Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 5, 2000

INITIATION SYSTEMS USING SECONDARY EXPLOSIVES

L. A. Luk'yanchikov

UDC 662.4

The paper reports the main results of the work on designing initiation systems and firing devices for industrial use, primarily in metal working, that was begun in 1961 at the Institute of Hydrodynamics and headed for a long time by Academician M. A. Lavrent'ev. Within the framework of this work, basic research on the initial stages of detonation transition was performed and the ablative mechanism of combustion of melting explosives, which, in particular, distinguishes them from smokeless powders, was revealed and studied. A dynamic initiation method that leads stably to the occurrence of this mechanism was proposed. Results of the studies have been used to design industrial explosive devices for metal working and initiation systems for mechanized priming in hydroexplosive forming and synthesis of ultradisperse diamonds.

The classical results obtained by M. A. Lavrent'ev in cumulation theory have led to the development of new approaches to the successful solution of many fundamental and applied problems of the motion of materials under explosion loading. Naturally, research in this area has become a main direction of scientific activities at the Institute of Hydrodynamics organized by Lavrent'ev.

The work in this area directed by M. A. Lavrent'ev was begun even in 1956 at the Moscow Physicotechnical Institute. Cumulation and flows in water and ground explosions were studied, and methods of high-velocity particle acceleration for problems of space engineering were developed. In 1957, most of the creative team moved to the newly founded Institute of Hydrodynamics of the Siberian Division, but until 1958, studies were performed on the experimental facilities at the Moscow Physicotechnical Institute.

Most explosive experiments require strict synchronization using microsecond detonators. Such a detonator was designed on the basis of RDX powder initiated by a pulsed spark discharge. It had a simple design and low sensitivity to external action.

In 1961, the Central Institute of Underground Mining Engineering presented a proposal to M. A. Lavrent'ev that shaped charges be employed for blasting of hard rocks. Over a short time, preliminary experiments were performed, and they confirmed the effectiveness of this blasting method. Therefore, the need arose to design an explosive actuating device for sequential explosion of a large number of simple charges delivered at specified points in a working space. Such an initiation system was designed on the basis of high-voltage, high-current detonators using secondary high explosives (HE).

Soon it was suggested that shaped charges be also used to solve another problem — designing a mechanized explosive installation for explosive forming of the fuselage of MiG-25 aircraft. The MiG-25 airframe was manufactured using new superstrong stainless steels, which, because of their low plasticity, could be molded only by a sequential explosion of a large number of small charges. This technology could be implemented only by explosive automatic control units ensuring a low cost of each explosion. Design of such devices was performed with participation of the Institute of Hydrodynamics of the Siberian Division

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 5, pp. 48–61, September–October, 2000. Original article submitted April 13, 2000.

 0021-8944/00/4105-0806 $25.00

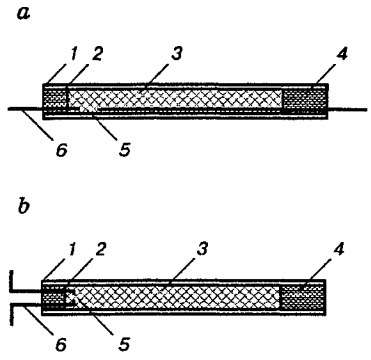

Fig. 1. Diagram of experimental setups for studying spark initiation of RDX: spark gap on the shell surface (a) and at the end of the sealing plug (b); 1) a glass or Plexiglas shell; 2) insulator; 3) RDX charge of bulk density; 4) charge of cast HE; 5) spark gap; 6) leads.

of the Russian Academy of Sciences, the Research Institute of Aviation Technologies, and the Novosibirsk and Gork'ii aircraft manufacturing plants. Extensive scientific research and developments were performed and the studies were basically completed in 1968. The Institute of Hydrodynamics designed an initiation system that comprised the final stage of the actuating device, which implemented underwater priming, and initiating pulse generators, which indicated the time when a HE charge reached the working space of the hydroexplosive tank, and, at this time, fired safe detonators with secondary HE at a specified point, thus initiating the primary charge.

For implementation of this program at the Institute of Hydrodynamics of the Siberian Division of the USSR Academy of Sciences, work was carried out in the following directions:

1. Investigation of the mechanism of initiation of secondary HE by a pulsed spark discharge;
2. Design of safe detonators for industrial use;
3. Design of an actuating device and generators of searching and initiating pulses.

The first direction is concerned with studying an important problem of the physics of explosion. Studies in this direction at the Institute of Hydrodynamics are still in progress. Along with a spark discharge, other energy sources that form an initiation spot have also been studied and this initiation method was called dynamic.

1. Dynamic Initiation of Secondary HE Powders. Investigation of the development of detonation transition in RDX powder of the standard commercial fractional composition was begun in 1961. Detonation was initiated in charges of bulk density placed in glass or organic glass shells by passing a current pulse through an initiating spark gap was studied. This gap was on the shell surface (Fig. 1a) or at the end of the sealing plug (Fig. 1b). The current pulse was produced by discharge of a capacitor with a capacitance of $C = 0.1$ μF through an inductance of $L = 10$ μH. The capacitor voltage U_0 was varied between 9 and 13 kV. Optical recording by a streak camera and oscillography of the current and voltage were performed.

Figure 2 gives a typical streak record of the transient process in RDX, which clearly shows three distinct stages. In the first (hot spot) stage, the glow is localized in the discharge region. In the second stage, a front forms at the center and moves at a velocity of about 1 km/sec. This front is gradually accelerated and becomes normal detonation. The low-velocity transient process was referred to as detonation and, in essence, was a low-velocity detonation, which should necessarily be driven by a shock wave. The hot-spot stage was followed by the second stage if an energy of 1.0–1.5 J was released in the spark gap within 3–5 μsec. An increase of in the source power by increasing U_0 reduced the time of the first stage. Similar results were obtained in [1], where RDX of the same density was initiated by an explosion of copper and Nichrome conductors. In this case too, it was assumed that occurrence of nonideal detonation is related to formation of a shock wave of sufficiently high intensity and the formation of this wave is the main stage of initiation.

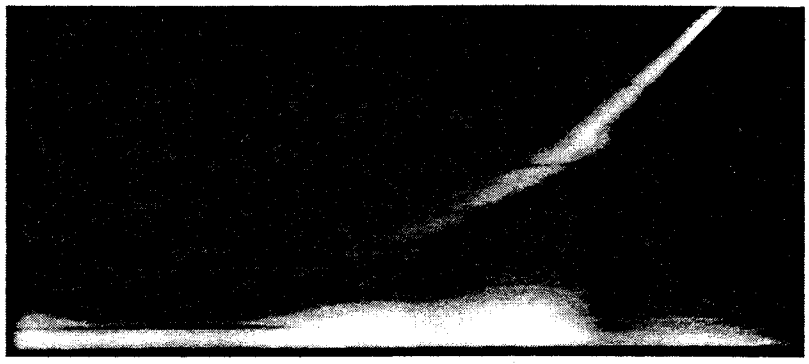

Fig. 2

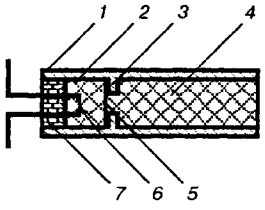

Fig. 3

Fig. 2. Streak records of the transient in RDX of bulk density.

Fig. 3. Diagram of the device for initiating powder HE during discontinuity decay: casing of thin steel (1), charge of smokeless powder (2), reference protrusion of the casing (3), a bulk PETN charge (4), gauged diaphragm (5), incandescence bridge (6), and sealing plastic fuse (7).

Rapid input of energy into the discharge channel facilitated formation of a shock wave because this provided for rapid pressing of the HE powder. The properties of the HE corresponded to the segment of the state diagram on which the velocity of sound increases with pressure buildup [2]. The further development of the discontinuity formed should result from the interaction of rarefaction waves resulting from dispersion upon collapse of the shell and the compression waves generated by the ignited HE, whose mass rate of combustion was assumed to be proportional to pressure.

In 1962, this hypothesis was tested in experiments in which a shock wave and a combustion zone behind the shock-wave front were formed by the classical shock-tube scheme (Fig. 3). A steel thin-walled tube with an inner diameter of 6 mm sealed at one end with a plug was divided into two parts by a diaphragm supported on a protrusion in the casing. A small charge of a smokeless fine-grained powder was placed between the plug and the diaphragm. An RDX charge of bulk density was located just behind the diaphragm ($\rho \approx 1$ g/cm^3). After ignition of the powder by means of a bridge, the chamber pressure began to increase until the diaphragm was broken. It was assumed that a shock wave was thus formed in the powder, and a certain part of the HE grains behind the shock-wave front was ignited and began to burn at a rate proportional to the pressure. Thus, conditions were created for the final stage of the classical deflagration-to detonation transition described in [3].

In the experiments performed, steady development of detonation in the RDX charge was detected if the chamber pressure before rupture of the diaphragm was not lower than 20 MPa. In this case, the transient process in the RDX was initially the same as that in initiation by a spark. The low pressure level behind the initial shock-wave front prevented direct initiation due to initial compression and predetermined the occurrence of combustion for implementation of the final stages of the explosive transformation. Results of these experiments did not contradict the initial hypothesis.

A more comprehensive investigation of the occurrence of nonideal detonation by spark and dynamic initiation was continued in the early 1970s. A rather coarse polydisperse PETN with grains having a surface area of about 500 cm^2/g was studied. The main transient processes were the same but were slower than those in RDX. Ultimately, it was possible to choose a charge geometry for which the rate of the process in the second stage remains constant and equal to about 800 m/sec over a rather great charge length [4, 5].

The possibility of using the well-known electromagnetic technique to measure the mass velocity U of moving PETN grains was tested in control experiments, in which the motion dynamics of flat pieces of an aluminum foil placed inside the HE powder along the normal to the charge axis was recorded by a PIR-4 x-ray apparatus. It was shown that when the foil pieces travel a distance equal to the HE grain diameter (about

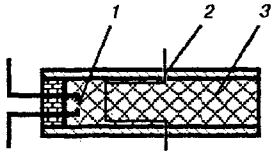

Fig. 4

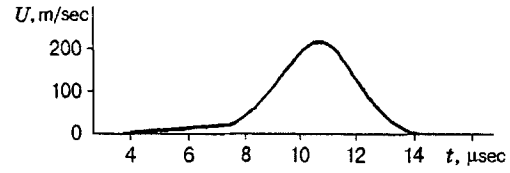

Fig. 5

Fig. 4. Diagram of experimental setup for mass velocity measurements during spark initiation using the electromagnetic technique: 1) spark gap; 2) U-shaped sensor from an aluminum foil; 3) PETN charge of bulk density.

Fig. 5. Mass velocity profile near the spark gap in polydisperse PETN of bulk density.

4 mm), they remain parallel and move forward. Therefore, this technique allows one to reliably determine the variation of the HE powder density during its compression in a stationary wave using the well-known relation

$$\rho = \rho_0 \frac{D}{D-U}. \tag{1}$$

Here ρ_0 is the initial bulk density of the HE and D is the velocity of propagation of the self-glow front. Figure 5 gives an oscillogram taken from the sensor located at a distance of 4 mm from the spark initiating gap as shown in Fig. 4 [4]. One can see a flat profile with a maximum at $U = 240$ m/sec, which is reached within 7 μsec after the beginning of motion of the grains. At the first stage, the material was accelerated only to 50 m/sec during 5 μsec, and this segment was treated as a precursor. After that, the velocity increased faster. The pressure was determined from the well-known relation

$$p = \rho_0 U D, \tag{2}$$

which is also valid for a two-phase reacting medium in the case where the flow is one-dimensional and the degree of decomposition for the condensed phase is several percent. The maximum pressure in the wave calculated with allowance for these conditions is equal to 200 MPa. Direct pressure measurements performed later (see [7]) with an error not higher than 10% using piezoelectric transducer coincided with these results. According to [8], compression in this wave cannot lead to formation of effective chemical reaction centers. We assumed (see [4]) that this transitional regime is a particular high-velocity form of convective combustion, and it does not occur in the classical deflagration-to-detonation transition because of premature compaction of the material by the compression waves generated by the burning area. In 1975, this assumption was confirmed experimentally in studies of the deflagration-to-detonation transition in a charge whose diagram is shown in Fig. 6. The compressibility of PETN in this charge was considerably decreased by a strong skeleton introduced into the HE. The skeleton consisted of 1-mm diameter copper beads in contact. The charge placed in a steel shell with a wall thickness of 0.25 mm was ignited by the standard electrical igniter of an ÉD-8 electrical detonator. As compared to the ordinary charge, the HE content per unit volume of this charge was markedly reduced and the heat removal from the initiated reaction zone was considerably increased. A streak record of the transient regime (Fig. 7) in this charge shows fast development of the process to the rate corresponding to the second stage and further to the ultimate stage of explosive transformation of this charge. Thus, after the introduction of the skeleton, the secondary HE gains the properties of a priming explosive.

A decrease in the degree of compaction of the HE, in turn, slows down the decrease in gas permeability. Therefore, the amount of hot combustion gases penetrating into the HE also increases. However, the effect of variation in the energy balance on the condensed-phase combustion mechanism is not clear. The importance of this process is indicated by the fact that the insignificant sensitization of PETN by coating its surface with a thin protective layer (for example, liquid petrolatum) prevents occurrence of the second stage both in the charge with the skeleton and in spark and dynamic initiation. Neither does this process occur in smokeless pyroxylin powder. In addition, the mass rate of layer-by-layer combustion, known from experiments at constant pressure [6], turned out to be not sufficient to ensure the gas evolution required for this wave.

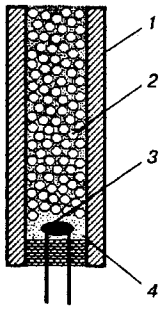

Fig. 6

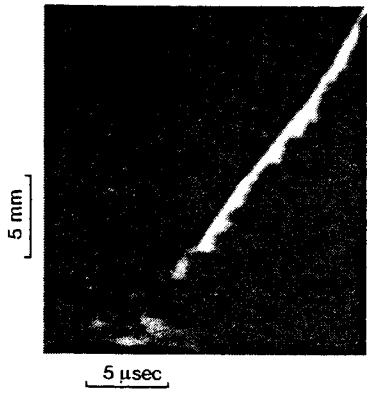

Fig. 7

Fig. 6. Diagram of a PETN charge with metal beads: 1) thin-walled steel shell; 2) copper beads; 3) electrical igniter; 4) PETN charge.

Fig. 7. Streak record of detonation initiation in the PETN charge with metal beads.

We assumed that the failure of the condensed phase is strongly affected by ablation effects that occur during flow of a high-enthalpy gas around the HE surface and considerably increase the burning rate of the grains. This hypothesis is proposed in [7] to explain the anomalously high burning rates. According to this hypothesis, the total rate of regression of the condensed phase is determined by the rate of failure of the evaporated layer due to instabilities that arise in this layer when it is in the high-velocity flow of combustion products. A disadvantage of this approach is that the process of formation of this layer itself is elimination from consideration. This concept was further developed in [9], where the interaction of individual PETN crystals with a gas detonation wave in a stoichiometric mixture of acetylene and oxygen was studied. This concept was developed with allowance for the well-known fact that a gas detonation can excite the same transient process as that occurring in spark and dynamic initiation [10]. This formulation makes it possible to subject individual particles of particular size to the action of a gas-dynamic flow whose flow parameters are known and can easily be varied by changing the initial pressure of the gas mixture.

For accurate determination of the onset of HE combustion against the background of the luminous gas detonation products, photomultipliers were used to measure the radiation intensity at a wavelength of $\lambda_1 = 589$ nm, at which the radiation spectrum of burning PETN has a characteristic maximum against the background of the relative minimum in the spectrum of the gas mixture detonation products, and the radiation intensity at a wavelength of $\lambda_2 = 475$ nm, which determines the luminosity of the detonation wave. This procedure allowed us to determine the range of initial pressures of the mixture at which the HE begins to react and the time required for development for this reaction. In experiments, the PETN combustion products were detected only if the initial pressure of the gas mixture exceeded 0.3 MPa and were recorded within about 5 μsec after passage of the shock wave. At lower pressures of the mixture, the reaction is not observed over the entire time of recording (30 μsec). In [9], such a nature of the entrance of PETN into the reaction was explained by development of instabilities in the micron-size layer of melt on the surface of the HE grains under the action of the flow of gas-detonation products. For the experimental conditions of [9], the thermal parameters of the detonation products are such that heating and melting can proceed to precisely this depth. The separated melt layer is rapidly mixed with the flowing products. The HE vapors are heated to a temperature much higher than 1000°C and react under these conditions within fractions of a microsecond. If this flow is produced inside a PETN charge with an initial bulk density of 0.9 g/cm^3 and a total surface area of the particles of 500 cm^2/g, about 1% of this HE burns in the wave, which is close to the value typical of a high-velocity convective combustion wave.

The convective nature of the wave of the transient regime is confirmed by experiments on transmission

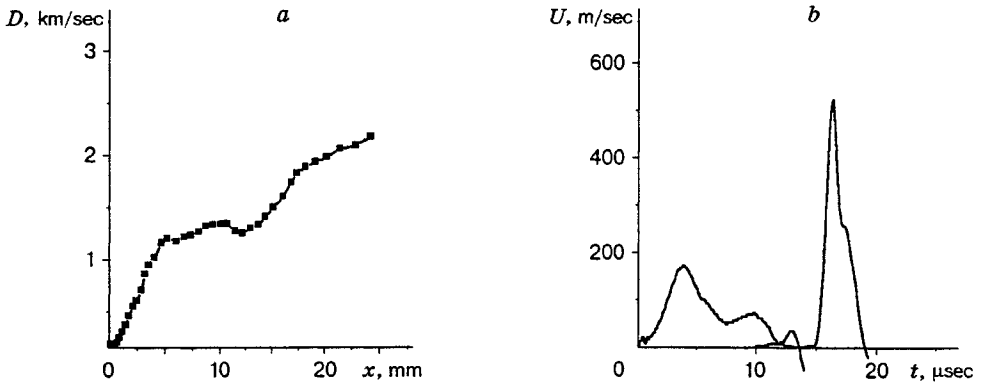

Fig. 8. Initiation of bulk PETN by overdriven gas detonation at an initial pressure of the mixture of 0.08 MPa: (a) velocity of the front; (b) time sweeps of the mass velocity at depths of 1.5 and 8.7 mm from the beginning of the charge.

of this wave through an inert target made of a material with close porosity. A target with a thickness of about the charge diameter does not change the wave characteristics. The reaction behind the target occurs not later than within 0.1 μsec after penetration of the hot flow. PETN sensitized with 1% liquid petrolatum and pyroxylin powder behaves in the target as an inert material. Indeed, the development of instabilities and failure of micron-size layers of petrolatum cannot lead to formation of a cloud of the mixture capable of fast ignition. At the same time, the powder does not form a molten layer and, prior to the onset of combustion, it should partly decompose in the condensed phase. Thus, the ablative mechanism in melting secondary HE differs from that in powders.

Activation of the ablative mechanism leads to a sharp increase in the rate of gas generation, and, streak records show this as a microexplosion, after which faster combustion waves propagate in both the straightforward and opposite directions. In turn, this indicates that the rate of regression of the condensed phase remains rather low up to failure of the melt layer. This is probably due to a decrease in the heat flux to the condensed phase with boiling of the molten layer. The feasibility of this mechanism was pointed out by Librovich [11] and confirmed by the experiments of Starkovskii et al. [12], where RDX and HMX were ignited by laser radiation with an igniting-source power exceeding $3 \cdot 10^2$ W/cm^2.

The initiation of detonation with ablative combustion proceeds in two stages. In the first stage, the gas flow should be formed and the surface layer of the HE grains should be melted. In the second stage, evolution, the fast combustion occurs. Conditions for occurrence of these stages are different. In the first stage, the main constraining factor, as shown above, is compaction of the layer of grains, which hinders filtration of the hot gas into the main mass of the HE. To overcome compaction, it is necessary to accelerate the hot gas. If this gas is formed during decomposition of the charge material by external energy input, it is important to produce a high power density and, if possible, to restrict the lateral dispersion, which leads to direct losses. Satisfaction of these conditions for materials with normal thermodynamic characteristics facilitates faster formation of the shock wave. However, for two-phase media of the type of particles-gas, the penetrating gas increases the counterpressure in the pores and slows down the motion of the grains. An initiating shock wave is formed in the third stage of the transition, which is not determining since ablative combustion is itself capable of propagating in unconfined charges, and ultimately, becomes normal detonation if the charge diameter is sufficiently large. Based on the propagation mechanism considered, a critical diameter should also exist for ablative combustion, but studies in this direction have not been performed. Obviously, the value of this diameter does not depend on the critical diameter of normal detonation.

The dynamics of occurrence of fast convective combustion and its development into nonideal detonation can be traced by mass velocity profiles in a PETN powder charge placed in an organic glass tube an initiated by an overdriven gas detonation wave of the same mixture that was used previously. The detonation wave

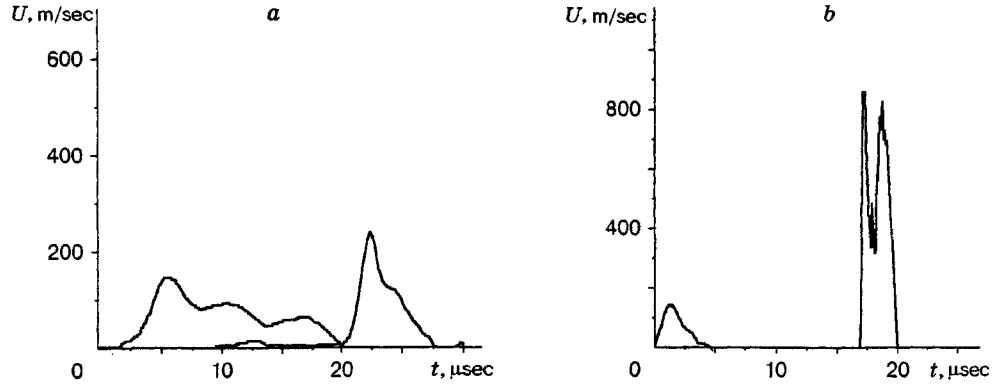

Fig. 9. Time sweeps of mass velocity for initiation of overdriven gas detonation: (a) $\delta = 3$ and 8 mm at $P_0 = 0.08$ MPa; (b) $\delta = 0$ and 15 mm at $P_0 = 0.1$ MPa.

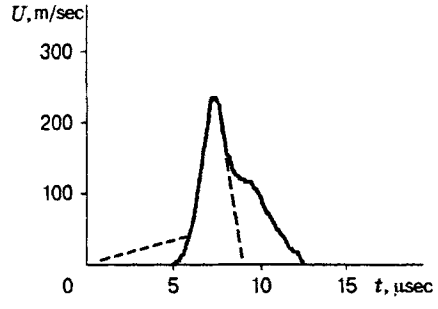

Fig. 10. Mass-velocity profiles for initiation by a spark (dashed curve) and by overdriven detonation (solid curve).

was incident normally on the free end of the bulk charge perpendicular to the axis of the tube. Figure 8a gives the propagation velocity of the self-glow D versus the distance x from the end of the charge. The mass velocity profiles in this wave recorded by foil sensors located at depths of 1.5 and 8.7 mm from the beginning of the charge are presented in Fig. 8b. The first sensor, near which the velocity D is lower than 1 km/sec records a flat front, typical of fast ablative combustion. The signal of the second sensor has a steep front similar to the shock-wave front. The wave in this case is accelerated to 1.5 km/sec. Figure 9 gives mass velocity profiles obtained in two experiments at different distance δ from the plane of initiation. The evolution of these profiles generally corresponds to that observed in [5] for spark initiation, but the precursor detected in spark initiation in the oscillogram of Fig. 5 for the same value of D in the overdriven detonation wave is absent. In other respects, as follows from Fig. 10, these profiles are superimposed on one other with allowance for the shift in time. The front with the precursor was recorded by a sensor located at 5 mm from the spark gap of the charge assembled by the scheme presented in Fig. 4. The duration of this precursor is equal to the duration of the hot-spot stage of the discharge, in which ablation has not yet developed and the heat flux to the condensed phase is limited by the HE vapors.

The results suggest that the ablative regime is also the main regime for other energy sources generating triggering pulses. For exploded conductors, this will be shown below. Information available on the development of detonation initiated by laser radiation (see, for example, [13]) refers to HE with very large grain sizes, in which case the wave forms over a short time, and this hinders a comparison.

2. Commercial High-Voltage Electrical Detonator. A high-voltage electrical detonator (Fig. 11) was designed in 1966–1968 as a result of joint work of the Institute of Hydrodynamics and the Novosibirsk plant "Iskra" and was used at the Novosibirsk and Gor'kii aircraft manufacturing plants for mechanized

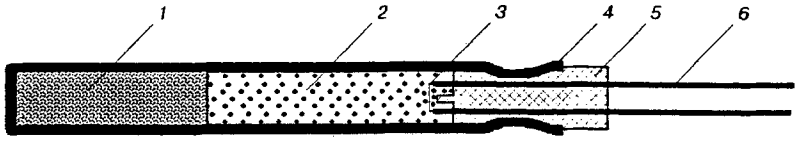

Fig. 11. Diagram of commercial high-voltage electrical detonator: 1) pressed RDX charge; 2) PETN charge of bulk density; 3) wire bridge; 4) steel casing; 5) plastic plug, 6) leads.

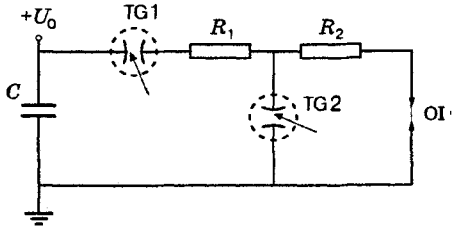

Fig. 12

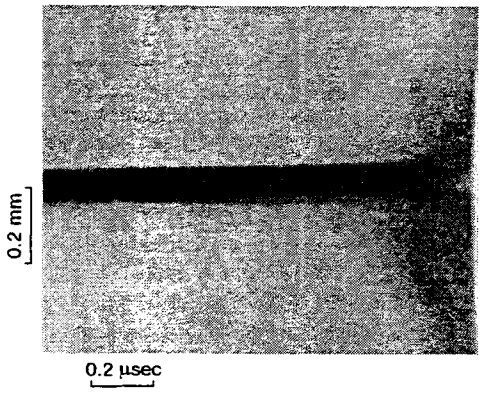

Fig. 13

Fig. 12. Diagram of a device for studying the sensitivity of the high-voltage electrical detonator to a current pulse: TG1 and TG2 are triggered high-current gaps; $R_1 = 10\ \Omega$ and $R_2 = 5\ \Omega$; OI is the site of connection of the object of investigation.

Fig. 13. Dispersion of a copper conductor at the moment of beginning of its electrical explosion.

(multipulse) and ordinary hydroexplosive forming of airframe parts from strong, hard-to-deform materials. In 1972, this detonator was permitted for industrial use in metal working to form, weld, and strengthen metal parts and then in building to perform blasting works within city boundaries. As compared to existing detonators of this type (see, for example, [14]), it has a greater spread of operation times, reaching ± 5 μsec, and its overall dimensions correspond to the standards for commercial detonators.

Initiation of detonation in a high-voltage electrical detonator proceeds through an ablative stage and is accomplished by an electrical detonation of a conductor. The requirements for the current that guarantees operation will be referred to as initiation conditions. The electrical circuit used to determine the initiation conditions is given in Fig. 12. The time constant RC was so large that over the entire period of time before occurrence of fast combustion, the current in the circuit decreased by not more than 5% if the triggered high-current gap (TG2) did not operate. The current pulse duration was limited by initiation of this gap by a signal with a specified delay in time. The discharge current and voltage were determined by oscillography using current shunts and ohmic voltage dividers with compensation of the reactive component by the method described in [15].

In processing experimental data, the resistance of the conductor is conveniently treated as a function of the current integral $J(t)$ given by

$$J(t) = \int_0^t I^2(t)\,dt, \tag{3}$$

since up to the beginning of explosion of the conductor, this relation is single-valued. By virtue of this, the moment τ_{expl} of the beginning of explosion of the conductor can be determined from the relation $J(\tau_{\text{expl}}) =$

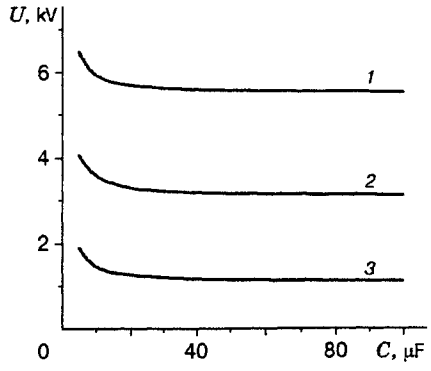

Fig. 14

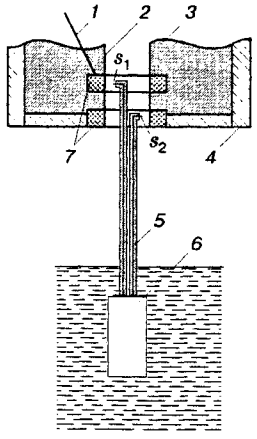

Fig. 15

Fig. 14. Capacitor voltage versus its capacitance: 1) $L = 10^{-5}$ H and $R = 1\ \Omega$; 2) $L = 5 \cdot 10^{-5}$ H and $R = 2\ \Omega$; 3) $L = 10^{-4}$ H and $R = 3\ \Omega$.

Fig. 15. Diagram of the actuating device of the setup for mechanized explosion in hydroexplosive forming: current lead from the initiating pulse generator (1), channel for transportation of the charge (2), insulator (3), metal casing (4), leads (5), HE charge (6), electrodes of the switching zone (7).

$J_0 = \text{const}$. The high-voltage electrical detonator uses a copper conductor of 90 μm diameter, for which $J_0 = 4.8\ \text{A}^2 \cdot \text{sec}$.

Experiments without a TG2 show that initiation with a small percent of probability begins for $I \approx 300$ A, and it becomes trouble-free for $I = 800$ A. This current will be referred to as guaranteed and denoted by I_g. For this current, the semitransparent layer of copper vapors begins to ablate from the conductor surface at the moment τ_{expl}, (Fig. 13), and the velocity of the leading edge of this layer is 800 m/sec. Fast combustion occurs within not more than 0.5 μsec after the moment τ_{expl} if $I(\tau_{\text{expl}}) = I_g$.

If the shunting gap is triggered before the moment $\tau_{\text{expl}} + 0.5$ μsec, this leads to occurrence of failures. With later triggering, there is absolute initiation. In this case, the rate of dispersion of the metal vapors remains unchanged, and this suggests that exactly this flow ensures initiation of detonation. Based on these results, the initiation conditions for lumped-parameter circuits with an inductance of more than 5 μH take the form

$$J(\tau_{\text{expl}}) = J_0, \qquad I(\tau_{\text{expl}}) = I_g. \tag{4}$$

These conditions are valid if the current does not pass through zero before the moment τ_{expl}.

Based on (4), for a series lumped-parameter (R, L, C) circuit and an ideal switcher, calculations were performed for three particular circuits. They yielded the dependence of the discharge voltage U_0 on the capacitance C for guaranteed ignition. The results presented in Fig. 14 show that for short explosive lines, which are commonly used in metal working, initiation is ensured by explosive devices with a voltage of about 1 kV.

3. Initiation Systems for Hydroexplosive Forming. Because of the low sensitivity to external action, a high-voltage electrical detonator completely mechanizes the transportation of a charge to the ignition zone without using any protective devices, thus reducing the cost of the charge used.

In designing the actuating device, the main difficulty was associated with connection of the charge circuit with a previously incorporated detonator to the circuit of the initiating current source. This problem was successfully solved by designing a system of high-voltage noncontact initiation, which eliminated the necessity of mounting a stationary explosive electrical circuit.

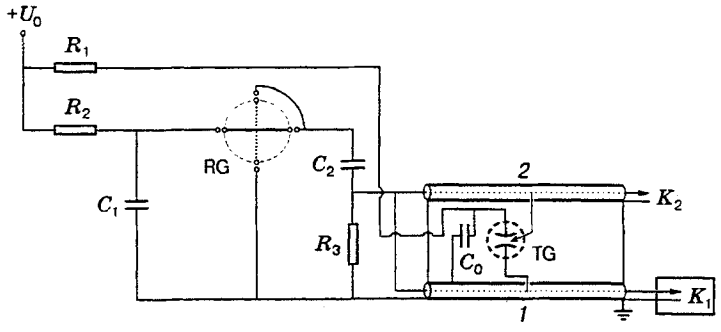

Fig. 16. Diagram of the initiating pulse generator for mechanized explosion: C_1, C_2, and C_0 capacitors with capacitances of 1 μF, 2 nF, and 0.5 μF, respectively; $R_1 = 20$ kΩ, $R_2 = 20$ kΩ, and $R_3 = 1$ kΩ; RG is rotating gap and TG is triggered discharge gap.

A diagram of the actuating device illustrating this method is presented in Fig. 15. The charge consists of a pressed TNT charge with a weight of about 50 g, in which a high-voltage electrical detonator is completely embedded. The detonator terminals are 30 to 80 cm long, depending on the depth of explosion, which is chosen according to the production technology for a particular part. The ends of the wires are stripped and shaped as shown in Fig. 15. The basic element of the actuating device is a switching unit, which comprises a through channel, along which the charge moves, and contact ring electrodes, which are fixed in the insulator and connected to a high-voltage pulse generator. Pulses are applied at a frequency of $f \approx 400$–800 Hz. The switching unit can be placed above a water surface or immersed in it. In this case, water is removed from it by compressed air. The charge is delivered to the channel from a charging device, and it moves to the ignition site under gravity. The initiating pulse is applied to the moving charge at the moment when the stripped ends of the leads reach the switching zone. As the charge moves over a certain switching time τ_s, the length of the overall air gap $S = S_1 + S_2$ between the moving and fixed electrodes passes through a minimum and remains nearly minimal. During this time, voltage sufficient for breakdown is supplied several times to the gap S filled with air. If the generator in this newly formed circuit is capable of generating a current pulse that satisfies conditions (4), the charge is ignited at a specified point of the working volume.

Tests of the setup showed that the actuating device should be compact and the distance between the fixed electrodes of the switching zone should not exceed 3–4 cm. Thus, the gap length S should not be less than 2 cm. To meet these requirements, the searching pulses of the generator that ensures switching should have a duration not longer than 1 μsec for a voltage of 30–40 kV.

At the same time, the cost of the charge should be minimal. This prohibits the use of insulation to prevent a premature breakdown of the lead into the water surrounding it. In the case of a false discharge, there is breakdown only in the gap S_1 and the resistance of the discharge circuit does not drop below 1 kΩ since the current necessarily passes through the liquid. This discharge cannot initiate the high-current detonator.

The indicated problems were solved using a special generator of searching and initiating pulses, which is shown schematically in Fig. 16. Searching pulses I are formed when the capacitor C_2 with a capacitance of about 2 nF is charged and discharged into two identical coaxial RK-50 cables 150 m long connected in parallel. The pulse repetition rate is specified by the angular rate of the rotor of the rotating gap. Upon reflection of the signal, voltage pulses with an amplitude of about 50 kV and a duration of about 1 μsec are formed at the end of each cable. One of the cables is connected to the fixed electrodes of the switching zone of the actuating device, and the second remains disconnected. At points 1 and 2 in the middle of each of the cables there are leads from the central conductor, which are connected to the initiating space of the triggered gap (TG). If there is no breakdown in the gap of the switching zone (point K_1), the voltage waves in both cables are identical and voltage does not arise in the initiating space of the TG. In the case of breakdown in the gap S of the switching zones, the resistance at the point K_1 becomes much lower than the wave resistance of the

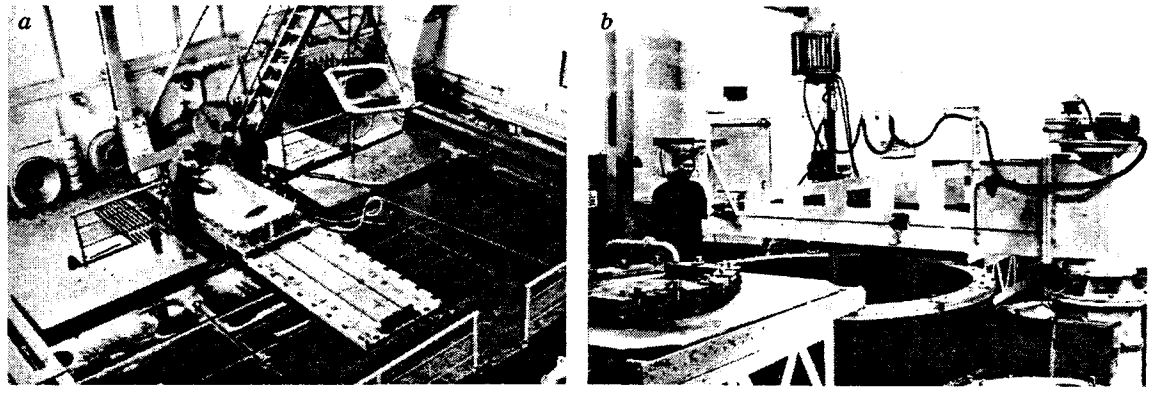

Fig. 17. Hydroexplosive forming shop at the Chkalov Novosibirsk aircraft manufacturing plant: (a) rectangular explosive tank; (b) BU-2.5 setup with mechanized initiation of charges with a weight of 50 g.

cable and the polarity of the reflected signal changes. As a result, a large difference in voltage arises between points 1 and 2. This leads to a breakdown of the initiating space and triggering of the TG. Charged to the power source voltage, the capacitor C_0 with a capacitance of 1 μF discharges through the circuit formed and fires the detonator and the entire charge. In a false breakdown, the TG is not initiated.

The initiation system considered was used to produce simple and stably operating actuating devices that withstand considerable shock loading and ensure initiation without using additional electrical insulation of the electrical detonator circuit.

Thus, the studies performed revealed a new mechanism of development of detonation transition in HE powders, which is based on the ablation effects due to failure of a thin melt layer on the surface of the melting secondary HE grains in a high-enthalpy flow. These effects provide for fast gas generation in a time of about microseconds when the total heating of the condensed phase is small and cannot ensure satisfaction of the ignition conditions formulated in [16]. The validity of this condition for fast heating is confirmed in [12]. It should be noted that powders that do not melt cannot burn by this mechanism, and, therefore, the ablative mechanism establishes a difference between these unitary fuels. It is known that the properties of powders and secondary HE differ greatly. Therefore, the sensitivity of the indicated materials to external energy action should be tested by a method that allows one to determine the probability of occurrence of the ablative mechanism. Such tests for unitary propellants have not been performed. There is no doubt that such tests are necessary.

Implementation of the developments reported here yielded a large economic benefit. Mechanized initiation devices have been successfully used at the Novosibirsk and Gor'kii aircraft manufacturing plants to manufacture the airframes of modern fighters. Figure 17 shows a general view of the hydroexplosive forming shop at the Chkalov aircraft manufacturing plant, where these detonators were employed for the first time.

Initiation of the charge in free fall was also used for automation of initiation in synthesis of ultradisperse diamonds. In this case, the charge moved in the gas atmosphere of an explosive chamber, which made it possible to stably excite detonation by a fast-flying body using an intermediate charge of PETN powder.

In addition, high-voltage electrical detonators are widely used in metal working by conventional blasting in explosive chambers and in loosening of frozen grounds in building under constrained conditions.

The established mechanisms of development of detonation transition makes it possible to design detonators triggered by an ignition spot containing only secondary HE. Such detonators can be used in blasting in the mining industry.

REFERENCES

1. G. M. Muller, D. B. Moore, and D. Bernstein, "Growth of explosion in electrically initiated RDX," *J. Appl. Phys.*, **32**, No. 6, 1065–1075 (1961).
2. G. M. Lyakhov and G. I. Pokrovskii, *Explosive Waves in Grounds* [in Russian], Nedra, Moscow, (1962).
3. A. F. Belyaev, V. K. Bobolev, A. I. Korotkov et al., *Conversion of Condensed-System Combustion to Detonation* [in Russian], Nauka, Moscow (1973).
4. V. V. Andreev, P. I. Zubkov, G. I. Kiselev, and L. A. Luk'yanchiov, "One regime of detonation propagation in low-density HE powder," in: *Dynamics of Continuous Media*, (collected scientific papers), [in Russian], No. 10, Novosibirsk (1972), pp. 183–188.
5. V. V. Andreev and L. A. Luk'yanchikov, "Mechanism of low-velocity detonation propagation in PETN powder with spark initiation," *Fiz. Goreniya Vzryva*, **10**, No. 6, 912–919 (1974).
6. K. K. Andreev, *Thermal Decomposition and Combustion of Explosives* [in Russian], Nauka, Moscow (1966).
7. V. V. Andreev, A. P. Ershov, and L. A. Luk'yanchikov, "Two-phase low-velocity detonation of a porous HE," *Fiz. Goreniya Vzryva*, **20**, No. 3, 89–93 (1984).
8. G. I. Seay and L. B. Seely, "Initiation of a low-density PETN pressing by a plane shock wave," *J. Appl. Phys.*, **3**, No. 6, 140–145 (1961).
9. V. V. Grigor'ev, L. A. Luk'yanchikov, and É. R. Pruuel, Ignition of PETN particles by a gas detonation wave," *Fiz. Goreniya Vzryva*, **33**, No. 2, 133–138 (1997).
10. V. V. Andreev, L. A. Luk'yanchikov, V. V. Mitrofanov, and V. S. Teslenko, "Detonation initiation of HE powder by detonating gas mixtures," *Fiz. Goreniya Vzryva*, **16**, No. 4, 153–155 (1980).
11. V. B. Librovich, "Ignition of powders and explosives," *Prikl. Mekh. Tekh. Fiz.*, No. 6, 74–79 (1963).
12. L. G. Starkovskii, P. I. Ulyakov, and E. I. Frolov, "Ignition of some secondary HE by laser radiation," in: *Combustion of Condensed Systems* (collected scientific papers) [in Russian], Inst. of Chem. Phys., Chernogolovka (1977), pp. 8–12.
13. *Fast Initiation of HE. Special Detonation Regimes* [in Russian], Inst. of Tech. Phys., Snezhinsk (1998).
14. H. Knoepfel, *Pulsed High Magnetic Fields*, North Holland, Amsterdam–London (1970).
15. L. A. Luk'yanchikov and G. I. Kiselev, "Compensation method for measuring pulsed current and voltage," *Prib. Tekh. Éksp.*, No 4. (1974), pp. 99–100.
16. A. É. Averson, V. V. Barzykin, and A. G. Merzhanov "Approximate method for solving problems of the thermal theory of ignition," *Dokl. Akad. Nauk SSSR*, **178**, No. 1, 131–134 (1968).