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Rate of long term bleaching in FK 51 optical glass darkened by Co^{60} ionizing radiation at dose rates of 10 krad/hr and 7 rad/hr

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ABSTRACT

A previous paper presented long term bleaching data on various glasses exposed to 10.6 krad of ionizing radiation. All the glasses reported except FK 51 have readily available "G" glass equivalents that are stabilized to the natural space environment. Yet, FK 51, because of its location on the Abbe diagram is extremely useful in certain lens design applications. To more fully explore the bleaching of FK 51, after the initial dose of 10.6 krad at 11.8 krad/hour, we irradiated three more samples at a similar dose rate but to different total doses. Since the dose rate for this study was significantly higher than the dose rate anticipated for glasses in a shielded space-based lens system (~3 rad/day), additional data were obtained at a lower rate of 7 rad/hour. While this dose rate is still higher than the anticipated operational rate, it is more than 1000 times lower than the dose rate used for our initial studies. The bleaching rate for the samples exposed at the lower dose rate is considerably less than for the samples exposed at the higher rate.

1. INTRODUCTION

All glasses studied in our previous report,[1] except FK 51, have readily available "G" glass equivalents that are stabilized against radiation darkening in the natural space environment. Yet, FK 51, because of it's location on the Abbe diagram, with a low refractive index and high Abbe number, is extremely useful in certain lens designs. In conjunction with lanthanum crown (LaK) glass, FK 51 provides good color correction and can greatly reduce spherochromatic aberration. The members of the FK series of fluor crown glasses, are phosphate or borosilicate glasses with fairly high fluorine content.[2] This high fluorine content separates this glass type from the other most frequently used optical glasses.

2. BLEACHING STUDY

To more fully explore the bleaching of FK 51 glass, after the previously reported study with a dose of 10.6 krad at 11.8 krad/hr[1], we irradiated three additional FK 51 samples to different total doses: 2.4 krad, 5.2 krad, and 7.3 krad. The samples in this second set were irradiated 18 months after the set that included the original FK 51 sample. All samples were positioned at the same pool location as previously, however the source had decayed in the intervening period so that the later set received only a 9.7 krad/hr dose rate. Bleaching data were obtained for each of the four different doses, enabling a comparison of the bleaching rate vs. total dose for samples irradiated at 11.8 and 9.7 krad/hr.

Since the dose rate for this study was significantly higher than the ~3 rad/day dose rate anticipated for glasses in a shielded space-based lens system, a question arose as to whether concurrent bleaching might significantly mitigate radiation darkening in samples exposed at lower dose rates. To explore this possibility, we obtained a third set of data starting four months after the second set and 22 months after the first set. Additional samples, obtained from Schott Glass Technologies Inc., were positioned in the Co^{60} pool to receive a dose rate of 7 rad/hour** and received total doses of 3.3 krad, 4.9 krad, and

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**At the time these measurements were done, the Co^{60} pool location used for the previous studies had a dose rate of ~9.4 krad/hr.

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6.9 krad respectively. The 7 rad/hr dose rate is more than 1000 times less than the dose rate used for our initial studies. While this slower rate is still higher than that expected from exposure to the natural space environment, it did reveal an unanticipated high sensitivity of bleaching rates upon dose rates. Because we did not anticipate this result, the experiment was not optimally designed to explore the relation between dose rates and bleaching rates. Nevertheless, the results permit some tentative conclusions regarding the mitigation of radiation darkening by concurrent bleaching.

3. RESULTS

In Figure 1 we show radiation induced absorption coefficients vs. time for the original sample set, which included one sample of FK 51. The wavelength, $\lambda = 450$ nm, is selected as representative in the region of higher absorption. The data for each glass type, except LaK 9, is remarkably well fit by a power law $\alpha = A\ t^{-b}$ where α is the radiation induced absorption coefficient, t is time after irradiation, and A and b are constants depending on the glass type, dose rate, λ , and perhaps other unidentified parameters. LaK 9 notably deviates from this power law behavior but can be reasonably well fit by using one pair of A, b values for times up to ~1 day (10^5 s) and another pair for times from ~1 day to 1 yr or more.

FK 51 bleaching data were obtained for the seven cases listed in Table 1. Tables 2 through 8 list transmissivities of the samples "a" through "g" (calculated from the measured transmittances) as a function of time after irradiation, for selected wavelengths (λ) ranging from 400 to 600 nm.

Figure 2 is a plot of the radiation induced absorption coefficients ($\lambda = 550$ nm) immediately following irradiation, i.e. before significant bleaching occurred, for each of the 7 FK 51 samples. At doses well below saturation, one expects to find a linear relation between the radiation induced absorption coefficient and dose: α = constant × dose; this is indicated by the line on the plot in Figure 2.[3,4]

Table 1: Doses and dose rates for FK 51 samples.
All samples .494 cm thick.

FK 51 sample	dose (krad)	dose rate (krad/hr)
a	10.6	11.8
b	7.3	9.7
c	5.2	9.7
d	2.4	9.7
e	6.9	.007
f	4.9	.007
g	3.3	.007

Figure 3 and Figure 4 are plots of five of the seven FK 51 samples at 450 nm and 550 nm respectively. For the two higher does rates (11.8 and 9.7 krad/hr) the power law $\alpha = A\ t^{-b}$ gives a remarkably good fit (straight lines on the plots) to the data over the entire time covered by our observations: less than one hour to more than one year. However the data for the three low dose rate samples (.007 krad/hr) cannot be well fit by a simple power law. The plot for these samples displays a "knee" where the curve bends downward. It appears that perhaps two separate power law fits, as was suggested for the LaK 9 data, may provide a reasonably good fit to the data. However, the "knee" occurs at about 1 month after irradiation rather than the 1 day observed for LaK 9. Error bars indicate $\Delta\alpha \sim \pm 01$, which is estimated from the observed errors in reproducing the measured transmittances. The two lowest total dose levels (2.4 and 3.3 krad) are not plotted. Though the data for these low doses is also reasonably well approximated by power laws, $\alpha = A\ t^{-b}$, estimated errors and scatter in the data are so large that the inference of a power law is less convincing than at the higher dose levels.

In all cases, the initial absorptivity increased with dose, regardless of dose rate. However, bleaching of samples exposed at low dose rates was very slow for up to approximately one month following irradiation. Consequently, at the end of one month, samples exposed at the lowest dose rate were significantly more absorbing than samples that initially received the same dose, or slightly higher doses, at the higher dose rates. This is shown graphically by the crossing of the absorption coefficient curves in Figures 3 and 4. There appears to be a direct relation between dose rate and bleaching rate.

4. SUMMARY

While we do not know how FK 51 would bleach if dosed at 0.1 rad/hr, our results suggest that radiation darkening at low dose rates is not significantly mitigated by concurrent bleaching. In fact, it appears the lower dose rates produce lower bleaching rates. The result is likely to be that opacity will continue to increase with total radiation exposure and the FK 51 glass will not bleach significantly over the lifetime of most optical sensors. These results again support the use of the more stable cerium dioxide, CeO_2, doped glasses for space based systems when those glasses are available. FK 51, the subject of this paper, cannot be *effectively* stabilized by use of CeO_2.[5] Any use of this or other non-stabilized materials must include an analysis of potential darkening versus program lifetime.

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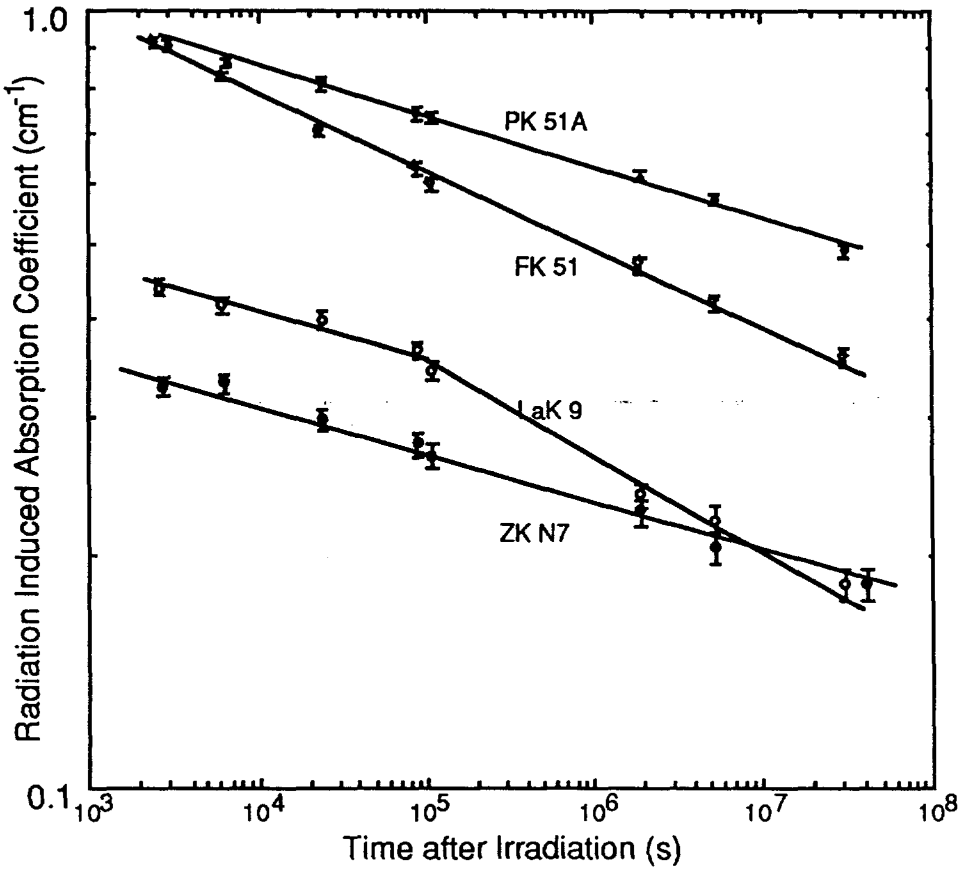

Figure 1: Radiation induced absorption coefficient vs. time after irradiation for four glasses ; λ = 450 nm, dose = 10.6 krad, dose rate = 11.8 krad/hr.

Table 2: Transmissivities: FK 51a

	wavelength (nm)				
time(s)	600	550	500	450	400
2.40×10^3	0.812	0.698	0.638	0.638	0.679
6.06×10^3	0.830	0.722	0.663	0.665	0.702
2.35×10^4	0.858	0.758	0.703	0.706	0.741
8.75×10^4	0.874	0.780	0.729	0.734	0.772
1.09×10^5	0.882	0.790	0.738	0.743	0.778
1.91×10^6	0.913	0.831	0.786	0.792	0.829
5.37×10^6	0.925	0.847	0.804	0.812	0.850
3.04×10^7	0.936	0.867	0.827	0.834	0.868

Table 3: Transmissivities: FK 51b

	wavelength (nm)				
time(s)	600	550	500	450	400
2.00×10^3	0.874	0.795	0.749	0.748	0.772
6.20×10^3	0.890	0.811	0.769	0.767	0.793
2.69×10^4	0.901	0.830	0.789	0.787	0.810
8565×10^4	0.907	0.840	0.800	0.800	0.823
1.14×10^5	0.912	0.846	0.807	0.807	0.828
4.73×10^7	0.935	0.890	0.859	0.859	0.874

Table 4: Transmissivities: FK 51c

	wavelength (nm)				
time(s)	600	550	500	450	400
2.90×10^3	0.922	0.869	0.838	0.838	0.856
7.10×10^3	0.916	0.867	0.839	0.837	0.853
2.78×10^4	0.937	0.890	0.863	0.863	0.879
8.65×10^4	0.942	0.899	0.873	0.874	0.888
1.14×10^5	0.943	0.901	0.876	0.876	0.890
4.73×10^7	0.953	0.924	0.904	0.904	0.913

Table 5: Transmissivities: FK 51d

	wavelength (nm)				
time(s)	600	550	500	450	400
3.80×10^3	0.947	0.917	0.896	0.897	0.904
7.90×10^3	0.946	0.916	0.898	0.899	0.908
2.86×10^4	0.967	0.939	0.921	0.922	0.932
8.71×10^4	0.973	0.947	0.930	0.931	0.940
1.15×10^5	0.974	0.949	0.932	0.934	0.942
4.73×10^7	0.965	0.947	0.934	0.934	0.937

Table 6: Transmissivities: FK 51e

	wavelength (nm)				
time(s)	600	550	500	450	400
2.70×10^3	0.898	0.819	0.772	0.773	0.798
1.75×10^4	0.903	0.823	0.776	0.777	0.803
8.70×10^4	0.905	0.825	0.779	0.779	0.806
1.09×10^5	0.905	0.826	0.780	0.780	0.806
3.60×10^5	0.904	0.824	0.777	0.778	0.804
2.52×10^6	0.906	0.832	0.787	0.788	0.812
5.36×10^6	0.910	0.839	0.794	0.796	0.820
6.57×10^6	0.911	0.840	0.796	0.797	0.821
8.38×10^6	0.919	0.846	0.801	0.803	0.828
3.28×10^7	0.915	0.853	0.814	0.814	0.833

Table 7: Transmissivities: FK 51f

	wavelength (nm)				
time(s)	600	550	500	450	400
2.70×10^3	0.947	0.900	0.873	0.875	0.892
1.75×10^4	0.946	0.900	0.872	0.874	0.890
8.70×10^4	0.946	0.898	0.870	0.871	0.889
1.09×10^5	0.947	0.902	0.874	0.875	0.892
3.60×10^5	0.947	0.903	0.875	0.877	0.894
2.52×10^6	0.944	0.900	0.874	0.875	0.891
5.36×10^6	0.954	0.912	0.885	0.887	0.903
6.57×10^6	0.953	0.911	0.885	0.886	0.903
8.38×10^6	0.950	0.910	0.884	0.886	0.902
3.28×10^7	0.941	0.906	0.883	0.883	0.894

Table 8: Transmissivities: FK 51g

time(s)	wavelength (nm) 600	550	500	450	400
4.50×10^3	0.956	0.922	0.901	0.901	0.916
2.30×10^4	0.959	0.930	0.911	0.912	0.923
9.10×10^4	0.959	0.926	0.904	0.905	0.919
1.06×10^5	0.963	0.929	0.908	0.909	0.922
1.78×10^5	0.962	0.934	0.915	0.916	0.927
1.04×10^6	0.963	0.931	0.909	0.910	0.923
1.06×10^6	0.958	0.926	0.904	0.905	0.917
1.15×10^6	0.966	0.938	0.919	0.920	0.931
1.40×10^6	0.962	0.934	0.915	0.916	0.926
3.56×10^6	0.960	0.930	0.909	0.909	0.920
6.40×10^6	0.963	0.934	0.914	0.914	0.925
7.61×10^6	0.965	0.935	0.916	0.917	0.928
9.42×10^6	0.968	0.940	0.920	0.921	0.933
3.37×10^7	0.953	0.929	0.912	0.912	0.919

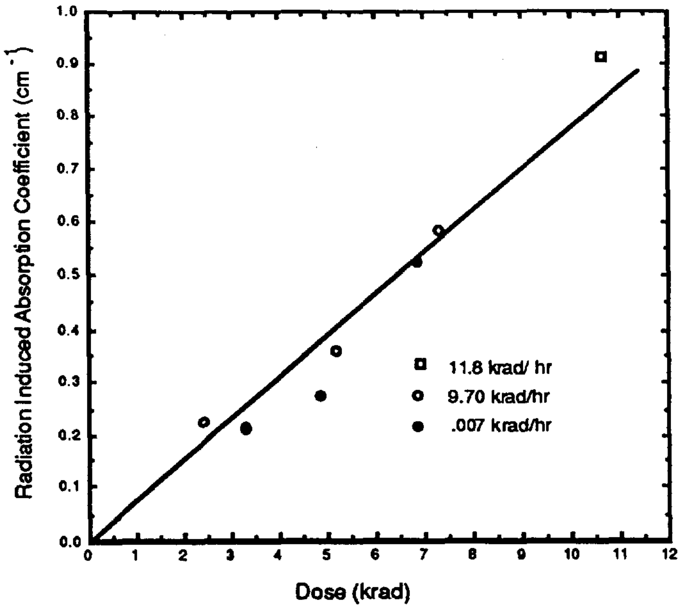

Figure 2: Radiation induced absorption coefficient immediately after irradiation ; 7 FK 51 samples; λ = 550nm

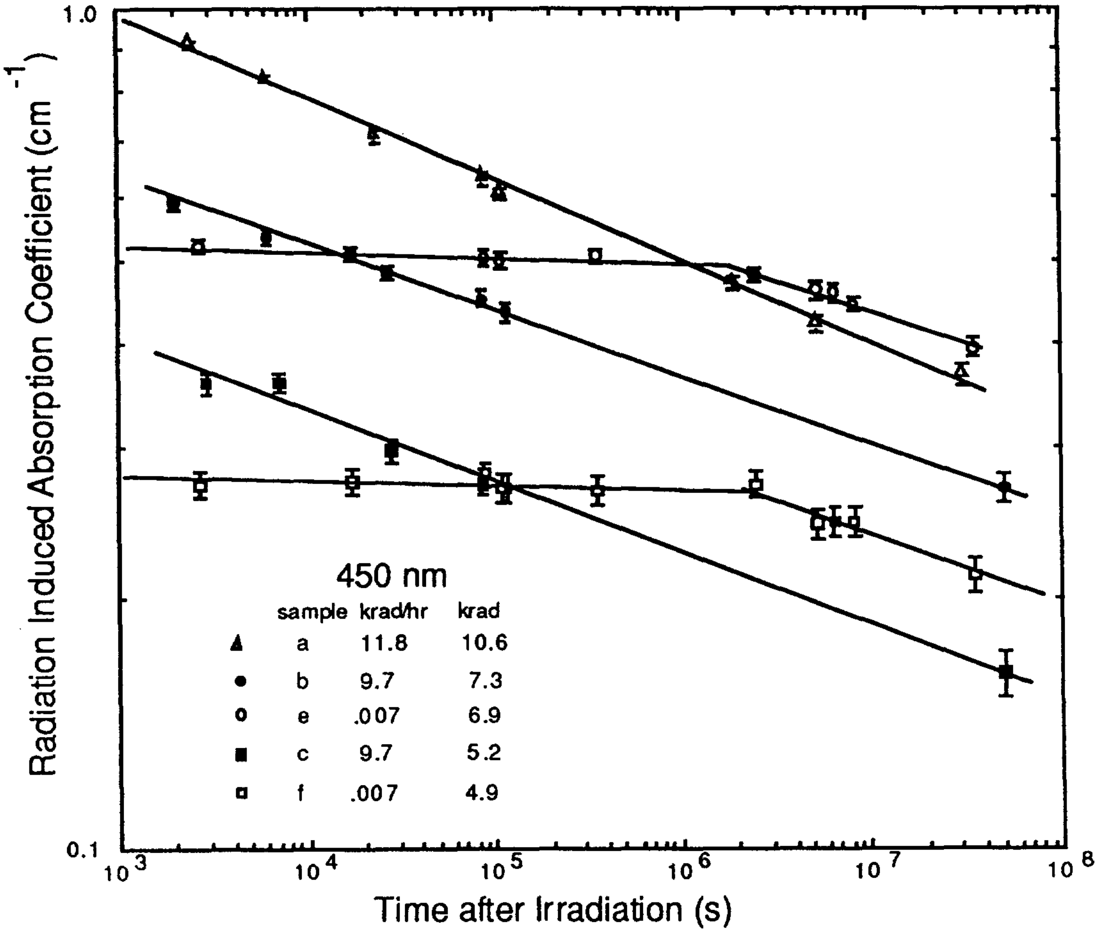

Figure 3: Radiation induced absorption coefficient (α) versus time since irradiation. λ = 450 nm, various doses and dose rates;. error bars show Δα = ±.01.

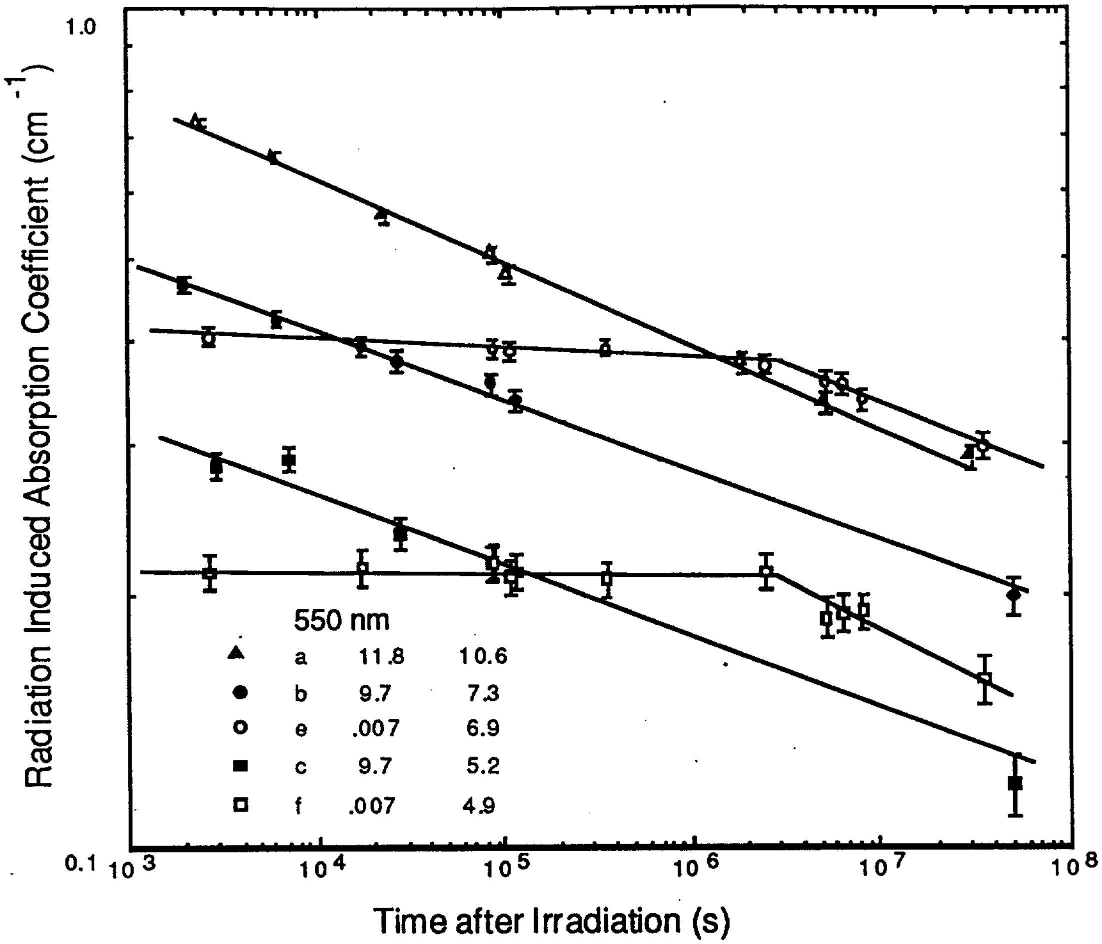

Figure 4: Radiation induced absorption coefficient (α) versus time since irradiation. λ = 550 nm, various doses and dose rates;. error bars show $\Delta\alpha = \pm.01$.

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