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INVESTIGATION OF LIGHT GUIDES FOR TRANSFER OF SOLAR RADIATION FROM THE FOCAL VOLUME OF A SUNLIGHT COLLECTOR TO A TECHNOLOGICAL ZONE

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The efficiency of light guides manufactured at the State Optical Institute on exposure of the inlet end to concentrated solar radiation under the conditions of an SGU-2 plant with a ∅1.5 m collector has been investigated. It has been established that all ∅2 mm light guides had a stability to concentrated solar radiation of the order of 600 W/cm^2; the damage threshold of ∅8 mm multistrand light guides was about 450 W/cm^2. It has been shown that TK1, TK3 and TK23 heavy crowns are the most stable to the action of 1500–1800 W/cm^2 fluxes. The possibility of restoring the transmission of light guides exposed to ionizing radiations through the use of concentrated solar radiation has been confirmed.

Solar radiation is the only energy source in near-earth space that is not transported from the earth. In a number of works ([1–4]), it has been shown that the concentrated radiant energy of the sun can be utilized in technological processes, for example, for smelting to produce alloys with special properties, zone refining and growing of single crystals, and welding, cutting, brazing, and heat treatment of products [5].

However, means of transferring the radiant flux from the focal volume of an optical system and manipulating it on a heated object are absent at present, and it is natural that it is precisely flexible light guides (optical fibers) or rigid ones of certain configuration that can successfully be used in the technological processes mentioned above. In the existing light guides, light transmission is based on the phenomenon of total internal reflection at the boundary of the strand and the fiber's cladding. In solar power engineering, one mainly uses a mirror paraboloid with an opening angle of 120° as the collecting element. For the light guide placed in the focal plane of the paraboloid to be able to absorb the radiant flux converging at an angle of 120°, its aperture must be no less than 0.86. Therefore, pairs of glasses with a large difference of the refractive indices are required.

In the focal spot of a ∅1.5 m mirror paraboloid, we have a high irradiance of the order of 1000–1500 W/cm^2 for which most of the optical materials are destroyed. The character of destruction is cracking, fusion, and "burning" or two forms of destruction simultaneously. Therefore, to create force light guides one must find optical materials stable to the action of high-density radiant fluxes and with a low light absorption. In selecting pairs, it is required that the coefficients of thermal expansion of the strand and cladding glasses be similar to the largest extent; the viscosities of the glasses must also differ to the smallest extent.

Tests for stability to the action of concentrated solar radiation have been carried out on an SGU-2 solar power plant (paraboloid mirror ∅1.5 m, focal distance 0.64 m, opening angle 120°, and diameter of the focal spot 6–8 mm). The energy parameters of the plant have been determined by the calorimetric-measurement method according to the procedure of [6].

The specimen is fastened in clamps and removed from the collector's focal zone. The mirror is guided to the sun; the specimen is gradually introduced into the focal spot. The flux is increased by gradually opening shutters up to the destruction of the specimen. If the destruction does not occur, the flux is brought to its maximum value and the specimen is held for 10 min.

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TABLE 1. Stability of the Existing Glasses to CSR

Glass	Type of light guide	Numerical aperture A_0	Flux at the light-guide inlet, W/cm^2	Results of tests
TK-LK6	Rigid	0.65	300	Fusion of the inlet end
TF-K17	»	0.86	300	The same
A19-129	Flexible	1.0	190	»
TBF1053-K1265	Rigid	1.0	190	»
BF25-K17	»	0.54	300	Stable
BF25-K17	Flexible	0.54	1630	Fusion of the inlet end

TABLE 2. Stability to the Action of a Concentrated Radiant Flux and Light Transmission of Force Light Guides

Type of light guide	Numerical aperture A_0	Diameter d, mm	Damage threshold P, kW/m^2	Light transmission T, %
Single-strand	0.71	9	$6 \cdot 10^3$	86
Single-strand	0.64	8	$6 \cdot 10^3$	85
Multistrand rigid	0.71	2	$6 \cdot 10^3$	–
Rigid	0.71	8	$4.5 \cdot 10^3$	30–40
Rigid	0.55	2	$6 \cdot 10^3$	–
Multistrand flexible	0.71	8	$(1–4.5) \cdot 10^3$	30

The specimens of the glasses represent ∅5 mm cylinders of length 10 mm or 5 × 5 × 10 mm parallelepipeds whose ends are polished. Into the focal spot, we introduce one end of the specimen. It is cooled by air fed from a compressor.

The stability of the pairs is determined in testing of either ∅5–10 mm rigid force light guides or flexible bundles of fibers about 10 mm in diameter. Initially, we tested the existing pairs of glasses (Table 1) for stability to concentrated solar radiation (CSR). The most stable is the BF25-K17 pair. However, when the irradiance in the focal spot is maximum, such bundles are also destroyed; therefore, they cannot be employed as force light guides in the entire range of heat fluxes ensured by a solar furnace.

To select new pairs we tested many different optical materials for stability to CSR (of the order of 1500–1800 W/cm^2). Heavy (dense) crowns (crown glasses) TK1, TK3, and TK23 have a comparatively high refractive index (1.56–1.58); therefore, they can be employed as the fiber strand. Glasses with refractive indices of less than 1.51, which are stable to intense fluxes and suitable for the claddings of light-guiding strands, are much more numerous. These include LK1, LK5, LK6, and LK8 light crowns, most of the tested electronic glasses, all quartz glasses, and glasses created as claddings for 129_0 and 157_0 high-aperture fiber-optical pairs. All the crystals tested, except for barium fluoride, are stable to CSR. All the tested flints (F4, TF5, TF10, BT12, OF3, and TBF3) are destroyed under the action of CSR. The character of their destruction is "burning" and fusion. The character of destruction of 3S9 electronic glass is the same. In certain glasses (A19, K1265, 305, and TBF25), first we have the fusion of the inlet end and then of the entire specimen if CSR does not cease to act.

For the remaining glasses the character of destruction is cracking.

As a result of mechanical treatment of the glass surface with abrasives, a microcracked layer with inclusions of abrasive grains, which are the centers of energy absorption and failure, is formed in grinding and polishing by the ordinary methods. Microcracks contribute to the failure of the surface and then of the volume of the glass. It has been experimentally confirmed that chemical polishing substantially improves the stability of glasses. The composition and concentration of the solution and the duration of etching are selected individually depending on the composition of the glass.

Of the tested glasses stable to CSR, we have selected the TK23–157_0 pair and have manufactured both rigid light guides and flexible fiber bundles which stably operated in the focal spot of the paraboloid mirror 1.5 m in di-

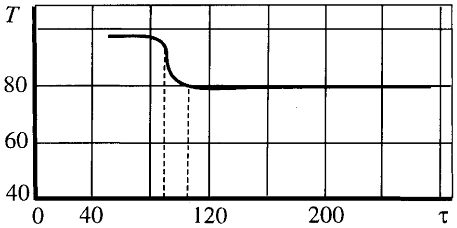

Fig. 1. Change in the light transmission T, %, of single-strand light guides under nonstationary conditions.

ameter for several hours. For an input flux of 500 W/cm^2, the output energy is sufficient to ignite paper and wood, to fuse POS-40 solder, and to raise stainless-steel foils to a red heat [7].

The basic method of increasing the damage threshold of light guides is the development of a technology enabling one to obtain a structure similar to monolithic glass on the end of the light guides.

With the aim of searching for high-aperture pairs, we have investigated low-refraction glasses of the Me_2O–B_2O_3–As_2O_3–SiO_2 system and high-refraction ones of the Me_2O–$MeO(Me_2O_3)(MeO_2)$–SiO_2 system, whose constitutents were K_2O, Na_2O, BaO, CaO, PbO, As_2O_3, Y_2O_3, and TiO_2 (here and in what follows, Me is a metal).

The stability of all the low-refraction glasses investigated exceeded the maximum radiation-power density realized in the solar power plant and equal to $1.5 \cdot 10^4$ kW/m^2. The threshold radiation-power density of the high-refraction glasses was $1 \cdot 10^4$–$1.5 \cdot 10^4$ kW/m^2. Three of the most technological core glasses in combination with the cladding glasses of those investigated were employed for manufacture of light guides. The numerical apertures of the light guides A_0, having cores from the Me_2O–(BaO + CaO)–B_2O_3–SiO_2, Me_2O–PbO–B_2O_3–SiO_2, and Me_2O_3–$Y_2O_3(As_2O_3)$–TiO_2–SiO_2 glasses, were equal to 0.55, 0.64, and 0.71 respectively.

From the glass pairs with a numerical aperture of 0.64 and 0.71, we manufactured ∅8 mm single-strand light guides of length $L = 0.5$ m. For multistrand light guides we used a triple system of glasses, which included, in addition to the pairs selected, a soluble glass of the Me_2O–$MeO(Me_2O_3)$–SiO_2–B_2O_3 system for the second cladding (Table 2).

The multistrand light guides had the form of rigid and flexible specimens with $d = 8$ mm and $A_0 = 0.71$ and rigid specimens with $d = 2$ mm and $A_0 = 0.55$. The length of the multistrand light guides was $L = 0.5$ m; the coverage of the end with the light-guiding cores was equal to $K = 0.55$. The end surfaces of all the light guides were treated by the method of deep grinding and polishing.

In the investigations, the angles of convergence of a conical flux corresponded to the numerical apertures of the light guides, which ensured the entry of the entire solar radiation into the light guide. The power of radiation guided into the light guide was brought to its maximum by gradual opening of the shutters. The light guide was irradiated for 30 min. The damage threshold was determined to a large extent by the presence of local defects in the form of cracks, filled with microscopic abrasive particles, on the surface.

Destruction began with the fusion of the zone about a defect and was accompanied by an avalanche-type ejection of a substance. In these specimens, the damage threshold increased 1.5 times on spalling of the polished surface; the end was simply fused in destruction.

The avalanche-type character of destruction is probably related to the process of reduction of arsenic contained in the strand glass. In the single-strand light guides, we observed the effect of decrease in light transmission under nonstationary conditions in the period of heating (Fig. 1). The decrease in light transmission attained 20% and ceased when thermal equilibrium was established within 50–120 sec after the opening of the mirror. The reason for the attenuation of the radiation transferred was probably the staining of the strand glass under the action of solar radiation. This process was probably enhanced by the heating of the specimen.

With the aim of studying the phenomenon of restoration of the light transmission of glasses and deepening the knowledge of the operating potential of light guides in sunlight collectors installed in an orbital space complex, we have investigated the influence of intense solar radiation on the characteristics of light guides exposed to ionizing radiation. The objects of investigation were specimens of ∅8–10 mm optical fibers of length 180 mm with strands from VS-80 germanate glass and VS-92 lead glass. The dose of ionizing γ radiation was 10^4 R. The work was carried out

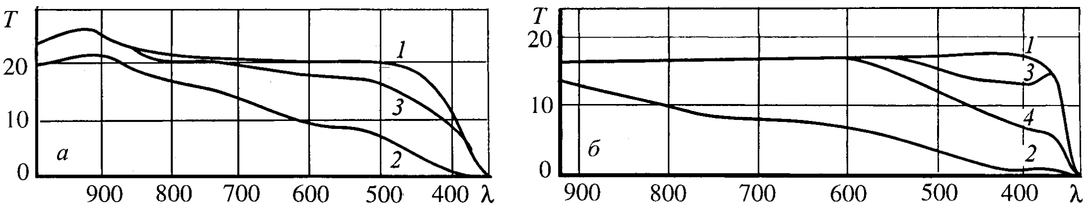

Fig. 2. Spectral dependence of the light transmission T, %, of optical fibers from VS-80 (a) and VS-92 (b) glasses: a) 1 and 2) before and after irradiation with a 10^4 R dose; 3) after annealing, $\tau = 10$ min; the average solar-radiation density is 600 W/cm^2; b) 1 and 2) before and after irradiation with a 10^4 R dose; 3 and 4) after annealing, $\tau = 1$ min, on the portions of length 0–90 and 0–180 mm respectively from the inlet end.

on an SGU-2 solar plant with a ∅1.5 m paraboloid mirror. In the case of the Gauss energy distribution in the focal spot, the average density of the power of radiation incident on the inlet of the light guide was 600 W/cm^2 in the ∅8 mm spot. The duration of treatment was determined visually from the bleaching of the light-guide core and attained 10 min.

The action of ionizing radiation of dose 10^4 R for 10 min leads to a nearly twofold increase in the absorption of visible radiation, whereas the action of sunlight for 10 min restores up to 88% of the initial light transmission (Fig. 2a).

Figure 2b gives the spectra of transmission of the optical fiber with a lead-glass strand. In this case the change in absorption in the visible region under the action of γ radiation is more substantial but it takes a much shorter time to restore the transmission under the action of concentrated solar radiation. Thus, even after a one-minute action by a 600 W/cm^2 radiation flux, we have a nearly complete restoration of transmission on the portion of length 0–90 mm [8]. In the experiments with a relatively short time of action of optical radiation, we observed the formation of a longitudinal inhomogeneity of light transmission with a characteristic profile.

The experimental investigations demonstrate a possible relation of the process of relaxation not so much to the thermal action as to the light action on the color centers.

CONCLUSIONS

1. As a result of the investigations, we have shown the possibility of creating force light guides for transfer of concentrated solar radiation by them from the focal zone of a sunlight collector to the site of utilization.

2. The investigations confirm the high efficiency of utilization of concentrated sunlight for restoration of the light transmission of light guides exposed to ionizing radiations. It is assumed that the presence of ionizing radiation will not result in a substantial energy loss in transfer of intense radiant fluxes by the optical fiber from the focal volume of the sunlight collector to the technological zone.

NOTATION

L, light-guide length, m; d, specimen diameter, mm; P, damage threshold, kW/m^2; A, numerical aperture of the light beam; T, light transmission of the light guide, %; λ, wavelength, nm; τ, time, sec. Subscript: 0, nominal.

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