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Ballistic Analysis of Polish Low-Vulnerability Gun Propellants

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Abstract. One direction of modern artillery ammunition development is to reduce its vulnerability to the effects of mechanical and thermal factors during transport, storage and operation. For LOVA, the reduced vulnerability of propellant explosives intended for loading into this ammunition is usually connected with a higher thermal ignition impulse threshold and reduced burning rate under low propellant gas pressure. Since 2016, work has been under way at the Military University of Technology (Warsaw, Poland), intended to develop a Polish low-vulnerability gun propellant for 120 mm tank ammunition. It was established during the initial stage of research and analysis, that the JA-2 gun propellant (more specifically, its energy and ballistics characteristics and geometrical dimensions of grains) will be the reference propellant for the low-vulnerability propellant in development. To this end, the authors performed closed vessel tests with JA-2 propellant (with seven-perforated grains designated LO5460).

This paper contains comparative (with the JA-2 propellant) results of closed vessel tests of several propellant blends developed by the MUT Faculty of New Technologies and Chemistry research team.

Closed vessel tests of these propellant blends were performed in the Ballistics Laboratory of the MUT Institute of Armament Technology using a manometric chamber with a volume W_0 = 200 cm^3. Experimental tests and theoretical analyses were performed based on provisions of the standardisation agreement STANAG 4115 [6], American military standard MIL-STD 286C [7] and original test procedures developed based on [8, 9]. The tests focused mainly on the issue of correlation between the chemical composition of the given propellant blend with the expected values of energy and ballistics characteristics in connection with the required shape of propellant grains.

Keywords: mechanics, internal ballistics, closed vessel tests, low-vulnerability propellant

1. INTRODUCTION

A basic operating requirement imposed on modern ammunition is reduction of its vulnerability to the effects of mechanical and thermal factors during transport, storage and operation. One direction in the development of this type of ammunition is LOw-Vulnerability Ammunition (LOVA). Reduced vulnerability of propellants intended for this ammunition (hereinafter LOVA propellants) is usually related to a higher thermal ignition impulse threshold and reduction in burning rate under low propellant gas pressure. The concept of such composite propellants arose as early as during World War II. It was then that the first propellants containing solid oxidiser particles in a plasticised polymer matrix (so called binder) were developed. During the last 50 years, many propellant blends of this type have been proposed and tested, which usually contain 70-80% high-energy filler – hexogen (RDX) or octogen (HMX) is usually applied in this role, 10-25% polymer and one or several plasticisers. In Poland, no research on such propellants had been done before 2016. It was then that the Scientific and Industrial Consortium (Mesko S.A., Polska Grupa Zbrojeniowa S.A., Warsaw University of Technology, Military University of Technology, Military Institute of Armament Technology) was established, whose task was to develop a new generation of Polish 120 mm kinetic energy penetrator tank ammunition, while one of the requirements imposed was to develop (aside from a self-combusting case and tungsten bars) a low-vulnerability gun propellant. This task was taken up by two teams from the Military University of Technology.

The Faculty of New Technologies and Chemistry research team is responsible for developing technology basics and preparing a LOVA propellant at the laboratory scale, while the Faculty of Mechatronics and Aerospace team – for conducting ballistic tests and simulation tests of the shot phenomenon in a 120 mm tank gun system using ammunition loaded with the LOVA propellant developed.

Simulation tests of the shot phenomenon, where the new Polish ammunition (with the LOVA propellant) will be applied, should be performed using actual data concerning propellant grain shape and values of energy and ballistics characteristics of these propellants, such as: specific force, co-volume, dynamic vivacity, burning rate. The values of these characteristics are determined by performing pyrostatic (closed vessel) tests using the intended propellants. Pyrostatics can and should also be used during the process stage for comparative assessment of the energy and ballistics properties of the resulting blends with the propellant adopted as the reference propellant.

During the initial stage of the research and development project, it was established that the JA-2 gun propellant (more specifically, its energy and ballistics characteristics and geometrical dimensions of grains) would be the reference propellant for the low-vulnerability propellant in development. The JA-2 propellant, used in M829A1/A2 120 mm tank ammunition with an APFSDS-T shell, belongs to the double-base propellant group produced using the SCDB technology (*Surface Coated Double Base*). The authors performed their own closed vessel tests of the JA-2 propellant (with seven-perforated grains, designation LO5460). Based on the registered charts of pressure changes (over time), specific force, propellant gas co-volume and dynamic vivacity curves were determined. Using the results of propellant grain geometry measurements, the linear burning rate coefficient was determined [5]. The authors' test of the JA-2 propellant demonstrated that the determined values of energy and ballistics characteristics – taking into account heat losses – are consistent with data from literature. The results of the authors' tests subsequently enabled preliminary simulation tests of the shot phenomenon in a 120 mm gun system to be performed.

2. CLOSED VESSEL TESTS OF SELECTED LOW-VULNERABILITY GUN PROPELLANTS

2.1. Test method

Closed vessel tests of the propellants were performed in the Ballistics Laboratory of the MUT Institute of Armament Technology using a manometric chamber with a volume W_0 = 200 cm^3. Two loading densities were applied during the tests: 100 kg/m^3 and 200 kg/m^3. Black powder-based primers were used to ignite the test propellant charges. Primer mass was selected in such a manner that the arbitrary ignition pressure value was 3 MPa. The result of the closed vessel tests are propellant gas pressure values as a function of time $p(t)$ for the loading densities applied.

The recorded *p*(*t*) charts for the JA-2 propellant and for new propellants served as a basis for performing comparative analyses concerning singularities of the propellant grain combustion duration and the values of:

- propellant gas Noble-Abel equation-of-state parameters (specific force f and co-volume α);
- dynamic vivacity L;
- linear and power forms of the burning rate law pressure function;
- coefficients: *AQ* (Absolute Quickness), *AF* (Absolute Force), *RQ* (Relative Quickness) and *RF* (Relative Force).

The above analyses were performed based on provisions of the standardisation agreement STANAG 4115 [6], American military standard MIL-STD 286C [7] and original test procedures developed based on [8, 9].

2.2. Chemical composition of new propellants and the values of energy characteristics

Suitability of the newly developed propellants for a specific gun system is determined by the values of its energy characteristics (specific force f and co-volume α) and its ability to create propellant gases at the right time, i.e. the rate of propellant gas flow into the space behind the shell. The initial stage of the closed vessel tests was focused on calculating the values of specific force and co-volume.

The basis for determining them is the maximum propellant gas pressure value determined during combustion of propellant with a specific chemical composition under isochoric conditions. The size and geometric shape of propellant grains has no significant impact on the values of the maximum pressure achieved.

A possible correction of the maximum pressure value takes into account heat losses due to different combustion time of propellant grains with different combustible layer thicknesses.

Three propellant blends (SC-30, SC 56p and SCX-64) were selected for closed vessel tests, and their percentage contents of chemical components are shown in Table 1, while the shape and dimensions of their propellant grains are summarised in Table 2.

Figure 1 shows a graphical comparison of the registered average values of maximum propellant gas pressure for loading densities of 100 and 200 kg/m^3, respectively. Table 3 summarises the experimental average values of maximum pressure (reduced by the adopted ignition pressure of 3 MPa) and maximum pressure corrected for heat losses.

Table 1. Chemical composition of SC-30, SC 56p and SCX-64 propellants

Component	**SC-30**	**SC- 56p**	**SCX- 64**
RDX-RS (Hexogen)	75.8	76.0	76.0
CAB (Cellulose acetate butyrate)	12.1	-	6.0
NC (12.6%)	4.0	16.0	10.0
TAC (Triacetin)	7.7	7.6	7.6
Akardite II	0.4	0.4	0.4

Table 2. Grain shape and dimensions of SC-30, SC-56p and SCX-64 propellants

Parameter	**SC-30**	**SC-56p**	**SCX- 64**
grain shape	cylinder	cylinder	cylinder
grain length *L* [mm]	35	7.80	37
grain diameter *D* [mm]	4.7	10.2	4.6
combustible layer thickness e_0 [mm]	2.35	3.9	2.3

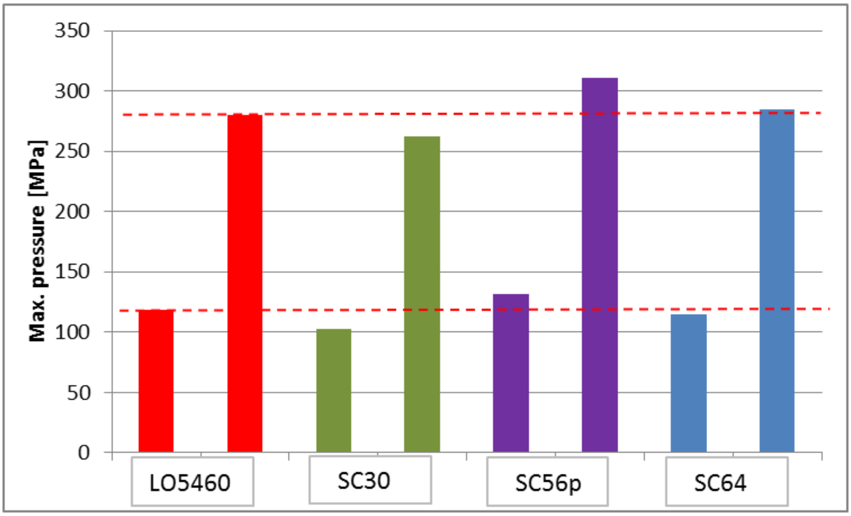

Fig. 1. Comparison of maximum pressure (reduced by ignition pressure) for loading densities 100 and 200 kg/m^3

Table 3. Measured p_m and corrected p_{mc} maximum pressure values (reduced by ignition pressure)

Δ [kg/m^3]	JA-2		SC-30		SC-56p		SCX-64	
	p_m [MPa]	p_{mc} [MPa]	p_m [MPa]	p_{mc} [MPa]	p_{ma} [MPa]	p_{mc} [MPa]	p_m [MPa]	p_{mc} [MPa]
100	121.2	130.1	101.9	114.1	131.6	135.5	114.4	123.5
200	283.1	290.5	261.9	272.1	311.2	314.1	284.8	293.6

The Noble-Abel gas equation-of-state

$$p_m = \frac{f\Delta}{1-\alpha\Delta} \tag{1}$$

and maximum pressure values ($p_{\mathrm{m}1}$, $p_{\mathrm{m}2}$) for two loading densities (Δ_1, Δ_2) served as basis for determining specific force f and co-volume α in accordance with the following relations

$$\alpha = \frac{\frac{p_{m2}}{\Delta_2} - \frac{p_{m1}}{\Delta_1}}{p_{m2} - p_{m1}} \tag{2}$$

$$f = \frac{p_{m1}}{\Delta_1} - \propto p_{m1} \tag{3a}$$

or

$$f = \frac{p_{m2}}{\Delta_2} - \propto p_{m2} \tag{3b}$$

Table 4 summarises the values of specific force f and co-volume α determined based on experimental values of maximum pressure (E), pressure values corrected for heat losses (Q) and values obtained from thermochemical calculations (T).

A comparison of the data included in Table 4 indicates that correction for heat losses enabled bringing the specific force and co-volume values to the values obtained in thermochemical calculations.

Based on the experimental tests and theoretical analyses performed, it was found that energy properties of SC-30 and SC-56p deviate significantly from the respective values of the JA-2 propellant (with LO5460 grains), considered the reference propellant. This is also confirmed by *RF* and *RQ* characteristics, summarised in Table 5.

Table 4. Specific force f and co-volume α values: experimental (E), corrected for heat losse (Q) and theoretical (T)

Parameter	**LO5460**	**SC-30**	**SC-56p**	**SCX-64**
(E) f, kJ/kg	1020	864	1141	956
(Q) f, kJ/kg	1154	1097	1263	1158
(T) f, kJ/kg	1161	1100	1239	1167
(E) α, dm^3/kg	1.359	1.815	1.334	1.644
(Q) α, dm^3/kg	1.001	1.065	1.088	1.128
(T) α, dm^3/kg	0.983	1.098	1.050	1.112

Relative Force (*RF*) represents a relative value (expressed in %) of maximum pressure between the test propellant and the reference propellant (in this case JA-2). The *RF* value is calculated using the following equation

$$RF = \frac{100}{m}\sum_{i=1}^{m}\left(\frac{T_{pmax}}{R_{pmax}}\right) \tag{4}$$

where:

T_{pmax} – maximum pressure for test *i* of the test propellant;

R_{pmax} – maximum pressure for test *i* of the reference propellant.

Conversely, Relative Quickness (*RQ)* represents a relative value (expressed in %) of pressure build-up rate between the test and reference propellant. The *RQ* value is calculated using the following equation

$$RQ = \frac{1}{m}\sum_{i=1}^{m}\left(\frac{100}{n}\sum_{j=1}^{n}\frac{T_{ij}}{R_{ij}}\right) \tag{5}$$

where:

m – number of tests performed (identical for test and reference propellant);

n – number of measurement points on the d*p*/d*t* = f(*p*) curve (at least 4);

T_{ij} – d*p*/d*t* value for test propellant during test *i* and in point *j*;

R_{ij} – d*p*/d*t* value for reference propellant during test *i* and in point *j*.

The measurement points on the d*p*/d*t* = f(*p*) curve should be selected in such a manner that they result from 27, 40, 53 and 66% value of the maximum pressure.

Table 5. Values of *RQ* and *RF* for propellants SC-30, SC-56p and SCX-64 (JA-2 propellant as reference)

Powder	**Δ = 100 kg/m^3**		**Δ = 200 kg/m^3**	
	RF	***RQ***	***RF***	***RQ***
JA-2 (LO5460)	100.00	100.00	100.00	100.00
SC-30	86.33	19.98	93.51	31.91
SC-56p	111.51	138.39	111.11	233.43
SCX-64	96.91	42.70	101.69	68.02

While the SCX-64 propellant has a similar value of force as the JA-2 propellant (similar *RF* value) and a slightly higher co-volume value, this propellant could not at this stage of the study be considered equivalent to the JA-2 propellant due to lower dynamics of pressure build-up rate during the main combustion period (lower *RQ*).

It was therefore necessary to test the combustion dynamics of a propellant equivalent to the SCX-64 propellant, but with grains with a shape and dimensions identical or similar to the shape and dimensions of the LO5460 grain.

2.3. Energy and ballistics properties of low-vulnerability gun propellant with seven-perforated grains

As was mentioned in section 2.2, propellant size and geometrical shape of a specific propellant composition has no significant effect on the maximum pressure value achieved during experimental (pyrostatic) tests.

Additionally, maximum pressure value correction for heat losses enabled the values of specific force f and co-volume α to be brought significantly closer to the values obtained in thermochemical calculations (Table 4). This leads to a conclusion that if propellant chemical composition and its combustion conditions are known accurately, thermochemical calculations can successfully replace closed vessel tests. Unfortunately, the role of thermochemical calculations can only be limited to assessing the energy properties of propellants. Assessment of combustion process dynamics remains the domain of pyrostatic tests. Correct conclusions concerning the assessment of this process make pyrostatic (closed vessel) tests of propellants with grains of similar shapes and geometric dimensions significantly easier. For this reason, the next stage of tests concerned propellants with seven-perforated grains, whose chemical composition is shown in Table 6, while dimensions, initial surface area and volume of a seven-perforated grain are summarised in Table 7.

Table 6. Chemical composition of SCX-72, SCX-82, SCX-86 and SCX-87 propellants

Component	**SCX-72**	**SCX-82**	**SCX-86**	**SCX-87**
RDX-RS (Hexogen)	76.0	67.2	76	75.5
CAB (Cellulose acetate butyrate)	6.0	5.0	6	6
NC (12.6%)	10.0	19.8	10	10
TAC (Triacetin)	7.6	7.6	7.6	7.1
Akardite II	0.4	0.4	0.4	0.4
Catalyst A	-	-	-	1

It must be noted that the chemical composition of the SCX-72 propellant is identical to the chemical composition of SCX-64. While reducing the length of SCX-86 and SCX-87 propellant grains compared to SCX-72 and SCX-82 propellants resulted in an increase of the ratio of initial grain combustion surface area to its volume, at the same time it changed the characteristics of grain shape from progressive to degressive.

Figures 2 and 3 show changes in propellant gas pressure, including both the initial propellant grain ignition period and the main period after reaching the arbitrary ignition pressure for the two loading densities of 100 and 200 kg/m^3. Compared to the JA-2 propellant, both the initial and main combustion periods of the new propellants are much longer, which confirms literature reports of reduced burning rate of these propellants under low propellant gas pressure.

Table 7. Dimensions, initial grain surface area and volume of the JA-2, SCX-72, SCX-82, SCX-86 and SCX-87 propellants

Parameter	**JA-2 (LO5460)**	**SCX-72**	**SCX-82**	**SCX- 86**	**SCX-87**
grain shape	7-perforated cylinder				
grain length *L* [mm]	15.5	15.5	14.9	4.5	4.5
grain diameter *D* [mm]	8.9	8.0	7.6	9.0	9.0
perforation diameter *d* [mm]	0.54	0.5	0.5	0.5	0.5
combustible layer thickness e_0 [mm]	0.873	0.8128	0.7625	0.9375	0.9375
initial grain combustion surface area S_{0p} [cm^2]	7.38	6.57	6.076	3.012	3.012
initial grain volume S_{0p} [cm^3]	0.939	0.757	0.655	0.280	0.280

Changing the RDX/NC ratio in the SCX-82 propellant had a negative effect both on the energy characteristics (Table 8) and combustion process dynamics.

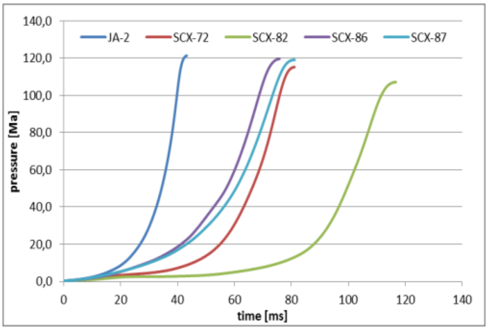

Fig. 2. $p(t)$ for the range up to the arbitrary ignition pressure value (for $\Delta = 100$ kg/m^3)

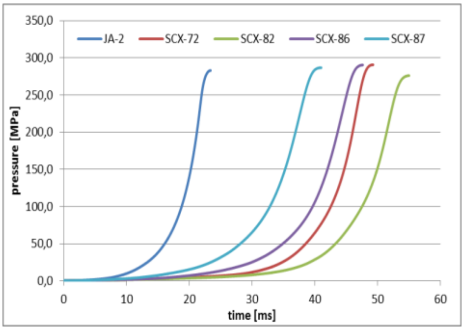

Fig. 3. $p(t)$ after reaching the arbitrary ignition pressure value (for $\Delta = 200$ kg/m^3)

Table 8. Specific force f and co-volume α values: experimental (E), corrected for heat losses (Q) and theoretical (T)

Parameter	**LO5460**	**SCX-72**	**SCX-82**	**SCX-86**	**SCX-87**
(E) f, kJ/kg	1020	934	848	978	985
(Q) f, kJ/kg	1154	1208	1128	1137	1144
(T) f, kJ/kg	1161	1167	1142	1167	1168.5
(E) α, dm^3/kg	1.359	1.757	1.895	1.219	1.532
(Q) α, dm^3/kg	1.001	1.025	1.103	1.200	1.109
(T) α, dm^3/kg	0.983	1.112	1.103	1.112	1.108

An important characteristic of combustion process dynamics assessment is dynamic vivacity. This characteristic, combining information on the progressiveness of the propellant grain shape and on burning rate, enables the assessment of the rate of propellant gas inflow. STANAG 4115 [6] defines propellant dynamic vivacity as:

$$L = \frac{1}{p\, p_{\max}} \frac{dp}{dt} \tag{6}$$

Vivacity is shown as a function of the ratio of current pressure (p) to maximum pressure (p_m) or as a function of relative combusted propellant mass (z). In order to use equation (6), a derivative of the curve $p(t)$ recorded during the closed vessel tests must be calculated.

Figure 4 shows charts of dynamic vivacity of the JA-2 propellant, determined with heat losses taken into account.

The authors' tests of the JA-2 propellant were intended to obtain reference data for the newly developed propellants. STANAG 4115 defines relative and characteristic propellant vivacity, which can be used for comparative assessment of new low-vulnerability propellants. Propellant relative vivacity values are calculated using the following formula:

$$L_{rel}(z) = \frac{\sum_{i=1}^{m} L(z)}{\sum_{i=1}^{m} L_{ref}(z)} \tag{7}$$

The symbol m stands for the number of test here.
Propellant characteristic vivacity is calculated using the following formula:

$$L_k = \frac{\sum_{i=1}^{5} L_{rel}(z_i)}{5}, \quad z_i = 0,3; 0,4; 0,5; 0,6; 0,7 \tag{8}$$

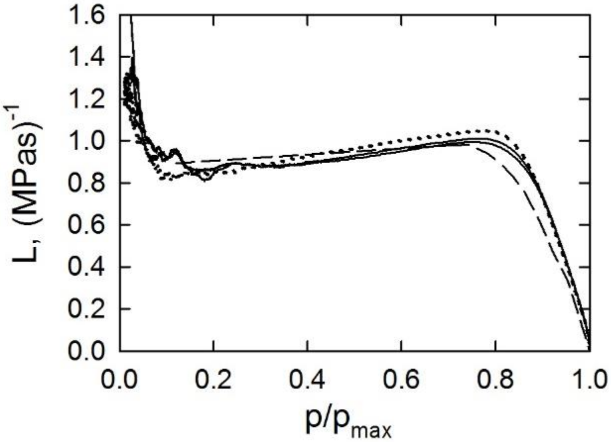

Fig. 4. Dynamic vivacity curves of the JA-2 propellant, determined with heat losses taken into account: solid lines – Δ = 100 kg/m^3, dotted lines – Δ = 200 kg/m^3, dashed line – chart from paper [10]

Figures 5-8 show dynamic vivacity curves of propellants SCX-72, SCX-82, SCX-86 and SCX-87 for two loading densities: 100 kg/m^3 (two tests) and 200 kg/m^3 (one test), as well as a comparative vivacity curve of the JA-2 propellant (from Fig. 4). Table 9 summarises the values of characteristic vivacity, compared to the JA-2 propellant (with LO5460 grains).

Table 9. Characteristic vivacity values of the tested propellants

JA-2	**SCX-72**	**SCX-82**	**SCX-86**	**SCX-87**
1.00	0.682	0.551	0.585	0.581

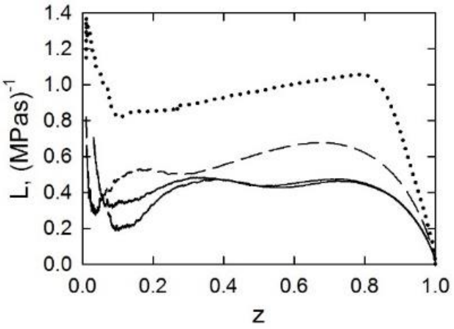

Fig. 5. Dynamic vivacity curves of the SCX-72 propellant:
solid lines – Δ = 100 kg/m^3,
dashed line – Δ = 200 kg/m^3; dotted line – JA-2 propellant (LO5460 grains)

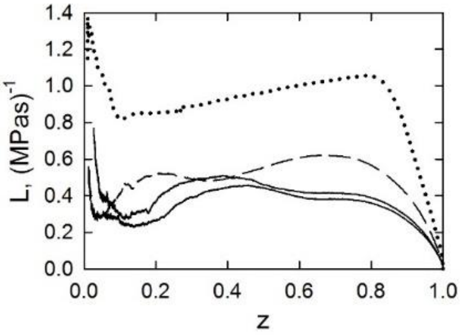

Fig. 6. Dynamic vivacity curves of the SCX-82 propellant:
solid lines – Δ = 100 kg/m^3,
dashed line – Δ = 200 kg/m^3; dotted line – JA-2 propellant (LO5460 grains)

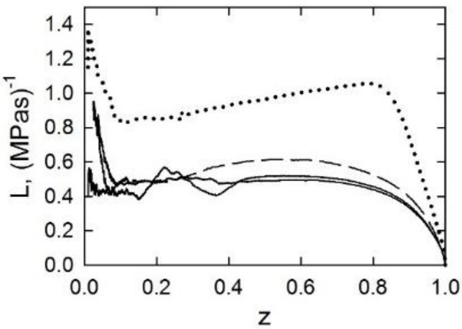

Fig. 7. Dynamic vivacity curves of the SCX-86 propellant:
solid lines – Δ = 100 kg/m^3,
dashed line – Δ = 200 kg/m^3; dotted line – JA-2 propellant (LO5460 grains)

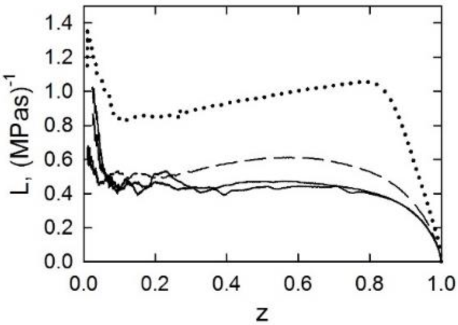

Fig. 8. Dynamic vivacity curves of the SCX-87 propellant:
solid lines – Δ = 100 kg/m^3,
dashed line – Δ = 200 kg/m^3; dotted line – JA-2 propellant (LO5460 grains)

An important ballistic characteristic that determines the suitability of the given propellant for the given gun system is burning rate.

According to STANAG 4115, the propellant burning rate equation is as follows:

$$r = \frac{de}{dt} = \frac{de}{dz}\frac{dz}{dp}\frac{dp}{dt} \tag{9}$$

where: z – relative mass of combusted propellant.

The de/dz values can be determined based on geometric characteristics of the grain, using the propellant grain relative combustion surface area *Φ(z)*:

$$\frac{de}{dz} = \frac{V_{0,p}}{S_{0,p}}\frac{1}{\Phi(\mathrm{z})} \tag{10}$$

where: $V_{0,\mathrm{p}}$ – initial volume of the propellant grain,
$S_{0,\mathrm{p}}$ – initial grain surface area.

The shape function Φ(z) determined for each geometrical form of grain, in particular for multi-perforated propellants, can be complex due to the occurrence of a progressive and degressive period during combustion.

The dz/dp derivative is calculated using the following formula

$$z = \frac{b_1 f_{ex}}{(f_{ex} + b_2 p_s)^2} \tag{11}$$

where: $p_s = p_i - p_z$ (p_z – ignition pressure),
$b_1 = \frac{1}{\Delta} - \frac{1}{\rho}$, $b_2 = \alpha_{ex,p} - \frac{1}{\rho}$,
f_{ex} – experimental specific force value,
Δ – loading density,
ρ – propellant density,
$\alpha_{ex,p}$ – experimental co-volume.

The dp/dt derivative is calculated using the recorded pressure change chart The values of coefficients of the power form of the burning rate law pressure function are summarised in Table 10.

Table 10. Constant and exponent values in the burning rate law

Powder	**JA-2**	**SCX-72**	**SCX-82**	**SCX-86**	**SCX-87**
β [cm/(MPa^{n}s]	0.167	0.085	0.0658	0.0335	0.0248
n	0.897	0.929	0.950	1.122	1.184

Figure 9 shows charts of the burning rate relation to pressure for propellants from Table 10. This summary indicates that the test propellants are characterised by a significantly lower burning rate than the JA-2 propellant.

This is also clearly visible in Figs. 2 and 3, where low burning rates can be observed, especially for low pressure values. It can therefore be stated, that at this stage of ballistic tests, they meet only one requirement for LOVA propellants.

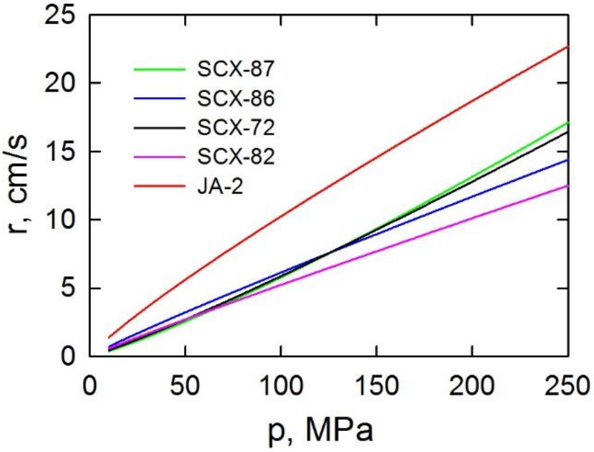

Fig. 9. Burning rate to pressure charts for propellants from Table 10

3. DISCUSSION AND RESULTS OF ANALYSIS

The analyses performed indicate that there is a necessity to change the dimensions of seven-perforated propellant grains with the composition of the SCX-72 and SCX-86 (SCX-87) propellants in order to obtain a similar – compared to propellant LO5460 – pressure build-up time for the main combustion period.

Due to the similar energy characteristics of these propellants, it would require achieving similar values of the time derivative of relative combusted propellant mass *z*:

$$\frac{dz}{dt} = \phi(z) r(p) \frac{S_{0p}}{V_{0p}} \tag{12}$$

Equality of the volumetric burning rates for two propellants leads to the following relation:

$$\phi(z) r(p) \frac{S_{0p}}{V_{0p}} = \phi_w(z_w) r_w(p) \left(\frac{S_{0p}}{V_{0p}} \right)_w \tag{13}$$

The subscript *w* indicates values for the reference propellant LO5460. As the test propellants have similar energy characteristics, z_w and z values are very similar and can be assumed to be equal.

Knowing the ratio of linear burning rate of the LO5460 propellant and SCX-86 (SCX-87) propellants, and the ratio of grain surface area to its volume, and the $\Phi_w(z)$ value of propellant LO5460, the required dimensions of the new propellant grain can be determined, which would ensure the right dynamics of the combustion process, necessitated by the requirement to utilise this propellant in a 120 mm tank gun system. This will be the subject of further deliberations during the next stage of the study.

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REFERENCES

[1] Leciejewski Zbigniew, Stanisław Cudziło. 2012. „Kierunki rozwoju miotających materiałów wybuchowych w aspekcie wymagań przyszłościowej broni palnej”. Materiały Wysokoenergetyczne 3 : 7-14.

[2] Janzon Bo, Joseph Jr. Backofen, Ronald E. Brown, Roxan Cayzac, Andre Diederen, Marc Giraud, Manfred Held, Albert W. Horst, Klaus Thoma. 2007. The Future of Warhead, Armour and Ballistics. In *Proceedings of the 23rd International Symposium on Ballistics*, 3-27, 16-20 April 2007, Tarragona, Spain.

[3] Horst W. Albert, Patrick J. Baker, Betsy M. Rice, Pamela J. Kaste, Joseph W. Colburn, Jennifer J. Hare. 2001. *Insensitive High Energy Propellants for Advanced Gun Concepts*, Technical Report ARL-TR-2584, Aberdeen.

[4] Manning G. Thelma, Joseph Leone, Martijn Zebregs, Dinesh R. Ramlal, Chris A. van Driel. 2013. “Definition of a JA-2 Equivalent Propellant to be Produced by Continuous Solventless Extrusion”. *Journal of Applied Mechanics* 80 (3) : 031405 (7 pages).

[5] Fikus Bartosz, Zbigniew Leciejewski, Jakub Michalski, Zbigniew Surma, Radosław Trębiński. 2017. „Wstępne analizy wymagań balistycznych prochów LOVA do amunicji czołgowej nowej generacji”. Materiały Wysokoenergetyczne 9 : 105-116.

[6] STANAG 4115, Edition 2. 1997. *Definition and Determination of Ballistic Properties of Gun Propellants*, Military Agency for Standardization, 30.06.1997

[7] MIL-STD 286C *Propellants, Solid: Sampling, Examination and Testing*.

[8] Sieriebriakow M., *Wnutrienniaja ballistika*, Moskwa, Oborongiz, 1949.

[9] Torecki Stanisław. 1998. Eksperymentalna ocena wpływu strat cieplnych na ciśnienie gazów prochowych w komorze manometrycznej. W *Materiały Międzynarodowej Konferencji Uzbrojeniowej „Naukowe aspekty techniki uzbrojenia”*, 333-341. Waplewo 27-29.10.1998.

[10] Conner C.B., W.R Anderson. 2009. Modeling the combustion of JA2 and solid propellants of similar composition, In *Proceedings of the Combustion Institute* 32 : 2131-2137.

Analiza balistyczna polskich małowrażliwych kompozycji prochowych

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Streszczenie. Jednym z kierunków rozwoju współczesnej amunicji artyleryjskiej jest zmniejszenie jej wrażliwości na działanie czynników mechanicznych i termicznych podczas transportu, przechowywania i eksploatacji. W przypadku amunicji LOVA zmniejszona wrażliwość wybuchowych materiałów miotających przeznaczonych do elaboracji tej amunicji jest z reguły powiązana z wyższą wartością progową cieplnego impulsu zapłonowego i zmniejszeniem szybkości spalania przy niskim ciśnieniu gazów prochowych. Od 2016 r. w Wojskowej Akademii Technicznej trwają prace nad opracowaniem polskiego małowrażliwego materiału miotającego do 120 mm amunicji czołgowej. Na wstępnym etapie badań i analiz przyjęto, że proch JA-2 (a właściwie jego charakterystyki energetyczno-balistyczne oraz kształt i wymiary geometryczne ziaren) będzie prochem referencyjnym w stosunku do opracowywanego prochu małowrażliwego. W tym celu przeprowadzono własne badania pirostatyczne prochu JA-2 (z ziarnami siedmiokanalikowymi o symbolu LO5460).

Artykuł zawiera porównawcze (z prochem JA-2) wyniki badań pirostatycznych kilku kompozycji prochowych, opracowanych przez zespół badawczy Wydziału Nowych Technologii i Chemii WAT. Badania pirostatyczne tych kompozycji prochowych przeprowadzono w Laboratorium Balistyki Instytutu Techniki Uzbrojenia WAT z wykorzystaniem komory manometrycznej o objętości W_0 = 200 cm^3. Badania doświadczalne i analizy teoretyczne realizowano w oparciu o zapisy porozumienia standaryzacyjnego STANAG 4115 [6], amerykańskiej normy MIL-STD 286C [7] oraz własne procedury badawcze opracowane na podstawie prac [8, 9]. W badaniach skoncentrowano się głównie na kwestii korelacji pomiędzy składem chemicznym badanej kompozycji prochowej a oczekiwanymi wartościami charakterystyk energetyczno-balistycznych, w powiązaniu z wymaganym kształtem ziaren prochowych.

Słowa kluczowe: mechanika, balistyka wewnętrzna, badania pirostatyczne, małowrażliwy materiał miotający