INTERNATIONAL SPECIALTY PRODUCTS
1361 ALPS ROAD, WAYNE, NJ 07470

GAFCHROMIC® EBT

SELF-DEVELOPING FILM FOR RADIOTHERAPY DOSIMETRY

August 2007

A BUSINESS UNIT OF ISP

INDEX

1.0 INTRODUCTION

GAFCHROMIC® EBT dosimetry film has been developed specifically to address the needs of the medical physicist and dosimetrist working in the radiotherapy environment. In common with previous GAFCHROMIC® films, EBT film is self-developing, but it also incorporates numerous improvements in ISP's radiochromic film technology. Some of these improved features include:

- Dose range 1cGy - 800cGy; EBT film is ten times more sensitive than its previous generation GAFCHROMIC® HS film and MD-55
- Energy independent from the keV range into the MeV range
- Uniformity better than 1.5%
- Larger with two different formats; 8"x10" and 14"x17"
- Faster and lower post-exposure density growth
- Will withstand temperatures up to 70°C

GAFCHROMIC® EBT dosimetry film has been in clinical and field evaluation for about 2 years. Earlier versions were field-tested at seven hospitals at the beginning of 2004. In the second phase of the clinical trial the film was provided to fourteen institutions worldwide where it has undergone clinical evaluation. Results from this work have been cycled back into improvements and GAFCHROMIC® EBT film was officially launched at ASTRO in October 2004. In North America, orders for EBT film can be placed by calling toll free 877-591-7884. For purchases outside North America our distributors are listed in ISP's website at www.gafchromic.com under 'Contact Us'.

2.0 CONFIGURATION AND STRUCTURE OF GAFCHROMIC® EBT

GAFCHROMIC® EBT is made by laminating two coatings. The coatings are manufactured to a single specification. The EBT laminate is identified by its batch number. At all steps of the manufacturing process the intermediates and components are identified by their batch numbers and the manufacturing process is done in compliance with cGMP as required for radiographic x-ray film FDA Class 1 medical device). The configuration of GAFCHROMIC® EBT film is shown in Figure 2.1.

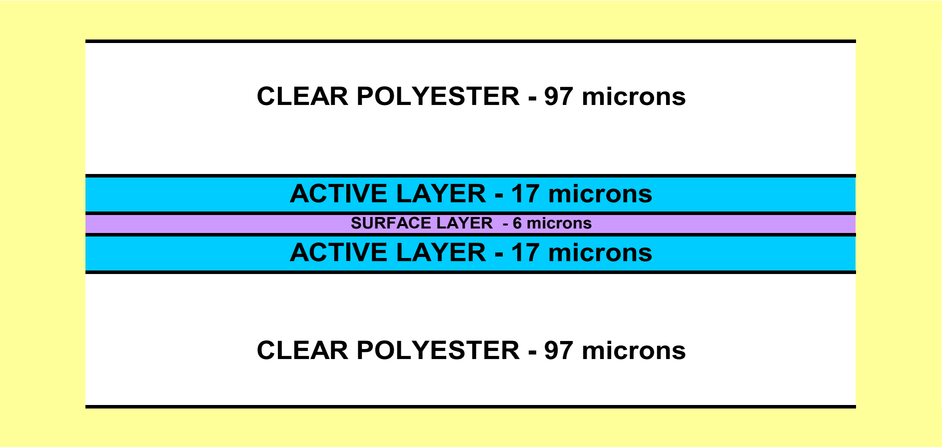

Figure 2.1: Configuration of GAFCHROMIC® EBT Dosimetry Film

3.0 GAFCHROMIC® EBT DOSIMETRY FILM CHARACTERISTICS

This high sensitivity radiochromic film has been designed for the measurement of absorbed dose of high-energy photons used in IMRT. We have designed the film for use in the 1cGy to 800cGy dose range. The response to photons has been found to be energy-independent in the MeV range and measurements at energies down to about 30keV reveal that the sensitivity changes by less than 10%.

3.1 STORAGE AND HANDLING

While GAFCHROMIC® EBT film has been designed to be handled in interior room light it is recommended that the film be kept in the dark when not in use. Exposure to sunlight should be avoided since the film may darken. The film may be stored at room temperature (20°-25°C), but as with other photosensitive products the best practice is to store the film at refrigerator temperature, or less. The shelf-life of the film is two years when stored at room ambient temperature. Brief exposures (e.g. <1min.) to temperatures up to 70°C, or more prolonged exposure (e.g. <1 day) at temperatures of 50°C should not affect EBT film. However, it is recommended that the film be handled, exposed and measured at room ambient temperature (20°-25°C).

Packages of EBT film are interleaved with a tissue paper. This provides a homogeneous environment around individual pieces of film. When using the film, it is recommended to continue employing the interleaving paper for all films, exposed and unexposed. *Note: For instructions on proper film handling, see article "Quick Start Guide - GAFCHROMIC® EBT Handling Instructions" in the www.gafchromic.com website under GAFCHROMIC® EBT.*

3.1.1 Water Immersion

The active layers in EBT film are protected by two layers of polyester. For this reason it is possible to immerse the film in water without causing permanent damage. Since the sides of the film are not sealed, water can penetrate the active layer. However, the rate of diffusion is slow enough that the film can be immersed for up to an hour without significantly changing the properties of the film, except at the very edges of the film where water can actually contact the active layer. The areas into which water has penetrated are obvious since they will become opaque, milky-white. Upon removal from immersion, the active layer will slowly re-clear as the water evaporates and the layer dries.

3.1.2 Cutting

GAFCHROMIC® EBT dosimetry film can be easily cut to required shape and size. It is preferable to use scissors or a guillotine cutter, but with care good results can also be obtained by using a scalpel or a sharp knife.

3.1.3 Marking

Since the outer layers are polyester, the film can be marked with a pen without damaging the active layer. If the marks interfere with scanning, or other measurements, they can be removed with a soft rag, or tissue moistened with an appropriate solvent, e.g. alcohol, acetone. Most solvents will not damage the polyester. If in doubt, test a corner of the film with the solvent to observe whether it causes harm.

3.2 CONSTRUCTION

GAFCHROMIC® EBT is made by laminating two film coatings each having an active layer approximately 17µm thick and a surface layer approximately 3µm thick. The coatings are applied to clear, transparent 3.8 mil (~97µm) polyester. The product is formed by laminating the two pieces of coated film by a proprietary technique requiring no intermediate adhesive layer.

3.3 ACTIVE COMPONENT

The active component in GAFCHROMIC® EBT is different than the active component of previous GAFCHROMIC® Dosimetry Films (MD-55, HS, HD-810, XR-R, etc.). The new active component is in the same chemical class as the previous active component. Details of the atomic compositions of GAFCHROMIC® EBT film are available upon request.

3.4 MEASUREMENT

GAFCHROMIC® EBT dosimetry film can be measured with transmission densitometers, film scanners or spectrophotometers. When the active component is exposed to radiation, it reacts to form a blue colored polymer with absorption maxima at about 636nm and 585nm. As shown in Figure **3**.1, the absorbance spectrum of EBT film is similar to that of GAFCHROMIC® HS except that the peaks are shifted about 35nm to shorter wavelength. Peak absorption of GAFCHROMIC® EBT is at 636nm. Consequently the response of this dosimetry film will be enhanced by measurement with red light.

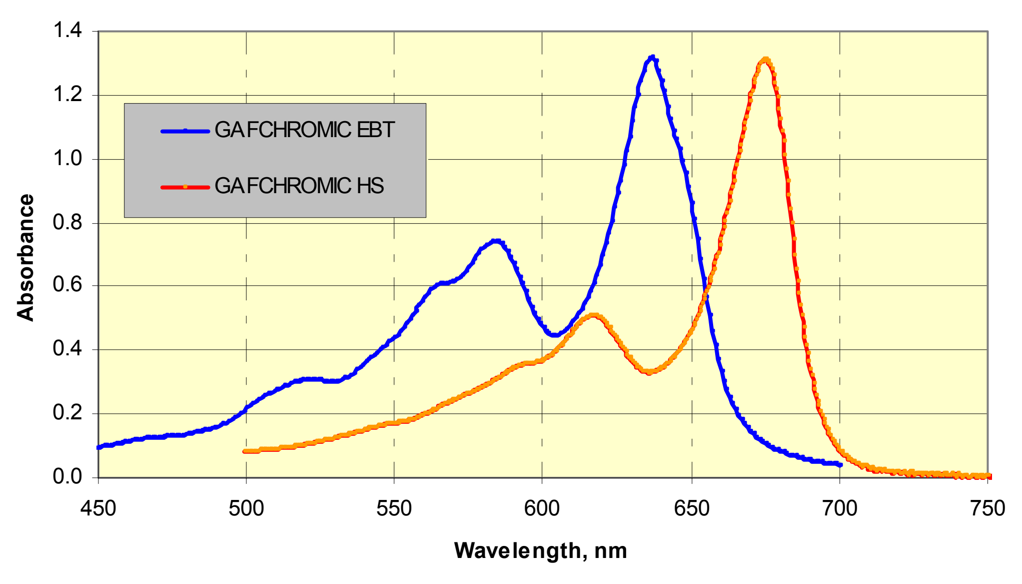

Figure **3**.1: Absorption Spectra of GAFCHROMIC® HS and EBT Dosimetry Films

3.4.1 Densitometry

Transmission densitometers measuring the visible density are commonly employed in measuring film and are suitable for measuring EBT film. However, the response can be very significantly increased by using a red filter while making densitometer measurements. A narrow band pass filter with central wavelength at around 636nm is ideal.

3.4.2 Scanning

EBT film can be read with a film scanner or digitizer, e.g. Vidar, Lumisys, Array, Molecular Dynamics, Photoelectron Corporation, Howtek, RadLink, Epson, Microtek, Agfa, Hewlett-Packard, etc. The response of EBT film will be enhanced if the spectral response of the scanner is matched to the absorbance of the film. The performance of EBT film with the Vidar VXR 12 and 16 scanners as well as the Epson 1680, 4990, V700, 10000XL and Microtek i900 scanners have been extensively investigated. The Epson and Microtek flatbed scanners are designed to scan color films. With EBT film they have their greatest response in the red color channel but Epson scanners namely Epson Expression 10000XL produces the optimum results with EBT film. Hence, it is the preferred scanner for EBT film digitization. (*Note: Epson V700 and Epson 4990 are equally good scanners but their small form factor limits the scanning of EBT 8”X10” to only one orientation. Any film larger than std 8”X10”cannot be used with these scanners. Epson 1680 has been discontinued*)

The Vidar scanners have a broad response across all visible wavelengths and give a lower contrast with colored films. *Note: Previously, a yellow optical filter sheet had been recommended to remove shorter visible wavelengths (<530nm) while scanning, however, further experimentation has revealed that the difference in results is negligible and the yellow optical filter is no longer recommended.*

A newer Vidar scanner model, the Dosimetry Pro Advantage, has been designed with the light source within a few millimeters of the film. With this design the film is illuminated with better uniformity across the width of the scanner. This is an improvement over earlier Vidar scanners in which the light source was several inches from the film. With this earlier design light scattering by EBT film as well as silver films could result in a higher response in the center of the scan window than at the edges *(see article “Effects of Light Scattering on CCD Scanners”).*

We have observed that the use of EBT film with Vidar scanners produces characteristic “contrast bands” across the top and bottom of the digitized images. These contrast bands can be eliminated by scanning the films in a clear polyester sleeve that extends 2” to the top and 2” bottom of the length of the EBT film (see Figure 3.2). Scanning in this manner allows the feed rollers of the Vidar scanner to feed the film so that the distance from the light source and the film remains constant for the duration of the scan. The use of the polyester sleeve will eliminate the characteristic contrast bands from the digitized image; however, a background correction is still necessary to achieve optimum results (see next section for further information on background correction). *NOTE: If you would like the use of such a sleeve, contact ISP or your local distributor.*

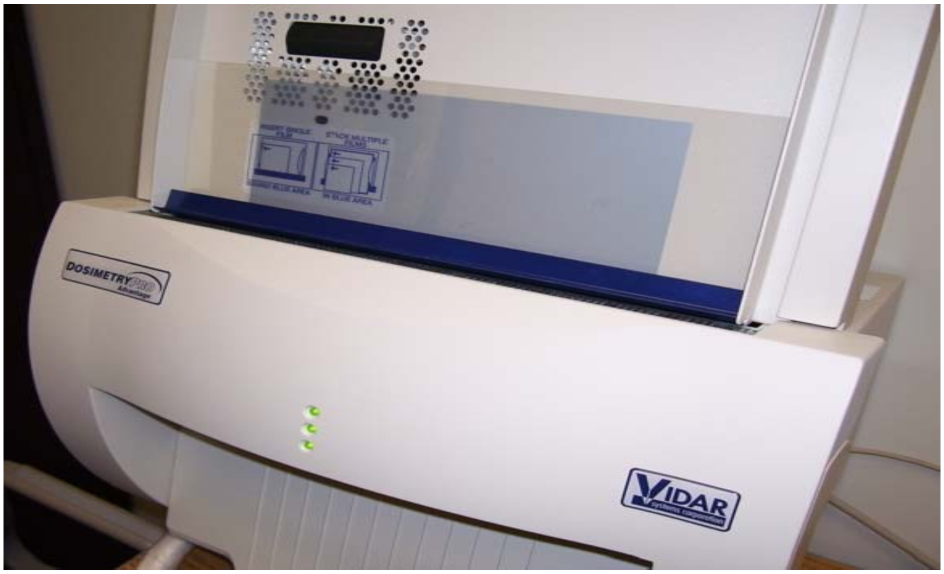

Fig **3**.2: scanning the films in a clear polyester sleeve that extends 2” to the top and 2”

HeNe laser scanners (Lumisys, Array, Molecular Dynamics) provide the highest response with EBT film because the laser has a wavelength of about 633nm, very close to peak absorbance. However, the coherent light of the laser scanners can produce artifacts caused by the interaction of polarized light with the film. If you are considering using a laser scanner, please contact us for our recommendations.

Many flatbed, color scanners (Epson, Microtek) do a pre-scan calibration through a blank area of the scanner bed to determine background levels of the glass through which they are scanning (e.g. Epson Perfection 4990 utilizes a small strip at the top of the scan area; Epson 1680 utilizes a separate, narrow window located outside the top of the scan area). It is important that that area is kept clear to ensure proper calibration.

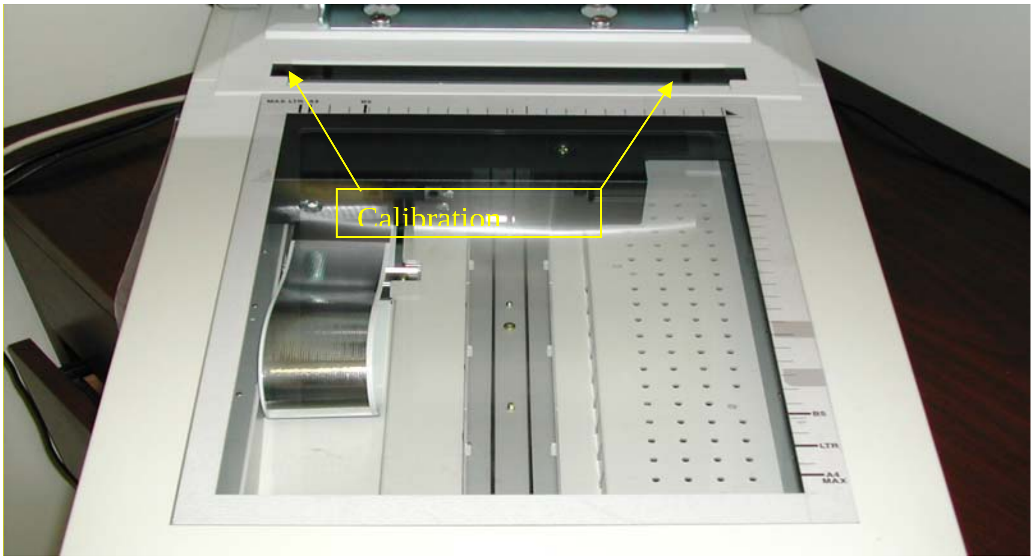

Figure **3**.3: Epson 1680 scan bed. *Note: Small calibration window at top of scan window should be kept clear at all times.*

There has been extensive research comparing the performance of the Epson flatbed scanners with the Vidar VXR-16 scanner to determine measurement consistency and single pixel measurement noise. The results show that the EpsonV700, Epson 4990 and Epson 10000XL flatbed scanners provide markedly more consistent measurements of small areas of interest in both transmission and reflection mode than the Vidar VXR-16. At densities <2, all scanners have consistency better than 1%. When the single pixel measurement noise is evaluated, the Vidar scanner produces slightly better performance than the Epson scanners. However, all scanners have a single pixel noise <1% over a large part of the measurement range. Furthermore, by using FilmQA™ verification Software to apply a 3x3 Weiner filter to the scan data, as would typically be done in an IMRT film dosimetry analysis, the single pixel noise is similar for all scanners and is <0.5% over much of the density range. Overall, the performance of the Vidar scanners and the Epson flatbed color scanners are very similar *(see article "Scanner Consistency and Noise").*

3.4.2.1 Film Positioning

We have observed that the response of scanners is not flat over of their scan field. These non-uniformities may be up to about 2% in magnitude and are most prominent within about 2-3cm of the left and right sides of the field. However, in our experience the field flatness of an individual scanner is consistent and the effects of field flatness can be measured and calibrated out through the scan image of an unexposed film.

To take best advantage of field flatness, it is recommended that films be positioned in the center of the scan area, away from the edges and in a landscape orientation. This is easily accomplished on the flatbed scanners for films with length less than or equal to 8" and Epson 10000XL for both small and large formats. On the VXR-16 it is helpful to set up a stop so that films can be fed squarely into the center of the scan feed area.

In order to ensure scanner field flatness and to overcome the effects of light scattering, it is recommended that a background correction be performed on the digitized film images using the scan image of an unexposed film. This background correction uses the unexposed film image to normalize the scanner response across the scan area. *NOTE: FilmQA™ by 3Cognition is currently the only IMRT verification software package that recognizes the necessity of the background correction, and has built-in features that implement it as a vital part of all patient QA (www.3cognition.com). (See article "Importance of Systematic Background Correction")*

3.4.2.2 Film Orientation

When a piece of EBT film is scanned, the pixel response of the scanner is affected by the orientation of the film in the scanner. This effect can be seen in Figure **3**.4, demonstrating the measured pixel responses of a Vidar medical scanner to an 8"x10" EBT dose-calibration tablet scanned in orthogonal directions at the same exposure setting. The response difference is the result of anisotropic light scattering (the anisotropic light scattering can be seen by observing the light transmitted by the film from a narrow source of illumination such as a recessed light fixture.)

The active component in EBT film is in the form of needle-like particles about 1-2µm in diameter and 15-25µm in length. The particles tend to align with their long axes parallel to the coating direction. As a result of the particle shape and alignment, more light is scattered normal to the coating direction than parallel to the coating direction. Since the coating direction is parallel to the short sides of EBT film sheets, more light is scattered in the plane normal to the film plane and parallel to the long sides of the film. This effect increases the amount of light captured by the optical system when the EBT film is scanned in landscape mode (short dimension of the film parallel to the scanning direction or to the long dimension of the scan bed).

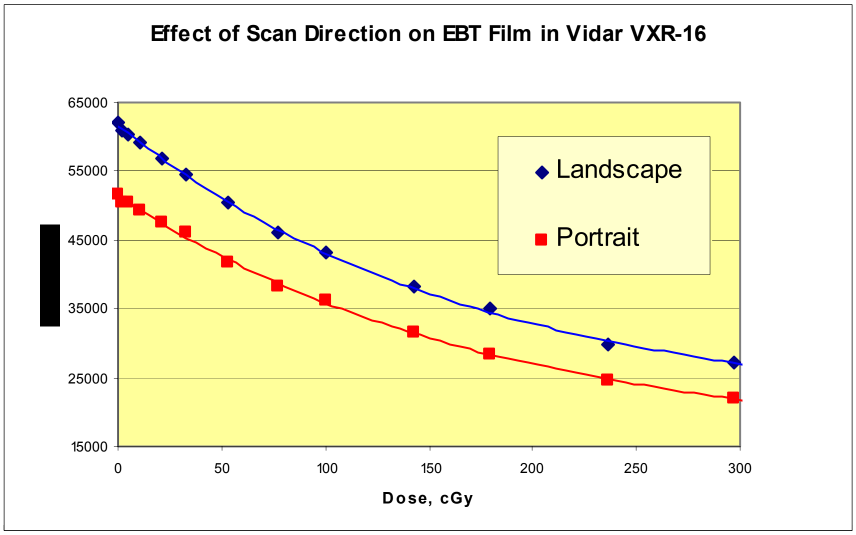

Figure 3.4: Effect of EBT Film Orientation on Scanner Response in Vidar VXR-16

As demonstrated in Figures 3.5a and 3.5b, the orientation effect is observed also with flatbed scanners. As with the Vidar scanner, the pixel values and light intensities are smaller when the EBT films are scanned in the portrait mode. However, the differences are substantially smaller than with the Vidar VXR-16 – about one half for the Microtek 9800XL scanner and one quarter for the Epson Expression 1680 scanner.

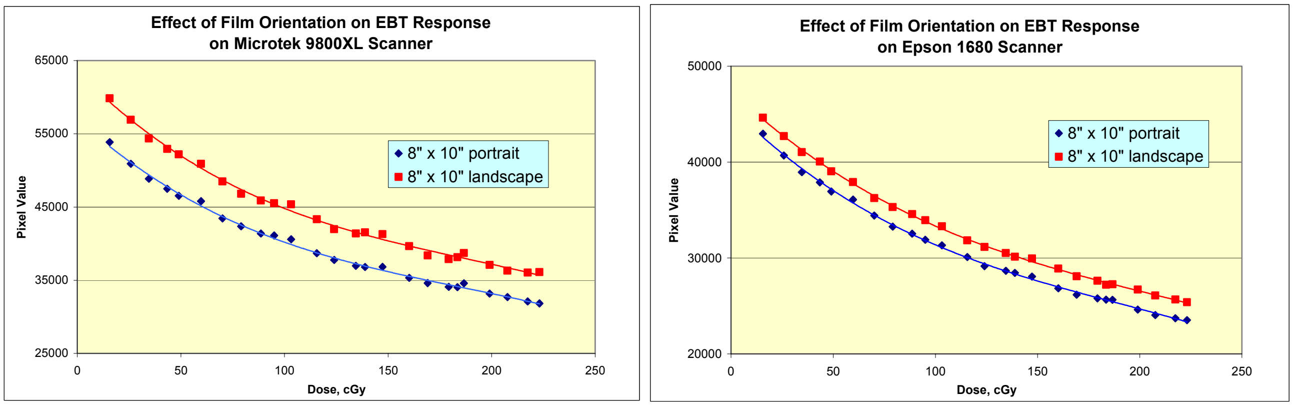

Figure 3.5a

Figure 3.5b

Figure 3.5a-b: Effect of EBT Film Orientation on Scanner Response:
a) Microtek 9800XL; b) Epson Expression 1680

Due to this directional effect, it is critical to **always scan EBT films in the landscape orientation.** Extensive research indicates that scanning the EBT films in the landscape orientation yields superior results. So, for films with sizes 8”x10” and above, Epson Expression 10000 XL flatbed scanners with large scanning bed work best. *So does Vidar’s Dosimetry Pro Advantage with red light with film oriented in the landscape mode. (Fig 3.2)*

4.0 PERFORMANCE DATA

Data has been gathered from a number of sources on the performance of EBT dosimetry film. The data presented below is provided for informative and/or guidance purposes and is not meant to be definitive. We believe that the data will be representative of the EBT film to be examined in this trial.

4.1 SENSITOMETRIC RESPONSE

4.1.1 Densitometer and Spectrophotometer Measurement

The data in Figure 4.1 shows the net density change for x-ray exposure (150kVp, 1mm Al filtration) of EBT film batch # 34016-3BX2. The densities were measured 1 hour after exposure. Net density is the change in density owing to the exposure dose, i.e. density after exposure minus (base + fog). Visual density measurements were made with an X-Rite 310T densitometer. Measurements were also made at peak wavelength (636nm) using a spectrophotometer.

As a means of comparison, the responses of GAFCHROMIC® HS dosimetry film and Kodak EDR-2 film are presented in Figure 4.1. For EDR-2, the exposure was with 6 MV photons and measurement of visual density was made with an X-Rite 310T densitometer. For HS film the exposures were made with 150 kVp x-rays with 1mm Al filtration and densitometry measurements were made 1 hour after exposure with an X-Rite 310T densitometer (visual density) and a Nuclear Associates Radiochromic Densitometer Model 37-443. This latter densitometer employs a red LED

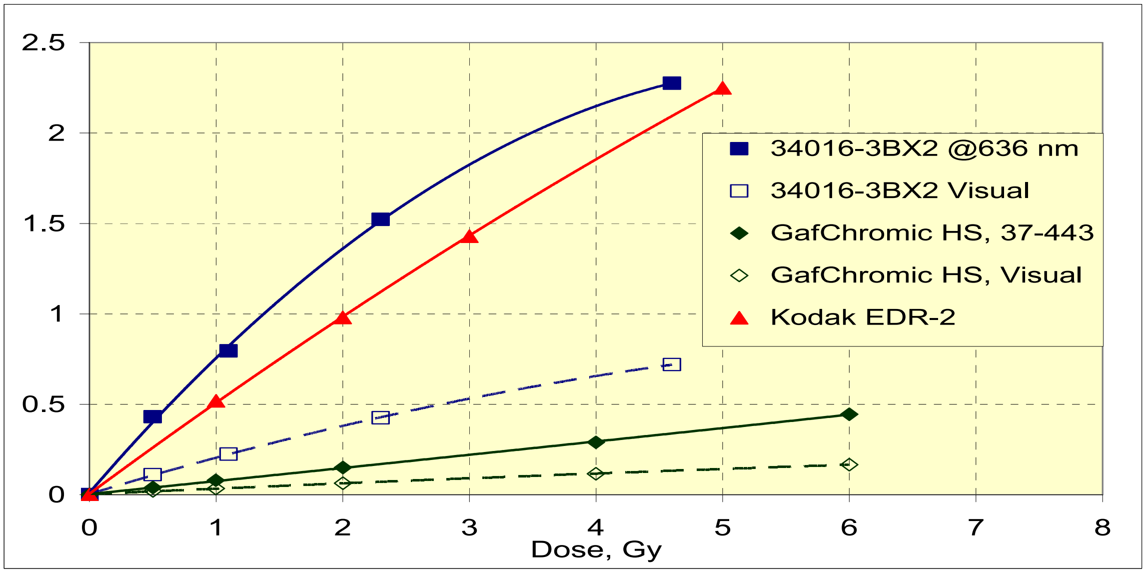

Figure 4.1: Sensitometric response of GAFCHROMIC® EBT dosimetry film (Batch# 34016-3BX2) and comparison with GAFCHROMIC® HS and Kodak EDR-2 dosimetry films.

source and filter to measure in a narrow band centered at ~670 nm and close to the λ_{max} for GAFCHROMIC® HS.

These data show that GAFCHROMIC® EBT is approximately ten times more sensitive than GAFCHROMIC® HS when the films are measured in similar ways – both measured with visual density or at a wavelength close to λ_{max}. Furthermore when EBT film is measured at a wavelength close to λ_{max}, it is substantially more sensitive than Kodak EDR-2 although it is less sensitive when measured in the visual wavelength band. The results indicate that it is desirable to measure the response of EBT film in the red wavelength band of the visual spectrum.

Figure 4.2 shows the response of EBT film to cobalt-60 radiation. The exposed film was measured in the visual and red spectral bands and the results demonstrate again the benefit of measuring the film in the latter manner.

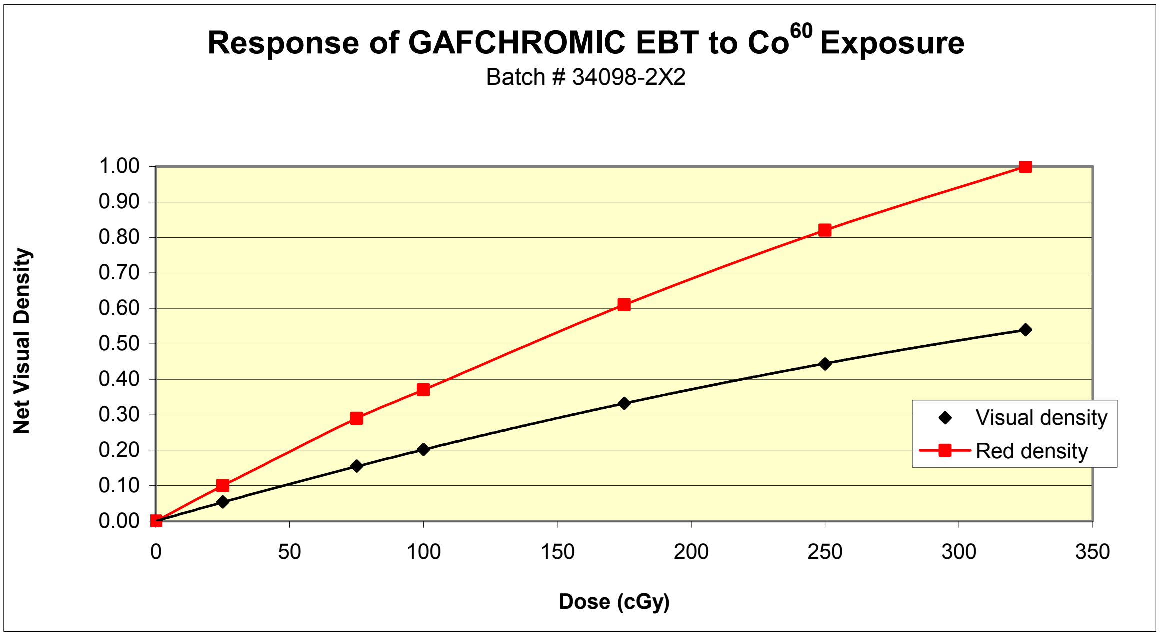

Figure 4.2: Sensitometric response of GAFCHROMIC® EBT in the visual and red color bands

4.1.2 Scanner Measurement

Figure 4.3 shows the response of EBT film as measured with a selection of film scanners. All these scanners (Epson 1680, Microtek 980XL and Vidar VXR-16) have 16 bit pixel depth and read the light transmission of film on a scale of 0 (no transmission) to 65535. The Vidar scanner measures only grayscale, but the Epson and Microtek scanners are color scanners and measure in three color bands – red, green and blue. Since EBT film absorbs red light more strongly than blue or green light the response is greatest in the red color channel of these scanners. The green channel has a lower response than the red channel. The blue channel response is the lowest. We are not aware of a standard for grayscale response, but practically speaking it is approximately the average of the responses of the red, green and blue channels.

The data in Figure 4.3 for the Epson and Microtek scanners show the responses in the red color channel. Note that it is possible to adjust the upper end of the transmission scale for each of the scanners so that the value of 65535 would correspond to the transmission of unexposed film. This would be equivalent to the "zeroing" of a manual densitometer. However, for the response data plotted in Figure 8, no attempt was made to adjust the scanner in this manner.

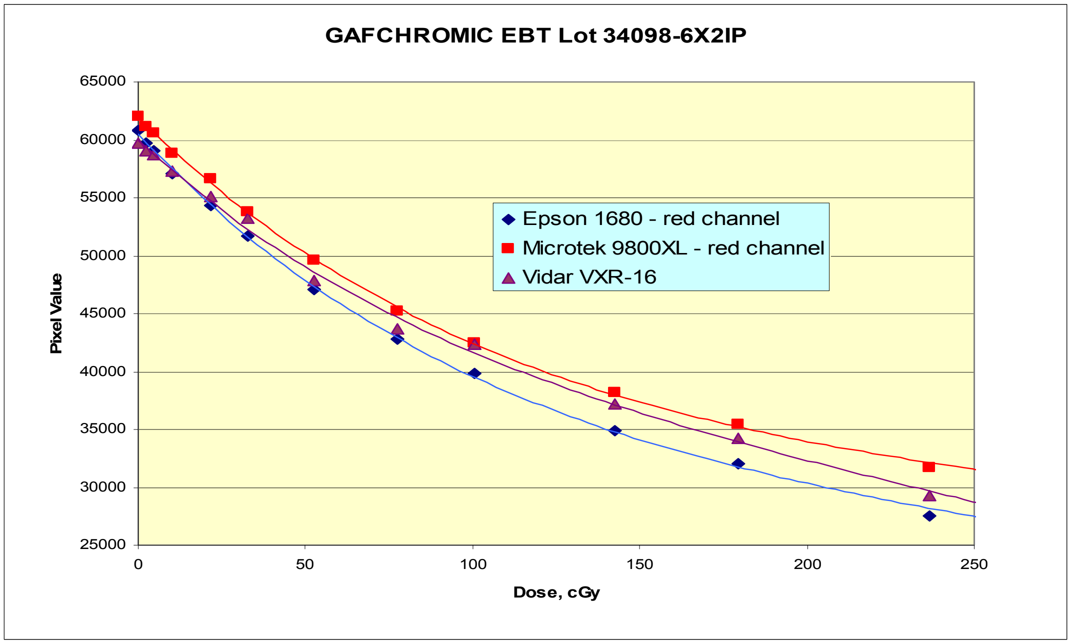

Figure 4.3: Sensitometric response of GAFCHROMIC® EBT in the visual and red color bands

4.1.3 Vidar's Dosimetry Pro Advantage Scanner response with Red LED

Vidar have developed a version of the Dosimetry Pro Advantage with features specifically designed to produce optimum results when digitizing GAFCHROMIC EBT film images. The Red LED Dosimetry Pro Advantage employs an LED light source with nominal maximum emission at 627nm and FWHM bandwidth of 20nm. This light source is very closely matched to the peak absorption of EBT film at 635nm. The red emitters in the Red LED scanner illuminate a translucent diffuser located within a few millimeters of the film thereby minimizing the effects of light scattering by the film-digitizer measurement system. Finally the Red LED scanner has been provided with rollers attached to the LED lamp cartridge to reduce flexing of film in the transport system that can lead to the appearance of artifacts in digitized images.
If possible, Dosimetry Pro Advantage should be sent back to the factory for an upgrade to a red light source. Contact you Vidar scanner distributor for upgrades.

4.1.3.1 Scanner response: Dosimetry Pro Advantage with Red LED vs VXR-16

The GAFCHROMIC® EBT calibration films were scanned on a Vidar VXR-16 and a Red LED Dosimetry Pro Advantage. The film images were evaluated by defining an area of interest about 1.5cm x 1.5cm at the center of each of the areas exposed to the calibrated doses and measuring the scanner response. The results are plotted in Figure 4.4. The values have been scaled to give the same response values for the unexposed film on the two scanners. The data show that the response of the Red LED scanner is greatly enhanced in comparison to the response of the VXR-16. For a dose of 250cGy the net response, compared to zero dose, for the VXR-16 is about 24000. At the same dose the net response for the Red LED is approximately 46000, almost 2X the response of the VXR-16. At lesser doses the net response of the Red LED scanner is between 2X and 3X greater than the response with the VXR-16.

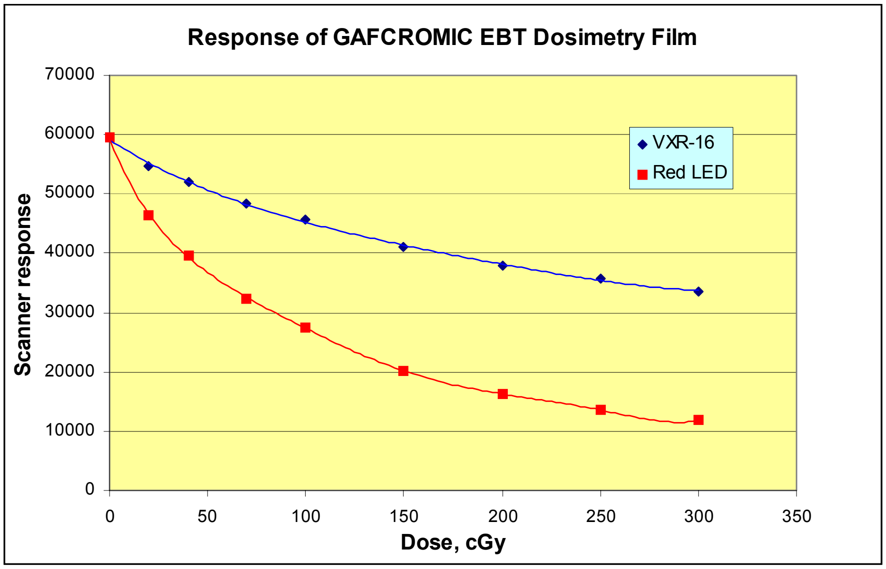

Figure 4.4: Dose Response of Radiochromic Film in the Red LED and VXR-16 Digitizers

5.0 DOSE RESOLUTION

A film scanner measuring a transparency determines the amount of light transmitted by the film. A scanner with 16 bit resolution assesses the transmission on a scale from 0 (no transmission) to 65535 (high transmission). The intensity of the transmitted light is reported as the pixel value (PV). The dose resolution, Δd, of a film and film-scanner system depends upon the slope of the dose response curve (PV vs. dose) and the standard deviation of a measurement $\sigma_{PV,d}$. This is depicted in Figure 5.1. Assuming that the variability of the measurement of a single pixel has a normal distribution and beginning with the criterion that we would like to know the dose of a single pixel to a confidence of 90%, we can evaluate the dose resolution at a dose d by calculating Δd for pixel values that range from PV-1.65 $\sigma_{PV,d}$ to PV+1.65 $\sigma_{PV,d}$.

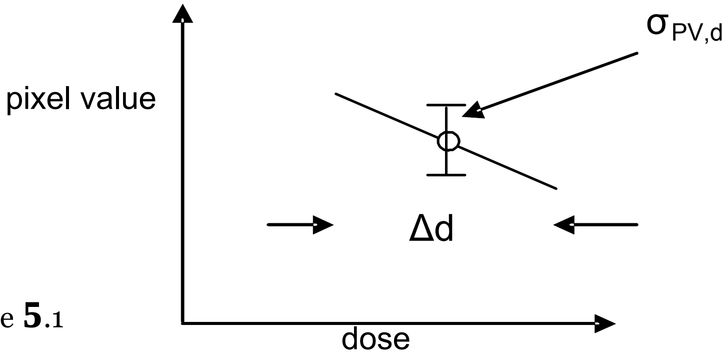

Figure 5.1

A step tablet was exposed on a sheet of EBT film (34098-6BX2, Prototype B configuration) at doses ranging from about 1cGy to about 300cGy. The steps were approximately 3cm x 2cm in size. The step tablet was scanned in four different ways. The Epson 1680 and Microtek 9800XL are flatbed RGB scanners. The step tablet was processed on these scanners at 75 pixels/inch in color mode and saved as a TIFF file. Data from the red color channel was then extracted and used for further evaluation. The Vidar VXR-16 is a grayscale scanner and the step tablet was scanned by itself and also in combination with a yellow optical filter to cut out light below about 550nm. The spatial resolution of the scans on the VXR-16 was 71 pixels/inch.

The scan images were processed by computing the average pixel value across 3x3 blocks of pixels. Using the scan images a small area of interest approximately 1.5cm x 1.5cm in size was drawn in the center of each step. All the pixel values within the area of interest were measured and the mean and standard deviation were determined. The data for each scan were plotted and fit to a third order polynomial. The slopes of the response curves vary with dose, but the slope at any point can be determined by calculating the first derivative of the polynomial fitting function. The dose resolution for each of the doses on the step tablet was calculated as described in the first paragraph of this section.

Figure 5.2 shows the results plotted as (dose resolution x 100)/dose vs. dose. Characteristically dose resolution/ dose is higher at lower doses and for each scanner the values appears to become fairly constant between about 100 and 300 cGy. Dose resolution/dose for the Microtek scanner falls to 1% above about 100 cGy, but the performances of the other scanners are superior. For the Epson scanner the dose resolution reaches about 1% between about 10cGy and 20cGy while the Vidar scanner reaches this plateau at about 30 cGy. At doses in the 75-300cGy range the Vidar and Epson scanners achieve about 0.5% dose resolution. (see Figure 5.2).

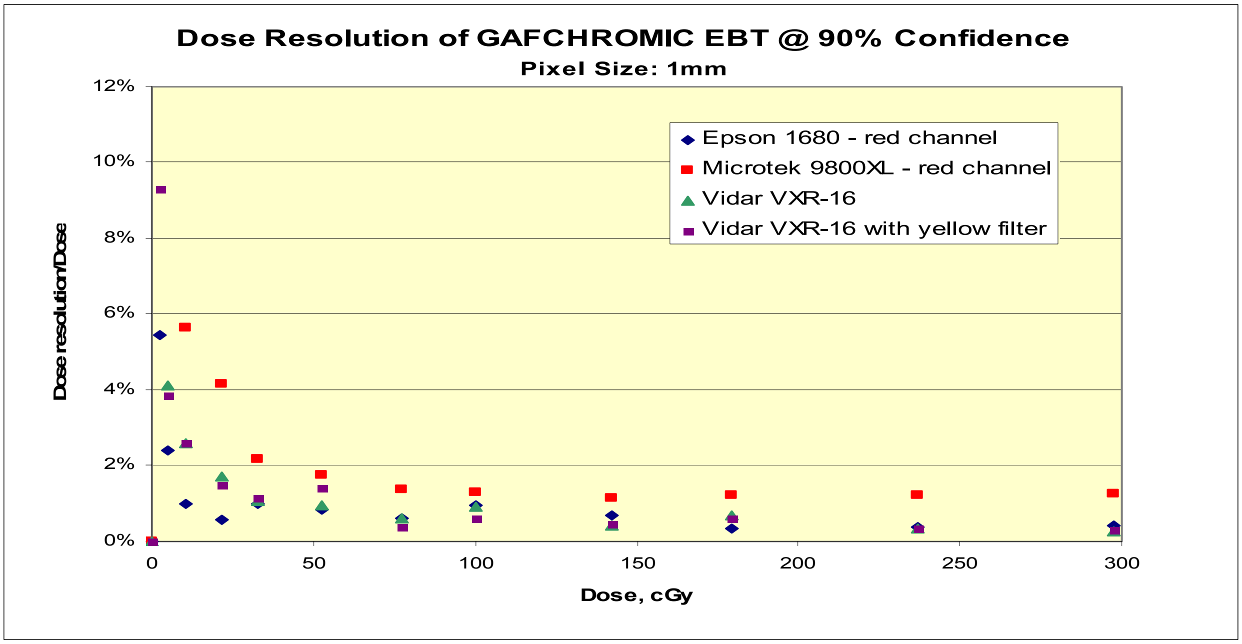

Figure 5.2: Dose Resolution of GAFCHROMIC® EBT Dosimetry Film with Film-Scanners

6.0 ENERGY DEPENDENCE and EFFECTIVE ATOMIC NUMBER

Table 1 contains details of the atomic compositions of GAFCHROMIC EBT dosimetry film. The effective atomic number has been calculated according to McCullough and Holmes, *Med. Phys.*, 12:237-242, 1985. The Z_{eff} is 6.98. This value is closer to the Z_{eff} of water (7.3) than the value for GAFCHROMIC® MD-55 (~6.5).

Atomic Composition						Zeff = [∑ αi (Zi)a]$^{1/a}$
C	H	O	N	Li	Cl	
42.3%	39.7%	16.2%	1.1%	0.3%	0.3%	6.98

Table 1: Atomic Composition and Effective Atomic Number of GAFCHROMIC® EBT Dosimetry Film

GAFCHROMIC® MD-55 and HS dosimetry films contain only low Z elements - C, H, N and O – and these films show a lower dose response to keV photons than MeV photons. At about 50keV the response is about 20% less than at 6 MeV. The presence of a minor amount of the moderate Z element chlorine in the atomic composition of EBT film suggests that photoelectric absorption of keV photons in this film will be boosted, particularly below 50 keV. Consequently EBT film may exhibit less energy dependency than the earlier radiochromic films. The energy dependence was assessed by measuring the dose-density response of the film with cobalt-60 radiation and with several different quality kilovoltage x-ray beams. The results shown in Figure 6.1a indicate that under these exposure conditions, at least, the EBT film has a very low energy dependency, showing not more than a 5% difference between MeV and keV photons.

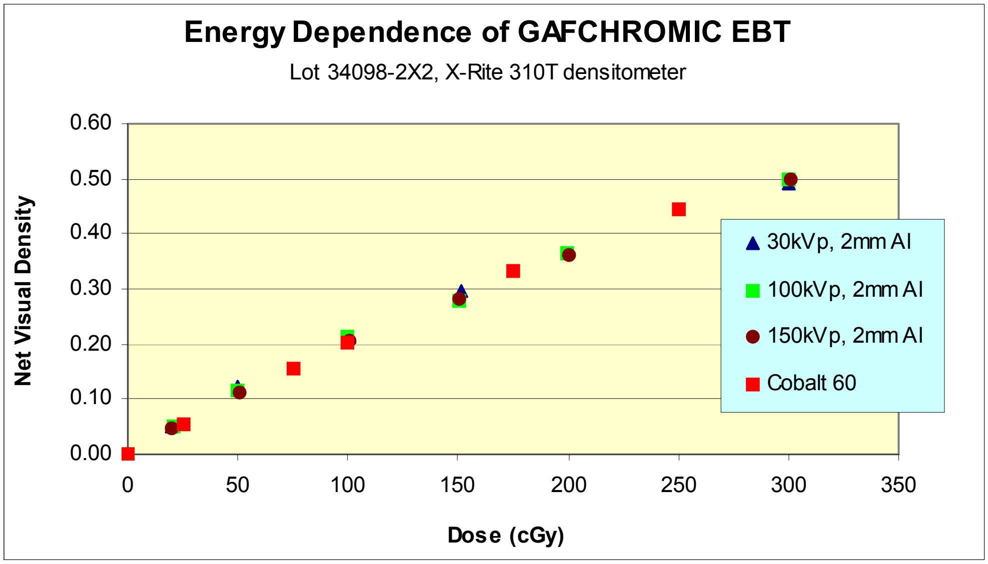

Figure 6.1a: Energy Dependence of GAFCHROMIC® EBT Dosimetry Film

Other measurements of EBT film with photons and electrons in the megavoltage region were reported at AAPM in 2004 by Jameson Baker, et al. Their data, Figure 6.1b, shows that the film has the same response to electrons at 6 MV and 15 MV and to 6 MeV, 12 MeV and 20 MeV photons.

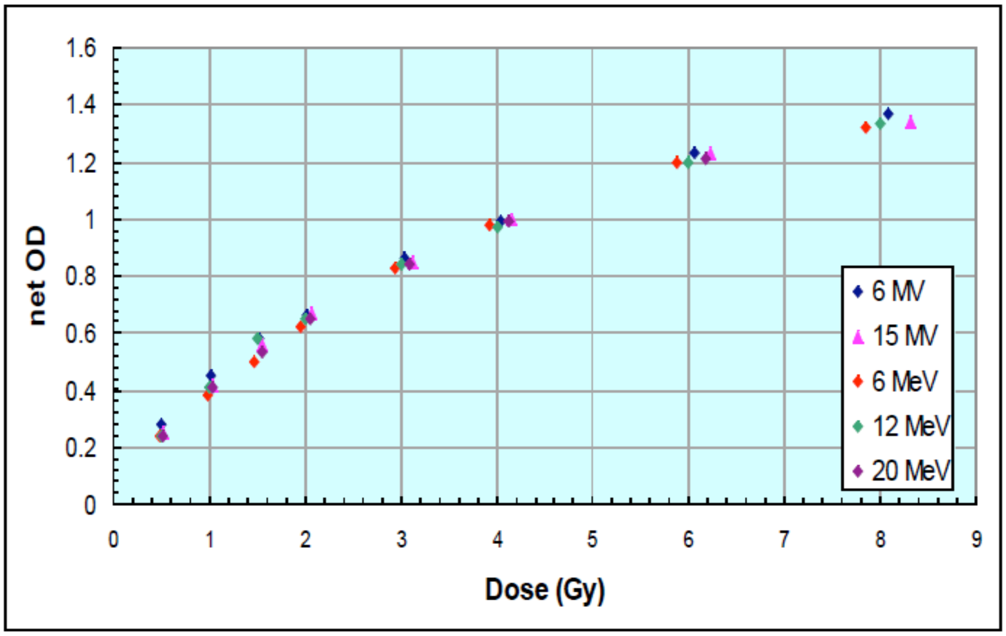

Figure 6.1b: Energy Dependence of GAFCHROMIC® EBT Dosimetry Film

7.0 DOSE FRACTIONATION

The effect of dose fractionation upon the exposure of GAFCHROMIC® EBT film was assessed by exposing film samples 5 Gy of 150 kVp x-rays with 2mm Al filtration. Three film samples were exposed to the 5 Gy in a single fraction in about 2 minutes. A further three samples were exposed to 5 Gy given in 1 Gy fractions at 30 minute intervals. The change in visual density of all samples was measured 24 hours later. Each sample was measured three times. The results in Table 2 indicate that the responses of the films exposed to a single fraction are indistinguishable from the response of the films given fractionated exposure. These data establish that EBT film is an effective dose integrator.

EXPOSURE	**NET VISUAL DENSITY CHANGE (average of 9 measurements)**
5 Gy in a single fraction	0.681 ± 0.015
5 Gy in 1 Gy fractions at 30min. intervals	0.677 ± 0.009

Table 2: Response of GAFCHROMIC® EBT Dosimetry Film to Fractionated Exposure

8.0 DOSE RATE

In a private communication, Alexandra Rink, et al report data showing that if time is allowed for the radiation induced polymerization to go to completion (>2hours), the EBT film does not exhibit a dose rate dependence.

9.0 POST-EXPOSURE DENSITY GROWTH

The post-exposure density growth of GAFCHROMIC® EBT dosimetry film has been investigated. In common with the currently available GAFCHROMIC® dosimetry films, the density of the developmental film increases with time following exposure. For all GAFCHROMIC® dosimetry films the density growth is approximately proportional to log(time after exposure). However, for the EBT film the post-exposure growth is substantially less than for previous GAFCHROMIC® films. Also the time period over which significant post-exposure occurs is much less for EBT film. Finally the magnitude and rate of post exposure changes in EBT film are dependent upon the mode of readout.

The data in Figures 9.1a and 9.1b respectively show the post-exposure density growth of GAFCHROMIC® HS dosimetry film and EBT film. In both cases the measurements were made at wavelengths close to the λ_{max} for each film type. The densities of film samples exposed to similar absorbances are plotted versus the time after exposure. The data show that after exposure the density growth in HS film is about 20% and the process is essentially complete within about 2 days. By comparison the growth of EBT film is <10% and is effectively complete in less than 2 hours. The measurements also indicate that post-exposure growth of HS and EBT films are slightly larger at lower doses than at higher doses.

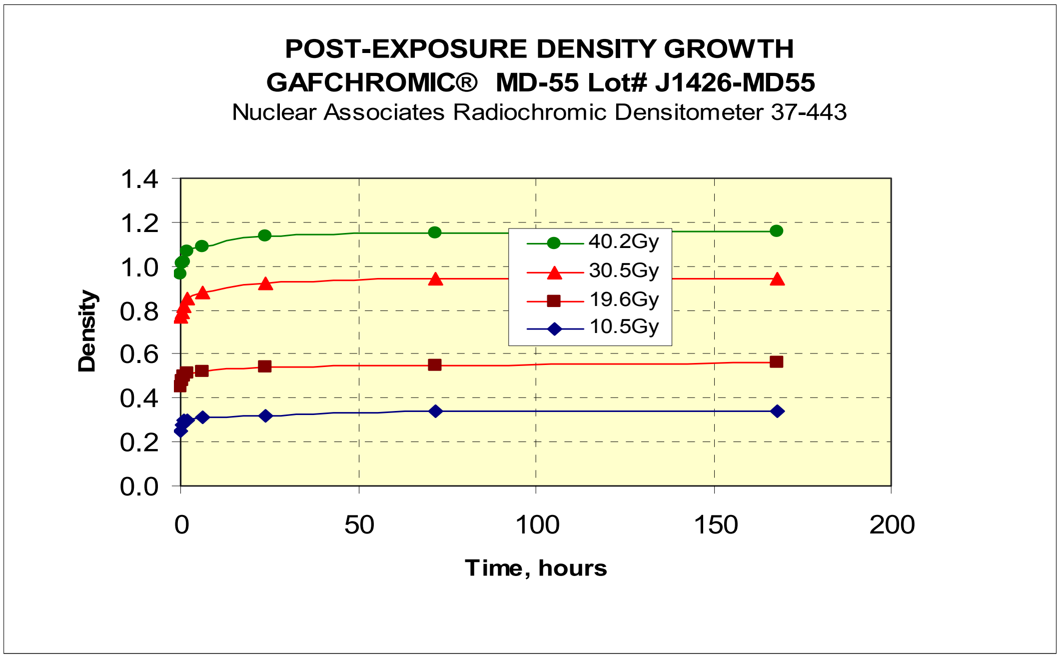

Figure 9.1a: Post-exposure density growth of GAFCHROMIC® HS dosimetry film

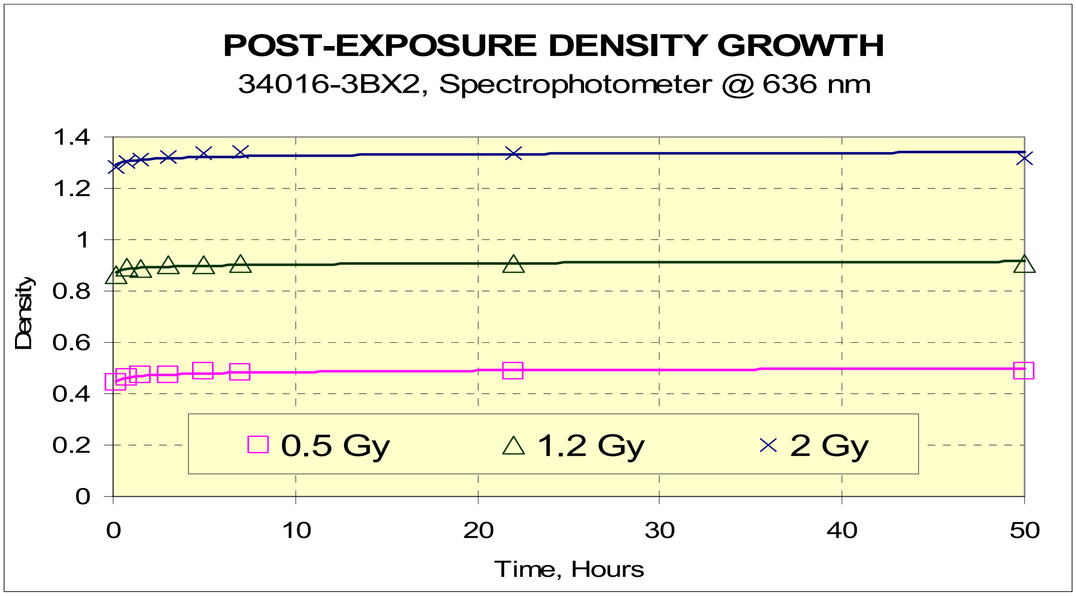

Figure **9**.1b: Post-exposure density growth of GAFCHROMIC® EBT Batch# 34016-3BX2

Densities are projected back to zero time after exposure and the growth data for each exposure have been normalized to the density at zero time. The results indicate that post-exposure growth is lower at higher exposures and that the growth is essentially complete within 2 hours after the exposure.

10.0 UNIFORMITY OF THE FILM AND FILM-SCANNER SYSTEM

We have measured the uniformity of EBT film (Batch 34098-6BX2). Films were exposed with a 15cm x 15cm flat field on a linear accelerator at a dose of about 223cGy and subsequently measured on an Epson 1680 flatbed film scanner. Noise in the scan data comes from contributions from the film, the film exposure and the scanner. The methodology described below is used to evaluate the noise from each of these sources.

10.1 SCANNER UNIFORMITY

Scanner noise evaluation begins by making repeated scans of a single exposed film at a spatial resolution of 75 pixels/inch. Scanning took place in RGB mode and data was saved in TIFF format. Other scan parameters were constant. The film was removed from the bed of the scanner and then replaced between each scan. No attempt was made to ensure perfect registration of the film. Film was repositioned within about ±5mm in the x and y directions. The red color channel data was extracted from the RGB files and the “red” images were saved. The scanner noise contribution was then measured by subtracting two “red” images to yield a difference image. This difference image was then divided by the mean pixel value in the flat field area of a “red” image before image subtraction and multiplied by 100. Assuming that the contributions of the film and film exposure have negligible contribution to differences between consecutive scans, the difference image is representative of the noise contribution of the scanner expressed as a percentage of the signal. Assuming that scanner noise is random, the standard deviation of the pixel values in the difference image will be √2 larger than the scanner noise. In the difference image an area of interest approximately 14cm x 14 cm was delineated in the area of the flat field exposure and the mean pixel value and standard deviation was calculated.

Figure **10**.1 shows an example of a difference image. The mean value of the pixels (expressed as a % of the signal) in the difference image is about 0.28% with a standard deviation of about 0.56%. The noise contribution of the scanner is thus estimated to be about 0.4% (0.55%/√2). Figure 15 depicts a profile across the center of the difference image (see the red cursor in Figure 14) showing noise levels generally <0.5% across the image – note that the flat field area extends from about Column 80 to Column 520.

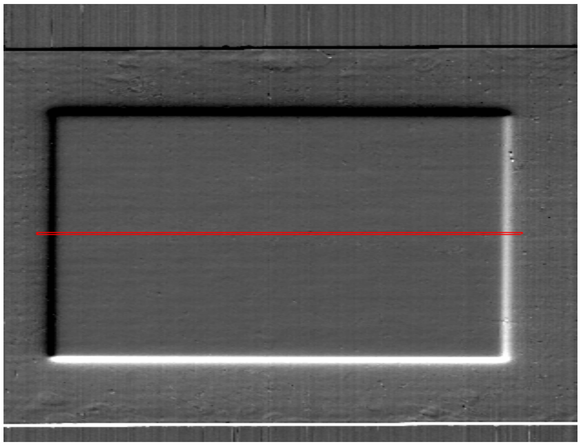

Figure **10**.1: Difference Image of Consecutive Scans of the Same GAFCHROMIC® EBT Film

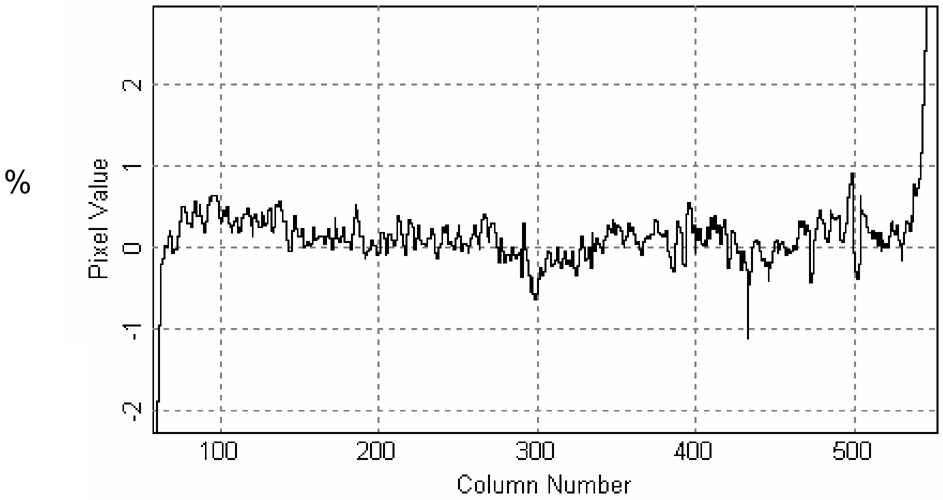

Figure **10**.2: Profile Across the Difference Image in Figure **10**.1 - *Note: the scale on the y axis is in %*

10.2 TOTAL SYSTEM UNIFORMITY

Evaluation of noise from all sources began by making scans of a single exposed film at several different orientations at a spatial resolution of 75 pixels/inch. Scans were acquired in RGB mode and data was saved in TIFF format. Other scan parameters were constant. After a first scan the film was rotated by 180 degrees about one of three axes. One axis was perpendicular to the film plane and the other two axes were in the film plane perpendicular to one another and parallel to the sides of the film. The film was removed from the bed of the scanner and then replaced between each scan. No attempt was made to ensure perfect registration of the exposed flat field area on the film. Film was repositioned within about ±5 mm in the x and y directions. The red color channel data was extracted from the RGB files and the "red" images were saved. The noise from all sources was then determined by calculating the difference between images scanned in different orientations. This difference image was then divided by the mean pixel value in the flat field area of a "red" image before image subtraction and multiplied by 100. This difference image is representative of the noise contribution of the scanner expressed as a percentage of the signal. Assuming that noise is random, the standard deviation of the pixel values in the difference image will be √2 larger than the total noise. In the difference image an area of interest approximately 14cm x 14 cm was delineated in the area of the flat field exposure and the mean pixel value and standard deviation was calculated.

Figure **10**.3 shows an example of a difference image. The mean value of the pixels (expressed as a % of the signal) in this difference image is about 0.2% with a standard deviation of about 1.3%. All the difference images had a standard deviation less than 1.9%. The noise contribution from all sources is thus estimated to be less than about 1.3% (1.9%/√2). Figure **10**.3 depicts a profile across the center of the difference image (see the red cursor) showing noise levels generally vary by <1% across the image – note that the flat field area extends from about column 90 to column 530.

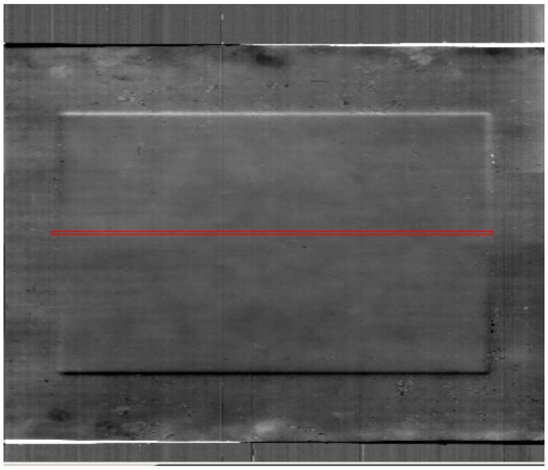

Figure **10**.3: Difference Image between Scans of EBT Film in Different Orientations

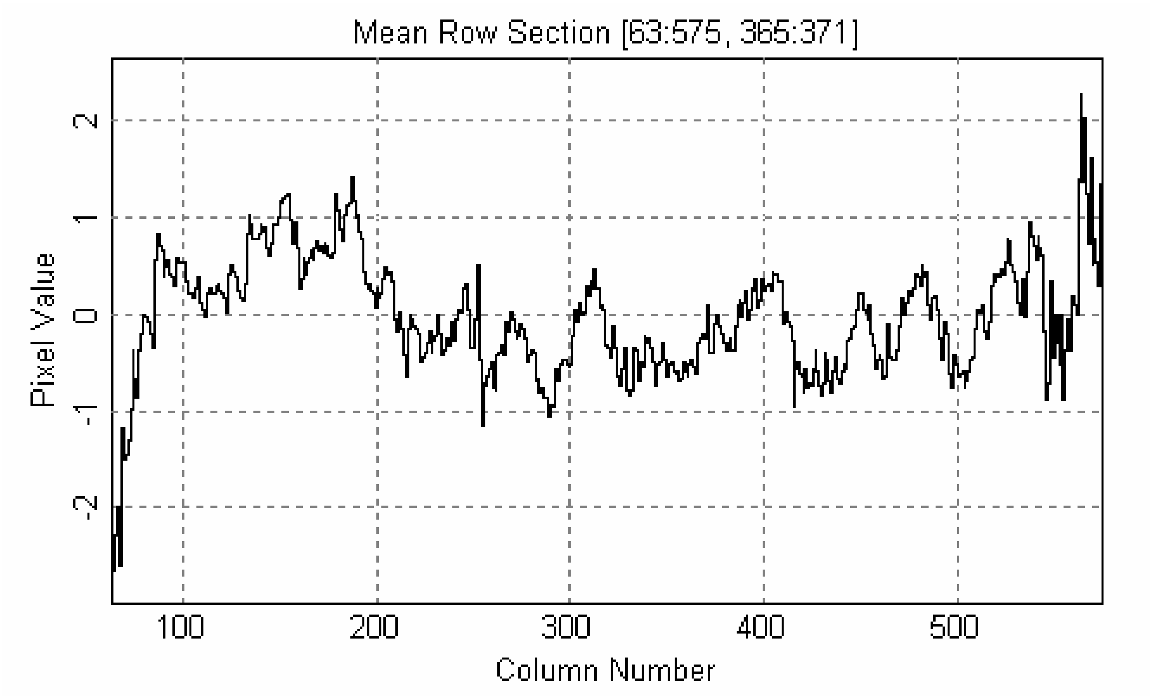

Figure **10**.4 Profile across the Difference Image in Figure **10**.1 - *Note: the scale on the y axis is in %*

10.3 FILM UNIFORMITY

Assuming that the noise contributors- scanner, film and film exposure - are acting at random, the components add in quadrature to produce the total noise. For the purpose of this evaluation we will assume that the flat field exposure really is flat and is perfectly symmetrical, i.e. it will make no contribution to the difference images. In this case the noise in difference images of the type depicted in Figure 12 will result from noise in the scanner and noise in the film, i.e. non-uniformity

SCAN-TO-SCAN DIFFERENCES	**DIFFERENCE IMAGE STATISTICS**		**SOURCE OF ERROR**			
	Mean PV	Std. Dev.	Total Error*	Scanner	Exposure	**Film**
Film replaced between scans	-4	69	0.4%	0.4%	Assumed to be zero	**Not applicable**
Film rotated 180° between scans axis normal to film plane	45	269	1.3%	0.4%	Assumed to be zero	**1.2%**
Film rotated 180° between scans axis in the film plane	81	192	0.9%	0.4%	Assumed to be zero	**0.8%**

Table 3: Noise Contribution from Various Sources

in the film response. The noise contributions from the scanner, the film exposure and the film are given in Table 3. Since scanner noise has been determined to contribute about 0.4% (see Section 10.1) the film non-uniformity is estimated to be less than about 1.2%.

11.0 SHEET-TO-SHEET FILM UNIFORMITY

Ten sheets of EBT film (Batch 34098-6BX2) were exposed to a 15 cm x 15 cm flat field in a linear accelerator (6 MV). Two exposures were made. For each, five sheets of film were placed between slabs of solid-water and given doses of approximately 100 cGy. The sheets were scanned in RGB mode on an Epson 1680 flatbed scanner at a spatial resolution of 75 pixels/inch. No attempt was made to ensure perfect registration of the flat field exposed areas on the scanner bed. However, placement of the exposed areas was within about ±5mm in the x and y directions. The data was saved in TIFF format. Other scan parameters were constant.

The red color channel data was extracted from the RGB files and the “red” images were saved. The film-to-film uniformity was determined by delineating an area of interest about 14 cm x 14 cm within the exposed area on each film and measuring the mean pixel value. The results are shown in Table 4. The mean pixel values ranged from 34909 to 35765 with a standard deviation of 272. The coefficient of variance (2σ/mean) was 1.5%.

Exposure No.	Mean Pixel Value in Flatfield
1	34961
2	34909
2	35180
3	35395
4	35362
5	35424
6	35765
7	35565
8	35171
10	35060
Average: 35279 **Std. dev. : 272** **2*std. dev./average : 1.5%**	

Table 4: Sheet-to-sheet Response Variations of GAFCHROMIC® EBT Dosimetry Film

Figure 11.1 depicts a representative difference image calculated by subtracting the red channel images of two sheets. Within the depicted area of interest the mean pixel value is about 0.1% of the mean pixel value in the original (un-subtracted) images and the standard deviation is 0.76%. Such results show that not only is the sheet-to-sheet response reproducible, but they also underscore the excellent uniformity within individual sheets of film. The horizontal and vertical profiles across the difference image in Figure 11.1 are depicted in Figures 11.2a and 11.2b. The horizontal profile is flat to within about 0.5% and the vertical profile to within about 1%.

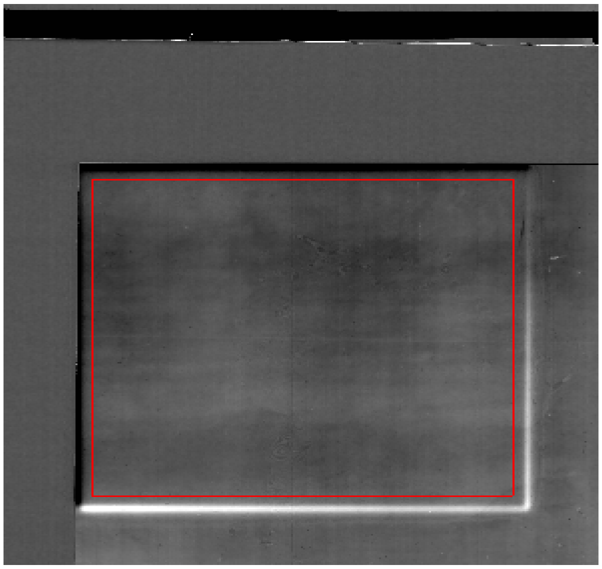

Figure **11**.1: Sheet-to-sheet Difference Image

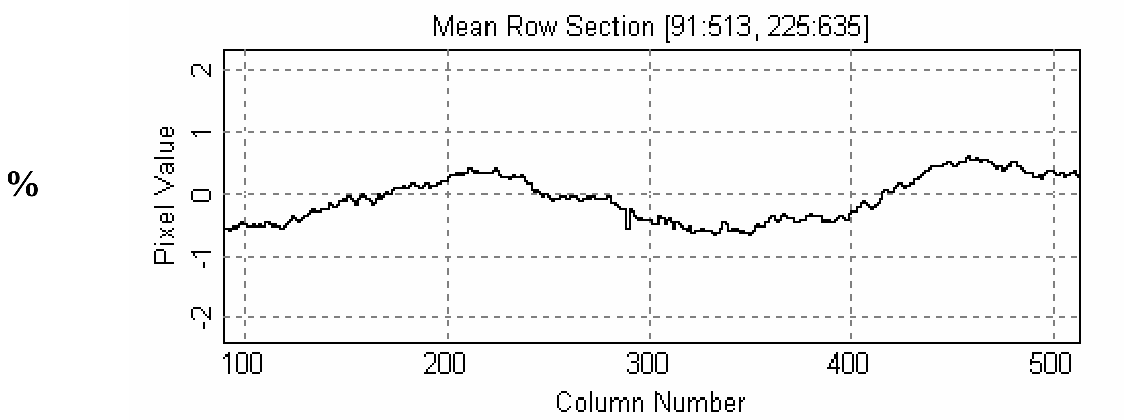

Figure **11**.2a: Horizontal Profile of the Image in Figure **11**.1 – *Note: the scale on the y axis is in %*

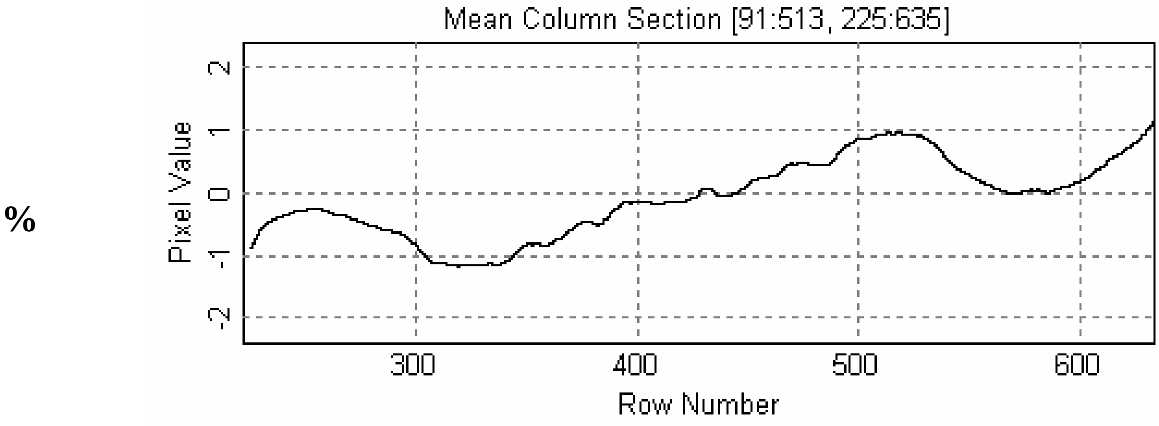

Figure **11**.2b Vertical Profile of the Image in Figure **11**.1 – *Note: the scale on the y axis is in %*

12.0 WHITE LIGHT SENSITIVITY

GAFCHROMIC® dosimetry films are not particularly sensitive to visible light although they are comparatively more sensitive to short wavelength light than to long wavelength light. The interior environment in buildings is predominantly illuminated with incandescent or cool white fluorescent light bulbs. These latter sources produce balanced proportions of blue, green and red light while the former emit a higher proportion of red light. In measuring the white light sensitivity of GAFCHROMIC® EBT dosimetry film, the performance has been evaluated under the more demanding conditions of exposure to the light from cool white fluorescent bulbs as are commonly found in interior workspaces.

The intensity of the illumination on working surfaces, e.g. desktops and laboratory benches, was measured in a representative number of offices and laboratories. It was found that the light intensity ranged from about 600 lux to 1000 lux. For the purpose of the evaluation it has been assumed that “standard” indoor illumination intensity is the greater of these values, i.e. 1000lux.

The data are plotted in Figure **12**.1. The trend of the data points suggests that the rate of change of density diminishes with exposure. This behavior is consistent with the white light sensitivity of previous GAFCHROMIC® dosimetry films. Continuous exposure in interior light for 24 hours (equivalent to an exposure of 1000 lux-days) would result in a density change of about 0.007, equivalent to a radiation exposure of about 3 cGy. This low white light sensitivity indicates that GAFCHROMIC® EBT dosimetry film can be handled in normal room light for at least several hours without noticeable effects. However, it also suggests that the film should not be left exposed to room light indefinitely. Best practice is to keep light exposure to a minimum and place the film in a dark container while it is not being used. The film should not be exposed to direct sunlight.

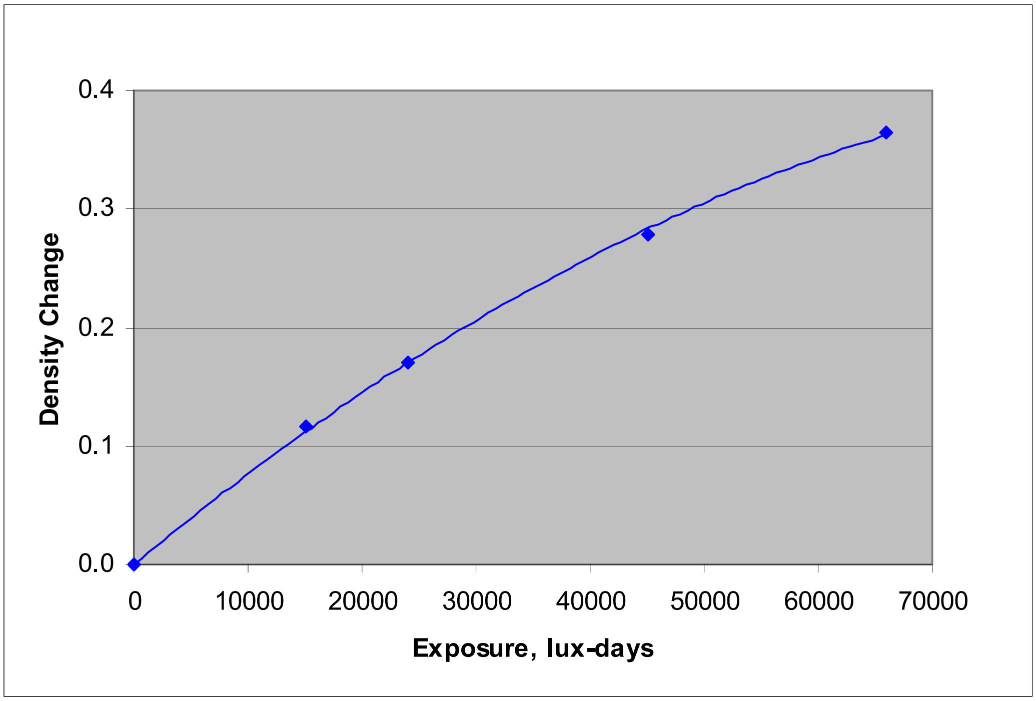

Figure **12**.1: White light sensitivity of GAFCHROMIC® EBT (34098-6BX2)