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Gun Pyrocartridge Unauthorized Ignitions

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Abstract:

During practical tests of a recently developed double-barrel fighter gun, some unauthorized ignitions of electrically activated pyrocartridges have occurred. After avoiding a malfunction of the gun electrical equipment, an influence of mechanical processes has been analyzed showing a possibility to cause the unwelcome phenomenon.

Keywords:

Pyrocartridge, pyrocontact, cap, ignition energy, temperature boost

1. Introduction

The recently developed 20 mm double-barrel aircraft cannon PLAMEN shots alternately out of its left or right combined barrels. The propellant gases from the firing barrel causes the barrels pair moving back and forward. Briefly said, after a shot in one (e.g. left) barrel had arrived, one half of the gun cycle operation has been accomplished involving reloading of the other (right) barrel, too. The operating cycle is then completed by the shot fired off the right barrel causing next recoil of barrels thus reloading the left barrel again. The cartridges are initiated electrically after an electronic control system has detected the barrels recoil had accomplished. The electronic system also controls a rate of fire in two values, either lower (780 min^{-1}) or higher (approx. 2500 min^{-1}), according to the pilot's choice.

In case that shooting failed, e.g. due to a cartridge jam or to having loaded a faulty cartridge etc., the move and reloading action of barrels is restored by means of firing a pyrocartridge (one of three disposable ones). The pyrocartridge (PYC) is fired electrically, too, by the cannon electronic control equipment.

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1.1. The problem: UPI

During shooting within flight-tests, unauthorized pyrocartridges ignitions (UPI) have been occurring repeatedly and irregularly, at both low and high rate of fire. Consequently, a set of measurements has been accomplished as well as an electronic equipment analysis resulting in information on base of which both a malfunction of electronic initiating subsystem and any unexpected electric phenomena igniting a pyrocartridge could be excluded [1].

Therefore, the focus turned to other possible reasons of UPI occurrence i.e. to the influence of mechanical actions and joined quantities.

1.2. PYC housing lay-out

Pyrocartridges are inserted in a pyrocassette which can accommodate up to three PYCs located so that their axes of symmetry are parallel to barrels axes (and to their recoil direction) and oriented so that bottoms of PYCs show towards barrels' muzzles. The same direction have axes of symmetry of three electric contacts (one for each PYC) located in a pyrocontact house, which is attached to the pyrocasette. These parts are fixed to the barrel-pair assembly and exposed to its move when recoiling.

1.3. Available introductory information

Before analyzing UPI possible reasons, the following information has been delivered coming from previous tests:

1. The UPI occurs only when shooting, mostly after firing for some time.
2. It hasn't succeeded to find any relationship between a phase of running operating cycle and the moment of UPI occurrence.
3. No relationship has been observed between UPI occurrence and either a precedent regular pyrocartridge ignition or the rate of fire.
4. Different UPI occurrence frequencies were observed for different PYC positions inside the pyrocasette but no conclusions have been established.
5. In the course of firing, the PYCs temperature rises. The temperature has not been measured. Only a sensoric evaluation is available saying that it was possible to touch the pyrocassette and PYCs by hand after having finished tests without getting burnt finger skin. On the other hand, no information has been supplied concerning the delay between end of a firing test and touching PYCs.
6. The electrical cap contact surface of a new pyrocartridge has a form of a circular plane located in the centre of the pyrocartridge body bottom from which the cap contact is electrically insulated. Inside the cap, there is an internal electric circuit (a resistive wire) connected between the contact and the body having a resistance of (1.5 to 2.5) Ω. A regular cap initiation is reached when the wire is flown through by an enough high electric current resulting also in raising the wire resistance to values of several orders higher in magnitude (the wire practically gets overburnt).
7. The cap utilizes a prime composition based on the lead trinitroresorcinate the auto-ignition temperature of which is reported to be about 275 °C [2].
8. The shortest time has been measured needed to initiate the PYC appropriately to the delivered current I. For every chosen level of current, a sample of 10 randomly selected PYCs has been tested. The originally supplied information is stated within upper three rows of following Tab. 1. It has been additionally fulfilled by last two rows so as to show a span of amount of energy W initiating

the PYC. Each of these rows applies for one of the new cap wire resistance limits mentioned above. Evidently, the minimal energy sufficient to ignite the cap is less than 1 mJ.

Tab. 1 Relation of PYC cap ignition current, time, frequency and energy

I [A]	0.3	0.3	0.5	0.5	1	1	3	3	5	5
t_{min} [ms]	11	12	2.5	2.6	0.5	0.55	0.07	0.08	0.03	0.04
# of initiated PYCs of sample of 10 PYCs	0	1	0	1	0	3	0	10	0	4
W [mJ] at $R = 1.5\ \Omega$	1.5	1.6	0.94	0.98	0.75	0.83	0.95	1.1	1.1	1.5
W [mJ] at $R = 2.5\ \Omega$	2.5	2.7	1.6	1.6	1.3	1.4	1.6	1.8	1.9	2.5

9. As follows from a record of the barrels' recoil movement, its waveform is roughly a harmonic one with amplitude (the recoil distance) 15 mm and a time to first return back to starting position (a half-period of the harmonic wave) makes 22 ms. In the beginning of the move, the velocity of barrel's assembly movement keeps approximately constant during several milliseconds. The starting acceleration strongly exceeds 250 g which value was the upper limit of disposable measuring equipment range. The mass of the recoiling part of the gun is 67.3 kg.
10. The electrical contact has a constructional form (see [3], p. 53) of a cylindrical rod 2.2 mm in diameter the cylindrical surface of which is covered by an insulating layer. The contact body is ended by a truncated cone with hemispherical touch face and is glidingly located inside a bush in the pyrocontact house. A spiral pressing spring inserted between the pyrocontact house wall and the contact takes up the play between the contact and the PYC's cap. The spring acts as well as a stop such giving the contact its lift. The length of free spring is L = 16.4 mm, the spring installed with a new PYC has the length L_{C} = 10.4 mm and causes a bias force F_{C} = 48.5 N. The spring abuts by F_{A} = 59.5 N and is then L_{A} = 9.1 mm long thus giving a nominal lift bias to spring's end stop (abut) l_{N} = 1.3 mm. Weights of contact rod insulating bush and pressing spring are 1.7 g, 0.29 g and 0.31 g, respectively.
11. At a cap contact surface of used PYCs, whether fired or not, a pit deformation has been observed there the depth of which is up to about 0.3 mm.

2. Mechanical actions and PYC initiation

The existence of the cap surface deformation gives an evidence of that a mechanical action resulting in contact bounces as outlined in Fig. 1 and impacts have taken place. Although the cap is primarily insensitive to mechanical impacts, it will be shown that repeated impacts of the electric contact body due to recoil actions can successively accumulate such amount of energy to the cap that is capable to warm up the cap to its auto-ignition temperature and thus cause UPI after some time of firing.

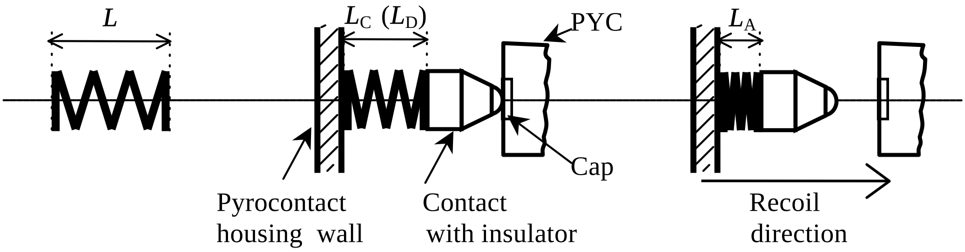

Fig. 1 Free (relaxed) contact spring (left), PYC and contact assembly in nominal position (middle), contact bounced to spring abut position (right).

2.1. Disposable contact spring energy

Considering zero losses, an uttermost mechanical energy W_M that can be delivered by impact of the contact on the PYC cap surface provided that the back motion of the contact assembly started from the spring abut position equals

$$W_M = W_A - W_C = 0{,}5[F_A(L - L_A) - F_C(L - L_C)] \qquad (1)$$

where L is the length of free spring,
L_C is the length of spring with the contact sitting on the cap,
L_A is the minimal length of spring (when pressed to its abut),
F_C is the bias force of the spring pressed to the length L_C,
F_A is the force of the spring pressed to its abut with the length L_A,
W_A is the energy accumulated in the spring when pressed to its abut,
W_C is the energy accumulated in the spring when pressed to the length L_C.

From Eq. (1), the maximal impact energy W_M = 72.5 mJ results using data given in ***1.3***-10 (item 10 in subchapter 1.3) when a new PYC with an undeformed cap has been installed. In case of a cap having already deformed contact area as reported in ***1.3***-11, the working lift of contact enhances to about l_W = 1.6 mm, L_C rises to L_D = 10.7 mm and the bias force for appropriate length of the spring decreases to F_D = (46.1 to 46.5) N. Hence, the disposable mechanical impact energy can be similarly evaluated up to W_D = 88 mJ. This is the uttermost amount of a single mechanical impact energy that approximately 80 times exceeds the least (but electric) energy needed to ignite the cap.

2.2. Effective mass of the contact assembly

The contact assembly consists of the contact, insulating cover and aliquot parts of both leading-in wire and the spring, too. The effective mass m of movable contact assembly is

$$m = m_C + m_I + 0{,}5m_S + m_W \qquad (2)$$

where m_C is a mass of the contact,
m_I is a mass of the insulator,
m_S is an effective mass of the spring and
m_W is a mass of the aliquot part of leading-in wire.

The latter has been reported to be about 0.8 g in average whilst all other mass values are known. The effective moving mass then makes about 2.94 g. This is very low value compared to the mass of the entire recoiling part of the gun (i.e. 67.3 kg) so that any motion of the contact assembly does not essentially influence the behaviour and course of recoiling procedure. Hence, dynamics of the contact assembly with respect to the recoiling set can be evaluated separately.

2.3. Contact assembly movement due to recoil

While the barrel-pair assembly starts its recoil move following a shot, a PYC contact assembly tends due to inertia to stay in its previous (say, nominal) position. This results in pressing the spring provided that the inertial force F_{I} overcomes the bias force F_{C}. This demands the acceleration to notably exceed a value

$$a = \frac{F_{\mathrm{I}}}{m} > \frac{F_{\mathrm{C}}}{m} = \frac{48.5}{2.94\times10^{-3}} = 16.50\times10^{3}\,\mathrm{ms}^{-2} \cong 1682\ g \qquad (3)$$

Deformation pits in cap surfaces give evidence, that it does it significantly.

After some time had passed, the first phase of contact replacement involving the pressing action has finished and the contact velocity of its motion relative to the pyrocontact house has just reached zero value. From this moment on, the second phase of contact replacement begins: the spring forces the contact to move back towards the PYC. The back motion of the contact ends by the latter impacting the cap.

To describe the contact movement in the first phase, let us introduce a coordinate system related to the pyrocontact house so that the *x*-axis lies in the centre line of both the contact and the spring, its zero point is a cross-point with the plane lying in moveable end of the spring and it aims towards spring’s fixed end (or the pyrocontact house wall).

Movement of the contact assembly within the first phase describes an equation

$$m\ddot{x} + k_{\mathrm{D}}\dot{x} + k_{\mathrm{S}}x = d(t)\,[F_{\mathrm{I}} - F_{\mathrm{C}}] \qquad (4)$$

where x is the lift of the contact assembly bounced from its nominal position,
k_{D} is a coefficient expressing damping of the move,
k_{S} is the spring constant and
$d(t)[F_{\mathrm{I}} - F_{\mathrm{C}}]$ denotes the impulse of acting force when using a new PYC.

From data in ***1.3***-10, for spring constant follows $k_{\mathrm{S}} = 8.46\times10^{3}$ N m^{-1} and for a period of undamped oscillations T = 5.9 ms. As the system does not involve any damping element, only some parasitic damping exists there due to a friction of the insulator sliding inside the pyrocontact house bush and to absorptions of the spring and of a part of the leading-in wire. Efficiencies of springs are generally about 90 % (corresponds to a relative damping less then 0.033) and the arrangement has an unartful structure with minimal friction losses so that a small relative damping about ζ = 0.3 can be assumed. Due to the damping, the period of oscillation rises to about 6.2 ms and still remains nearly by one order shorter than the period of oscillations of the cannon’s recoiling part.

The first phase movement lasts utmost only to a moment in which the contact assembly reaches zero velocity either before pressing the spring up to abut or when it occurs and the duration does not exceed 3.1 ms. In order to get the abut, the recoil acceleration has to reach not more than 2064 g i.e. less than 23 % more than is necessary for the bounce just to occur.

For the second phase, let us therefore assume the spring abut is present. We pose the origin of time scale to this moment now, the origin of *x*-axis to the position of the spring-contact junction and an orientation towards the cap. Provided that the velocity of recoiling cannon's part movement from its start on remains constant till the impact, following equation with the same left-side parameters as in (4) applies for the second phase displacement approximately

$$m\ddot{x}+k_{\mathrm{D}}\dot{x}+k_{\mathrm{S}}x=1(t)\;F_{\mathrm{A}} \tag{5}$$

where x means displacement of the contact assembly from the abut point. The system tends to get to a position with length of free spring, i.e. with $x_0 = L - L_A$ = 7.3 mm but after some time t_I needed to shift over way $x_I = L - L_C$ = 1.3 mm an impact takes place. From well-known general solution of Eq. (5) and for above mentioned x_0, T and ζ follows

$$x=7.3\times10^{-3}\left[1-1.048\exp(-498t)\sin(1583t+1.266)\right] \tag{6}$$

which yields for $x = x_I$ and $t = t_I$ a transcendent function of t_I

$$1=1.275\exp(-498t_{\mathrm{I}})\sin(1583t_{\mathrm{I}}+1.266) \tag{7}$$

numerical solution of which gives t_I = 0.39 ms.

Derivative of (6)

$$v=\frac{\mathrm{d}x}{\mathrm{d}t}=7{,}65\times10^{-3}\exp(-498t)[498\sin(1583t+1.266)-1583\cos(1583t+1.266)] \tag{8}$$

shows the velocity of the contact assembly which is, at the first impact moment t_I, equal to v_I = 6.07 m s^{-1}. Hence, the impacting contact assembly delivers W_K = 54.1 mJ of kinetic energy which is partly absorbed by deforming the cap and partly transforms to heat. However, all the distance, time, velocity and energy rise with advancing bombardment of the cap and the distribution of deformation/heating energy changes in favour of the heat because of enlarging of the interfacial area; after having reached some degree of deformation, all kinetic energy transforms into heat. Considering the way enhanced by the deformation depth according to ***1.3***-11 up to 1.6 mm results in a time to impact and velocity 0.44 ms, 6.54 m s^{-1} , respectively and a kinetic energy

$$W_{\mathrm{KD}}=62.9\ \mathrm{mJ} \tag{9}$$

Note the good agreement between this value and the utmost deliverable energy given in ***2.1***.

A total time span from beginning of the recoil move to the impact is a sum of lasting of the first and of the second phase of contact assembly movement and is shorter then 3.6 ms. Comparison with data stated in ***1.3***-9 shows that the entire bounce of contact takes less than 1/3 of a quarter-period of roughly sinusoidal course of the recoil. Hence, the above adopted assumption has been justified concerning the recoil velocity being approximately constant till the impact moment.

2.4. Possible mechanism of UPI

As it has been shown above, during a firing some amount of energy is delivered to PYC at every single shot. After several shots had passed one can expect that the cap deformation has reached its final state and all energy of following impacts transforms into heat. The system naturally tends to establish a dynamic thermal equilibrium at which the delivered energy (heat) is laden off to neighbouring parts. The cap temperature is rather higher than that of them and within the cap itself a thermal gradient also occurs.

To evaluate a cap parts thermal boost demands to know both energy (i.e. heat $Q = W_{KD}$) flowing through the cap and the thermal paths inclusive their thermal resistances R between the cap contact and PYC body etc.

As can be seen in Fig. 2 and in [3], p. 46, the electric cap interior consists of a metallic central contact with a metallic shim and a circular pillule with prime composition and a metallic flash bowl with firing composition (covered at its outer side by a metal leaf). The circular pillule is made of insulating laminated plastic in form of a circular ring double-sided covered by copper layers. Between both copper layers there is the resistive wire connected and surrounded by the prime composition (based on plumbous ferrocyanide, potassium perchlorate and boron colophonium) which is located in the middle of the ring. The entire assembly is closed in the cap metallic body from which the central contact, the shim and the adjacent side of the circular pillule are electrically insulated by a slot board separator and the plastic body of the circular pillule. The ignition cap body is tight-fitted into the metallic PYC shell.

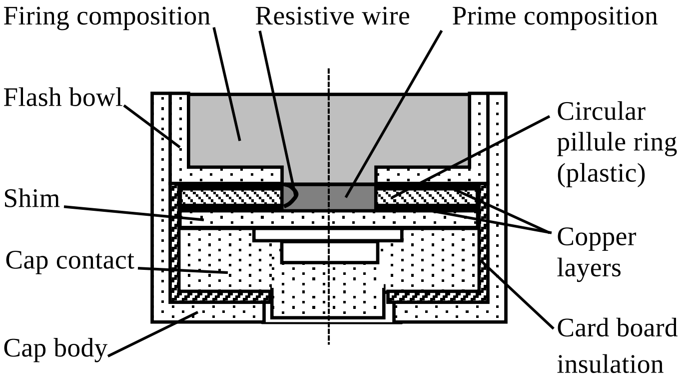

Fig. 2 Schematic section of cap assembly: cap body, flash bowl, cap contact and shim are made of brass.

Hence, different thermal paths inside the cap exist having their thermal resistances. The most significant of paths are those via non-metallic parts, i.e. the slot board insulation and the circular pillule plastic because of their very low thermal conductivities compared to those of other (metallic) cap parts. The thermal resistances of slot board insulation and circular pillule plastic that act in parallel combination have been appreciated as 12.7 K/W and 61.1 K/W respectively taking into account dimensions and thermal conductivities according to [4] and [5].

No relevant information is available on thermal conductivity of both the prime and firing compositions. Nevertheless, none of them contains any free metallic part and their densities are very similar to those of substances which thermal conductivity are about by one order less than that of slot board or circular pillule plastic. Therefore, thermal resistance of resting path between metallic contact and body of the cap via compositions can be considered much greater than that of the paralleled paths and its influence can be neglected. Hence, resulting thermal resistance of the total path is about $R_T = 10.5$ K/W.

Inside the slot board insulation and circular pillule, there is the greatest thermal gradient expectable so that the temperature of the shim, cap contact and the primary composition on its boundary line with the shim rise over that of cap body and flash bowl. For the increase in temperature of the shim and adjoining primary composition after some number of shot has been fired it applies, in average

$$\Delta J = \frac{\mathrm{d}Q}{\mathrm{d}t} R_\mathrm{T} = W_\mathrm{KD} \frac{r_\mathrm{F}}{60} R_\mathrm{T} \quad , \tag{10}$$

where r_F is the rate of fire. Considering nominal fire rates either lower 780 min^{-1} or higher 2600 min^{-1} gives temperature boosts 12 °C or 40 °C, respectively.

3. Conclusions

The temperature boost 12 °C or 40 °C adds to the temperature of the pyrocassette which is attached near to cartridge chambers of barrels. Those parts are the ones most exposed to a heat accompanying the firing. Temperature of these parts inclusive the pyrocassette was not measured during tests.

To prevent from UPI due to the temperature boost caused by contact bounces, several possibilities to avoid bounces themselves were at hand:

1. to modify the orientation of the pyrocassette so as to get axis of PYC’s symmetry perpendicular to barrels’ recoil direction. This would require a re-construction of some parts of the gun;
2. to shorten the free length of the contact spring so as to make all forces acting at the contact assembly smaller. Although bounces of the contact assembly would not be by this excluded the energy delivered by impacts to the cap could be perhaps kept enough small. On the other hand, this way could give a rise to problems with electric connection to caps and hence with regular initiations of PYCs;
3. to use a contact spring with such a high spring constant which would prevent the inertial force to overcome the bias one;
4. to shorten the contact lift for example by underlying the spring by a shim to both rise the bias force and shorten the spring lift. This set-up is the simplest, easiest and the most recommendable.

The last mentioned possibility had been utilized and succeeded. The contact lift has been diminished by making the contact compartment of the pyrocontact house shorter which has made the UPI occurrence frequency decreased more than by an order to a negligible level.

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