad de los Andes - Colombia* [6]. Although this rocket is in a fairly advanced state of design and construction, there are still many outstanding issues to be solved in telemetry, control, conditioning, testing and launching of a possible mission, in this case with a stratospheric reach. Is in this scenario when surges the necessity of re design an optimization of the liquid stage of the *AINKAA VI* [7], [8], which results in the development of the *SUA II* rocket engine.

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# METHODOLOGY

## *Background*

The second-generation rocket engine *SUA II* was developed from the *PUA-1L-6S-2000N* engine (See Figure 1), which was designed and built for the first time in 2011 by *PUA* researchers, and subsequently due to failures and design problems, different research projects proposed constructive changes, materials and operating pressures, without modifying the essence of its operation [7], [8].

The *PUA-1L-6S-2000N* was a liquid engine rocket which worked with liquid oxygen LOX as oxidizer and regular gasoline as combustible. Both fluids were stored in separated pressure vessels, which are opened by the operation of two solenoid valves, allowing the flow of the fuel and oxidizer into the combustion chamber, where they are atomized by spray nozzles. This allowed their combustion and subsequent acceleration through a divergent nozzle [6]. In this engine, the oxidizer was stored at a cryogenic temperature to maintain it in a liquid state, and had to pass through a copper coil around the tank and through a jacket of cooling of the combustion chamber, which allowed its gasification before injection in the combustion chamber [6].

Figure 1. The *PUA-1L-6S-2000N* engine with its casing test jacket [8].

This liquid rocket engine was initially designed to generate a thrust of approximately 2000 N by 6 seconds and had an approximate height of 1,8m and a weight of 40 kg, which would allow it to reach a theoretical altitude close to 6 km a.s.l. [6]. The main construction materials for this motor were carbon steel (not optimal, but selected by budget restrictions) used in the storage tanks and combustion chamber, and stainless steel for the pipe and connection accessories. The storage pressures of the LOX and fuel were 600 and 200 PSI respectively. The *PUA-1L-6S-2000N* motor was tested in 2014, resulting in a thrust of approximately 600 N, this because of problems with the pressures of operation, which finally were much lower that the initial design [8].

Further research projects [7], [9] proposed the use of lighter materials such as aluminum and fiber glass with the objective of reducing the total weight of the engine, introduce pressure regulators, as well as increasing the operating time of the engine (increasing its height and diameter) and also the operating pressures in order to reach the stratospheric altitude goal, a key objective for the academic and investigation interests of the *PUA*. All this local design experience was then revised and rethought for the final construction of the *SUA II* engine.

The construction of this rocket motor was then possible due to the participation of metal mechanic companies (*Engicast LTDA*), management of special gases industries (*Matheson Colombia S.A.* and *Servitech Omma S.A.S.*) and the financial support of the association of graduates of *Universidad de los Andes –Uniandinos-*.

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## *The vehicle*

The *SUA II* engine was designed to be the first stage of the *AINKAA VI* rocket (See Figure 2). This is a two-stage rocket with stratospheric reach (+12 km a.s.l.) developed since 2011 by the *PUA*. In the second stage of this vehicle is located the solid fuel engine (candy type) *Kappa Delta Uniandes*, developed by the same research group. The *AINKAA VI* is proposed as a low cost vehicle developed and assembled completely with techniques and methods of manufacture available in the local market. This vehicle also aims to become the first liquid propelled rocket to reach a stratospheric altitude in Colombia.

The *PUA* researchers expects that the development and optimization of its own liquid propellant will serve as the basis for later missions with greater apogees, until it can consolidate a vehicle capable of placing an object in Earth orbit.

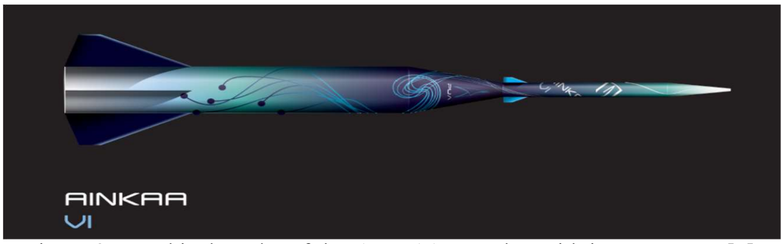


Figure 2. Graphical render of the *AINKAA VI* rocket with its two stages [7].

## *Design*

The main objective of the *SUA II* engine was increase its performance (in comparison with *PUA-1L-6S-2000N*) to reach an approximate altitude of 12 km a.s.l; with this in mind, the design was based on the next principles:

a) To increase the burst time of the motor, resulting in a greater total thrust of the rocket engine, allowing it to reach higher altitudes.
b) To decrease the total weight of the engine by reducing unnecessary components and using lighter materials such as aluminum.
c) To maintain the design of elements associated with the rocket motor combustion process: injectors, combustion chamber, cooling jacket and nozzle.
d) To decrease manufacture and assembly costs of the engine, selecting more suitable, effective and efficient manufacture methods and avoiding over specification of hydraulic components.
e) To guarantee the safety and reliability of the engine, increasing its performance without the use of excessive pressures and the use of safe materials (compatible with the oxidizer and fuel).

The methodology for engine design was the same that the used for the *PUA-1L-6S-2000N,* and was the proposed by Krzycki [2]. This method is based on the required thrust and burn time (estimated according to simulations from the required apogee) and taking in account the selected fuel and oxidant (specifically its ISP) to calculate all other geometrical and operating parameters of the combustion chamber, nozzle and engine tanks. The design parameters of the *SUA II* motor are then presented in Table 1.

Table 1. General characteristics and design parameters of the *SUA II* engine.

| **General** | | | |
|---|---|---|---|
| Type | Pressurized vessels | **Combustion chamber** | |
| Oxidizer | Liquid Oxygen | Diameter | 0,08 m |
| Fuel | Gasoline | Length | 0,12m |
| Rate O/F | 2,5 | LOX injectors | 3 |
| Thrust | 1700N | Fuel injectors | 1 |
| ISP | 275 s | Oxidizer flow | 150 gal/min |
| Burst time | 25 s | Fuel flow | 3,8 gal/min |
| Total Impulse | 40000 N.s | **Vessels** | |

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| | | | |
|---|---|---|---|
| Class[1] | O | LOX vessel length | 1 m |
| Length | 2,4 m | LOX vessel diam. | 0,19 m |
| Diameter (max) | 0,24 m | LOX vessel volume | 25 L |
| Weight | 35 kg | LOX pressurization | 500 PSI |
| Expected apogee | 10-12 km | LOX regulation set | 330 PSI |
| **Nozzle** | | Fuel vessel length | 0,5 m |
| Exit velocity | 2630 m/s | Fuel vessel diam. | 0,19 m |
| Throat velocity | 1150 m/s | Fuel vessel volume | 14 L |
| Throat diameter | 0,02 m | Fuel pressurization | 250 PSI |
| Exit diameter | 0,05 m | Fuel regulation set | 150 PSI |
| Rate areas | 7 | | |
| Rate Velocities | 2,3 | | |
| Nozzle type | De Laval | | |

Figure 3 shows a schematic model of the *SUA II* engine, where it can be observed the principal parts of the rocket engine: a) LOX system (including hydraulic components and connections), b) fuel system and c) combustion system.

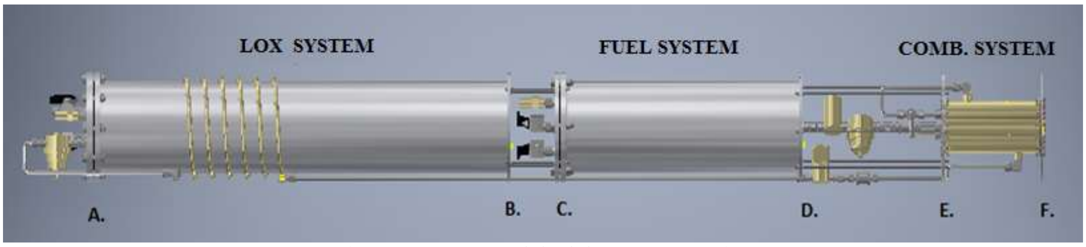


Figure 3. CAD model of the *SUA II* engine

a) LOX System:

The oxidizer was stored at liquid state in a pressure vessel at cryogenic temperature (-196 ° C). In the vessel outlet a solenoid valve is activated to allow the flow into the combustion chamber. While valve is closed gasification process of LOX guarantees pressurization of the vessel until the required value (500 PSI). A relief valve settled at 550 PSI was used to avoid over pressures. Before reaching the cooling jacket, the oxygen flows through the coil of copper pipe, in order to facilitate the process of gasification. This was a device introduced previously in *PUA-1L-6S-2000N* engine [6] and which it is decided to conserve due to the proper functioning of it.

The material selected for the construction of the vessel was the 6061-T6 Aluminum alloy. This can be classified as aluminum to silicon-magnesium, which acquires resistance properties very similar to those of a conventional low carbon steel by the formation of precipitates by means of an aging thermal treatment. This type of material has the advantage over steel of being three times lighter, with similar strength and high ductility at cryogenic temperatures [10]. The disadvantages of using this material are the low chemical compatibility for the handling of liquid oxygen (aluminum is highly flammable in presence of oxygen and releases a large amount of energy when burned with it) [11], [12], and possible damage to the microstructure of the material by welding processes [13], [14]. To overcome first problem, it was decided to apply an inner coating of the tank in aluminum oxide (alumina). For the second one, only machining processes were used, avoiding then welding procedures for the manufacture of the vessel. Analyzes and simulations were performed to ensure the structural integrity of the tank at pressures greater than 600 PSI.

[1] *Classification according to National Association of Rocketry (NAR) Standard Motor Codes.*

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Fittings, pipes and valves for LOX system connections were selected in Stainless Steel AISI 316 and Copper. This because the high compatibility of these materials with LOX handling [11], [12]. Additionally, ASTM G93[2] standard practices were required to fittings, accessories and valves suppliers. Finally, all components were verified to operate correctly at maximum pressure design conditions (550 PSI).

Regulation and LOX tank pressure was determined with base in the flux curve of the injectors to be used. To reduce the manufacturing complexity and cost of the tank, the lowest possible working pressure was selected to meet the flow rate required for combustion. Compared to previous models (500 PSI vs 1000 PSI [7]) this lower working pressure not only allowed the construction of lighter tanks, but resulted in the use of less resistant and specialized, and therefore cheaper, hydraulic components.

In comparison with the *PUA-1L-6S-2000N* engine [6], [7], the oxygen tank height was modified to provide a greater amount of oxidizer to the engine. To do this, the volume of the vessel was increased, which allowed have a greater amount of oxygen. In addition to this, more ullage for the self-pressurizing gas was contemplated, which allows a smaller drop in pressure as the LOX leaves the tank (see Figure 4). A pressure regulator was also added at the outlet of the tank to ensure a minimum pressure of 330 PSI and thus obtain a longer operating time without having to increase the initial pressure of the tank (500 PSI).

b) Fuel system:

In similar way to the oxidizer system, fuel was stored in a pressure tank operated by a solenoid valve. The gasoline was stored in liquid form and pressurized up to 250 PSI by injecting gaseous nitrogen. The operating pressure was set at 150 PSI by placing a pressure regulator in the outlet of the tank. A relief valve settled at 300 PSI was used to avoid over pressures and a check valve ensured the flow direction of fuel. The tank and regulator pressures were selected taking in account the flow curve of the selected injector. The lowest pressures were selected to reduce the complexity and cost of the system (see Figure 4).

The 6061-T6 Aluminum alloy also was selected like the construction material for this vessel because of its resistance properties and low density in comparison with other materials of similar properties. Analyzes and simulations were performed to ensure the structural integrity of the tank at pressures greater than 350 Psi.

Due to the lower pressures managed in this system, its operation at room temperature, and the lower risks of oxidation and ignition compared to the LOX system, the fittings, accessories and valves of this system were selected in materials such as galvanized steel and copper, resulting cheaper than accessories of the LOX system.

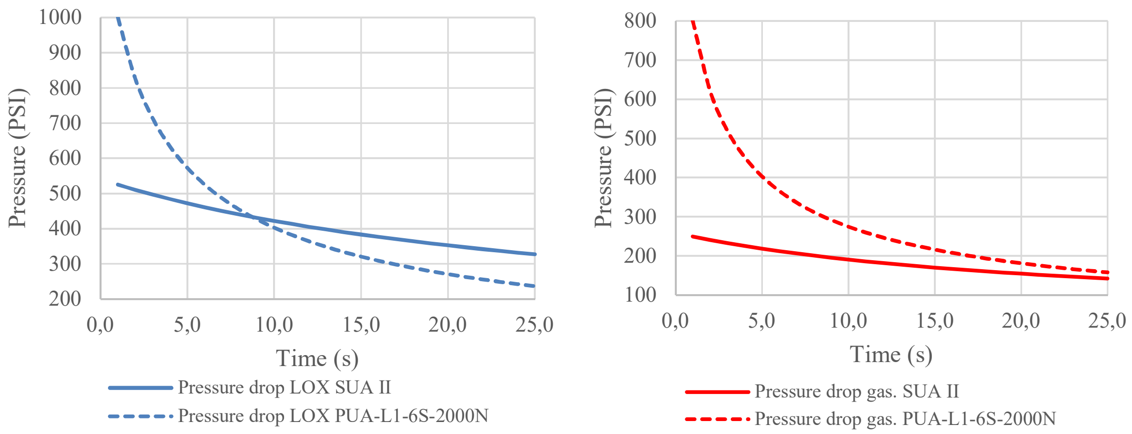


Figure 4. LOX and gasoline pressure drops of the *SUA II* engine tanks Vs. *PUA-1L-6S-2000N.*

[2] *ASTM G93 Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments, Level C. According to SC-11 Swagelok ® Special Cleaning and Packaging.*

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c) Combustion system:

This engine subsystem consists primarily of the fuel and oxidant injectors, the combustion chamber, the nozzle and the cooling chamber. Because of the good performance of this configuration in the previous model *PUA-1L-6S-2000N*, the design of the *PUA II* engine contemplated minimum modifications on it.

The injection system of oxidizer and fuel into the combustion chamber was designed taking in account the local availability of commercial solid cone spraying nozzles. The number of necessary nozzles was calculated with the knowledge of the required flows of gasoline and oxygen (Rate O/F, see Table 1) and the catalog of the nozzle supplier.

Since the injection conditions of the oxygen to the combustion chamber affect its density, it was necessary to estimate the conditions of its entry into the injectors to ensure the O/F ratio. This wasn't a simple problem since there was a turbulent flow through pipes with different materials, diameters, different modes of heat transfer during the oxygen path (through the copper spiral and the cooling jacket) and transient flow and temperature conditions. To make an estimate of the oxygen injection conditions, first a pressure of 10% is assumed by the route through the pipes and accessories from the tank outlet. For the calculation of the temperature increase, some sources suggest the calculation of a general coefficient of heat transfer through the cooling jacket [2]. The cited source presents a coefficient of $q = 3\ BTU/in \cdot s^2$ for a small chamber made of copper, being able to make an analogy with steel (taking into account the differences in the thermal conductivities of both materials in Equation (1). According to this, Equations (2) and (3) were used to estimate the increase of temperature for the LOX. In Equation (2), $\dot{Q}$ is the global heat transfer and $A_T$ the total area of heat transfer (included nozzle and combustion chamber walls). In Equation (3) $\dot{m}_{LOX}$ is the average flow of oxygen at regulation pressure, $C_{pLOX}$ is the specific heat of LOX and $h_{vapLOX}$ the vaporization enthalpy of the LOX (assuming its state change).

$$q_{steel} = 0.12\ q_{cupper} = 3\frac{BTU}{in^2 \cdot s} \cdot \frac{1.055\ kJ}{1BTU} \cdot \frac{1in^2}{6.45x10^{-4}m^2} \cdot\ 0.12\ \cong\ 600\frac{kJ}{m^2 \cdot s} \tag{1}$$

$$\dot{Q} = q_{steel} A_T \cong 25\ kJ/s \tag{2}$$

$$\dot{Q} = \dot{m}_{LOX}(C_{pLOX}\Delta T + h_{vapLOX}) = (0{,}42\ kg/s)[(1{,}7\ kJ/kg.K)\Delta T + (220\ kJ/kg)] \tag{3}$$

$$\Delta T \cong 100°C \tag{4}$$

As it can be observed in Equation (4), the estimated increase of temperature of oxygen in the refrigeration jacket is approximately of 100°C. Taking into account the passage through the copper spiral, the temperature of the oxygen will have a slightly higher increase, estimating then its injection temperature at a value as close as -50 ° C. With this temperature and pressure estimates and using the software *Engineering Equation Solver (EES)®,* oxygen density was calculated like 43,5 kg/m$^3$. Temperature and pressure estimates can be validated after the testing bench by the researches to adjust the model.

For fuel injection, one *UniJet® Spraying Systems* nozzle of 1/4-inch diameter was selected. In this nozzle type, liquid passes through an internal strainer and into one slotted core and disc where a swirling occurs. The breakup of the liquid occurs as it exits the orifice, producing a well-defined cone pattern [15]. The calculated total fuel flow was 3,8 gal/min. Three *SpyralJet® Spraying Systems* nozzles in stainless steel and 3/8-inch diameter were selected for the LOX injection. These have a solid cone-shaped spray pattern and gives maximum liquid throughput for a given pipe size. In this nozzles, the liquid enters and passes through a void in spiral and as it deflects off the spiral surface, form a full cone pattern. [15]. The calculated total LOX flow was 150 gal/min As is shown in Figure 6, to obtain a good mix of propellants, the gasoline spray nozzle was located in the central part of the combustion chamber, while the LOX injectors were located equally in a circular pattern around the fuel injector.

A cooling jacket was considered in the *PUA-1L-6S-2000N* engine. The function of this jacket was to cool the combustion chamber by the flow of liquid oxygen around it, and at the same time use this heat to facilitate the gasification process of the LOX before being injected into the combustion chamber [6].

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The entire combustion chamber, cooling jacket and nozzle assembly was manufactured in low carbon steel and a nickel coating was applied to increase its resistance to corrosion by oxygen flow. For the seal between the combustion chamber, the nozzle and igniter support-cover, Viton O-rings coated with special silicone for high temperature (until 300°C) were used. Between the combustion chamber and the cooling jacket the seal was achieved by the use of gaskets fabricated in asbestos sheet with high temperature resistance (until 800°C).

### *Manufacture and assembly*

Tanks:

Some special considerations had to be made in its design due to selection of the 6061-T6 aluminum alloy as tanks material. Since this aluminum alloy acquires its properties by the inclusions of silicon and magnesium at microstructural level, the welding processes are harmful to its resistance [13]. In addition to this for the oxidizer tank an inner coating should have been considered. The objective was to protect the aluminum from the oxidative action of the LOX and to prevent possible ignitions caused by it [12].

The need of application of the surface coating had like consequence that the tank had to have a removable cover in at least one of its ends, which would allow its sealing once the coating was done. This cap could not be welded because of the first requirement mentioned above. Also, temperature rise generated by a welding process would have damaged the applied coating. This left as the most viable option the implementation of a flange joint for one end of the tank.

For the manufacture of the body of both tanks it was decided to do it machining from a solid bar of the required aluminum alloy. In this way, welding procedures were avoided and a closed end of the tank could be generated, while in the other a non-standard flange was machined to be sealed using a manufactured blind flange separately. Calculations and simulations were performed to size the flanges and select the number bolts required to operate at the design pressure of both tanks with an appropriate safety factor (at least three).

Figure 5. *Left*, Internal machining of the LOX tank in aluminum 6061-T6. *Right*, finished tanks of gasoline and LOX (anodized).

Tanks machining was made using conventional lathe and a CNC machining center. Due to the characteristics of the material, a careful machining process was carried out. Cutting speeds and cutting depths were limited at minimum values ensuring the flow of coolant liquid to not affect aluminum microstructure by any temperature rise. Because of tanks size (1.0 and 0.5 meters), considerable material removal was necessary through machining, resulting in a long process that represented an important part of the engine cost (about $ 3000 USD including material). However, it should be noted that in this way special welding processes, treatments, tests and certifications were avoided, resulting in minor costs.

To improve engine safety, a thin protective oxide surface film of alumina ($Al_2O_3$) was applied to the internal surface of the LOX tank. This film of approximately 100 μm provided a resistance to aluminum reactions in oxygen atmosphere. Aluminum's tough, tenacious oxide, which has a melting point of 2342 °C, protects the base metal from ignition. Particle impact tests on anodized aluminum targets have indicated that anodizing the surface increases the resistance to ignition by particle impact [16].

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The non-conventional flanged design of the tanks required the use of gaskets between the joints to prevent gas or liquid leaks. In the case of the LOX tank this meant the selection of a cheap and suitable material, since conventional polymer packages would crystallize due to the cryogenic temperature (-196°C). In addition, the packaging material to be selected should be oxygen compatible to reduce the risk of ignition [12]. Based on the requirements, a Teflon-silica-based flat ring (Garlock Gylon® Style 3502) was selected. This type of packaging is widely used in oxygen systems, resisting temperatures of less than -200 ° C and withstanding internal pressures up to 1000 PSI [17]. To reduce the risk of leakage it is decided to use raised face ends in both tanks. In addition to this, due to problems obtaining the seal of the tank during the tests at 650 PSI, a groove was made on the face of the flanges to ensure the correct seal of the cover.

Finally, it was decided to cover the LOX tank with a ceramic blanket of 0.5 cm thickness. This was done with the objective of increasing the thermal insulation of the vessel, reducing the gasification rate of the oxygen and increasing the time of auto pressurization of it. More time in which the oxygen pressurize the vessel facilitates the processes of filling of the motor, as well as all the enlistment of the rocket during tests or launches.

Combustion system:

The entire combustion subsystem was made of SAE 1020 low-carbon steel for economic reasons. This system included the combustion chamber, the nozzle, the igniter support-cover and the cooling jacket. These elements were manufactured entirely in the facilities of the Universidad de los Andes. For this purpose, conventional lathes, milling machines and welding equipment were used. To all the pieces of this system, a nickel or galvanized coating with a depth of 50 µm was applied. This coating was made to protect steel parts from the oxidizing effects of the LOX.

Figure 6. *Left*, parts and assembly process of the combustion system. *Right*, finished combustion system with bolts and hydraulic connections.

The nozzle, igniter support-cover and combustion chamber were machined as separate pieces. To achieve seal during the assembly, O-rings in Viton were used and coated with special silicone for high temperature (up to 300°C). Between the cooling jacket and the nozzle there were used flat gaskets made of compressed asbestos with a temperature resistance up to 800 ° C (See Figure 6).

Figure 7. Finished assembly of *SUA II* engine and its casing test jacket.

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## *Testing*

The *Proyecto Uniandino Aeroespacial* since 2010 has developed testing bench prototypes to perform measurements and evaluations of its rocket engines. In 2016 researchers designed and constructed the *UCAND II* testing module for the latest generation of motors (*SUA II* included). This is a second generation testing bench designed by students of mechanical engineering from previous works and prototypes. The *UCAND II* is a testing module with 3 meters of length and 350 kg weight, able to operate with motors up to 2.5 m length, 30 cm in diameter and a maximum thrust of 10 kN. It has the capacity to be used both vertically and horizontally, allowing it to be used with liquid and solid engines (See Figure 9). This module was equipped with a mechanism to mount a load cell for thrust measurements and three connection points available for temperature and other relevant parameters measurement.

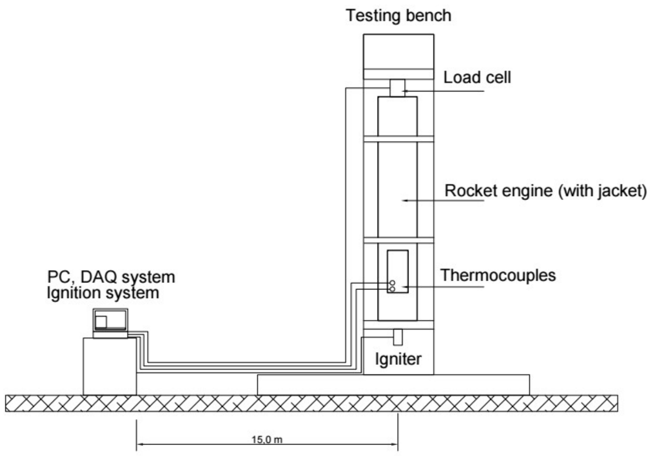


Figure 8. Schematic diagram of experimental set-up for *SUA II* engine test (not at scale).

For the test of the *SUA II* engine a test casing (jacket) was fabricated (See Figure 7). The function of this was to contain the engine inside, to give structural resistance, to allow its location and subjection in the test bench and to transmit the thrust of the engine to the load cell. Aluminum foils with a thickness of 2.5 mm were used, which were folded and welded to form the necessary cylindrical geometry.

An Omegadyne® "S" load cell with a capacity up to 2 Ton (20 kN) of force was used for the *SUA II* test. This load cell worked at compression and was located on top of the test module. In addition, two K-type thermocouples were used for the measurement of relevant temperatures (LOX line just before injection and top of combustion chamber). The load cell and the thermocouples were connected to a DAQ card (National Instruments® 9211 model). A manometer was mounted on combustion chamber to record the pressure inside it during the ignition of the engine (See Figure 8).

The rocket motor and the testing bench were transported to the *Pozos Azules* zone, located near to *Villa de Leyva* town in Colombia. For safety reasons this was the place selected for the test by the research group. The test had the accompaniment of technician personnel expert in the handling of special gases for the manipulation and filling of the LOX and the fuel tanks. Strict protocols and safety procedures were also developed and applied for the development of the test.

For the engine ignition a controller mechanism was designed and constructed using an Arduino UNO® module and a four relay card. The control was equipped with a battery of 12V-7000 mAh and a series of special switches to assure the reliability of the controller. The control mechanism was located within a 15-meter radius of the test module and wired to the servo valves of the LOX and fuel systems and to the ignitor located in the combustion chamber. A timed sequence was programmed to achieve activation of the ignition, valve opening and allowing time to reach a safe distance (100m) from the test module.

Based on previous experiences [6], [8], igniters was fabricated using gray powder and "candy type fuel" (mix of potassium nitrate and sugar) [18]. These igniters had dimensions of approximately 8 cm in length and 1.5 cm in diameter. The purpose of these large igniters was not only to ignite the mixture, but also to generate a preheating of the combustion chamber by its ignition and burn.

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## RESULTS AND DISCUSSION

The ignition of the engine was successfully achieved in two attempts. The operating burn time was approximately 19 seconds. This time was less than expected (more than 25 seconds) because the ignition of the engine burned the power cables, which were not adequately protected during their pass by the test bench structure. Since the solenoid valves used were of the normally closed type, once the flow of energy has been interrupted, they were closed and ended the firing time of the engine early.

Figure 9. *Left*, *SUA II* engine mounted in *UCAND II* testing bench before ignition. *Right*, Motor firing during test.

The temperature measurements on the igniter cover (top of the combustion chamber) and on the LOX line before the injection into the chamber were recorded successfully and are presented in the Figure 10. As can be seen in the graphs, the ignition of the engine starts at time 220 seconds and ends at 240 approximately. The maximum temperature reached in the wall of the combustion chamber cover does not exceed 120 ° C, so that the thickness of it is adequate. As for the LOX line, it was useful for researchers to have an approximate value of the temperature at which the gas enters the combustion chamber, which is close to -60 ° C.

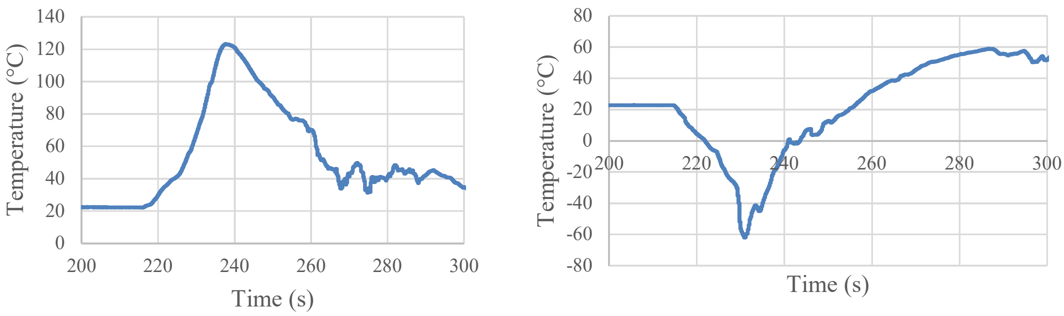


Figure 10. *Left*, Temperature registered at the top of the combustion chamber. *Right,* Temperature of the LOX line before refrigeration jacket injection.

This measured value of the temperature on the oxygen line before injection in the chamber was very close to the estimated value (-50 ° C). This validates the approximations and the model used for the temperature increase estimation and indicates that the O/F ratio was correct.

Figure 11 shows the thrust curve registered at bench testing for the *PUA-1L-6S-2000N* engine [8]. The maximum force exerted by the *SUA II* engine was 1800 N. This force value was very close to the design thrust expected for this motor. As it can be observed, the stabilization of the combustion process takes 5 seconds approximately. This is the time that takes the engine to reach its mean thrust value. Both engines suffered structural damages (walls melted) in its combustion chambers due to the high temperatures and the oxygen flow around the chamber. This could be observed on the thrust curve like a descent of the force in second 16 approximately. The registered operating time of

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approximately 19 seconds, less than the design time of 25 seconds, is explained by the damage suffered by the power cables of the solenoid valves.

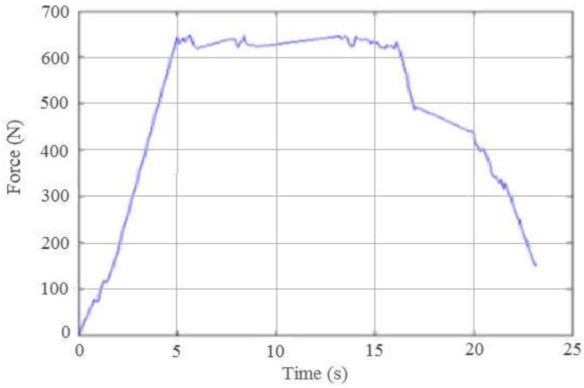

Figure 11. Thrust registered at bench testing for the *PUA-1L-6S-2000N* engine. [8]

During the structural revision of the engine subsequent to the test, it was found that both the nozzle and the combustion chamber were seriously damaged (See Figure 12). In the case of the nozzle, the metal melted in the throat area generating a hole about 2 cm in diameter. The combustion chamber presented even more damage as almost half of its wall melted. Analyzing the possible causes for these failures, it was observed that they occurred in both elements on the same side. In addition to this, its location coincided with the point of entry of the LOX into the cooling jacket. It was concluded that the damage in the system was generated due to an excessive increase of the wall nozzle temperature, which was attacked by the LOX. The oxygen jet striking directly against the hot material of the nozzle acted as a torch generating oxidation and melting of the material. Once the nozzle damage was generated, the gases and the combustion heat escaped into the cooling jacket, generating a mixture of oxygen-rich gases that burned and generated the melting of the combustion chamber wall.


Figure 12. *Left*, hole caused in the throat of the nozzle. *Right*, damage in the combustion chamber wall.

The mentioned problems had an impact on the operation of the motor and its occurrence can be reflected in the registered graphs. Damages to the nozzle and combustion chamber affected normal engine operation by generating a conflagration during the last 10 seconds of operation. Two possible solutions to this problem were proposed. In the first place the change of the material of manufacture of the chamber and the nozzle for other that was more resistant to the action of liquid oxygen. In this case, it was determined that AISI 304 stainless steel was a better choice than conventional carbon steel. On the other hand, also the application of a ceramic coating to the interior of the nozzle and the combustion chamber was proposed. This coating has the function of isolating and protecting the metallic material from the large heat flux generated by the combustion, minimizing the possibility of melting. The selected option for this coating was a 200 µm thick layer of a mixture of alumina, zirconia and chromium oxides applied by HVOF thermal spraying.

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## CONCLUSIONS

After the bench test, the behavior and characteristics of the designed and constructed rocket motor were found within the expected ranges: thrust, burnt time and temperatures. The combustion chamber, tanks and other structural and hydraulic elements behaved in safely and properly way during the operating time, which supported its correct selection and design process.

The design and testing process of the *SUA II* engine was of great importance to the researchers of the *PUA* group as it allowed them to develop manufacturing processes with lighter and more suitable materials such as aluminum alloys as well as the selection of safer and economical hydraulic elements, optimizing costs and ease of construction of liquid combustion engines. So, in comparison with similar previous models, there was evidence of improvements in the use of materials, manufacturing techniques and components selection with a better final performance.

The *SUA II* motor, being one of the first rocket engines of its type at regional level, can be considered a great success for the national aerospace industry of Colombia. It is important to point out that it was possible to build and test it in an environment with academic staff, using the local industry and materials and with a budget of less than USD 10,000.

In this way, with the construction and successful test of *SUA II* engine, it can be said that the Colombian industry is in capacity to produce devices of this type. Through this type of experiences, it's possible to think in a future with the association of a group of companies dedicated to the manufacture of low cost rocket engines with the capacity to reach ever higher altitudes.

At being a second-generation engine, and having been tested successfully and safely, the *SUA II* engine (with some minor modifications) is ready to be used as an engine base for a rocket-type vehicle with a stratospheric or higher apogees. However, still it is necessary to improve the techniques and methods of instrumentation used during the measurement processes. This is due to the fact that difficulties presented in this processes make it difficult to obtain and verify results at the experimental level, difficulty the labor and development investigation group.

The rocket motor developed at this project, due to its reliability and good performance, could be considered like a serious option to be used in a tandem type configuration (parallel or serial), to obtain a rocket with the capacity to reach orbital apogees. With this project the *PUA* research group has acquired a greater knowledge and management of the organization, logistics, coordination, development of safety protocols and development of missions involving complex engines (specifically liquid propulsion with stratospheric apogees).

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