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DESIGN OF A CANDY PROPELLANT ROCKET MOTOR BY A COMPUTER AIDED SYSTEM AND ITS PERFORMANCE IN STATIC TESTING

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Abstract
The present work describes the calibration and implementation process of a computer aided system used for *Candy* propellant rocket motors design. It also presents the static testing of an experimental rocket motor, manufactured by the *Proyecto Uniandino Aeroespacia*l (PUA), comparing its performance test results with predictions made by the system. It was registered a maximum thrust of 5430 N for the motor, which gives a magnitude for its performance, despite the failures that arose in the measurement systems. Comparing test partial results with software predictions, relative errors of approximately 32% appear, leading to conclude that this rocket motor can potentially reach the expected power output.

1. Introduction

With the clear objective of putting a satellite into orbit with Colombian technology by 2030, the *Proyecto Uniandino Aeroespacial* (PUA) of the University of Los Andes has been working during the last fifteen years in the development of the local aerospace technology. In spite of the incipient development of aerospace engineering in Colombia, the work and research conducted within the PUA have yielded concrete results. Until now, three launch missions have been completed with success: The SENECA I, which launched the AINKAA I vehicle and achieved a height of 800 m over the launch platform; the SENECA III, which launched the AINKAA III vehicle and achieved a height of 5 km over the launch platform; and the SENECA IX, which launched the AINKAA VIII vehicle with a biological mission on board and achieved accelerations greater than 8 g. It is expected that for 2017, new launch missions like SENECA II, SENECA V, SENECA VII and SENECA X had been completed.

Successful missions outlined above belong to vehicles propelled with *Candy*[1] solid fuel, also known as KNSB. A low cost, low performance, sugar based solid propellant used mostly in amateur and experimental rocketry. Thanks to these experiences on solid propellant motor technology, it becomes possible for the PUA to develop new technological tools that summarize this knowledge for the benefit of new investigations and advances. This work centers its motivation in that exact need and is, indeed, an effort to create and implement a computational tool that helps with the design and prediction of solid propellant (*Candy*) rocket motors performance.

In that sense, the objective of this document is to present the development of a computer aided solid propellant rocket motor design system, called SOLMOTOR-PUA, and its implementation on the design of a high power rocket motor, the GHOST I. On subsequent pages the theoretical and empirical foundation for design and performance analysis of a solid propellant rocket motor used to build the SOLMOTOR-PUA software, is going to be presented along with its calibration process. On the second part of the document, it is described a new KNSB propellant high power rocket motor designed and manufactured by PUA and the partial results obtained from its static testing.

[1] By Candy we refer to a type of solid fuel composed by a mixture of 65% Potassium Nitrate and 35% Sorbitol.

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2. SOLMOTOR-PUA

As a first step, the computer system developed as a tool for designing and predicting KNSB propellant rocket motors within the PUA, will be explained. This system, called SOLMOTOR-PUA, is essentially a MS Excel workbook, composed by 5 modules (performance, nozzle, materials, drawings and comparison), that allows the user to: predict KNSB solid rocket motor performance; compare different possible manufacturing materials; see the motor's principal drawings; and finally contrast the software results with experimental observation in case this becomes possible. Besides this, SOLMOTOR-PUA is a calibrated software based on experimental data, to achieve better approximations to real solid fuel motors behavior and, has been left opened in its code, so that its operation can be verified and improved by any user.

2.1 Theoretical models

The first four modules that compose SOLMOTOR-PUA use thermodynamics, strength of materials and geometrical laws to compute its calculations. Despite this, it should be noted that the module that uses the most important models and equations for the prediction of motors behavior, is the 'Performance' module, in which the propellant combustion is simulated and the motors thrust curve is determined. The 'Nozzle' module computes simple geometrical calculations in order to give a general sizing of the motor; the 'Materials' module applies the strength of materials theory with the aim of helping the user with materials selection for motor manufacturing; the 'Drawings' module uses calculations of previous modules to determine dimensions and tolerances of the motors casing and nozzle; and finally, the 'Comparison' module uses experimental input data of a real motor in order to compare this with theoretical predictions made by the software.

SOLMOTOR-PUA simulates the propellant combustion by radial length intervals, in which it is assumed that the propellant grain is cylindrical and tubular, as a BATES type grain (Figure 1). For every interval, the software computes the mass of the combustion gases, the combustion time, the variation of grain's combustion area, the pressure within the combustion chamber and the exerted thrust, among other variables, thus building the motor's thrust curve. These performance prediction calculations could be done by two main methods: a CFD model using finite elements method that simulates propellant combustion and gas flow through the nozzle, or simplified thermodynamic and empirical models that describe, in a general manner, the combustion and gas flow phenomena that takes place in a solid rocket motor. Given that the scope of this project does not go beyond experimental rocketry, and that SOLMOTOR-PUA is intended as a preliminary design help tool, here it is used the second method for performance calculations. The system uses the subsequent models to compute KNSB rocket motor thrust curves:

- The empirical combustion Saint Robert's law, from which it is obtained the combustion rate for the propellant.

$$r = aP_c^n \tag{1}$$

  Where a and n are empirical constants characteristic of the propellant type, and P_c represents the combustion chamber pressure. Despite the KNSB propellant does not follow entirely this model, its behavior could be divided by regimes of pressure in which the mathematical model adjusts with different a and n constants. Richard Nakka performed these measurements for the KNSB propellant and his results are shown in Table 1. (Nakka, 2002)

Table 1: Constants $\boldsymbol{a}$ and $\boldsymbol{n}$ of the Vielle´s law measured by Nakka for the KNSB solid propellant. [3]

a (mm/s)	n	Pressure Range (MPa)
10,708	0,625	0,103 - 0,807
8,763	-0,314	0,807 - 1,500
7,852	-0,013	1,500 - 3,790
3,907	0,535	3,790 - 7,030
9,653	0,064	7,030 - 10,670

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- Assuming that the working fluid, product of KNSB propellant combustion, is an ideal gas, and its expansion process in the nozzle is steady, one – dimensional and isentropic, one can derive from thermodynamic laws an expression for thrust (T). [6]

$$T = \eta_t P_c A_t \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\left(\frac{P_s}{P_c}\right)^{\frac{k-1}{k}}\right]} \quad (2)$$

Where η_t is the nozzle efficiency, P_c is the combustion chamber pressure, A_t is the nozzle throat area, k is the specific heat relation and P_s is the nozzle exit pressure.

- The law of ideal gases, from which it is obtained the combustion chamber pressure.

$$P_c = P_{atm} + \rho RT \quad (3)$$

Where P_{atm} is the atmospheric pressure, ρ is the gas density, R represents the individual constant of an ideal gas and T the temperature within the combustion chamber.

It can be seen that, all three equations above depend on the internal chamber pressure P_c. Even in equation 3 the gas density ρ is also a function of P_c, which is an obstacle to start computations for chamber pressure and thrust. This is solved by introducing the initial condition of chamber pressure equal to atmospheric pressure at the beginning of combustion, initializing variable P_c with a magnitude equal to P_{atm}.

$$P_{c@t=0} = P_{atm} \quad (4)$$

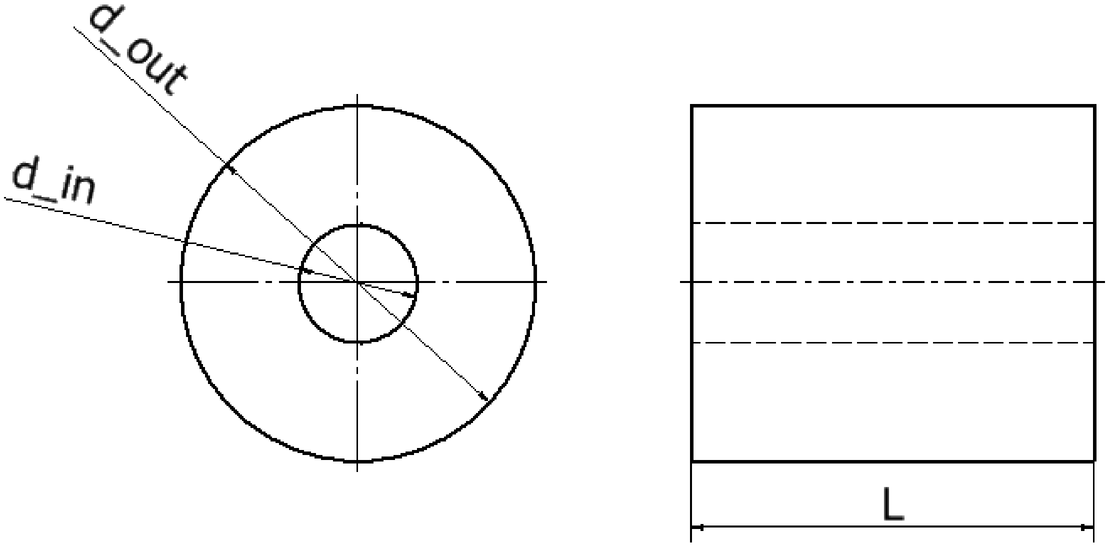

Figure 1: BATES type grain configuration schematic used by SOLMOTOR-PUA.

Models listed before are a summary of the most important computations done by SOLMOTOR-PUA to estimate a motor's performance. In the following table is presented the needed input data and resulting output data from every module of the system.

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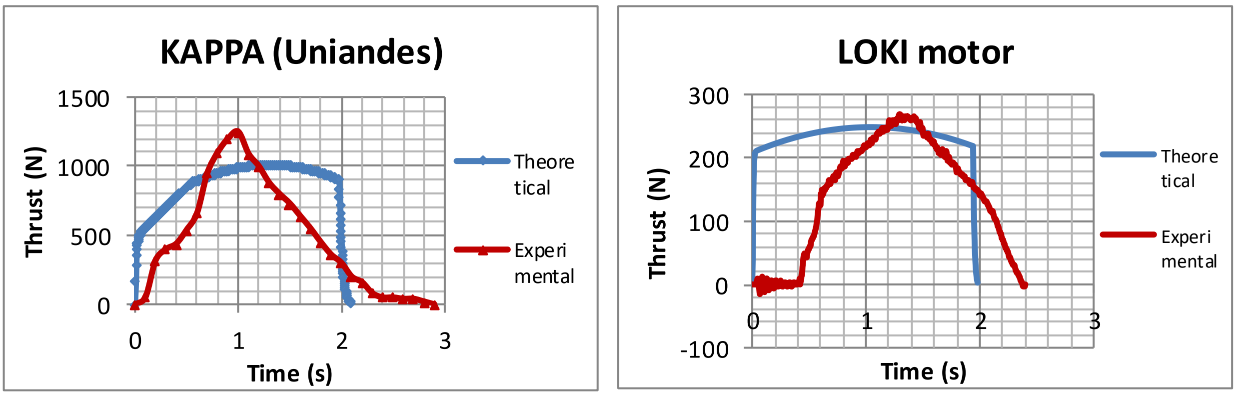
Table 2: Inputs and outputs of SOLMOTOR PUA software.

Module	Input data	Output data
Performance	Combustion chamber internal diameter Combustion chamber length Grain external diameter Grain internal diameter Grain length Maximum objective pressure within the combustion chamber Operation atmospheric pressure Densities ratio (real/ideal) Nozzle efficiency Target nozzle expansion ratio	Theoretic and calibrated motor thrust curves Motor's general performance data (Total impulse, specific impulse, maximum thrust and combustion time)
Nozzle	Convergence angle Divergence angle Chamber's internal radius Throat's radius Exit radius Combustion chamber length	General motor's sizing
Materials	Safety factor (n)	Suggested manufacturing materials
Drawings	Selected material from the 'Materials' module database	Drawings for the three motor's principal components (Casing, cover and nozzle)
Comparison (Optional)	Experimental data from real tested motors	Comparison charts between SOLMOTOR - PUA's predictions and experimental test data

2.2. Calibration

After implementing some simulations and comparing the software results with real experimental data from 8 different KNSB propellant rocket motors, it was observed that the theoretical models outlined before do not represent very accurately the real performance and behavior of KNSB propellant motors, as can be seen on Graph 1. Because of this, and considering the objective of the software, it is clear that it must be calibrated so that results from its simulations stand closer to the real KNSB propellant motor's behavior.



Graph 1: Contrast between experimental data (red line) and SOLMOTOR-PUA simulations (blue line). Motor data taken from references [7] and [8].

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The system calibration was performed acknowledging the fact that experimental thrust curves shape is very similar to the Gaussian function. Under this reasoning, it was decided to adjust a function of the form:

$$T = a \times \exp[-(t-b)^2/c^2] \quad (5)$$

to each one of the 8 experimental KNSB propellant motor thrust curves found, varying parameters a, b and c of the function to fit with real motor thrust data. It should be noted that parameters a, b and c could be associated with physical variables of motor´s performance. Thus, parameter a indicates the maximum thrust, parameter b indicates the time at which thrust is maximum and parameter c, that mathematically represents the standard deviation, can be seen as a multiple of motor's combustion time. A schematic of this is shown in Figure 2.

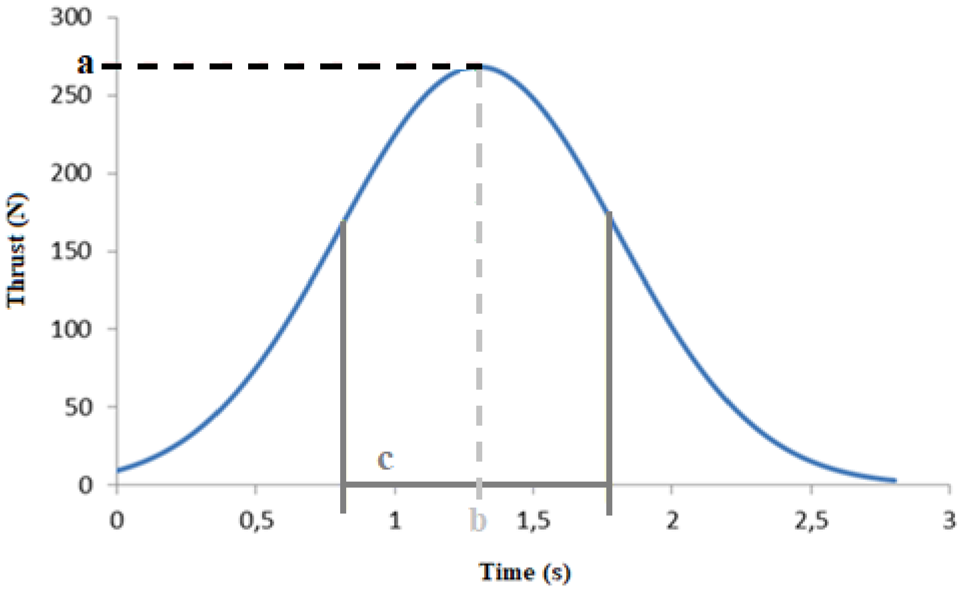

Figure 2: Basic Gaussian function with parameters a, b and c indicated.

After adjusting those three parameters for eight different KNSB propellant rocket motors from various ranges of low thrust (less than 1600 N), relations between a, b and c and theoretical performance computations of SOLMOTOR-PUA were observed. With the aim of predicting actual motor's performance from theoretical computations, these found relations were included into the software using the following expressions:

$$a = 1{,}178 \times T_{max} \quad (6)$$

$$b = 1.096 \times \frac{t_b}{2} \quad (7)$$

$$c = \frac{b}{1.8} \quad (8)$$

These expressions represent the average behavior of the eight KNSB propellant rocket motors used for calibration, however, adding new motor performance results calibration could be modified and improved [2].

2.3. Results and comparison

After implementing the calibration to SOLMOTOR-PUA simulations, it is necessary to check its functioning and limits. To do that, simulation predictions were compared with the available experimental data of KNSB solid fuel rocket motors (GITA, KAPPA and LOKI) and results are shown in Graph 2 and Table 3.

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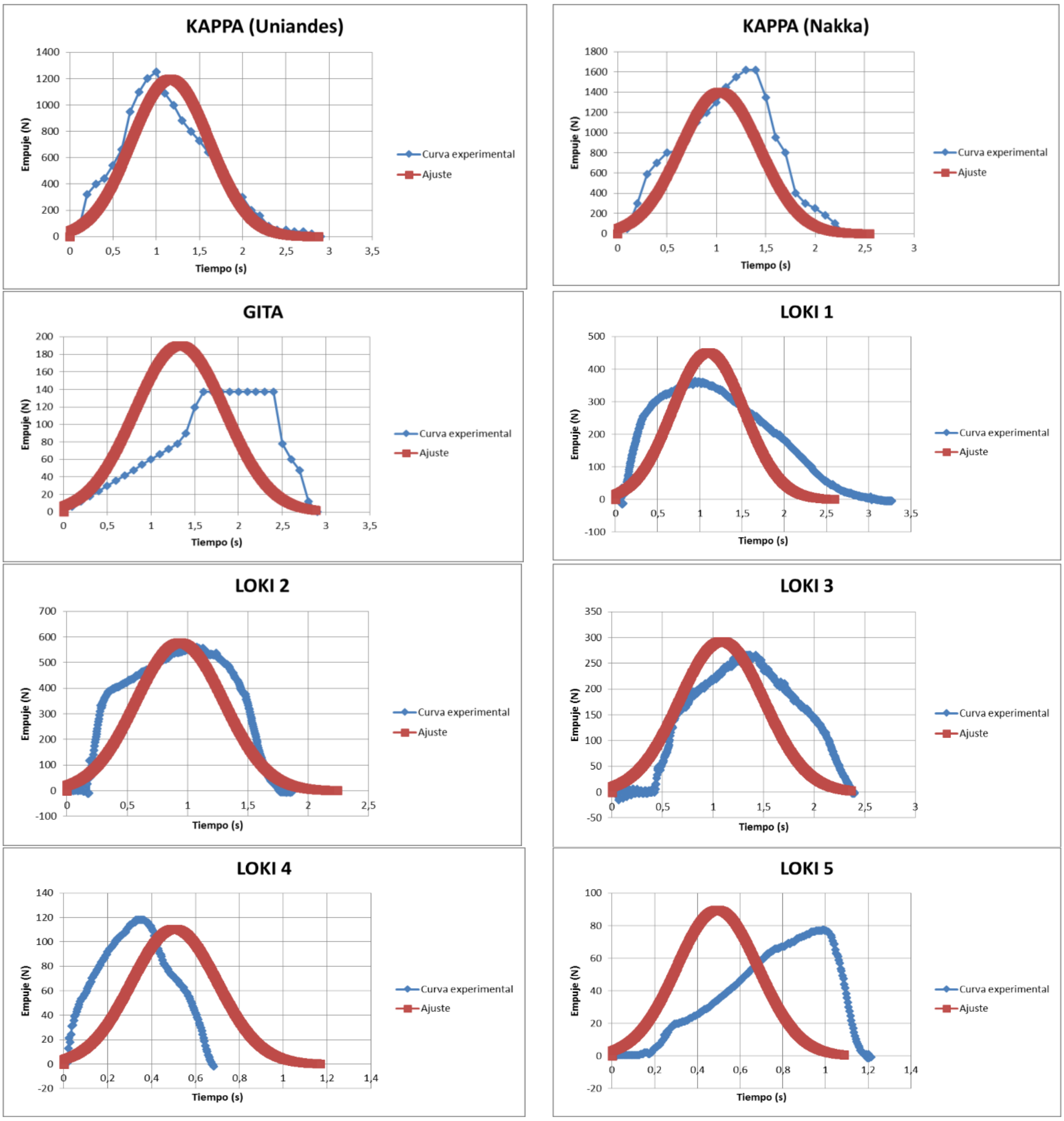

Graph 2: Compilation of comparison graphs for the 8 available *Candy* propellant rocket motor thrust curves. Red curve indicates SOLMOTOR-PUA result and blue curve represents experimental data. Motor data taken from references [3], [7] and [8].

Table 3 illustrates relative errors of SOLMOTOR-PUA predictions on performance parameters for KNSB propellant motors. Divergences oscillate in an approximate range between 5% and 30% showing that predictions improved and SOLMOTOR-PUA could be used for preliminary experimental rocket launch missions within the *Proyecto Uniandino Aeroespacial*. However, system implementation is limited due to the rigid and simplified method of calibration, and these results warn the user about precaution that must be taken with SOLMOTOR-PUA simulations. Despite its good approximations, it does not reproduce exactly the KNSB propellant rocket motor behavior, establishing a need to continue improving its calibration. As a general tendency, it can be observed from Table 3 that predicted total impulse is lower than that of experimental data, while maximum thrust on calibrated curves is generally higher than maximum thrust on experimental curves, facts that should be considered when interpreting results form SOLMOTOR-PUA [2].

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Table 3: Performance comparison between SOLMOTOR-PUA predictions and real *Candy* propellant motors data.

KAPPA (Uniandes)	SOLMOTOR	Experimental	Relative error
Max thrust (N)	1196.6	1250.0	4.28%
Total Impulse (N.s)	1302.6	1435.0	9.23%
Burning time (s)	2.70	2.90	7.00%

LOKI 2	SOLMOTOR	Experimental	Relative error
Max thrust (N)	577.8	560.3	-3.11%
Total Impulse (N.s)	522.9	632.8	17.37%
Burning time (s)	2.24	1.76	-27.35%

KAPPA (Nakka)	SOLMOTOR	Experimental	Relative error
Max thrust (N)	1401.2	1620.0	13.50%
Total Impulse (N.s)	1375.4	1835.0	25.05%
Burning time (s)	2.47	2.30	-7.20%

LOKI 3	SOLMOTOR	Experimental	Relative error
Max thrust (N)	292.6	268.5	-8.98%
Total Impulse (N.s)	306.8	335.0	8.42%
Burning time (s)	2.37	2.38	0.57%

GITA	SOLMOTOR	Experimental	Relative error
Max thrust (N)	190.4	137.3	-38.61%
Total Impulse (N.s)	238.8	218.8	-9.16%
Burning time (s)	2.77	2.90	4.59%

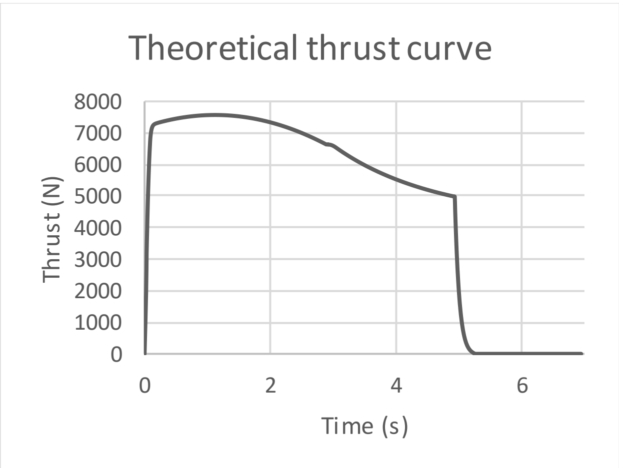
LOKI 4	SOLMOTOR	Experimental	Relative error
Max thrust (N)	110.7	118.0	6.13%
Total Impulse (N.s)	54.0	49.2	-9.88%
Burning time (s)	1.17	0.68	-71.95%

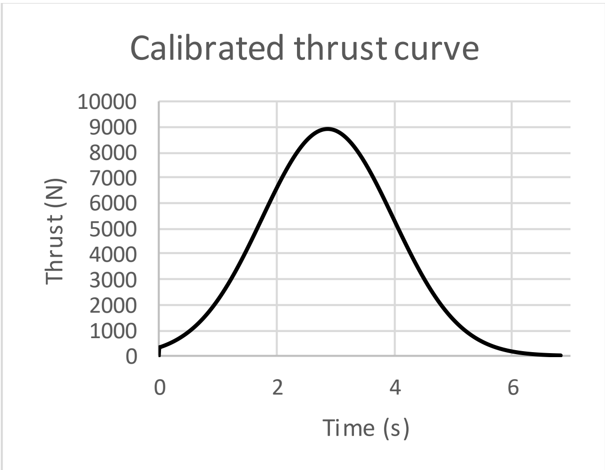
LOKI 1	SOLMOTOR	Experimental	Relative error
Max thrust (N)	451.7	363.9	-24.13%
Total Impulse (N.s)	479.4	603.3	20.53%
Burning time (s)	2.60	3.11	16.55%

LOKI 5	SOLMOTOR	Experimental	Relative error
Max thrust (N)	89.7	77.6	-15.55%
Total Impulse (N.s)	42.7	44.4	3.67%
Burning time (s)	1.09	1.19	8.65%

3. KNSB propellant motor : GHOST I

It was decided to build a high power experimental KNSB fuel rocket motor to test SOLMOTOR-PUA's utility. Considering manufacturing and industry limitations, the biggest motor that *Proyecto Uniandino Aeroespacial* could handle was a 160 mm diameter and 1 m length solid rocket motor. Inserting those dimensions and the other required input data in SOLMOTOR-PUA, predictions for this new motor, called GHOST I, resulted in the following thrust curves:





Maximum Thrust	7568.79	N
	771.54	kgf
Total Impulse	32863.42	N.s
Specific Impulse	133.91	s
Burn Time	5.24	s

Maximum Thrust	8916.02	N
	908.87	kgf
Total Impulse	24805.65	N.s
Specific Impulse	100.61	s
Burn Time	6.83	s

Graph 3: Predicted thrust curves for GHOST I motor by SOLMOTOR-PUA. In green the theoretical thrust curve and in blue the calibrated one.

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According to the National Association of Rocketry, the GHOST I is classified as an O type motor [3], considered a high power rocket motor. A comparison among these simulations with similar motors available on the market, like the Cesaroni Pro 150 [1] (Table 4), it can be seen that theoretical estimations are not far from an expected performance for the GHOST I motor.

Table 4: Performance comparison between Cesaroni Pro 150 and GHOST I (theoretical thrust curve). Retrieved from http://www.pro38.com/products/pro150/motor.php

	Cesaroni Pro 150	**GHOST I (SOLMOTOR - PUA)**
Motor case dimensions (mm)	161 x 754	160 x 960
Total Impulse (N.s)	30605.7	32863.4
Maximum thrust (N)	6338.7	7568.8
Average thrust (N)	5786.6	6271.6
Specific Impulse (s)	223.7	133.9
Burn time (s)	5.3	5.2

3.1. GHOST I motor test

The GHOST I rocket motor consists of a 160 mm diameter, 6.35 mm thick low carbon steel combustion chamber with 975 mm of length, and a conic nozzle with an expansion ratio of 2.5. The loaded weight for this motor is 59 kg, represented by a 42.4% of KNSB propellant and 57.6% of empty weight due to materials used for this prototype. This motor was designed and built with a high safety factor intended to test and compare predictions made by SOLOMOTOR – PUA. Within the combustion chamber five different propellant grains (BATES type) are housed, each with approximately 155 mm of outer diameter, 50 mm of inner diameter and 170 mm of length. The grains were made using customized molds, shaped to the specific geometry and inhibited with paperboard and insulation tape on its outer face. Figure 3 shows one of the propellant grains used in the GHOST I test, and Figure 4 shows the GHOST I rocket motor assembly [4].

Figure 3: BATES grain manufactured for GHOST I rocket motor.

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Figure 4: GHOST I motor assembly.

The experimental setup for the static testing of GHOST I motor is shown in Figure 5. This test bench, the UCAND II, has a height of 2.4 m and is 0.6 m wide; it was built using 1" schedule 40 galvanized steel pipe with threaded unions. Thrust is measured vertically using a 2000 lbf range tension-compression load cell and a lever mechanism with a calibrated mass to remove the motor's weight from data. The test took place in a controlled area with safety procedures in case of failure.

Figure 5: Experimental setup for GHOST I rocket motor in a testing bench.

Although static firing test resulted in failure of the test bench, partial measurements were obtained during the experiment. Structural integrity of the bench failed to resist the motor's thrust due to design errors, causing failure of measurement systems and allowing the motor to fly out just 4 seconds after ignition. Graph 4 shows registered data during the test, displaying a peak thrust of 5 432 N before bench failure. Ignition was made remotely using a pyrogen igniter specially made for this motor, system that showed a correct operation.

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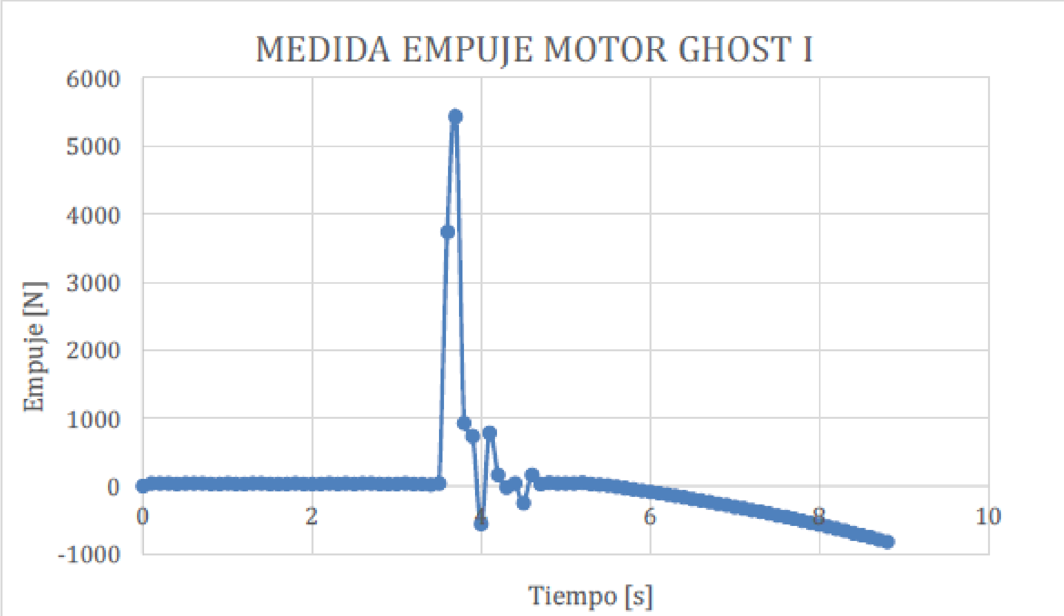

Graph 4: Measured thrust before bench failure. Peak thrust of 5432 N.

4. Results Discussion

SOLMOTOR-PUA system is based on well understood theoretical and experimental basis to execute its simulations. However, calibration must be improved by gathering further KNSB propellant rocket motor test data, and, besides, refining the model used for adjusting curves. Then, thrust estimation errors will be reduced. On the other side, performance predictions made by SOLMOTOR-PUA can provide an accurate prediction for the expected order of magnitude for the KNSB propellant rocket motor performance.

Partial results were obtained from the static test for the GHOST I motor due to problems of structural integrity on the test bench. Nevertheless, a peak thrust of 5 432 N was obtained from the experiment giving an estimate of the motor's capacity. This measurement shows that it is likely that the GHOST I can generate a thrust similar to SOLMOTOR-PUA's prediction of approximately 7 000 N to 8 000 N. The test highlight was the motor's behavior, which exhibited a proper ignition and fuel burning. The design and manufacturing process of this motor is documented so improvements and advances can be made from an already working reference, with the final objective of using the GHOST I motor for a 50 km apogee launch mission, called the SENECA X. Another important aspect of the test, was the recognition of the need for a new test bench that can withstand the stresses generated by high power rocket motors with a proper safety factor.

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