Central European Journal of Energetic Materials, **2015**, *12*(3), 553-561
ISSN 1733-7178
e-ISSN 2353-1843

X-ray Investigations of Combustion Phenomena Occurring in Confined Pyrotechnic Charges

Maciej MISZCZAK *, Marcin NITA, Radosław WARCHOŁ

Military Institute of Armament Technology,
7 Wyszyńskiego St., 05-220 Zielonka, Poland
E-mail: mpf.miszczak@op.pl

Abstract: Investigation of the combustion processes occurring in end-burning, multi-segment, delay elements of hand-grenade firing-explosive trains using Real-Time X-ray Radioscopy (RTR) are presented. RTR detection, operating at 30 frames per second, registered the development of the combustion process, visualized as the border between the burnt and unburnt parts of the pyrotechnic column, travelling from the ignition (input) end to the output end. This border had a variable shape, ranging from planar to very non-regular. At the end of the combustion process, *i.e.* during burning of the final-output pyrotechnic segment, the formation of a longitudinal cavity beginning from the output end of the delay element and reaching a depth of nearly 40% of the total length of the pyrotechnic column, was detected. Such strong erosion of the output part of the pyrotechnic column indicates that in the creation of the output combustion products (firing output impulse) of the tested delay element, a relatively significant mass of the pyrotechnic charge was involved.

Keywords: pyrotechnic charges, delay element, combustion, Real-Time X-ray Radioscopy (RTR)

1 Introduction

Experimental methods for detecting and registering the combustion process of confined pyrotechnic charges by means of X-rays are not common. Only a few literature references were found on the detection, by X-rays, of the burning of pyrotechnic charges inserted into metal bodies of relatively high X-ray transmittance [1-3].

According to [1], pyrotechnic charges composed of 80% iron and 20% potassium chlorate(VII) ($KClO_4$) were inserted into stainless steel tubes closed at both ends, and ignited at one end by an electric igniter. Using a dynamic Radioscopy system equipped with an electro-optical system of image recording, the combustion zone was detected, as a moving layer of different density to that of the unburnt part of the pyrotechnic charge. The combustion zone had a variable curved profile. The quality of the images of the combustion profiles was very poor.

In [2], X-ray flash photographs of the combustion zone taken during the burning of a pyrotechnic composition comprised of potassium chlorate(V) ($KClO_3$) and methylaminoanthraquinone (MAA), inserted into a metal, cylindrical body of length 94 mm and diameter 58.5 mm, were presented. From the X-ray photographs, it was concluded that during the burning process of these pyrotechnic charges, the combustion zone had a planar shape with a growing conical hollow directed towards the ignition end.

In [3], the application of impulse Radioscopy was presented for the detection of combustion zone movement in a thermite composition of iron(III) oxide (Fe_2O_3) and aluminum mixed in a weight ratio of 75/25, inserted into steel tubes of length of 20 mm and diameter 15 mm. The wall thickness of the tubes was 3 mm. The thermite charges were ignited from one end. The detection of the combustion zone movement was possible because of high differences in density between the burnt and unburnt parts of the tested pyrotechnic charge.

Taking into account the above observations gathered from the literature references [1-3], showing the abilities and limitations in X-ray detection and the recording of the combustion processes of confined pyrotechnic charges, trials were undertaken to use Real Time X-ray Radioscopy (RTR) in the hope of obtaining more details on the combustion processes occurring in the confined, delay end-burning, segment pyrotechnic charges.

2 Experimental Part

2.1 Test samples and measurement arrangement

The tested samples were delay elements (Figures 1 and 2) used in UZRGM fuze firing trains of hand-grenades − F1 defensive and RG-42 offensive ones [4].

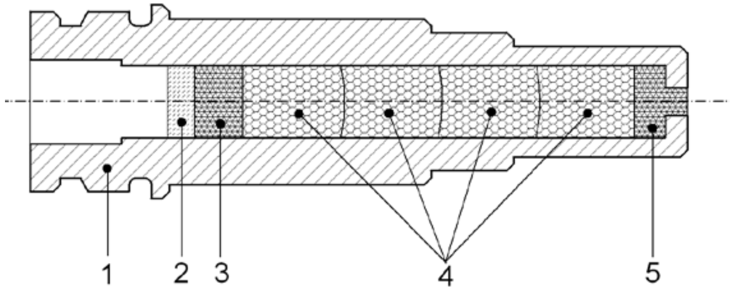


Figure 1. Axial, longitudinal cross section of design of tested multi-segment delay element before its firing.
1: Aluminum body of delay element; 2: Ignition – input segment composed of SC-1 pyrotechnic mass; 3: Combustion stabilizing segment composed of W-11 pyrotechnic mass; 4: Four delay segments composed of MGS-54 pyrotechnic mass; 5: Output segment composed of W-11 pyrotechnic mass.

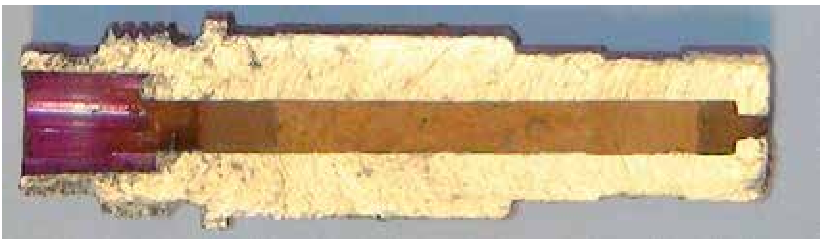


Figure 2. Longitudinal, half cross section of tested multi-segment delay element before its firing.

Each tested delay element was consisted of seven pyrotechnic segments (layers) pressed into the channel of an aluminum body, open at both ends. The total length of the pyrotechnic multi-segment column was 27.5 mm. The outlet of the output channel of the delay element body was narrower than the remaining main part of the delay element channel accommodating the pyrotechnic segments. The external pyrotechnic segments, *i.e.* the first two ignition-input segments and the final-output segment, contained lead compounds in specific amounts. The first input segment was composed of SC-1 pyrotechnic mixture, consisting of 74.5% lead(II, IV) oxide (Pb_3O_4), 23.5% zirconium powder and 2% nitrocellulose. The second ignition-input and combustion stabilizing segment, was composed of W-11 pyrotechnic mixture, consisting of 24.2% barium chromate(VI)

($BaCrO_4$), 52.3% lead(II, IV) oxide (Pb_3O_4), 16.3% zirconium powder, 2.9% potassium chlorate(VII) ($KClO_4$), 2.3% sulfur and 2% nitrocellulose. The four internal, main delay element segments were composed of MGS-54 pyrotechnic mixture, consisting of 78.2% barium chromate(VI) ($BaCrO_4$), 9.9% potassium chlorate(VII) ($KClO_4$), 9.9% antimony pentasulfide (Sb_2S_5) and 2% nitrocellulose. The last, output segment, dedicated to the initiation of the next element of the firing chain in the UZRGM fuze of the hand-grenade, was composed of W-11 pyrotechnic mixture.

Each tested delay element was inserted into the detection chamber of Real-Time X-ray Radioscopy (RTR) MU-17F-225-9 diagnostic system (YXLON International X-ray Corporation), and then the structure of the delay element was examined by X-ray (Figure 3).

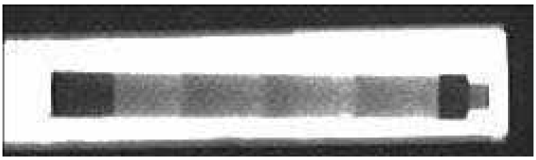


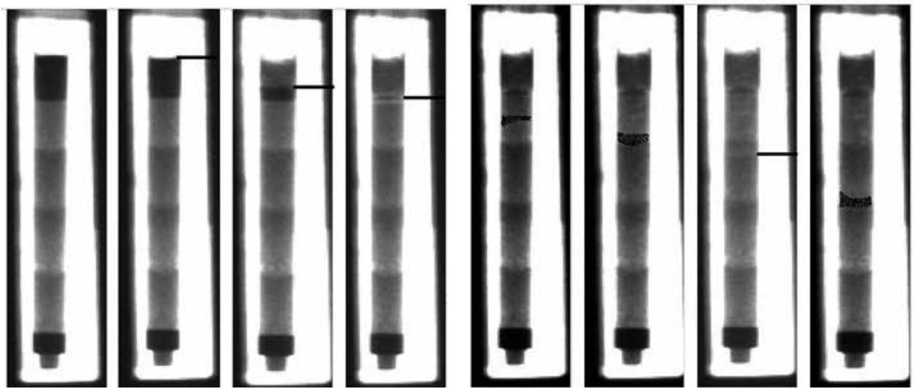
Figure 3. Real Time Rentgenoscopy image of tested multi-segment delay element before its firing.

Figure 3 shows that the delay element had no distinct structural defects such as voids and cracks. The MGS-54 segments did not have a homogeneous density. Each MGS-54 segment had a higher density in the part situated closest to the ignition end of the delay element. The external segments, comprising the lead compounds, were distinctly "darker" than the MGS-45 segments.

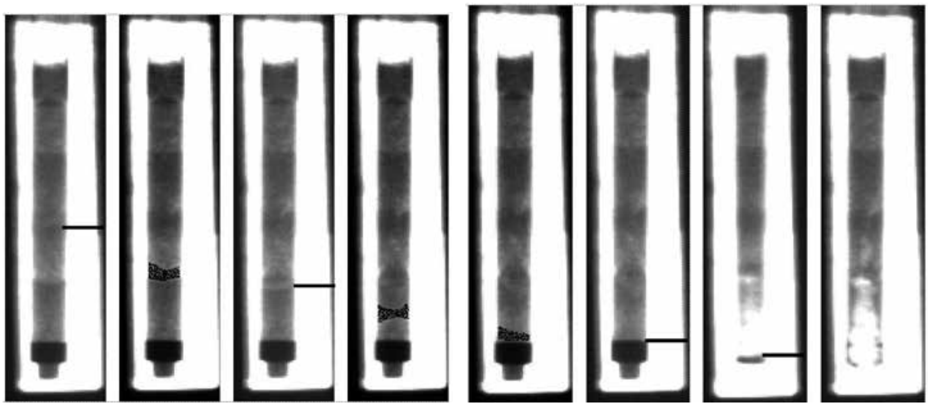
After X-ray examination, the tested delay element was ignited in the RTR chamber by an electric match head mounted 5 mm from the surface of the SC-1 segment. The combustion of each pyrotechnic segment was detected and recorded by the RTR diagnostic system, at 30 frames per second and resolution 1528×1052 pixels.

2.2 Test Results and Discussion

From the RTR film (a typical sequence of RTR frames of the combustion process of the delay element charges, is shown in Figures 4(a-p)), it was possible to distinguish the combustion zone as a brighter, more or less narrow layer propagating along the MGS-54 pyrotechnic segments (Figures 4(d-m)), or as a boundary between areas of different density moving along the SC-1 and W-11 pyrotechnic segments (Figures 4(b, c, n, o)).



a. 0 s **b.** 0.16 s **c.** 0.46 s **d.** 0.72 s **e.** 1.12 s **f.** 1.25 s **g.** 1.61 s **h.** 2.04 s



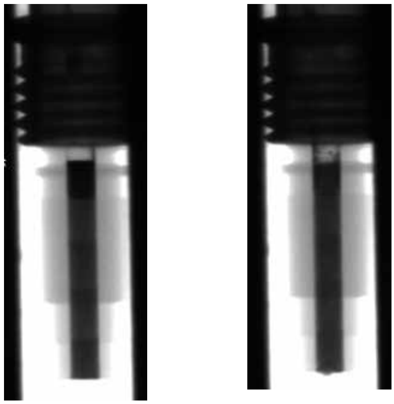
i. 2.40 s **j.** 2.77 s **k.** 3.23 s **l.** 3.69 s **m.** 3.79 s **n.** 3.85 s **o.** 3.89 s **p.** 3.92 s

Figure 4 (a-p). Sequence of RTR images registering combustion process of tested multi-segment delay element of UZRGM fuze of hand-grenade. Time points of each frame, are shown in the bottom part of each frame, and they are given in seconds.

Because the combustion zone was visible by RTR during its movement through all of the pyrotechnic segments, this means that the highly undesirable, very dangerous phenomenon called "premature effect" of delay element performance was absent. The premature effect occurs when the final output segment of the fired delay element, is activated (fired and/or exploded) before the arrival of the combustion zone at this segment. The premature effect causes undesirable, unacceptable shortening of the assumed (designed) delay period for a given delay element. The mechanism of the evolution of the premature effect and some examples of the occurrence of this effect in delay pyrotechnic compositions based on barium chromate(VI) ($BaCrO_4$) and boron, are described in [5].

The RTR visualization of the combustion zone was poorest for the MGS-54 segments, in their lower density parts. To obtain a more distinguishable positioning and shape of the combustion zone, in Figures 4(e, f, h, j, l, m), the areas occupied by the combustion zone were marked with dark dots. In the rest of the frames given in the above sequence, *i.e.* in Figures 4(b, c, d, g, i, k, n, o), apart from the frames corresponding to Figures 4(a) and 4(p), the position of the combustion zone was marked by a horizontal line. The recorded combustion zone had various shapes. The combustion zone was usually more planar when travelling through the first two segments (Figures 4(b, c)), through the initial part of each MGS-54 segment (Figures 4(d, g, i, k)), *i.e.* travelling through each MGS-54 part of higher density, and through the final output W-11 segment (Figures 4(n, o)). In the less dense parts of the MGS-54 segments, the combustion zone became broader and more irregular in shape (see Figures 4(e, f, h, j, l, m)), *i.e.* similar to those described in [6].

When the combustion zone reached the output pyrotechnic segment (W-11), it appeared a bright flash, starting from the output end of the delay element and propagating through the whole length of the final, *i.e.* fourth, MGS-54 segment and through about half the length of the third MGS-54 pyrotechnic segment (Figures 4(o, p)). This bright flash began, together with the opening of the outlet of the output channel of the delay element, and it had a longitudinal, irregular shape narrowing towards the input-ignition end of the delay element. Figures 4(o, p) indicate that the burning process of the output W-11 pyrotechnic segment was occurring in two stages. The first stage (Figure 4(o)) comprised the burning up of the main part of the W-11 segment, and resulted in the opening of the outlet of the output channel of the delay element. At the end of the first stage, the residual part of the W-11 segment, distinguishable as a darker narrow layer situated at the output end of the channel, just before the outlet of the delay element, remained unburnt (Figure 4(o)). In the second stage, this residual part of the W-11 segment was burnt up (compare Figure 4(p) with Figure 4(o)). It seems that during combustion of the output W-11 pyrotechnic segment, the built-up pressure and flow of its combustion products destroy, erode and penetrate the above mentioned, two final MGS-54 pyrotechnic segments. Due to the opening of the outlet of the output channel of the delay element, the combustion products of the output W-11 segment and the burnt mass (combustion products) from the destroyed parts of the two MGS-54 segments situated closest to the output end of the delay element, flow through the outlet of the output channel. In order to confirm this scenario, a shorter delay element was prepared, *i.e.* without the final-output W-11 segment and without a narrower output outlet (which was cut off). Subsequently, this delay element was fired in the RTR chamber. The RTR images of this shortened delay element, before and after firing are shown in Figures 5(a) and 5(b), respectively.



a ***b***

Figure 5. RTR images of tested multi-segment delay element without last W-11 output segment and without output outlet: (a) before firing and (b) after firing. Firing of tested delay element, starts over its top part.

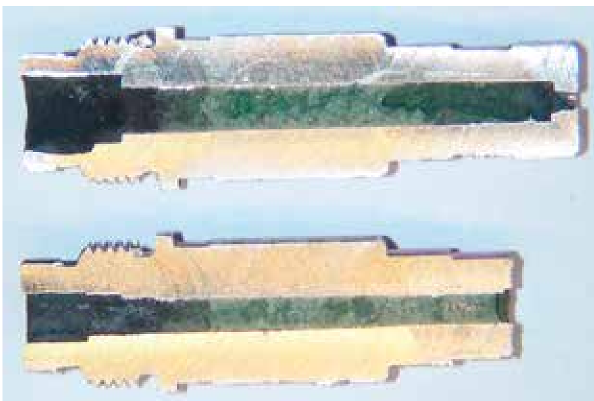


Figure 6. Longitudinal half cross section of fired multi-segment delay element with last W-11 output segment (upper section) and longitudinal half cross section of fired shortened delay element without last W-11 output segment (lower section).

From a comparison of Figures 5(a) and 5(b), it could be concluded that the combustion process of the pyrotechnic charge inserted (pressed) in the channel of the shortened delay element, did not create any cavity in the MGS-54 pyrotechnic segments. Finally, this observation was confirmed by comparison of the longitudinal half-tube cross section of the fired delay element with the W-11 output segment (Figure 6 – upper image), with the half-tube cross section of the fired delay element without the W-11 output segment (Figure 6 – lower image).

The cross section of the fired delay element with a W-11 output segment (Figure 6 – upper image) showed the presence of the above mentioned large cavity in two final MGS-54 segments. The cross section of the fired delay element without a W-11 output pyrotechnic segment (Figure 6 – lower image) did not show the presence of such a cavity.

The total burning time of the tested delay element was determined from the sequence of frames of the RTR images detecting the first movement of the combustion zone and from the first frame detecting the opening of the outlet hole of the delay element. For each tested delay element, this total time was between 3.70 and 4.00 seconds. The total combustion times of the delay elements obtained by RTR were in good accordance with the requirements given [4] for the delay elements of F-1 and RG-42 hand-grenade UZRGM fuzes.

3 Conclusions

On the basis of the experimental measurements and observations presented, it was possible to come to the following conclusions:

Using the RTR technique, it is possible to continuously (more precisely − quasi-continuously) detect and record combustion phenomena occurring in confined, end-burning multi-segment pyrotechnic charges. The basic characteristics and phenomena of the burning process of the tested delay elements, detected and recorded by RTR, were: the combustion zone movement, the combustion zone shape and the presence of a long cavity within the area of the output W-11 segment and final two MGS-54 segments. This cavity was caused by the pressure build-up and flow of combustion products of the W-11 output pyrotechnic segment towards the ignition end of the tested delay element. The presence of this cavity also indicates that in the creation of the output combustion products (firing output impulse) of the tested UZRGM delay element, all of the mass of the output of the W-11 pyrotechnic segment and the evacuated burnt up mass from the two MGS-54 pyrotechnic segments situated closest to the output end of the delay element were involved.

In addition, using the RTR technique, it was possible to observe the presence or absence of the "premature effect" during the burning process of the pyrotechnic charges of the tested delay elements. Confirmation of the presence or absence of such an effect, is of critical importance from the viewpoint of safety and reliable functioning of the fuzing systems (firing-explosive chains) of any combat system.

The sequence of RTR image frames obtained allowed the total combustion time of the tested delay elements to be determined. These total combustion times were in accordance with the requirements given [4] for hand-grenade fuze delay elements.

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