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Development of a Programmable 16-Frame Electron-Optical Camera NANOGATE-22/16 and its Application for Measuring the Space-Time Characteristics of Fast-Flowing Processes in Ballistics and Explosion Physics

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Abstract

The paper presents the main technical characteristics and results of the application of the programmable electron-optical camera NANOGATE-22/16, developed at NANOSCAN LLC, Moscow. The frames of characteristic experiments from the field of explosion physics are presented. The electron-optical camera is an 8-channel system consisting of one input lens, a mirror-lens unit for dividing the image into eight channels (an additional lens, an octagonal mirror prism, eight mirrors) and the electron-optical channels themselves (K-1, K-8). The data obtained as a result of recording images of a fast-flowing process is transmitted through eight fiber-optic communication lines to a transceiver that converts signals at eight optical inputs into a signal at a single USB-3 output, which is connected to the corresponding computer input. All 16 registered images are visualized on the computer monitor. The dust- and moisture-proof housing of the electron-optical camera provides the possibility of its use in landfill conditions.

Keywords: high-speed electron-optical camera, explosion physics, shock wave, detonation wave, explosive, scientific visualization.

1. Introduction

The improvement of scientific visualization methods [1-10] is largely determined by the capabilities of modern registration tools. The eight-channel 16-frame electro-optical camera is designed for high-speed image recording of fast-flowing processes in the nano- and microsecond time ranges. The appearance of the camera is shown in the Fig. 1.

Figure 1 - 8-channel 16-frame camera "NANOGATE 22/16".

A simplified optoelectronic circuit of the camera is shown in Figure 2.

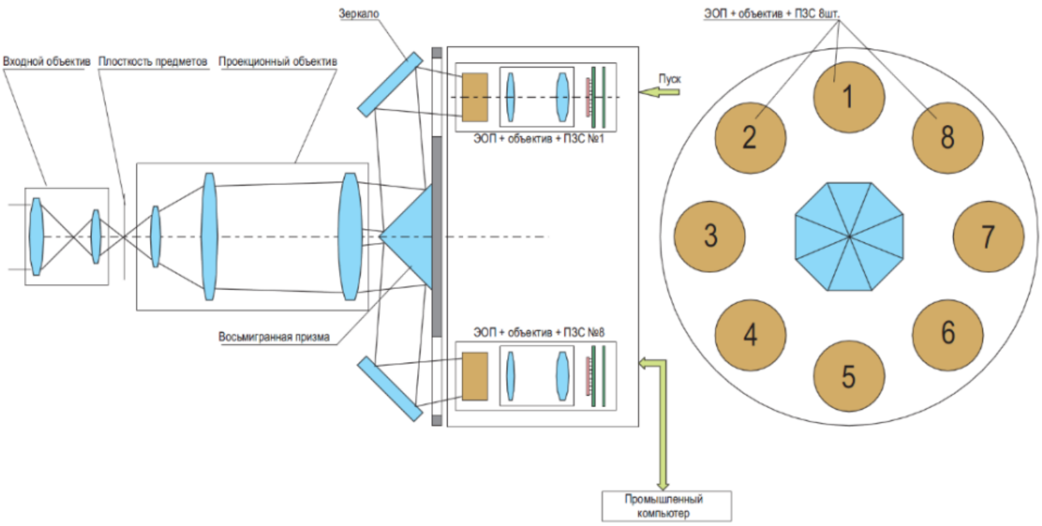


Figure 2 – Optical-electronic circuit of the camera.

The recorded image, passing through the input lens, falls on a pyramidal mirror beam-splitting system with eight electron-optical channels (EOC). The hardware composition of the channel: shutter - a planar image intensifier tube (IIT) with a diameter of 18 mm; image transfer – a 1:1 projection lens with an aperture of 18°; sensor - a CCD sensor with a size of 15.4×15.4 mm, 2048×2048 elements. The sensitivity of each channel is independently regulated by adjusting the voltage on the microchannel plate of the image intensifier, which allows you to study processes with a wide range of brightness. Each of the eight channels registers two frames, the parameters of which are set independently both in terms of exposure time (5 ns ÷ 20 microseconds) and in the inter-frame interval (5 ns ÷ 1000 microseconds). Each channel can operate in multiple exposure mode, registering several phases of the process per frame. The latest modification of NANOGATE-22/16 is a dust- and moisture-proof version of the camera, has increased reliability and is designed to work in landfill conditions. This application is not available for foreign cameras of a similar class – CORDIN Model 222 (USA) and pco.dicam C8 UHS (Germany) [11,12].

Table 1 - The main technical characteristics of the NANOGATE-22/16 camera

Parameter	Value
The number of independent electron-optical channels	8
The number of frames recorded during a single launch	16
The spectral range of the IIT photocathode	from 400 to 850 nm
The working diameters of the IIT photocathodes	18 mm
The duration of the gating (gate) pulse (set independently for each channel in 1 ns increments)	from 5 ns to 20 μs
Spatial resolution at all values of the duration of strobe pulses, at least	44 pairs of lines/mm

The time interval between frames (channels)	from 5 ns to 20 µs
Shutter release time delay (set in 5 ns increments)	from 80 ns to 1,000 µs
The absolute error of setting the shutter delay	10^{-5}
Temporary instability (jitter) of the EOC trigger, no more (in another version of the camera, instability of less than 1 ns is possible due to a deterioration in the absolute error of the shutter delay value to 5×10^{-2})	5 ns
The voltage on the microchannel plates of the IIT (set in 1 V increments)	from 400 to 850 V
Resolution	2048×2048
The ADC bit rate	12 bit
Extension of the saved image file	*tiff
The number of fiber-optic communication lines (fiber optic lines) for communication with a computer	8
The length of the fiber optic cable	from 5 to 300 m
Overall dimensions (without lens)	575×265×295mm
Power consumption	60 W

2. Results

Application of the NANOGATE-22/16 camera in experiments.

2.1 Institute of Problems of Chemical Physics of the Russian Academy of Sciences (Chernogolovka)

All experiments were performed by the staff of the IPHF RAS under the guidance of leading researcher Dudin S.V. [13,14].

Experiment No. 1. Registration of a detonation converging wave.

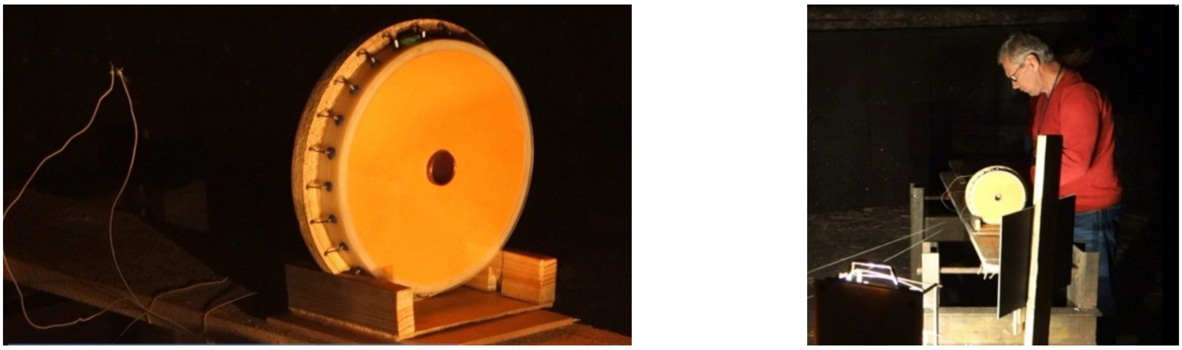


Figure 3 – The explosive charge and the process of preparing the experiment.

Experience preparation. The detonation converging wave is launched from 24 points evenly spaced around the circumference of the disk. Numbering of frames from left to right and from top to bottom. The exposure time of all frames is 20 ns. The intervals between frames are 1.4 microseconds.

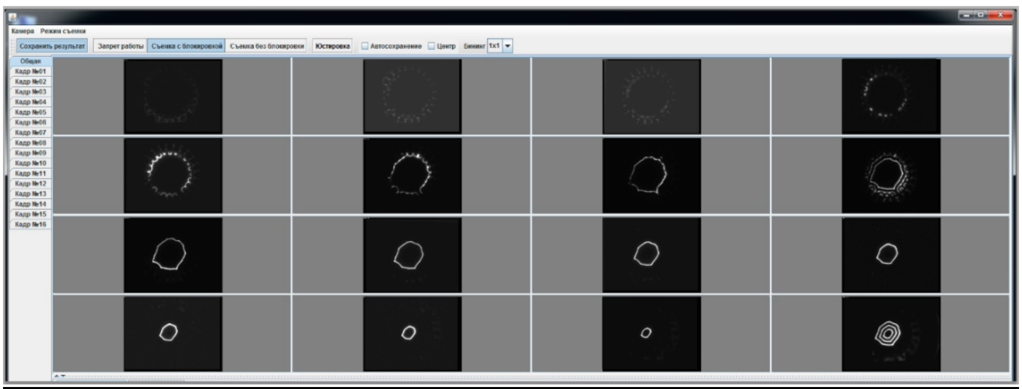


Figure 4 – Results of registration in the experiment.

In the 8th and 16th frames, the multiple exposure mode is enabled (superimposing multiple IIT exposures on one frame in the CCD matrix). In the 8th frame, exposures are made at moments 2, 4, 6 and 8 frames. In the 16th frame, exposures are made at moments 11, 13, and 15 of the frame. With a set of precision parameters, the NANOGATE-22/16 camera has the ability to measure the spatiotemporal characteristics of fast-flowing processes in the nanosecond time domain with an error of up to 1%. The results of 3x exposure in the 16th frame are shown below, the times of which coincide with the times of the above 3 frames.

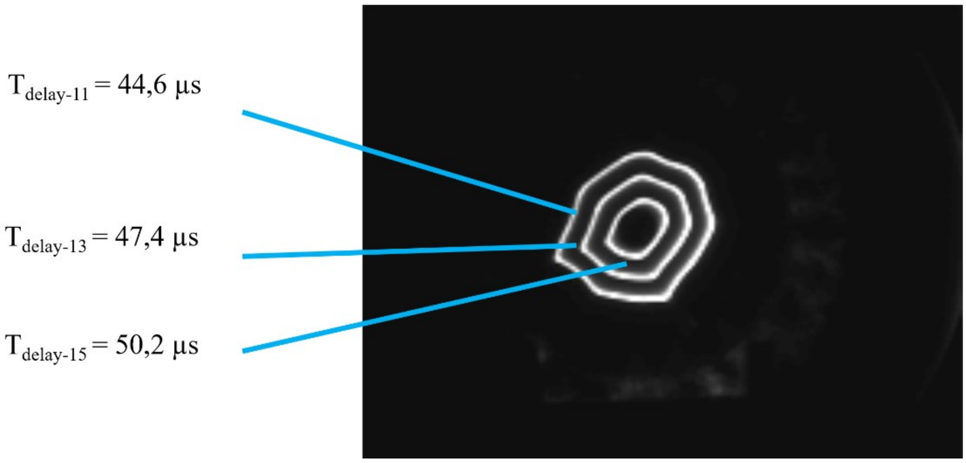


Figure 5 – Construction of the 16 registration frame.

From the analysis of the images obtained in each of the 16 frames, including those in which the multiple exposure mode was turned on, it was concluded that in such an experiment, it is possible to register not 16, but 64 phases (at least) of the detonation converging wave. To do this, in each of the 16 frames, the 4-fold exposure mode is turned on with an interval between repeated exposures $T_{rep} = 1/64 \times T_{exp}$, after about 290 ns (the entire recording time was T_{exp} = 18.2 microseconds). Such a number of phases of the detonation converging wave has made it possible to register a change in the velocity and shape of the detonation converging wave as it moves from the periphery of the disk to the center.

Experiment No. 2. The development of detonation in a bulk high explosive (HE). During the experiment, the velocity spread of the detonation wave (DW) in a bulk HE was measured. During the experiment, the detonation rates from each initiating detonation cord (DC) have been measured. The information obtained allow us to estimate not only the average speed of the engine, but also the magnitude of its standard deviation (SD), which is the most important characteristic of any HE. Additionally, the effectiveness of using the strobing mode of the NANOGATE 22/16 camera during experiments of this type has been tested. Due to the fact that in all experiments the velocity of the detonation wave front at different phases of the process ranged from 2.5 to 9 km/s, the exposure duration of each of the 16 frames was set to 10 ns. The values of the moment of registration (Δi) are indicated from the time of the explosive pulse. In the seventh frame, the multiple exposure mode is enabled (the IIT shutter opens 6 times and the integral image from the IIT screen accumulates in one frame of the CCD matrix). An image of six phases of the process, four of which are duplicated in other channels to verify the accuracy of the inter-frame positioning of the NANOGATE 22/16 camera as a whole. The multiplicity of the DW images is caused by the use of a household mirror, which forms parasitic reflections from the glass surface.

Despite the simultaneous initiation of all DC of equal length, the time of transmission of detonation to the tested explosive is different. Such a difference in timing is more or less characteristic of any multipoint initiation systems due to technological variations in the parameters of explosives in the DC. Nevertheless, the analysis of the propagation of DW in the vertical direction makes it possible to measure the vertical velocity of DW from each initiation point with high accuracy. The average speed of the engine was 5.630 km/s.

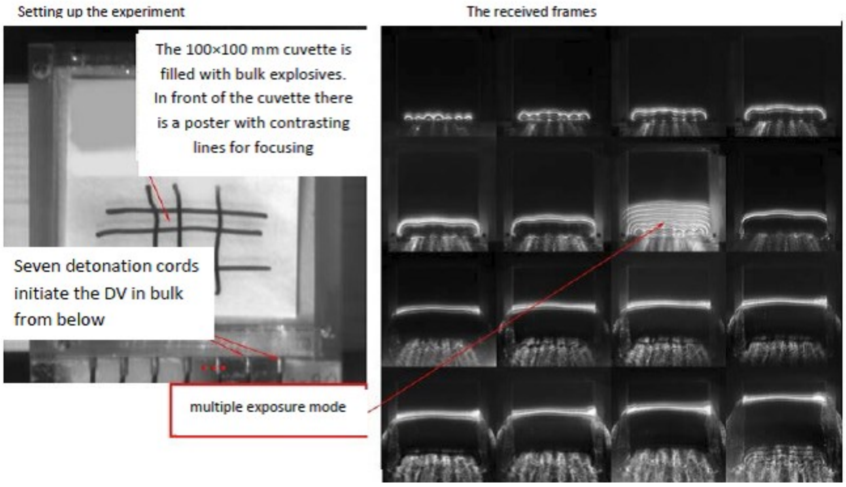


Figure 6 – Results of registration in experiment No. 2.

Experiment No. 3.

Testing of a cylindrical implosive device. The annular DW is formed by the supply HE rods. The symmetry of the converging DW is ensured by the use of a focusing system (FS). The purpose of the experiment is to work out the FS, to clarify the parameters of the mathematical model of

explosive kinetics.

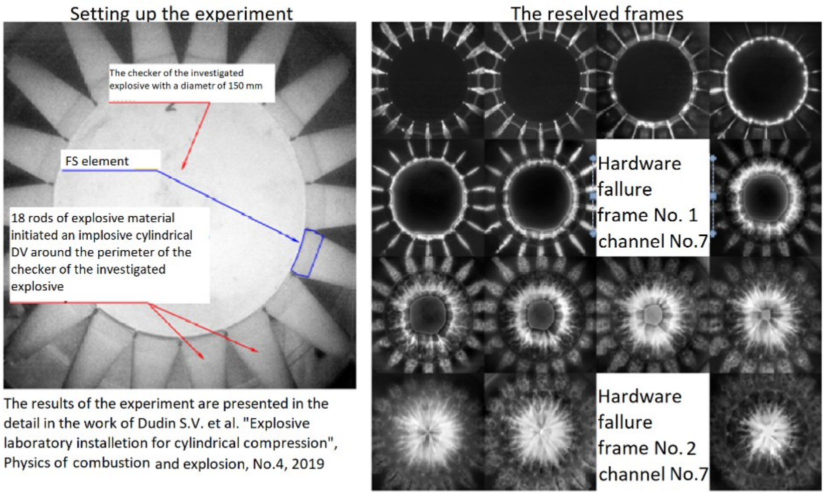


Figure 7 – Results of registration in experiment No. 3.

The exposure duration in each frame is 10 ns, the interval between frames is 1 microsecond. To demonstrate the recording quality at an exposure duration of 10 ns, Figure 8 shows an enlarged image of the 13th frame separately. Figure 8 – Registration frame No. 13 in experiment No.3.)

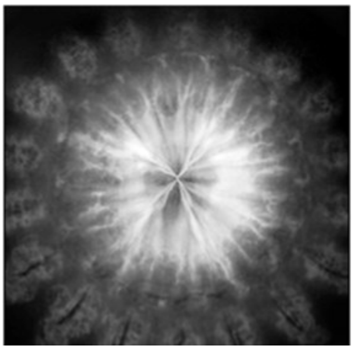


Figure 8 – Registration frame No. 13 in experiment No.3.

2.2. RFNC VNIIEF, SarFTI (Sarov)

Experiment No. 1. Registration of the propagation of the detonation wave of the photosensitive explosive composition VS-2[15,16]. Strips of photosensitive explosive VS-2 measuring 10×80 mm, applied to a polished aluminum sheet measuring 23x100x0.15 mm, were attached with adhesive tape to a witness plate with dimensions of 60x300x4 mm (Figure 9).

Figure 9 – The witness plate with the composition of VS-2.

The initiation of the VS-2 composition was carried out using an EVIS-3 gas discharge emitter, remote at a distance of 14 mm. The streamer of the gas discharge emitter was located at a distance of 10 mm from the edge of the strip with the composition VS-2. The appearance of the experimental installation is shown in Figure 10.

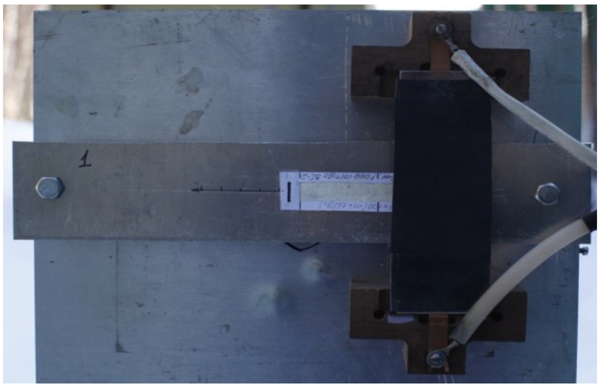
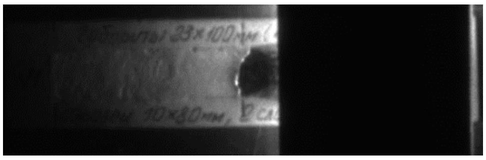
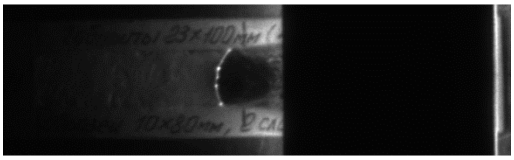


Figure 10 – The appearance of the experimental installation

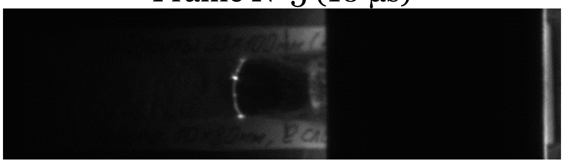
The exposure duration in each frame is 20 ns, the interval between frames is 1 microsecond.



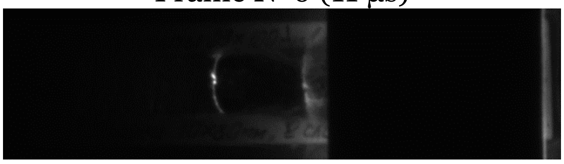
Frame №5 (10 µs)



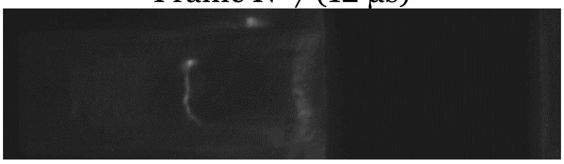
Frame №6 (11 µs)



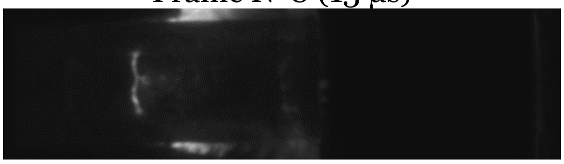
Frame №7 (12 µs)



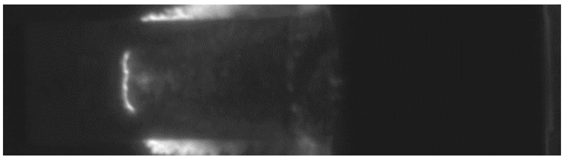
Frame №8 (13 µs)

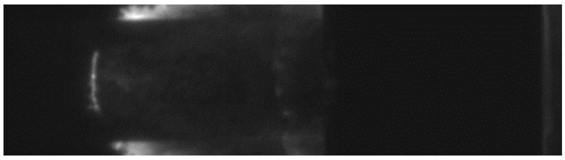


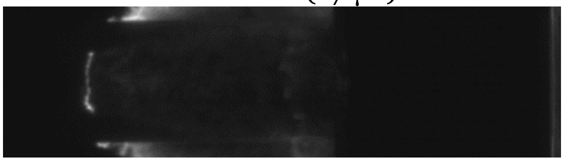
Frame №9 (14 µs)



Frame №11 (16 µs)


Frame 12 (17 μs)


Frame 13 (18 μs)


Frame 14 (19 μs)

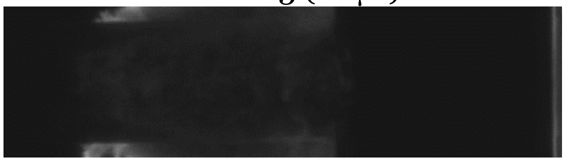

Frame 15 (20 μs)

Figure 11 – Fragments of registration frames in experiment No. 1.

Based on the data obtained, the dynamics of the movement of the detonation wave front was estimated. The assessment was carried out at two points: the coordinates of the maximum (1) and minimum (2) remote part of the detonation wave front relative to the right edge of the strip with the composition of VS-2. The average velocity of the detonation wave front in the experiment was 4375 m/s.

Experiment No.2. Explosive throwing of a barrier simulator model. In the experiment, the design of a small-size explosive throwing device was worked out, the integrity of the barrier simulator model was monitored. Registration was carried out against the background of a scattering screen illuminated by explosive light sources. The exposure duration in each frame is 100 ns, the interval between frames is 5 microseconds.

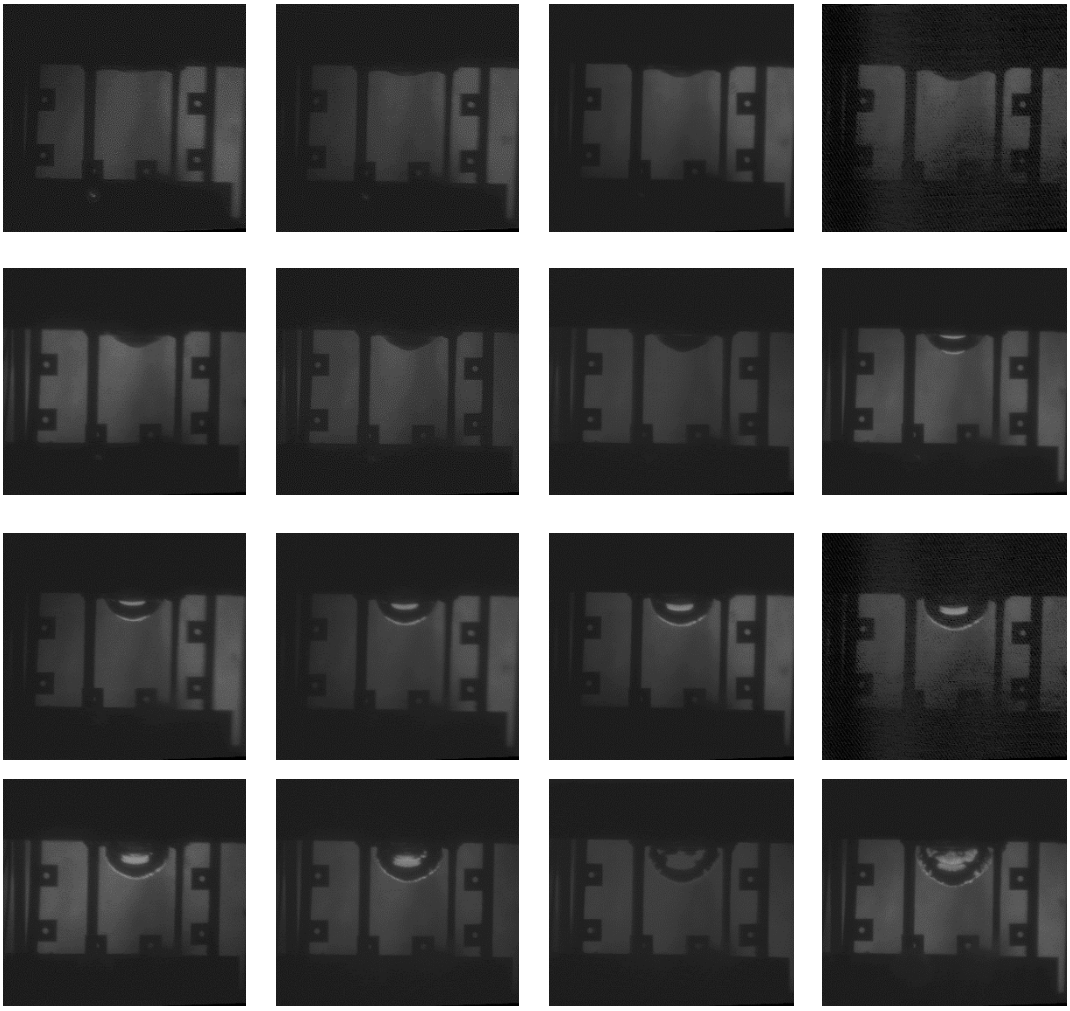


Figure 12 – Fragments of registration frames in experiment No. 2

According to the obtained motion picture of the barrier simulator model, the speed of movement of the silhouette boundary was determined, which amounted to 1900 m/s.

Experiment No. 3. Optical recording by a high-speed NANOGATE 22/16 camera of the throwing process of an barrier simulator model (BSM) using a model explosive throwing device (ETD) against the background of a scattering screen.

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Figure 13 – Photo of the working field in experiment No. 3

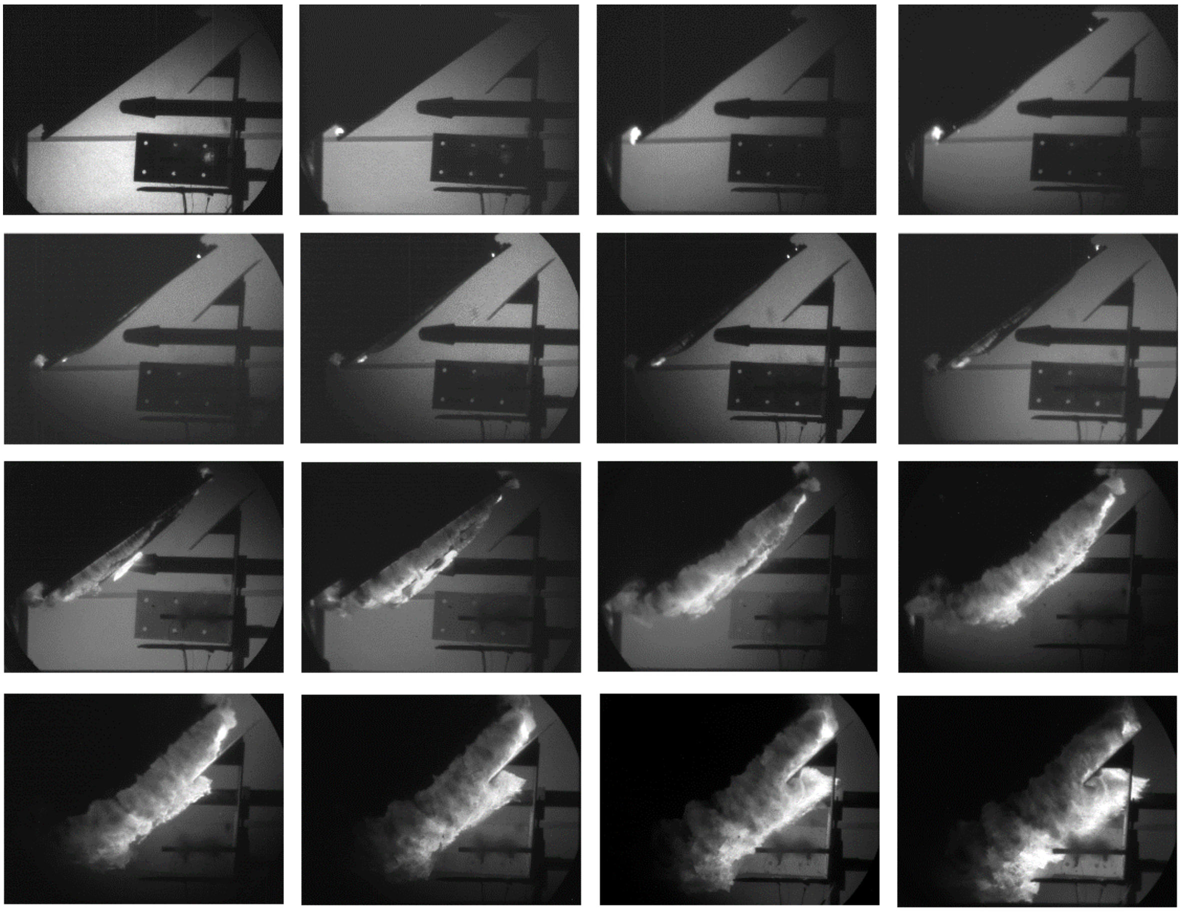


Figure 14 – Registration frames in experiment No. 3.

The speed of movement of the BSM silhouette boundary was determined using 14 frames with an assumed frame-to-frame interval of 8.75 microseconds (shooting speed 114270 fps).

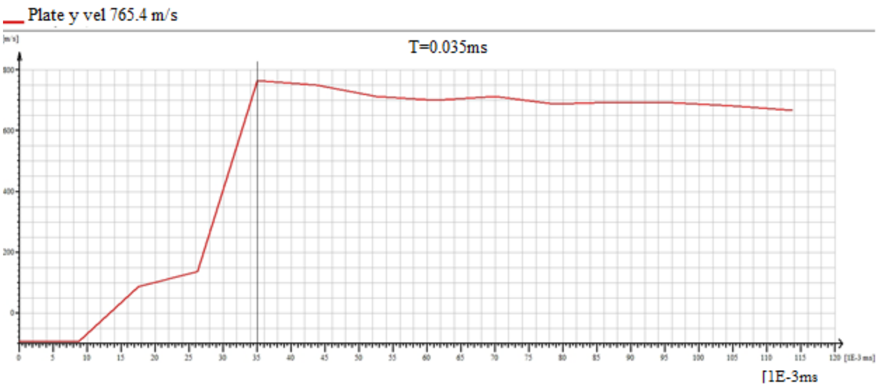


Figure 15 is a graph of the speed change.

The values of the angle of rotation of the BSM silhouette boundary have been measured. The measurement results are shown in Table 2.

Table 2 – Measurement results

Time, ms	The angle of the BSM silhouette,°
0,000	37,2
0,009	37,2
0,018	37,8
0,026	39,4
0,035	41,2
0,044	41,5
0,053	41,7
0,061	41,7
0,070	41,7
0,079	42,0
0,088	42,7
0,096	42,9
0,105	43,2
0,114	43,5

Experiment No. 4. Registration of the nature of detonation transmission through a steel plate with a thickness of 10 mm (300x200x10 mm) by the electron-optical camera Nanogate-22/16 on the second charge of the TNT-Hexogen 40/60 mixture (total weight 0.34 kg). The registration of an electrical signal from the "CONTROL" output of the Nanogate-22/16 electron-optical camera determined the image formation times. The assembly included two charges measuring 100x100x10 mm, separated by a steel plate (glued to it) with a thickness of 10 mm, in the center of one of which an electric detonator is installed. The appearance of the installation is shown in Figure 16.


Figure 16 – The appearance of the installation.

Registration was carried out during the daytime at an ambient temperature of plus $19^{o}C$ and an atmospheric pressure of 746 mm Hg.

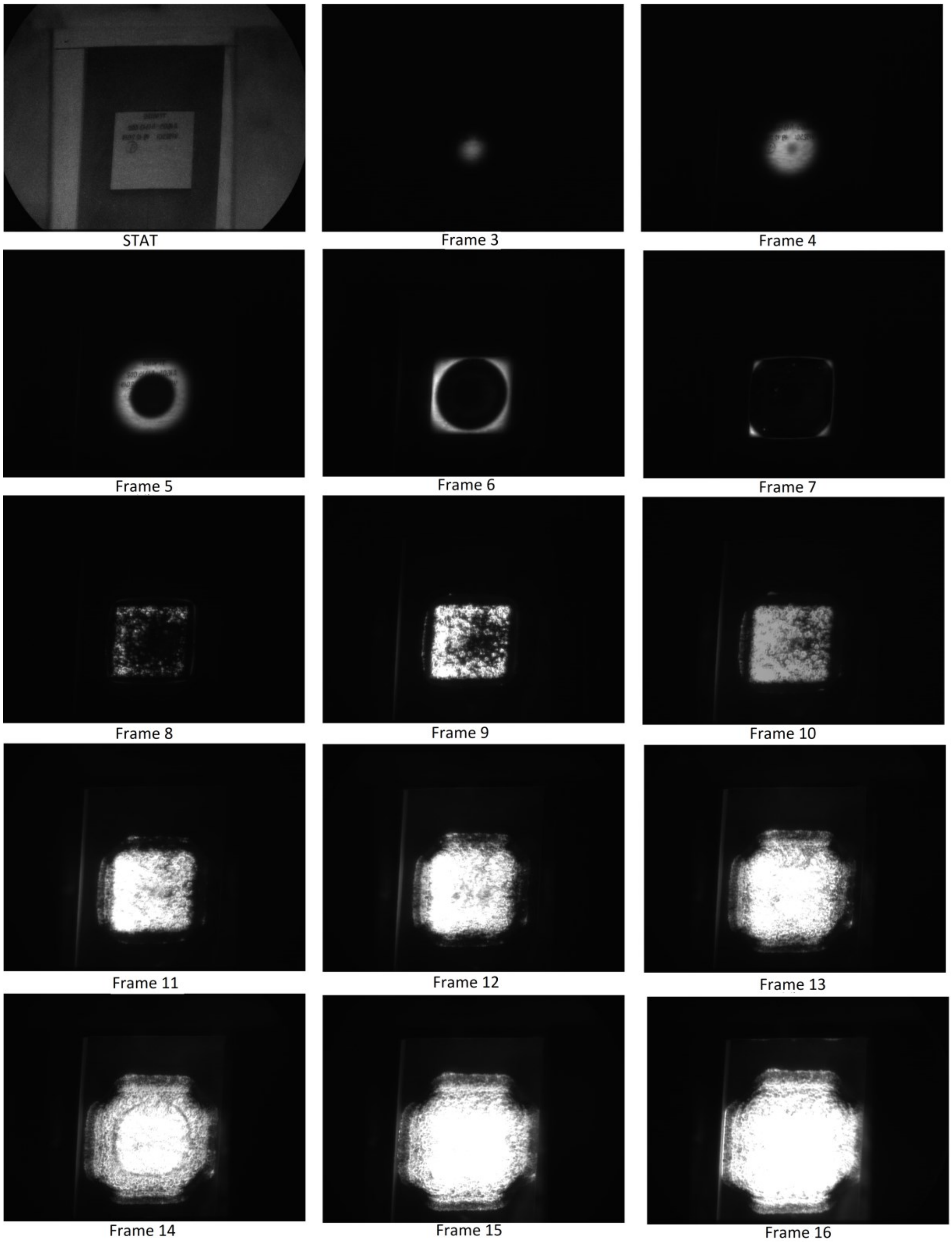


Figure 17 - The sequence of frames in Experiment No. 4.

A digital oscilloscope registered a signal from the CONTROL output of Nanogate-22/16. Cursor measurements determine the frame construction times relative to the synchro pulse of the explosive installation of the demolition set. The measurement results are shown in Table 4, and the waveform of the recorded signals is shown in Figure 18. Table 4 – Image construction times. Nanogate-22/16. Рисунок 17 – The sequence of frames in Experiment No. 4.

Table 3 – Nanogate Settings-22/2

Parameter	Value
launch delay, μs	3
exposure, ns	500
image size, pixels	1660x1248
shooting speed, frame/s	500 000
focal length, mm	300
aperture	2,8
IIT voltage, V	600

A digital oscilloscope registered a signal from the CONTROL output of Nanogate-22/16. Cursor measurements determine the frame construction times relative to the synchro pulse of the explosive installation of the demolition set. The measurement results are shown in Table 4, and the waveform of the recorded signals is shown in Figure 18.

Table 4 – Image construction times Nanogate-22/16

Frame no.	1	2	3	4	5	6	7	8
time, µs	3,2	5,2	7,2	9,2	11,2	13,2	15,2	17,2
Frame no.	9	10	11	12	13	14	15	16
time, µs	19,2	21,2	23,2	25,2	27,2	29,2	31,2	33,2

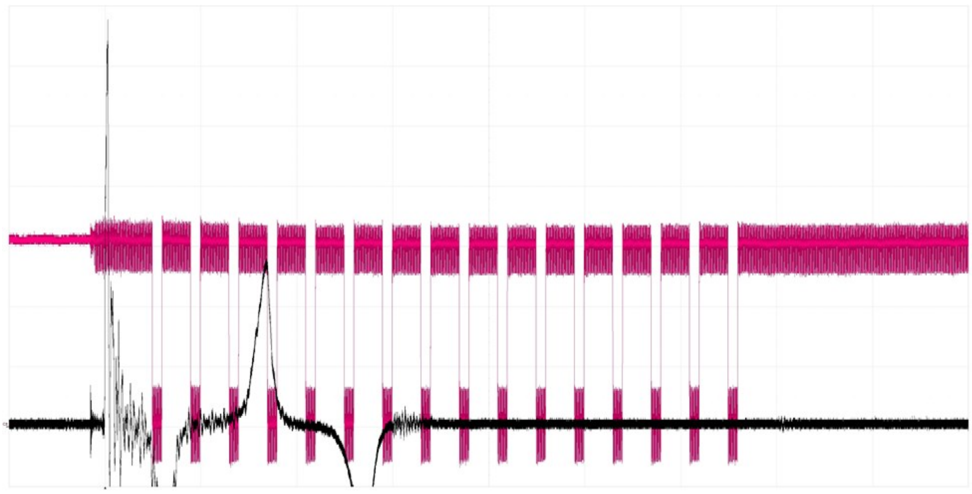
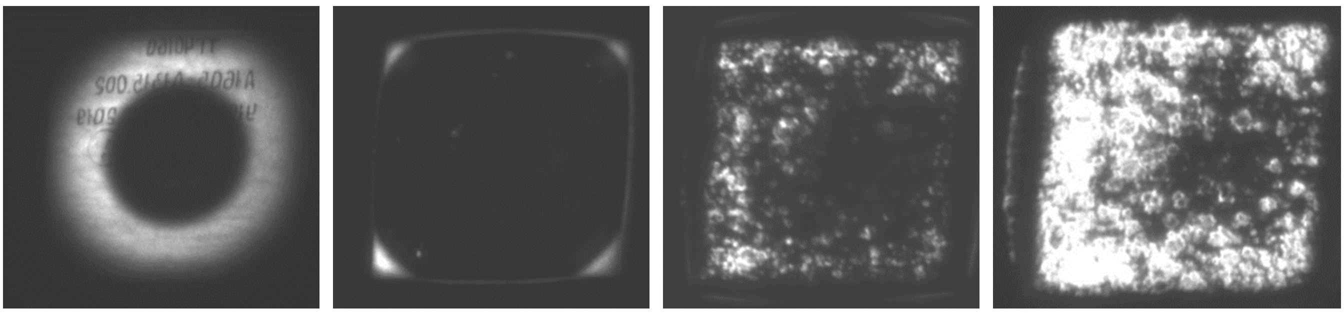


Figure 18 – Waveform of the signals recorded in the experiment

Separately, in Fig.19, the frames are highlighted after the calculated output of the shock wave to the frontal surface of the second (passive) HE2 charge (tx = 9.7 microseconds).



T = 11 µs T = 15 µs T = 17 µs T = 19 µs

Figure 19 - Individual frames of the process.

When the DW reaches the surface of the passive charge, there is an annular expansion of the "internal" backlight (by glue), making visible the inscription on the back surface of the charge (t = 11 µs.). Upon reaching the front of the luminous zone of the periphery of the charge, a shock wave in the air (t= 19 μs) is formed, and "hot spots" appear in the charge with the growth towards the center of the charge.

Experiment No. 5. Registration by the Nanogate-22/16 electron-optical camera of the fact of detonation transfer from a TNT-Hexogen 40/60 charge with a size of 100x105x10 mm to a similar charge through a steel plate with a thickness of 20 mm (300x200x20 mm) (HE charges are glued to it with epoxy resin). Two electric detonators are installed in the upper part of the active charge HE1. The appearance of the installation is shown in Figure 20.

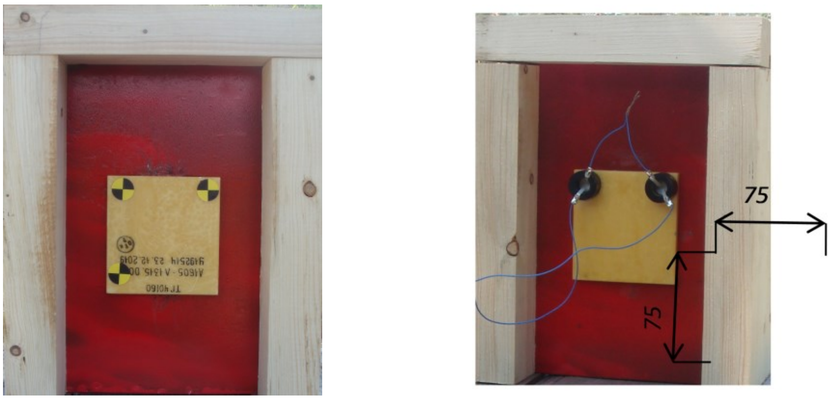
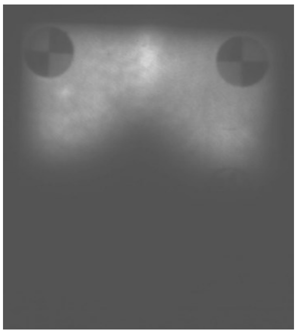


Figure 20 – The appearance of the installation (HE1 on the right, HE2 on the left).

Figure 21 shows individual frames of the detonation transmission process.

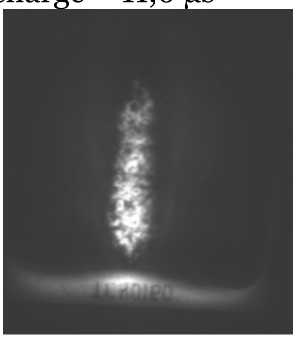
The recorded back surface of the HE2 charge; the estimated time for the release of SW to the front surface of the HE2 charge = 11,6 μs



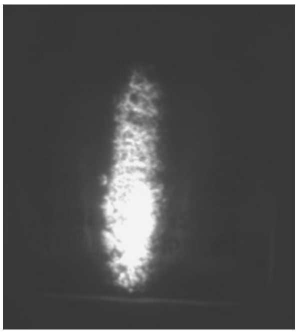
t=11 μs

t=15 μs

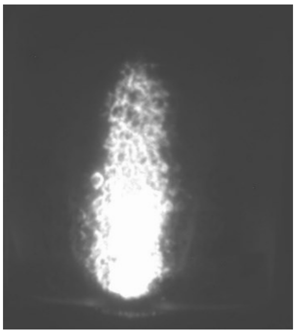
t=17 μs



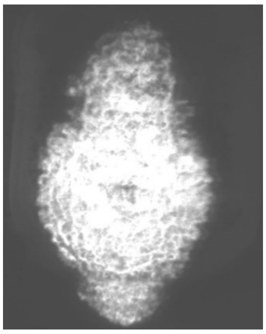
t=19 μs



t=21 μs



t=23 μs



t=33 μs

Figure 21- Detonation transmission

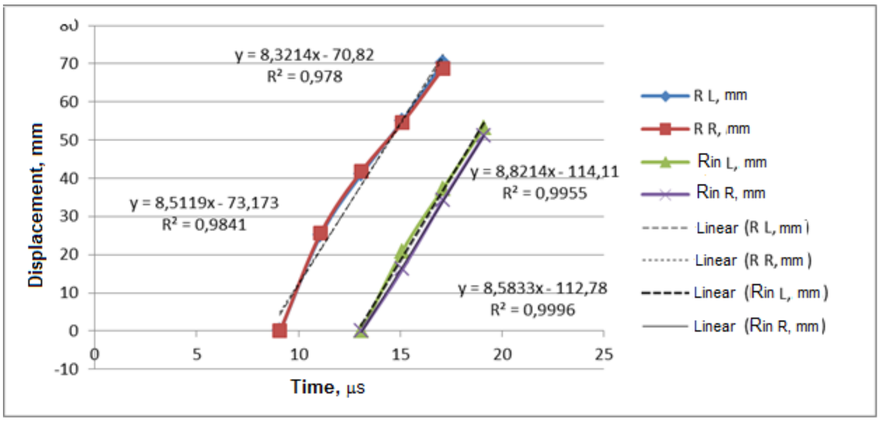


Figure 22 – Moving the boundaries of the shock wave front

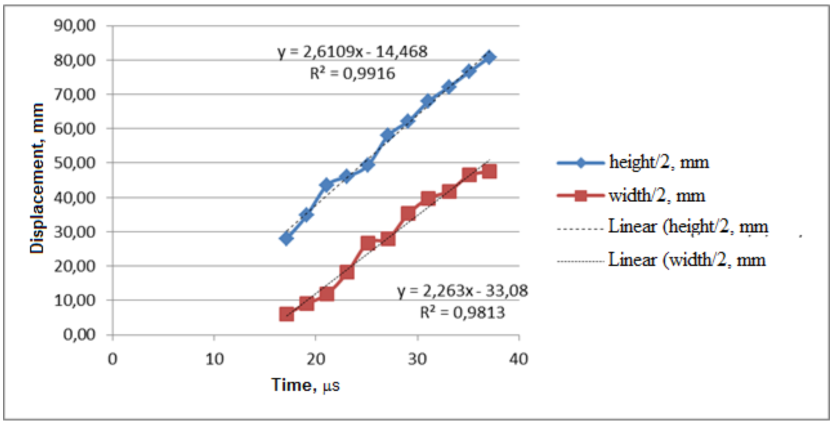


Figure 23 – Propagation of the boundaries of the luminous zone

The propagation of the shock wave front along the adhesive layer through the HE2 charge with a light transmission coefficient of 0.1 (frame 2-7) was recorded, followed by detonation excitation in the entire charge (frame 6-16). The displacement of the anterior and posterior boundaries of the shock wave front propagating in the adhesive layer is estimated (see frame 2-7 (t=9-15 microseconds). The graph of movement from time is shown in Figure 22. According to registration frames 6-16, the propagation of the boundaries of the luminous zone in the horizontal and vertical directions was estimated (Figure 23). Thus, it was shown that with an increase in the thickness of the steel plate to two thicknesses HE1, the initiation of HE2 is possible with the interaction of two DW in HE1 (for example, in the plane between the detonators). The appearance of the plate after the experiment is shown in Figures 24, 25.

a) b)

Figure 24 – The appearance of the steel plate after the experiment: a) from the side of the main charge b) from the side of the passive (additional) charge).

Figure 25 – Large-scale rupture of a steel plate

3. Conclusion

The developed domestic camera NANOGATE-22/16 has confirmed its characteristics in the study of fast processes and will be used in measurement techniques for experiments on a rocket track (on a dynamic loading bench.

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