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Research paper

X-ray Investigation of Dynamic Phenomena Occurring during Combustion of the Pyrotechnic Charges of 40 mm Grenade Fuze Delay Systems

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Abstract: Experimental Real Time X-ray Radioscopy (RTR) investigation of dynamic phenomena occurring during the combustion of end-burning pyrotechnic charges confined in the fuze body, utilized in the delay systems of 40 mm grenade fuzes, are presented. These pyrotechnic delay systems delay the arming distance pyromechanism and the self-destroying timing assembly. The charge in the delay arming distance pyromechanism was a black powder pellet supported by the safety pin kept in constant position by its driving compressed spring. The self-destroying timing assembly comprised three pyrotechnic segmented columns connected at their ends with ignition relay channels, creating a zig-zag firing train. The following dynamic phenomena were detected and registered by RTR at a frequency of 30 FPS:

(i) combustion zone travelling along the pyrotechnic charges,
(ii) displacements of the pyromechanism safety pin caused by either the pressure of its spring after burning out of the black powder pellet or by pressure of the combustion products escaping from the zig-zag firing train,
(iii) transfer of the ignition impulse between the adjacent pyrotechnic columns,
(iv) pressure action of the combustion products on the pyrotechnic columns during transfer of the ignition impulse, and
(v) transfer of the final output ignition impulse from the last (third) pyrotechnic column through the channel leading directly to the chamber used for accommodating the fuze detonator.

Keywords: military ammunition, pyrotechnic end-burning charges, combustion, Real-Time X-ray Radioscopy

Nomenclature:

RTR	Real Time X-ray Radioscopy
SM-300	Name of pyrotechnic composition
W-11	Name of pyrotechnic composition
W-11/SM-300	Mixture of pyrotechnic compositions W-11 and SM-300
SC-1	Name of pyrotechnic composition

Units:

FPS	Frames *Per* Second

1 Introduction

This paper is a continuation of Real Time X-ray Radioscopy (RTR) investigations, conducted under static firing conditions, on burning phenomena occurring in pyrotechnic items applied in military munitions in service with the Polish Army.

Earlier works dealt with the investigation of combustion phenomena occurring in the pyrotechnic delay elements of hand grenade fuzes [1], pyrotechnic delay elements of impact detonating artillery fuzes and tracers of antitank guided missiles [2]. All of the tested pyrotechnic items contained end-burning pyrotechnic charges.

The present work presents experimental RTR investigation of dynamic phenomena occurring during combustion of end-burning charges of two pyrotechnic delay systems applied in 40 mm grenade fuzes. These systems are the delay arming distance pyromechanism and the self-destroying timing assembly. They are components of critical importance in the firing train of the grenade fuze because they ensure its correct operational modes during grenade firing, especially grenade fuze arming at the appropriate grenade distance from the launcher and grenade self-destruction after a missed target.

During grenade movement in the launcher tube, the grenade fuze peripheral ignition pin, parallel to the axis of the fuze and situated in front of the peripheral ignition primer, moves under the influence of axial inertial forces towards this primer and stabs it. Flames from the primer, are simultaneously transferred and distributed to the input port of the delay arming distance pyromechanism and to the self-destroying timing assembly, igniting their end-burning pyrotechnic charges. The charge of the pyromechanism and the system of pyrotechnic charges of the self-destroying timing assembly should burn for 168-266 ms and 24 ±5 s, respectively.

After burning out of the pyrotechnic charge of the pyromechanism, its peripheral safety pin, coaxial to the central firing pin of the grenade fuze and supporting this charge from its bottom through the driving spring, is released and goes forward under pressure from this spring. Such a position change of the safety pin opens free space for radial movement of one of two safety cylinders locking axial movement of the central firing pin towards the central ignition primer. The second safety cylinder is kept in constant position by its radial spring.

A delay time, dependent on the burning period of the pyrotechnic charge of the pyromechanism, is clearly required to guarantee the minimum safe distance between shooter and grenade when it leaves the launch tube.

During grenade flight, spinning centrifugal forces cause radial displacement of both safety cylinders towards the perimeter of the fuze body. From this point the central firing pin is unlocked, *i.e.* it has open space to move towards the central ignition primer. When the grenade hits the target (before 24 ±5 s have elapsed), the central firing pin moves towards the central ignition primer and stabs it. Flames from the central ignition primer pass along the central axial channel connecting the central ignition primer with the detonator and initiate explosion of the detonator, which causes explosion of the main high-explosive charge of the grenade.

In the case of the target being missed, after 24 ±5 s have elapsed, the output ignition impulse from the self-destroying timing assembly passes along a narrow transverse channel situated in the rear part of the fuze body, directly initiating explosion of the detonator, which causes explosion of the main high-explosive charge of the grenade.

2 Experimental

2.1 Test samples and measuring arrangement

The selected munitions for the tests under static firing conditions, were 40 mm high explosive grenade rounds (with prefragmented liner) (Figures 1 and 2). Looking at Figure 2 it is possible to distinguish some parts of the grenade round items, such as the fuze safety cylinder kept in constant position by its radial spring, the detonator inserted into the high explosive charge, the grenade round case with its high pressure chamber accommodating the igniter, and the empty, low pressure chamber.

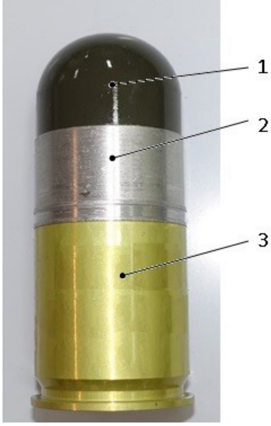


Figure 1. Image of the 40 mm high explosive-prefragmented grenade round selected for the tests: 1 – ballistic cap, 2 – grenade body, 3 – case

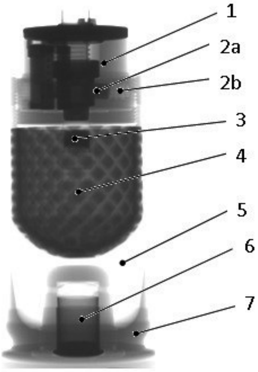


Figure 2. Real Time X-ray Radioscopic image of the 40 mm high explosive-prefragmented grenade round selected for the tests: 1 – fuze, 2a – radial safety cylinder supported by its radial spring (2b), 3 – detonator, 4 – main high explosive charge with rhombic pattern of prefragmented liner, 5 – decompression chamber, 6 – high pressure chamber with igniter, 7 – case
Note: The ballistic cap of the grenade was not detected by the RTR technique due to its low density.

Each grenade round was disassembled into its propelling and payload (grenade) parts. Before a static firing test, the fuze was removed from each grenade. From the fuze body, the ignition primers were removed, *i.e.* the central and peripheral ones, and the detonator. The ignition impulse paths and the deployment of the pyrotechnic charges of the delay arming distance pyromechanism and the self-destructing timing assembly, are schematically illustrated in Figure 3.

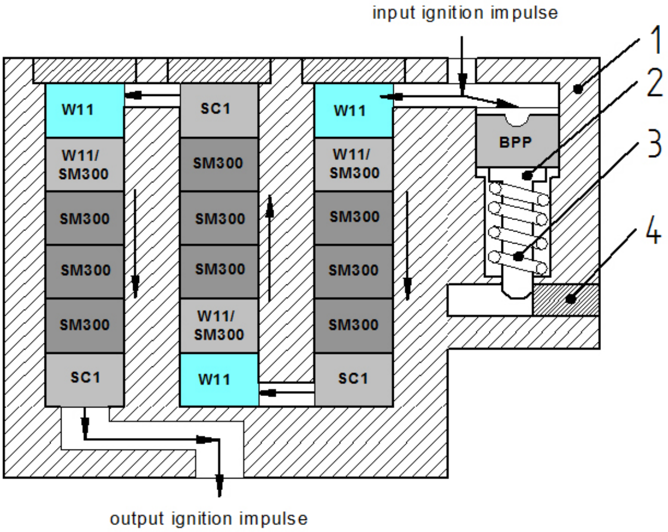


Figure 3. Illustrative simplified scheme of the pyrotechnic delay systems of a 40 mm grenade fuze: 1 – fuze body, 2 – peripheral safety pin, 3 – spring, 4 – radial safety cylinder
Note: Arrows mark the direction and distribution of the firing impulses and movement of the burning zone along the pyrotechnic columns and channels connecting the columns.

The short delay (168-266 ms burn) pyrotechnic charge of the pyromechanism, was a black powder pellet of diameter 3.6 mm and length 3.6 mm. The pellet was situated in the fuze body, on its perimeter, and axially oriented in relation to the axis of the fuze. The pellet had a small central hemispherical cavity on its forward facing surface for easier ignition due to the increase in initial combustion surface.

The long delay (24 ±5 s burn) pyrotechnic system of the self-destroying timing assembly was situated adjacent to the black powder pellet, and comprised three pyrotechnic segmented columns deployed in the fuze body, along its perimeter. The pyrotechnic columns were oriented parallel in relation to the axis of the fuze, and connected at their ends by ignition relay (transfer) channels. The ignition train comprising the pyrotechnic columns formed a zig-zag path.

Each pyrotechnic column was 20 mm long, had a diameter of 4.5 mm, and consisted of six pressed increments (segments). For each column, the ignition sequence of the segments was as follows. The first ignited segment *ca.* 2.0 mm long, *i.e.* the input one, was obtained from W-11 pyrotechnic mixture, composed 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 second segment *ca.* 2.3 mm long, was composed of a mixture of W-11 and SM-300 pyrotechnic compositions (W-11/SM-300). The SM-300 mixture was composed of 42% $BaCrO_4$, 40% bismuth chromate(VII) ($BiCrO_4$), 8% $KClO_4$, 8% sulfur and 2% nitrocellulose. The next three segments, each 4.6 mm long and forming the main delay part of the pyrotechnic column, were composed of SM-300 mixture. The final segment *ca.* 1.9 mm long, *i.e.* the output one, was obtained from SC-1 pyrotechnic mixture, composed of 74.5% lead(II, IV) oxide (Pb_3O_4), 23.5% zirconium powder and 2% nitrocellulose. So, the burning sequence of the six segments for each pyrotechnic column was as follows: W-11, W-11/SM-300, SM-300, SM-300, SM-300, SC-1. The W-11 composition was the most sensitive to ignition, the W-11/SM-300 segment combined the sensitiveness to ignition of the W-11 composition with the delaying ability of the SM-300 mixture, the SM-300 segments were typical delay ones, and the SC-1 composition had the highest output ignition power and pressure of the combustion products.

Each investigated 40 mm grenade fuze, was inserted into the detection chamber of a Real-Time X-ray Radioscopy (RTR) MU-17F-225-9 diagnostic system (YXLON International X-ray Corporation), and then examined by X-rays (Figure 4).

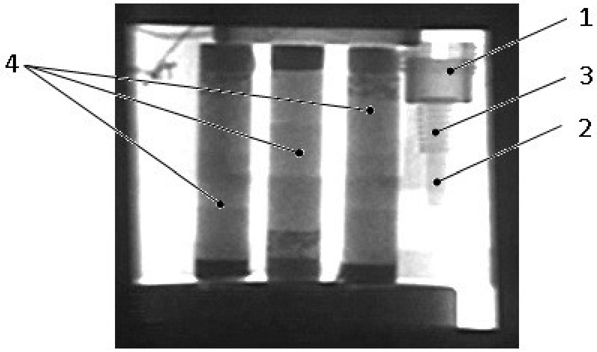


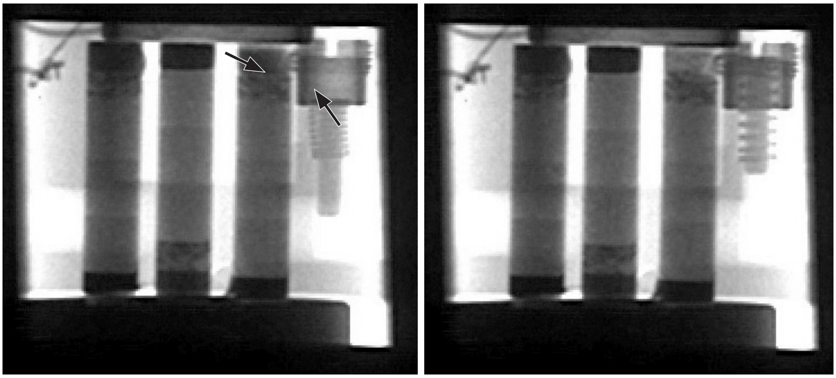
Figure 4. RTR image of the investigated parts of the delay arming distance pyromechanism and the pyrotechnic self-destroying timing assembly of the 40 mm grenade fuze before the static firing test: 1 – black powder pellet, 2 – peripheral safety pin with its driving spring (3), 4 – pyrotechnic, segmented columns

Figure 4 shows that the segmented pyrotechnic columns of the self-destroying timing assembly and the black powder pellet of the delay arming distance pyromechanism are properly deployed in the fuze body, and that they had no distinct structural defects, such as voids and cracks. The safety pin and its compressed spring of the pyromechanism are also in their proper positions. Each pressed pyrotechnic segment of the pyrotechnic columns had the appropriate height. The main delay SM-300 segments had a relatively uniform density. The external segments of the pyrotechnic columns, *i.e.* situated at both ends of each column, *i.e.* W-11, W-11/SM-300 and SC-1, are "darker" in comparison with the SM-300 segments and the black powder pellet due to the presence of lead in the W-11, W-11/SM-300, and SC-1 compositions.

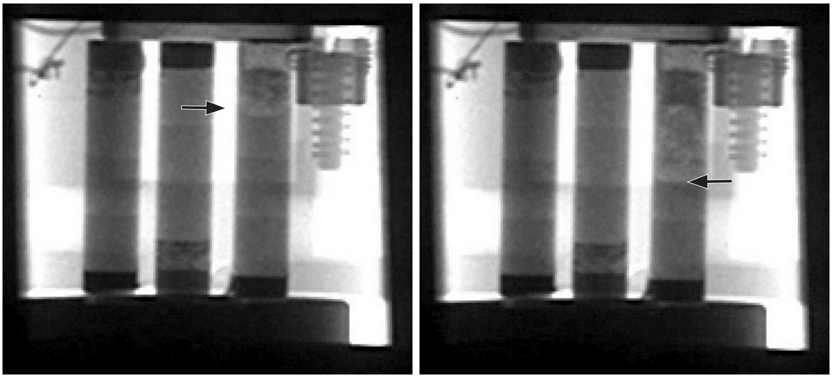
After X-ray examination, each test sample was ignited in the RTR chamber by an electric fusehead situated in the forward (upper) part of the fuze body. Dynamic phenomena accompanying combustion of the pyrotechnic charges of the delay arming distance pyromechanism and the self-destroying timing assembly were detected and recorded by the RTR diagnostic system, at 30 FPS and a resolution of 1528 pixels × 1052 pixels.

3 Test Results and Discussion

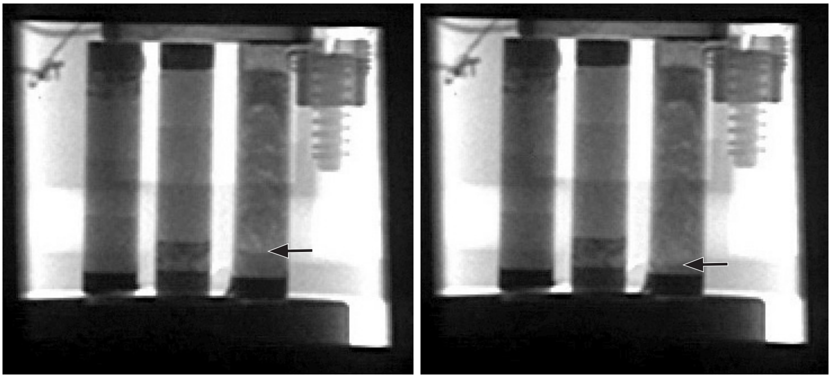
A typical sequence of RTR images (frames) selected from the RTR film, is shown in Figures 5(a)-5(r) (re)presenting the main stages of operation of the delay arming distance pyromechanism and the self-destroying timing assembly after ignition of their pyrotechnic charges. The development of the combustion process could be observed due to the movement of the burning zone as a brighter, relatively narrow transverse layer, usually of a planar or flattened convex shape, travelling along the pyrotechnic charges.



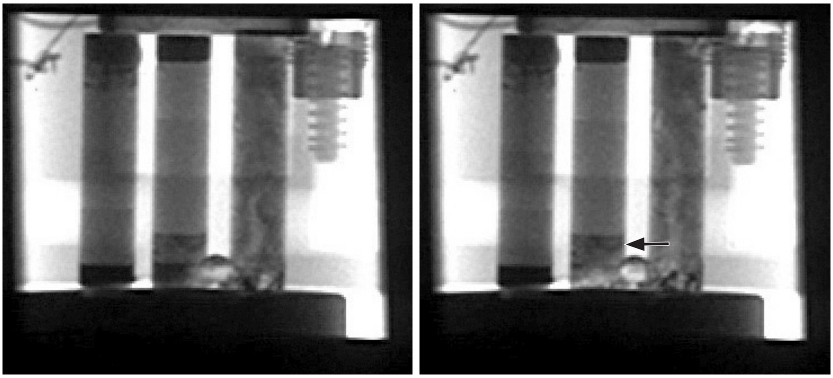
(a) 0.033 s (b) 0.233 s



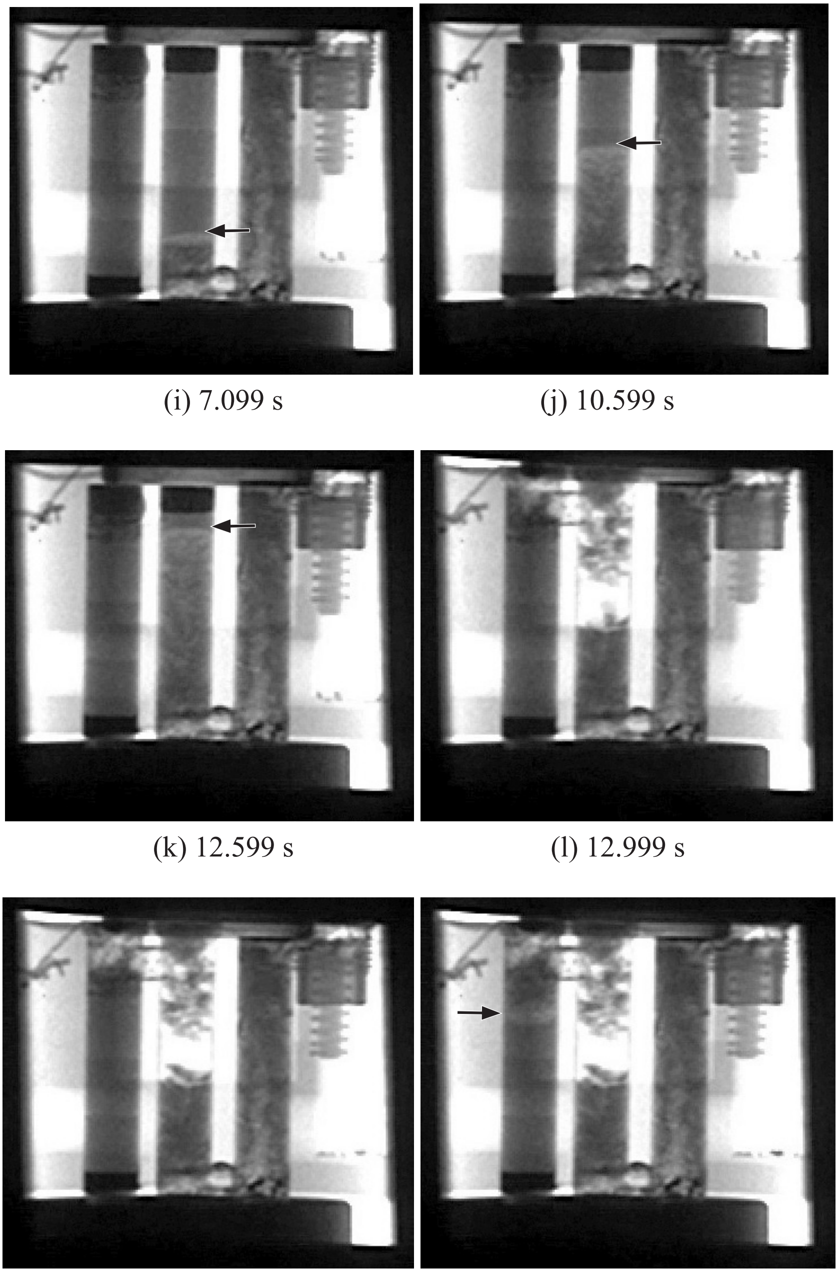
(c) 1.899 s (d) 3.799 s



(e) 5.633 s (f) 6.066 s



(g) 6.199 s (h) 6.266 s



(i) 7.099 s

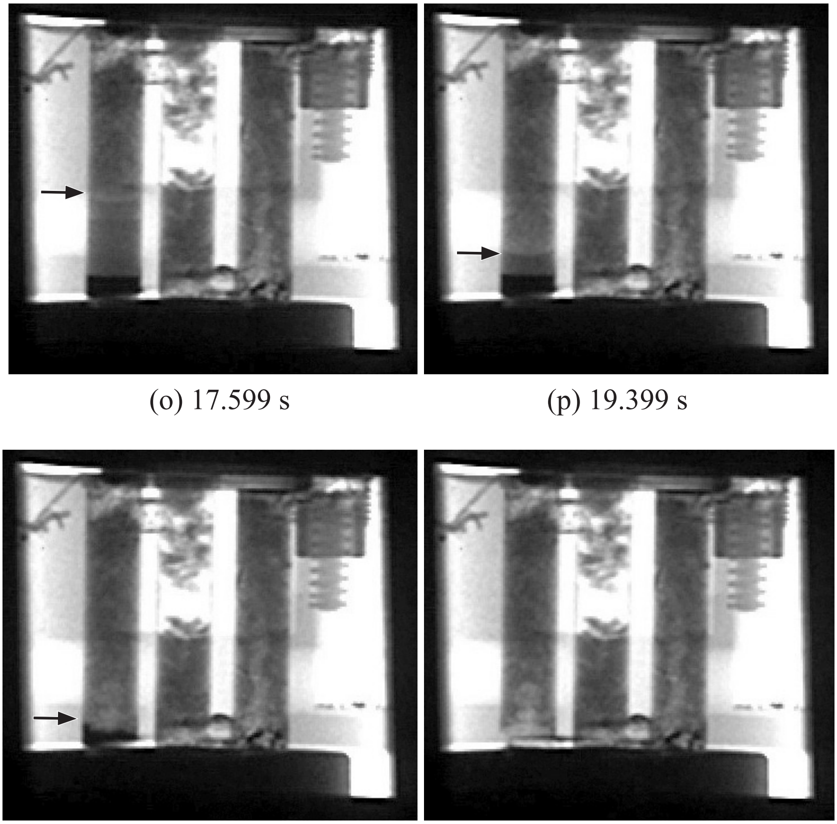
(j) 10.599 s

(k) 12.599 s

(l) 12.999 s

(m) 13.033 s

(n) 15.099 s



(o) 17.599 s (p) 19.399 s

(q) 19.866 s (r) 20.633 s

Figure 5. Sequence of RTR images (re)presenting the main stages of operation of the delay arming distance pyromechanism and the self-destroying timing assembly of the 40 mm grenade fuze
Notes:
(i) Arrows show positions of combustion zones.
(ii) Time points of each frame are shown below each image.

The operation of the delay arming distance pyromechanism and the pyrotechnic self-destroying timing assembly started from the ignition of the head surface of the black powder pellet of the pyromechanism and side ignition of the W-11 segment of the first column of the pyrotechnic self-destroying timing assembly. The initial combustion surface of the black powder pellet increased and evolved as a convex one, reaching the size of the diameter of the pellet (Figure 5(a)). Unfortunately, due to the relatively low density of the pellet and the lack of lead in its composition, evolution of its burning surface was difficult to detect, but it was possible. The operation of the delay arming distance pyromechanism ended with the safety pin displacement from its lower to its upper position (compare the positions of the safety pin in Figures 5(a) and 5(b)) after the burning out of the pellet. On the basis of the time of registration of Figure 5(b), *i.e.* the first frame registering a position change of the pyromechanism safety pin, the time of operation of the pyromechanism, namely the pellet burning time, was estimated as *ca.* 233 ms. This means that the burning time of the black powder pellet fell between the admissible time limits required for its burning.

On the basis of the time of ignition of the first column (Figure 5(a)), the times of ignition transmission between the first and the second columns (Figures 5(g) and 5(h)), the times of ignition transmission between the second and third columns (Figures 5(l) and 5(m)) and the time of the output ignition impulse from the last column to the channel leading to the detonator (Figure 5(r)), it was estimated that the first, second and third columns were burning for *ca.* 6.2 s, 6.8 s, and 7.6 s, respectively. This means that the total burning time of the series of the three delay columns was *ca.* 20.6 s, and thus fell into the range 19-29 s, determined as the admissible threshold required for burning of such pyrotechnic systems. The next important tested parameters, describing more precisely the dynamics of the combustion process, were the burning rates of each type of pyrotechnic segment or group of such segments. Due to the violent combustion of the SC-1, W-11 and W-11/SM-300 pyrotechnic segments in the stages of transmission of the ignition impulse between the adjacent columns, there were no estimated mean burning rates of these segments. The movement of the burning zone was much better detected and registered when it travelled along the SM-300 segments (Figures 5(c), 5(d), 5(e), 5(f), 5(i), 5(j), 5(k), 5(n), 5(o) and 5(p)).

Taking into consideration the number of frames corresponding to the registration of a stable burning process in all (nine) SM-300 segments responsible for the main delay time of the zig-zag ignition train (*ca.* 18.8 s), it was estimated that the mean burning rate of the SM-300 composition was *ca.* 2.2 mm/s. At this point it is worth mentioning that according to the Russian patent RU 2 185 355 [3], such a burning rate is too high because a higher burning rate of the pyrotechnic delay system forces more space to be designed into this system in the ammunition fuze body. Moreover, a delay system with a higher burning rate in its pyrotechnic charges has a more complicated construction in comparison with a delay pyrotechnic system comprising slower burning charges. According to this patent [3], the burning rate of pyrotechnic charges in the confined spaces of such delay items should be less than 1.0 mm/s.

The most spectacular sequence of frames, because of the relatively violent phenomena occurring, presents the transfer of the ignition impulse between adjacent pyrotechnic columns, *i.e.* between donor and acceptor pyrotechnic columns (Figures 5(g), 5(h), 5(l) and 5(m)). These transfers were visualized by violent displacement of solid combustion products and through their collection on the walls of the channels connecting the pyrotechnic columns. Before ignition transfer, these relay channels were not visible (Figures 5(a)-5(f)). During transfer of the ignition impulse between the first and second columns (Figures 5(g) and 5(h)) and between the second and third columns (Figures 5(l) and 5(m)), *i.e.* ignition impulse transfer from the SC-1 segment of a donor pyrotechnic column to the W-11 segment of the acceptor pyrotechnic column, the W-11 and SC-1 segments are clearly destroyed, mainly by gaseous combustion products evolved from the SC-1 segment. The pressure of the combustion products of the SC-1 mixture also caused the formation of cavities in the segments occupied by W-11 in the acceptor column, and by SC-1 and two adjacent SM-300 segments of the donor column. The greatest destruction was observed in the second pyrotechnic column, in its upper part (Figures 5(l) and 5(m)), *i.e.* in the place earlier occupied by the SC-1 segment and two SM-300 segments. Generally, during the transference of the ignition impulse between adjacent columns, much greater destruction (cavities) were observed in the column that was burnt out than in the column that was initiated to burn. This was probably caused by the lower mechanical strength of the burnt out pyrotechnic donor column to the impact (blow) of the combustion products in comparison with the mechanical strength of acceptor column initiated to burn.

In addition, during ignition transfer between the adjacent columns, ventilation of the zig-zag ignition path by combustion products was observed. This ventilation was manifested as axial displacement of the safety pin of the pyromechanism from its lower to its upper position, caused by the flow and pressure of the combustion products escaping from the lower part of the zig-zag pyrotechnic path (compare the position of the rear (lower) end of the safety pin in Figures 5(k) and 5(l)).

The final stage of operation of the self-destroying timing assembly is visualized (Figures 5(q) and 5(r)) by transfer of the ignition impulse (output one) from the final segment, *i.e.* from the SC-1 one of the third pyrotechnic column through the transverse channel leading to the detonator chamber. This transfer is visualized by collection of the solid combustion products along the horizontal part of this channel (bottom part of Figure 5(r)). This output ignition effect was accompanied by the creation of a cavity in the third pyrotechnic column, starting from the column output and reaching the last SM-300 segment (Figure 5(r)).

4 Summary and Conclusions

Using the RTR technique, it is possible to quasi-continuously detect and record the combustion zone movements during the burning of the pyrotechnic charges of the delay arming distance pyromechanism and the self-destroying timing assembly of a 40 mm grenade fuze. Changes in the positions of the combustion zones along the pyrotechnic charges were distinguished as brighter narrow border zones between the burnt and unburnt parts of these charges.

RTR detection and recording of displacement of the pyromechanism safety pin from the pressure of its driving spring, after burning out of the black powder pellet, allowed the operation time of this pyromechanism to be estimated, and thus the burning time of this pellet, which was *ca.* 233 ms.

RTR detection and recording of the combustion zone movements along all of the segmented pyrotechnic columns of the self-destroying timing assembly, allowed the delay time of self-destruction of the 40 mm grenade to be estimated as *ca.* 20.6 s.

This means that the pyrotechnic charges of the self-destroying timing assembly of a 40 mm grenade fuze, were successively burnt, and during their combustion there were no premature effects that could result in a shortening of the required time for self-destruction of the grenade.

RTR detection and recording of the combustion zone's stable movement along all pyrotechnic SM-300 segments of the self-destroying timing assembly, allowed their mean burning rate to be estimated as *ca.* 2.2 mm/s. At this point, it is worth once again mentioning the guidelines given in the Russian patent RU 2185355 [3] suggesting usage of very slow burning delay pyrotechnic compositions, *i.e.* burning rates of much less than *ca.* 2 mm/s. From the above guidelines, pyrotechnic mixtures with burning rates of less than 1 mm/s are preferred. The use of such very slow burning compositions should simplify the design of pyrotechnic self-destroying assemblies, and reduce their sizes. Reduction of the sizes of the delay systems of the 40 mm grenade fuze, should increase the space in the grenade for the accommodation of a useful payload, *e.g.* high-explosive charge.

The most spectacular RTR recorded dynamic phenomena accompanying burning of the pyrotechnic columns of the self-destroying timing assembly, were the successive transfers of ignition impulses between adjacent columns. These transfers were visualized by the formation of relatively large cavities in these columns, violent displacement of solid combustion products along the columns and collection of solid combustion products on the walls of the channels connecting the columns. Such violent phenomena were mainly caused by the gaseous products evolved from burning SC-1 segments. In order to best avoid the marked destruction of the W-11 pyrotechnic segments of each acceptor column by the ignition impulse from the SC-1 pyrotechnic segments of each donor column, it would seem reasonable to hide the acceptor column beyond the opening of the relay (transfer) channel and/or diminish the mass of the donor SC-1 segments. Due to such changes in the design of the firing train in the self-destroying timing assembly, the acceptor segments will be ignited from their head surfaces instead of from their side surfaces, resulting in much less violent and a much more stable end-burning process in the acceptor columns.

During transfer of the ignition impulse between the pyrotechnic columns, a subtle but distinguishable axial movement of the safety pin caused by the pressure of the combustion products escaping from the ignition train of the self-destroying timing assembly was also observed. Such escaping combustion products seem to cause serious problems because of a possible action of hot combustion products on the surrounding parts of the fuze, especially on the central ignition primer and/or detonator.

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