Scientific Journal of the Military University of Land Forces
ISSN: 2544-7122 (print), 2545-0719 (online)
2018, Volume 50, Number 4(190), Pages 101-115
DOI: 10.5604/01.3001.0013.0725

Original article

Laboratory methods for testing the performance of pyrotechnic delay elements

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INFORMATIONS

Article history:

Submited: 11 November 2017

Accepted: 23 May 2018

Published: 31 December 2018

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ABSTRACT

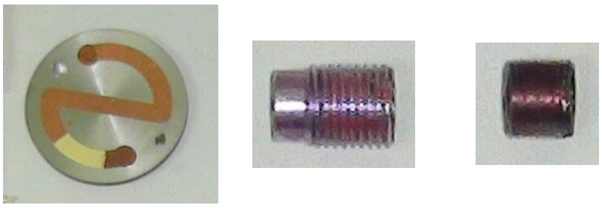
Pyrotechnic delay elements owing to their simple structure and reliability are very often used as part of the design of ammunition. Their basic task consists in generating a specified delay between the respective actions of two elements/systems, required to ensure the safe and reliable work of ammunition. The paper presents laboratory methods employed for testing the performance of pyrotechnic delay elements (PDEs) used in means of combat. The introductory part describes pyrotechnical delay elements and the task fulfilled by them in ammunition. The next part discusses performance parameters of pyrotechnic delay elements, decisive for their proper operation, and factors influencing such operation. In its main part the article presents the standard defining the laboratory methods to be employed for testing pyrotechnic delay elements. According to the above-mentioned standard, the laboratory methods of testing pyrotechnic delay elements can be divided into tests in the open and closed systems. Further, the paper discusses both types of test systems. Taking account of a wide thematic scope of the discussed issue, this article focuses mainly on presenting new methods of testing pyrotechnic delay elements, which have not been mentioned in the standard. Provided examples of tests of pyrotechnic delay elements have been taken from the Polish and foreign literature. Two methods of testing pyrotechnic delay elements are worth paying special attention, one making use of a thermal imaging camera, and the other relying on Roentgen radiation.

KEYWORDS

pyrotechnic delay element, ammunition, X-ray radiography, thermal imaging

Introduction

The paper presents laboratory methods of testing the performance of pyrotechnic delay elements used in ammunition. The information has been gathered from the available design documentation, standards, patents and studies, both national and foreign. Pyrotechnic delay elements owing to their simple structure and reliability are very often used as part of the design of ammunition. Their basic task is to generate a delay between the respective actions of two elements/systems, required to ensure the safe and reliable work of ammunition. Pyrotechnic delay elements include delayers, self-destruct fuses and locks. With respect to their design the PDEs listed hereinbefore are identical to some extent as they all have one component part in common, namely a pyrotechnic delay composition (PDC – one or several ones), which is pressed into the PDE shell and forms a pyrotechnic delay charge (PDCh). It happens that a given means of combat has several PDEs, being the elements that act independently of each other and have different functions and names. For example, in a fuse used in anti-tank guided projectiles there are three types of PDE (Fig. 1): self-destruct fuse (a) – self-destruction of the projectile if the target has been missed, delayer (b) – a time delay in the projectile activation after it has penetrated into the target, lock/safety pellet (c) – delay in the activation of the fusing mechanism.



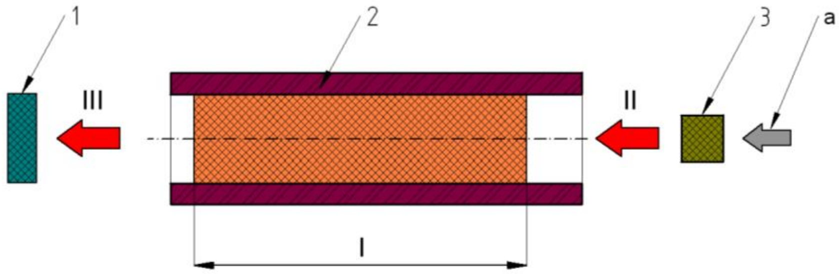
a b c

a – self-destruct fuse; b – delayer; c – lock

Fig. 1. Pyrotechnic delay elements
Source: [own work].

1. Laboratory testing of pyrotechnic delay elements

Laboratory tests consist in verifying the performance parameters of PDEs, decisive for their safe and reliable operation. Figure 2 presents the operating diagram of a PDE in the explosive train. The PDE (2) is initiated by the igniting element (3), which is triggered by an external ignition source. Then, the PDE, having burnt within a specified time, ignites the next element in the explosive train or, in some cases, unlocks safety and arming devices. The performance parameters of PDEs include: time of burning (**I**), sensitivity to the flame coming from the igniting element (**II**) and ability of a PDE to ignite the next element in the explosive train (**III**).



1 – element ignited by the PDE; 2 – PDE filled with the PDCh; 3 – element igniting the PDE;
l – "time" of burning; II – trigger from the igniting element;
III – trigger from the PDE to the next element in the explosive train;
a – external ignition source initiating the igniting element

Fig. 2. Operating diagram of a PDE in the ammunition explosive train
Source: [own work].

The verification of the performance parameters of PDEs is also carried out before and after other PDEs tests, e.g. air-tightness testing, mechanical testing (force application) or testing of the influence of low and high temperatures. Only after all these tests are successfully completed, which confirms that the PDE has fulfilled the assumed performance parameters, such PDE can be approved for use.

While testing PDEs it is important to know what factors affect their performance parameters. These factors can be divided into the internal and external ones [Warchol et al. 2016]. Internal factors are related mainly to physical and chemical properties of respective elements or compounds forming a PDC. External factors are linked to the operating environment of a PDE, i.e. ambient temperature, external pressure, design of such PDE, and forces acting during firing and at the phase of ammunition flight.

Laboratory methods of testing PDEs are described in the industry standard [*Pirotechniczne zespoly*… 1984], concerning laboratory tests of pyrotechnic fuse assemblies (PFA), whereby this name covers delayers, locks/safety pellets, and self-destruct fuses. As the pyrotechnic assemblies occur not only in fuses, but also in other types of ammunition, one name has been adopted for use in the article – pyrotechnic delay elements (PDEs). Table 1 presents the classification of methods used for testing the time of burning according to the above-mentioned standard. The referenced standard contains the still valid methodology for testing a PDE, which determines:

– the conditions of burning (testing) a PDE: open or confined space (open/closed system),
– the type of the element igniting the PDE: black powder priming, igniting primers, electric primers,
– the way in which the element igniting the PDE is initiated: resistance wire, electric pulse, externally applied force (force of inertia, centrifugal force),
– the methods to determine the start and the end of burning of the PDE: acoustic, photoelectric, electromechanical.

Table 1. Methods of testing the times of burning of PDEs

No.	Combustion conditions for pyrotechnic assemblies	Ignition sources for pyrotechnic assemblies	Methods of igniting pyrotechnic assemblies	Determination of the start of burning
1.	In the open space	Pyrotechnic priming (PP)	Igniting PP with a wire heated up by electrical current	Photoelectric – photocell light as a response to the flame
2.	In the confined space	Igniting primer KW	Piercing of KW by striking mechanically at the firing pin under stationary conditions	Electromechanical – making an electric circuit at the moment the weight strikes the firing pin
			Piercing of KW as a result of the action of the force of inertia, centrifugal force or otherwise	Electromechanical – making or breaking an electric circuit
3.	In the confined space	Igniting primer KW	Piercing of KW as a result of the action of the force of inertia, centrifugal force or otherwise	Acoustic – sound generated by the action of the primer
		Electrical primer EW	Activation of EW while transferring an electric pulse onto the bridge	Electric – starting the chronograph by the voltage pulse transferred onto the EW bridge
4.	In the confined space	Electrical primer EW	Activation of EW while transferring an electric pulse onto the bridge	Starting the chronograph at the moment a pulse is applied to activate EW

With regard to the entries in Table 1, in the column presenting the characteristics of the explosive train in the tested special assemblies, at present, while testing a PDE, there are no limitations regarding the possibility of using other elements of the explosive train in the open or closed system. The application of additional elements depends on the adopted method of testing the PDE, making it possible to obtain reliable results, and on the observance of occupational health and safety regulations.

Table 1. Continue

No.	Determination of the end of burning	Test method	Ranges of the measured times of burning [s]	Measurement error [s]	Characteristics of the explosive train of the tested special assemblies
1.	Photoelectric – photocell light as a response to the flame	A	from 1*10^{-3} to 1*10^{3}	/1+0.3t/*10^{-4}	The following elements of the explosive train are absolutely not allowed: boosting primer, electric boosters, relays, boosters
	Electromechanical – making or breaking an electric circuit	B	from 1*10^{-3} to 1*10^{3}	/1.1+0.3t/*10^{-4}	
2.	Photoelectric – photocell light on or off	W	from 1*10^{-3} to 1*10^{3}	/3.1+0.3t +ab/*10^{-4}	
	Electromechanical – making or breaking an electric circuit	G	from 1*10^{-3} to 1*10^{6}	3*/1+t/*10^{-4}	Elements of the explosive train are allowed provided that the occupational health and safety regulations are observed
3.	Acoustic – sound generated by the movement of a part of the fuse or by the action of an element of the explosive train	D	above 1 second	0.2 + Δ	Elements of the explosive train are allowed provided that the occupational health and safety regulations are observed
	Photoelectric – photocell light on or off	E	from 1*10^{-3} to 1*10^{3}	/1.1+0.3t/*10^{-4}+t_{EW}	Elements of the explosive train are absolutely not allowed
	Electromechanical – making or breaking an electric circuit	Z	from 1*10^{-4} to 1*10^{6}	/1.1+0.3t/*10^{-5}+t_{EW}	Elements of the explosive train are allowed provided that the occupational health and safety regulations are observed
4.	Acoustic – sound generated by the movement of a part of the fuse or by the action of an element of the explosive train	J	above 1 second	0.2 + Δ	Elements of the explosive train are allowed provided that the occupational health and safety regulations are observed

where: T – measured time of burning in seconds; B – gap between the primer and the firing pin of the tested special assembly in mm; A – 1 s/mm – rate; Δ – chronograph error; tEW – chronograph action time, s.

However, the columns in Table 1 that inform about the range of the measured times of burning and about measurement errors are no longer valid, because of technological advancements observed if the apparatus existing at the time when the standard was developed is compared with the present one. The availability of measuring instruments, e.g. oscilloscopes, offers the possibility of measuring a wide range of time delays, whereas the determination of the error of measurement applies to the testing of a given type of a PDE with the use of instruments having specific characteristics.

Currently, several types of elements initiating PDEs are available and new methods have been introduced to determine the start and the end of burning. Taking account of a wide thematic scope of the discussed issue, this article focuses mainly on presenting these methods of testing PDEs which are not listed in Table 1.

It should be also emphasised that the referenced standard does not inform that the obtained times of burning for the same PDE tested in the open and confined space are different in the majority of cases. PDEs tested in the closed system obtain significantly lower times of burning [Kosanke 2004] in comparison with the open system. It is connected with the fact that the head of the burning front of a PDCh is influenced by pressure formed in the combustion chamber by gaseous products of combustion of the igniting element and the PDCh.

1.1. Tests in the open system

During the tests of PDEs in the open system their ignition and burning take place with gases escaping freely to the surrounding atmosphere. The testing of PDEs in the open system is justified in the case where the obtained times of burning of a given PDE are identical for both the open and closed systems. However, analysing the Polish and foreign literature concerning the design of and tests on PDEs it can be observed that there are only few solutions for a PDE in which the times of burning in both testing systems are the same. Yet, it happens that in some design documentations [*Przeciwpancerny pocisk*… 1980], in the method of inspecting the time of burning of a PDE, values for the time of burning are provided for both the open and closed system.

The study [Shaw et al. 2015] presents the results of testing of a PDE used in signal rocket flares. The times of burning of the PDE were tested in both the open and closed system and the results recorded for the open system were approximately twice as high as those obtained in the closed system.

In Table 1, in methods A and B, pyrotechnic priming was specified as the source of ignition of a PDCh, whereas the said priming is ignited by a wire heated up by electric current. Such way of initiating a PDE complicates the test, as it becomes necessary to insert or press the priming into the PDCh, however, the method is still in use, as evidenced, for example, by the studies [Miklaszewski et al. 2014; Shaw et al. 2015], where a heated up nichrome wire is used for igniting a PDCh through the black powder priming.

At present, other mechanisms for igniting PDEs are employed, such as [Davitt et al. 1983; Beck et al. 1992] a shockwave of low-energy detonating fuses or systems of the “Nonel” type. A laser is increasingly often used as a source of ignition [Trunov et al. 2005; Borkowski et al. 2013], because the initiation with a beam of laser radiation makes it possible to deliver to the tested system a specified amount of energy within a given time. The use of optical waveguides provides the possibility of initiating a PDE located at a considerable distance from the source of light, while concurrently eliminating the threat posed by stray currents and static electricity.

High-speed cameras are often used to measure the time of burning of a PDE. In the study [Poret et al. 2012] a high-speed camera, Vision Research V7, was used with a Nikon 20-80 mm lens. The recording rate was 100 frames per second and the PDE was initiated with the use of a heated up nichrome wire. The measurement of time consists in dividing the recorded film into frames and establishing when the flame from the initiator side and the muzzle flash appear (Fig. 3). Furthermore, when a high-speed camera is used, it is possible to observe the process of forming the muzzle flash shape and the presence of solid particles in it, facilitating the ignition of the next element in the explosive train.

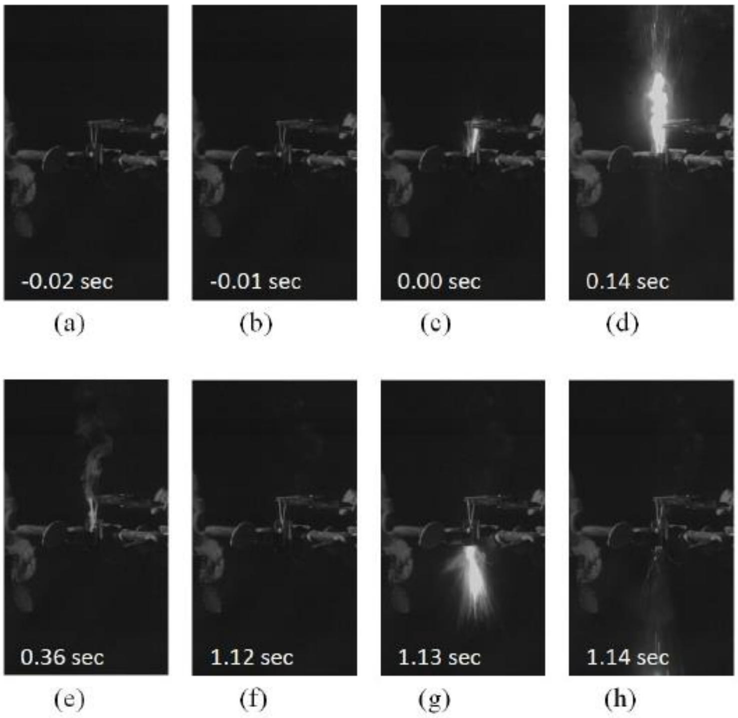


Fig. 3. Sequence of photos taken while measuring the time of burning of a PDE obtained with the use of a high-speed camera

In some publications, instead of the time of burning, the authors determine the rate of burning of a PDCh placed in the PDE shell having the specified dimensions. In the paper [Ricco et al. 2004] to measure the rate of burning two thermocouples were used, placed at the beginning and at the end of the PDCh. In [Focke et al. 2012] a high-speed infrared camera was used while testing the process of burning of the PDCh (fast- and slow-burning) pressed into the steel shell of the PDE. One of the objectives of the test was to analyse the rate of burning of the PDCh. The infrared camera used for the purpose of this study recorded the temperature profiles of the surface of the PDCh in real time. Then, on the basis of a mathematical model the temperature profiles inside the PDE were determined and average and instantaneous rates of burning were calculated. For the fast-burning PDCh the obtained results were unsatisfactory, whereas in the case of the slow-burning PDCh the results made it possible to determine its rate of burning. Figure 4 contains pictures taken with an infrared camera during the burning of a PDCh.

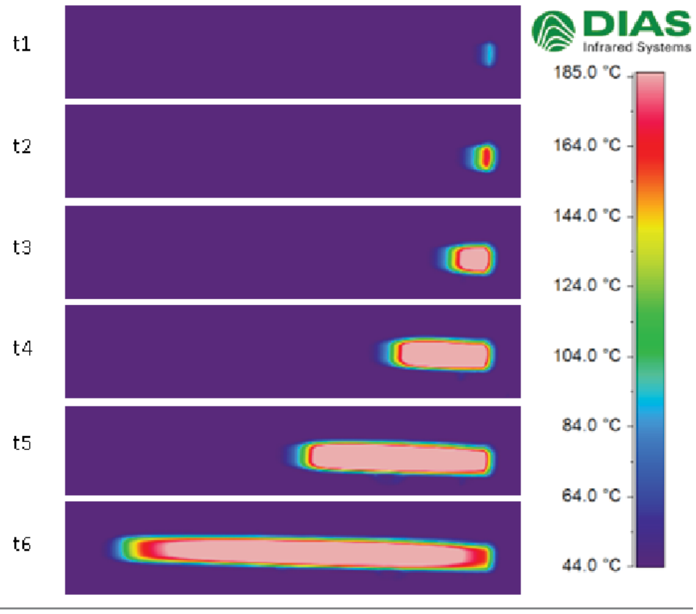
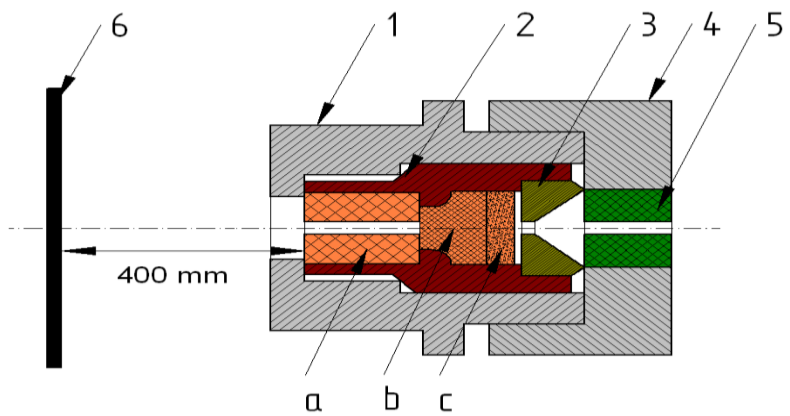


Fig. 4. Photos taken with an infrared camera during the burning of a PDCh



1, 4 – steel frames; 2 – PDE filled with the PDCh; 3 – wad; 5 – black powder relay;
a – booster charge; b – delay charge; c – igniting charge

Fig. 5. Schematic diagram of the test of a PDE for flame propagation:
Source: [own work].

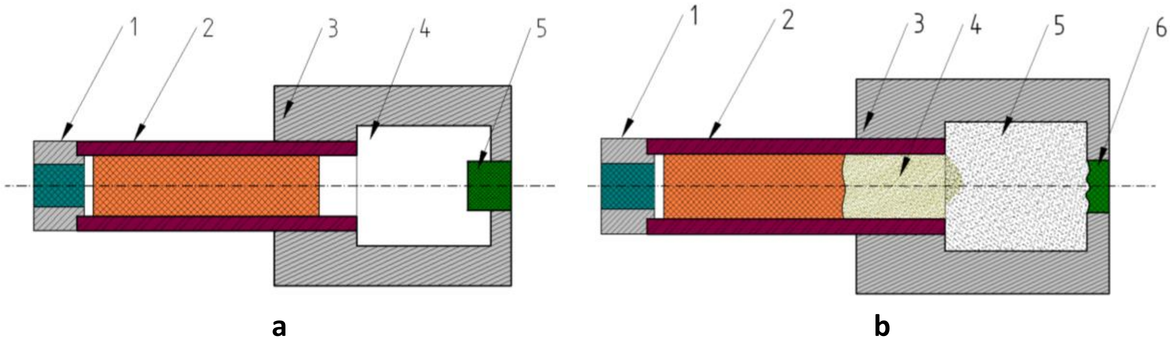
In the documentation [*Dokumentacja konstrukcyjna*… n.d.] the parameter which determines the ability of the PDE to ignite the next element in the explosive train is verified, i.e. the PDE is tested for flame propagation. Figure 5 presents the schematic diagram of the test. The PDE (2) is filled with three types of charges made of one type of PDC. The pyrotechnic delay charge is composed of: booster charge (a), delay charge (b) and igniting charge (c). The PDE is inserted into the streel frames (1, 4). The wad (3) protects the igniting charge from the solid products formed when the primer is activated. In the test the ignition of the PDCh is effected through a black powder relay (5) initiated with a heated up wire. The test is successfully completed if the PDE ignites black powder placed on the plate having the dimensions of 90×90 mm or fi 90 mm at a distance of 400 mm from the booster charge.

1.2. Tests in the closed system

According to the referenced industry standard the testing of PDEs in the closed system is carried out while burning a PDCh in the confined space (without gases being released freely to the atmosphere), i.e. in the special testing assembly or in the appropriately modified ammunition. The term "confined space" should be understood as a specified volume of free space from the side of initiating the PDE, where the combustion products from the PDCh and the igniting element, e.g. primer, will gather, thus generating the external pressure at the head of the burning front of the PDCh. Figure 6 presents the schematic diagram of the test of a PDE in the closed system.

A laboratory test in the closed system reflects most closely the actual operating conditions of a PDE, as the test rig corresponding to the real operating conditions of the PDE is used for this test. Usually, the PDE is tested together with the other elements of the explosive train, which makes it possible to check three performance parameters of the PDE.

The performance of the PDE tests in the closed system is more complicated in comparison with the open system, because of, among others, the necessity to prepare additional systems that will trigger the element igniting the PDE, for example as a result of the action of the force of inertia or centrifugal force. In addition, sensors recording the start and the end of the time of burning have to be properly scaled, so that they are not activated by the operation of elements from the additional systems and they have to be located at the appropriate places to avoid their damage caused by the action of respective elements of the explosive train.



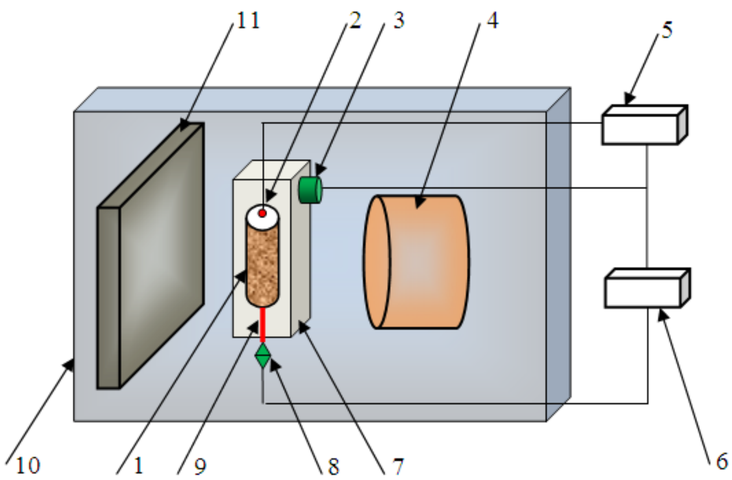
a – before activation; b – after activation;
1 – element ignited by the PDE; 2 – PDE filled with the PDCh; 3 – shell of the combustion chamber;
4 – combustion chamber; 5 – gaseous products formed as a result of the operation of the initiator and the burning of the PDCh; 6 – element igniting the PDE

Fig. 6. Schematic diagram of the test of a PDE in the closed system
Source: [own work].

The study [Swanepoel et al. 2010] describes the testing of a PDE used in mining fuses. A shock tube was employed as a source of ignition, initiated by a primer. The measurement was started by an acoustic signal, produced by the primer activation with the use of an acoustic sensor, whereas the end of measurement (muzzle flash) was recorded by means of a thermocouple. Both recording sensors (sound, temperature) were connected to the oscilloscope.

The publication [Tichapondwa 2015] presents the test of the time of burning of a PDE placed together with a boosting primer. The PDE was initiated by means of the "Nonel" system. The start of the time of burning corresponded to a light pulse generated by a shockwave in the "Nonel" tube and recorded by the photodiode. The end of burning was determined by a pressure transducer, started at the moment when the boosting primer was activated. The photodiode and the pressure transducer were connected to the electronic measurement system, whereas the initiating device – "Nonel" – had its own firing system.

In the patent [Miszczak et al. 2014] the method of testing the time of burning of a PDE is proposed, making use of the Roentgen radiation and an additional measuring system consisting of an acoustic sensor and an optical sensor. Figure 7 presents the schematic diagram of the testing rig that can be used in both the open and closed system. The PDE (1) is placed in the air-tight combustion chamber (7), inside the booth of the X-ray apparatus (10), between the X-ray lamp (4) and the digital image processor (11). The PDE is initiated by an electric primer (2), which is initiated by the firing system (5). The activation of the primer is the start of measurement of the time of burning of the PDE, recorded by the acoustic sensor (3) placed on the outside surface of the side wall of the combustion chamber. The end of measurement is recorded by the optical waveguide (9) with a photovoltaic cell (8). The acoustic sensor, optical waveguide with a photovoltaic cell and the firing system are connected to the oscilloscope (6) and located outside the combustion chamber.



1 – PDE; 2 – electric primer; 3 – acoustic sensor; 4 – X-ray lamp; 5 – firing system; 6 – oscilloscope; 7 – combustion chamber; 8 – photovoltaic cell; 9 – optical waveguide; 10 – X-ray booth; 11 – digital image processor

Fig. 7. Schematic diagram of the rig for testing the time of burning of a PDE with the use of an X-ray apparatus

Source: [own work].

The essence of the patent is the method to determine the time of burning of a PDE on the basis of the sequence of X-ray images, on which it is possible to observe the stages of shifting of the zone with changes in density in the PDCh, corresponding to the burning zone. In addition, the time of burning is also measured in parallel by the second measurement system consisting of an acoustic sensor and a photodiode. At present, the method of testing PDEs with the use of the X-ray system is further developed in order to optimise the testing system.

The article [Miszczak et al. 2016] presents the method of testing of a PDE used in fuses of RGM-2 type with the use of the Roentgen diagnostic system MU-17F-225-9, relying on the RTR (Real-Time X-ray Radioscopy) technique. The test was performed in the closed system, reproducing the real operating conditions of PDEs. The initiation of the PDE was effected by means of an electric primer. The whole process of burning of the PDE was recorded at the rate of 30 frames per second. Then, on the basis of the obtained X-ray images (Fig. 8) the authors determined the time of burning of the PDE.

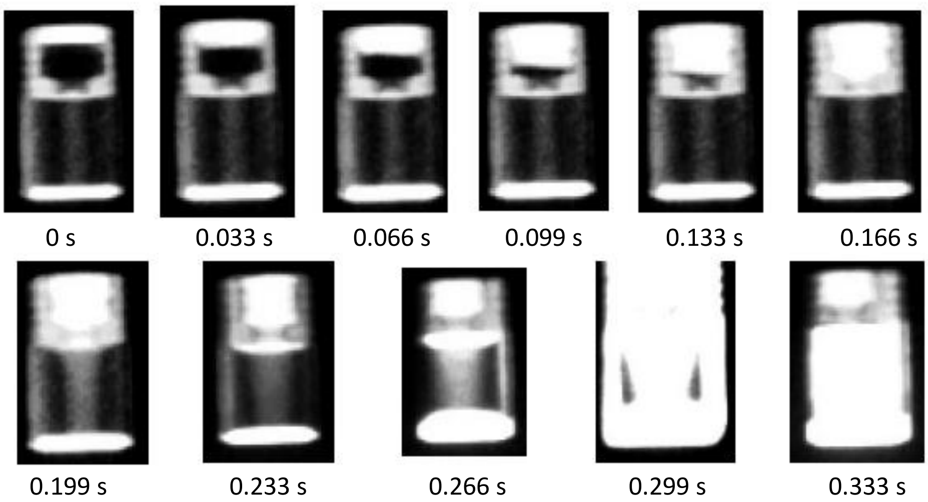
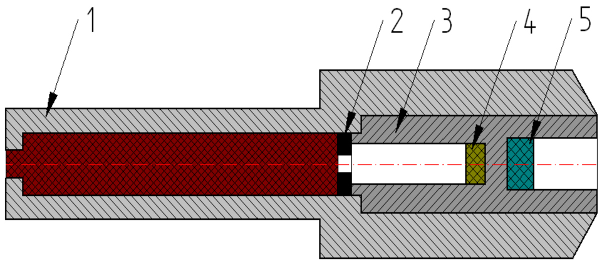


Fig. 8. Sequence of X-ray images showing the process of burning of the tested PDE and indicating instantaneous values of the time of burning
Source: [own work].

In the article [*Badania pirotechnicznego*… n.d.] the authors presented the test of the time of burning of a PDE (1), being a component part of the pyrotechnic ignition delay (with the time of burning of 300±15 ms), used in anti-tank guided projectiles. In the casing of the PDE there is a sleeve containing a flame boosting primer (5), which boosts, through the steel barrier (without destroying it), the igniting element (4), which ignites the PDE. The time of burning was tested employing three methods:

– using a high-speed camera – time-lapse analysis of the film,
– acoustic sensor connected to the oscilloscope – sound recording during the ignition and during the ejection of combustion products,
– photodiode connected to the oscilloscope – blaze recording, from the ignition and from the muzzle flash.

The initiation of the primer (5) was effected by means of a laser radiation pulse. The laser was connected to the oscilloscope to determine the duration of the pulse. Discrepancies regarding the times of burning of the PDE, obtained using the three methods, were from 5 to 10 ms.



1 – PDE filled with the PDCh; 2 – spacing sleeve; 3 – sleeve; 4 – igniting element; 5 – flame boosting primer

Fig. 9. Pyrotechnic ignition delayer
Source: [own work].

Conclusions

The article presents the information collected from the available literature, both Polish and foreign, concerning the laboratory methods of testing pyrotechnic delay elements. In the introductory part of the paper the role performed by PDEs in ammunition is explained and elements classified as PDEs are listed, i.e. delayers, self-destruct fuses, and locks, and their design is described briefly. The next part presents the performance parameters of PDEs which are subject to verification tests, ensuring the safe and reliable operation of PDEs in ammunition. These parameters include the time of burning, sensitivity to flame from the igniting element and the ability of a PDE to ignite the next element in the explosive train. Thereupon, it has been emphasised that during the tests of PDEs various factors, divided into the external and internal ones, can influence the obtained results. The main part of the article provides the characteristics of the industry standard, describing the methods of testing the times of burning of PDEs under laboratory conditions. Although the standard was issued in 1984, the methodology of testing PDEs is still valid to a considerable extent and the provisions of this standard are still referenced in various ammunition design documentations. In 2002, the Polish Committee for Standardization (Polski Komitet Normalizacyjny – PKN) [*Jaki jest status*… n.d.] ceased to issue any industry standards, however, such standards can still be used voluntarily in technical specifications, provided that they do not contain any invalid technical data. In connection with the development of the measurement instruments some data comprised in the standard, such as ranges of measured times of burning and measurement errors, are no longer valid at present. New methods have been implemented to determine the start and the end of burning, e.g. with the use of high-speed cameras, pressure sensors or thermocouples, and also new ways of igniting PDEs – lasers or detonation systems of the "Nonel" type. In the main part of the article two basic systems used for laboratory testing of PDEs have been described – the open and closed system. In the open system usually a PDE only is tested, whereas in the closed system the PDE is tested together with the elements of the explosive train. The testing of a PDE in the closed system makes it possible to verify all its performance parameters, however, such tests require more preparations with respect to apparatus or protection of the rig from explosion products of respective elements of the explosive train. It should be pointed out that the majority of PDEs obtain different times of burning depending on the test system selected. It happens that the difference between the obtained times of burning for the same PDE tested in two systems is two- or threefold. Therefore, the methodology of testing should be developed separately for each type of PDE. Including by manufacturers in the design documentation the data regarding the time of burning of PDEs, in both the open and confined space, would be the best solution.

The paper presents also two methods of testing PDEs, one making use of an infrared camera and the other relying on the Roentgen radiation. For both methods it is necessary to employ expensive apparatus, specialist equipment and qualified personnel. However, these methods make it possible to extend the possibilities of testing PDEs and to learn more about the processes that occur during the combustion of a PDCh. In the thermal imaging method it is possible to obtain temperature profiles for the burning PDCh, on the basis of which the rate of burning can be established. However, according to one of the studies presented in the article, this method does not work in the case of testing fast-burning compositions. In the tests of PDEs making use of the X-ray technique, apart from non-destructive tests, i.e. the verification of the correct assembling of a PDE, it is also possible to perform destructive tests. The test consists in measuring the time of burning and observing, at the same time, the shift of the zone with changes in density in the PDCh, corresponding to the combustion zone. At present, both methods are further developed to obtain the best possible results, e.g. by combining a high-speed camera with an X-ray system.

Conflict of interests

The author declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Radoslaw Warchol – The author declared that he has no ORCID ID's

Marcin Nita – The author declared that he has no ORCID ID's

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How to cite this paper

Warchol, R. and Nita, M. (2018). Laboratory methods for testing the performance of pyrotechnic delay elements. *Scientific Journal of the Military University of Land Forces*, vol. 50, no. 4(190), pp. 101-115, http://dx.doi.org/10.5604/01.3001.0013.0725