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Considerations Regarding Modern Solid Rocket Propellants

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Abstract—**The aim of this paper is to provide an overview of the main physico-chemical and ballistic characteristics of modern solid rocket propellants. In this regard, oxidizers, metallic fuels, and various additives are presented and their role is discussed. Furthermore, the experimental methods and the mathematical models used to determine the ballistic parameters (pressure, thrust, burning rate and specific impulse) are detailed. For a better understanding and exemplification, the burning process and static tests of on a subscale rocket motor are presented, the tests being performed using an environmentally friendly propellant developed in the Military Technical Academy "Ferdinand I".**

Index Terms—**ballistic parameters, binder, oxidizer, metallic fuels, rocket propellants.**

I. INTRODUCTION

Rocket propellants represent a special class of energetic materials, developed to supply the thrust necessary for the propulsion of spaceships, ammunitions or other projectiles. The main energetic transformation ensuring propulsion is a controlled combustion in a confined system, specially designed to generate hot gases at high pressures that are evacuated at high speeds. The resulting gas products expand and accelerate in the nozzle, developing the force (thrust) necessary to ensure the transport capacity of the system into the air [1, 2].

Considering the materials used in the manufacturing process and the physical state in which they are found at the end of it, rocket fuels are divided into four classes:

- solid propellants;
- liquid propellants;
- hybrid propellants;
- "gel" propellants [1 - 3].

Solid propellants represent a distinct class, due to the materials used in their development process which are mostly in solid state (crystalline oxidizers, powder metallic fuels), except for binders and some additives (for example, plasticizers). In terms of chemical configuration, these propellants can be classified into:

i. homogenous (colloidal) propellants;
ii. heterogeneous propellants [1 - 3].

Homogeneous propellants, known in the specialized literature as colloidal propellants, are gels based on nitrocellulose (NC) plasticized with nitroglycerin (NG) [2, 3]. Depending on their applicability, these propellants can be obtained in different configurations, by means of two techniques: extrusion and casting [4].

Double-base propellants contain NC with a degree of nitration between 12.6 and 13.5%, having the role of energetic base and polymeric binder, NG as the second energetic base and plasticizer of NC, stabilizers from the centralite class, burning rate regulators, usually oxides or salts of heavy metals (Pb, Cr), as well as other additives with technological roles [4].

Modern-day propulsion systems predominantly use heterogeneous solid propellant rocket motors due to their high performance and superior mechanical properties.

Structurally, heterogeneous rocket fuels are composite materials, obtained as mechanical mixtures of three basic components: (i) a *binder* (usually polyurethane) that acts as a binder (matrix) but also as organic fuel; (ii) a *solid crystalline compound* (the oxidizer) which is the main source of oxygen and (iii) as main fuel a *metallic powder* which is the primary source of thermal energy.

In addition to the mentioned components, other compounds are introduced in the formulations of a composite rocket propellant, in small proportions, such as: combustion rate regulators, stabilizers that improve its chemical stability over time, phlegmatizers that inhibit the combustion process and the possibility of detonation, plasticizers and binding agents that actively participate in improving the mechanical properties, but also in the ease of manufacturing process, bonding agents [1 - 3].

II. PROPELLANTS' COMPONENTS

A. Oxidizers for solid rocket propellants

The oxidizer represents the major ingredient of the composite propellants, constituting approximately 70% of its amount. It must be compatible with the other ingredients, must have a high oxygen content, high density, good thermal stability and low hygroscopicity [1, 2]. The oxidant should generate a high volume of gaseous products and should also allow safe handling.

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The type of oxidant used has a considerable influence on the initiation and combustion of the composite propellant. Usually, the amount of oxidant contained in this type of propellant does not exceed the percentage of 75%. A large number of solid materials will affect the mechanical properties (especially the mechanical strength, the mechanical shock absorption capacity, and the glass transition temperature) of the grain.

The particles sizes must enable mixing and uniform distribution within the polymer matrix. Thereby, the oxidant crystals are sorted according to particle size, as follows: macrogranular (400 − 600 µm), medium (50 − 200 µm), fine (5 −15 µm), and ultrafine (< 5 µm) [1]. To maximize the amount per unit volume in the composite formulations, a mixture of bi-modal (bi-granular) particles is usually used [1, 2].”

Considering the provisions of the environmental legislation in EU, and the toxicity of the decomposition products, the oxidizers could be classified in two categories:

a. “non-environmentally friendly” oxidizers;
b. “eco-friendly” oxidizers.

Ammonium perchlorate (AP) is the most consecrated oxidizer used for these types of applications. This perchlorate compound has both suitable energetic characteristics, but also a high toxicity and the capacity to produce toxic combustion products (hydrochloric acid) that affect the environment. Due to the high oxygen content and complete decomposition in gaseous products it is very suitable for these heterogeneous formulations, providing the highest specific impulse. Usually, the AP crystals used for this purpose have a spherical shape which minimize the specific surface and eases the mixing compared to those with an irregular shape. The dimensional applicability range of the particles is found to be in the range of 40 – 300 µm. The particles below 40 µm in size are considered dangerous because they can easily initiate and lead to uncontrolled combustion, leading to inefficiency or destruction of the propulsion system [1, 2].

From the class of perchlorates, it is also worth mentioning the *potassium perchlorate* ($KClO_4$) which due to the large mass of solids in the combustion products did not make its use favorable as an oxidant in rocket propellants, but rather in the gun propellants (black powder) and the *nitrile perchlorate* (NO_2ClO_4), an extremely hygroscopic compound, which by hydrolysis leads to the formation of nitric acid and perchloric acid [2, 5, 6].

Since the products resulting during the decomposition of this category of oxidants are harmful to the environment and human health, specialists in the field have considered it imperative to develop or search for possible new candidates capable of replacing them. Among the most studied “eco-friendly” crystalline materials, the following can be mentioned: ammonium nitrate (AN), ammonium dinitramide (AND), hydroxylammonium nitrate (HAN) and hydrazinium nitroformate (HNF) [1, 2, 7]. Although considered to be “greener”, these compounds present some disadvantages, such as: low oxygen balance, incompatibility with other compounds (diisocyanates) used in the embedding process, polymorphic changes at ambient temperature, high hygroscopicity and sensitivity to the mechanical stimuli.

B. *Metallic powders as fuels*

In order to maximize the energetic output of the propellant, high energy fuels are also introduced in the heterogeneous mixtures in addition to oxidants.

In terms of chemical configuration within solid composition propellants we can meet two categories of fuels:

a. *metallic fuels*, which are represented by metallic powders which have a well-defined grain size and a very high heat of oxidation;
b. *organic fuels*, which most often are also the binders [1, 2].

Modern solid composite propellants contain exceptionally fine metallic powders, in proportions between 5 – 20%. Their role is to improve the chemical energy of the propellant by increasing the combustion temperature and ignition sensitivity.

In this case, their applicability is limited to light metals, such as: aluminum (Al), magnesium (Mg) and aluminum-magnesium alloy (magnalium; PAM) [1-3].

For a better understanding of the applicability of these metallic fuels within heterogeneous mixtures, Table I, briefly presents their physico-chemical characteristics of interest [1, 2, 6].

TABLE I. PHYSICO-CHEMICAL PROPERTIES OF METALLIC POWDERS

Characteristics	**Aluminum**	**Magnesium**	**PAM**
Chemical formula	Al	Mg	Al-Mg (50:50)
Aspect	- metallic powder; - gray or black color (depending on the materials used for protection)	- metallic powder; - silver or black color (depending on the materials used for protection)	- metallic powder; - silver color (depending on the materials used for protection)
Granulation	- from the "micro" to the "nano" domain; - spherical.	- from the "micro" to the "nano" domain; - spherical.	- from the "micro" to the "nano" domain; - spherical.
Density [g/cm^3]	2.69	1.74	2.00
[1]T_p [°C]	660	650	600
[2]T_f [°C]	2270	1107	n/a
Reactivity with air	- stable;	- oxidizes very easily;	- acceptable;
[3]Chemical compatibility	- NH_4ClO_3 (**0**); KNO_3 (**s**); NH_4NO_3 (**0**); $K_2Cr_2O_7$ (**0**); $KClO_4$ (**0**); $KClO_3$ (**0**);	- NH_4ClO_3 (**a**); KNO_3 (**a**); NH_4NO_3 (**a**); $K_2Cr_2O_7$ (**a**); $KClO_4$ (**a**); $KClO_3$ (**a**);	- NH_4ClO_3 (**s**); KNO_3 (**s**); NH_4NO_3 (**0**); $K_2Cr_2O_7$ (**0**); $KClO_4$ (**0**); $KClO_3$ (**s**);
[4]$Q_{ex.}$ [kcal/kg]	7130	6000	6524
Toxicity	- inflammation of the respiratory tract;	- inflammation of the respiratory tract;	- inflammation of the respiratory tract;

[1] *melting point;* [2] *boiling point;* [4] *combustion heat;*
[3] *chemical stability with oxidants*
*(**0**-stable; **s**-it reacts extremely hard; a-very high reactivity)*

C. *Binders*

The mechanical behavior of the composite grains is strictly dependent on the physico-chemical properties of the polymeric materials used as binders. Usually, the polymer matrix is obtained from a bi-organic mixture based on a polyol (the prepolymer) and a polyisocyanate (the cross-linking agent). The type of binder chosen also has a high impact on grain propellant energetic performance, propellant processing complexity, storage, aging and costs. In addition to the two components, it also can use binding agents, catalysts of the cross-linking reaction, antioxidants, stabilizers, etc.

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The physical properties of the composite grain, such as mechanical compressive and tensile strength, glass transition temperature, etc., can be tailored by using distinct types of binders, by varying their mass fractions in the mixture, or by changing the sizes of the oxidizer and fuel particles.

When it comes to the polyurethane matrix, the *"-NCO group content"* of the isocyanate and the *"-OH group content"* of the polyol must be carefully considered. The *"-NCO: -OH molar ratio"* also influences the duration of the curing process of the propellant grain.

Overcoming the mechanical issue, literature studies have reported that it is not always necessary to use metallic fuels in composite fuels, because in addition to the role of binding agent of the solid mixture, the binder also plays the role of an *organic fuel*.

Historically, in the heterogeneous composite mixtures proposed to equip rocket motors, *polysulfide polymers* were firstly used as a binding agent. The downside of this polymer was its high incompatibility with metallic fuels, causing safety problems occasionally leading to self-ignition during long-term storage [2, 8]. In this context, the need to develop a new class of binders has become imperative.

Polymers with polybutadiene chains have proven to be the most suitable binders for energy composites for this purpose, due to their high elasticity and low glass transition temperature. *Copolymers of butadiene* with acrylic acid (PBAA) were the first to be used in this class [1, 2, 8].

Carboxyl-terminated polybutadiene (CTPB) based composites showed significantly improved mechanical properties, especially at lower temperatures, compared to *Copolymers of butadiene* with acrylic acid (PBAA) or *polybutadiene acrylonitrile (PBAN) copolymers* binders, without affecting specific impulse, density, or solid loading ratios [1, 2, 8-9]. The cross-linking agents used for these types of polymers to be able to use them as binder matrix are based on di- or tri-functional epoxides or aziridines [8].

The discovery of *hydroxyl-terminated polybutadiene* (HTPB), an inert binder in the same class as CTPB, provided the optimal combination of thermodynamic and mechanical properties [8, 10-12]. HTPB binders exhibit superior elongation at low temperatures and better aging properties compared to CTPB. The cross-linking process of HTPB is faster due to the use of isocyanates [9, 13-14]. Despite these advantages of HTPB, the problem of using this type of inert binder in a composite rocket propellant is the need to add an additional amount of oxidant to improve the oxygen balance to obtain adequate energy performances. Consequently, it is desirable to develop more versatile polymers with substantial energetic character.

The integration of "azido- " or "nitro-" side functional groups of the polymeric chain can be achieved for a significant improvement in performance, with lower amounts of energetic materials.

The most representative candidate of this class is glycidyl azido polymer (GAP) [8, 15]. GAP is considered an excellent energetic polymer due to the unique structure, which provides a high heat of formation. These polymers are recommended for rocket propellant composites containing "eco-friendly" oxidants with lower energetic characteristics, such as AN, to compensate for the energy lost caused by the replacement of AP [15].

Depending on the desired viscosity of the composite mixture before the cross-linking stages, the percentage of polyurethane used does not exceed 20% of the mass of the propellant.

For a polymer to be used as a binder in the process of obtaining solid propellants for rocket motors, it must present certain properties. The most important of which are:

- to be chemically compatible with the other components of the propellant;
- the polymer chain must have a high C:H ratio;
- the average molecular weight must be between 2000-3500 g/mol;
- the molecular weight distribution must be as regulated as possible to obtain the best possible mechanical properties;
- must have an acceptable viscosity;
- when incorporating a quantity of solids (approx. 85 - 90%), it must have high mechanical performance (tensile and compressive), to avoid damage to the structural integrity of the grain during handling or operation;
- the polyurethane matrix must have a glass transition temperature as low as possible [1, 2, 8, 16].

D. Additives

Although added in small proportions, additives are substances used for:

- acceleration the curing of the propellant grain;
- improving the physico-chemical, rheological properties, facilitating the loading process;
- limiting the migration of chemical species from the propellant to the binder or vice versa, minimizing slow oxidation or chemical deterioration during storage;
- improving aging or moisture resistance characteristics.

Binding agents are substances that facilitate the adhesion between the solid ingredients (oxidant and fuel) and the binder. *Stabilizers* are used to minimize slow chemical or physical reactions that may occur in fuels. *Catalysts* are sometimes added to the cross-linking agent to increase the rate of cross-linking. *Lubricants* help the extrusion process. *Desensitizing agents* make the propellant more resistant to accidental thermal or mechanical stimuli [1 - 3].

III. BURNING CHARACTERISTICS OF PROPELLANTS

A. Combustion regimes

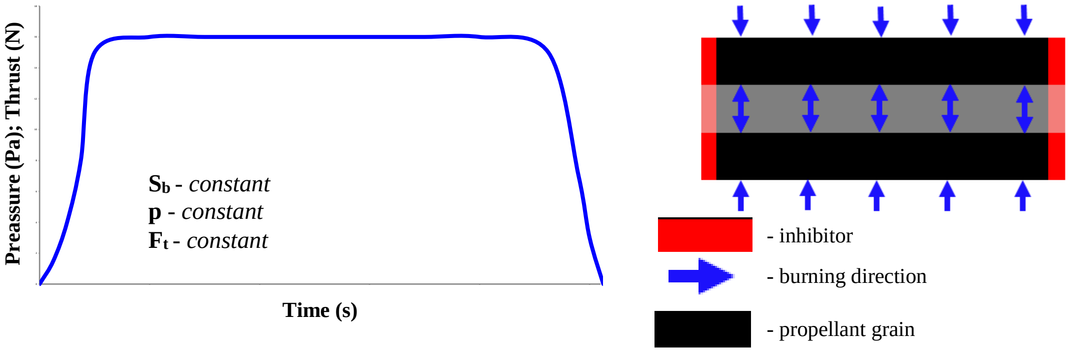
Composite solid propellant formulations intended to be used in rocket motors must meet specific requirements regarding the processability, ballistic performance, and chemical composition.

Based on the applicability of the system, several types of geometries are sought to ensure various ways of evolution of the surface of the combustion area, respectively of the burning rate of the composite grain.

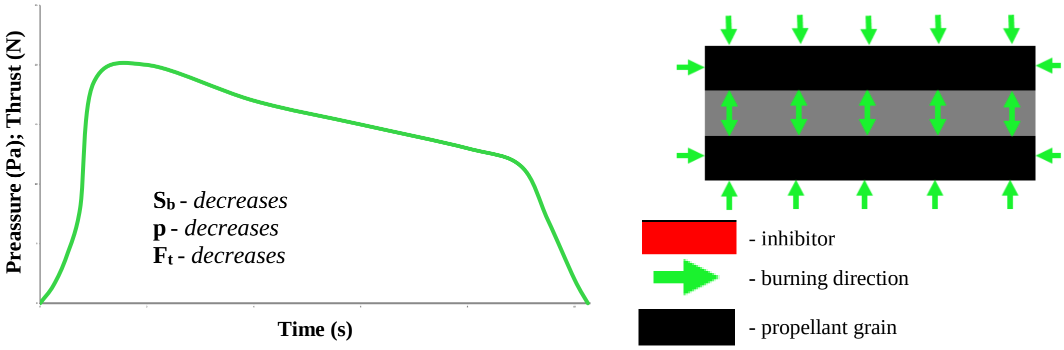
In general, the behavior of fuels during combustion varies according to the geometry of the charge, as shown in Fig. 1.6 [1 - 3]. Thus, there are three types of combustion regimes:

- neutral
- progressive;
- regressive.

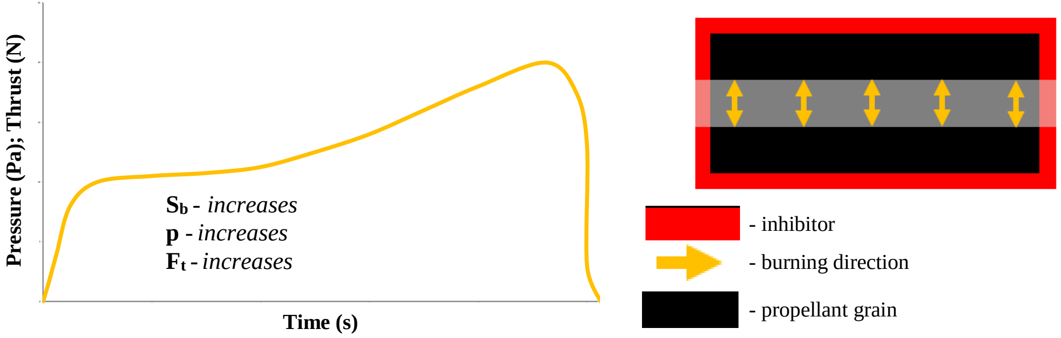
Achieving a complex combustion geometry is one of the most complicated steps in the development process. Thereby, another method to obtain the desired combustion regime is *inhibition*. The process is selectively applied to restrict certain surfaces of the propellant grain from combustion in order to obtain the desired combustion variant. For instance, a propellant grain with inhibited ends results in a *neutral profile* (Fig. 1a); without any inhibited surface it will produce a *regressive profile* (Fig. 1b), and with the inhibition of the side surfaces and those on the ends, it produces a *progressive profile* (Fig. 1c). In Fig. 1, $\mathbf{S_b}$ – burning surface; **p** – pressure; $\mathbf{F_t}$ – thrust.



a. neutral burning profile



b. regressive burning profile



c. progressive burning profile

Figure 1. Burning regimes obtained by inhibition of a single perforated (tubular) rocket propellant grain

B. *Ballistic parameters*

The propulsion of munitions or spaceships is an interdisciplinary subject that interweaves the basic principles of mechanics, thermodynamics, and chemistry. Propulsion is achieved by generating a thrust force resulting from the combustion of a propellant, regardless of its nature (solid, liquid or hybrid). The hot combustion gases inside the motor chamber are pushed and accelerated through a nozzle from which they are ejected at high speed, thus imparting motion to the system. The nozzle consists of a converging section, a passing zone, and a diverging section, which can be conical or bell-shaped, as shown in Fig. 2.

For a better understanding of the phenomena that take place in a rocket engine, in Fig. 2, the parameters of interest that must be considered in the combustion process are represented, where p_a – atmospheric pressure, [Pa]; m_p – propellant weight, [kg]; S_c – combustion surface, [m^2]; de – combustion thickness, [mm]; ρ_p – propellant density, [kg/m^3]; u – burning rate, [mm/s^1]; Z_c – convergent area; D_{crt} – critical diameter area; Z_d – divergent area; $\dot{m}_e$ – mass flow rate, [kg/s]; p_e – gas pressure at the nozzle exit.

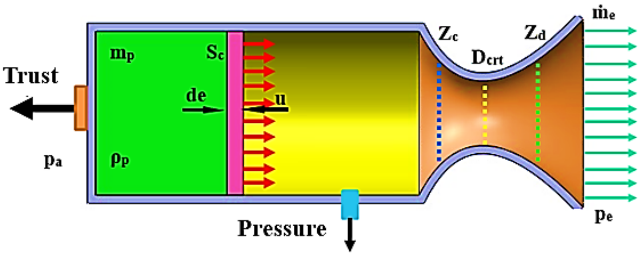


Figure 2. Parameters of interest inside the rocket motor

The combustion trend at the level of composite solid mixtures consists of an initial condensed phase and a final gas phase, which may exhibit stable or unstable behavior. In most cases, the reaction products are gaseous, except for compositions containing metallic powders where incandescent solid particles can be observed during combustion.

The interface between the condensed phase and the gas phase is called the *combustion surface*. The rate of propagation of this interface is known in the specialized literature as the *burning rate* or as *the regression rate* of the condensed phase [1 - 3]. For many studies it is convenient to define, more precisely, a linear burning rate, where the burned area per unit time is in the direction perpendicular to the burning surface. In Fig. 3 are presented schematically the areas within the combustion process.

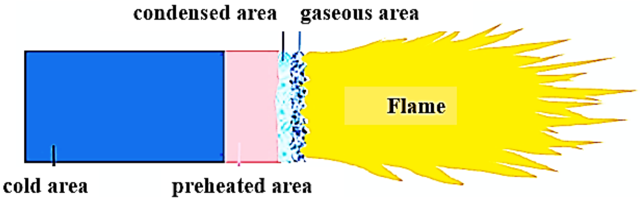


Figure 3. Burning areas of a propellant grain

Therefore, the burning surface of solid energetic materials (for example: pyrotechnic compositions and gun propellants), evolves in a direction perpendicular to itself. In other words, hypothetically speaking, it could be considered that, solid propellants burn in parallel layers, and the grain tends to keep its initial configuration until it is completely consumed [2, 17]. However, the actual combustion surface and its evolution over time depend on the initial geometry of the propellant and the general combustion processes taking place at its level.

Under equilibrium conditions and for a given initial temperature, Vielle's law (1) is used empirically to describe the pressure dependence of the burning rate [2, 17]

$$u = Ap^{\upsilon} \tag{1}$$

where: A, υ – experimental coefficients that depend on the nature of the propellant and its burning conditions; p – experimentally determined pressure value.

Another empirical formula used for the estimation of the burning behavior is Muraour's equation (2), which is a simplified form of (1) [17]

$$u = ap + b \tag{2}$$

where: a, b – experimental coefficients that depend on the nature of the propellant and the conditions for performing the experimental tests; p – experimentally determined pressure value.

The above equations are usually used to determine the burning rate laws for high values of pressure at constant volume using a device known as a *closed vessel*. This system is used to experimentally determine the variation of pressure as a function of time, at various loading densities.

Another method to determine the burning rate is based on the experimental tests conducted in a *rocket motor testing stand*. A small piece of equipment that can be used to experimentally determine the variation of both pressure and thrust as a function of time.

The parameters of interest in a pressure versus time measurement are presented in Fig. 4, while (3) is used for calculating the burning rate as a function of pressure and burning time [17], where t_0 – ignition time (due to an electrical or mechanical stimulus); t_z – beginning of burning; t_{zef} – effective beginning of burning; t_h – end of burning; $t_{p/2}$ – half pressure value; t_{vef} – effective efflux time; t_v – end of efflux time.

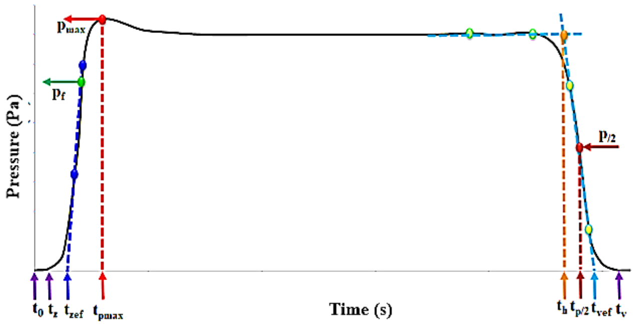


Figure 4. Parameters of pressure-time variation

$$\overline{u_{th}}\left(\overline{p_{th}}\right) = \frac{e_1}{t_h - t_z} \tag{3}$$

$$\overline{p_{th}} = \frac{1}{t_h - t_z}\int_{t_z}^{t_h} p(t)\,dt \tag{4}$$

where: $\overline{u_{th}}$ – average burning rate, [mm/s]; $\overline{p_{th}}$ – average pressure value, [Pa]; e_1 – burning thickness, [mm]; $(t_h - t_z) = t_b$ is the total burning time (Fig. 4) [s].

Thrust represents the force developed by a propulsion system acting on a component of interest within the system. More specifically, it is determined by the combustion reaction of a propellant grain inside the rocket motor which generates high amounts of hot gaseous products, subsequently ejected at high speed through the nozzle. Rocket propulsion differs from projectile propulsion. Rocket propulsion involves certain amounts of energetic materials being carried inside the vehicle and ejected at high speeds [1, 2, 17].

The traction force due to a momentum variation is given in (5). In this case the force represents all the propulsive force when the pressure at the nozzle exit is equal to the atmospheric pressure [17]

$$F_t = \frac{dm}{dt}v_e = \dot{m}v_e \tag{5}$$

where: v_e – velocity of exhaust gases at the exit of the nozzle, [m/s]; $\dot{m}$ – mass flow rate, [kg/s].

Due to the nozzle geometry and the variation of ambient pressure with altitude, an imbalance of the external environment or atmospheric pressure (p_a) and the local exhaust pressure (p_e) may occur. Thus, for a uniformly operating rocket propulsion system moving through a homogeneous atmosphere, the total force can be expressed by (6) [17]

$$F_t = \dot{m}v_e - \left(p_e - p_a\right)A_d \tag{6}$$

where: A_d – the area of the divergent nozzle section, [m^2].

Similar to pressure, thrust can be determined experimentally by performing experimental tests on the rocket motor test stand. Based on the curve obtained, this can

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empirically write in the form of (7) [17]

$$F_{tm} = \frac{1}{t_b}\int_0^{t_b} F dt \tag{7}$$

The total impulse is the traction force (which may vary with time) integrated over the burning time according to (8). In other words, it represents the area under the graph of the traction force represented versus time [17].

$$I_t = \int_0^{t_b} F dt \tag{8}$$

In the case of a combustion regime when the traction force is considered constant and the transitions that may occur at the ignition and at the end of combustion are neglected, the above equation can be written in the following form [17]:

$$I_t = Ft\,. \tag{9}$$

The most important performance parameter of a propellant is the *specific impulse* (I_s). This represents the ratio of total impulse per unit weight of the propellant (10). The higher its value, the more efficient the propulsion system is [17].

$$I_s = \frac{\int_0^{t_b} F dt}{g_0 \int_0^{t_b} \dot{m} dt} \tag{10}$$

In the case where the thrust and mass flow rate are considered constant, the above equation can be written simplified as:

$$I_s = \frac{I_t}{m_p g_0} \tag{11}$$

where m_p – propellants weight, [kg].

IV. ROCKET PROPELLANT TESTING

Small-scale rocket propellant testing was performed for a solid composite formulation shown in Table II.

TABLE II. COMPOSITION OF THE TESTED PROPELLANT FORMULATION

Sample	**Proportions [%]**					
	PSAN_0[1]	**AP**	**PAM**	**PU_31**[2]	**TEGDN**[3]	**α-Fe_2O_3**[4]
GP030	72	-	12	10.5	4.5	1
1 - phase-stabilized ammonium nitrate with potassium nitrate, as oxidizer; 2 - polyurethane based on polyester-polyols that resulted from the degradation of polyethylene terephthalate waste, Setathane and Desmodur; 3 - triethylene glycol dinitrate, as energetic plasticizer; 4 - nano-iron oxide, as burning catalyst agent.						

For the experimental firing on the rocket stand, the mixture was wet pressed and cross-linked into a cylindrical configuration, as can be observed in Fig. 5.a. Thus, to obtain a neutral burning profile, the sample had the side cylindrical surface inhibited (see Fig. 5.b, c). Firstly, the propellant grain was coated with a mixture of inert polyurethane (see Fig. 5.b), over which a textile material was attached (see Fig. 5.c). Finally, the textile was embedded with inert polyurethane mixture and a fine layer of graphite powder (see Fig. 5.a), to prevent heat transfer and erosive burning.

The arrangement of a propellant grain within the test system is shown in Fig. 5.a. Following its combustion, the surface of inhibitory material was not affected, aspect illustrated in Fig. 5.d. A composite mixture based on potassium perchlorate (71%), aluminum (12%) and polyurethane (15%), was used to initiate the composite solid propellant. The ignition composition has been compacted so that combustion takes place slowly and in a controlled manner (see Fig. 5.e).

In Fig. 6, the configuration of the flame at the nozzle outlet and ambient pressure recorded with a thermal and ultrafast device at different times is shown.

The experimental burning profile for the analyzed sample is depicted in Fig. 7. Although the appearance of the pressure-time profile has low values, it perfectly matches the theoretical neutral combustion profile. In the present case it was highlighted that the obtained results are promising for this type of application. It is well known that in the case of rocket propellant formulations based on phase-stabilized ammonium nitrate their initiation is difficult, due to the low energy considerations of this type of oxidizer.

A solution to improve the ignition consists in placing on the combustion surface of the propellant an initiation mixture capable of leading to a proper priming. In Table III are presented the values of the maximum pressure, the average pressure, and the burning speeds, calculated with (3), respectively (4). The average values of the ballistic parameters are consistent with those found in the specialized literature [18].

TABLE III. THE VALUES OF THE PARAMETERS SPECIFIC FOR SUBSCALE TESTING

Parameter Sample	Burning time [s]	Burning thickness [mm]	Burning rate [mm/s]	Maximum pressure [bar]	Average pressure [bar]
GP030C	2.92	3.67	2.52	31.47	28.94

a. b. c. d. e

Figure 5. Inhibition process, set-up and burning of the rocket propellant formulation

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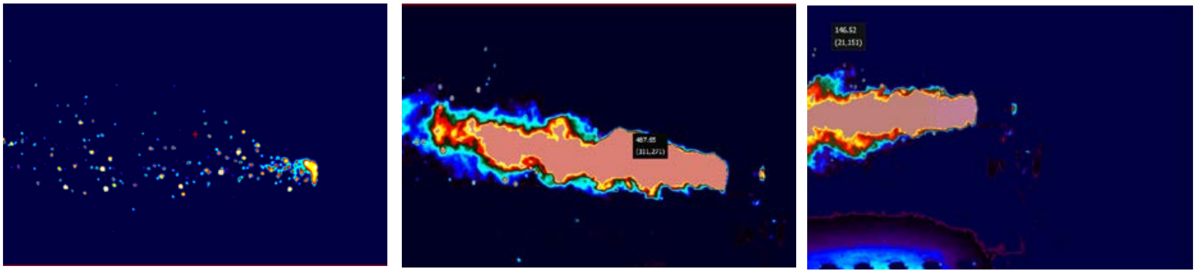
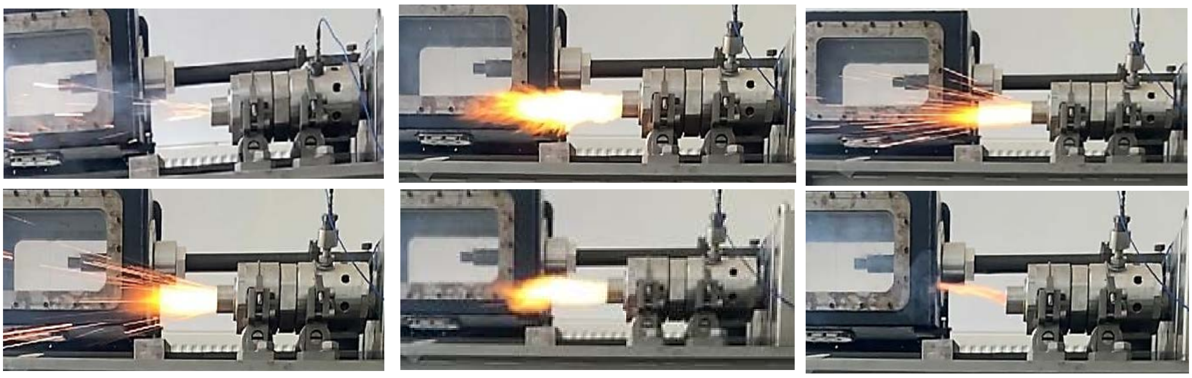
Burning at ambient pressure



Thermal – primer; burning of the grain



Visible – burning at nozzle exit

Figure 6. Flame aspect of the rocket propellant at various moments of time

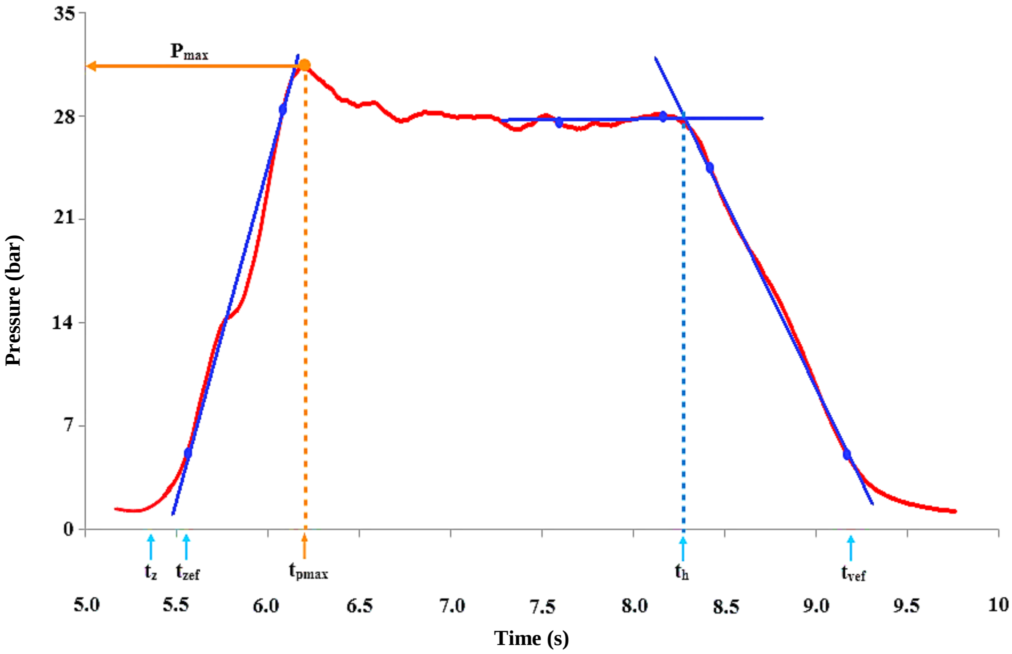


Figure 7. Diagram of pressure variation as a function of time

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V. CONCLUSION

The main aspects that influence the combustion behavior are the components and the geometrical configuration of the propellant granules. Structurally, solid composite rocket propellants are usually based on a heterogeneous mixture of different compounds that serve as fuel, oxidizer, burn rate modifiers, and binder. Propellant selection is critical to rocket engine design.

The performance characteristics of a composition were determined by conducting experimental firings in specific ballistic analysis equipment. During the study it could be observed that the success of these tests depends on many factors, such as: the composition of the mixture, the configuration of the analyzed sample, the quality of the inhibitory material, etc. The mixture was designed to be used as a solid composite propellant, and it seems that the results obtained represent the perfect background for future research in the field of energetic composite materials.

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