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To cite this article: N P Satonkina 2017 *J. Phys.: Conf. Ser.* **894** 012136

View the article online for updates and enhancements.

Duration of the zone of high electrical conductivity at the detonation of RDX of different densities

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Abstract. This paper presents the results of measuring the duration of the zone of high electrical conductivity during detonation of RDX of different density. It is shown that the density of RDX has a weak effect on the duration of this zone.

1. Introduction
The detonation wave in condensed explosives consists of the shock wave, the reaction zone, the Chapman–Jouguet (CJ) plane (a CJ point in the one-dimensional case), and the Taylor rarefaction wave. In Zeldovich–Neumann–Doring theory [1, 2, 3], the CJ point separating the regions of subsonic and supersonic flows corresponds to the end of the chemical reaction zone. It has been suggested [1] that the reaction zone correlates with the high-pressure region and that the specific volume and pressure in the reaction zone are related by the equation

$$p - p_0 = -\frac{D^2}{v_0^2}(v - v_0),$$

where p is the pressure, v is the specific volume, and D is the detonation velocity; the subscript "0" denotes the parameters of the initial state. The chemical spike is studied using spatial distributions of mechanical parameters such as density, mass velocity, and pressure. An overview of the data the duration of the reaction zone Δt is presented in [4]; different methods give significantly different results.

This paper presents the results of measuring the duration of the zone of high electrical conductivity which may be useful for studying the reaction zone [5] as these regions correlate with each other.

2. Experiments
The techniques of electrical conductivity measurement and data processing were considered in detail in [5, 6], and here we give only a brief description.

The explosive was placed in a copper coaxial cell (Figure 1). The diameter of the explosive charge was $b = 8$ mm. The outer electrode was compound, and its parts *1, 2* were tightly connected to each other by screw threads. The inner copper electrode *3* of the diameter $c = 2$ mm was placed in the explosive and mounted in a Plexiglas plug *4*, which was fixed by a copper
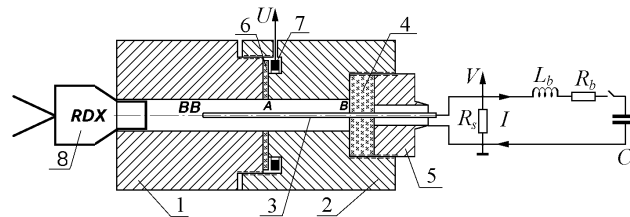
Figure 1. Electrical circuit and experimental cell.

bolt *5*. A toroidal coil *7* which served as a conductivity sensor was placed in the cavity of the outer electrode. The narrow gap between the cavity and the measuring volume of the cell was filled with Plexiglas insulator *6* $0.2 \div 0.7$ mm thick. The cavity in the coaxial cell was filled with the investigated explosive, which was initiated by RDX of density $\rho = 1.1$ g/cm^3 through an axial channel of 2.4 mm diameter in a Plexiglas plug *8*. The total length of the explosive charge was 50 mm. The critical diameter of RDX with a density close to the maximum is 2 mm [7]. Using a thick copper shell reduces it by a factor of 6 to 8 [8].

The cell was supplied with current I from a capacitor through a ballast resistor R_b; a shunt R_s was connected in parallel to the cell. The supply voltage $V(t)$ and the signal at the sensor $U(t)$ were measured. The electrical conductivity in the plane of the gap was proportional to the signal from the coil:

$$\sigma(t) = \frac{\ln(b/c)}{2\pi DM} \frac{U(t)}{V(t)}. \tag{1}$$

Here, t is the time elapsed after the detonation front has passed the gap, D is the detonation velocity, M is the mutual inductance between the coil and the cavity circuit. The signal was corrected to eliminate the distortion of $U(t)$ due to the sensor inductance.

The spatial resolution of the circuit is estimated at one-quarter of the thickness of the insulator *6*. The error in measuring the electrical conductivity did not exceed 20%. By the time the detonation wave reached the insulator *6*, the detonation front had traveled a distance equal to more than four diameters of the explosive from the initiation point. The detonation velocity D was measured on the base $AB \approx 15$ mm. The point A corresponds to the time the detonation wave passes through the section of the outer electrode and insulator, and the point B corresponds to the time the detonation wave arrives at the end of the charge.

Figure 2 shows a typical electrical conductivity profile for condensed explosives with a negative oxygen balance of about 20 %. The profile contains four regions: the increase to the maximum value σ_{max}; the decrease to the point indicated as σ_{ec}; the transition region at $0.05 > t > 0.1$ μs; the region at $t > 0.1$ μs corresponding to the rarefaction wave. In the graph, one can clearly see the triangular zone of high electrical conductivity at $0 > t > 0.05$ μs; the procedure for determining the duration of τ from the front to the intersection of the approximating lines is shown.

3. Results of the experiments

Figure 3 shows data on the durations of the zone of high electrical conductivity τ for different densities of RDX (points); there is no pronounced dependence of τ on density; a value close to 40 ns is present in the entire range of densities.

For a bulk density $\rho \approx 1.2$ g/cm^3, data for different grain size are presented. Earlier [9], a decrease in the duration of the zone of high electrical conductivity τ by a factor of about two with increasing grain size of explosives was obtained for RDX, HMX, and PETN. The difference between the maximum value in Figure 3 (68 ns for a grain size of 160μm) and the minimum value
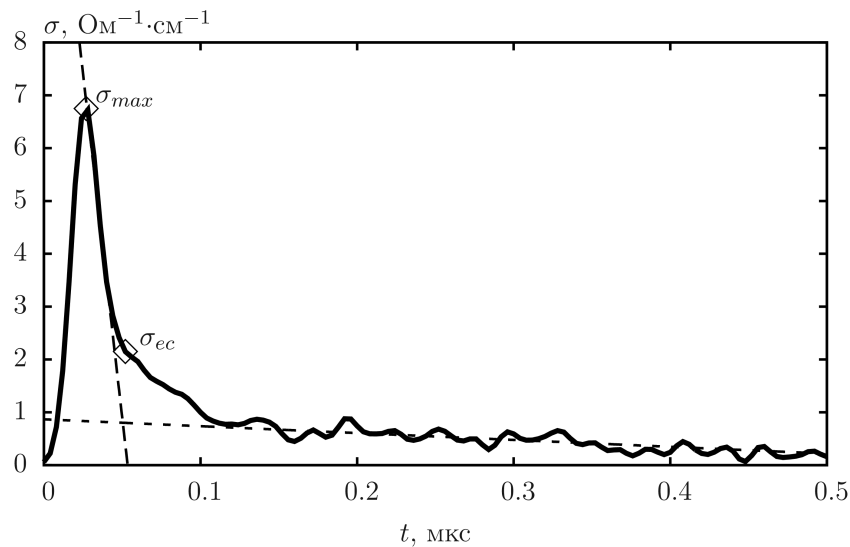
Figure 2. Electrical conductivity profile in detonating condensed explosives. The duration of the electrical conductivity peak is determined from the intersection of two approximating lines.
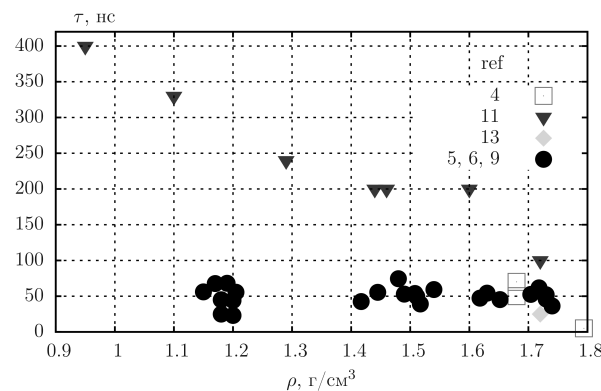

Figure 3. Duration of the chemical peak for RDX of different densities, the points are data on the electrical conductivity distribution, and the remaining symbols correspond to mass velocity and pressure profiles.

(23 ns for a grain size of 11 μm) is 45 ns. The effect of grain size on the mass velocity distribution has previously been found [10] with a similar experimental setup. This effect manifests itself in a decrease of the mass velocity and is explained by an increase in the fraction of material reacted in the front. With the preservation of the high-pressure region associated with the reaction zone, its duration changes.

Note that no effect of the grain size on the duration of the reaction zone for RDX of bulk density was found in work[11], which contradicts to the data of work[10]. The reason is in work[11] the grain size of the explosive was not small enough (150 and 450 μm).

The duration of τ for a density of 1.4–1.75 g/cm^3 is given for an average grain size of 160 μm. The same graph shows data on the duration of the reaction zone Δt obtained from the mass velocity distribution for a charge diameter ≥ 40 mm [4, 12, 13]. The values τ and Δt are similar

only for a density close to the maximum density, with the difference between them increasing with decreasing density.

It can be assumed that during detonation, the sequence of chemical reactions in the reaction zone does not depend on the charge parameters, but the geometry and density of the charge influence the pressure and mass velocity distributions in the DW. This may be responsible for the difference between τ and Δt obtained by different methods.

4. Discussion

It has been assumed [14, 15] that in the detonation of $C_aH_bN_cO_d$ type explosives, the electrical conductivity is determined by the presence of carbon in the explosive. The following model has been proposed: before the arrival of the detonation front, the explosive is a dielectric, and carbon is bound in molecules. The increase of the electrical conductivity to the maximum σ_{max} (Figure 2) corresponds to the destruction of the molecules of the original explosive with simultaneous growth of carbon grids. The decrease of the electrical conductivity from σ_{max} to σ_{ec} reflects the transition of carbon to a nonconducting form. This can be explained by carbon oxidation, as a result of which the conductive structures are thinned, and part of them is destroyed. In the region between 0.05 and 0.1 μs, $\sigma(t)$ has a lower gradient, which may be explained by a decrease of the oxidation rate due to a decrease of the concentration of the reacting components. The model described above implies that σ_{max} and σ_{ec} are characteristics of the same structure at different times, the change in electrical conductivity reflects the evolution of carbon grids, and the aggregation of individual carbon atoms into structures of different scales occurs before the electrical conductivity in the reaction zone has been reached the maximum value.

Thus, condensed carbon, as it is understood in calculations, is not released at the CJ point, but it is a residue of the structures formed in the reaction zone.

The early aggregation of carbon atoms is supported by the following observations. Anisichkin et al. [16, 17, 18, 19] assert that the aggregation of carbon atoms occurs in the reaction zone. It has been found [17] that the carbon components of highly dispersed composite explosives are fully mixed before the onset of oxidation, i.e., in the reaction zone, and oxidation reactions occur later. From energy considerations, Breusov [18] showed that the formation of carbon clusters is associated with a partial rupture of bonds in molecules and the formation and growth of a carbon skeleton. Molecular dynamics simulation [19] of the clustering of carbon upon heating of TATB, HMX, and PETN molecules has shown the formation of carbon nanostructures in the reaction zone.

The following data on the sequence of chemical reactions are reported in the literature. Calculations of Tarver [20, 21] showed that for condensed explosives, the synthesis of water occurs before the formation of CO_2. It was found [21] that the formation of water, CO_2, and N_2 and the release of condensed carbon occur simultaneously in the final stage of chemical reactions. Anisichkin [16], having analyzed the results of isotope tracer experiments, also claims that water production proceeds before the formation of CO and CO_2. Carbon is oxidized to a gaseous state after the formation of diamond and non-diamond phases. Thus, the authors of the above-mentioned papers agree that the reactions with carbon end no later than other chemical reactions.

Papers [16] and [20, 21], although disagreeing with each other in detail, nevertheless agree that carbon oxidation reactions end no earlier than others. Since the end point of chemical reactions with water and nitrogen approximately corresponds to the end of carbon oxidation, it can be assumed that the change of electrical conductivity through due to the change of the state of carbon reflects the kinetics of the reaction zone.

5.   Conclusions

Experimental data on the duration of the zone of high electrical conductivity in detonating RDX are presented, showing that the density of RDX has a weak effect on the duration of this zone. It is suggested that the electrical conductivity traces the chemical state of the material during detonation. The previously proposed model of electrical conductivity and the relationship between the zone of high electrical conductivity and the reaction zone are discussed.

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