Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

TECHNICAL REPORT

TÍTOL DEL REPORT: Early Tests of the WikiLauncher First Stage

AUTORS: Joshua Tristancho Martínez, Myriam Andrea Tarazona Romero

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Report title: Early Tests of the WikiLauncher First Stage
Authors: Joshua Tristancho Martínez, Myriam Andrea Tarazona Romero
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Overview

This is a technical report for the early nine test of the first stage of a mini-launcher to put up to six femto-satellites in a 250 km Low Earth Orbit. These nine tests were performed in a stone quarry in order to gain experience in real cases to see if student calculations were sized properly. The experiments and simulations were focused in three lines: Determination of the solid propellant burn rate, structural sizing and thermal load.

Keywords:

Mini-Launcher, Solid Propellant, Ammonium Perchlorate Composite Propellant

ABSTRACT

This is a technical report for the early nine test of the first stage of a mini-launcher to put up to six femto-satellites in a 250 km Low Earth Orbit. These nine tests were performed in a stone quarry in order to gain experience in real cases to see if student calculations were sized properly. The experiments and simulations were focused in three lines: Determination of the solid propellant burn rate, structural sizing and thermal load.

CHAPTER 1. INTRODUCTION

The purpose behind these early nine tests were to improve the team knowledgement for low-cost rocketry in order to build a mini-launcher with a total mass less than 4 kg. This mini-launcher should put up to six femto-satellites (Less than 100 grams each satellite) in a Low Earth Orbit (LEO) of at least 250 km in altitude.

For this reason, few technical challenges should be overcome. The main challenge is to have a full operative satellite in this mass budget. This is the case of the **WikiSat** [1] and **KickSat** [2]. The following challenge is to have a solid propellant engine with a propellant mass fraction higher than 60%. Early tests demonstrated that a propellant mass fraction of 55% is feasible but should be improved in the future. The mini-launcher was designed to start from the stratosphere as a combination between a balloon and a rocket called **Rockoon**, a well known system developed in the late 50's. As we demonstrated in the **GranCanaria spaceport** [3] launch, we are able put a rocket at 32 km altitude in nearspace In order to keep in the light free balloon category; the overall mass of the mini-launcher should be not much higher than 4 kg. A combination of multistage launcher will be used as soon as the engine performances are set.

The rocket engine will be based on Commercial-Off-The-Shelf (COTS) components. These are the selected components:

- **Soda Can.** Working pressure 15 Bar (1.5 MPa). Burst pressure is 19 Bar (1.9 MPa). The volume of 330 cm^3 will allow a propellant mass fraction about 80%. In the Stage2 Burn50th we achieved a propellant mass fraction of 82.4%.
- **Spray Can.** Working pressure 20 Bar (2.0 MPa). Burst pressure is 45 Bar (4.5 MPa). The volume of 750 cm^3 will allow a propellant mass fraction of about 70%
- **Argon welding bottle.** Working pressure 65 Bar (6.5 MPa). Burst pressure is 165 Bar (16.5 MPa). The volume of 950 cm^3 will allow a propellant mass fraction of about 50%

1.1 Construction parameters

Figure 1 has some design parameters of the engine based on an Argon welding bottle and two types of nozzles, one has 4 mm throat and the other has 9 mm throat. We started with the Argon welding bottle component because of the higher safer pressure limit.

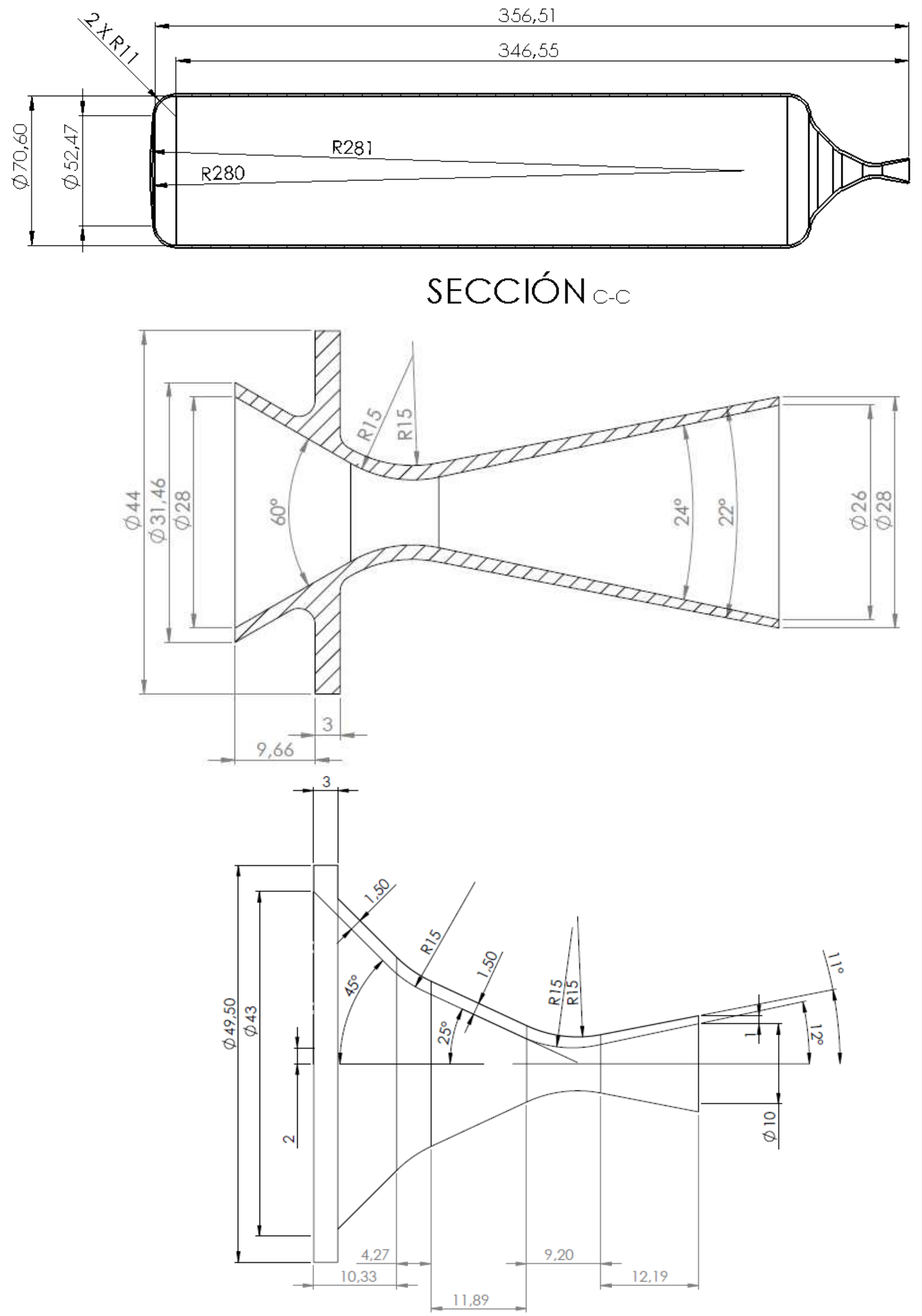
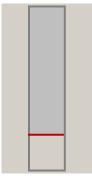
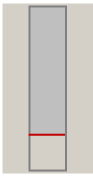
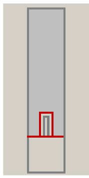
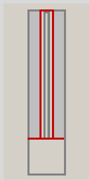
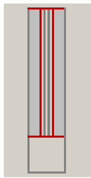
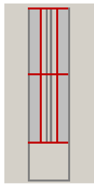


Figure 1 – Bottle, 9 mm and 4 mm throat nozzle parameters

Table 1 summarizes the six propellant burner simulations changing the throat diameter, the nozzle exhaust diameter and the burner type, in such a way we can compare different cases with later real burns.

Table 1 - Summary for various cases of simulation series

Parameter	Case1	Case2	Case3	Case4	Case5	Case6
Throat diameter	2.4 mm	4 mm	4 mm	9 mm	9 mm	9 mm
Exhaust diameter	9.1 mm	10 mm	10 mm	26 mm	26 mm	26 mm
Expansion ratio	14.4:1	6.3:1	6.3:1	8.3:1	8.3:1	8.3:1
Total impulse	3.08 kN·s	2.63 kN·s	2.72 kN·s	2.76 kN·s	2.78 kN·s	2.79 kN·s
Specific impulse	**222.7 s**	**190.6 s**	**197.0 s**	**201.3 s**	**202.6 s**	**203.6 s**
Maximum thrust	101.45 N	45.28 N	294.72 N	976.79 N	726.43 N	533.35 N
Maximum pressure	152.6 atm	29.5 atm	163.6 atm	107.8 atm	81.8 atm	61.8 atm
Burnout time	30.22 s	58.13 s	46.76 s	7.03 s	6.70 s	6.44 s
Geometry type	End burner  Nozzle side	End burner  Nozzle side	Core burner Core length 33 mm Core diam. 6 mm  Nozzle side	Core burner Core length 220 mm Core diam. 6 mm  Nozzle side	Core burner Core length 225 mm Core diam. 6 mm  Both sides	Core burner Core length 112 mm Core diam. 6 mm  2 segments
Trajectory apogee	159.1 km	98.2 km	122.0 km	143.7 km	146.6 km	149.4 km

1.2 Burner type study and selection

In this section, six burn cases are studied in order to select the optimum burner configuration for the best trajectory in terms of maximum apogee.

The **WikiSat** team has got two types of nozzles, one with 4 mm throat and one with 9 mm throat. This is why simulations are using these sizes but we calculated the one with maximum specific impulse which corresponds to a 2.4 mm throat. The **Case1** optimizes the bottle parameters in terms of maximum pressure and total impulse, etc. but we do not have such a nozzle and burnout time is larger than other cases. In addition, this tiny nozzle should be made in tungsten instead of steel.

We look for the highest possible specific impulse. In table 1, the highest Isp is achieved by a small nozzle of 2.4 mm in diameter with the maximum thrust. The point is that, the faster burn, the better trajectory performance is because the gravity field is subtracting energy every second. The better case is the **Case6** but it is complicated to manufacture. The curve thrust vs time of the **Case4** has a huge pressure peak while **Case5** and **Case6** are softer.

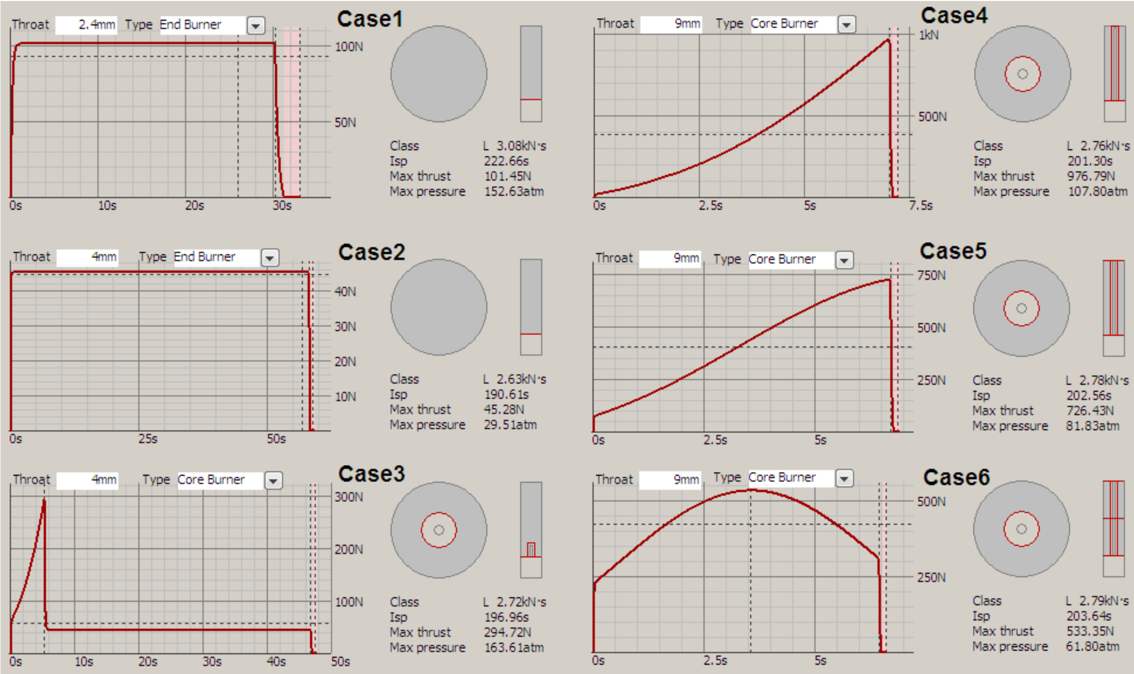


Figure 2 – Thrust vs time for each case

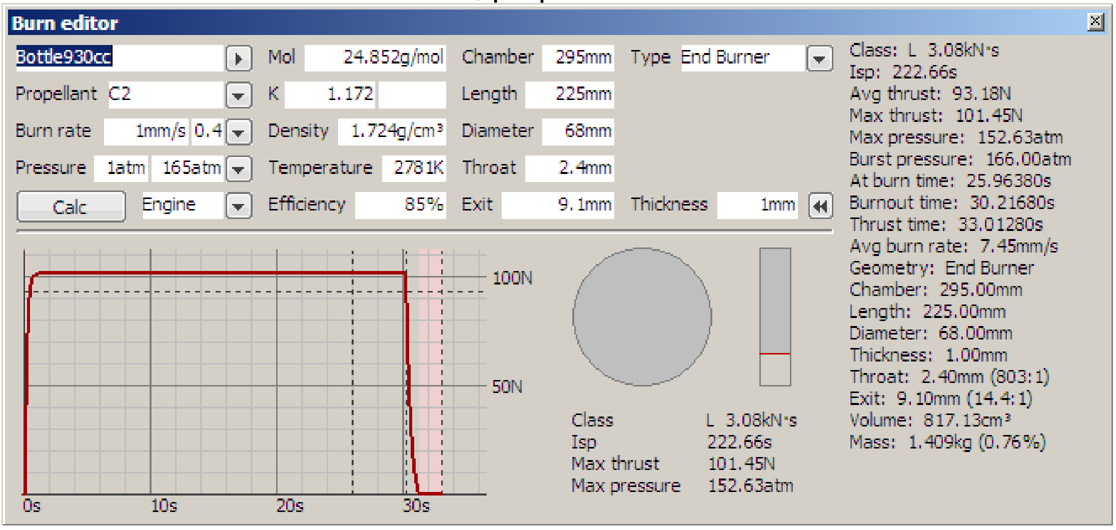
Figure 2 is a summary of each case in the same environmental conditions like, burned at same altitude, same C2 propellant, 1234 grams of dry mass, same throat efficiency of 85%, same payload (200 grams which corresponds to an IRIDIUM locator[1]), as can be seen in section *1.3 Performance calculations* section. Hence, the optimum case is the **Case4**. Compare to the bore burner, only an extra operation is required: to drill the core with a 6 mm bit in order to burn in only 7 seconds the 1.4 kg of propellant achieving an specific impulse of Isp = 201 seconds and a maximum thrust of 977 N. As can be seen in table 1, the shorter burnout time, the greater trajectory apogee is, despite a lower specific impulse. This effect is due to the gravity force is relevant for every second of flight, more than specific impulse is.

1.3 Performance calculation

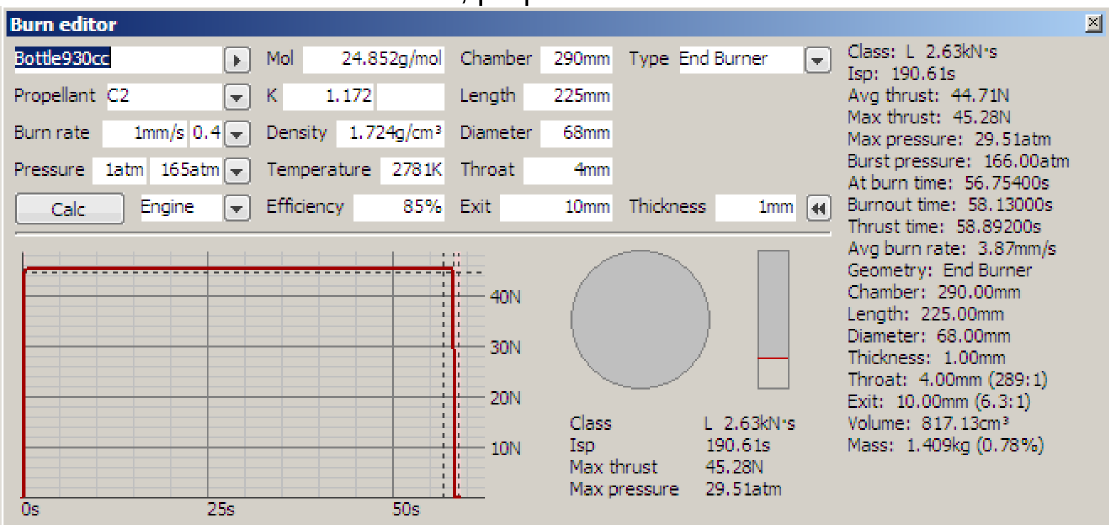
This section presents the final design performance calculations in terms of thrust vs time, pressure vs time and burn rate vs time for the burn case selected. For this purpose, we have designed a burner module in the open source **Moon2.0** simulator showed in the following reports for each case. Finally, an additional case is presented based on another structure component.

1 http://www.iridium.com/products/NAL-SHOUT-nano-Personnel-Tracker.aspx?productCategoryID=11

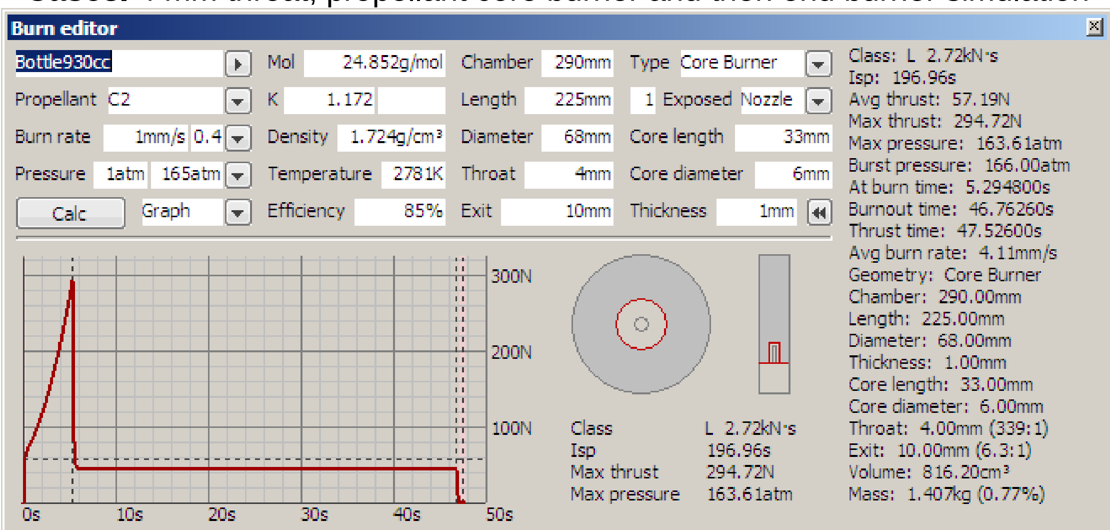
Case1. 2.4 mm throat, propellant end burner simulation



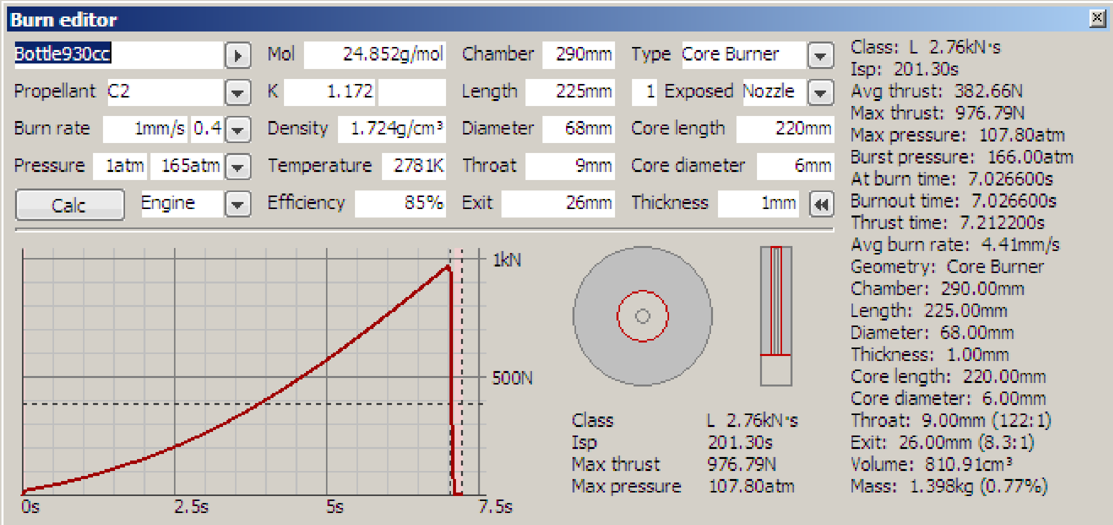
Case2. 4 mm throat, propellant end burner simulation



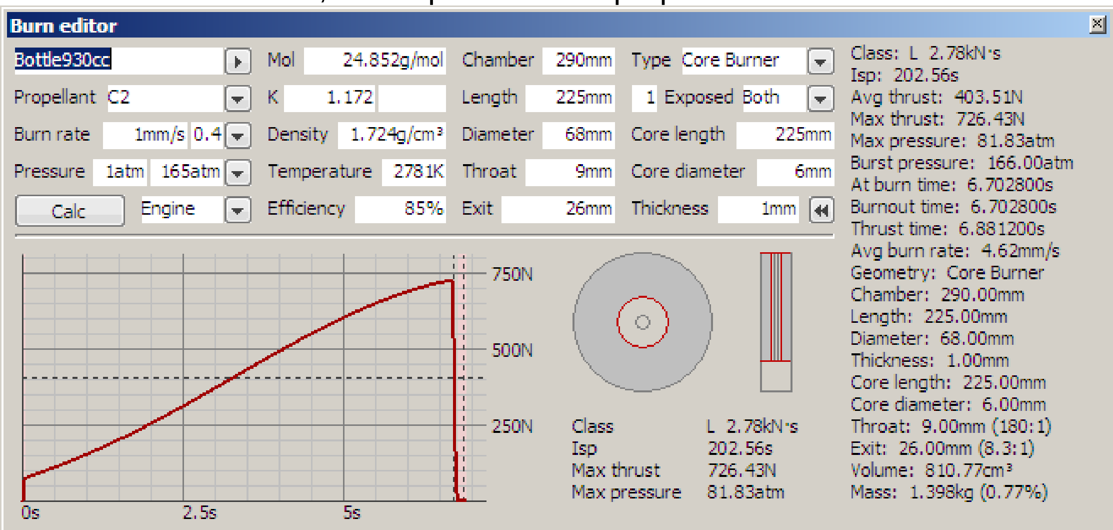
Case3. 4 mm throat, propellant core burner and then end burner simulation



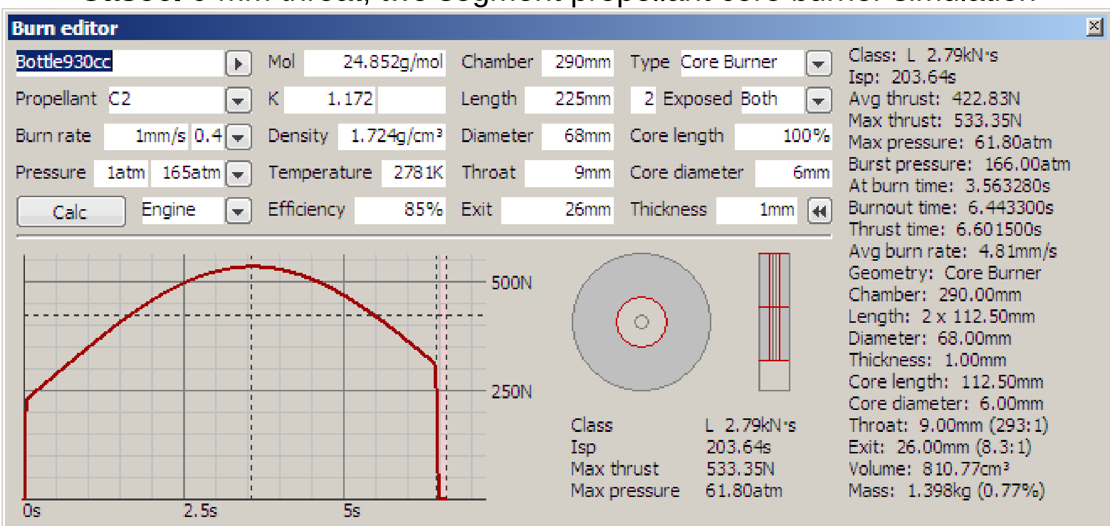
Case4. 9 mm throat, propellant core burner simulation



Case5. 9 mm throat, two exposed fronts propellant core burner simulation



Case6. 9 mm throat, two segment propellant core burner simulation



As presented in section *1.1 Construction parameters*, the selected configuration was the **Case4**. The following curves were generated by the simulator **Moon2.0** based on the equations presented by **Nakka**'s amateur engines study [4].

Figure 3 is the curve of thrust vs time where thrust is increasing exponentially due to the burn cylinder is lager every time up to a limit.

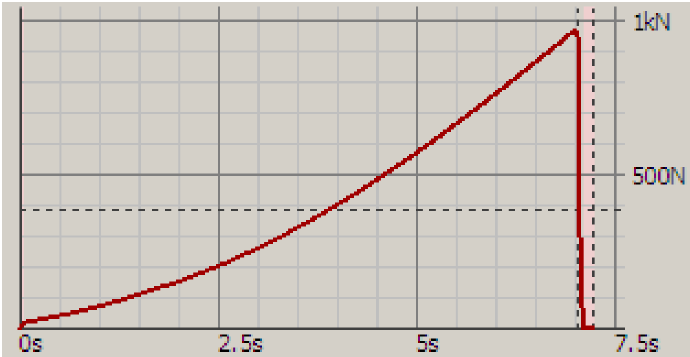


Figure 3 – Thrust vs time for the optimum case

Figure 4 is the curve of pressure vs time where pressure is increasing exponentially as well.

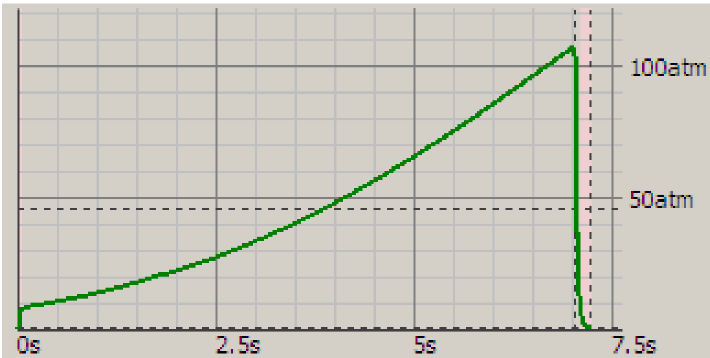


Figure 4 – Pressure vs time for the optimum case

Figure 5 has the curve of burn rate vs time that presents a lineal increase.

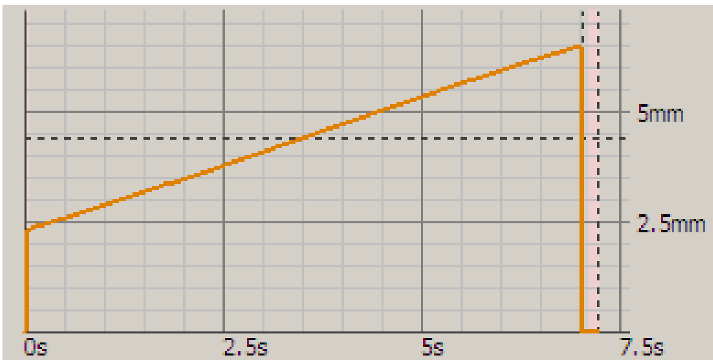


Figure 5 – Burn rate vs time for the optimum case

1.4 The FOAM spray Case7

An additional simulation (Marked as **Case7**) based on the FOAM spray structure was performed and showed in figure 6. The light structure mass (150 grams) allows a propellant mass fraction of 77.6% and an apogee of 453.7 km with a working pressure of 24 Bar.

Case7. 4 mm throat, propellant end burner simulation

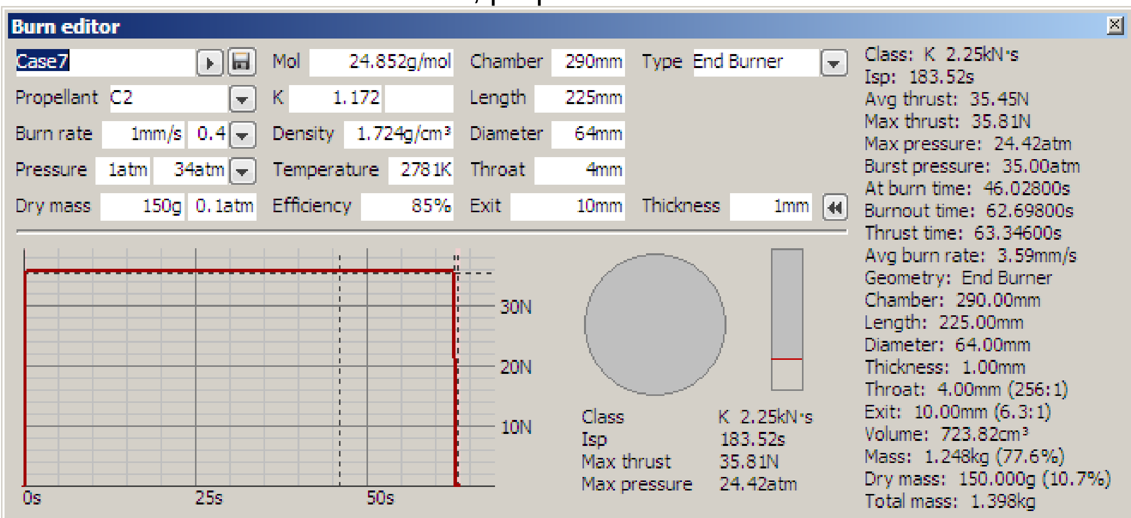


Figure 6 – Case7. Propellant end burner simulation

CHAPTER 2. ENGINE TESTS

2.1 WikiLauncher Stage1 Burn01st Test

The **Stage1 Burn01st** test was done in december, 2011. This test is based on a FOAM Spray bottee in order to determine the pressure limits. The bottle resisted at least 34 Bar of pressure.

2.2 WikiLauncher Stage1 Burn02nd Test

The **Stage1 Burn02nd** test was done in december, 2011. This test (See figure 7) is based on a FOAM Spray bottle full of propellant and a 9 mm throat nozzle but it exploded after 10 seconds of burn.

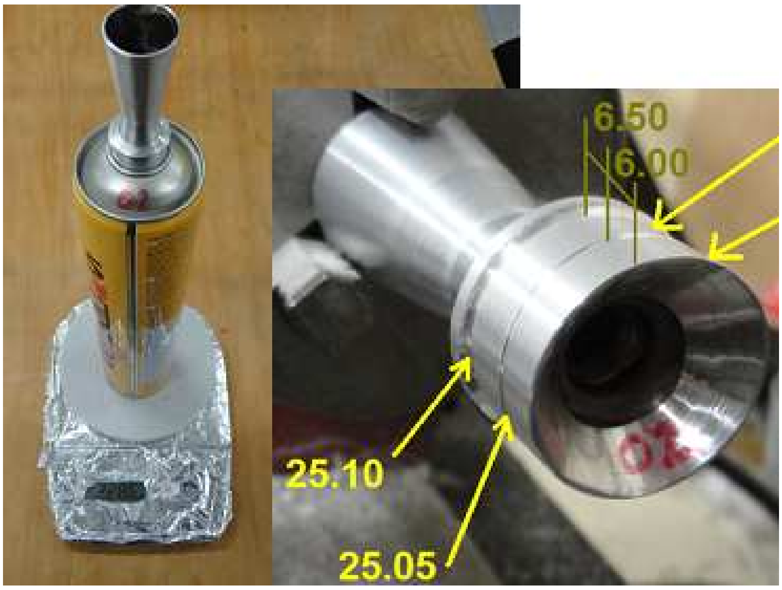


Figure 7 – Stage1 Burn03rd pictures

2.3 WikiLauncher Stage1 Burn03rd Test

The **Stage1 Burn03rd** test was started on July 27th, 2012 and burned on January 27th, 2013. We have to wait 6 month until safe conditions were achieved and a collaborating agreement with a quarry was obtained.

2.3.1 Test setup

This burn is based on C1 propellant inside a 930 cc Argon welding bottle. The nozzle was a 4 mm throat attached with only nine bolts of M2 size.

2.3.2 Results

The nozzle was ejected during the explosion as seen in figure 8. Initial hypothesis was too much powder in the ignition. Later we saw that the problem was the lack of ablative material between the bottle metal and the propellant grain.

Figure 8 – Stage1 Burn03rd pictures

This was our first burn in the quarry. The placement resulted very safe even the huge explosion. People were in safe conditions during all the test. A report was published in **WikiSat** YouTube channel here:
http://www.youtube.com/watch?v=sPDQE7tLEQ0

2.4 WikiLauncher Stage1 Burn04th Test

The **Stage1 Burn04th** test was started on February 25th, 2013 and burned on March 03rd, 2013 bud ignition failed. Second attempt was performed on March 10th, 2013.

2.4.1 Test setup

This is a burn based on a C1 propellant inside a 930 cc Argon welding bottle and a steel nozzle with bold seal. Bottle pressure was released. A small hole was performed in order to ensure the pressure is down and empty from Argon. Mixture was done inside the bottle. Upper bulkhead flattened and the igniter was placed in the center. Eleven bolts M3 closed the structure and the nozzle through a fiberglass and epoxy seal

2.4.2 Results

The igniter failed in the first attempt. A relievable igniter was developed and the stage was burned in a second attempt. The stage burned very slow without a supersonic flame except for a moment as seen in figure 9. During this sudden increase of pressure the seal failed. Epoxy should be avoided in this seal. The propellant mixture process was bad. In future mixing procedures, a premix will be done in a cup. Since the burn time was 421 seconds and propellant length was 216 mm, the burn rate at a low pressure was set initially at 0.51 mm that is very slow compared to 6 mm/s that APCP composite propellant has. Thanks to this parameter, **Moon2.0** propellant burn calculations were corrected.

Figure 9 – Stage1 Burn04th pictures

A report was published in **WikiSat** YouTube channel here:
http://www.youtube.com/watch?v=50vRoOJKgeY

2.5 WikiLauncher Stage1 Burn05th Test

The **Stage1 Burn05th** test was started on March 12th, 2013 and burned on March 24th, 2013 but ignition failed. Second attempt was performed on April 04th, 2013.

2.5.1 *Test setup*

This is a burn based on a C2 propellant inside a 930 cc Argon welding bottle and a 4 mm throat steel nozzle with bold seal. Bottle flange was polished as well as the nozzle flange. The closure will be through 27 bolts M2x17 mm and nuts without no gasket or joint hoping that closure will be tightness and no pressure leak at this point. Propellant will be premixed in a cup adding 170Ap and 60St. We needed 6 cup but there is room for extra propellant if bolts were installed before filling the bottle. Next time, consider to install an protect bolts before filling.

2.5.2 *Results*

Due to the ignition failed in the first attempt and ablative material was not added at this time, we decided to do not use the nozzle and reuse it in the Burn08th as seen in figure 10. Since the burn time was 383 seconds and propellant length was 208 mm, the burn rate for the C2 propellant at low pressure was set at 0.54

mm/s that is higher than C1 burn rate as expected. Thanks to this parameter **Moon2.0** propellant burn calculations were corrected.

Figure 10 – Stage1 Burn05th pictures

The ablative problem is only seen if nozzle is present. Now we know. The ignition used was a reliable one so ignition reliability is increasing every attempt. A report was published in **WikiSat** YouTube channel here:
http://www.youtube.com/watch?v=XHli4xr_ytI

2.6 WikiLauncher Stage1 Burn06th Test

The **Stage1 Burn06th** test was started on March 19th, 2013 and burned on March 24th, 2013. The manufacturer time and test time was reduced to only one week.

2.6.1 Test setup

In this burn we are putting 4 mm throat nozzle to the limit with higher flow, larger burn time and a hotter/abrasive propellant which is the C2. This is a burn based on a 930 cc Argon welding bottle and a steel nozzle of 4 mm throat with bolted metallic seal. Bottle flange (46 mm of nominal diameter) was polished as well as the nozzle flange. The closure was done through 27 bolts M2x17 mm and nuts. C2 propellant was premixed in seven cups. Last cup was C1 propellant, without aluminum, to ensure a good slow propellant start. Bolts were installed before filling the bottle so higher volume was filled with APCP this time. Igniter has been normalized but this is the first real test for this kind of igniters.

2.6.2 Results

The nozzle was ejected during the explosion but supersonic flame was achieved for a moment before the explosion as seen in figure 11. We realized that, even the nozzle was attached by 27 bolts, the pressure increases any case so the problem is not the ignition, is the lack of ablative material between the bottle metal and the propellant grain.

Figure 11 – Stage1 Burn06th pictures

The huge explosion was recorded by our slow motion camera. A report was published in **WikiSat** YouTube channel here:
http://www.youtube.com/watch?v=xlRSAT0ghIo

2.7 WikiLauncher Stage1 Burn07th Test

The **Stage1 Burn07th** test was started on March 24th, 2013 and burned on March 27th, 2013. This is the faster test we have done up to now from the beginning of manufacturing until a succeeded burn and report only in 3 days.

2.7.1 *Test setup*

This is a burn based on C2 propellant inside a 930 cc Argon welding bottle and a 9 mm throat steel nozzle with bold seal and no joint. In order to avoid the explosion, an ablative layer was attached to the bottle interior walls. Igniter worked for the second time. Metallic seal remains closed.

2.7.2 *Results*

Moon2.0 burn editor simulation said 64 seconds of burn time while real burn was between 60 and 80 seconds. Flame was not supersonic as seen in figure 12 where pressure was not high enough.

Figure 12 – Stage1 Burn07th pictures

Next burn can have the 4 mm throat because looks like the explosion problem was fixed. A report was published in **WikiSat** YouTube channel here: http://www.youtube.com/watch?v=xg5LbAJ94K4

2.8 WikiLauncher Stage1 Burn08th Test

The **Stage1 Burn08th** test was started on April 02nd, 2013; first try was on April 07th, 2013 and finally burned on April 21th, 2013. The 4 mm nozzle was tested with a Bore burner.

2.8.1 Test setup

This burn is based on C2 propellant inside a 930 cc Argon welding bottle and a 4 mm throat steel nozzle with bold seal and no joint. Ablative material was applied and bolts were placed before propellant insertion. Igniter was the same as previous burns. First try was a single igniter. Second attempt we installed two igniters. It worked, but second igniter blocked the throat and provoked the explosion.

2.8.2 Results

In the first attempt ignition failed, powder was loosed during tighten nuts. In the second attempt, the nozzle was ejected during the explosion as seen in figure 13. Looks like, second igniter block the throat and nozzle was shooting. Bolts are too weak. M3 mm bolts should be used instead of M2 mm bolts.

Figure 13 – Stage1 Burn08th pictures

This burn should be repeated but using stronger bolts. A report was published in **WikiSat** YouTube channel here:
http://www.youtube.com/watch?v=Ok4caEWjMGU

2.9 WikiLauncher Stage1 Burn09rd Test

The **Stage1 Burn09th** test was started on April 07th, 2013 and burned on April 14th, 2013. This burn was dedicated to test a Core burner instead a Bore burner.

2.9.1 Test setup

This is one of the development prototypes for the stage1 rocket of the WikiLauncher. It is a burn based on C1 propellant inside a 930 cc Argon welding bottle and a 9 mm throat steel nozzle, core burn and 6 mm drill, with bolted seal and ablative material between metal and propellant. Igniter is the same as previous burn but positioned at the final moment. Looks like vibrations during tight nuts made these igniters fail as happened in Burn05th and Burn08th.

2.9.2 Results

Pressure increased slowly and exploded after 25 seconds. Before the rapid explosion, the fast camera recorded an under-expanded flame as shown in figure 14 and a weak flame during the burn. The propellant was fractured and then exploded. Metallic fragments of the bottle were small. Nozzle required a 22 mm exhaust diameter instead of 26 mm of the used nozzle.

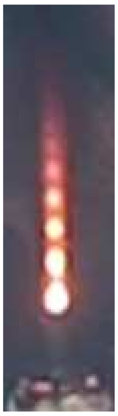
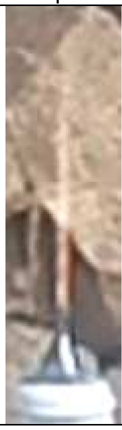
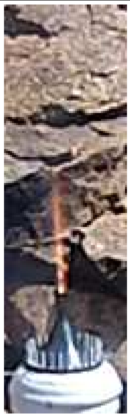
Figure 14 – Stage1 Burn09th pictures

The test could be repeated with an adapted nozzle but looks like Core burner has too much pressure to be supported by the propellant then soft propellants should be developed. A report was published in **WikiSat** YouTube channel here:
http://www.youtube.com/watch?v=cS1yJ17QyeE

2.10 WikiLauncher Stage1 Stage1 Burn tests summary

Following, table 2 is a summary of the main results for the seven burn tests performed during this work.

Table 2 - Summary for stage1 burn tests

Burn test number	03rd	04th	05th	06th	07th	08th	09th
Development (Days)	180	7	27	5	3	5	7
Burned date (2013)	27/Jan	10/Mar	07/Apr	24/Mar	10/Mar	21/Apr	14/Apr
Propellant used	C1	C1	C2	C2	C2	C2	C1
Propellant mass [grams]	1364	1380	1330	1445	210	1405	1414
Dry mass [grams]	1152	1215	1200	1167	1254	1207	1234
Propellant mass fraction	54.2%	53.2%	53.8%	**55.3%**	14.3%	53.8%	53.4%
Burner type	Bore	Bore	Bore	Bore	Bore	Bore	Core
Burn time [seconds]	1	421	383	14	80	10	25
Nozzle throat [mm]	4	9	4	4	9	4	9
Nozzle bolt [mm] / Qty.	2x9	3x9	2x27	2x27	3x18	2x27	3x18
Ended Burned/Exploded	Explod	Burned	Burned	Explod	Burned	Explod	Explod
Supersonic flame	No		No		No		No

CHAPTER 3. CONCLUSIONS

A high valued experience was added to the **WikiSat** team thanks to these nine real tests. Many parameters were calibrated thanks to the experimental results; mainly the burn rate and thermal load. End burner type is the best selection for this king of engines due to the stable working pressure. The propellant mass fraction should be improved to achieve the goal of to build such a small launcher that will inject into orbit femto-satellites.

CHAPTER 4. REFERENCES

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