https://doi.org/10.38013/2542-0542-2020-4-69-76
UDC 536.46

Ignition of lead styphnate by a filament in an explosive attachment

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It is shown that the ignition temperature of lead styphnate can be described by a transcendental equation including the inertia of the initiating composition and the depth of its heating. The filament temperature at the moment of ignition of the initiating substance was calculated. It was found that, when the heating element current is close to 5 A, the combustion of lead styphnate leads to an explosion (detonation). At the same time, when the filament current equals 2 A, the combustion rate of lead styphnate ranges from 215 m/s to 750 m/s.

Keywords: explosive attachment, ignition temperature, lead styphnate.

For citation: Lipanov A. M., Golovatenko V. D. Ignition of lead styphnate by a filament in an explosive attachment // Journal of “Almaz – Antey” Air and Space Defence Corporation. 2020. No. 4. P. 69–76. https://doi.org/10.38013/2542-0542-2020-4-69-76

Для цитирования: Липанов А. М., Головатенко В. Д. Воспламенение тринитрорезорцината свинца от нити накаливания в пироузле // Вестник Концерна ВКО «Алмаз – Антей». 2020. № 4. С. 69–76. https://doi.org/10.38013/2542-0542-2020-4-69-76

Submitted on 29.10.2020 *Reviewed on* 13.11.2020 *Approved on* 02.12.2020 *Published on* 30.12.2020

It is known from thermodynamics that ignition temperature is an intensive (qualitative) characteristic, which, together with entropy, determines the energy that has to be applied to fuel for its combustion to start. Since in each particular case the rate of energy supply from a heat source and the conditions in which the investigated substance resides are different, the obtained experimental results cannot be unambiguously used for describing cases of ignition in other devices and heating conditions. Thus, the value of lead styphnate ignition temperature, as given in papers [1–5], lies within 265...280 °C, and the flash point of this substance according to the Concise Chemical Encyclopaedia [6] is 240 °C. Since it is infeasible to determine lead styphnate ignition temperature immediately in an explosive attachment by heating up filament with electric current, it has to be determined analytically, using thermophysical properties of the initiating substance and the value of electric voltage applied to the filament in a particular explosive attachment design.

The explosive device (attachment) used in the experiments comprised two heating elements (HE) made from constantan wire with diameter of 40 μm and length of 3.3 mm (the length given here is that of the wire contact with lead styphnate between electric pins in the explosive attachment) soldered to electrical contacts contained in an electrical insulator, with lead styphnate powder pressed over the contacts under a pressure of 30 MPa and a pyrotechnic mixture,

isolated from the environment by a membrane, pressed on top of the powder. The assembled circuit is placed in a steel cylindrical enclosure which has a lead-out to the electrical contacts on one side and a passage for combustion products outflow on the other.

Given in Fig. 1 is a schematic diagram of the installation, consisting of the following blocks:

– power supply B5.30/10; contactor TKD 503;

– measuring and computing complex MAK 520 and four-channel analogue-to-digital converter N1 9215.

The equipment ensures stable flow of electric current of 2 and 5 A through the HE till the moment of lead styphnate ignition.

The circuit is implemented using resistors of grade MLT-0,5: R1 – 100 kΩ, R2 and R5 – 10 kΩ, R3 – 15 kΩ, R4 – 1.5 kΩ, and R6 – 1.0 kΩ. The power supply source was calibrated for respective current at supply voltage of 27 V with the use of variable resistor R1, made from nichrome wire 1 mm in diameter with bifilar winding; calibration was done individually for each explosive attachment because HE in the manufactured attachments had a spread in ohmic resistance values within 0.8...1.1 Ω. The HE resistance was measured by means of portable DC bridge R3043 T2 TO 3.454.020 with accuracy class 5. The assembled circuit ensured parameter polling with 50 Hz frequency.

The method for determining the temperature of compacted lead styphnate powder ignition in an explosive attachment is based on determining time interval between the start of electric current flow through the working heating element and the moment of destruction of telemetric bridgewire, arranged in parallel to the working one at a fixed distance, when it is acted upon by the combustion (detonation) products of the initiating substance, thus enabling to determine the amount of energy spent on ignition of lead styphnate in the ignition cylinder. Based on the available technical data of the explosive attachment, density (confinement) of the compacted lead styphnate was 2.9 g/cm^3. It is known from literature [7] that at confinement $\Delta = 1$, the detonation velocity is 1603 m/s, and at $\Delta = 2.9$, it reaches 5200 m/s (data from [1]).

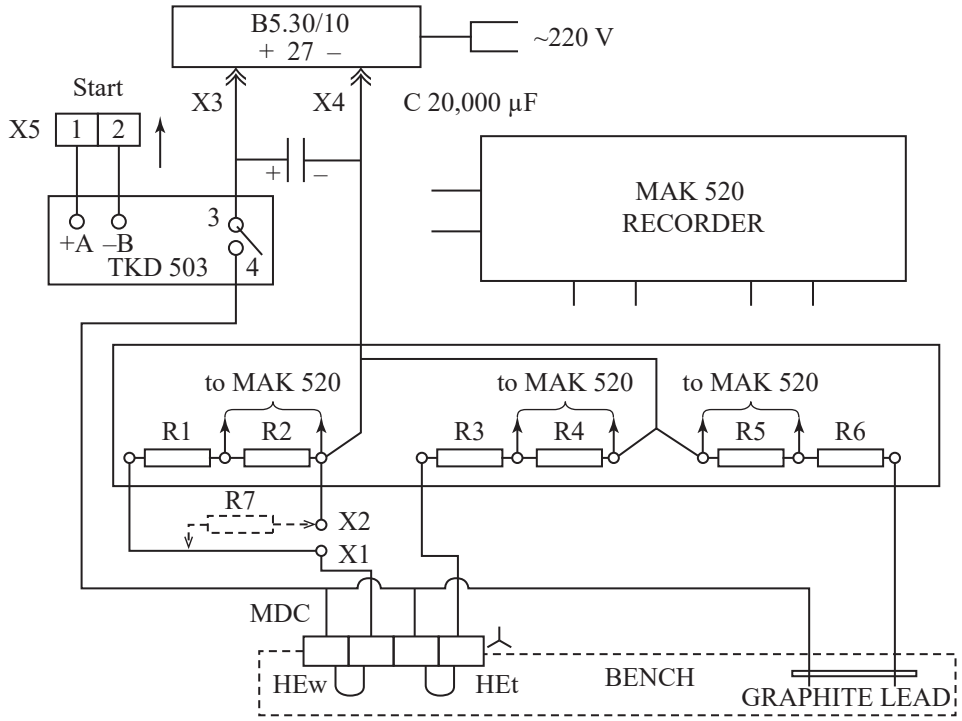

Fig. 1. Schematic diagram of installation for determining time of NE destruction in an explosive attachment under the action of lead styphnate explosion products

Crystalline density of lead styphnate is equal to 3.1 g/cm^3, whereby the detonation velocity is 5500 m/s. The latter value is determined under assumption that lead styphnate detonation velocity, same as the detonation velocities of explosives studied by the authors of [2], is in linear relationship with confinement in the tested attachment. To determine the start of detonation products movement from the explosive attachment's inner space, which was also taken for the start of ignition of the pyrotechnic composition applied over lead styphnate, a rod was secured, thrusting with its one end against protective membrane of the pyro initiator (explosive attachment) and touching a graphite rod with the other (Fig. 2). The moment of graphite rod destruction marks the start of movement of the combustion products of substances contained in the experimental attachment. It is presumed that graphite leads of 2 mm diameter extracted from drawing pencils have a high degree of brittleness and, as verified experimentally, fairly small electrical resistance.

To theoretically determine the temperature of substance ignition, let us write down an equation for temperature change depending on the heat flow created by a heating element while electric current is flowing through it:

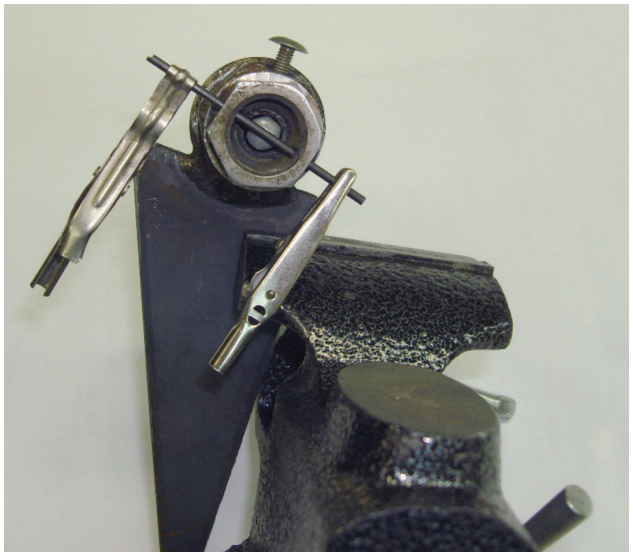

Fig. 2. Explosive attachment appearance (attached to graphite rod are current collectors)

$$\frac{h\ell}{4a}\frac{d(T-T_0)}{dt} + (T - T_0) = \frac{₱th}{\lambda F}, \qquad (1)$$

where:

h – depth of lead styphnate heating before ignition, depending on compaction density and fraction of the initiating substance powder;

ℓ – length of heating element wire;

α – thermometric conductivity;

λ – lead styphnate thermal conductivity coefficient;

F – contact surface between filament and lead styphnate through which heat transfer is effected;

T – temperature of the area of lead styphnate contact with the heating element through which electric current flows;

T_0 – initial temperature of the tested explosive attachment;

t – current time;

$₱ = rI^2$ – electric circuit power;

I – value of electric current flowing through filament;

r – resistance of electric bridge filament.

It is assumed that heat flow from the filament occurs instantly and retains a constant value throughout the process. The latter complies with K. Drekopf's experimental and calculation data (see [8]). Thus, the time of current rise up to 2 A (see below in Fig. 3) was 0.02 ms, and the time interval of current rising up to 5 A was 0.1 ms.

We shall use the following denotations:

$$\frac{h\ell}{4\alpha} = \tau;\ T - T_0 = y;\ \frac{₱th}{\lambda F} = \beta. \qquad (2)$$

Then equation (1) will take the form:

$$\frac{\tau dy}{dt} + y = \beta. \qquad (3)$$

Seeking a solution to the homogeneous part of equation (3)

$$\tau\frac{dy}{dt} + y = 0, \qquad (4)$$

whose solution, after its integration, will have the form:

$$\ln y = -\frac{1}{\tau}t + \ln C, \qquad (5)$$

where C – constant of integration,

or $$y = Ce^{-\frac{1}{\tau}\cdot t}. \quad (6)$$

Substituting the solution of equation (6) in differential equation (3) and assuming constant C dependent on t, we have

$$\tau\left[\frac{dC}{dt}e^{-\frac{1}{\tau}t} - \frac{C}{\tau}e^{-\frac{1}{\tau}t}\right] + Ce^{-\frac{1}{\tau}t} = \beta,$$

or $$\tau\frac{dC}{dt}e^{-\frac{1}{\tau}t} - Ce^{-\frac{1}{\tau}t} + Ce^{-\frac{1}{\tau}t} = \beta.$$

Transforming the latter relationship, we have

$$\tau\frac{dC}{dt}e^{-\frac{1}{\tau}t} = \beta,$$

and then $$\frac{dC}{dt}e^{-\frac{1}{\tau}t} = \frac{\beta}{\tau}.$$

Integrating the latter equation relative to constant C:

$$dC = \frac{\beta}{\tau}e^{\frac{1}{\tau}t}dt\,,\ \int dC = \int\frac{\beta}{\tau}e^{\frac{t}{\tau}}dt,$$

we have

$$C = \frac{\beta}{\tau}\tau e^{\frac{1}{\tau}t} + K = \beta e^{\frac{1}{\tau}t} + K, \quad (7)$$

where K – new constant of integration.

Substituting equation (7) in equation (6), we have

$$y = \left(\beta e^{\frac{1}{\tau}t} + K\right)e^{-\frac{1}{\tau}t} = \beta + Ke^{-\frac{1}{\tau}t},$$

or $$y = \beta + Ke^{-\frac{1}{\tau}t}.$$

Proceeding from conditional variables (2) to the actual ones, we have:

$$T = T_0\frac{Pth}{\lambda F} + Ke^{-\frac{1}{\tau}t}.$$

Assuming $K = -\frac{Pth}{\lambda F}$, we find a particular solution:

$$T = T_0 + \frac{Pth}{\lambda F}\left(1 - e^{-\frac{1}{\tau}t}\right), \quad (8)$$

where $\tau = \frac{h\ell}{4a}$ – complex determining response rate of the system (or time constant of the studied device process, see [9]).

A solution to the formulated problem is represented in the form of a transcendental equation. The latter includes two unknown physically dependent variables, namely, lead styphnate ignition temperature and heating depth h, which are determined by the heat exchange rate between filament and initiating substance. In its turn, the filament heating dynamics depends on the value of electric current flowing through it. Solution uncertainty can be eliminated by invocation of experimental data. Thus, assuming the data [8] on instant lead styphnate ignition at a temperature of 623 K, we can determine heating depth h of the initiating substance, with account of experimental data obtained under the currents of 2 A (Fig. 3) and 5 A (Fig. 4). We also assume that in case of small time periods of current flowing through filament, as experimentally shown by K. Drekopf (see [8]), heat losses in the connecting pins to the filament can be neglected, and the filament itself has the same temperature over its entire length under the above values of electric current flowing through it. It is assumed therewith that lead styphnate ignition may start from any of its grains in contact with the heating element. The lead styphnate heating depth was determined, under assumption that the ignition temperature for this substance is equal to 623 K [10], by equation (8) solved according to h, and using the experimental data (see Figs. 3 and 4).

Given in Figs. 3 and 4 are characteristic copies of oscillograms under the current of 2 and 5 A (top to bottom). All tests were conducted at ambient temperature of 22 °C.

The values of physical characteristics of lead styphnate used in the calculations, as determined for serially produced standard devices, where: λ = 0.165 W/msºC and c = 750 J/kgºC.

It is obvious that the values of lead styphnate ignition temperature are different from the magnitudes of temperature to which the filament will have time to heat up with electric current flowing through it within the given time period. This was first determined, theoretically and experimentally, by K. Drekopf (see [8]). With the amount of heat liberated in the filament while electric current was flowing through it, as determined by the Joule-Lenz law, and filament physical characteristics (its mass, metal thermal capacity) known, the temperature was

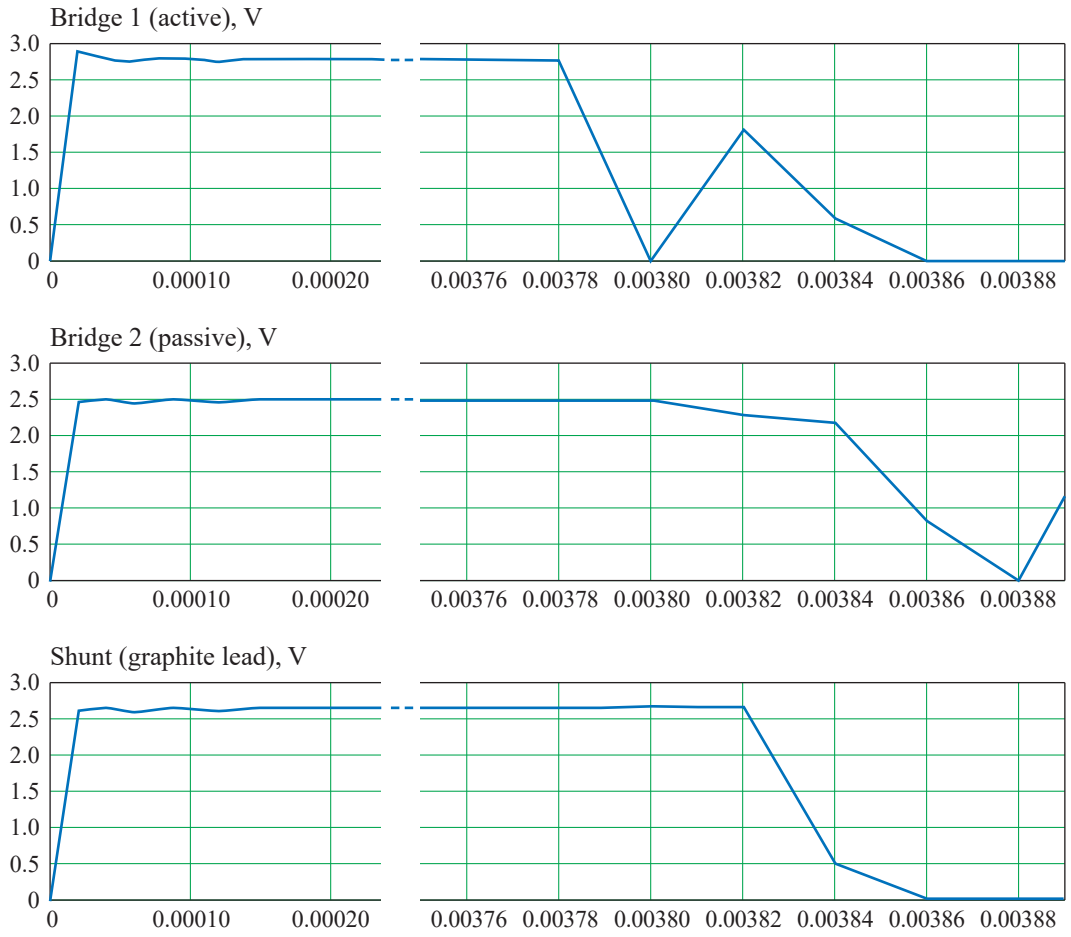

Fig. 3. Test with 2 A current flowing through filament

determined, to which the filament will be heated before lead styphnate ignition. Naturally, the value of this temperature will be dependent on the magnitude of current having flown through filament and characteristics of the latter in the same explosive attachment design. Thus, for the case of 2 A current flowing through the filament in the studied attachment, the former was heated up to 890 °C before lead styphnate ignition, and under 5 A current, the temperature of filament heating at the moment of lead styphnate ignition was within 1100…1200 °C (constantan melting point is known and equal to 1290 °C). Such uncertainty is associated with the fact that Pb is present in the lead styphnate decomposition product, while the pyrotechnic composition included aluminium as a combustible substance, and after disintegration of the oxidant, which was potassium perchlorate, a KCl liquid phase appeared among the electricity conductors. At that, lead styphnate combustion velocity under the current of 2 A, with the distance between the active bridge (filament) and the passive bridge being 4.3 mm, was estimated at 215 m/s, and in certain cases it would accelerate and reach 750 m/s. Such change of velocity for the primary and secondary explosives, i.e. accelerating combustion, is pointed out by the authors of [11] for the secondary explosives as well. Under the current of 5 A, it can be presumed that lead styphnate blasting (detonation) occurs, since no time difference was revealed between lead styphnate combustion start and the moment of passive filament destruction, as measured on the developed installation (see Fig. 1).

The rate of combustion products expansion from the attachment's inner space was determined for the case shown in Fig. 3 at 132.5 m/s, and for the experiment (see Fig. 4), this rate was determined at 345 m/s.

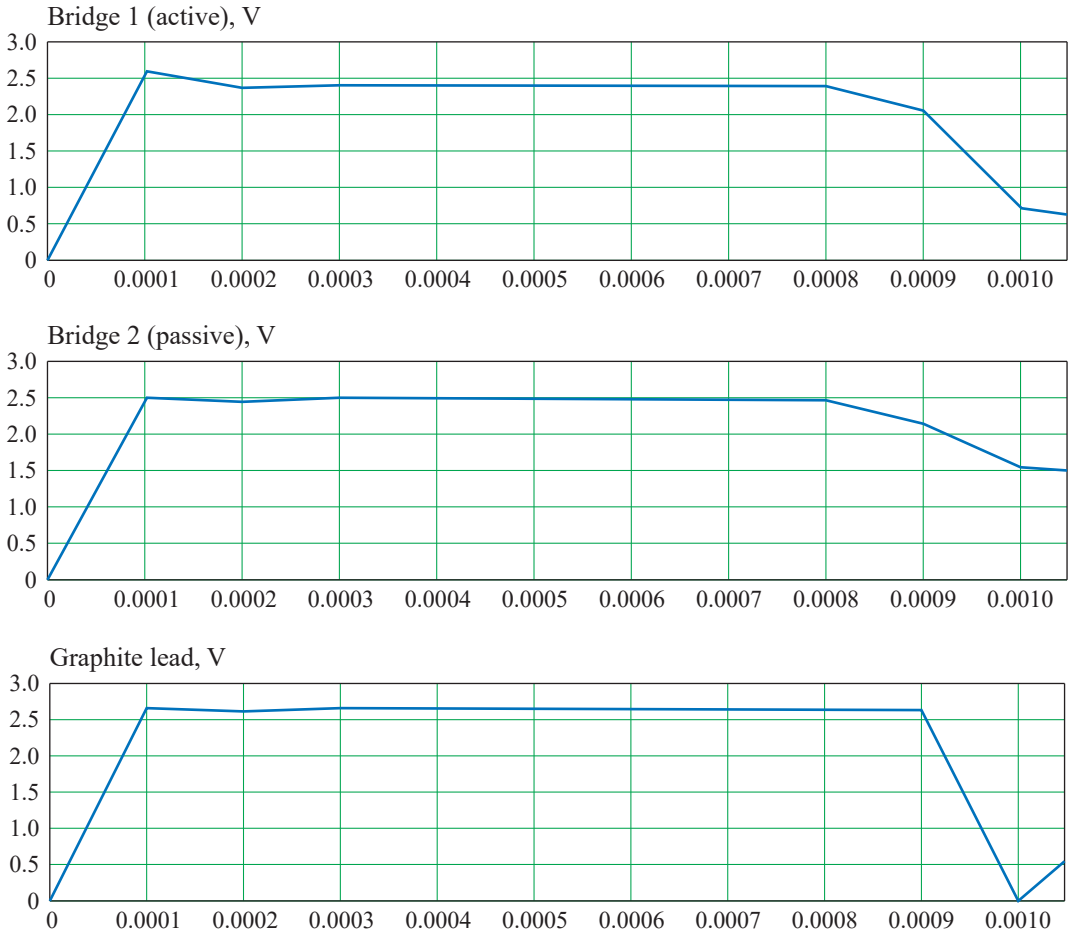

Fig. 4. Test with 5 A current flowing through filament

Calculation of the lead styphnate heated layer thickness before its ignition, performed as per equation (7), at lead styphnate ignition temperature of 623 K [10], yields in the first approximation a value of ≈ 0.1 μm for the current of 2 A supplied to the bridgewire. This value can be compared with the data given in [11] for the secondary explosives: TEN, hexogen, and tetryl, for which the critical radius of heating for the case of blast initiation by an impact from which combustion starts, has a value within 1...10 μm. In this way, the value of heating depth of explosives before their blasting (detonation) also determines the qualitative difference between the initiating and secondary explosives. It should be noted that, according to [11], the instant temperature of explosive ignition is much higher than under thermal action (see [6]) and can be 1.5–2 times as high, proceeding from the data obtained in blast initiation by a shock impact on the explosives.

It was determined that ignition temperature of the initiating substance and heating depth of the latter before ignition are functionally related and are defined by a transcendental equation, as shown above, and in its turn, this dependence (by the parameter values) is determined by the particular explosive attachment design. Hence, the aforementioned calculated parameter values of the studied explosive attachment show the order of unknown magnitudes that will be observed when determining a sought parameter in other designs as well.

Conclusion

1. The temperature of lead styphnate ignition in an explosive attachment, as an intensive component of J. W. Gibbs thermodynamic energy equation, together with an extensive component, i.e. heating depth of the explosive, is represented by a transcendental equation.

2. From the experimental data and the transcendental equation, heating thickness of compacted lead styphnate powder in explosive attachment was determined, being equal to about 0.1 μm in case of filament heating with the current of 2 A.

3. Lead styphnate combustion velocity in the studied explosive attachment, under the current of 2 A in the heating element filament, was within the range of 215...750 m/s, with the first value corresponding to stable combustion and the maximum one, to accelerated combustion.

4. Under the filament heating current of 5 A, combustion of the ignited lead styphnate changes over to detonation, with, presumably, simultaneous blasting of the explosive attachment's heating element.

5. The rate of pyrotechnic add-on combustion products outflow from the explosive attachment used in the experiments was determined as lying within 132.5...345 m/s, depending on the value of electric current supplied to the filament.

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Воспламенение тринитрорезорцината свинца от нити накаливания в пироузле

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Показано, что температура воспламенения тринитрорезорцината свинца описывается трансцендентным уравнением, включающим инерционность инициирующего состава и глубину его прогрева. Произведен расчет температуры нити накаливания в момент воспламенения инициирующего вещества. Найдено, что при значениях тока накаливания на нагревательном элементе, близких к 5 А, горение тринитрорезорцината свинца переходит во взрыв (детонацию), а при токе на нити накаливания 2 А скорость его горения находится в пределе от 215 до 750 м/с.

Ключевые слова: пироузел, температура воспламенения, тринитрорезорцинат свинца.

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Область научных интересов: исследование импульсных процессов, протекающих в установках малой мощности автоматизации летательных аппаратов.