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# Dose depth and penetration of light dependence in the irradiated optical glass by reactor neutrons

N. Baydogan *, A.B. Tugrul *

*Istanbul Technical University, Energy Institute, Ayazaga Campus, Maslak, 34469 Istanbul, Turkey*

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ABSTRACT

The effect of absorbed gamma dose of the optical glass containing $B_2O_3$ and BaO was examined at nine different dose levels, ranging between ~1 and 36 kGy, in order to explain dose depth and penetration of light dependence. The specific light absorbance per unit area was examined to determine the changes in penetration ability of light photons into the irradiated glass structure due to the absorbed dose. Determining the increase in the absorbance of light photons is proposed as an approach to create the equivalent dose estimation. Examination of the penetration of light photon for the visible range presented an importance to evaluate absorbed dose depth in optical glass. The variations of light absorbance in the standardisation concept were controlled by the absorbed dose in a practical way. A calibration curve was determined depending on the variations of absorbed dose depth and optical density at 620 nm in the visible range. The effect of neutron and mixed gamma/neutron radiation in the tangential beam tube and the central thimble of the nuclear reactor, respectively were evaluated by means of equivalent gamma dose in order to explain the light absorbance in the irradiated glass.



## 1. Introduction

Several types of glass are used in irradiation constructions, hot cell windows, and peeping holes during irradiation processes with direct and/or indirect ionizing radiation at high doses. The duty of optical material during its service life in the irradiation field is required to perform a considerable optical performance at the visible range (~380–780 nm) [1–3]. Optical materials can subject to ionizing radiation during their missions at different absorbed dose levels in either terrestrial or space applications. Hence the changes of optical properties in the visible range present an importance with the increase of absorbed dose. Typical onboard sources of radiation in space vehicles include nuclear reactors as typical internal radiation sources. Ionizing radiations (such as neutrons, gamma rays and beta particles) are produced by the isotopes in the onboard sources of space vehicles [4].

When high refraction index is required in glass, it is usually necessary to have appreciable amounts of heavy metals such as lead and barium in the glass. However lead-free crystal has a similar refractive index to lead crystal, but it is lighter and it has less dispersive power. Lead-free crystal glass generally comprises 50–75 wt.% $SiO_2$, 2–15 $Na_2O$, 1–15 $K_2O$, 3–12 CaO, 1–10 BaO, 0–1- $B_2O_3$, 0–5 $Al_2O_3$. Barium oxide or potassium oxide are used in this crystal glass instead of lead oxide to increase the optical performance. $B_2O_3$ and BaO improve appearance and strength. But BaO provides less chromatic dispersion than $B_2O_3$ in lead-free glass. Hence, translation of colour in glass with BaO is more true and more distinctive with no fringing than translation of colour in glass with $B_2O_3$. BaO in the glass gives more vivid image than $B_2O_3$ in the glass. Besides, BaO has some advantages in lead-free crystal glass depending on the application purposes. The glass containing barium is lighter in weight than glass with lead but the barium gives comparable brilliance due to its high refractive index.

Much of the published materials data concerned Co-60 gamma ray exposure in air environment, and is 50 years old in the space applications. Optical glass is shielded, but its outer surface can receive very high surface doses. Hence the optical changes of glass require evaluating dose–depth curves. Generally accepted: "equal dose gives equal damage", regardless of radiation type. Dose–depth profiles can be different depending on the type of ionizing radiation and the surface doses can be higher for ionizing radiation. It is difficult to simulate the irradiation effect realistically due to different dose–depth curves and different physics of interaction [4]. Differing penetration depths were investigated by using the changes in the penetration ability of the light photons in the irradiated optical glass to evaluate the changes of absorbed dose–depth in this study. The specific light absorbance per unit area was examined to determine the changes in the penetration ability of the light photon. The purpose of this study is to

* Corresponding authors. Tel.: +90 212 285 34 92 (N. Baydogan), tel.: +90 212 285 38 84 (A.B. Tugrul).

*E-mail addresses:* dogannil@itu.edu.tr (N. Baydogan), beril@itu.edu.tr (A.B. Tugrul).

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determine a calibration curve in order to investigate the absorbed dose according to the standardisation concept in a practical way. A calibration curve of the specific absorbance of light photons per unit area, $\alpha_v(\%)/d^2$ (mm) was used to control the absorbed dose. The effect of equivalent gamma dose of neutrons on glass was evaluated using dose depth and specific light absorbance relation.

## 2. Experimental studies

### 2.1. Optical characterisation

Optical crown glass containing $B_2O_3$ and BaO was supplied in three different thicknesses; 3, 6, and 10 mm from the major glass company SISECAM in Turkey. Both surfaces of the glass samples were polished. Firstly, samples were rubbed with SiC abrasive paper at various grain sizes, and then polished with a CeO solution. Smooth and plane parallel surfaces were performed without optical distortion. Optical crown glass, a type of alkali-lime-silica glass, has low-dispersion and is used for making optical equipment. This type of colourless silica glass is manufactured generally from combinations of $SiO_2$ with $K_2O$, $Na_2O$, CaO and other oxides (network modifiers) [5]. Soda-lime-silicate glass has a composition of in wt. 70% $SiO_2$, 15% $Na_2O$ and 10% CaO [6]. Adding soda ($Na_2O$), and sometimes potash ($K_2O$), to silica lowers its softening point by 800–900 °C. Lime (CaO) and sometimes magnesia (MgO) and alumina ($Al_2O_3$) are added to improve its chemical resistance [7]. Boron provides good chemical resistance and high dielectric strength because of its low thermal expansion [5,6,8]. Modern optical glass usually contains barium oxide instead of lime. The element Barium is the hardest member of the alkaline earth group element [9]. Barium oxide is added to soda-lime-silicate glass in order to decolourise glass [10]. Besides, barium has the highest neutron-cross section in alkaline earth group [2,3,10–12]. Table 1 illustrates a Philips PW 1606 X-ray Fluorescence (XRF) Spectrometer, used to determine the chemical composition of glass.

A Perkin Elmer, Lambda-9 UV/VIS/NIR spectrophotometer was used to measure the spectral transmittance and reflectance of samples between 280 nm and 2200 nm in order to examine the influence of radiation on glass. Optical measurements were recorded at different times during the gamma irradiation step. The direct light transmittance ($\tau_v$), the direct light reflectance ($\rho_v$), and the direct light absorbance ($\alpha_v$) of the glass were calculated for the unirradiated and the irradiated states in the visible range according to European Standards. Details of $\tau_v$, $\rho_v$, and $\alpha_v$ are described elsewhere [10,12–15].

### 2.2. Irradiation process using a Co-60 radioisotope

A projection type Co-60 radioisotope with 362.6 GBq was used as the gamma source. The glass specimens with different thicknesses such as 3, 6, and 10 mm, were set up panoramically at several distances from the gamma ray source [16–18]. The collision possibility of photons with atoms increased due to the increase in thickness.

Irradiated glasses can present an initial rapid fading in their optical response. Hence, the irradiation process was performed in dark at a hot cell to protect the induced colour changes by irradiation in case of the optical changes before expected. The optical measurements were performed at the end of the gamma irradiation process to eliminate the early fading problem. The irradiation time intervals have taken hours for less doses (<~5 kGy) and it has taken days for high doses (>~5 kGy).

The values of elements in glass are illustrated in Table 1. Nine different dose levels were selected in order to evaluate the characteristics of light absorbance and optical density of the glass; ~1.0, 2.2, 4.5, 8.0, 12, 15, 21, 30, and 36.0 kGy. The maximum irradiation dose at ~25 kGy helps reduce some radiation effects, such as decrease material strength or colour change in the material [19]. On the other hand, irradiation is used for special radiosterilisation purposes at ~1–10 kGy, and specialised organisations of the United Nations Organization (FAO, IAEA, WHO) recommend that member states authorise these absorbed dose levels [20]. The absorbed dose at ~35 kGy is the killing dose of several microorganisms for the medical sterilisation of products [21]. In this study, the maximum applied dose was selected as 36 kGy in order to examine changes in optical behaviour.

A measure of how deep gamma radiation was evaluated to explain the changes of penetration depth for gamma ray in the irradiated glass by using Beer–Lambert law. The change of penetration depth of the absorbed dose was evaluated by using gamma transmission technique in the irradiated glass. Hence it can be possible to assess the changes of transmittance of gamma ray with the increase of glass thickness in the irradiated glass. For this purpose a certified Co-60 radioisotope was performed to investigate the changes of gamma transmittance in monochromatic conditions at ~1.25 MeV. The increase of the absorbed dose affected the gamma transmittance of glass and the raise of glass thickness causes to decrease the gamma transmittance of glass. Gamma transmittances of glass were presented with the increase of glass thickness for unirradiated and irradiated states in Fig. 1. The background is detected as I0 = 10,332 ± 43. The variations on gamma transmittance indicate that the transmittance of gamma ray in the irradiated optical glass decreases with the increase of the absorbed dose.

### 2.3. Irradiation processes at research reactor

Samples were irradiated in a neutron beam collimator inserted inside the tangential beam tube, as illustrated in Fig. 2. The $10 \times 15 \times 25$ mm$^3$ unirradiated specimens with a 10 mm thickness were placed in the Tangential Beam Tube of ITU TRIGA Mark-II Reactor. A bismuth filter was inserted into the hole to absorb the gamma rays and the filter enabled the neutrons to pass through the collimator [22]. It was possible to obtain the thermal and epithermal neutron fluency and n/$\gamma$ ratio was $1.44 \times 10^4$ n cm$^{-2}$ s$^{-1}$ mR$^{-1}$ in that tube. The inlet diameter of the collimator, D, was 17 mm, and the length of the collimator hole, L, was 2407 mm. The thermal neutron fluency at the inlet of the tube, $\phi_1$, was $1.67 \times 10^{11}$ n cm$^{-2}$ s$^{-1}$ [22]. Measurements were taken using activation analysis $(n,\gamma)$ reaction, using gold foils. The specimen was irradiated in the tangential beam tube of the reactor for 30 min and the reactor was operated at a power of 250 kW. The specimen was placed at a distance of ~407 mm to the filters system in the inlet of the collimator for the effective use of the thermal and epithermal neutron fluency. Hence, specimens were placed as near as possible to the reactor core.

**Table 1**
The chemical composition of optical crown glass containing $K_2O$, $Na_2O$, CaO, $B_2O_3$, and BaO.

| Chemical composition in wt (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BaO | $SO_3$ | $SiO_2$ | $K_2O$ | $Na_2O$ | $B_2O_3$ | SbO | $Al_2O_3$ | $Fe_2O_3$ | NiO | CaO | $TiO_2$ |
| 1.00 | 0.25 | 70.442 | 9.00 | 9.00 | 1.00 | 0.18 | 0.10 | 0.01 | 0.00026 | 9.00 | 0.018 |