Effect of Simulated Space Radiation on Selected Optical Materials

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The effect of simulated Nimbus spacecraft orbital (1100 km, circular, and polar) radiation on wide-bandpass glass filters, narrow-bandpass thin-film interference filters, and several fused silicas was determined by transmittance measurements over the 200–3400-nm wavelength region. No changes were observed in the filters, which were shielded with fused silica during irradiation, after exposure to a 1-yr equivalent orbital dose of electrons, nor were changes observed in the fused silicas after the same electron exposure plus a 1-yr equivalent dose of protons. Exposure to a $\frac{1}{2}$-yr equivalent dose of solar uv radiation, however, caused a significant degradation in the transmittance of two uv-transmitting interference filters but had no effect on two colored glass filters that transmitted in the visible and near-ir regions. As a result of the uv exposure, the fused silicas exhibited losses of several percent over the 200–300-nm wavelength region.

Introduction

Current emphasis on meteorological and earth resources satellites has brought about a significant increase in the use of optical materials in space. This, in turn, has required an increased awareness of the effect of the space environment on such materials. Reflectance and transmittance, for example, can be severely affected by particulate and solar radiation impinging on optical elements.

Results are given in this paper of the effect of electron, proton, and uv radiation on the transmittance of various fused silicas, colored glass filters, and thin-film interference filters proposed for use in the optics of the Earth Radiation Budget (ERB) experiment. The ERB experiment package is to be flown on a Nimbus spacecraft. The experiment will simultaneously measure the quantity of electromagnetic radiation emanating from the earth and that incident upon it. Optical materials will be utilized in the experiment package in a number of earth-looking channels, one of which will use a wide-bandpass glass filter, and sun-looking channels that use either wide-bandpass glass filters or narrow-bandpass interference filters. The filters used in all channels will be shielded by fused-silica windows.

The fused-silica shielded filters were exposed to electrons and uv radiation; the fused silicas were exposed to protons as well. The particle fluences used in this study were equivalent to those that will be experienced by the satellite during 1 yr in orbit. In most cases the filters and the fused silicas were exposed to uv radiation equivalent to $\frac{1}{2}$ yr in orbit. In some instances, however, the exposure was somewhat less than or greater than $\frac{1}{2}$ yr in orbit.

All irradiations were performed at a pressure of 1×10^{-5} Torr or less. Transmittance measurements were made in air between 5h and 24 h after irradiation.

Radiation Test Levels

Charged Particle Radiation

Data on integral flux vs particle energy for a 1100-km polar orbit (Nimbus orbit) were furnished by the Theoretical Studies Branch at NASA's Goddard Space Flight Center; these data are shown in Fig. 1. To simulate as closely as possible the actual space radiation spectrum, electron energy levels of 0.3 MeV, 0.5 MeV, 1.0 MeV, and 1.5 MeV and proton energy levels of 0.5 MeV, 1.5 MeV, and 2.0 MeV were utilized in this study.

The estimated maximum yearly fluence at each of the above energies was determined from the flux-energy data and was used in conjunction with an obscuration factor of 0.5 to calculate dosage. This obscuration factor took into account the partial blocking out of radiation as a result of optical component positioning within the experiment housing. The energies and fluences for the particle irradiations are given in Tables I and II.

Ultraviolet Radiation

The solar-viewing channels will receive approximately 2200 h of solar radiation in 1 yr, and the earth-

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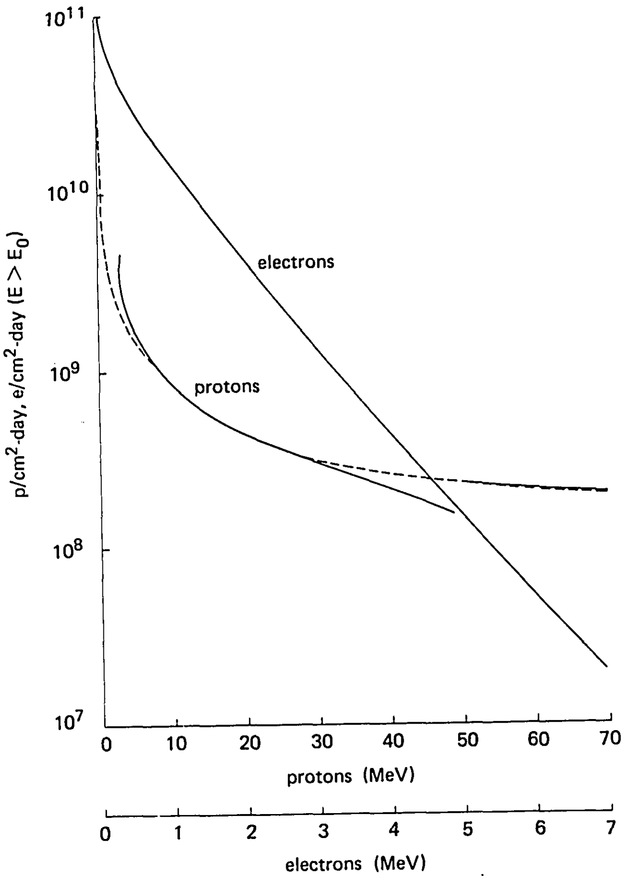

Fig. 1. Electron and proton fluxes encountered in the Nimbus orbit.

viewing channels somewhat less. All the materials investigated in this study were proposed for use in the solar-viewing channels; some were proposed for both solar- and earth-viewing channels. Most of the materials were irradiated at 2.0 uv solar constants (UVSC) for a period of 550 h or 1100 equivalent uv solar hours (EUVSH). This approximates $\frac{1}{2}$ yr in orbit. Some materials, however, were irradiated at 3.5 UVSC for equivalent periods of much less than 1 yr in orbit, in some instances this shorter period being sufficient to indicate that the material would be unsatisfactory for the intended application.

Materials and Experimental Procedure

The materials irradiated, samples of which were provided by the National Environmental Satellite Service of the National Oceanic and Atmospheric Administration, were (1) Dynasil 1000 (fused silica), (2) Suprasil-W (fused silica), (3) Corning 7940 (fused silica), (4) Infrasil II (fused silica), (5) Schott filter glass OG530 (wide bandpass), (6) Schott filter glass RG695 (wide bandpass), (7) interference filter 1 (250–300 nm), (8) interference filter 4 (350–450 nm), (9) interference filter 5 (400–500 nm), and (10) interference filter 7 (700-nm cuton).

The Dynasil 1000 samples were obtained from Dynasil Corporation (U. S.). Corning 7940 is commercially available from Corning Glass Works (U. S.). The Suprasil-W, Infrasil II, and Schott filter glasses were manufactured by Engelhard-Heraeus-Schott (West Germany). The interference filters used Dynasil-1000 substrates and were produced by Thin Films Industries (U. S.).

Schott filter glasses OG530 and RG695 and the interference filters were placed behind 3.1 mm of Corning-7940 fused silica during electron and uv exposure. Since the penetration range of the highest energy electrons (1.5 MeV) is 2.5 mm in fused silica,[1] the Corning-7940 shielding was sufficient to prevent any penetration by the electrons. Any significant damage that might occur in the case of electron exposure, therefore, would be attributable to bremsstrahlung.

The penetration of 2.0-MeV protons into fused silica is 0.03 mm.[1] Since this penetration is relatively insignificant and since bremsstrahlung produced by protons is negligible, it was not considered necessary to expose the filters to proton irradiation.

The samples were measured for transmittance before and after irradiation. All samples, except the interference filters, were cleaned with toluene before the optical measurements were made; the interference filters were wiped with lens tissue.

Charged Particle Irradiation

Samples were exposed in a vacuum of 1×10^{-5} Torr to electrons from a Van de Graaff accelerator. The beam flux was kept at 10^{11} electrons/cm^2-sec for all exposures. Samples exposed to protons were in a vacuum of 1×10^{-6} Torr with a beam flux of 10^{10} protons/cm^2-sec. Transmittance measurements in all cases were made within 5 h after irradiation.

Ultraviolet Irradiation

Upon termination of the charged-particle irradiation, the samples were exposed to uv radiation. During this irradiation, the samples were maintained at a temperature of approximately 15°C in a vacuum of 1×10^{-7} Torr. Exposure was at 2.0 UVSC from a xenon

Table I. Electron Irradiation Test Levels

Energies (MeV)	Electron fluence (electron/cm^2)
0.3	1.4×10^{13}
0.5	7.3×10^{12}
1.0	3.7×10^{12}
1.5	1.6×10^{12}

Table II. Proton Irradiation Test Levels

Energies (MeV)	Proton fluences (proton/cm^2)
0.5	3.3×10^{11}
1.5	3.8×10^{10}
2.0	1.7×10^{10}

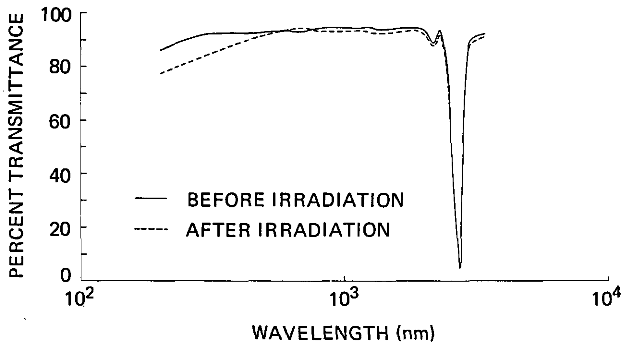

Fig. 2. Transmittance of Dynasil-1000 before and after uv irradiation at 2.0 UVSC for 1100 EUVSH.

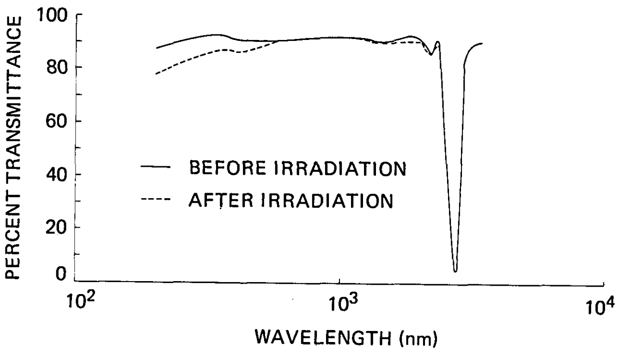

Fig. 3. Transmittance of Dynasil-1000 before and after irradiation by electrons of energies 0.3 MeV, 0.5 MeV, 1.0 MeV, and 1.5 MeV to a total flux of 2.7×10^{13} electrons/cm^2, plus protons of energies 0.5 MeV, 1.5 MeV, and 2.0 MeV to a total flux of 3.9×10^{11} protons/cm^2, plus uv radiation at 2.0 UVSC for 1100 EUVSH.

lamp for 550 h to give 1100 EUVSH. Corning-7940, Suprasil-W, and Infrasil-II samples were exposed in vacuum to uv radiation from a mercury arc at 3.5 UVSC. After irradiation the samples were kept cool and dry in a refrigerated desiccator until the transmittance measurements were made. Before the measurements were carried out, the samples were allowed to come to room temperature. All measurements were made within 24 h after irradiation.

Optical Transmittance Measurements

The transmittances of the fused silicas and the Schott glass filters were measured over the 200–3400-nm wavelength region. These measurements were made with a Beckmann DK-1A spectrophotometer that was accurate to within two transmittance percentage points. The interference filters were measured over their respective ranges with a Cary-14 spectrophotometer that was accurate to within one-half of a transmittance percentage point.

Experimental Results

Dynasil-1000

Within the accuracy of the transmittance instrument, Dynasil-1000 was not affected by electron or proton irradiation at the levels encountered in the Nimbus orbit over a 1-yr period. In this connection, Heath and Sacher[2] found in fused silica (described as Dynasil optical grade) significant degradation below 300 nm caused by 1-MeV and 2-MeV electron bombardment; however, the fluence used in their study (2×10^{14} electrons/cm^2) was larger than in the present case.

Ultraviolet irradiation, on the other hand, significantly decreased the transmittance of Dynasil-1000 in the 200–400-nm wavelength region, as is shown in Fig. 2. The cumulative effects on transmission of electron, proton, and uv irradiation are shown in Figure 3.

Suprasil-W

Electrons of 1.0-MeV energy had no effect on Suprasil-W during an exposure equivalent to approximately $\frac{1}{3}$ yr in orbit (i.e., 1×10^{13} electrons/cm^2). After a total dose of 1×10^{14} electrons/cm^2, however, significant transmission loss occurred from 200 nm to 300 nm (Fig. 4). Irradiation by 1.5-MeV electrons to

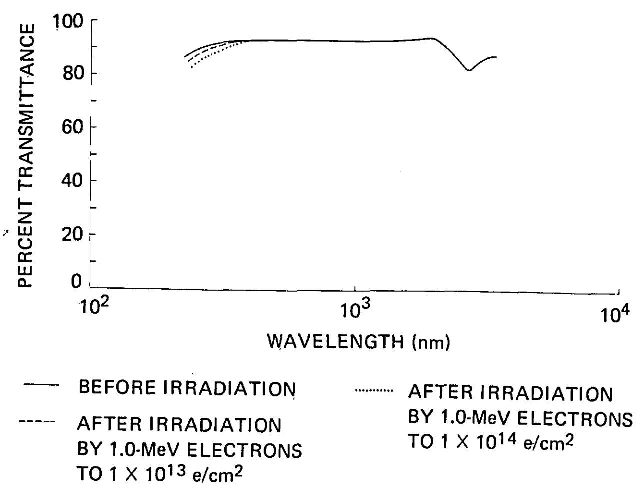

Fig. 4. Transmittance of Suprasil-W before and after irradiation by electrons of 1.0-MeV energy to a total flux of 1.0×10^{13} electrons/cm^2 and after irradiation by electrons of 1.0-MeV energy to a total flux of 1.0×10^{14} electrons/cm^2.

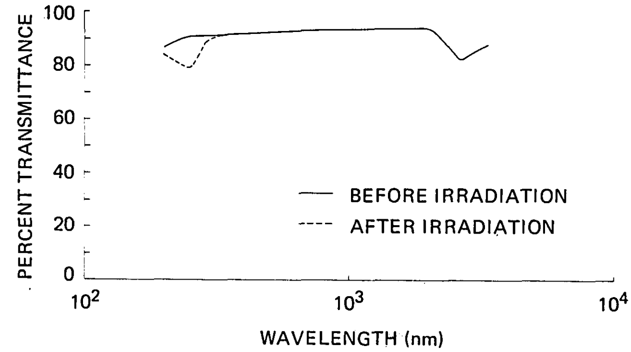

Fig. 5. Transmittance of Suprasil-W before and after irradiation by electrons of 1.5-MeV energy to a total flux of 1.0×10^{14} electrons/cm^2.

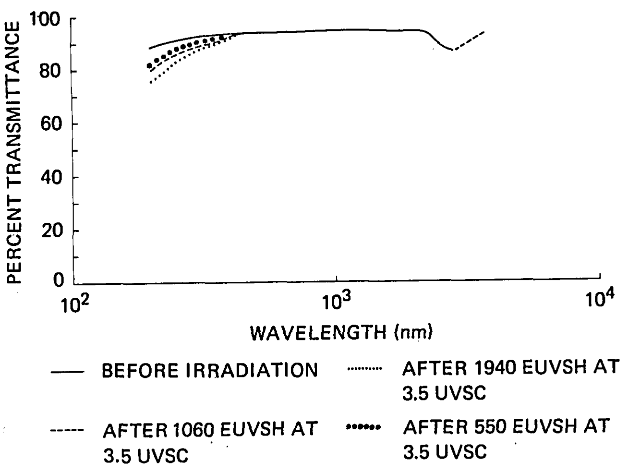

Fig. 6 Transmittance of Suprasil-W before and after uv irradiation at 3.5 UVSC for 550, 1060, and 1940 EUVSH.

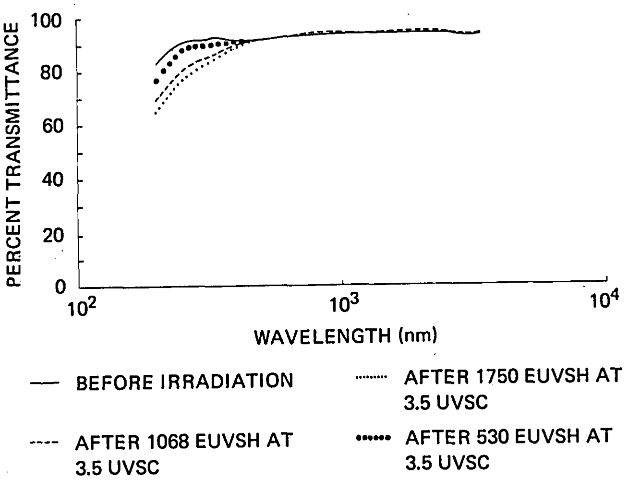

Fig. 7. Transmittance of Infrasil II before and after uv irradiation at 3.5 UVSC for 530, 1068, and 1750 EUVSH.

1×10^{14} electrons/cm^2 caused a considerable loss in transmittance at 250 nm (Fig. 5). This loss approximates that of the fused silica evaluated by Heath and Sacher.[2] Upon exposure to uv radiation, the material exhibited a definite loss in transmittance between 200 nm and 400 nm (Fig. 6). It appears that the degradation increases linearly up to about 1200 EUVSH and then begins to level off.

Infrasil II

Infrasil-II fused silica was exposed to uv irradiation only. It exhibited a significant decrease in transmittance, as is shown in Fig. 7.

Corning 7940

Samples of Corning-7940 fused silica were exposed to charged particles and to uv irradiation, although transmittance data were obtained only after the latter exposure. The material was exposed at rates of 2.0 and 3.5 UVSC; the results are shown in Fig. 8 and 9, respectively.

Schott Colored-Glass Filters

The spectral transmittances of Schott filters OG530 and RG695, when suitably shielded from electron and uv radiation with fused silica, exhibit no significant changes.

Interference Filters

The results of irradiation on the interference filters are shown in Fig. 10–13. Filters 1 (Fig. 10) and 4 (Fig. 11) showed a significant change after uv irradiation. There was a decrease of approximately 72% in the transmittance peak of filter 1 and a 28% decrease in the peak height of filter 4 after an exposure of 1100 EUVSH. Figures 10 and 11 also show transmittance

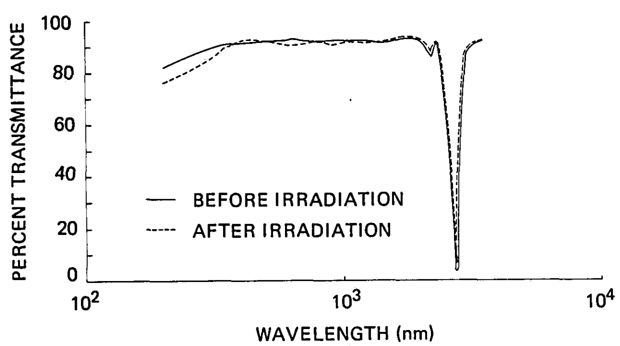

Fig. 8. Transmittance of Corning 7940 before and after uv irradiation at 2.0 UVSC for 1100 EUVSH.

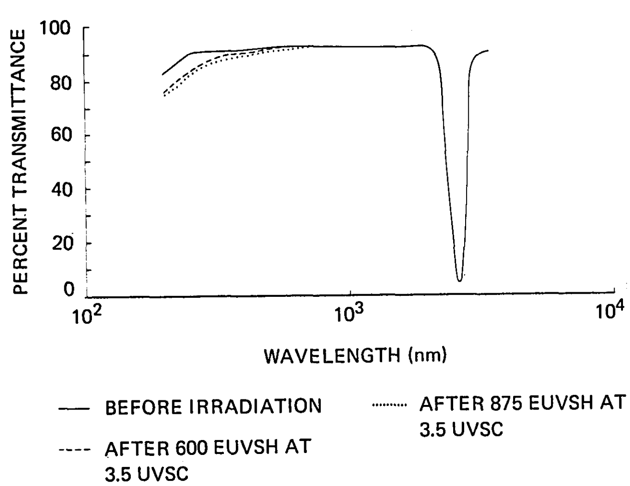

Fig. 9. Transmittance of Corning 7940 before and after uv irradiation at 3.5 UVSC for 600 and 875 EUVSH.

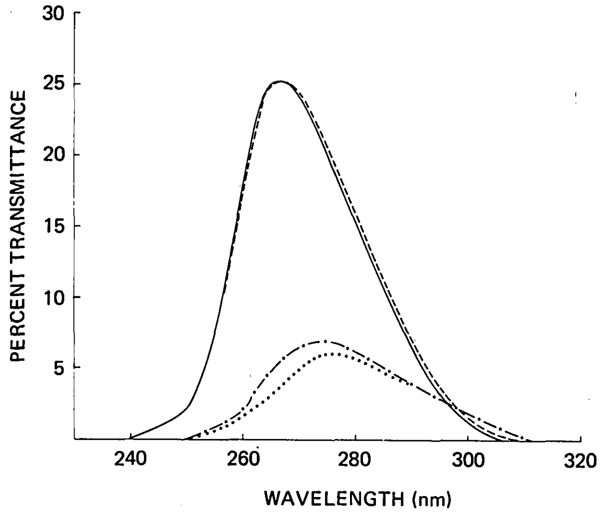

Fig. 10 Transmittance of interference filter 1 (250–300 nm) before and after irradiation by electrons of energies 0.3 MeV, 0.5 MeV, 1.0 MeV, and 1.5 MeV to a total flux of 2.7 $\times$ 10^{13} electrons/cm^2 and after irradiation by the above electrons plus uv radiation at 2.0 UVSC for 1100 EUVSH. Measurements were also made 170 h after the uv irradiation. The filter was shielded from direct radiation by 3.1 mm of fused silica.

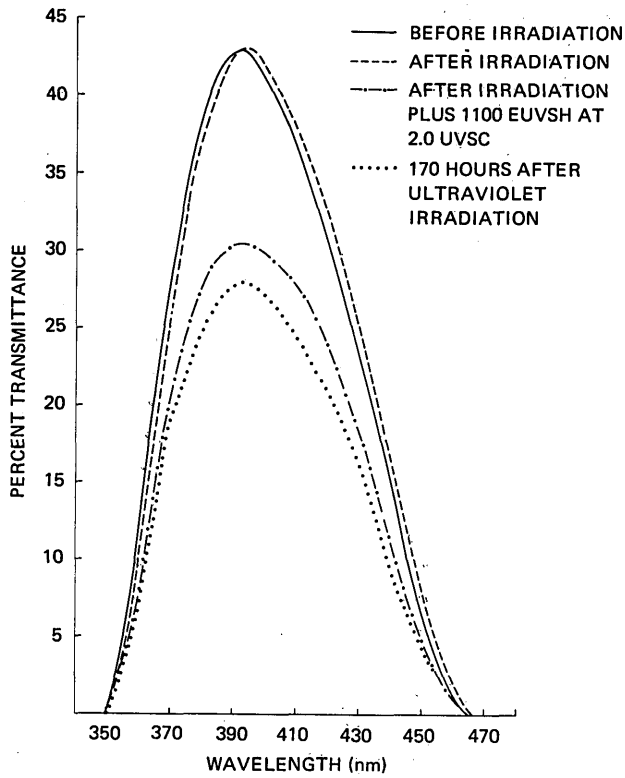

Fig. 11. Transmittance of interference filter 4 (350–450 nm) before and after irradiation by electrons of energies 0.3 MeV, 0.5 MeV, 1.0 MeV, and 1.5 MeV to a total flux of 2.7$\times$ 10^{13} electrons/cm^2 and after irradiation by the above electrons plus uv radiation at 2.0 UVSC for 1100 EUVSH. Measurements were also made 170 h after the uv irradiation. The filter was shielded from direct radiation by 3.1 mm of fused silica.

measurements made 170 h after irradiation. These measurements were made to determine if annealing of the radiation damage took place during that period. Within the reproducibility of the spectrophotometer, there does not appear to be any annealing effect. To reduce the possibility of annealing, the samples had been kept at approximately 8°C in a desiccator immediately following the postirradiation measurement. No changes due to irradiation were observed in filter 5 (Fig. 12) or filter 7 (Fig. 13).

Conclusions

No significant changes occurred in the transmittances of any of the fused silicas as a result of exposure to electron and proton radiation equivalent to 1 yr in space; nor was there any change in the filters (shielded with fused silica), which were exposed to electrons only. The study shows, however, that exposure to electron fluences of 2 $\times$ 10^{14} electrons/cm^2 or greater with electron energies of 1.0 MeV and higher can be expected to cause significant transmittance losses in fused silica. For electron energies up to 1.5 MeV, a 3.1-mm thick fused silica shield sufficiently protects both wide-bandpass glass and narrow-bandpass interference filters.

Resistance to uv radiation appears to be the most important factor in the selection of a fused silica for

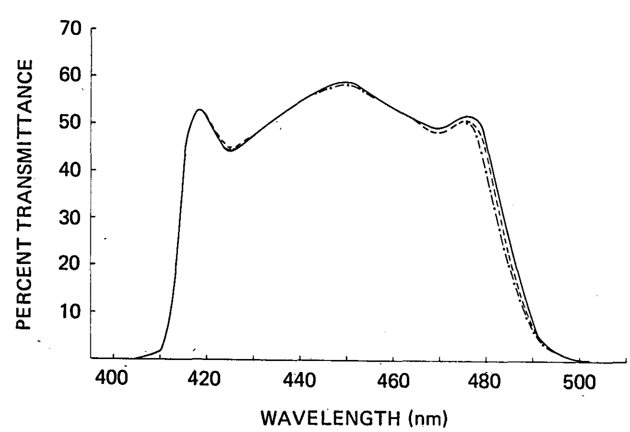

Fig. 12. Transmittance of interference filter 5 (400–500 nm) before and after irradiation by electrons of energies 0.3 MeV, 0.5 MeV, 1.0 MeV, and 1.5 MeV to a total flux of 2.7 $\times$ 10^{13} electrons/cm^2 and after irradiation by the above electrons plus uv radiation at 2.0 UVSC for 1100 EUVSH. The filter was shielded from direct radiation by 3.1 mm of fused silica.

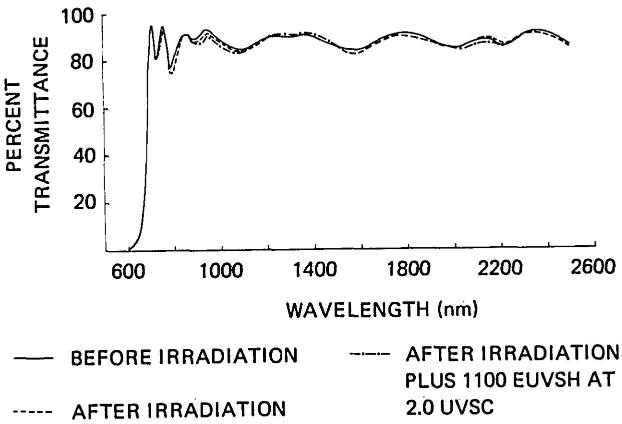

Fig. 13. Transmittance of interference filter 7 (700-nm cuton) before and after irradiation by electrons of energies 0.3 MeV, 0.5 MeV, 1.0 MeV, and 1.5 MeV to a total flux of 2.7×10^{13} electrons/cm^2 and after irradiation by the above electrons plus uv radiation at 2.0 UVSC for 1100 EUVSH. The filter was shielded from the direct radiation by 3.1 mm of fused silica.

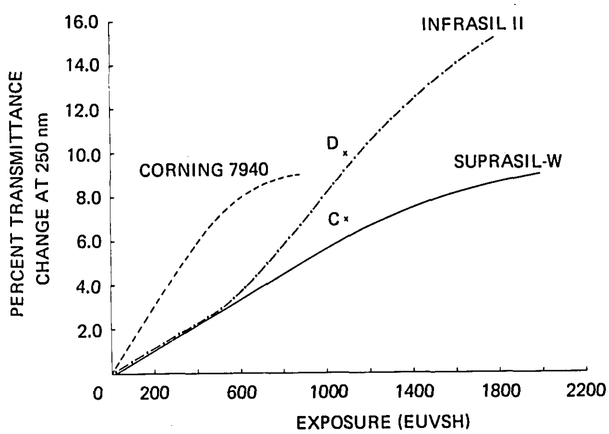

Fig. 14. Comparison of the effect of uv irradiation (at 3.5 UVSC) on the transmittance of fused-silica shielding material.

space use. Figure 14, a plot of transmittance change at 250 nm vs exposure hours, is illustrative. Points C and D represent changes experienced by Corning 7940 and Dynasil-1000, respectively, after 1100 EUVSH at 2.0 UVSC. As the figure indicates, Suprasil-W appears to be the most resistant to uv irradiation, followed by Corning 7940. Dynasil-1000 and Infrasil II exhibit much greater degradation.

Schott filters OG530 and RG695, when sufficiently shielded by fused silica against electrons and protons, are suitable wide-bandpass filters.

Interference filters 1 and 4 exhibited far too much uv degradation for use in the solar channels of the ERB experiment. The decrease in transmittance observed in the Dynasil-1000 samples as a result of the uv irradiation is not sufficient to account for the losses exhibited by these filters, which have Dynasil-1000 substrates and protective covers. Filter 1 was composed of layers of aluminum and cryolite with a thorium-fluoride overcoat. Filter 4 was composed of layers of silver and cryolite with no overcoat. In both cases, the protective covers were attached to the filter and separator rings with a neoprene adhesive.

Although no experiments were carried out to determine the exact cause of the degradation, it seems reasonable to conclude that it is due to the thin-film materials and/or the neoprene adhesive used to assemble the filters. The results obtained on filters 1 and 4 show that, in the selection of uv and near-uv interference filters for space applications, care must be taken to ensure that proper thin-film and assembly materials are used.

References

1. V. Linnenbom, Naval Research Lab. Rep. 5828 (1962).
2. D. Heath and P. Sacher, Appl. Opt. **5**, 937 (1966).
