INVESTIGATION OF OPTICAL PROPERTIES OF SHOCK COMPRESSED LEAD GLASS (ELASTIC–PLASTIC WAVE IN GLASS)

S. B. KORMER, G. V. KRUSHKEVICH, and K. B. YUSHKO

Submitted to JETP editor January 20, 1967

J. Exptl. Theoret. Phys. (U.S.S.R.) **52**, 1478–1484 (June, 1967)

Results are presented of an investigation of the behavior of lead glass under shock loading. An optical method (light-reflection method) is used to reveal the configuration of the shock waves in the glass under different dynamic loads. It is shown that when the pressures in the wave exceed 80 kbar and go as high as 170 kbar, two waves propagate in the glass, an elastic one followed by a plastic wave of lower velocity. At pressures higher than 170 kbar, a single elastic-plastic wave propagates in the glass. The equilibrium Hugoniot adiabat of the glass is deduced on the basis of the obtained experimental results. The relaxation character of the transition of the glass from the elastic state to the plastic one is revealed; at a pressure $P > 265$ kbar the transition time amounts to $\tau \leq 10^{-12}$ sec. The optical properties of shock-compressed lead glass are described.

IT is known that when substances undergoing a first-order phase transition are shock-compressed the flow is characterized by a two-wave configuration.[1-3] A two-wave profile characterizes also elastic-plastic waves.[4, 5] A many-wave configuration was registered by various methods: electric contact,[1,2] optical,[4] with the aid of a capacitive pickup,[3, 5] and electromagnetic.[6, 7] Among the transparent substances, the most thoroughly investigated where the elastic-plastic flow of crystalline and fused quartz.[4] Wackerle[4] reported anomalous behavior of pyrex and crown glass and advanced the hypothesis that other glasses may also exhibit a similar behavior under shock loading.

The wave configuration in transparent media can be investigated by the light-reflection method,[8] which not only makes it possible to investigate the dynamic characteristics of the medium, but also yields information on the structure of the shock waves by determining their reflecting ability. This method was used in the present investigation to study the profile of the shock wave in TF-5 (heavy flint) glass.

The lead glass, the chemical composition of which can be written in the form $K_2O \cdot 4PbO \cdot 8SiO_2$,[9] has a density $\rho_0 = 4.78$ g/cm^3 and a refractive index $n_0 = 1.755$.[10] According to Kisin,[11] the Young's modulus of lead glass is $E = 5528$ kg/mm^2 and its Poisson coefficient is $\mu = 0.244$. These parameters correspond to an elastic speed of sound

$$c_{el} = [E(1-\mu) / \rho_0(1+\mu)(1-2\mu)]^{1/2} = 3.67 \text{km/sec} \quad (1)$$

and a plastic speed

$$c_{pl} = [E / 3\rho_0(1-2\mu)]^{1/2} = 2.72 \text{ km/sec}. \quad (2)$$

EXPERIMENTAL RESULTS

The schematic diagram of the experiments, which is analogous to that described earlier,[8] is shown in Fig. 1a.[1) Beam I from an argon flash source passes through a rectangular slit S, strikes one of the faces of organic-glass prism 1, passes through alternating layers of liquid (2, 4) and glass (3, 5) ("sandwich"), and is partly reflected from the optical boundaries. The reflected rays II–IV emerge from the other face of the prism and are recorded by a photochronograph (SFR-2M). A plane shock wave is generated either directly by a powerful explosive, or by impact against a metallic plate accelerated by explosion product. By varying the strength of the explosive, and also by choosing the liquid 4 to be of suitable dynamic rigidity, it is possible to vary the pressure on the fronts of the shock waves propagating in the sandwich. The diameter of the sandwich was 120 mm, the thickness of the glass samples about 10 mm, the thickness of the liquid layer 2 was ~5 mm, and that of liquid 4 was 5–20 mm.

Figure 1b shows a photochronogram of an experiment in which two lead-glass samples are sepa-

_____

[1)]Reference [8] includes a photochronogram of an experiment in which reflection of light from the shock front in TF-5 glass was recorded.
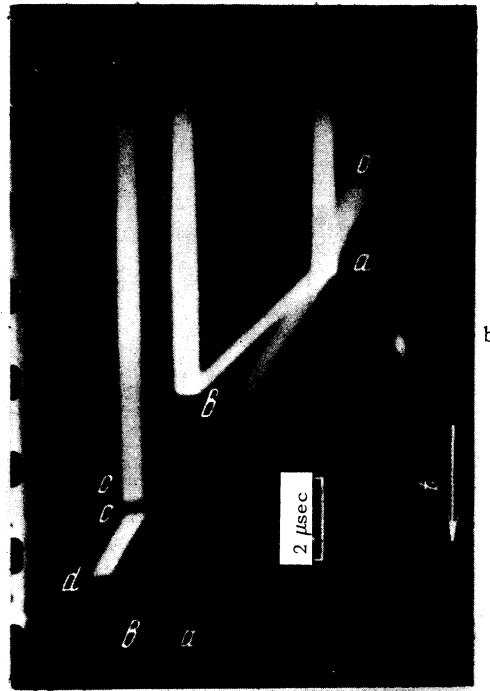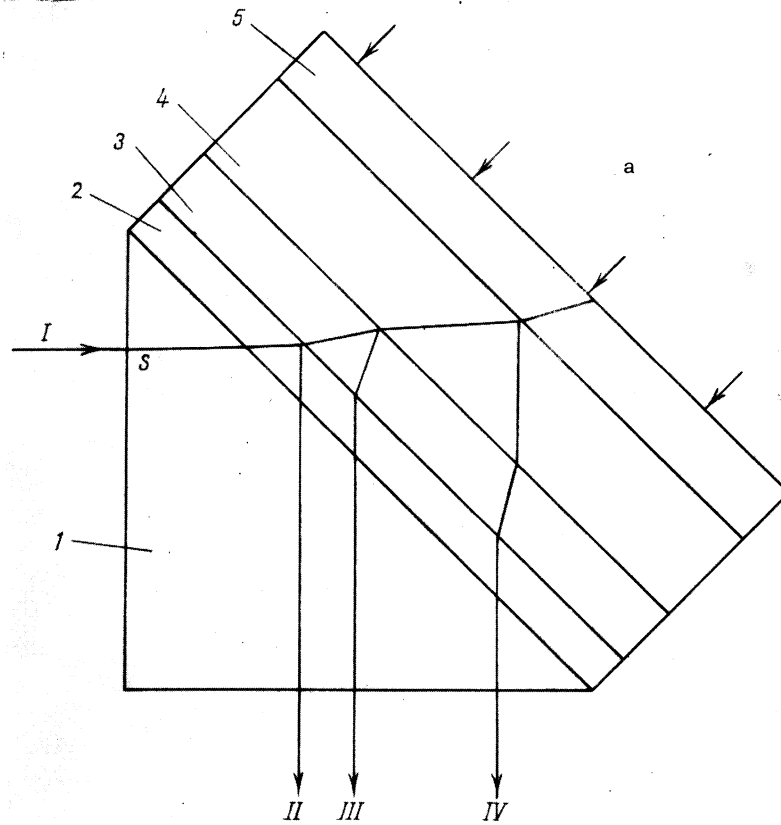
FIG. 1

rated by a layer of alcohol (layer 4) 15 mm thick. The shock wave was produced by a 50/50 alloy of TNT and hexogene. It is seen from the photochronogram that in the first glass (5), where the pressure is ~ 330 kbar, the front of the shock wave reflects the light (line o-a). The wave is then damped as it passes through the alcohol, and no reflection of light from the shock-wave front is registered in the
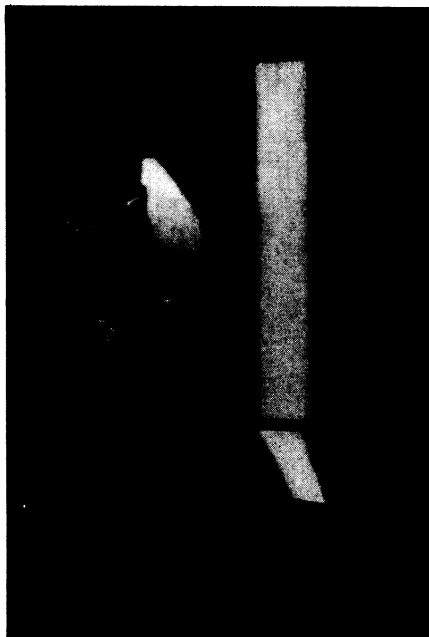
FIG. 2

Table I.

P, kbar	σ	R, %	n
215	1.41	0.40	1.97
215	1.41	0.49	2.00
262	1.45	0.65	2.04
335	1.53	0.95	2.12
370	1.57	1.17	2.15
743	1.88	2.12	2.34

second glass plate (3).[2] One can clearly see in this case, through the compressed glass 3, the reflection of the light from the two moving boundaries between the alcohol and the glasses 5 and 3, namely the rays a—a and b—b, which are continuations of the vertical rays IV and III corresponding to light reflection from the same boundaries prior to the emergence of the shock wave from them. Another distinctive characteristic is that when the wave goes over from the second lead-glass plate to the liquid 2 bordering on it (CCl_4 in this case), a so-called "pause"—a dip in the reflectivity—is observed on section c—c. The lines a—b and c—d represent the reflection of the light from the front of the shock wave in the respective liquids (alcohol and carbon tetrachloride).

Figure 2 shows a photochronogram of an experiment in which the shock wave was produced in the glass by an aluminum striker plate 2 mm thick, having a velocity w = 5.6 km/sec; the corresponding pressure in the glass was ~ 740 kbar. The experimental setup differed somewhat from that shown in Fig. 1a in that the plate struck against the glass 3 of thickness 25 mm, and layers 4 and 5 were absent. In this case a centered rarefaction wave overtakes the front of the shock wave and attenuates the latter, and reflection of light from the shock wave, of varying intensity, is registered in the glass. It is seen from the photochronogram

that, starting with the instant t_1 at which the relaxation wave overtakes the shock wave, the intensity of the reflected light decreases, corresponding to the decrease in the degree of compression in the shock-wave front; the reflection practically disappears starting with some instant of time t_2.

The foregoing investigation of the optical properties of glass in which shock waves propagate has shown that at pressures P > 170 kbar (the maximum attained was ~ 740 kbar) the shock-compressed glass is opaque (to the visible part of the spectrum) and the front of the shock wave reflects specularly. When P < 170 kbar the glass remains partly transparent (the degree of transparency increases with decreasing pressure), and the reflectivity of the front is quite small, so that no reflected light is registered in the experiment. Table I presents the reflection coefficients R of light from the shock-wave front in lead glass, obtained in a manner similar to that used in [8], for different wave amplitudes. The angle of incidence of the light on the front of the shock wave in the glass was 36°.

The dependence of the refractive index[3] n of the shock-compressed glass on the degree of compression $\sigma = \rho/\rho_0$ (ρ-density of compressed glass) is shown in Fig. 3. The circles represent the results of experiments performed in accordance with the scheme of Fig. 1. The solid line represents the averaged results of the reduction of data obtained in an experiment in which a damped shock wave propagates in the glass (see Fig. 2). The results obtained at P ≳ 265 kbar (σ ≳ 1.46) are described by the linear relation

$$(n - n_0)/(\sigma - 1) = 0.67 \qquad (3)$$

which is represented by the dashed line in Fig. 3. The dash-dot line is a plot of n(σ) in accordance with the Gladstone—Dale formula

$$(n - 1)/\rho = \text{const.} \qquad (4)$$

---

[2]The apparatus makes it possible to register 0.1 - 0.2% of the light from an argon flash lamp at an exposure 10^{-7} sec using a photographic emulsion having a sensitivity of 1600 GOST units.

[3]The values of n were calculated from the experimentally obtained values of R under the assumption that the Fresnel formulas are applicable.
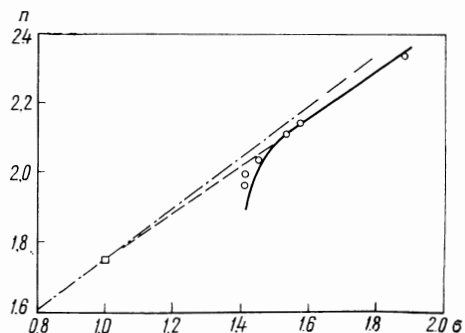
FIG. 3

FIG. 4

Just as in the case of ionic crystals,[12] the experimental slope $dn/d\sigma$ (in accordance with (3)) turned out to be smaller in glass than the slope corresponding to Eq. (4). At the same time, at pressures $P < 265$ kbar, the values of the refractive index n turned out to be smaller than expected from the linear relation (3); the deviation increased with decreasing pressure.

Besides the reflectivity of the front, we registered the velocity of the shock wave in the TF-5 glass. In three series of tests (each consisting of 3–4 experiments), we varied the intensity of the shock wave in the lead glass, from 90 to 170 kbar, by using different combinations of explosives and screen materials (see Table II). The experimental scheme was similar to that of Fig. 1a, except that the layers 4 and 5 were replaced by the sandwich listed in Table II. In all cases, the velocity, determined from the time between the entrance of the shock wave into the glass and the start of the "pause," was 3.77 km/cm regardless of the applied pressure. In the experiments performed in accordance with the scheme of Fig. 1a, the wave propagation velocity in the second glass 3 (as determined in 5 experiments) was also 3.78 km/sec, whereas in the first glass it ranged, depending on the explosive power, from 3.88 to 4.6 km/sec.

The points of the dynamic adiabat in the region $P > 170$ kbar were obtained by measuring the wave velocities in the glass and in the layers in contact with it (in accordance with the scheme of Fig. 1a), and also by determining the wave and mass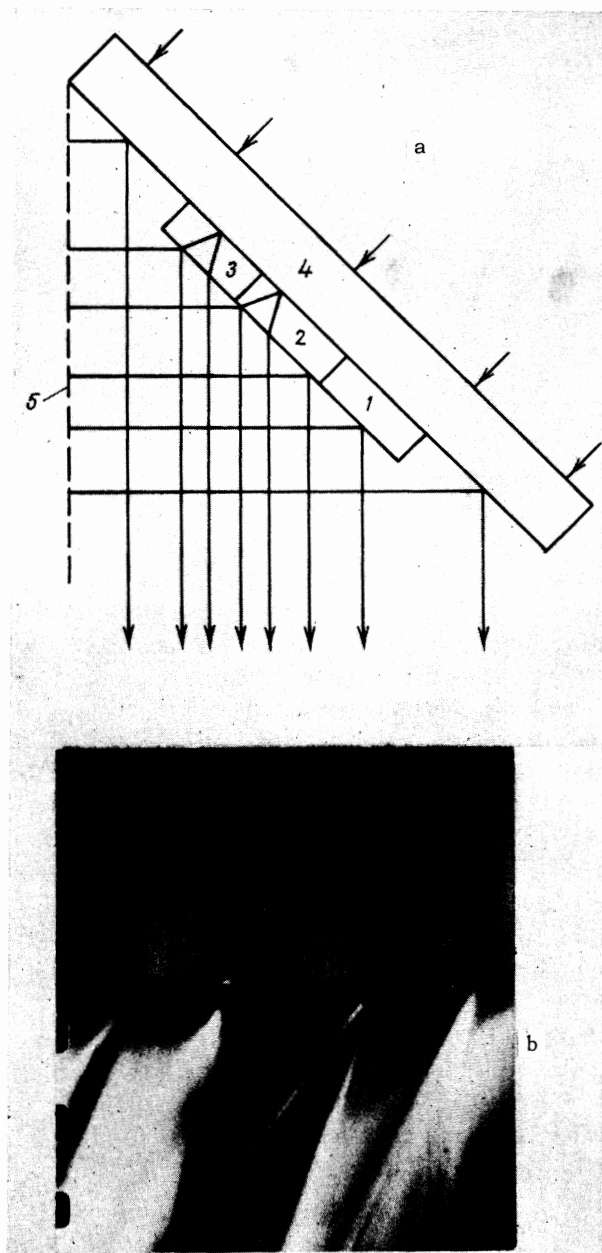 velocities in accordance with the scheme of Fig. 4a. In this case we registered on film the time-scanned reflection of the raster 5, illuminated by an argon flash lamp. The raster was reflected from the polished surface of metallic screen, from the surface of a platelet of lead glass 2, and also from the surfaces of control aluminum (or Plexiglas) platelets 1 and 3 (having known dynamic adiabats). The emergence of the shock wave from the screen is accompanied by cutoff of the raster light reflected from the metallic surface of the screen, since the surface of the glass in contact with the screen becomes opaque and cuts off the light, even if the glass itself remains transparent.

Figure 4b shows a photochronogram of similar experiments. The emergence of the shock wave to

Table II.

TNT charge	Sandwich	P, kbar	D, km/sec
$\rho = 1.6$	Cu + acetone + glass	~90	3.76
$\rho = 1.6$	Cu + CCl$_4$ + glass	~126	3.79
$\rho = 1.4$	Al + glass	~170	3.76

FIG. 5

Table III.

Type of experiment	Sample thickness mm	D, km/sec	u, km/sec	P, kbar	V/V_0
2*	5.47	3.79	1.09	197	0.713
1**	9.40	3.88	1.05	195	0.729
1	9.15	3.95	1.14	215	0.711
1	9.22	4.06	1.2	232	0.705
1	9.73	4.19	1.31	262	0.687
1	9.60	4.28	1.39	284	0.676
1	10.80	4.33	1.44	298	0.667
2	5.25	4.41	1.59	335	0.640
2	5.20	4.43	1.6	338	0.639
1	10.00	4.50	1.56	335	0.653
2	5.55	5.68	2.72	738	0.521
2	5.11	5.68	2.72	738	0.521
2	5.12	5.70	2.72	740	0.523
2	5.22	5.8	2.70	747	0.534

*According to scheme of Fig. 4a.
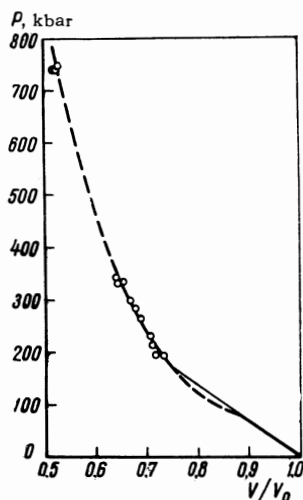**According to scheme of Fig. 1a.

the free surface of the glass and of the control platelets is accompanied by an inclination of the raster lines. The slope (angle α, reckoned from the vertical to the inclined lines of the raster in clockwise direction) is connected with the speed w of the free surface by the simple relation

$$w = \frac{vk\,\mathrm{tg}\,\alpha}{2\sin\varphi},$$

where v is the velocity of the beam sweep over the film, k the reduction of the optical system, and φ the angle of incidence of the light on the reflecting surface. The mass velocity was assumed equal to half the velocity of the free surface.

Figure 5 and Table III show the kinematic parameters of the shock wave in the glass and the parameters of the obtained dynamic adiabat.

The pressure region from 170 to 740 kbar is described by the relation (in km/sec)

$$D = 2.72 + 1.12u. \tag{5}$$

DISCUSSION OF EXPERIMENTAL RESULTS

The experimental results can be fitted into a unified picture within the framework of the concepts of elastic-plastic flow.
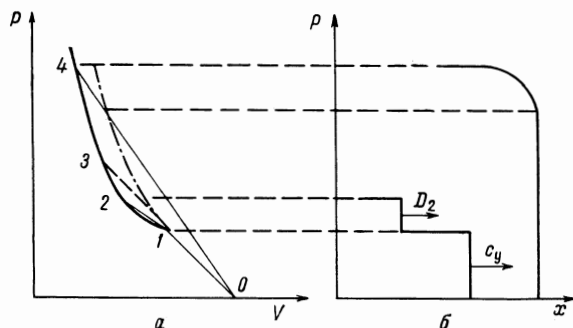

FIG. 6

Figure 6 shows the schematic form of the Hugoniot adiabat. Up to the pressure P_1, which is determined by the dynamic yield point, the glass is compressed elastically. To determine the value of P_1, the capacitive-pickup method[5] was used to measure the mass velocity behind the elastic wave,[4] which amounted to $u_1 = 0.44$ km/sec, giving $P_1 = 79$ kbar[5] at $c_{el} = 3.77$ km/sec. The dash-dot line shows the position of the non-equilibrium elastic adiabat, of which section 0-1 is a part.

In the pressure interval $P_1 < P < P_3$ there propagates in the glass an elastic wave (see Fig. 6b) with velocity c_{el}, followed by a plastic wave with velocity $D_2 = u_1 + D_{21}$, where u_1 is the velocity of matter behind the front of the elastic wave and D_{21} is the velocity of the wave relative to the medium ahead of its front. This is the reason why a constant velocity $c_{el} = 3.77$ km/sec is registered regardless of the applied pressure when $P_1 < P < P_3$. This velocity agrees sufficiently well with the value $c_{el} = 3.67$ km/sec obtained from Young's modulus, the Poisson coefficient, and the density of the lead glass.

The position of the point 3 on the P-V plot is determined by the intersection of the wave ray 0-1-3 with the Hugoniot adiabat described by relation (5). The velocity $c_{el} = 3.77$ km/sec corresponds to $P_3 = 170$ kbar and to $V/V_0 = 0.75$. At pressures $P < 170$ kbar an elastic wave emerges to the interface between the lead glass and the liquid,

---

[4] The measurements were made at our request by S. A. Novikov and V. A. Sinitsyn.

[5] It is interesting to note that in lead glass the transition from elastic to plastic flow occurs at higher pressures than in metals. Thus, whereas $P_1 \sim 80$ kbar for TF-5, the maximum value of P_1 for metals, according to Ivanov et al. [5], is ~ 30 kbar (quenched 30KhTSA steel).

followed by a plastic wave. The difference between the arrival times of these waves determines the existence and the duration of the "pause." As P approaches P_3, the value of D_{21} increases and the duration of the "pause" decreases. Weak reflection, not registered in the experiment in the case of the two-wave configuration, is determined by the fact that the jumps in the density (and hence in the refractive index) are relatively small in each wave. Whereas one wave with amplitude 170 kbar reflects ~ 0.5% of the incident light, a stepwise loading to the same pressure leads to a "bleaching" of the reflecting layer, wherein the reflections of the elastic and plastic waves are 0.15% and 0.10%, respectively, which is at the sensitivity limit of the method.

On going over to pressures $P > P_3$, the elastic and plastic compression zones come closer together and form a unified shock-wave profile (Fig. 6b). The velocity of such a wave exceeds c_{el} and the "pause" vanishes. The reflectivity increases with increasing pressure. At $P > 265$ kbar this growth occurs in accordance with the density jump on the front, and at $P < 265$ kbar the actually registered reflection coefficients are smaller than those calculated from the jump in density on the shock-wave front. This indicates that in lead glass, just as in KBr and KCl,[12] the registered reflection is determined by the density jump on the non-equilibrium adiabat (dash-dot line of Fig. 6a). The transition to the plastic state is by relaxation. When $P > 265$ kbar, the transition time, determined by the same method as in [12], is $\tau \le 10^{-12}$ sec.

It was noted earlier that at $P < 170$ kbar lead glass is opaque, and that at $P > 170$ kbar it remains partially transparent. This behavior is apparently determined also by the difference in the character of its compression. When the glass is compressed essentially elastically, it remains transparent, but at large pressures in the plastic waves the transparency is lost. This loss of transparency is obviously connected with the loss of optical homogeneity of the medium, for if the opacity were to result from a change in the optical properties, then relaxation of the glass would restore its transparency. Our experiment, in which the glass was allowed to relax after the compression, has shown that its transparency is not recovered.

[1] D. Bancroft, E. L. Peterson, and S. Minshall, J. Appl. Phys. **27**, 291 (1956).

[2] L. V. Al'tshuler, M. N. Pavlovskiĭ, L. V. Kuleshova, and G. V. Simakova, FTT 5, 279 (1963), Soviet Phys. Solid State 5, 203 (1963).

[3] S. A. Novikov, I. I. Divnov, and A. G. Ivanov, JETP **47**, 814 (1964), Soviet Phys. JETP **20**, 545 (1965).

[4] J. Wackerle, J. Appl. Phys. **33**, 922 (1962).

[5] A. G. Ivanov, S. A. Novikov, and V. A. Sinitsyn, FTT 5, 269 (1963), Soviet Phys. Solid State 5, 196 (1963).

[6] A. N. Dremin and T. A. Adadurov, FTT 6, 1757 (1964), Soviet Phys. Solid State 6, 1379 (1964).

[7] L. V. Al'tshuler, UFN **85**, 197 (1965), Soviet Phys. Uspekhi **8**, 52 (1965).

[8] Ya. B. Zel'dovich, S. B. Kormer, M. V. Sinitsyn and K. B. Yushko, DAN SSSR **138**, 1333 (1961), Soviet Phys. Doklady **6**, 494 (1961).

[9] L. I. Demkina, Issledovanie zavisimosti svoĭstv stekol ot ikh sostava (Investigation of the Dependence of the Properties of Glasses on Their Composition), Oborongiz, 1958.

[10] GOST 3514-57, Moscow, 1958.

[11] B. I. Kisin, Optiko-mekhanichskaya promyshlennost (Optical-Mechanical Industry) No. 11, 36 (1959).

[12] S. B. Kormer, K. B. Yushko, and G. V. Krishkevich, JETP Letters **3**, 64 (1966), transl. p. 39.

Translated by J. G. Adashko
180