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Video Recording of an Air Blast Wave Resulting from Initiation of a Light-Sensitive Explosive Composition

S. I. Gerasimov[a,b,c,d] **and N. A. Trepalov**[a]

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Abstract: This paper presents experimental data on the parameters of an air blast wave resulting from initiation of VS-2 light-sensitive composition by laser diode radiation. The propagation of the air blast wave front was recorded by the background-oriented schlieren method. The air blast wave front was visualized using cross-correlation processing. Empirical dependences characterizing the propagation of the air blast wave front resulting from initiation of a light-sensitive composition of arbitrary weight. Experiments confirmed the possibility of initiating VS-2 light-sensitive composition using an EV-15 electric igniter.

Keywords: high-speed video recording, background-oriented schlieren method, light-sensitive composition, air blast wave, electric igniter, X-ray recording.

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INTRODUCTION

Light-sensitive initiating explosives are used in specific technical devices for civilian and military purposes [1]. The promising class of light-sensitive explosives includes some coordination compounds of heavy and transition metals. Originally, (5-cyanotetrazolato-N_2) pentaammine cobalt (III) perchlorate (CP) was proposed as a new explosive in blasting caps [2]. Then, tetraammine-cis-bis (5-nitrotetrazolato-N_2) perchlorate cobalt (III) (BNCP) was proposed as one of the most effective initiating explosives [3]. BNCP charges in electric and laser detonators decompose in deflagration-to-detonation transition and function as both a primary and a secondary blasting explosive. Furthermore, BNCP is less sensitive than PETN to impact on an impact test machine. The light-sensitive complex perchlorates CP and BNCP are widely used in laser optical initiation systems. Subsequently, a number of complex compounds of *d* metals with high ionization potentials, reactive high-enthalpy ligands, and effective oxidizing anions were obtained [4, 5]. These are, first of all, (5-hydrazo-1H-tetrazole) mercury perchlorate (II) (VS-2), a silver compound which is the first representative of the new class of coordination compounds—complex perchlorylamides, and di-(3-hydrazino-4-amino-1,2,3-triazole)-copper (II) perchlorate. These compounds exhibit extremely high susceptibility to a laser single pulse. For the first of these, the threshold initiation energy is about 5 $\mathrm{mJ/cm^2}$, and for the other two, it is slightly higher.

The VS-2 composition is proposed to be used in a number of applied problems associated with testing the strength of materials and structures with simultaneous loading of their surface by explosion products: using wireless initiation in various optically transparent media and initiation by standard electric blasting caps. Therefore, we investigated the initiation of PETN by a standard cap with VS-2 composition.

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[a] Institute of Experimental Physics (VNIIEF), Russian Federal Nuclear Center, Sarov, 607190 Russia; s.i.gerasimov@mail.ru.

[b] Sarov Institute of Physics and Technology—Branch of MEPhI National Nuclear Research University, Sarov, 607186 Russia.

[c] Alekseev Nizhny Novgorod State Technical University, Nizhny Novgorod, 603950 Russia.

[d] Institute of Mechanical Engineering Problems of Russian Academy of Sciences—Branch of the Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, 603024 Russia.

One of the indicators characterizing the energy of an explosive is the air blast wave (ABW) with its characteristic parameters. The most complete information about the ABW shape and its propagation in space can be obtained by high-speed video recording of the explosion process. The initial region of ABW generation is of particular importance and interest for consideration. In this experiment, we used the background-oriented schlieren method for video recording of the propagation of an ABW generated by initiating a light-sensitive explosive composition. The obtained data made it possible to determine the propagation velocity of the ABW front and the overpressure in the ABW front.

1. EXPERIMENTAL SETUP

1.1. Light-Sensitive VS-2 Explosive Composition

The basis of the light-sensitive VS-2explosive composition is the complex compound of mercury (II) perchlorate with 1-H-5-hydrazinoterazole as a ligand [6]. In the preparation of the energetic light-sensitive VS-2 composition, the inert matrix (binder) is the optically transparent copolymer of 2-methyl-5-vinyltetrazole (≈98%) and methacrylic acid (≈2%). The final composition contains 10% polymer and 90% mercury (II) perchlorate complex. The VS-2 composition is a white crystalline substance with a single crystal density of 3.45 g/cm^3 [7, 8].

In the experiments, we used a light-sensitive element consisting of ≈0.1 g of VS-2 placed in a brass cap.

The possibility of initiating an assembly of several caps with VS-2 by incoherent radiation has been demonstrated in [9]. A diagram of the experiments is presented in Fig. 1. An assembly of five light-sensitive elements was mounted along the streamer track of a linear gas-discharge incoherent radiation source powered by an electric energy storage device (150 J, 15 kV). The start of the energy storage device and the X-ray source was controlled using a delayed pulse generator. Shooting time intervals in four experiments were chosen equal to 0, 5, 10, and 30 μs from the moment of light pulse generation. The results of X-ray recording are shown in Fig. 2. The data obtained indicate the relative synchronization of detonation. The times of initiation of light-sensitive elements in the assembly are in the range ±3 μs [9], which satisfies the conditions for the solution of most gas-dynamic problems [10]. The initiation time does not exceed 10 μs [9].

Additionally, we experimentally tested the possibility of initiating VS-2 using an EV-15 electric igniter [Russian Industry Standard (OST) No. 84-124-75], which is a miniature (∅5.35 × 5.5 mm) device for initiating fine granular powders. The assembly with PETN in a DShE-12 [Russian Standard (GOST) No. 6196-78] detonating cord was tested. Fragments of the video recording of the initiation process and a photograph of the witness plate after the experiment are presented in Fig. 3. The results confirm the initiation of VS-2 with the EV-15 electric blasting cap followed by the initiation of steady detonation in the energetic blasting substance (PETN).

The possibility of initiating a light-sensitive element by a laser diode radiation was demonstrated in [11]. This method was used in our experiments with ABW video recording.

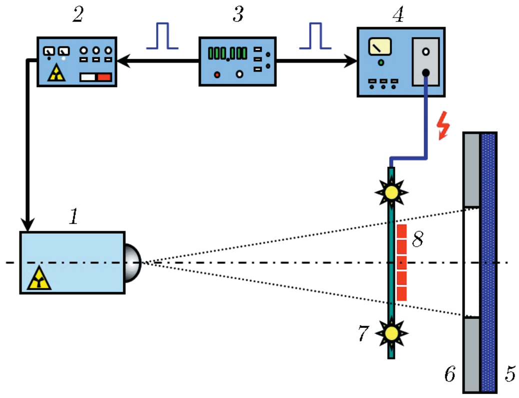

Fig. 1. Diagram of experiment: (*1*) X-ray source; (*2*) control panel; (*3*) delayed pulse generator; (*4*) electric energy storage device; (*5*) protected cassette with X-ray film; (*6*) radiation absorbing lead mask; (*7*) incoherent light source; (*8*) experimental assembly.

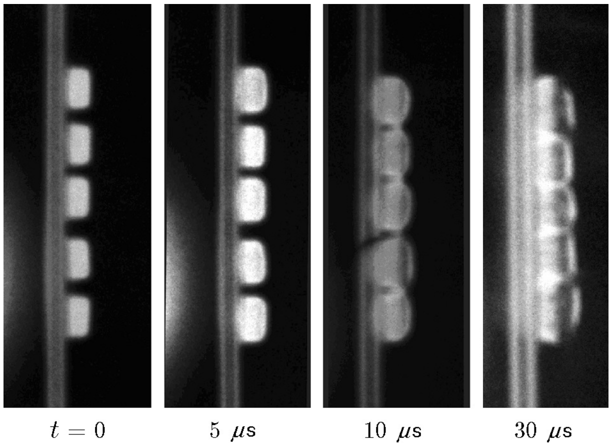

Fig. 2. X-ray images of the detonation process.

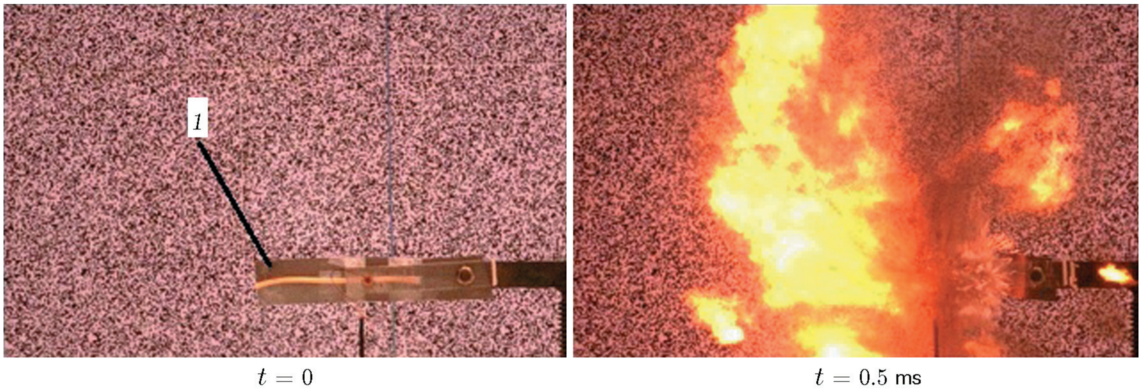

Fig. 3. Fragment of the video recording of the initiation of the assembly with an EV-15 electric blasting cap.

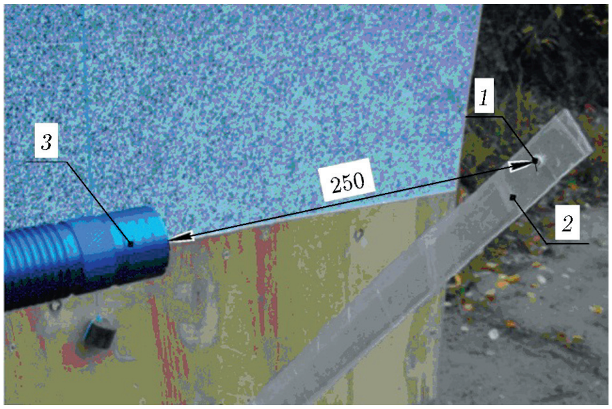

Fig. 4. Arrangement of the components of the initiation circuit: (*1*) light-sensitive element; (*2*) Plexiglas plate; (*3*) emitter (laser diode).

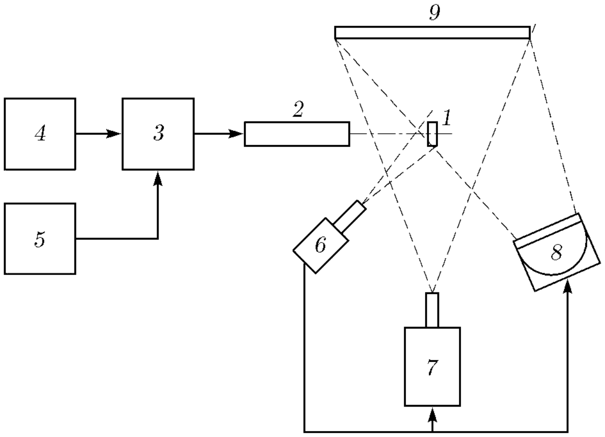

Fig. 5. Diagram of the experiment: (*1*) light-sensitive element; (*2*) emitter (laser diode); (*3*) control unit; (*4*) power supply; (*5*) pulse generator; (*6*) photodetector; (*7*) high-speed video camera; (*8*) pulsed light source; (*9*) background screen.

1.2. Recording Circuit

To record the ABW generated during the initiation of VS-2, the light-sensitive element was mounted in a mounting through hole at a height of ≈1.5 m in a Plexiglas plate (Fig. 4). The VS-2 composition was illuminated by a laser diode in the single-pulse mode with a duration of 1 s. The pulse duration was selected with a large margin for safety of the experiment in the case of inaccurate focusing of the laser diode. The initiation and optical recording circuits are shown in Fig. 5.

The initiation circuit includes an emitter (*2*) based on a laser diode, a power supply (*4*), a control unit (*3*) and a pulse generator (*5*). The control unit performs switching of the power supply for the operation of the laser diode for the time set by the pulse generator.

Video recording of the propagation of the ABW generated during the initiation of the VS-2 composition was carried out by the background-oriented schlieren method [12] with external illumination. At the moment of initiation of VS-2 (appearance of light radiation), the photodetector (*6* in Fig. 5) starts the high-speed video camera (*7*) and the IIS-5 pulsed gas-discharge light source (*8*). The amplitude light intensity of IIS-5 $6 \cdot 10^6$ cd ± 15% and the pulse duration ≈5 ms provide sufficient illumination of the background screen (*9*) during the recording time (the presence of the ABW in the frame). The shooting frequency was 9300 fps, and the exposure time 6.76 μs. An artificially generated screen with Gaussian noise consisting of square elements was used as a background screen. The grain size of the screen was chosen so that one screen element corresponded to 4 pixels of the video camera array.

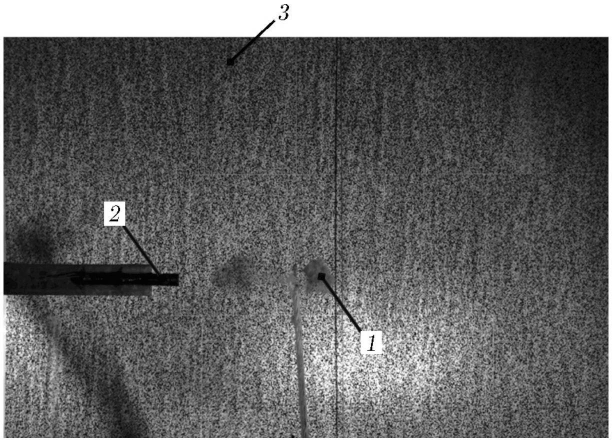

Fig. 6. Video recording frame: (*1*) explosion products; (*2*) emitter (laser diode); (*3*) background screen.

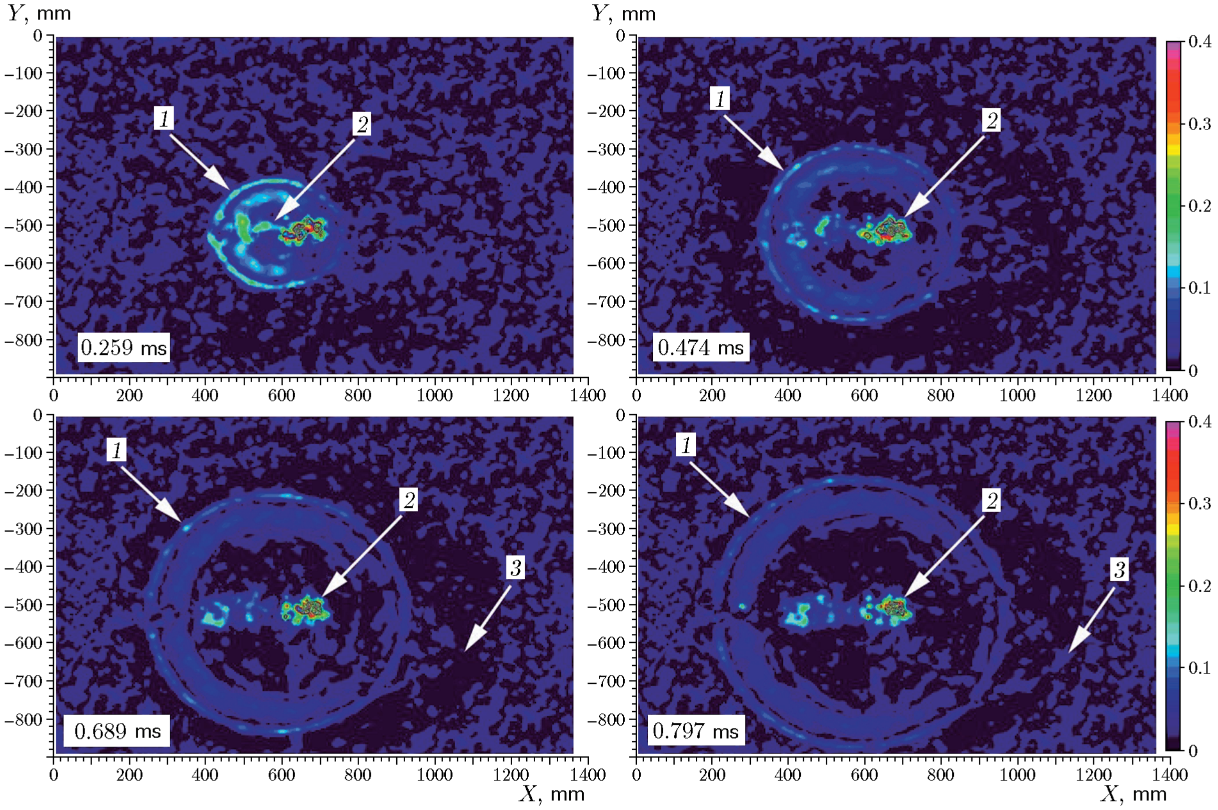

Fig. 7. Visualization results: (*1*) ABW front; (*2*) explosion products; (*3*) fragment.

1.3. Recording Results

Figure 6 shows one of the video frames obtained at time 0.8 ms after the initiation of VS-2. The test conditions were as follows: an ambient temperature of 6°C, an atmospheric pressure of 99 125.2 Pa, and a relative humidity of 95%.

To visualize the ABW, the obtained video information was processed using the PIVview program (demo). A multipass cross-correlation processing algorithm with a square polling window and a 50%-overlap was used. The interrogation window size was iteratively decreased from 192 to 8 pel. The correlation function was approximated using a three-point Gaussian interpolation with-

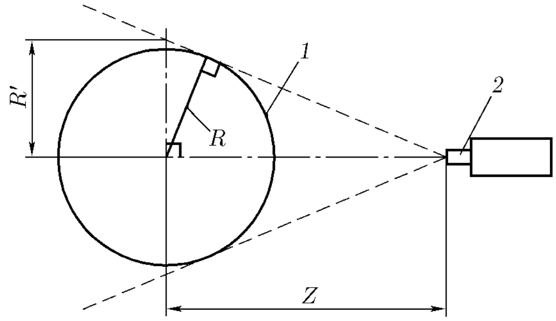

Fig. 8. Optical recording circuit: (*1*) ABW front; (*2*) high-speed video camera.

out preliminary image processing. A median filter with a 3 × 3 mask was applied to the resulting field between the cross-correlation iterations. Processing results with a time origin at the beginning of the explosion are presented in Fig. 7. At the initial stage of ABW propagation, the front exhibited nonsphericity, which decreased over time. The nonsphericity is due to the design of the light-sensitive element and its mandrel (Plexiglas plate) for fixing in space. Starting at a time of 0.582 ms after the initiation of VS-2, motion of the fragment ahead of the ABW front is observed.

1.4. Determination of the ABW Parameters

The results of visualization of the ABW were used to plot a diagram of the ABW front propagation, and then the overpressure in the front was determined. The ABW parameters were determined according to the algorithm described in [13].

Taking into account the nonsphericity of the ABW, the average value of the front radius R' was calculated by the formula

$$R' = m\sqrt{S/\pi}, \tag{1}$$

where m is the scale factor and S is the image area bounded by the ABW front.

The area S was determined using the ImageJ software—a free cross-platform software. In view of the features of the optical recording circuit of the spherical ABW (Fig. 8), the radius of the ABW front R was determined by the formula

$$R = Z\sin[\arctan(R'/Z)], \tag{2}$$

where Z is the distance from the high-speed video camera to the location of VS-2.

Figure 9 shows data on the ABW front propagation obtained in two experiments. The error of the radius of the ABW front is due to the spatial resolution of the optical recording system, and its standard deviation was 0.9 mm. The experimental results were supplemented by a value $R_0 = 1.96$ mm (radius of the sphere corresponding to the volume of VS-2 in the light-sensitive element) at time $t = 0$. The resulting dataset was approximated by the relation

$$R(t) = A + Bc_0t + C\ln(1 + c_0t) + D\sqrt{\ln(1 + c_0t)}, \tag{3}$$

where A, B, C, and D are the approximation coefficients and c_0 is the speed of sound in the undisturbed medium 334.85 m/s (at an ambient temperature of 6°C). It was found that the approximation coefficients of function (3) were: $A = 2.163\cdot10^{-3}$, $B = 1.095$, $C = -0.302$ and $D = 0.244$. By differentiating the dependence $R(t)$, we obtained the propagation velocity of the ABW, whose values were used to calculate the overpressure in the ABW front:

$$\Delta p = \frac{2\rho_0}{k+1}\,(D_f^2 - c_0^2), \tag{4}$$

where $\rho_0 = 1.238$ kg/m^3 is the air density in the undisturbed medium at an ambient temperature of 6°C and

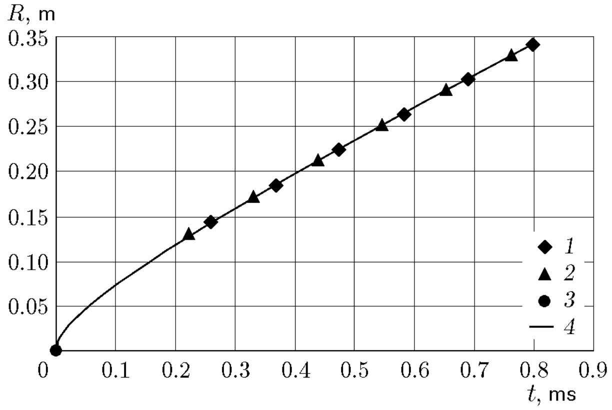

Fig. 9. ABW front propagation in experiment (points *1* and *2*) and the approximation curve *4* taking into account the radius R_0 (point *3*).

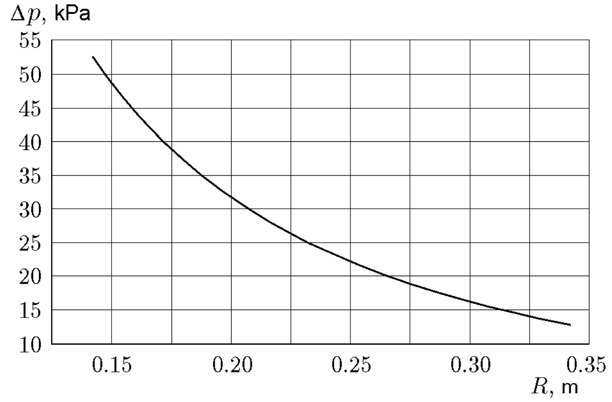

Fig. 10. Experimental dependence of the overpressure in the ABW front.

a pressure in the undisturbed region of 99 125.2 Pa; $k = 1.4$ is the Poisson adiabatic exponent for air; D_f [m/s] is the velocity of the ABW front, and $c_0 = 334.85$ m/s. The resulting dependence is shown in Fig. 10.

2. ANALYSIS OF EXPERIMENTAL DATA

In practice, one often uses modeling, which is understood as the prediction of parameters of full-scale blast waves from the parameters of explosions performed in reduced scales under benign conditions. This modeling is based on the cubic root principle first formulated by Hopkinson in 1915 [14] and independently by Cranz in 1926 [15]. Modeling using the Hopkinson–Cranz method is valid only for the ambient pressure and the speed of sound at which the measurements were performed. Dependences of blast wave parameters on geometric and energy quantities cannot be called universal since they do not reflect the effect of the initial pressure and speed of sound in the medium. Sachs variables [16] are more suitable for describing blast wave parameters. The Sachs method takes into account changes in atmospheric pressure and temperature.

Experimental data on the ABW front propagation (see *1–3* in Fig. 9) were made dimensionless using the Sachs method and the formulas [17]

$$R_s = R/S, \quad t_s = ct/S,$$
$$S = \sqrt[3]{W}\,\sqrt[3]{101.325/p}, \quad c = \sqrt{T/288.6}, \tag{5}$$

where R and t are the measured radius and its corresponding time of the discrete location of the ABW, S and t_s are the scale factors, W [kg] is the weight of the charge, p [kPa] and T [K] are the ambient pressure and temperature during the experiment, respectively.

The data obtained were approximated by the relation (Fig. 11)

$$R_s(t_s) = A + Bc_0t_s$$

-1.5mm

$$+ C\ln(1 + c_0t_s) + D\sqrt{\ln(1 + c_0t_s)}, \tag{6}$$

where is the speed of sound in the undisturbed medium c_0 corresponds to the normal climatic conditions ($c_0 = 340.9$ m/s). Based on experimental results the approximation coefficients of function (6) for VS-2 were $A = 0.042$, $B = 1.066$, $C = -0.452$, and $D = 1.481$.

Figure 12 shows experimental data on the propagation of the ABW front from the VS-2 composition and other explosives [13, 17–19]. All experiments were performed under normal climatic conditions with an explosive weight of 1 kg. As can be seen from the graphs, the dynamics of the ABW front for VS-2 at the initial stage is comparable to the data for lead azide, and from time 7.5 ms, it is comparable with the data for TNT.

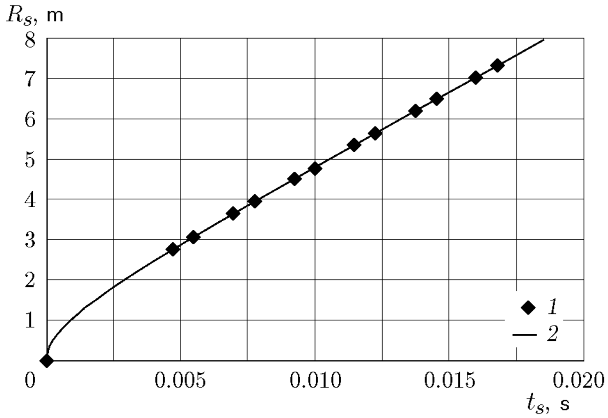

Fig. 11. Diagram of the ABW front propagation in the given coordinates: (*1*) experimental values; (*2*) approximation curve.

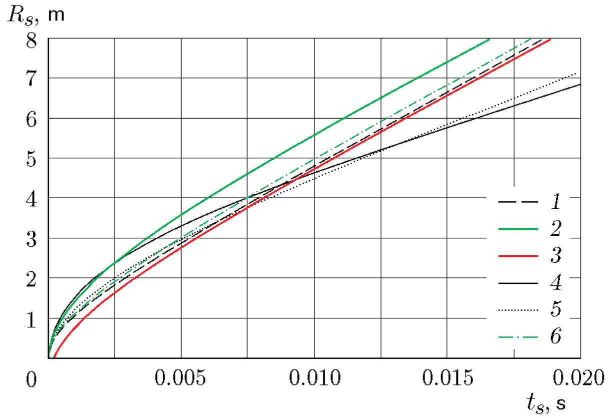

Fig. 12. Dynamics of ABW front propagation during explosion of an explosive weighing 1 kg under normal climatic conditions: (*1*) VS-2; (*2*) PVV-7 [8]; (*3*) TNT [12]; (*4*) PETN [13]; (*5*) acetone peroxide [13]; (*6*) lead azide [14].

CONCLUSIONS

The results of video recording of the ABW front propagation during the initiation of ≈0.1 g of the light-sensitive VS-2 composition placed in a brass cap were used to obtain a diagram $R(t)$ of the ABW front propagation and the dependence of the ABW overpressure on the radius of the front $\Delta p(R)$. The coefficients of the empirical equation describing the propagation of the

ABW front resulting from the initiation of the light-sensitive composition weighing 1 kg under normal climatic conditions were obtained by the Sachs method. The data of this study can be used in applications based on contactless initiation of caps with VS-2 included in the detonator design, as well as for evaluation of the parameters of ABWs resulting from the initiation of the light-sensitive VS-2 composition of arbitrary weight under arbitrary ambient parameters.

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