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SPECIFIC FEATURES of X-RAY EXPERIMENTS to STUDY EJECTA

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The flash X-ray radiography is a method used to study ejection. This method is capable to give obvious results and to record the structure and average density of the cloud along the X-ray beam, as well as to record position of sample's free surface. X-ray diagnostics of ejection is performed in conditions of the radiation – matter interaction with the photon energy up to 500 keV (photo-effect region) due to low density of the ejecta cloud (≤0.1 g/cm^3). For the hard γ-quanta (>0.1 MeV), the cloud is transparent (white). For soft quanta (<0.1 MeV), the cloud turns to be semitransparent (gray) and appropriate for diagnostics.

A radiation source, material, and thickness of shielding plates must be taken such that radiation attenuation in shielding plates would be minimal and attenuation in the ejecta cloud would be maximum.

The paper presents results of X-ray diagnostics of the model cloud. The model looks like a wedge sample made from the metal with ϱ=7.8…16.6 g/cm^3, Z=26…82, h<1.5 mm. Thickness of wedge steps is 20…280 µm. The diagnostic mode is E_γ<0.5 MeV (mainly) but in certain cases 3 MeV and 3.8 MeV. IGUR-3.5 pulsed X-ray generator provides threshold radiation energy of E_γ=0.5…3.8 MeV. Spectrum s continuous within 0… E_γ. The soft part of spectrum allows registration of low-density ejecta bunches.

The material of the explosion-proof shielding plate is aluminum. The shielding-plate thickness from the side of the source and from the side of the recorder is the same, i.e. 2 mm each.

Experiments and Monte Carlo simulations (PRIZMA code) were used for diagnostics purposes.

Radiation attenuation results are presented versus the generalized parameter $Z^k \varrho h$, where k-is a fitting parameter. The relationship $k(E)$ is the same as the photons-atom interaction cross-section, $\sigma(E)$. This novelty is conditioned by the photo-effect.

Scientific novelty of the paper is the following:

- presentation of radiation attenuation in metals versus the complex parameter $Z^k \varrho h$ as a response to the photo-effect mode;
- demonstration of the attenuation pattern in the range of metal thicknesses simulating the ejecta cloud (tens and hundreds micrometers: this is 1000 times less compared to the traditional thickness).

Calculation of radiation attenuation in metals

The spectrum of electrons striking upon the target was determined from the oscillogram of high-voltage pulses of voltage and current through the diode of the accelerating tube. The material of the anode pin in the diode of the accelerating tube is tantalum. Then, the ɣ-radiation spectrum was calculated for energies $E_ɣ$<0.5 MeV (figure 1).

Results of calculations of the radiation attenuation using the spectrum obtained in the assumption of mono energy electrons with E_e=0.5 MeV are practically no different from the results of calculations using the spectrum given in figure 1.

Calculations of radiation attenuation used the scheme given in figure 2. Interaction of photons with the materials of the recorder was not taken into consideration.

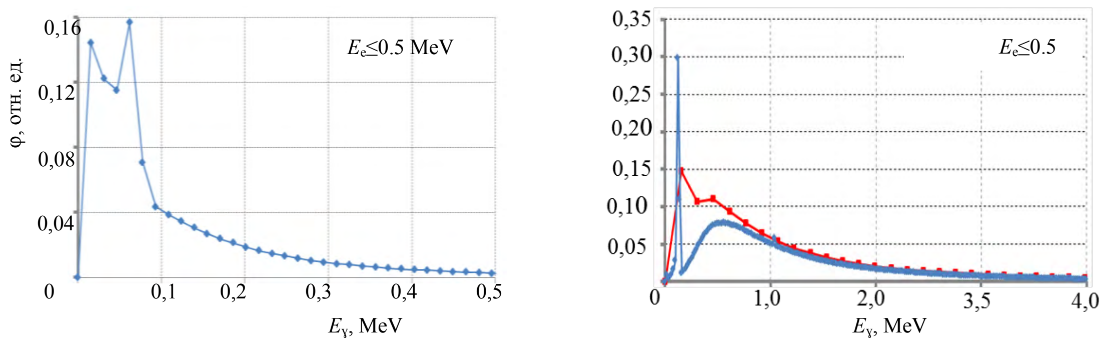

Figure 1. Spectrum of γ-radiation

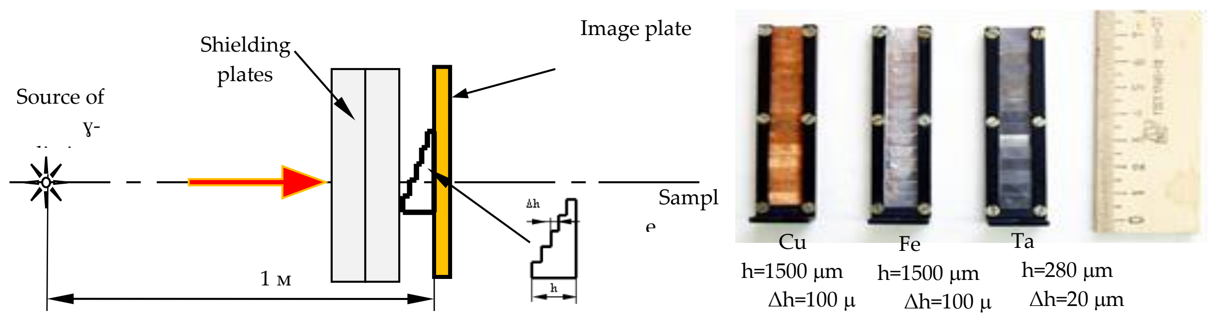

Figure 2. Computational scheme

The radiation attenuation process with E_γ<0.5 MeV in metal films is clear from plots in figure 3.

A new fact – is presentation of the experimental data as the relationship $N/N_0(Z^{3/2}\varrho h)$ (figures 3c and 3d) instead of the traditional relationship $N/N_0(\varrho h)$ (figures 3a and 3b) and this is due to the photo-effect.

The parameters of the X-ray diffraction method sensitivity is a module of the radiation intensity attenuation derivative, N, in the matter, i.e. $|dN/d\varkappa|$. Agreed notation: h-is the matter thickness, ϱ – is the matter density, Z-is the number of electrons in the matter, $\varkappa=Z^{3/2}\varrho h$. The greater is the module, the more sensitive is the recording method. Values of modules were determined through interpolation of absorption curves $N/N_o=f(\varkappa)$ by the second-degree polynomial.

Figure 4a shows how the material of shielding plates influences sensitivity of the X-ray diffraction method at the photon energy E_γ<0.5 MeV. The aluminum shielding plate with the thickness of 2 mm+2 mm has no influence on the X-ray diffraction method sensitivity. Our calculation showed that the same-thickness beryllium shielding plate also has no impact on the ejecta recording efficiency. This effect is explained by the small Z (Z_{Be}=4, Z_{Al}=13).

Figures 4b, 4c give calculated modules $|d(N/N_o)/d\varkappa|$ with and without shielding plates. In both cases, the X-ray diffraction method sensitivity at 0.5 MeV is higher compared to that one at 3.8 MeV. The difference in sensitivity goes down with the increase of the sample thickness. At $Z^3/^2\varrho h \geq 250$-300 g/cm², the radiation energy exerts no influence on the method sensitivity.

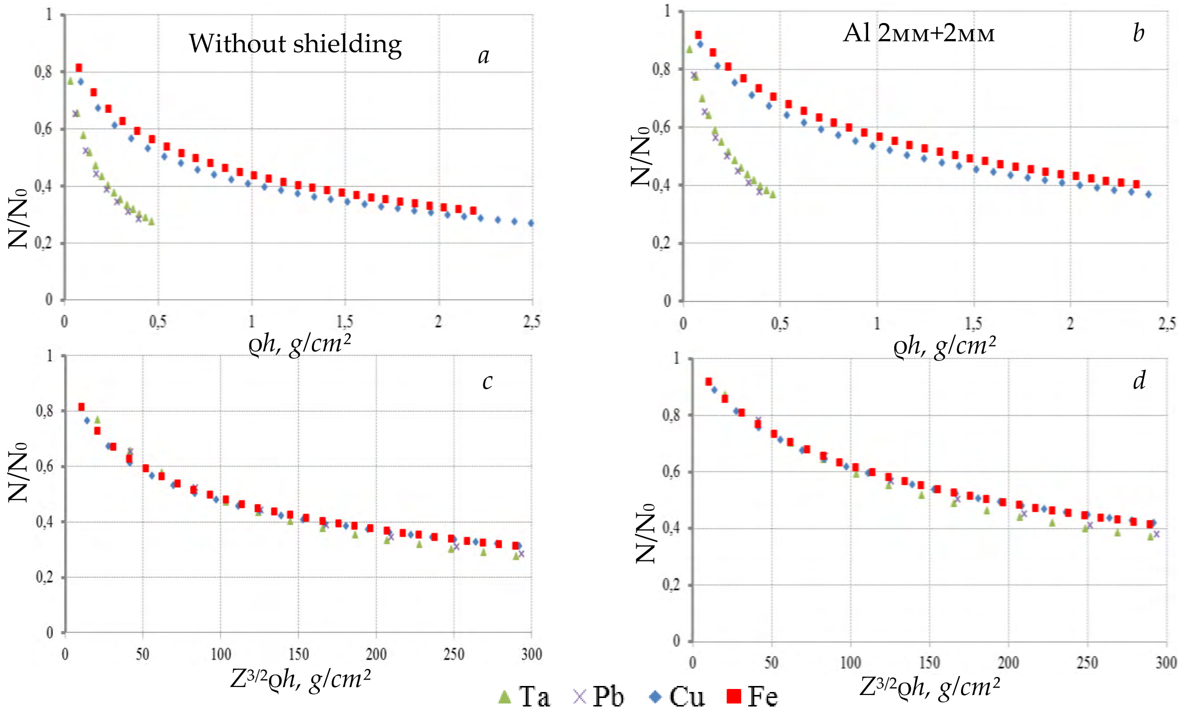

Figure 3. Calculated curves of radiation absorption E_γ<0.5 MeV in metals

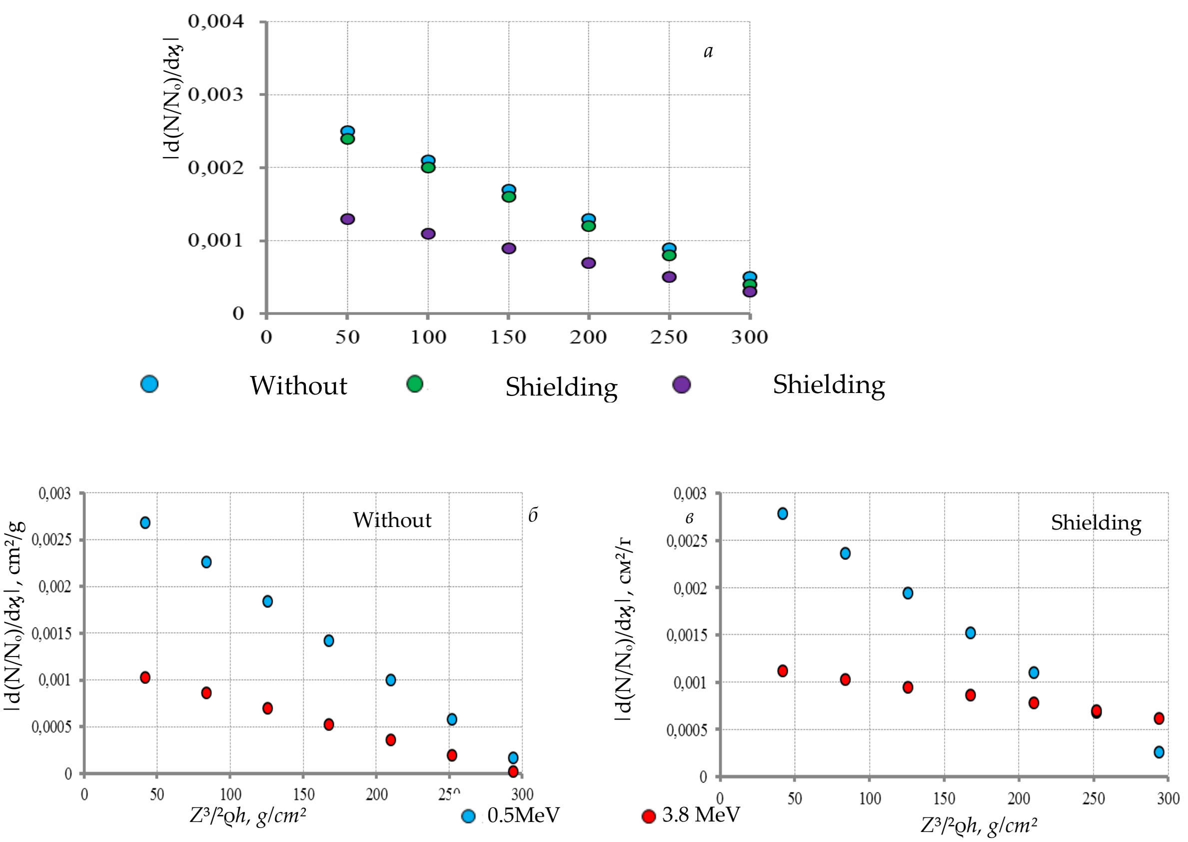

Figure 4. Calculated relationship: module of the derivative $|d(N/N_o)/d\varkappa|$ of $Z^{3/2}\varrho h$

Experimental study of radiation attenuation in metals

Experiments used IGUR-3.5 radiographic facility [2].

The experimental setup to determine radiation attenuation in metals at energies E_γ<0.5 MeV and E_γ<3.8 MeV are given in figure 5.

Figure 6 shows experimentally recorded radiation attenuation in such metals as Cu, Fe, Ta, and Pb, i.e. E_γ<0.5 MeV and E_γ<3.8 MeV versus thickness, h (μm), unit length mass along the sounded ray, ϱh (g/cm^2), and complex quantity, $Z^{3/2}\varrho h$ (g/cm^2) (Z, ϱ, h- are atomic number, density, and thickness) [1].

The test materials can be broken down into two groups: 1) with small Z=26 and 29 (Fe, Cu) and 2) large Z=73 and 82 (Ta, Pb). We obtained two variants of diagrams, i.e. versus the linear thickness of the target, h, (figures 6a, b) and versus its optical thickness, ϱh, (figures 6c, d). The same experimental data are presented as the relationship $N/N_0(Z^{3/2}\varrho h)$ (figures 6e, f) [1].

Let results from figure 6(e, f) be presented as the damped exponential curves for E_γ<0.5 MeV and E_γ<3.8 MeV $N=N_0(e)^{-\mu x}$ where N_0=1, N<1, $\varkappa=Z^{3/2}\varrho h$ (g/cm^2), $\mu=1/\varkappa_0$ (cm^2/g). Increment of argument $\varkappa+d\varkappa$ gives variation of the function N-dN. Correspondingly, $dN=|N/N_0'|\,d\varkappa$, where $|N/N_0'|= N_0\mu\,(e)^{-\mu\varkappa}$(cm^2/g) – is the gradient module that turns out to be a key parameter of this problem.

Estimation of the minimum recordable thickness. Let us estimate the minimum thickness of the object for x=50 and 200 g/cm^2 as this thickness is tangible for X-ray imaging. Let us take data observed in the mode with E_γ<0.5 MeV (figure 6) as this mode is most informative. Previous reasoning leads to $d\varkappa=dN/N/N_0'|$, from here it follows that $d(\varrho h)=dN/(N/N_0')|\ Z^{3/2})$ and $dh=dN/(|N/N_0'|Z^{3/2}\varrho)$. Let us assume that d$N$=0,02 what corresponds to the ratio error of the radiation field non-uniformity.

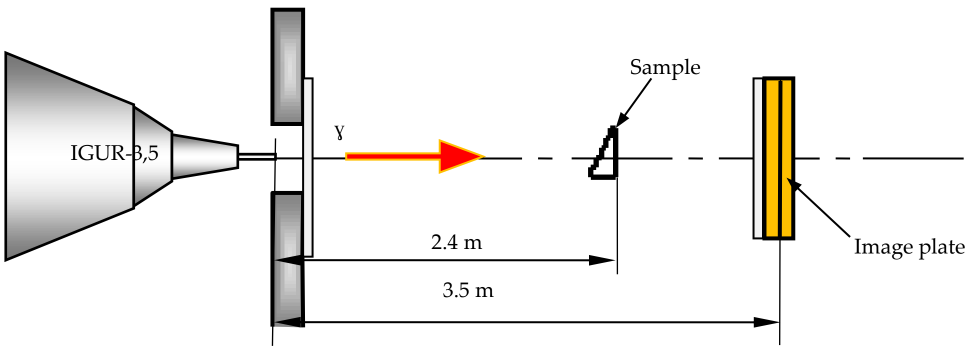

Figure 5. Experimental setup and the photo of wedges

Table 1. Minimum recordable thickness of the metal

$\varkappa$(g/cm^2)	50	200
$d(\varrho h)_{Cu}$(mg/cm^2)	26	65
$d(\varrho h)_{Pb}$(mg/cm^2)	6	15
$d(h)_{Cu}$(μm)	29	73
$d(h)_{Pb}$(μm)	5	13

Figure 7 compares modules given by the calculation and the experiment. The experiment gave the module that is larger than that given by the calculation. For the photon energy E_γ<0.5 MeV, the discrepancy is small, while the discrepancy is noted to be greater for E_γ<3.8 MeV.

At $Z^{3/2}\varrho h$≥250-300 g/cm^2, the calculated and experimental sensitivity of the method coincide at energies E_γ<0.5 MeV and E_γ<3.8 MeV.

The calculation took no account of the recording system effect on attenuation and this can explain discrepancy in the computational and experimental results as for the photon energy. Another probable source of this discrepancy is the influence of the soft part that is smaller in the calculated radiation spectrum compared to the actual radiation spectrum.

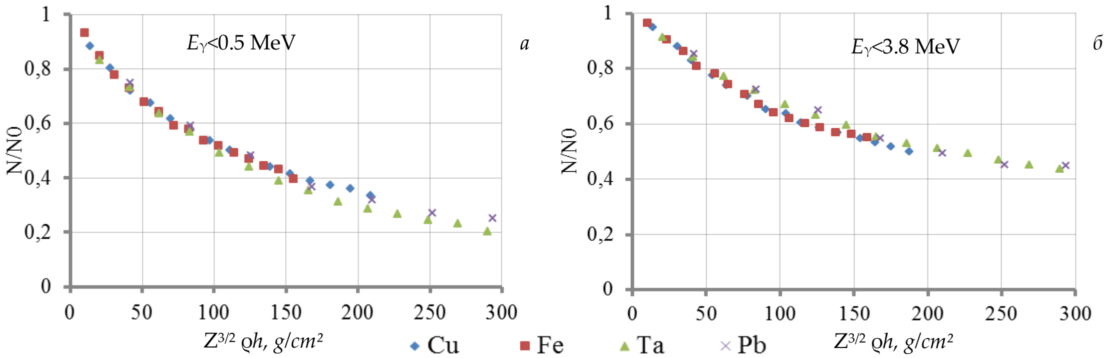

Figure 6. Experimental results for radiation attenuation

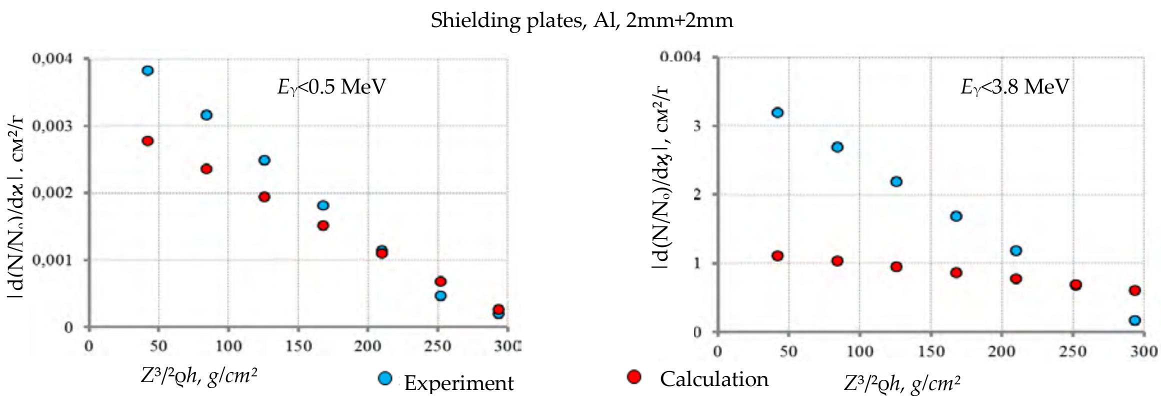

Figure 7. Experimental and calculational modules $|d(N/N_o)/dϰ|$

Explosive experiments were performed to study efficiency of the X-ray radiography mode with E_γ<0.5 MeV and E_γ<3 MeV. The experimental setup is given in figure 5. Shielding plates made of D16-grade aluminum (2.7 g/cm³ density and 2mm+2 mm thickness) were used to protect radiation sources and the recording system.

Lead was taken to be the material of test samples. Figure 8 shows the experimental setup with the assembly that included the sample in the form of a plate, the PETN-based explosive charge (length×width×height =40 mm×40 mm×12 mm), and the D-22 electric detonator.

X-ray diffraction images of experiments to record ejection of lead samples are given in figure 9. Surface finish of samples was of two types: Rz 40 and Rz 200. Lead ejection from the surface with Rz 40 was 3 mg/cm² and from the surface with Rz 200 – 25.5 mg/cm².

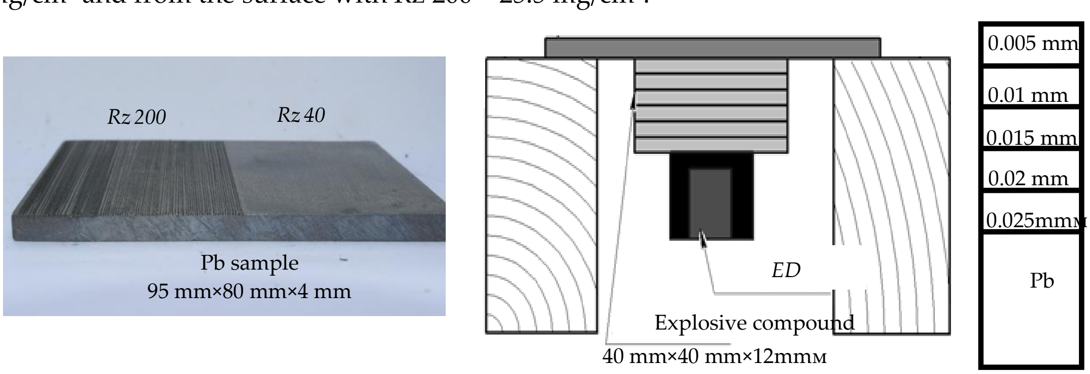

Figure 8. Schematic experimental assemblies

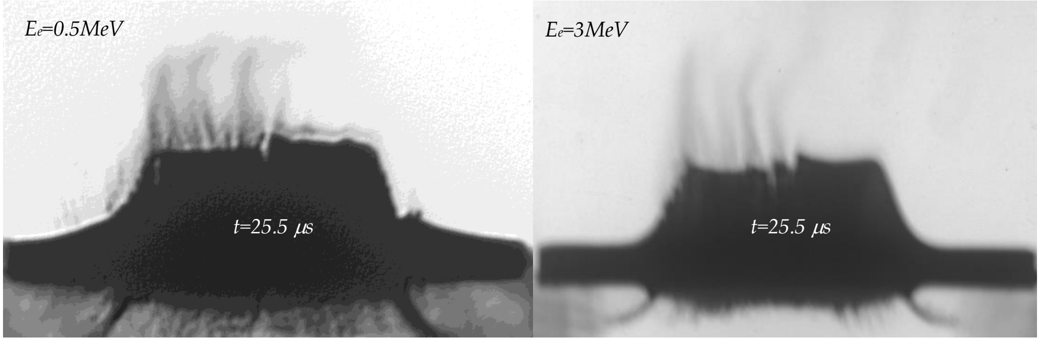

Figure 9. X-ray diffraction images of experiments on Pb ejection, t – time from the instant of shock-wave arrival at the free surface

Analysis of radiation attenuation investigation results

Experiments and calculations of attenuation of radiation with the photon energy E_γ<0.5 MeV demonstrated that the relationship $N/N_0(Z^{3/2}\varrho h)$ exists for metals Fe, Cu, Ta, and Pb (figures 3, 6) in the range of thicknesses up to 1.5 mm ($Z^{3/2}\varrho h$<300 g/cm^2).

Dependence $N/N_0(Z^{3/2}\varrho h)$ allows the ejecta cloud density to be estimated even when the wedge and the test sample are made of different materials. We have $Z^{3/2}\varrho h$=const for N/N_0=const that corresponds to the calibration wedge and the ejecta cloud. From here it follows that for two different materials, i.e. the wedge and the cloud (*i* and *j*), we have $\varrho_j=\varrho_i\cdot(h_i/h_j)\cdot(Z_i/Z_j)^{3/2}$.

Conclusion

Radiation attenuation in metal films with the thickness of tens and hundreds micrometers and with the density of 8-20 g/cm^3 when these films simulate the mass density (g/cm^2) of the ejecta cloud was studied in experiments and in calculations and results these investigations are presented. Investigations used IGUR-3.5 as the radiation source with E_γ<0.5 MeV: voltage at the accelerating tube is 0.5 MeV; current through the accelerating tube is 8 kA; full width at half maximum is 160 ns.

Results of experimental and calculational studies of radiation attenuation in metals are presented in the form of the relationship $N/N_0=f(Z^{3/2}\varrho h)$, where Z, ϱ, h- are the atomic number, density, and thickness of a metal. This relationship can be used to estimate mass and density of the ejecta cloud in experiments wherein the test sample and the wedge are made of different metals.

Sensitivity of ejection recording is 8.9 mg/cm^2 with shielding plates having optical density of 1.08 g/cm^2 (Al, 2mm+2mm). Metals and nonmetals with small ϱ and Z, i.e. aluminum, beryllium, plastics, and rubber, are most preferable as shielding plates in ejection-record experiments.

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