Combustion of Metallised ADN/GAP Solid Rocket Propellants with Focus on Agglomeration Effects

V. Weiser*, A. Franzin*, V. Gettwert*, and L. T. DeLuca⁺ * ICT Fraunhofer-Institut für Chemische Technologie Joseph-von-Fraunhofer-Str. 7, Pfintzal, D-76327, Germany ⁺Department of Aerospace and Science Technology, Politecnico di Milano Via La Masa 34, Milan, I-20156, Italy

Abstract

Addition of metals, typically Al powder under several ways (micron-sized, nano-sized, activated, amorphous, etc.) is a well-known approach to increase the gravimetric as well as volumetric (or density) ideal specific impulse of solid rocket propellants. However, it is also well-known that aggregation/agglomeration phenomena, at or near the burning surface, penalizes the specific impulse increase making its delivered value appreciably less than the corresponding ideal value. An impressively large body of literature is available discussing this issue for the classical ammonium perchlorate (AP) / hydroxyl terminated polybutadiene (HTPB) / micrometric Al used for decades in propulsion missions aimed at space access. In this case, the recommended [1] international standard for the two-phase flow losses reads as

$$(\Delta I_{sp})_{2p} = C_3 \frac{\xi_{cc}^{C4} d_p^{C5}}{p_{cc}^{0.15} \varepsilon^{0.008} d_t^{C6}}$$

where:

 $\begin{aligned} \xi_{cc} &= \text{molar fraction condensed products in combustion chamber (moles/100g);} \\ d_p &= \text{average diameter of the condensed particles (} \mu m); \\ p_{cc} &= \text{combustion chamber pressure (psi);} \\ \epsilon &\equiv A_e/A_t = \text{geometric expansion ratio of the nozzle;} \\ d_t &= \text{throat area diameter (in);} \\ C_3, C_4, C_5, C_6 &= \text{correlation constants.} \end{aligned}$

The main difficulty in using this equation concerns the parameters associated with the type of loaded solid propellant before and after combustion (respectively ξ_{cc} and d_p). A survey of the many effects and pathways associated with different metal burning in traditional HTPB bound composite solid rocket propellants was offered some time ago [2]. On the contrary, very little can be found in the open literature regarding the ADN/GAP formulation, meant to be a green and highly performing new composite propellant. Which specific path comes out to be the dominating one when AP/HTPB is totally replaced by ADN/GAP at this time is unknown. In this work substitution of AP/HTPB with ADN/GAP is experimentally assessed, by comparing a standard AP/HTPB/Al formulation to the corresponding ADN/GAP/Al formulation in terms of burning rate and agglomeration effects. Thermochemical calculations are carried out to quantify the ideal performance gain obtainable when adding micrometric Al to ADN/GAP matrix as well as the performance loss reasonably associated with the resulting two-phase flow.

1. Introduction

The growing public awareness toward the environment problem, which has driven the last decades of aeronautical research to find a "green fuel", could not leave out the scope of space propulsion. The solid propellant formulations, commonly used for space access until today, contain mostly ammonium perchlorate in combination with hydroxyl terminated polybutadiene (AP/HTPB). One of the main combustion products is hydrogen chloride (HCl) that should be considered critical under pollution aspects, since it contributes to acid rains and causes environmental damage and corrosion around the launch base. The boosters that contain this type of solid propellants, burn in the order of tons per second, releasing large quantities of HCl, which can reach more than 20% of the reaction products at the nozzle (Fig. 1). Also aluminium chloride and other intermediate reaction products, which are not more than 2%, will cause additional serious problems when the huge quantities of expelled mass are considered.



Figure 1: Reaction products obtained by ICT-code (nozzle expansion under shifting equilibrium)

These are the main motivations to develop a new kind of green propellant that possibly will feature better propulsive performance as well. Ammonium dinitramide (ADN) seems to be a good substitute to ammonium perchlorate, as shown by Larsson and Wingborg [3]; being chlorine free, one of the main pollution responsible can be eliminated. Due to its lower oxygen balance of +25.8%, instead of +34.04% for AP, an energetic binder is needed to compensate this handicap. The main problem of ADN is his reactivity with some polymeric binders or at least the ingredients of the polymerization rocess. To overcome this problem, coated ADN prills shall be used; for details see [4].

An appropriate binder is GAP (glycidyl azide polymer), an energetic polymer treated with bispropargyl-succinate and isocyanates [5].

The purpose of this paper is to report some initial results in the study on and characterization of the aluminized ammonium dinitramide-glycidyl azide polymer (ADN/GAP/Al)formulation, that, as green propellant, could replace the well-known ammonium perchlorate based propellants. In this preliminary study the influence of different types of loaded aluminium fuel has been investigated.

2. Propellant samples

2.1 Tested Formulations

Four propellant formulations having the same nominal composition but loaded with different types of aluminium particles were prepared. The exact propellant composition is listed in Table 1, while the four types of loaded aluminium are shown in Table 2. Prilled ADN was produced by an emulsion prilling method at ICT, starting from neat ADN delivered by Eurenco Bofors with a particle size distribution for ADN 208 μ m of d(0.1) 122 μ m, d(0.5) 208 μ m, and d(0.9) 349 μ m and ADN 55 μ m of d(0.1) 33 μ m, d(0.5) 55 μ m, and d(0.9) 100 μ m [4]. GAP-diol prepolymer (M_n = 1685, M_w = 1909, equivalent weight 1160g/mol) was purchased from Eurenco (France); the isocyanate curing agent Desmodur E305 (equivalent weight 328 g/mol) from Bayer Material Science (Germany); and the alkyne curing agent bispropargylsuccinate (BPS, equivalent weight 97g/mol) was synthesized from succinic acid (Merck 822260) and propargyl alcohol (Merck 807050) by ICT. The curing catalyst dibutyltin dilaurate (DBTDL) was bought from Merck Schuchardt (8.20421.0250).

A quite large amount of 16% aluminium was chosen to achieve an optimum value of specific impulse, as indeed found in several space launchers. This choice worked well with samples D and G; see Table 2. To provide as much as possible comparable combustion tests, it was chosen to use the same amount of nano-aluminium for samples E and F; see Table 2.

The mixing and casting of propellant sheets using 18 μ m and 5 μ m aluminium proceeded without any problems. But for propellants containing nano-aluminium (100 nm) it was impossible to prepare sheets of good enough quality because of the high viscosity of the resulting propellant slurry. The sheets were prepared like rolling a paste and not by casting. From the sheets, propellant strands of 4 x 4 x 35 mm³ were cut for combustion tests.

	ADN ^a	GAP Diol	E305 ^b	BPS	Al	DBTDL ^c	$\mathbf{NCO} / \mathbf{OH}^c$	BPS/OH ^c
[%]	60	19.59	3.1	1.31	16	0.04	0.56	0.8

Table 1. Composition of Al/ADN/GAP

^{*a*}Prills 208 µm - ICT Fraunhofer, ^{*b*}Desmodur, ^{*c*} Catalyst are not included in final formulation

Formulation ID	G	D	F	Ε
Aluminium type and	A-81	Alcan 400	nAl, Al ₂ O ₃	L-ALEX ^a
size	18 µm	5 µm	100 nm	100 nm

Table. 2. Aluminium types used in Al/ADN/GAP propellant

^{*a*}Stearic acid coated before air exposure

2.2 Mixing of propellant ingredients

The ingredients were mixed one at a time in a planetary centrifugal vacuum mixer (Thinky mixer ARV-310) with 1600 cycles per minute at a pressure of 35 mbar for two minutes. GAP-diol was added into a beaker and mixed with DBTDL and aluminium, followed by ADN 208 μ m. The mixture was cooled down to room temperature. E305 and BPS were added together to the dispersion. Propellants containing nano-Aluminium (nAl) were prepared in the same way, but the amount of

nano-Aluminium was split off in two parts and added and mixed separately. The final mixture was like a sandy material and not flowable.



Figure 2: Thinky mixer

3. Thermodynamic calculations

Table 3 lists the results of thermodynamic calculations using the ICT-Thermodynamic code, also in comparison with the combination of other possible propellant formulations, when replacing ADN by AP and GAP by HTPB.

Table 3: AP/HTPB/Al compared with ADN/GAP/Al thermochemical calculations under shifting equilibrium

	AP/HTPB/Al	ADN/HTPB/Al	AP/GAP/Al	ADN/GAP/Al
Density [kg/m ³]	1578	1522	1808	1735
P _c [MPa]	7	7	7	7
T _c [K]	2357	2570	3624	3565
Cp [J/(kg K)]	2047.2	2289.9	1918.2	2051.4
γ	1.29	1.28	1.26	1.26
Sound Velocity [m/s]	1055	1106.1	1137.8	1190.5
C*	1387	1458	1530	1593
I _{sp} [s] Vacuum	271.3	279.6	291.1	300.3
I_{sp} [s]	247.4	257.5	265.5	274.7
Combustion Products (chamber) [mol/kg]	47.45	51.07	36.64	40.32
Condensed products (chamber) [%]	8.64	14	7.77	7.29
Combustion Products (nozzle) [mol/kg]	48.85	52.98	35.38	39.32
Condensed products (nozzle) [%]	17.6	18.75	8.38	7.54

composition studied for all propellants: 60% oxidizer, 24% binder, 16% Al

4. Experimental setup

The combustion behaviour was investigated at ICT window bomb under 0.1, 1, 3, 7 and 10 MPa nitrogen. The chimney type pressure vessel is equipped with 4 windows adaptable with different types of window glasses, also to allow spectroscopic investigations in UV, Vis, NIR and MIR range. Ignition was performed using a fuse wire enhanced with about 50 mg of a booster mixture. No inhibitor on the lateral surface of the strands was used.

To visualize the propellant combustion, a 24 bit colour high-speed camera (Motion Pro^{TM} X-3, Redlake) equipped with a 105 mm macro lens was used. The maximum sensor resolution is 1280 x 1024 Pixel. This can be used up to a recording frequency of 2000 fps. By reducing the image section, a maximum frequency of 64000 fps is possible. The procedure reported in [14] was used to measure steady burning rates.

To observe particle agglomeration and the ignition of single particles close to the propellant surface, a long range microscope (Carl Zeiss LRM), with a focus distance of 220 mm and a maximum enlargement scale of 40 related to miniature film 135, was mounted instead of the macro lens. In combination with the MotionProTM X-3, an optical resolution of 8 μ m per pixel can be achieved.

The long distance between the microscope and the strands, due to the size of the ICT-window bomb, made it impossible to get a picture quality like e.g. that reached in [9] due to limited depth of focus of < 0.5 mm. To achieve a better study of agglomerate sizes, the corresponding tests were performed at 1 MPa and 3 MPa. No test was carried for 0.1 MPa in micro-configuration yet.

5. Burning behaviour

All propellant samples could be ignited and burnt starting from 0.1 MPa up to all the considered pressures, implying that PDL (Pressure Deflagration Limit) falls in the subatmospheric range. At 0.1 MPa all samples burnt with a linear regression rate. But at higher pressure levels and caused by the high porosity, the samples E and F containing nano-aluminium burnt inside out in a regime of porous combustion also expulsing fragments [12, 13]. No burning rate could be measured and the samples at these pressure levels were no longer considered. The samples D and G containing micro sized aluminium result in linear burning rates. Figure 3 shows pictures of sample D that are optimized to visualise hot particles by a strong reduction of exposure time.



Figure 3: Combustion of HISP 31D at various pressure levels.

In Fig. 4 the measured burning rates of samples D and G are presented as a function of pressure. Also the values of samples E and F at 0.1 MPa are itemised. The absolute values of burning rates of D and G are in the same magnitude. Applying Vieille's law to the totally investigated pressure range, a linear fit does not describe the data well due to the low values at 0.1 MPa. Excluding results at 0.1 MPa leads to a significantly better agreement. The pressure exponents are also depicted in Fig. 4 and are in a similar range (0.52 for sample D and 0.64 for sample G) when the spread of the burning rate values is considered.

At 0.1 MPa a clear ranking is given for the samples differing only in the type of aluminium particles, with an increase of about a factor 2 from sample to sample. Sample G with 18 μ m particles burns slowest followed by sample D (5 μ m) and the uncoated nano-aluminium (sample F). Sample E, with particles coated with stearic acid, features the highest burning rate. But anyway it has to be pointed

out that sample E burns at 0.1 MPa with a similar burning rate than D and G at 1 to 2 MPa. For 0.1 MPa tests, movies clearly indicate a regular propellant combustion and no porous behaviour.



Figure 4: Burning rate Vs Pressure of investigated samples.

6. Agglomeration

6.1 Formation, size and behaviour

The agglomeration behaviour and formation has been studied by using both micro and macro configuration measurement.

The study of the agglomerate size was done analysing the video record and taking the sizes of all welldefined and detached particles, as shown in [7]. Further analysis was made on the velocity of the same particles, utilizing the pixels reticule and the relative coordinate differences between successive frames.

The difficulty to get well-defined images trough the flame as close as possible to burning surface for the time being leads to a small number of available results for agglomeration study purpose. However, consistent results have been achieved despite the low number of available measuring points (in one case only 80 well focused Al-particles) for each video record.

No agglomeration analysis was made for either nano-Al formulations (Propellant E & F); these samples began to show porous combustion starting at 1 MPa. So, further tests will be made in future by limiting the amount of aluminium which seems to be the main reason for the porosity problem.

Qualitative macro tests at 0.1 MPa have been done on nano-aluminium loaded propellants and these have shown the typical well-known behaviour of nano-aluminium, with the pre-agglomeration stage and detachment (Fig. 5) discussed in Ref. [8]. The main difference with respect to the observations made by the authors in AP/HTPB/Al propellant with nano aluminium is the absence of well-defined agglomeration behaviour before and after detachment. In fact the structure of the aggregates seems not to change during the time of evolution, and not to present the typical configuration of the spherical droplets at least in the proximity of the burning surface, also when detached.

In fact, it was observed, that the pre-agglomeration structure, better shown in [9], is still maintained at detachment and then for the entire flying path which start from burning surface. For these kinds of aggregate melting is difficult and thus they continue to accumulate over the surface. As a consequence, the aluminium fibre can grow up to half a millimetre in length (figure to be confirmed) and later detach maintaining the same shape.

The above remarks are strictly preliminary and need to be confirmed by the more extensive experimental campaign currently under progress.



Figure 5: Nano aluminium behaviour in E (left) and F (right)

Concerning propellants G and D, which use respectively 18µm-Al and 5µm-Al, interesting results regarding the average agglomerate diameter $D_{[4,3]}$ and $D_{[3,2]}$ are shown in Table 4

Formulation ID	Average diameter	D _[4,3]	$D_{[3,2]}$	
	[µm]	[µm]	[µm]	
H31G	165.39±5.49	187.36	179.46	
	(1 MPa)	(1 MPa)	(1 MPa)	
	129.22±3.9	131.93	131.93	
	(3 MPa)	(3 MPa)	(3 MPa)	
H31D	167.83±7	200.06	189.42	
	(1 MPa)	(1 MPa)	(1 MPa)	
	126.68±4.75	143.97	138.88	
	(3 MPa)	(3 MPa)	(3 MPa)	

Table 4: Sizes of aluminium agglomerates (micro scale measurement)

The measurements show average size behaviour quite independent from the initial aluminium particle size. Although propellant G has particles more than three times larger than propellant D, it seems to generate agglomerates of the same average size.

This trend is found at both investigated pressures, but more tests are required to confirm.

Looking at the distribution histogram in Fig. 6, it is possible to see that the shape of the distributions and the position of the maximum is instead quite dependent on the initial size of Al, generating a narrow distribution for the smallest initial particles and a relatively broad distribution for the biggest ones.

This trend of distribution was observed for all the tests carried out.





Figure 6: on the left, G-test 5, on the right, D-test 3 (1MPa)

To better understand the behaviour of detached agglomerates, and to validate the results despite the low number of measurements done for each video analysis, a detailed study on mean velocity, mean momentum and mean kinetic energy of the particles was also carried out.

No consideration on density has been done, since the oxidation seems to be strongly space-time dependent it was impossible to define a clear value of weighted density between pure aluminium and aluminium oxide, hence the results are in units of length to the fifth per time squared for kinetics energy and in units of length to the fourth per time for momentum.

As expected, results show that also average kinetic energy will not vary too much between different tests, and can be used as discriminant point for a critical post-evaluation of the data obtained.

Since volume is used, erroneous measurements will be amplified by an exponential factor of 3 in kinetic energy quantity, heavily influencing the average.

For this reason it was decided only to take a look on the order of magnitude of average kinetic energy and of average momentum of each agglomeration test, obtaining an overall order of magnitude of 10^{-8} m⁵s⁻² for kinetic energy and overall order on magnitude of 10^{-12} m⁴s⁻¹. The modulus variation of this quantity can reach a factor 3, but it should not influence the validity of the analysis since only order of magnitude was taken as discriminant factor.

This analysis fully confirmed expectations, and allows rejecting non-coherent results.

An increase of size (Tab. 5) and a reduction in quantity of agglomerations was observed, in fact, with respect to AP/HTPB based propellants.

Propellants	Pressure [MPa]	Average Diameters [µm]	D _[4,3] [μm]
A^a	1	154	175
\mathbf{B}^{b}	1	120	181
\mathbf{A}^{a}	2.5	129	146
\mathbf{B}^{b}	2.5	75	141

Table 5:	AP/HTPB/Al	agglomerations	size	[10]
----------	------------	----------------	------	------

^{*a*} 58% AP 200 μm, 10 % AP fine, 14 % binder, 18% Al 30 μm ^{*b*} 55% AP 200 μm, 14 % AP fine, 12 % binder, 19% Al 30 μm

In both cases shown in Tab. 5, the amount of aluminium was higher and the initial size of Al particles was almost double the largest one used for ADN/GAP formulations, nevertheless the agglomerates show smaller size.



Figure 7: Macro image of flying particles of sample G at 1 MPa

This behaviour is confirmed by the lower number of agglomerates, but seems not to be due to the higher residence time. In fact, the higher burning rate leads to a lower residence time for ADN/GAP formulations, so the aluminium particles have less time to aggregate on the burning surface.

A possible explanation can be found analysing the burning process of GAP. At the beginning of the burning process, this polymer releases azide groups and leaves a carbon structure with high porosity in the proximity of the burning surface and then completes the combustion. Probably the aluminium particles begin to aggregate inside the pores of the burning GAP, few micrometers below the burning surface, in a way that, once the burning surface reaches them, they are ready to complete a transition between aggregate and agglomerates.

This hypothesis is confirmed by video analysis since some particles on the burning surface tend to "disappear" into the propellant and re-appear again after some frames, suggesting a complex porous structure of the reacting surface layer.

Further observations were made on agglomeration, and in particular macro scale measurement revealed the same size trend, and quite the same results. But due to the low resolution of the images, the uncertainty of measurement was too large ($\pm 11.29 \mu m$). Thus, these findings should be used with care.

Macro scale allowed also other kinetic energy measurements and a better study of the flying behaviour of particles. Plotting a sketch of the flight directions of the particles, they show a quite chaotic trend near the burning surface, which evolve in a linear trend from surface in macro scale. The result also show that the kinetic energy does not change significantly between the two types of particles, and it means that it should be considered quite constant at different distances from burning surface; but to confirm these observations, a different setup of equipment is needed and dedicated tests should be performed.

6.2 Gravimetric Specific Impulse losses

The only considered gravimetric specific impulse loss is the one due to the simultaneous presence of liquid aluminium and gas in the combustion products. The liquid state of aluminium was confirmed by measurement and observation. In fact the collision shown in Fig. 8 allows considering a completely inelastic behaviour, confirming the liquid state of agglomerates.



Figure 8: Inelastic collision between three agglomerates

To evaluate the two-phase losses, international standard recommended Eq. 1,

$$(\Delta I_{sp})_{2p} = C_3 \frac{\xi_{cc}^{C4} d_p^{C5}}{p_{cc}^{0.15} \varepsilon^{0.008} d_t^{C6}}$$
(1)

where ξ_{cc} is the molar fraction of condensed products in the combustion chamber (mol/100g), d_p is the average diameter of the condensed particles (µm), p_{cc} is the combustion chamber pressure (psi), ϵ is the geometric expansion ratio of the nozzle, d_t is the diameter of the throat area (in) and C3, C4, C5, C6 are correlation constants.

For a matter of comparison, it was decided to evaluate the ADN/GAP losses with the same values used in Ref. [11], though for this composition other empirical constants are very likely in order, but no work in this direction is known to the authors. The molar fractions of condensed products for ADN/GAP are obtained by thermochemical calculations using the ICT-code and give a result of 0.2916 mol/100g.



Figure 9: Comparison between the different formulations at 7 MPa



Propellants	D	G	Α	В	
$\Delta I_{sp}^{a}[s]$	67.07	66.29	61.79	50.61	
^{<i>a</i>} C3=7.58, C4=0.5, C5=0.8, C6=0.33, $\xi_{cc_A} = \xi_{cc_B} = 0.284 \text{ mol/100g}, d_t = 0.125 \text{ m}, \varepsilon = 40, p_{cc} = 1MPa$					

As expected the results show higher losses for the ADN/GAP formulation due to the larger size of agglomerates. However the losses in specific impulse due to the two-phase flow are lower than the increment gained by the combustion temperature of the new formulation, shown by the results of thermochemical calculations.

7. Conclusion and Future Work

A first survey of metallised ADN/GAP propellants revealed a number of different properties as compared to the metallised AP/HTPB propellants currently in use. Under standard operating conditions, the ideal gravimetric specific impulse is larger (300 s for ADN/GAP/Al vs. 271 s for AP/HTPB/Al), while density is slightly lower due to the oxidizer replacement ($\rho = 1.812$ g/cm³ for ADN vs. 1.949 g/cm³ for AP). Likewise, the adiabatic flame temperature and characteristic velocity are sensibly increased. A welcome feature is the much decreased fraction of condensed combustion products at the nozzle exit (7.5% for ADN/GAP/Al vs. 17.6% for AP/HTPB/Al).

In terms of steady burning rate, the tested ADN/GAP/Al formulations are about 3-4 times faster than the current AP/HTPB/Al formulations over the standard pressure range of solid rocket motors for space access.

Ob the other hand, the average agglomerate size seems larger for ADN/GAP/Al formulations and little sensitive to operating conditions. This is probably due to the porous surface structure of the burning sample, with respect to that of AP/HTPB/Al formulations, trapping the particles and thus favouring the growth of agglomerates of relatively large size. A similar effect was noticed for AN/HTPB/Al formulations due to the tick liquid layer associated with AN melting. In spite of the large burning rates, trapping particles in the burning layer strongly increase the effective residence times.

Overall, it seems very valuable to extend the current investigation and assess how suitable the ADN/GAP/Al formulations are for practical applications.

References

[1] D. Reydellet et al., "Performance of rocket motors with metallized propellants", in AGARD Advisory Report AR-230. AGARD PEP WG-17, Paris, France, 1986.

[2] L.T. De Luca, E. Marchesi, M. Spreafico, A. Reina, F. Maggi, L. Rossettini, A. Bandera, G Colombo, and B.M. Kosowski, "Aggregation versus Agglomeration in Metallized Solid Propellants", Journal of Energetic Materials and Chemical Propulsion, 9, 1, 2010, pp. 91-105.

[3] A. Larsson and N. Wingborg, "Green Propellants Based on Ammonium Dinitramide (ADN)", Advances in Spacecraft Technologies, Dr Jason Hall (Ed.), 2011

[4] T. Heintz, H. Pontius, J. Aniol, C. Birke, K. Leisinger and W. Reinhard, "Ammonium Dinitramide (ADN) – Prilling, Coating, and Characterization", Propellants, Explosive and Pyrotechnics, 2009, 34, 231-238

[5] T. Keicher, W. Kuglstatter, S. Eisele, T. Wetzel and H. Krause, "Isocyanate-Free Curing of Glycidyl Azide Polymer (GAP) with Bis-Propargyl-Succinate (II)", Propellants, Explosive and Pyrotechnics, 2009, 34, 210-217

[6] V. Weiser, N. Eisenreich, A. Baier and W. Eckl, "Burning Behaviour of ADN Formulations", Propellants, Explosive and Pyrotechnics, 1999, 24, 163-167

[7] L.T. DeLuca, L. Galfetti, F. Maggi, G Colombo, A. Reina, S. Dossi, D. Consonni, and M. Brambilla, "Inovative Metallized Formulation for solid or Hybrid Rocket Propulsion", Chinese journal of energetic materials, 2012, 20(4):465-474

[8] L.T. DeLuca, "Burning of Aluminazed Solid Rocket Propellants: from Micrometric to Nanometric Fuel Size", Theory and Practice of Energetic Materials, VOL. VI, IASPEP, Xi'an, China, 2007

[9] L.T. DeLuca and L. Galfetti, "Burning of Metallized Composite Solid Rocket Propellants: from Micrometric to Nanometric Aluminum Size", AJCCP, Gyeongju, Korea, 2008

[10] F. Maggi, A. Bandera, L. T. DeLuca, V. Thoorens, J. F. Trubert and T. L. Jackson, "Agglomeration in Solid Propellants: Novel Experimental and Modeling Method", Progress in propulsion Physics 2 (2011) 81-98

[11] F. Maggi, A. Bandera, L. Galfetti, L. T. DeLuca and T. L. Jackson" Efficient Solid Rocket Propulsion for Access to Space", Acta Astronautica (2009), doi:10.1016/j.acastro,2009.10.012

[12] A. Koleczko, W. Ehrhardt, S. Kelzenberg and N. Eisenreich, Plasma Ignition and Combustion, Propellants, Explosives, Pyrotechnics, Volume 26, Issue 2, 2001, PP. 75–83.

[13] N. Eisenreich, T. S. Fischer, G. Langer, S. Kelzenberg and V. Weiser, Burn Rate Models for Gun Propellants, Propellants, Explosives, Pyrotechnics, Volume 27, Issue 3, June 2002, PP. 142–149.

[14] Weiser, V.; Ebeling, H.; Weindel, M.; Eckl, W.; Klahn, T.; Non-intrusive burning rate measurement under pressure by evaluation of video data; 35th International Annual Conference of ICT, June 29-July 2, 2004, Karlsruhe, pp. 158-(1-6)