Investigation of optical effects induced by gamma radiation in refractory elements

M -R. IOAN, I. GRUIA[a], P. IOAN, I. L. CAZAN, C. GAVRILA[b]
"Horia Hulubei" National Institute for Nuclear Physics and Engineering, P.O. Box MG-6, RO-077125 Bucharest-Magurele, Romania
[a]Faculty of Physics, University of Bucharest, Romania
[b]Faculty of Building Services and Equipment, Technical University of Civil Engineering Bucharest, Romania

A study of the effects of ^{60}Co gamma radiation (E~1,25 MeV, dose rate level 96 Gy/h in air and 325 Gy/h in water pool) on the transmission of three optical glass types (BK-7, ZF-7, KU-1) to central value of band wavelengths: 415 nm-violet 473 nm-blue, 532 nm-green, 580 nm- yellow, 605 nm-orange, 685 nm-red and 800 nm -near infrared is presented. Optical glasses are similar to those of windows and lenses for video surveillance devices in radioactive environment [1-8] and processing lasers [9, 10, 11]. For such applications, gamma radiation induced optical degradation imposes a severe limitation. In all samples, the affected region is that of the visible light spectrum, especially in the ultraviolet region - blue-green. Transmission spectra of the optical glasses analyzed in this study are presented as a function of the glass type and gamma radiation dose (up to 4 MGy). Transmission curves of three kinds glasses, irradiated during tens of hours to different doses of gamma radiation, were studied at room temperature under low or high level of gamma rays. It is therefore necessary to study the degradation of the optical properties for optical material, to assess system life-time. This loss of transmission is detrimental to the performance of optical systems and must be reduced to low level. Test results will be presented for glass radiation resistant and non-resistant to radiation and will be compared three types of glasses.

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Keywords: Optical glass, refractors, gamma radiation, degradation of transmission

1. Introduction

Various systems and equipment operating in radioactive environments are composed of glass elements such as lenses and transparent windows for protection. It is known that gamma ionizing radiation can induce many changes in the optical properties of glasses. Starting from certain doses, the most important visible effect is a gradual change of glass samples color. This is caused by the accumulation of defects in the irradiated volume of the sample.

This work represents the first step in the implementation of a special laser system used for sealing enclosed gamma sources or for fixed radioactivity decontaminations. There are major problems related to solving the effective operating mode and to the optimal process visualization, even in terms of cost efficiency. An ideal system would be composed of an optical system for focusing the laser beam and associated monitoring room made of glass trade. An estimation of the radiation resistance of optical and electronic systems can be done by studying the behavior of each component separately.

We find the best-fit exponential and linear curve using transmittance (T) in percent as a function of dose (D) in Gy, for estimated dose level in the glass and a decrease estimated a transmission level.

2. Experimental procedure

Before performing the gamma irradiation procedure, we determined the following samples characteristics:

- average thickness – ((BK-7) – 9.92 mm ± 2.3%, (ZF-7)-8.20 mm ± 0.9%. (KU-1)-1.56 mm ± 1.9%);
- optical spectra in visible region for - 11 samples (BK-7), 7 samples (ZF-7) and 4 samples (KU-1) - in order to detect any initial dispersion in optical transmission due to potential differences in concentrations of elements or impurities' chemical and dimensional differences of samples from the same batch.

The samples were irradiated under the conditions presented in Table 1.

Optical transmission properties in visible region (350÷850) nm were measured before and after irradiation using a *Varion Cary 100 Bio UV-VIS* spectrophotometer (Dual Beam, Scanning 190nm ÷ 900nm) by means of an adaptation for our samples. Samples were exposed to different gamma radiation doses up to 4MGy as a function of glass type (Table-1). The gamma irradiations have been performed at the "Horia Hulubei" National Institute for Nuclear Physics and Engineering, Bucharest-Magurele, Romania.

BK-7 and ZF-7 samples were placed circular in a rigid support around the cylindrical source at 25 cm in air, for irradiation. Samples of KU-1 glass type were irradiated from a pool type source, inside a sealed irradiation chamber at a distance of 5cm from the source. Source pencils are arranged in an annular ring which surrounds the cylindrical irradiation chamber that is submerged at 3m depth during irradiation.

Table 1: The samples were irradiated at parameters and conditions presented.

Material Type	Geometrical parameters (mm)	^{60}Co – gamma, Mean energy: E = 1.25MeV, Room temperature: T = 20^{o} ±10% Flow measurement of dose was performed with a standard dosimeter ethanol-chlorine benzene (2σ) ^{X} - absorbed dose												
		Dose rate 96Gy/h ±7% in air to 25cm						Dose rate 325Gy/h ±5.8% in water to 5cm						
		Absorbed dose (kGy)												
		32 $*10^{-4}$	64 $*10^{-4}$	128 $*10^{-4}$	256 $*10^{-4}$	528 $*10^{-4}$	1056 $*10^{-4}$	1.2	2.3	4.6	16	250	1000	4000
BK-7	Cylinder 24*(9.9mm±2.3%)	x	x	x	x	x	x	x	x	x	x			
ZF-7	Parallelepiped 7*7*(8.2mm±0.9%)	x	x	x	x	x	x							
KU-1	Plate 6*6*(1.53mm±1.9%)											x	x	x

During irradiation, room temperature was about 20^{o} C. This range of gamma ionizing radiation has been chosen for this purpose because it is very penetrating and easy to be utilized. Simulation of accumulated gamma rays doses for samples from different optical systems will be presented in the following section.

3. Results and discussions

For the three different types of glass used in this study, twenty glass devices having average thicknesses of 9.92mm, 8.2mm and 1.56mm were prepared as it follows: ten crown type BK-7, six extra-thick lead glass type ZF-7 and three type KU-1 fused silica. The glass samples were exposed to gamma radiation doses presented in Table 1. Dose variation was established for each type of sample and a threshold value for comparison (105.6Gy) was adopted. This value of the threshold dose was chosen due to the fact that, in many applications, a value of 100Gy is a point where some optical elements are considered unusable [7].

It is known that gamma rays have a significant impact on the degradation of transmission in visible range. Fig. 1 shows the transmission spectra of our samples irradiated at the absorbed doses presented in table 1. From this graph (Fig.1), we see that for absorbed doses up to 105.6 Gy the transmission is unchanged for KU-1 and more impaired for BK-7 and ZF-7, while a significant degradation occurs for KU-1 starting from 1MGy and BK-7 starting from 1 kGy. Also, ZF-7 samples degradation is about two times more intense than the samples BK-7 even for relatively low doses, up to 105.6Gy. The working range of the unirradiated optical glass samples starts in the shorter wavelength from 200nm for KU-1, 350nm for BK-7 and 450nm for ZF-7. It can be seen in figure 2 that after irradiating at various doses the BK-7 type glass samples, the most affected region of the transmission spectra is that of the short wavelengths. This fact is reflected in a sharper decrease of the transmission by increasing the absorbed gamma radiation dose at shorter wavelengths.

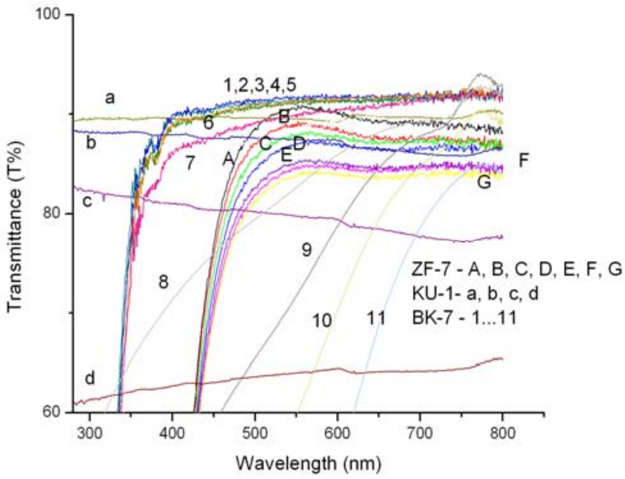

*Fig.1. The VIS- transmission spectra of our samples up 4MGy irradiated doses versus VIS-wavelength (**ZF-7**- A-0Gy, B-3.2Gy, C-6.4Gy, D-12.8Gy, E-25.6Gy, F-52.8Gy, G-105.6Gy; **KU-1**- a-0Gy, b-0.25MGy, c-1MGy, 4MGy; **BK-7**- 1-0Gy, 2-3.2Gy, 3-6.4Gy, 4-12.8Gy, 5-25.6Gy, 6-52.6Gy, 7-105.6Gy, 8-1.2kGy, 9-2.3kGy, 10-4.6KGy, 11-16kGy).*

Response transmissions depending on the dose for the three types of glass tested are shown in Fig. 2. Taking into account the threshold gamma radiation dose value chosen for comparison, the tests performed have shown the followings:

- for doses below the threshold value (105.6 Gy), the transmission decreases in BK-7 glasses with: 7% for 415nm-violet, 4.8% for 473nm-blue, 3.2% for 532nm- green, 2.2% for 580nm-yellow, 2.1% for 605nm-orange 1.3% for 685nm-red and 0.6% for 800nm-near infrared (Figure 2-a);

- while for ZF-7 glasses the transmission decreases by: 11% for 415nm-violet, 9% for 473nm-blue, 8% for 532nm-green, 7% for 580nm-yellow, 6.5% for 605nm-orange, 6% for 685nm-red and 5% for 800nm-near infrared (Fig. 2b) .

Also, these tests have shown how the transmission decreases in BK-7 glasses while irradiated to doses up to 16kGy. It can be seen in Figure 2-c that in the case of BK-7 glass the transmission decreases with: 96.9% for 415nm-violet, 90.8% for 473nm-blue, 81.6% for 532nm- green, 72.3% for 580nm-yellow, 67.6% for 605nm-orange, 45.6% for 685nm-red and 13.7% for 800nm-near infrared.

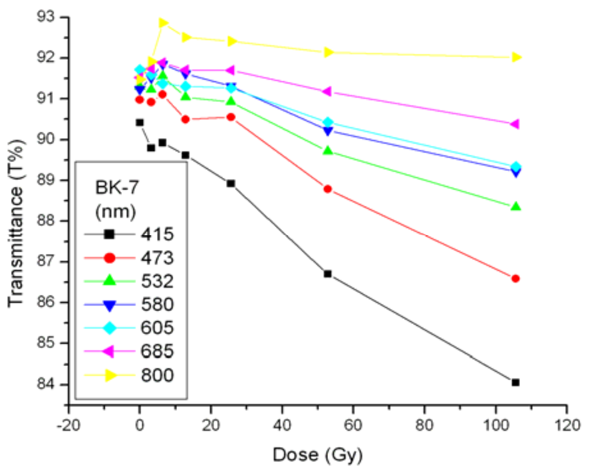

Fig.2a. Response VIS- transmission versus reference sample according to up 105.6Gy irradiation dose, for type crown samples BK-7

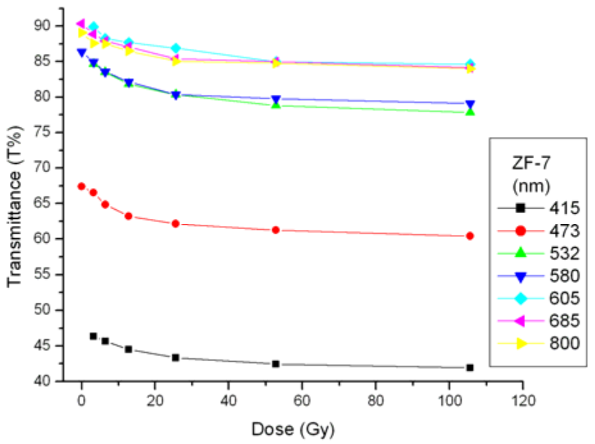

Fig.2b. Response VIS- transmission versus reference sample according to up 105.6Gy irradiation dose, for type extra dense lead samples ZF-7

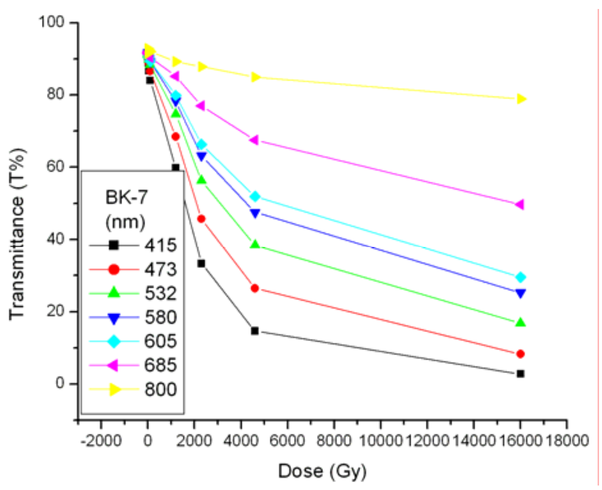

Fig.2-c. Response VIS - transmission versus reference sample according to irradiation dose, for type crown samples BK-7

On the other hand, the tests have shown that in the case of KU-1 glasses for gamma radiation doses up to 4000kGy the transmission decreases with: 31% for 415nm-violet, 30.5% for 473nm-blue, 29.8% for 532nm-green, 29.2% for 580nm-yellow, 28.9% for 605nm-orange, 27.9% for 685nm-red and 28.4% for 800nm-near infrared.(Fig 2-d)

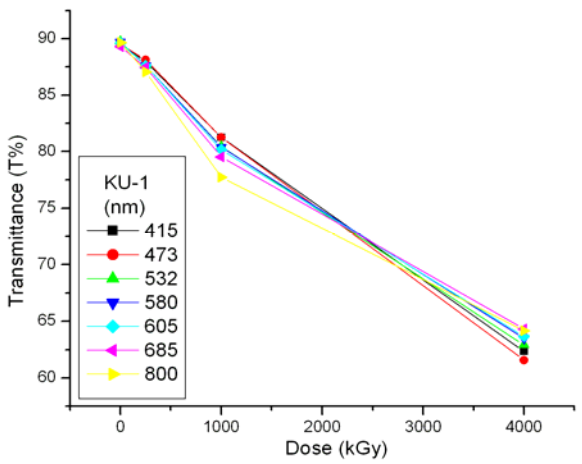

Fig.2-d. Response VIS- transmission versus reference sample according to irradiation dose, for type fuse silica samples KU-1

In Fig. 3, the relative loss in irradiated samples for transmission wavelengths of interest is presented, i.e. the central wavelengths of band components (color bands) in the visible spectrum. For samples BK-7 and ZF-7 (at doses below 105.6Gy), but for KU-1 (at doses below 4MGy), relative loss in transmission has a constant evolution for the entire visible spectrum, with a level of such losses below 11% for ZF-7 and BK-7 and approximately 30% for KU-1. The exception is BK-7 (at doses below 16kGy) where the evolution of relative losses in transmission presents a sharp drop, all visible from about 97% (purple area) – 415nm up to about 14% (near infrared region) – 800nm.

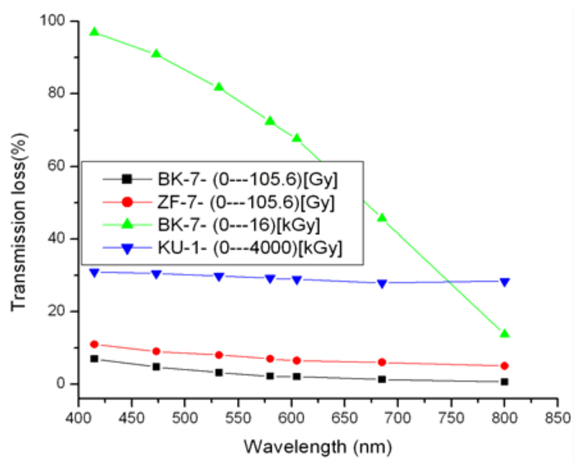

Fig.3. Relative VIS-transmission loss to central value for wavelengths versus reference sample: 415nm-violet 473 nm-blue, 532 nm-green, yellow-580 nm, 605 nm- orange, 685 nm-red and 80 0nm-near infrared.

The transmission loss in the near infrared band can be considered acceptable even for high dose. To estimate the gamma radiation dose effects, it is necessary to have information about the effects of gamma radiation on each kind of optical glass used in the systems lens. For this reason, the procedure to calculate the dose coefficient to determine the transmission loss for any kind of gamma radiation at a certain total dose is quite reasonable. Such a procedure allowed the calculation of the dose coefficients for three analyzed glasses, as can be observed in Fig.4. Dose coefficient curves measured after ^{60}Co gamma radiation exposure the dose coefficient curve with the dose value, differing even for glasses which belong to the same family. However, despite its lower resistance to ionizing radiation previously shown, the BK-7 glass presented a behavior which converges to a universal coefficient curve (fig.4-a).

By analyzing graphs in Figure 4, which shows the variation coefficient gamma dose experiments, we note that one can not determine a unique evolution curve for all dose range used, after which they can expand conclusions from gamma irradiation to other types of radiation, electromagnetic or corpuscular nature.

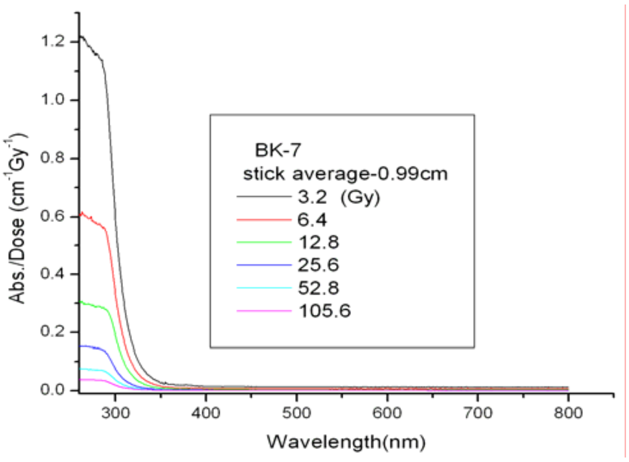

Fig.4-a. Curves for dose coefficient for optical glass versus VIS-wavelength (BK-7)

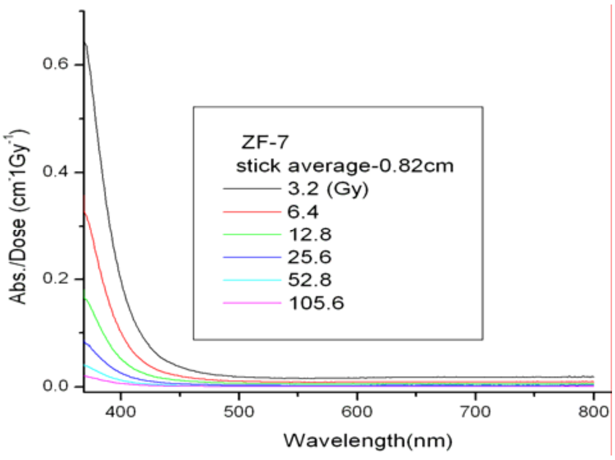

Fig.4-b. Curves for dose coefficient for optical glass versus VIS-wavelength (ZF-7).

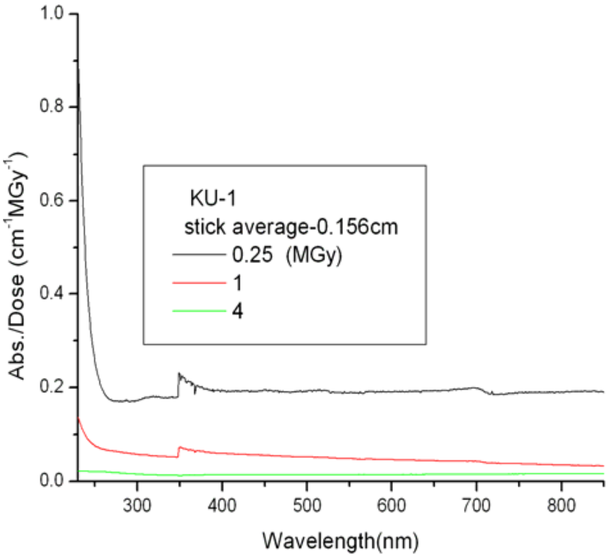

Fig.4-c. Curves for dose coefficient for optical glass versus VIS-wavelength (KU-1).

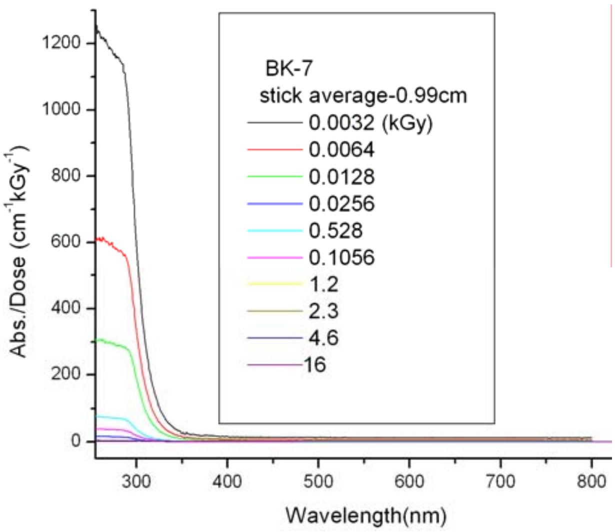

Fig.4-d. Curves for dose coefficient for optical glass versus VIS-wavelength (BK-7).

We find the best-fit exponential and linear curve using transmittance (T) in percent as a function of dose (D) in (Gy) (Fig.5), to mean wavelength of visible spectra (415, 473, 532, 580, 605, 685 and 800)nm. (See Annexes: 1, 2, 3). These results may provide a database for the three types of optical glass analyzed, which will be used in our similar experimental applications without having to repeat it. In all the cases shown, the value of coefficients of determination R^2 is over 90%, which indicates the proportion that is explained by the correlation model chosen. The remaining percentage of mismatch (up to 100%) is due to other causes.

Table-2: The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 105.6Gy) to BK-7-after irradiation

Material Type	Wavelength (nm)	Absorbed dose range (0÷105.6)Gy The relationship between the VIS-transmission versus absorbed dose	Coefficient of determination (R^2) (%)	Relative transmission loss (%)
BK-7	415	T=(90.26±0.13) - (0.06±0.002)*D	98.94	7
	473	T=(91.19±0.13) - (0.04±0.0001)*D	96.8 2	4.8
	532	T=(91.46±0.1) - (0.03±0.002)*D	97.31	3.2
	580	T=(91.69±0.15) - (0.024±0.003)*D	91.46	2.2
	605	T=(91.65±0. 05) - (0.02±0.001)*D	98.56	2.1
	685	T=(91.85±0.02) - (0.01±5.3E^{-4})*D	99.26	1.3
	800	T=(92.5±0.11) - (0.01±0.002)*D	80.55	0.6

Table 3: The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 105.6Gy) to ZF-7-after irradiation.

Material Type	Wavelength (nm)	Absorbed dose range (0÷105.6)Gy The relationship between the VIS-transmission versus absorbed dose	Coefficient of determination (R^2) (%)	Relative transmission loss (%)
ZF-7	415	T =(41.53±0.19) + (4.88±0.26)exp[-D/(14.218±1.18)]	98.91	11
	473	T =(1.34±0.01) + (0.14±0.01)exp[-D/(25.28±5.92)]	97.62	9
	532	T =(60.75±0.41) + (6.75±0.4)exp[-D/(14.35±2.34)]	98.52	8
	580	T =(84.37±0.27) + (6.05±0.36)exp[-D/(14.9±2.43)]	98.54	7
	605	T =(83.52±0. 2) + (6.5 ±1.64)exp[-D/(15.24±1.64)]	99.36	6.5
	685	T =(83.97±0.17) + (4.86±0.27)exp[-D/(15.92±3.2)]	97.84	6
	800	T =(41.53±0.19) + (4.89±0.26)exp[-D/(14.18±1.98)]	98.91	5

Table 4: The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16kGy) to BK-7-after irradiation

Material Type	Wavelength (nm)	Absorbed dose range (0÷16000)Gy The relationship between the VIS-transmission versus absorbed dose	Coefficient of determination (R^2) (%)	Relative transmission loss (%)
BK-7	415	T = (89.71±0.78)exp[-D/(2540.29±108.19)]	99.67	96.9
	473	T = 8.29 + (82.63±0.62)exp[-D/(3112.66±116.92)]	99.74	90.8
	532	T = (15.18±1.53) + (76.15±1.58)exp[-D/(3950.73±200.07)]	99.82	81.6
	580	T = (23.03±1.37) + (69.58±1.39)exp-[D/(4550.29±222.7)]	99.81	72.3
	605	T = (26.92±1.32) + (64.62±1.33)exp[-D/(4719.32±243.31)]	99.82	67.6
	685	T = (46.27±1.04) + (45.49±1.04)exp[-D/(6156.75±329.76)]	99.83	45.6
	800	T = 78.88 + (13.37±0.18)exp[-D/(5443.63±401.15)]	98.83	13.5

Table 5: The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16kGy) to BK-7-after irradiation.

Material Type	Wavelength (nm)	Absorbed dose range (0-4000)kGy The relationship between the VIS-transmission versus absorbed dose	Coefficient of determination (R^2) (%)	Relative transmission loss (%)
KU-1	415	T = (89.28±0.6) – (0.007±2.7E^{-4})*D	99.69	31
	473	T = (89.1±0.6) – (0.006±2.9E^{-4})*D	99.44	30.5
	532	T = (88.87±0.9) - (0.006±4.7E^{-4})*D	99.01	29.8
	580	T = (88.74±1.03) - (0.006+/-4.9E^{-4})*D	99.80	29.2
	605	T = (88.62±1.11) - (0.006±5.4E^{-4})*D	98.60	28.9
	685	T = (88.17±1.35) - (0.006±6.5E^{-4})*D	97.76	27.9
	800	T = (87.66±2.07) – 0.006*D	94.65	28.4

3. Conclusions

We provided experimental working conditions in the gamma radiation for three types of glass (BK-7 crown (Schott), lead glass extra-dense ZF-7 (China) and KU-1 pure fused silica (Russia)) which are similar to those commonly used in the manufacture of optical components (lenses and protection windows) and are important parts of optical instruments and equipment for different applications.

In conditions of each experiment we found that the transmission loss is inferior relative to the type of glass KU-1, so that one is more resistant to gamma radiation and has a lifespan of hundreds of times larger than the other two.

In addition, it was observed that the optical transmission of BK-7 glass samples and ZF-7 is quite acceptable in the near infrared spectral region (800nm), even if it is severely affected in other regions due to extreme radiation conditions.

Dose coefficients curves for all three samples type does not converge to a single curve (Fig.4). Therefore, experimental data results can not be generalized for other types of radiation. Relations in Fig. 5, 6,and 7 can be used for the same types of glass (BK-7, ZF-7, KU-1) and the same operating conditions to estimate radiation doses that give a certain range transmission loss without repeating the experiments. Their disadvantage lies in a low generalization of the results and the need to be trained curves and correlation relationships between sizes "*cause*" and "*effect*" caused by the conditions and parameters in concrete applications for all possible cases.

Global survey of real optical systems is destructive and costly. For this reason there were chosen three most common types of glass. They are easy to procure and have a low price. There are special glasses (with increased resistance to radiation) obtained only on demand and prices to match. This test component allows a first estimate of the effectiveness of the entire optical system. Therefore, first we need to know the behavior of the camera room. This requires knowledge of radiation resistance but also generate electromagnetic noise in the presence of ionizing radiation levels possible. Operating time of a radioactive source is about 1 min. Although there is a rich literature in the field, the results revealed do not clearly show a degree of generalization. Due to the multitude of parameters involved in the radiation (radionuclide type of the radioactive source and the decay scheme, the type of radiation emitted and energy spectrum associated source activity and half-life, product absorbed dose rate at a distance from the source, the temperature irradiation, and chemical composition of the target material, number, type and concentration of impurities (responsible for changes of optical parameters irradiation), the effect of self-return time or return induced by heating the sample thickness, roughness, and so on), specific evaluations are needed. Moreover, in case of any type of glass coming from different manufacturers differences of their behavior in the field of radiation may arise. This is because different recipes and content of impurities (intentional or not). For these reasons we conducted this study. Quantitative data obtained in our conditions of irradiation (Tables: 2, 3, 4 and 5) allow a more realistic estimate of the results, which allows taking appropriate protective measures or estimate a more efficient maintenance program. All this is aimed at a good efficiency and reasonable cost for system maintenance. Electromagnetic noise problem to be analyzed after commissioning of video viewing system by analyzing images obtained during operation, reading and their subsequent processing using its own program processing.

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Annex-1: The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data(up to 16Gy) to BK-7-after irradiation

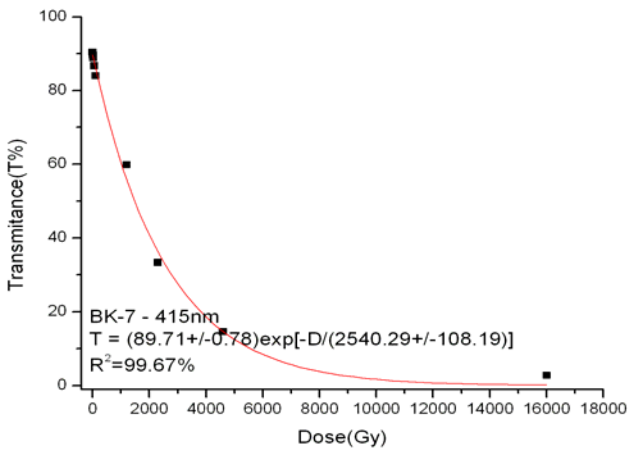

Fig.5-a. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16 kGy) BK-7-after irradiation to VIS-Wavelength – 415nm.

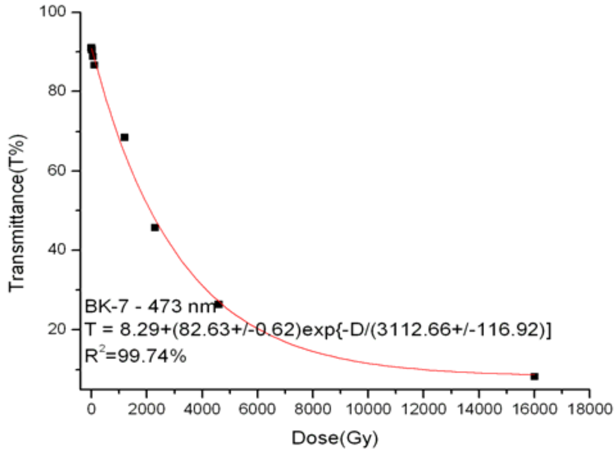

Fig.5-b- The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16kGy) BK-7-after irradiation to VIS-Wavelength – 473nm.

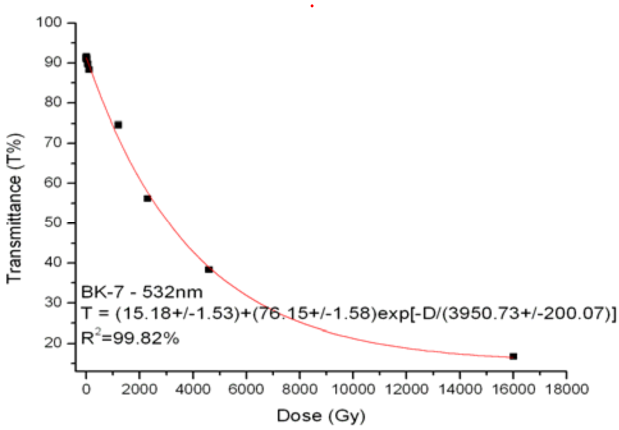

Fig.5-c- The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16kGy) BK-7-after irradiation to VIS-Wavelength – 532nm.

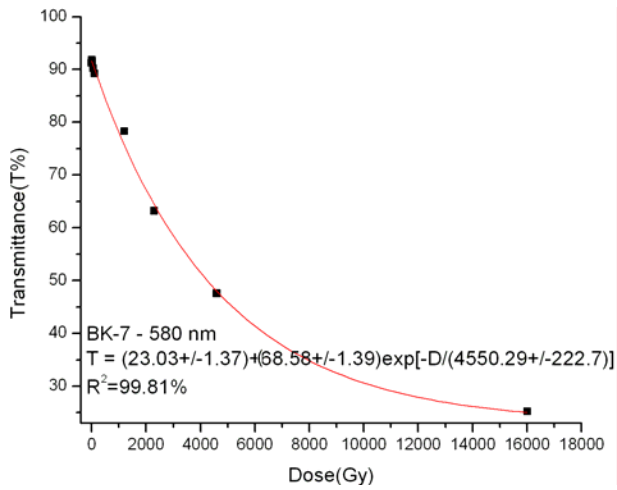

Fig.5-d. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16kGy) BK-7-after irradiation to VIS-Wavelength 580nm.

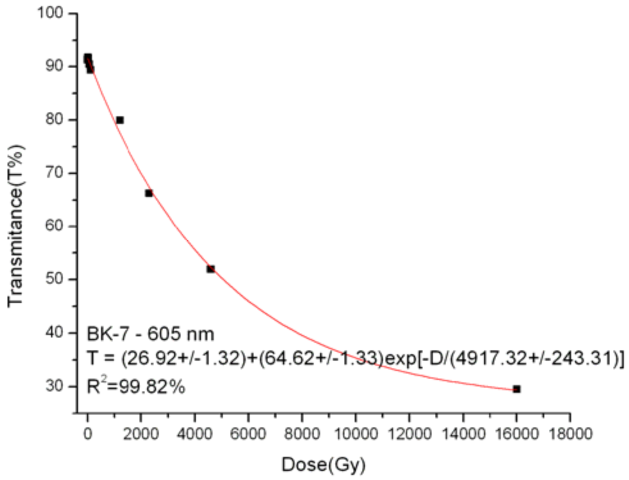

Fig.5-e. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation to VIS-Wavelength – 605nm.

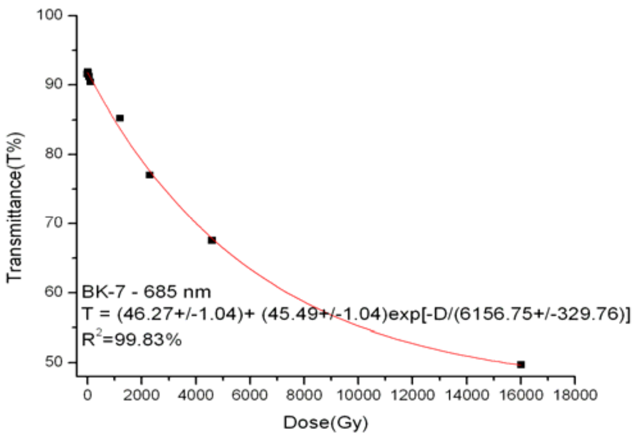

Fig.5-f. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16 kGy) BK-7-after irradiation to VIS-Wavelength 685 nm.

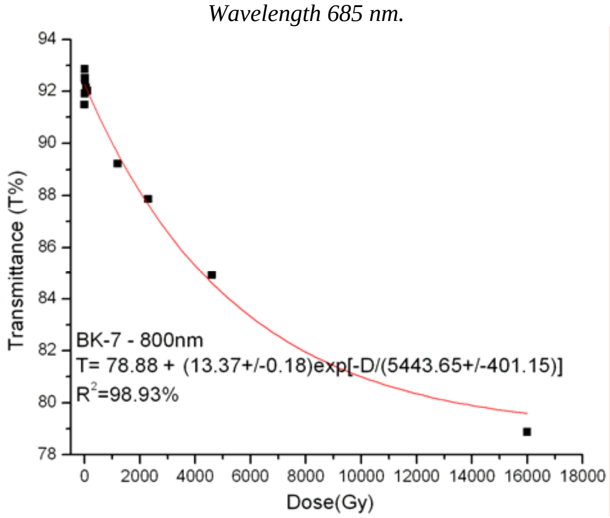

Fig.5-g. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 16 kGy) BK-7-after irradiation to VIS-Wavelength 800 nm.

ANNEX-2. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation.

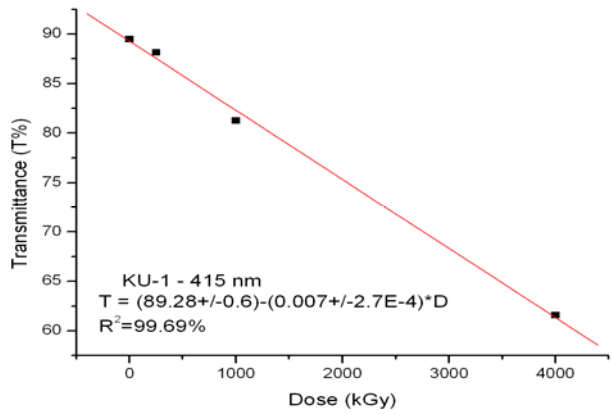

Fig.6-a. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4 MGy) KU-1-after irradiation to Wavelength 415 nm.

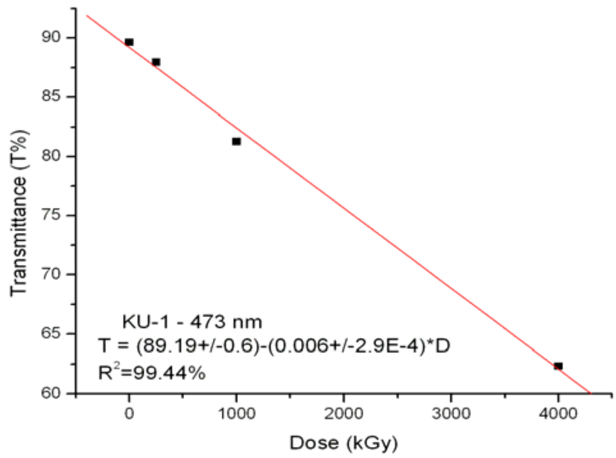

Fig.6-b. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4 MGy) KU-1-after irradiation to Wavelength 473 nm.

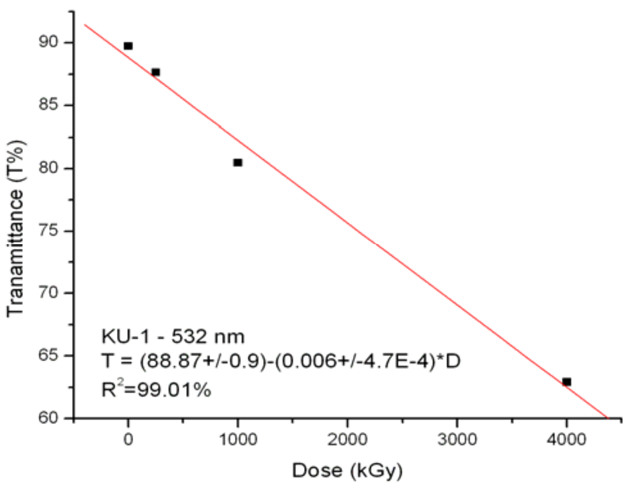

Fig.6-c. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation to Wavelength 532nm.

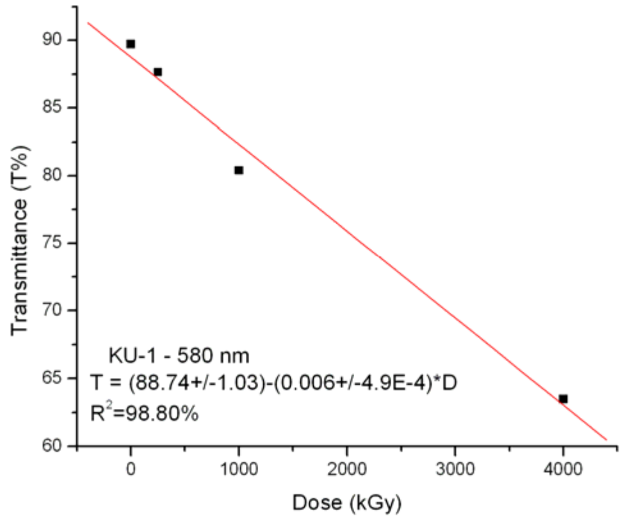

Fig.6-d. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation to Wavelength 580nm.

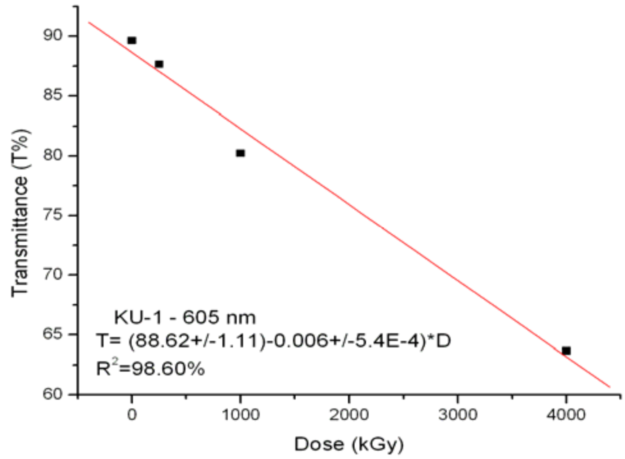

Fig.6-e. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation to Wavelength 605nm.

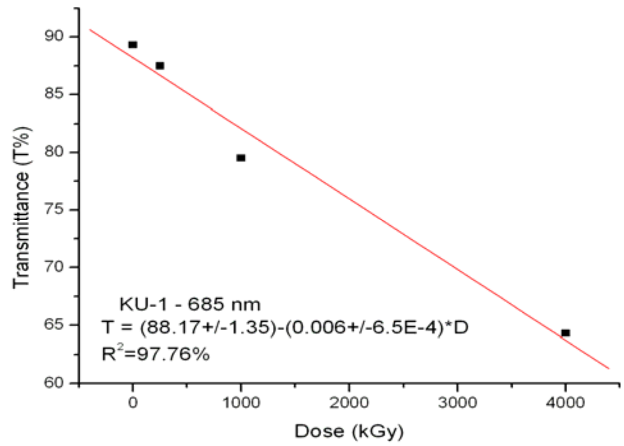

Fig.6-f. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation to Wavelength 685nm.

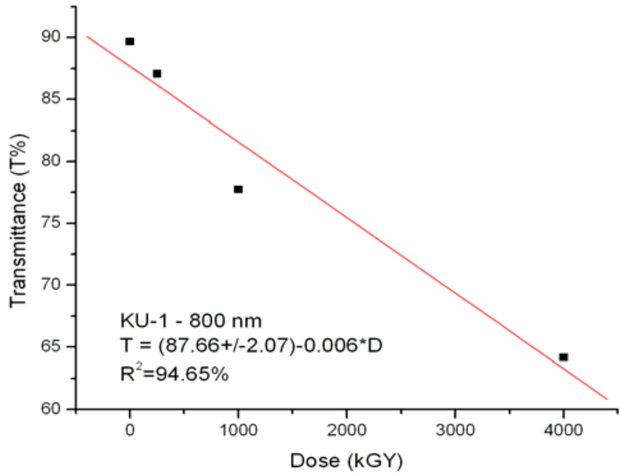

Fig.6-g. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4 MGy) KU-1-after irradiation to Wavelength 800 nm.

ANNEX-3. The relationship between the VIS transmission versus cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7-after irradiation.

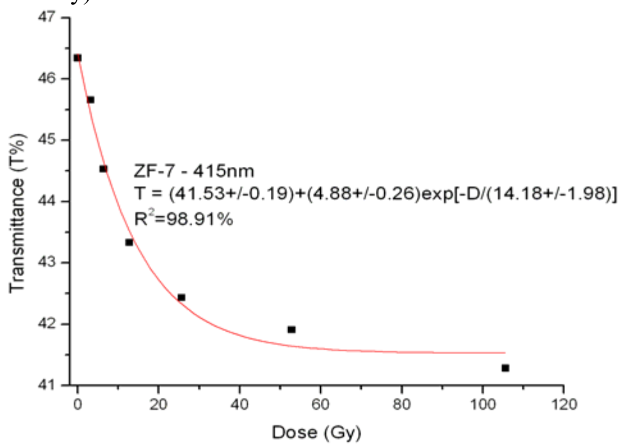

Fig.7-a. The relationship between the transmission and cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7-after irradiation to Wavelength 415nm.

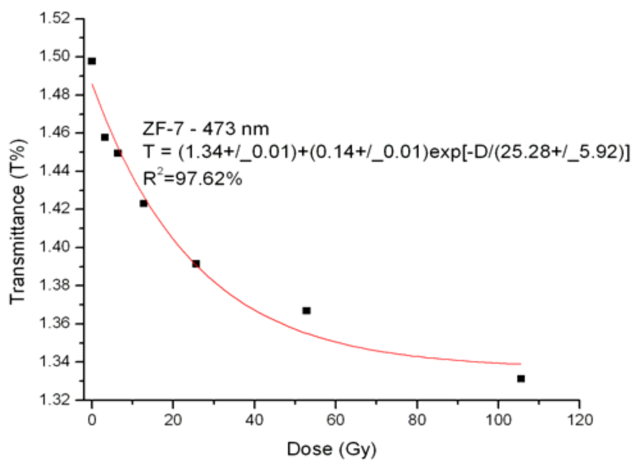

Fig.7-b. The relationship between the VIS-transmission versus cumulative absorbed dose response curve fitting and data (up to 4MGy) KU-1-after irradiation to Wavelength 473nm.

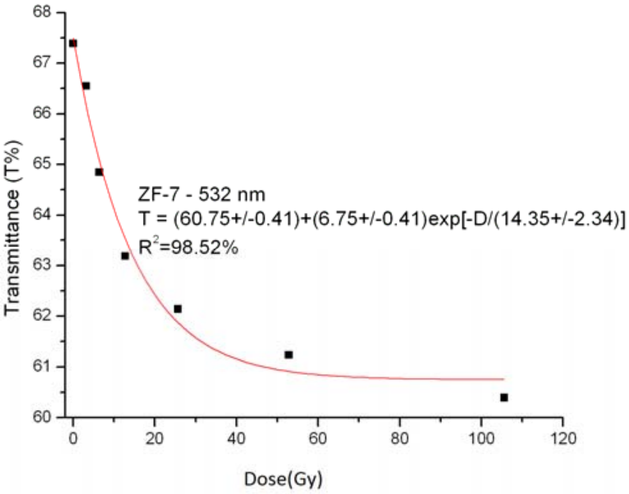

Fig.7-c. The relationship between the transmission and cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7after irradiation to Wavelength 532nm.

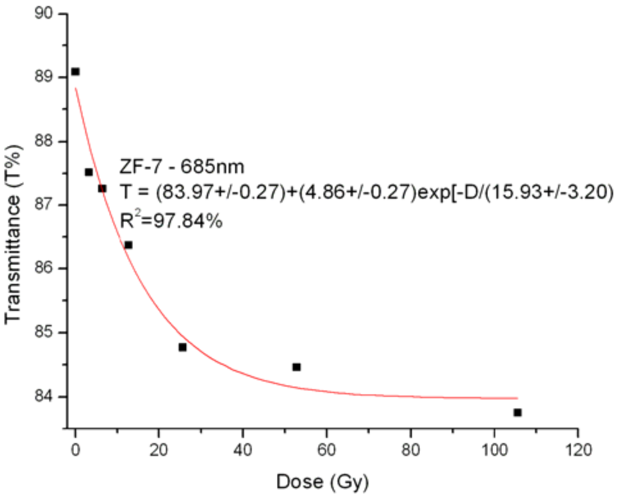

Fig.7-f. The relationship between the transmission and cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7-after irradiation to Wavelength 685nm.

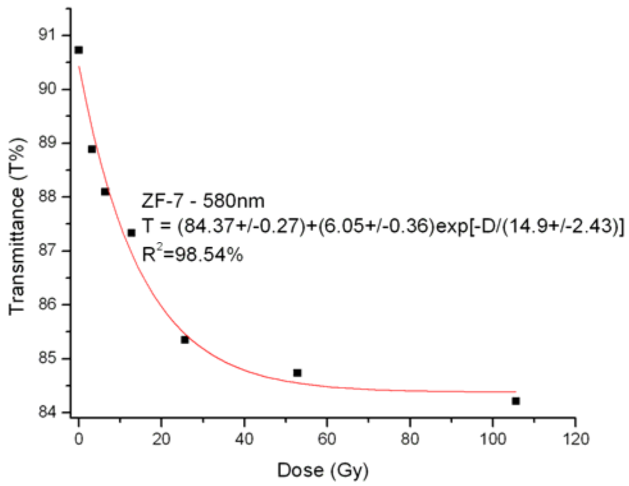

Fig.7-d. The relationship between the transmission and cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7-after irradiation to Wavelength 580nm

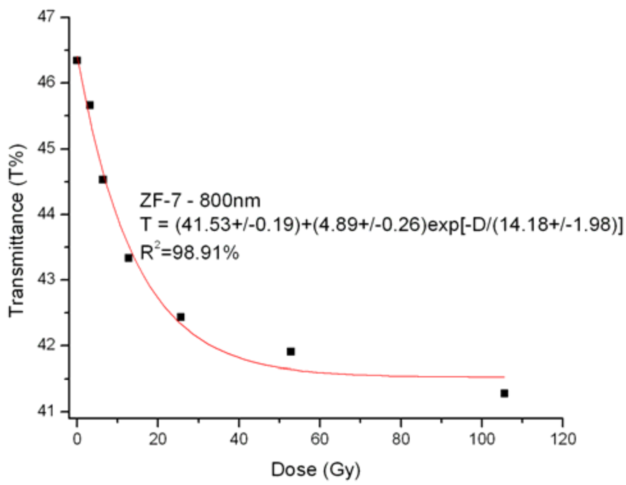

Fig.7-g. The relationship between the transmission and cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7-after irradiation to Wavelength 800nm

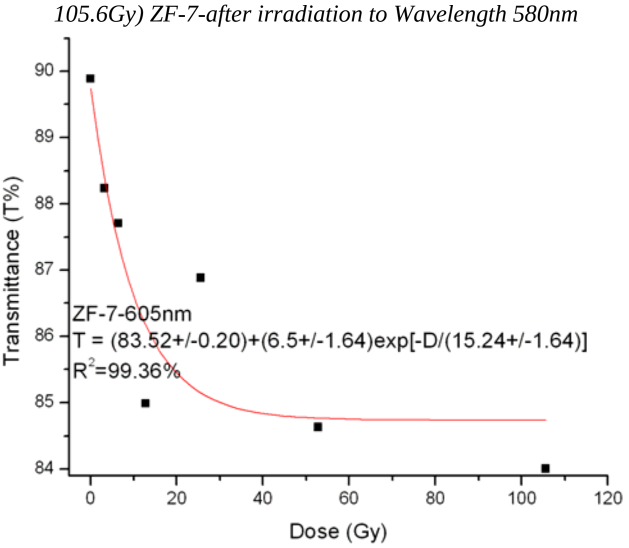

Fig.7-e. The relationship between the transmission and cumulative dose response curve fitting and data (up to 105.6Gy) ZF-7-after irradiation toWavelength 605nm.

*Corresponding author: gruia_ion@yahoo.com