8. O. E. Marin, N. F. Pilipetskii, and V. A. Upadyshev, "Emergence of laser-induced nucleated cracks," Mekh. Polim., No. 1 (1973).
9. V. M. Likhachev, V. M. Salmanov, and I. D. Yaroshevskii, "Thermal irradiation of transparent dielectrics being broken down by a laser beam," Fiz. Tverd. Tela, 10, No. 1 (1968).
10. N. P. Novikov, Yu. I. Yudin, and G. V. Mikhailov, "Formation of gases from laser-irradiated PMMA," Dokl. Akad. Nauk SSSR, 182, No. 4 (1968).
11. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Oxford University Press (1959).
12. K. S. Shifrin, Scattering of Light in a Turbid Medium [in Russian], Izd. Akad. Nauk SSSR, Moscow–Leningrad (1951).
13. R. W. Hopper and D. K. Uhlmann, "Mechanism of inclusion damage in laser glass," J. Appl. Phys., 41, No. 10 (1970).
14. S. Madorsky, Thermal Degradation of Organic Polymers, Wiley (1964).
15. V. V. Kel'tsev and P. A. Tesner, Carbon Black Properties, Production, and Use [in Russian], Gostoptekhizdata, Moscow (1952).
16. A. S. Shteinberg and V. B. Ulybin, "Thermal decomposition and burning of polymers," in: Papers from the Second All-Union Symposium on Combustion and Explosion. Authors' Summaries of Reports [in Russian], Chernogolovka (1969).
17. P. A. Tesner, Formation of Carbon from Gas-Phase Hydrocarbons [in Russian], Khimiya, Moscow (1972).
18. E. A. Taft and H. R. Philip, Optical Properties of Graphite [Russian translation], Byuro Perovodov., VINITI, Moscow (1960).
19. A. G. Merzhanov and F. I. Dubovitskii, "Theory of steady-state combustion of gunpowder," Dokl. Akad. Nauk SSSR, 129, No. 1 (1959).

ELECTRIC STRENGTH OF SCATTERED DETONATION GASES

P. I. Zubkov, L. A. Luk'yanchikov, and Yu. V. Ryabinin

UDC 537.527

INTRODUCTION

One of the most important characteristics in schemes used for the formation of high-power pulses of a given shape by means of condensed explosives [1] is the current density that can be attained in the detonation wave. Whenever the electrical conductivity is determined directly by the detonation process, the maximal current density depends on the maximal electric field strength at which breakdown of the detonation gases no longer occurs, i.e., on their electric strength. This magnitude also determines the characteristics of safety detonators operating at high inverse voltages [2]. Prediction of the parameters of detonators maintained at a high voltage requires knowledge of the electric strength of the detonation gases as a function of pressure. This is because the gaps formed as current is switched off are found under conditions characterized by nonstationarily expanding explosion gases, as a result of which their electric strength is time-dependent as a function of pressure. The required parameters of safety detonators can be obtained from a joint solution of the gasdynamic scatter problems for detonation gases and the motion of current-carrying elements and of electric circuit equations if the dependence of electric strength on pressure is known. In the current work, fundamental results are set forth from an experimental study of the electric strength of expanding detonation gases from bulk density PETN and Hexogen charges.

The scheme of a safety detonator with a gap in which the electric strength of detonation gases was studied is depicted in Fig. 1. The safety detonator consists of cylindrical steel electrodes 1 measuring 42 mm in diameter, lateral surface insulators of the electrodes 2, a plastic plug-type fuse 3 with exploding bridgewire 4, a resistance ring made of Plexiglas 5, and a bulk density explosive 6. The Plexiglas resistance range eliminates

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, January-February, 1976, 134-138. Original article submitted November 25, 1974.

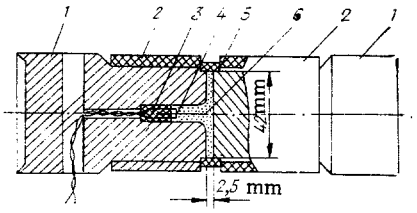

Fig. 1

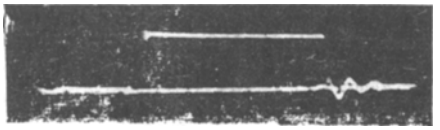

Fig. 2

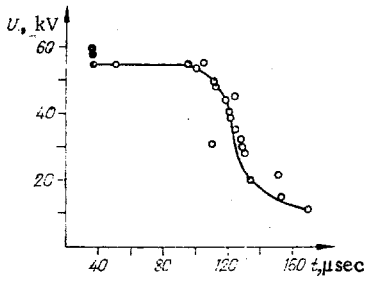

Fig. 3

explosive compression and ensures an initial gap between the electrodes of 2.5 mm. The assembled safety detonator is placed in a blasting chamber and additional electrodes are added to it when assembled.

High-voltage priming by means of an exploding bridgewire situated in the cavity of one of the electrodes of the given gap is used to improve synchronization of charge detonation, feeding of voltage across the gap, and the measurements. The cavity dimensions allow development of a detonation normal for the explosive density (about 10-12% of the total weight of the charge was placed in the cavity).

The bridgewire is exploded and the explosive triggered as the high-voltage pulse is delivered. The resistance ring breaks following the arrival of the detonation wave to the charge face, and the detonation gases, in front of which a shock wave forms, begin to scatter. The lateral surfaces of the electrodes within the gap are insulated and voltage is fed across the gap within a period of time ensuring departure of the shock wave to a sufficient distance in order to eliminate any breakdown in the detonation wave through the conduction zone and in the air through the shock wave.

The safety detonator described above allows us to obtain axisymmetric scattering, which makes it possible to estimate the parameters of the scattered detonation gases. The high temperatures and pressures in the detonation front prevent us from using ordinary diagnostic methods during a long-term process. An actual circuit breaker used in inductive tank circuits and in high-current pulsed shaping ciruits is approximately modeled by a safety detonator selected in this way.

Separation of the electrodes during the explosion was registerd by x-ray photography. The processing of the x-ray photographs demonstrated that the electrodes symmetrically scattered and that the distance between them increased from 2.5 to 4.5-5 mm 30 μsec after the triggered pulse had been delivered, and that the gap remained constant to within a measurement error of 0.5 mm for 90-100 μsec. The rate of expansion subsequently increased somewhat, which may be due to the arrival of a rarefaction wave from the free end of the additional electrodes maintaining the safety detonator in the chamber. The waves pass through the electrodes in 130 μsec. The behavior of the gap after 150 μsec was not studied.

Voltage was delivered across the gap by means of a tripling circuit 35 μsec following the delivery of the trigger pulse, resulting in a 90-kV voltage across the gap. The circuit constant is $9 \cdot 10^{-3}$ sec. The signal is taken from a capacity divider and recorded on the OK-25 oscillograph.

Figure 2 depicts a typical oscillogram for the voltage across the gap. Scanning began with the delivery of the trigger pulse. A voltage maintained for 65-67 μsec was fed across the gap 35 μsec after the triggering and a breakdown that became decaying ciruit oscillations then set in.

A curve (Fig. 3) depicting the time lag of the gap breakdown as a function of the amplitide of the applied voltage pulse was constructed on the basis of the experimental data. The magnitudes of the applied voltage, whose precision was 3%, are laid out along the y axis, while times following the delivery of trigger pulses until gap breakdown are laid out along the x axis. The calculation error for the time interval from the moment at which the detonation wave passed through the charged space amounts to 6-7% and was basically determined by the dispersion of the detonation development time. The time for passage through the charge face was 10-15 μsec after the start of triggering and was found from photographs of the explosion process at HsSP [High-speed Streak Photography] under time magnification conditions. The start of triggering was determined on the photographs in terms of a spark in a gap fixed in an exploding bridgewire circuit, while the moment at which the detonation passed through the charged space was determined from its glow. It is clear from Fig. 3 that a gap filled with expanding explosion gases possesses a region in which the electric strength is saturated, after which this strength begins to rapidly fall.

The electric strength of the detonation gases was unexpectedly low (100-120 kV/cm) within the saturation region. In fact, the electron mean free path is about 10^{-7} cm in slightly expanding gases. For such mean free paths, gases will possess an electric strength of 10^5 kV/cm.

The lack of correspondence between the experimentally obtained results and the anticipated electric strength of detonation gases may be attributed to: 1) a decrease in ion mobility with increasing density, which leads to a more rapid growth in the electric field of the avalanche space charge producing the streamer; 2) a growth in the number of excited particles, whose radiation ionizes the gas, with increasing pressure, this ionization being the basic mechanism for streamer breakdown; 3) shifting of ionization equilibrium towards increasing number of ions and electrons in the gas with increasing temperature and a growth in pressure above 50 atm [3].

The segment in Fig. 3 at which a rather rapid drop in the curve is observed corresponds to the time within which gas density is 100 times greater than the initial density (based on estimates of the scatter of detonation gases when a charge between large-diameter electrodes explodes). Since the distance between the electrodes remains practically invariant as the curve falls, while gas temperature according to [4] is low prior to this moment, we may expect that gap breakdown will depend only on the pressure in the gap.

A model of quasistationary adiabatic gas outflow from a cylindrical cavity was examined in order to determine the nature of the pressure drop of detonation gases as a function of time; i.e., it was assumed that the parameters of the cavity gas depend only on time, which may be assumed valid for pressures and densities in gases already beyond a rarefaction wave reflected from the center of symmetry.

The calculation was carried out numerically on a computer in the case of scattering in air. For scattering in a vacuum, we obtain the analytical dependence

$$p(t) = p_i\left[1 + \frac{\gamma - 1}{R} c_i \sqrt{\frac{2}{\gamma + 1}}\, t\right]^{-\frac{2\gamma}{\gamma - 1}}, \qquad (1)$$

where p_i and c_i are the initial pressure and speed of sound in the detonation gases, γ is the adiabatic index, which varied discretely in the computation in accordance with previous [4] data, and R is the cavity radius.

Numerical calculation of the expansion times of gases flowing into air from a pressure of $2 \cdot 10^3$-$3 \cdot 10^2$ atm with $\gamma = 1.46$ and from $3 \cdot 10^2$-2 atm with $\gamma = 1.25$, differed by less than 4% from the corresponding time found using Eq. (1) in the case of scattering in a vacuum. In view of these assumptions, it is therefore reasonable to use Eq. (1).

If we assume that the electric strength of detonation gases, like that of air up to $2 \cdot 10^3$°C [5], weakly depends on temperature, the nature of the variation of the electric strength of the gap in the case of adiabatic expansion will more nearly correspond to the variation of the gas density, which is connected to pressure by the equation

$$p = \text{const}\ \rho^{\nu}. \qquad (2)$$

A steeper drop in density found using Eqs. (1) and (2) than occurs in Fig. 3, accounts for the behavior of the curve and the small dispersion between the experiments with identical voltage (overvoltages occur a ross the gap due to the rapid drop in its density).

A breakdown at voltages of 11-12 kV and distance between the electrodes of 5-6 mm may be attributed to the inertial nature of the detonation gases, as a consequence of which gap pressure is less than atmospheric pressure [6]. We must bear in mind that gas density will be lower when the gap pressure reaches 1 atm than under normal conditions.

The experiments described here did not allow us to study the electric strength of gases prior to being scattered. Experiments were therefore conducted using a new safety detonator that differed from the preceding one (cf. Fig. 1) by a greater diameter of the insulators ($d \geq 200$ mm) in order to eliminate gap breakdown at an earlier stage of the process, and by a lesser electrode diameter ($d = 20$ mm). The parameters of the charge were as follows: density 1 g/cm^3, diameter 30 mm, thickness 2.5 mm. Voltage was fed across the electrodes after the detonation had passed from the junction betwen them.

On the one hand, we may use the experimental data to approximate the conduction zone of a detonation wave, and, on the other hand, determine the maximal voltages U_{max} that maintain the gap prior to the start of scattering of the detonation gases. The presence of a dielectric surface bounding the charge throughout its height allowed us to decrease to 15 μsec the time at which the voltage was fed across the electrodes following the start of triggering at U_{max}. Prior to this time detonation gases in natural motion behind the detonation wave were not involved in the radial motion induced by the scattering. In the case of shorter periods of time a breakdown will occur at the moment the voltage is fed. It will appear, not in the detonation gases, but along the shortest path through the detonation front. At voltages $U > U_{max}$ a discharge will develop throughout the gases, which can clearly be seen from the oscillograms. The discharge will be aperiodic in the case of gas breakdown, and not oscillatory, as in the case for surface breakdown of the insulators and for breakdown along the detonation front.

The maximal voltage that the gap will maintain for 15 μsec is 45 kV. This agrees with earlier experiments if we take into account the fact that in this case the electrodes scattered to a lesser extent.

In conclusion, let us note that the maximal electric strength of detonation gases of bulk-density charges of PETN and Hexogen is on the order of 100-120 kV/cm and that the time lag of the gap breakdown is determined by the parameters of the outflowing explosion gases.

LITERATURE CITED

1. A. P. Ershov, P. I. Zubkov, and L. A. Luk'yanchikov, "The use of the electrical conductivity zone in the case of a detonation wave from condensed explosives and the electric strength of detonation gases for shaping given high-current pulses and switching off high currents," in: Continuum Dynamics [in Russian], No. 16, Izd. Inst. Gidrodinam. Sibirsk Otd. Akad. Nauk SSSR, Novosibirsk (1974).
2. H. Knoepfel, Ultra-High-Power Pulsed Magnetic Fields [Russian translation], Mir, Moscow (1972).
3. B. L. Timan, "Influence of particle interaction on ionization equilibrium in a thermally ionized gas," Zh. Éksp. Teor. Fiz., 25, No. 6(12), 733-738 (1953).
4. N. M. Kuznetsov and K. K. Shvedov, "Isentropic expansion of hexogene detonation gases," Fiz. Goreniya Vzryva, 3, No. 2 (1967).
5. A. H. Shanbaugh, D. R. White, P. K. Watson, T. H. Lee, and A.H. Greenwood, "An investigation of the breakdown strength of nitrogen at high temperatures using a shock tube," Trans. IEEE. Power Apparatus and Systems, 80, 333-344 (1961).
6. K. P. Stanyukovich, Nonsteady Continuum Motion [in Russian], Nauka, Moscow (1971).