Design, production and trial of a firefighting projectile

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Abstract

The forest is an integrating part of the Portuguese environment, landscape and economy. However, it is every year victim of a violent wave of fires, due to natural and manmade causes, that destroy several hectares of this natural resource.

The efforts of the firefighting corporations and the Civil Protection are untiring, but the conventional means had shown themselves insufficient. As so, the FIREND projectile appears as a way to complement these means. This project has been in development over the last years, with the most recent developments being the mechanical design and the study of tensions on a projectile made of a polymeric material.

The objective of this thesis consists on the design, production and test of a projectile with a caliber of 105 mm, made on a polymeric material, and the subsequent corrections of the errors found on the shooting trials. There were made three shooting trials, and, as so, three types of prototypes of the projectile. It was decided that the range of the projectile should be of 2000 m, for an initial velocity of 200 m/s. In order to complement this data, it was also made an analysis of the internal, external and terminal ballistics of the FIREND projectile.

In the end, according to the developments achieved, it was developed the design of a projectile for the caliber 155 mm, and presented the main conclusions extracted from the tests, as well as proposals for future works.

Keywords: Firefighting projectile, polymeric projectile, internal ballistics, external ballistics, reengineering

1. Introduction

Every year, forest fires are a scourge for the Portuguese environment and economy. In 2016, it was burnt more than 160000 hectares, as it can be seen on the map below:

Figure 1: Map of the burnt area in Portugal, in 2016 [1]

In order to counter this problem, the efforts of the Civil Protection means include not only the firefighting corporations, but also the Armed Forces, the GNR and the Red Cross, and these institutions use not only human means but also all terrain and aerial vehicles, like airplanes and helicopters.

The aerial means represent a versatile solution to be used on places hard to reach by the land vehicles, and capable of carrying a large quantity of water, but still present some disadvantages. Firstly, its cadence is very low, as it takes a lot of time to reload. Most of the water released is not useful, as it is soaked in by the soil. Apart from this, bad weather conditions as strong winds and dense smoke, and bad visibility situations, such as during the night, make the usage of the aerial means very difficult, and even impossible.

The FIREND projectile appears as a way to complement all this means. Using the fire rate of the howitzers used by the Portuguese Army, these projectiles are launched towards the fire containing a fire-retardant substance inside it. Once it comes above the fire it opens and releases the substance, to maximize the area exposed to it. The cost of the usage of the FIREND projectile is low comparing to the conventional means: 6 howitzers firing 6 projectiles per minute have a cost of 0,82 €/L, while the usage of the Canadair CL-215 has a cost of 1,40, €/L, and the Bombardier 415 has a cost of 1,12 €/L.

This project has been in development since 2005, with the design of a metallic, mechanically activated projectile for the caliber 105 mm and the most recent developments being the development of an electronic fuse, and the design and study of the tensions on a projectile made of biodegradable polymeric materials, for the caliber 155 mm. This reduced the costs of production of the projectile, and reduced its impact on the environment. Besides, as the projectile was lighter and less rigid than the metallic one, it was easier for the howitzer teams to handle it, and made the detonation process simpler.

Due to logistics considerations of the army, the 155 mm caliber projectile had to be postponed, and the 105 mm projectile advanced. This project was financed by the Ministry of Defense, and counted on several partners: The Military Academy and the IST on the design of the projectile, Forma 3D and IPCA were responsible for its production, CEIF performed studies on the fire-retardant substance, and the Navy

Explosives Laboratory was to supply gunpowder and perform studies on internal ballistics.

As it was previously stated, the objective of this project was to launch a projectile at 2000 m. Because of a question of similarity to the M1 HE projectile, it was stipulated that the muzzle velocity should be of 200 m/s.

2. Ballistics overview

2.1. External Ballistics

External ballistics is the science that studies the motion of the projectile on its atmospheric movement, when it leaves the gun. The projectile is subject to several forces that will now be explained [2]:

Firstly, the rotation and the gravitational field of the Earth induces these forces on the projectile:

- The gravity force, given by:

$$F_g = -m_p \cdot \vec{g} \tag{1}$$

- Centrifugal force:

$$F_Z = m_p \cdot \omega_E^2 \cdot r_E * \begin{pmatrix} -\sin(\varphi)\cdot\cos(\alpha) \\ \cos(\varphi) \\ \sin(\varphi)\cdot\sin(\alpha) \end{pmatrix} \tag{2}$$

- Coriolis Force:

$$F_c = 2 \cdot m_p (v \times \omega) \tag{3}$$

$$\omega = \omega_E \begin{pmatrix} \cos(\varphi)\cdot\cos(\alpha) \\ \sin(\varphi) \\ -\cos(\varphi)\cdot\sin(\alpha) \end{pmatrix} \tag{4}$$

With exception of the gravity force, the values of this forces are very low, due to the low mass of the projectile and the low range (the Coriolis force is only considered on ranges superior to 20 km [3]).

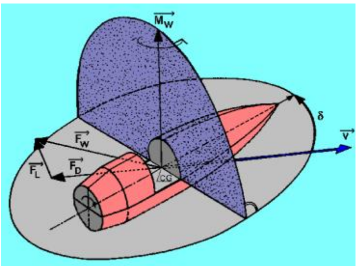


Figure 2: Aerodynamic forces and moments applied on the projectile [3]

The air surrounding the projectile will create some aerodynamical forces on the projectile. The projectile leaves the gun with a misalignment between its longitudinal axis and the direction of the movement, the yaw angle. This angle will increase the section of the projectile resisting the air, thus creating the wind force – F_W – and the wind moment – M_W:

$$M_W = \frac{\rho}{2} \cdot A \cdot c_M \cdot v_w^2 \cdot d \tag{5}$$

The wind force can be decomposed on its horizontal and vertical components: the drag force and the lift force.

$$F_D = -\frac{\rho}{2} \cdot A \cdot c_D \cdot v_w^2 \tag{6}$$

$$F_L = \frac{\rho}{2} \cdot A \cdot c_L \cdot v_w^2 \tag{7}$$

The spin induced by the grooves of the gun will have influence on the forces and moments applied. As it is moving on a fluid, there will be viscous interaction between the air and the projectile, thus creating a moment that will reduce the angular velocity of the projectile, the spin damping moment:

$$M_S = -\frac{\rho}{2} \cdot A \cdot c_{spin} \cdot v_w^2 \cdot d \cdot \frac{\omega \cdot d}{v_w} \tag{8}$$

Finally, the difference of pressures on the superior and inferior part of the projectile, due to the difference of velocity in the air flow, will create a force, the Magnus force:

$$F_M = \frac{\rho}{2} \cdot A \cdot C_{Mag} \cdot \frac{\omega \cdot d}{v_w} \cdot v_w^2 \tag{9}$$

This force will create a moment on the center of gravity of the projectile, the Magnus moment, that will force the longitudinal axis of the projectile towards the direction of the movement, reducing the yaw angle.

$$M_M = \frac{\rho}{2} \cdot A \cdot c_{Mp} \cdot \frac{\omega \cdot d}{v_w} \cdot d \cdot v_w^2 \tag{10}$$

2.1.1. Stability of projectiles

All these forces and moments contribute the stability of the projectile. But to say that a projectile is stable, it must meet three conditions [3]:

- Be statically stable:

The projectile acquires a gyroscopic effect due to the rotation imposed by the grooves of the gun. The stability of this effect can be computed by the gyroscopic stability factor:

$$S_g = \left(\frac{I_{xx}}{I_{yy}}\right) \cdot \left(\frac{\omega \cdot d}{v_w}\right)^2 \cdot \left(\frac{2 \cdot I_{xx}}{\rho \cdot \pi \cdot d^5 \cdot c_{M\alpha}}\right) \tag{11}$$

The value of this factor should be between 1,2 < Sg < 1,5.

- Be dynamically stable

To be dynamically stable, the projectile must reduce the yaw angle along the trajectory. This condition may be calculated with the dynamical stability factor:

$$S_d = \left(\frac{C_{L\alpha} - \frac{m \cdot d^2}{I_{xx}} \cdot C_{M_{p\alpha}}}{C_{L\alpha} - C_D + \frac{m \cdot d^2}{I_{yy}} \cdot (C_{mq} + C_{m\dot{\alpha}})}\right) \tag{12}$$

And a projectile is considered stable if:

$$S_g > \frac{1}{4 \cdot S_d \cdot (1 - S_d)} \tag{13}$$

- Have tractability

If the projectile is over-stabilizer, it will become unstable. This means that the angle between the longitudinal axis and the direction of flight is constant along the trajectory. To avoid this, the projectile must have a tractability factor superior to 5,7.

$$f = \frac{1}{|\delta_p|} = \left(\frac{I_{xx}}{I_{yy}}\right) \cdot \left(\frac{\omega \cdot v_w}{4 \cdot \vec{g} \cdot \cos\Theta}\right) \cdot \left(\frac{1}{S_g}\right) \tag{14}$$

δ_p being the yaw of repose, that is the angle between the axis of precession of the projectile and the direction of flight:

$$\delta_p = -\frac{8 \cdot I_{xx} \cdot \omega}{\pi \cdot \rho \cdot d^3 \cdot C_{M\alpha} \cdot v_w^4} \cdot \left(v_w \cdot \frac{dv_w}{dt}\right) \tag{15}$$

- Deceleration

Deceleration is the diminution of the velocity per 1000 m, due to the drag:

$$\frac{dv}{dx} = \frac{1000 \cdot \rho \cdot V \cdot A \cdot C_x}{2 \cdot m_p} \qquad (16)$$

- Ballistic coefficient

The Ballistic coefficient is a way to measure the capacity of the projectile to counter the air resistance. The higher its value, the most stable will the flight be:

$$C = \frac{m_p}{d^2} \qquad (17)$$

2.2. Internal Ballistics

The internal ballistics is the science that studies the motion of the projectile inside the weapon, from the moment when the deflagration of the gunpowder occurs, until the projectile leaves the weapon.

The evolution of the pressure inside the barrel can be computed through some methods, the most approximated being the exponential equation [7]:

$$P(x) = P_0 \cdot a \cdot x \cdot e^{1-a\cdot x} \qquad (18)$$

Being P_0 the maximum pressure and *a* a variable related to the pressure distribution curve. The maximum pressure can be computed through the equation of the velocity of the projectile:

$$v_s(a, L_t) = \sqrt{\frac{2}{m_p}\left[\frac{e \cdot P_0 \cdot A}{a}\left(1 - (1 + a \cdot L_t) \cdot e^{-a \cdot L_t}\right) - f_a \cdot L_t\right]} \qquad (19)$$

Where f_a is a friction factor related to the pressure at the end of the barrel. Varying the value of *a* it is possible to obtain different types of pressure curves:

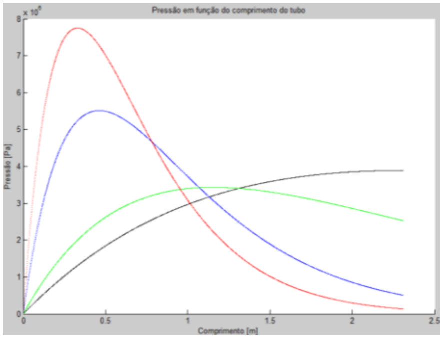


Figure 3: Evolution of the pressure curve for different values of *a*

The most suitable value for *a* is $a = 5/L$, represented by the blue curve.

2.2.1. Gunpowder analysis

Different types of gunpowder grains can be used as a propellant to an artillery projectile. The shape and dimensions of grains will have influence on the burn velocity and volume of gas produced on each grain.

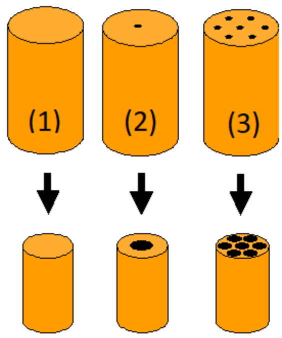


Figure 4: Different types of grains: (1) Cilyndrical; (2) Monoperforated; (3) Multiperforated [4]

As seen on Figure 4 the way how a grain burns is related to its shape. A cylindrical grain will have a regressive burning, which means that the area that is burning will decrease over time. A monoperforated grain will have a neutral rate of burning, meaning that the burning area will remain constant. And a multiperforated grain will have a progressive rate of burning, meaning that the burning area will increase over time.

Table 1: Characteristics of the grains of M1 HE projectile gunpowder [5]

Charge	Perforation	Grain	Grain Length [mm]	Grain Diameter [mm]	Weight of the charge [g]
1	Monoperforated	Neutral	6	1	241
2	Monoperforated	Neutral	6	1	43
3	Heptaperforated	Progressive	6	3	65
4	Heptaperforated	Progressive	9	3	110
5	Heptaperforated	Progressive	9	3	162
6	Heptaperforated	Progressive	9	3	245
7	Heptaperforated	Progressive	9	3	392

The M1 HE projectile has seven bags of gunpowder that are to be used according to the desired range. As seen on Table 1, the first two bags contain neutral grains. As the mass of gunpowder increases, the burn velocity should increase as well, so the last five bags have multiperforated grains.

It is possible to quantify the amount of gunpowder necessary propel the FIREND projectile [6]. Considering a muzzle velocity of 200 m/s and a mass of 2,6 kg:

$$v_s = 1482 \times \left(\frac{C_0}{m}\right)^{0,4892} \quad (20)$$

Resulting in C_0=43,34 g. This corresponds to a charge 2 bag. Although this equation was plotted based on experimental results, it represents a good starting point for the shooting trials.

2.2.2. Driving Band

The driving band is the component responsible for the contact between the projectile and the grooves inside the barrel. It also must center the projectile inside the barrel, and prevent the gases from the deflagration of the gunpowder to overcome the projectile, thus sealing it [9].

Given that the FIREND projectile is spin stabilized, and the driving band is responsible to transfer the rotation of the grooves, it is important to understand how it contacts with the barrel. So, on Figure 5 a section view of a barrel is represented, with its main dimensions

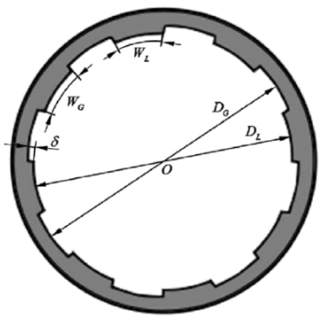


Figure 5: Section view of a barrel [8]

D_G: Groove to Groove diameter

D_L: Land to land diameter

W_g: Groove width

W_L: Land width

δ: Groove depth

2.3. External ballistics simulation

The equations relating projectile stability stated before are too complex to be resolved efficiently. So, the usage of a ballistics software becomes necessary. The chosen software was PRODAS V3.5, which allowed to compute the main coefficients related to the projectile stability.

Starting from Almeida's project [10], it was considered that the projectile was full of water with $\rho_{water} = 1{,}00\ [g/cm^3]$;, and had a mass of clay on the top, with $\rho_{clay} = 1{,}60\ [g/cm^3]$ simulating the weight of the fuse. The software used the following model:

Figure 6: Projectile used on PROVAS V3.5

It was considered a muzzle velocity of 200 m/s, an exit angle of 45º and the yaw and pitch angle was 0º. The materials used were the following:

- The base and the ogive in ABS with $\rho_{ABS} = 1{,}04\ [g/cm^3]$;
- The driving band in PE with $\rho_{PE} = 0{,}96\ [g/cm^3]$;
- The tube in acrylic with $\rho_{Acrílico} = 1{,}18\ [g/cm^3]$;

The software allows to calculate the spin of the projectile. Given the muzzle velocity of 200 m/s and a twist of the barrel of 20,5 calibers/revolution, it was obtained an angular velocity of 5572 rpm, resulting on a ration between the linear and angular velocity of:

$$\frac{v_s}{v_{ang}} = \frac{200}{5572} = 0{,}0359\ [m/s/rpm] \quad (21)$$

The results of the simulations are described on the following table. The simulations were made by decreasing the size of the projectile, starting from 340 mm.

Table 2: Simulations for different lengths

Length. [mm]	Mass [kg]	CG from nose [mm]	I_{xx} [kg.m^2]	I_{yy} [kg.m^2]	Range [m]	S_g	Deceleration [m/s/1000m]	C
340	2,69	166,022	0,00327	0,02567	47,55	0,72	41,44	0,682
320	2,53	156,119	0,00306	0,02142	1873,2	0,85	45,50	0,621
300	2,37	146,229	0,00286	0,01766	2291,2	1.02	50,11	0,563
280	2,20	136,355	0,00265	0,01439	2342,6	1,25	55,19	0,511
260	2,04	126,501	0,00244	0,01155	2278,9	1,57	60,90	0,463

As it can be seen above, when the length decreases, S_g increases, having an optimal value for 280 mm. On relation to the range, it only reaches the proposed values after a length of 300 mm. Although reducing the length is good for the projectile stability, it also means less mass and less volume for the fire-retardant liquid. This is seen on the deceleration and the ballistic coefficient: the lesser the mass, the worse these parameters are.

2.3.1. Simulations with the fire-retardant liquid

There were developed studies related to the fire-retardant liquid by CEIF. The liquid with the best results was FR161 of Budenheim [11], with a density of a $\rho_{FR161} = 0{,}975\ [g/cm^3]$, and an efficiency 60% superior to water.

In relation to the previous simulations, it was considered the 280 mm projectile, having the FR161 instead of water. Both results are shown below for comparison.

Table 3: Comparison between water and FR161

Liquid	Mass [kg]	CG from nose [mm]	I_{xx} [kg.m^2]	I_{yy} [kg.m^2]	Range [m]	S_g	Deceleration [m/s/1000m]	C
Water	2,20	136,355	0,00265	0,01439	2342,6	1,25	55,19	0,511
FR161	2,17	135,949	0,00261	0,01421	2326,2	1,24	56,10	0,503

As it can be seen, as the FR161 has almost the same density as water, the results obtained are very similar, meaning that the projectile carrying the liquid is acceptable in terms of external ballistics. The range is superior to the defined objective, and the S_g is within the stipulated range of values.

3. Experimental procedures and equipment used

3.1. Equipment used

3.1.1. HPI B251 piezometer

This equipment is placed on the rear of the barrel, near the breech, and is designed to stand the high pressures of the gunpowder deflagration.

Figure 7: Piezometer

It is designed to register the values of maximum pressure (until 800 MPa), the maximum temperature and the pressure curve.

3.1.2. RSL Muzzle Velocity Radar System

This radar system can detect the muzzle velocity of any projectile with a caliber superior do 20 mm and with velocity between 50 and 2000 m/s. The system can be placed in front of the gun (as in the figure) or attached to the barrel.

Figure 8: Muzzle velocity radar, in front of the gun

When it detects the vibration of the air due to the mass of the projectile, it detects its velocity with a precision of 0,1 %.

3.1.3. Howitzer M101 A1

Despite not being the current 105 mm gun, this was the howitzer used on the shooting trials, as its characteristics are similar to the one that is used.

Figure 9: M101 A1 howitzer

The main characteristics of the howitzer are:

Table 4: Characteristics of M101 A1

Caliber	105 mm
Mass	2260 kg
Lenght	5940 mm
Barrel lengh	2310 mm
Action angles	-5.5º to 65º
Rate of fire	10 rounds/minute
Maximum range	11270 m

On relation to the barrel section, as seen before, it has the dimensions stated on Table 5. The grooves are oriented clockwise.

Table 5: Characteristics of the howitzer barrel

D_G [mm]	106,7
D_L [mm]	104,7
Number of grooves	36
W_g [mm]	4
W_L [mm]	5
δ [mm]	1

3.2. Experimental procedures

During the shooting trial, the following procedure was followed:

- Introduction of the projectile in the breech;
- Measurement of the mass and kind of gunpowder used;
- Introduction of the gunpowder bags and the piezometer on the cartridge;
- Introduction of the cartridge on the weapon;
- Shooting;
- Register of the impact point and the values obtained on the equipment.

4. Production and trial of the projectiles

4.1. Production of the first prototype

Figure 10: Exploded view of the projectile

The first prototype was composed of 6 parts. These parts were joined with a chemical glue ACRIFIX 1S0107, filled with water and with a mass of 160 g of clay on the ogive, to simulate the weight of the fuse.

The base (1) and the ogive (6) were produced in ABS by thermoforming on the FORMA 3D factory. The driving band (2) was machined on nylon with 30% glass fiber, with three different diameters: 105 mm, 106 mm and 107 mm. It was difficult to find a tube with the dimensions pretended for the projectile body (3), so it was decided that it should be made on a commercial acrylic tube with 100 mm of diameter and 4 mm of thickness. There were machined grooves in order to fit in the driving band. The central separator (4), which has the function of passing the rotational motion to the water and the fuse cover (5) were produced by laser cutting an acrylic sheet.

4.2. First shooting trials

The first trial occurred on the 18th of May in Vendas Novas, and started with the shooting of 10 M1 HE, following 4 FIREND projectiles, described on Table 6:

Table 6: Projectiles fired

Shot	Driving band diameter [mm]	Gunpowder mass [g]	Grooves cut
1	106	43	No
2	107	50	Yes
3	107	120	Yes
4	106	240	Yes

The main problems found on this trial was that the driving band was too strong to deform plastically on the grooves.

Figure 11: Driving band used on the second shot

As seen on Figure 11, although the grooves were already half cut, the rest of the band remained uncut. Another problem found was that the base of the projectile was too fragile and broke with the pression of the gunpowder gases and the forcing cone of the barrel (Figure 12).

Figure 12: Broken projectile base

4.3. Corrections to the prototype

Based on the errors found, the main corrections made were that the material of the driving band should be changed to a more ductile one, and that the base of the projectile should be reinforced.

Some minor changes were made as well, as changing the external diameter of the ogive or adding two holes in the fuse cover.

4.4. Production of the second prototype

According to the corrections mentioned before, the base was reinforced as seen on Figure 13. Although, this correction made the base heavier (66,5g to 220g).

Figure 13: Base used on the first and second prototypes

The material chosen to the driving band was polyethylene, which is more ductile and less dense than the previously used.

4.5. Second shooting trials

The second trial happened on the 31st of May, and in addition to the material previously mentioned, it was also used a high velocity camera PHOTRON FAST CAM MINI AX200. With the use of this camera it was possible to get results about the linear and angular velocity of the projectile, as seen on Table 7

Table 7: Results of the second shooting trial

N.º	Projectile Mass [kg]	Gunpowder mass [g]	V_s [m/s]	V_{ang} [rpm]	V_s / V_{ang}	Driving band [mm]	Grooves cut	Range [m]
1	2,6704	83,2	40,47	1071,43	0,0377	105	No	111
2	2,6498	86,1	53,13	1442,3	0,0368	106	No	100
3	2,6367	241,9	170	-	-	105	No	250
4	2,6199	85,6	58,62	1056,33	0,0554	105	No	166
5	2,6122	128,4	50	1293,1	0,0386	107	Yes	143
6	-	128	58,62	1630,43	0,0359	106	No	250
7	2,6442	85	51,52	1612,9	0,0319	107	Yes	166
8	2,7606	128	48,57	2142,9	0,0226	106	No	166
9	2,7484	242,2	242,85	-	-	106	No	333
10	2,6292	240,7	141,67	3846,2	0,0368	106	Yes	330

As seen on the table, it is with 240 g of gunpowder (charge 1) that the linear velocity comes to values close to the expected. On the other hand, the values of the angular velocity are very far for what it was supposed to be (5572 rpm). On most cases, though, the ratio between the two velocities is in concordance of what was previously calculated (around 0,036).

The images captured by the camera showed that the obturation is not efficient.

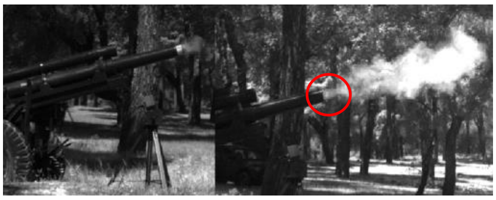


Figure 14: Liberation of gases before and after the projectile

On Figure 14 it is possible to see that there are gases liberated before the projectile leaves the gun, and after it leaves gases are released on small smoke clouds. This means that there are gases passing between the driving band and the grooves (as seen on Figure 15), and that the driving band is not rigid enough to hold the projectile until all the gunpowder is burnt.

Figure 15: Driving band of a projectile

After leaving the barrel, the projectiles demonstrated a flight quite unstable, as seen on Figure 16. This may have happened not only because of the low linear and angular velocities, but also because of the increment of the weight due to the reinforcement on the projectile base.

Figure 16: Misalignment between the projectile and the trajectory

The maximum range reached was only 333 m, a lot lower than what was expected. This can be justified by the inefficiency on the burning of the gunpowder, which conditioned the linear and angular velocity, and by the instability shown on the atmospheric flight.

4.6. Corrections to the prototype

The most important correction to be made was to increase the stiffness on the interior part of the projectile, near the driving band. The solution found was to insert a reinforcement ring inside the base, as seen on Figure 17.

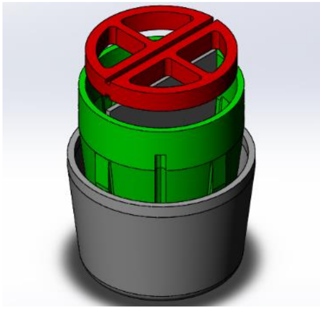


Figure 17: New base's CAD

It will be tested three different diameters of the driving band, 107 mm, 107,5 mm and 108 mm, with three different materials: nylon, polyethylene and polypropylene.

As having the grooves previously cut did not show any advantages, this possibility was abandoned on this trial.

Due to its stability advantages, it was also decided that the projectile should have a length of 280 mm instead of 340 mm.

4.7. Production of the third prototype

The objective of this prototype was to choose the best material/diameter configuration to the driving band. So, a total of 18 projectiles were produced, 3 for each material to the diameters 107 mm and 108 mm.

The base was reinforced as seen on Figure 17. This added additional weight to the projectile, as the new base weighted 293,4 g.

Apart from the projectiles that were supposed to be produced, another projectile was made by a material addition process, in the IST laboratories. This projectile had the same configuration of the remaining ones, but was made on PLA and had a driving band of 107,5 mm. The objective of this projectile was to test the possibility of using this manufacturing process to produce the projectiles.

Figure 18: Projectile produced by addictive manufacturing

4.8. Second shooting trials

The third shooting trial occurred on the 24th of July, and 19 FIREND projectiles were shot. Obtaining data was more difficult than in the previous trials due to the lack of measurement equipment.

The results obtained on this shooting trial are displayed on Table 8.

Table 8: Results of the third shooting trial

	Projectile mass [kg]	Gunpowder mass [g]	Driving band diameter [mm]	Driving band material	Range [m]	Notes
1	2,20	85,2	107	Nylon	125	Broken
2	2,18	85	107	PP	-	Broken
3	2,16	85,4	107	PE	200	Instable flight
4	2,17	85,2	108	PE	250	Broken
5	2,09	86	107,5	PLA	-	Broken
6	2,17	85,7	108	PP	250	Bad obturation
7	2,19	85,5	108	Nylon	-	Broken
8	2,19	130	107	Nylon	-	Broken
9	2,20	130	107	PP	110	Bad obturation
10	2,20	130,5	107	PE	110	Bad obturation
11	2,18	129,9	108	PP	100	Bad obturation
12	-	136,5	108	PE	-	Broken
13	2,16	194,2	107	PE	400	Instable flight
14	2,19	387	107	Nylon	700	Broken
15	-	387,5	108	PE	250	Instable flight
16	2,19	291	108	PP	380	Instable flight
17	2,18	201,6	107	PP	400	Instable flight
18	2,20	202	108	Nylon	600	Broken
19	2,20	204,3	108	Nylon	370	Bad obturation

It was possible to see that the obturation is not optimized yet. During the shootings the exit of burning gunpowder was seen after the projectile left the barrel. The passage of gas could also be seen on the remaining of the projectiles, as seen on Figure 19.

Figure 19: Driving band of one of the projectiles tested

In the cases that the projectile came out of the barrel without breaking, the driving band deformed elastically, but not plastically enough, as the depth of the markings of the grooves on the driving band is of approximately 0,3 mm, and is of 1,5 mm.

Figure 20: Representation of the position of the projectile on the barrel

A bad insertion of the projectile in the howitzer, due to a bad dimensional tolerance of the projectile, was responsible for breaking some projectiles. As seen on the figure above, the distance between the projectile and the beginning of the grooves made it gain some acceleration, breaking it on its most fragile point (the acrylic tube) when it touched the grooves. The parts of the projectile moved through the barrel separated, as seen on Figure 21.

Figure 21: Projectile that broke inside the barrel

The additive manufacturing projectile had a similar behavior to the last ones, since it broke on top of the driving band, as seen on Figure 22. This may have happened because this projectile is made by “slices” of material, being more fragile on each “slice”.

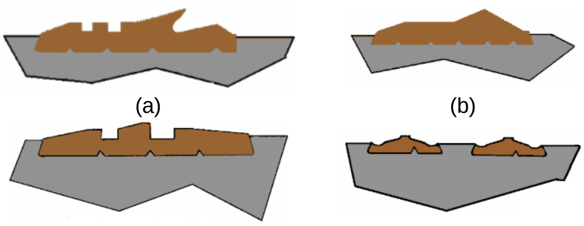
Figure 22: Fragments of the additive manufacturing projectile

It could be seen during the trials that the projectiles where not stable yet. This may have happened because of the increase of weight on the base, or because of the inefficient obturation of the projectile.

4.9. Corrections to the prototype

The acrylic tube revealed to be the most fragile component of the projectile, so it should be substituted by another material or configuration of tube.

Both the polyethylene and the polypropylene had a good behavior in relation to the driving band. But the geometry of the driving band should be altered. In some projectiles, the functions that were mentioned before are divided, as seen on Figure 23



(a) (b) (c) (d)

Figure 23: Different types of driving bands [9]

The driving band with divided functions could imply using different geometries and materials, but should be made a finite elements analysis first.

5. 155 mm Projectile

Almeida designed and studied the tensions of a 155 mm projectile [12], but he never had the chance to test his work. Based on the design made by Almeida and the advances made on this work, it will now be proposed a design for the 155 mm projectile.

As proposed by Almeida, the materials chosen for the projectile were Polylactic Acid for the tube, polycarbonate for the ogive and the base, with a thickness of 4 mm. The driving band should be produced in Polypropylene.

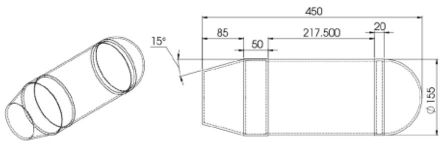


Figure 24: Projectile proposed by Almeida

Similarly to what was made with the 105 mm projectile, there were developed dome ballistic simulations. The stipulated velocity was 150 m/s, to a range of 2000 m.

Table 9: Result of the ballistics simulations for two different velocities

Velocity [m/s]]	Length [mm]	Mass [kg]	CG from nose [mm]	I_{xx} [kg.m^2]	I_{yy} [kg.m^2]	Range [m]	S_g	Deceleration [m/s/1000m]	C
150	450	8,01	213,876	0,02150	0,13122	1576,7	1,07	36,91	0,609
	430	7,641	204,083	0,02046	0,11438	1565,9	1,21	39,22	0,572
200	450	8,01	213,876	0,02150	0,13122	2297,9	1,09	51,91	0,542
	430	7,641	204,083	0,02046	0,11438	2277,1	1,23	55,09	0,510

As seen on Table 9, the velocity of 150 m/s is not enough to reach the proposed range. So it was decided to increase the velocity to 200 m/s. And as the ballistic coefficients to the length proposed by Almeida were optimal values, the length decreased to 430 mm.

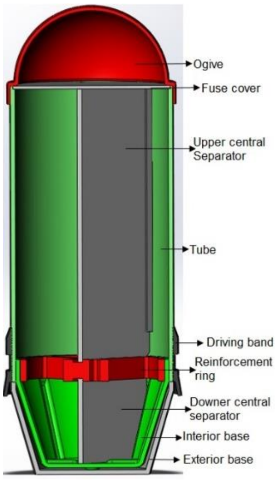


Figure 25: 155 mm projectile

On Figure 25 is shown a section view of the projectile. The central separator was kept to force the water to rotate in concordance with the projectile. The reinforcement ring was also kept as a way to increase the stiffness of the projectile

The driving band proposed is similar to the one represented on Figure 23 (a), where its functions are divided. This driving band should be subjected to a finite elements analysis in order to verify its behavior.

6. Conclusions

The main objective of this work was to test and improve the FIREND projectile, in order to create a functional firefighting artillery projectile.

The most important conclusion is that it was proven to be possible to shoot a projectile made entirely of polymeric materials.

According to the ballistics simulations the projectile should reach the range of 2000 m. This was not possible due to the inferior performance of the driving band. This performance had consequences on the linear and angular velocity.

Thermoforming proved to be a fast and cheap way to create prototypes, because of the versatility and low price of the molds use. On the other hand, the bad tolerances due to this method were critical on some of the shooting trials.

The chemical connections used to unite the parts of the projectile were string enough to withstand the pressures and to seal the projectile.

As the projectile is produced in polymeric materials, its stiffness is a lot lower than the gun, so the interaction of these two components is completely different than expected. The driving band deforms elastically instead of plastically, and that’s why the marks of the grooves have less depth than expected.

Having the grooves previously cut on the driving band did not show any significant advantage, so this hypothesis was dismissed.

References

[1] 9º Relatório provisório de incêndios florestais (2016), Departamento de Gestão de Áreas Públicas e de Proteção Florestal
[2] Carlucci, D and Jacobson, S (2014) Ballistics: Theory and design of guns and Ammunition (2nd ed.). Boca Raton, FL: CRC Press
[3] Nennstiel Ruprecht (2006) How do bullets fly?
[4] http://www.thegasgun.com/technology/advantages/gasgun-vs-propellants/, seen on 27/09/2017
[5] Almada, S. (2017) Caracterização da pólvora propulsora, Laboratório de Explosivos da Marinha
[6] Dyckmans, G., Fundamentals of ballistics, Royal Military Academy, Belgium
[7] Denny, M. (2011). Their arrows will darken the sun: The evolution and science of ballistics. Baltimore: The Johns Hopkins University Press
[8] Wu, B., Zheng, J., Tian, Q.-t., Zou, Z.-q., Chen, X.-l., & Zhang, K.-s. (2014a). Friction and wear between rotating band and gun barrel during engraving process. *Wear*, 106-113.
[9] Driving Bands (2006), obtained from http://www.ammunitionpages.com/
[10] Almeida, L. (2017) Relatório FIREND versão 105 mm
[11] Pinto, C. et al, (2017) Relatório do Estudo de Produtos Aplicáveis na Extinção de Incêndios, Universidade de Coimbra
[12] Almeida, L. (2016), Stress analysis and design of a 155mm projectile Shell to be used in fire fighting. Master’s Thesis, Instituto Superior Técnico