revista mexicana de física **26** no. 3 (1980) 483-501

PRACTICAL USE OF SOME ROUTINE RADIATION DOSIMETERS*

Roberto M. Uribe R. and Javier Reyes L.(+)
Instituto de Física
Universidad Nacional Autónoma de México

(recibido 16 de agosto 1977)

ABSTRACT

The preparation and response characteristics of some secondary radiation dosimeters are described.

Their practical utility and sensitivity are analyzed in detail. Radiation yields (G values) and calibration curves for some of these dosimeters were measured, and their application and limitations in radiation processing were compared.

RESUMEN

Se hace una revisión sobre algunos dosímetros secundarios de radiación describiendo sus mecanismos y forma de preparación.

Además, se discute su utilidad como sensores de radiación, así como dónde y cómo utilizarlos.

La discusión incluye algunas observaciones ilustradas en la sección experimental, en la que además, se determinan los valores G para los sistemas químicos, curvas y distribución de dosis dentro de una cámara de irradiación.

INTRODUCTION

In radiation processing applications absolute methods for the determination of dose by primary standard dosimeters such as calorimeters and ionization chambers are complicated and time consuming. This can be a disadvantage when quick dose determinations are required or where frequent determinations are needed.

Thus several routine secondary systems have been developed and

---

* Work done during a short stage at the Accelerator Department, Danish Atomic Energy Commission, Research Establishment, Risø Denmark (presently Risø National Laboratory), Supported by the Consejo Nacional de Ciencia y Tecnología.

(+) Instituto Nacional de Investigaciones Nucleares, Salazar, Edo. de México.

applied, in order to determine the dose in a simple and efficient way, mainly in those fields where radiation is used as an industrial tool.

The selection of a dosimeter for a given purpose depends of the following criteria(1).

1) Independence of response on radiation energy.
2) Water or tissue equivalent absorption characteristics.
3) Linear dose vs. response relationship.
4) Wide dose range.
5) Independence of dose rate.
6) Good accuracy.
7) Good reproducibility.
8) Response independent of environmental conditions.
9) Independence of impurities.
10) Well-defined reaction mechanism.
11) Good storage stability before and after irradiation.
12) Cheapness and simplicity in use.

No one system so far fulfills all the above requirements, although a few come fairly close. The selection of a particular system requires an assessment of priorities and depends on the process and type of material to be irradiated.

In the following pages a critical examination of some routine dosimeter systems is presented. They have been grouped as liquid chemical plastics and dye dosimeters.

CHEMICAL DOSIMETERS

Any system in which a measurable chemical change takes place upon irradiation may be termed a chemical dosimeter. Solid, liquid and gaseous systems have been explored, although only aqueous chemical systems will be discussed in this section.

Radiation effects produced in a chemical dosimeter are caused primarily by fast electrons (either as the primary radiation or as photoelectrons or Compton electrons in gamma irradiation). When a fast primary electron passes through a material it loses its energy gradually by exciting and ionizing the atoms of the medium. The secondary electrons may be able to cause further excitation and ionization, whose processes eventually lead to chemical reactions.

The dose absorbed in a chemical dosimeter is measured by the change in some property of the system that is directly dependent on the integral amount of certain products of radiolysis. This is analyzed frequently by measuring the change in optical density (OD) at characteristic wavelengths of absorption bands induced due to product accumulation.

From this measurement and the definition of radiation yield (G-value)*, dose can be computed as:

$$D = \frac{\Delta \ \mathrm{OD}}{\rho \ G \ell \ \varepsilon} \times 0.964 \times 10^9 \ \text{rads} \qquad (1)$$

where ρ is the density of the solution, ε the molar extinction coefficient and ℓ the optical pathlength in the analyzing cell.

In conclusion, if we know the G value and the molar extinction coefficient we can compute the dose from accurate readings of ΔOD.

FRICKE DOSIMETER(2a)

The ferrous sulfate dosimeter or "Fricke" dosimeter is based on the radiation oxidation of an acidic aqueous ferrous sulfate solution.

$$Fe^{2+} \rightsquigarrow Fe^{3+}$$

The dose is found by analyzis spectrophotometrically at 305nm wavelength of the ferric ion concentration after irradiation.

The dosimeter solution consists of 0.4$\underline{M}$ H_2SO_4 and $10^{-3}\underline{M}$ Fe^{2+} in triply distilled H_2O. Some workers add 0.001$\underline{M}$ NaCl to desensitize the solution to organic impurities. For high dose rate experiments NaCl must not be added, since it has a pronounced effect on the Fe^{3+} yield in such cases. For this condition it is recommended to use the "super" Fricke dosimeter which is prepared in the same way as the Fricke dosimeter though the ferrous concentration is increased from $10^{-3}\underline{M}$ to 10^{-2}M, and the solution is saturated with oxygen to a concentration of about 1.1m$\underline{M}$. This

---

* Where G value is equal to the number of radiation produced molecular species per unit energy absorbed (e.g. number of Fe^{3+} per 100 eV).

prevents back reactions of electrons, H-atoms or HO_2 radicals with Fe^{3+} and also radical $-H_2O_2$ reactions.

The reaction mechanism of the dosimeter has been studied extensively. At low dose rates the oxidation may be represented simply by the following scheme:

$$Fe^{2+} + OH \rightarrow Fe^{3+} + OH^-$$

$$H + O_2 \rightarrow HO_2$$

$$Fe^{2+} + OH_2 + H^+ \rightarrow Fe^{3+} + H_2O_2$$

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^-$$

thus: $$G(Fe^{3+}) = G_{OH} + 3G_H + 2G_{H_2O_2}$$

Values of G_{OH}, G_H and $G_{H_2O_2}$ are quoted in Table I. From these a value of $G(Fe^{3+}) = 15.6$ has been obtained in agreement with the best experimental values, for ^{60}Co γ-radiation.

TABLE 1.- Primary species yields of OH, H and H_2O_2 to calculate $G(Fe^{3+})$ at pH 0.46

G_{OH}	G_H	$G_{H_2O_2}$	Reference
2.89	3.62	0.759	3
2.9	3.7	0.8	4
2.9	3.9	0.785	5

In principle, a previous knowledge of the reaction mechanism of the dosimeter determines its G value, which can be used to compute the dose. In this sense the Fricke solution can be used as a secondary standard (indeed the Fricke dosimeter has received final approval as an American Society of Testing and Materials (ASTM) standard)(15).

Doses can be measured with an accuracy of 1-2% in the range from 4 to 40 krad, if preparation of solutions of pure ingredients in ultra-clear glass containers is followed very carefully.

THE FERROUS CUPRIC DOSIMETER(2b)

In this dosimeter the process employed for the determination of dose is the oxidation by irradiation of ferrous ions in an aqueous sulfuric acid solution containing cupric sulfate and ferrous ammonium sulfate. The determination of dose is carried out by spectrophotometric measurement at 305nm wavelength of the ferric ion concentration after irradiation.

Since the $G(Fe^{3+})$ decreases slightly with dose(2b) a calibration curve must be made.

The absorbed energy is derived from the concentration of ferric ions after irradiation. The system consists of an oxygen-saturated solution of ferrous ammonium sulfate, cupric sulfate, and sulfuric acid in triply distilled water. The concentrations are: $0.005\underline{M}\ H_2SO_4$, $10^{-3}\underline{M}\ Fe^{2+}$, $10^{-2}\underline{M}\ Cu^{2+}$.

The range of the absorbed dose is usually from 50 krad to 10^3 krad. The response is independent of dose rate for electron irradiation below 100 rad/pulse with a pulse length of 1.1 μsec(6).

THE CERIC SULFATE DOSIMETER(2c)

The process employed for the determination of dose is the reduction of ceric ions to cerous ions by irradiation. The dose is derived from the difference in ceric ions before and after irradiation.

The system is a solution $10^{-2}\underline{M}$ in Ce^{3+}, $10^{-2}\underline{M}$ in Ce^{4+}, $0.4\underline{M}$ in aqueous H_2SO_4. The initial concentration of ceric ions is varied within the range of 0.2-50m$\underline{M}$ according to the total dose to be measured. The initial cerous sulfate concentration is equal to the ceric sulfate concentration.

The useful dose range is from 10 krad to 20 Mrad.

There is no dose rate effect for electron irradiation with 1.1μsec pulse length below 100 rad/pulse(2c).

This system is especially sensitive to impurities; even one n$\underline{M}$ of organic impurities makes and appreciable change in the G value, so one has to take care of factors such as the chemical purity of reagents, of the water (must be triply distilled), cleanliness of glassware, and the system should be protected from ultraviolet light. It is also recommended to wash the ampoules used as dosimeter containers twice with the dosimetric solution before filling and sealing.

The determination of ceric concentration is accomplished by spectrophotometric measurement at 320nm wavelength. After irradiation, dilution of the solutions is needed to bring the optical density within the validity of Lambert-Beer's law (.004-.2m$\underline{M}$). All dilutions are made with 0.4$\underline{M}$ H_2SO_4.

The G value for the reduction of ceric ions varies with initial ceric ion concentration(2c). Using the appropriate G value the dose can be calculated as:

$$D = \frac{\Delta\ OD \times d}{G} \times 3.343 \times 10^5 \quad \text{(rads)} \qquad (2)$$

where d is the dilution factor and the constant 3.343×10^5 takes into consideration the density, molar extinction coefficient of the ceric ions, ($\varepsilon = 5610\ \ell\ mol^{-1} cm^{-1}$) and the optical path length.

Dosimetry with the ceric sulfate system must be considered not only on the basis of scientific results, but of procedure techniques since to get reproducible results many careful procedures must be followed and the system must be managed with a long period of experience. This dosimeter should be used only in those places where it will be used continuously, because a systematic procedure is very important. If it is intended to use this dosimeter only rarely, is not as good as other systems, because the technique requires more experience in order to get accuracy in the results. All this will be illustrated in the experimental section of this work.

PLASTIC AND DYE FILM DOSIMETERS

Upon irradiation many plastic and dyed plastic systems undergo, a fairly reproducible and permanent change in the near ultraviolet and visible absorption spectrum. Calibration curves are generated by means of spectrophotometry, which gives readings of the change in optical density as a function of dose at a selected wavelength in the material of interest. In general it is necessary to calibrate the radiation response of these systems by means of calorimetry(7) or by a standard chemical dosimeter (e.g. Fricke)(2), for different lots of the same material.

Advantages of using these plastic dosimeters are their inexpensiveness, easy of handling and ruggedness.

Their main disadvantages are$^{(8)}$: limited reproducibility, possible systematic errors due to variation of response with dose rate and environmental factors (temperature, humidity, illumination), instability under certain conditions, batch-to-batch variations, anomalies in thickness or the distribution of dyes or other sensitizers.

The change in optical density at a specified wavelength is obtained by placing the dosimeter in a reproducible way in spectrophotometer or a densitometer equipped with narrow bandpass filters$^{(8)}$. With some systems it is necessary to apply a post-irradiation treatment due to the instability of the absorption spectra. With all systems, it is necessary to treat the optical surfaces carefully, so as to avoid scratches, finger-prints, dust, etc., which would influence the optical density readings. When possible it is recomended to monitor the optical density before irradiation, and to correct for variations in thickness.

PARAROSANILINE DYE SYSTEMS$^{(9)}$

This dosimeter is based in a triamino-triphenyl-methane dye cyanide precursor, available in the form of films, gels, papers and liquid solution. Dose ranges are from 10^4 - 10^8 rads for the liquid dosimeter and its response independent of dose rate below 10^{15} rad/s.

The main advantages of these systems are: long shelf-life, dose rate independence, low atomic number constituents (C,H,N,O), insensitivity to presence or absence of oxygen, no temperature dependence during read-out, image stability, linear dose response to ionizing radiation, high-resolution images, no need for ultraclean handling, and simple read-out.

Their disavantages are: sensitivity to ultraviolet light, and response affected by extremes in relative humidity, and to large changes in temperatures during irradiation.

The dye is an effective energy sink and has a high molar extinction coefficient at the wavelength of maximum absorption, thus ensuring efficient dosimetry if proper activators and stabilizers are used.

The radiation chemical effects in these dye systems comes mainly from radiationless molecular excitations and bond polarization produced by very low energy secondary photons or electrons as well as from the higher energy ionization events.

The radiation chemical mechanism involves a break in the C-CN bond of the triamino triphenylaceto nitrile molecules, yielding the color formation by salt isomerization to the dye form(10).

In general, G values are dependent on dye concentration, because the critical radiation absorption processes occur efficiently in both solute and solvent. At about 5m_M_, the G value is only half the value at 10m_M_(9).

This is a very suitable system for dosimetry because its effective atomic number can be varied to match the atomic number of the material to be irradiated. In such systems it is not necessary to apply cavity theory correction for differences in radiation absorption cross sections when these systems are incorporated into the material to be irradiated.

RED PERSPEX DOSIMETER(11)

The system consists of red-dye polymethylmethacrilate (Perspex) Harwell type 4034 available in the form of sheets of approximately 3mm thick. Under radiation to doses greater than 10^6 rads the material darkens measurably owing to the formation of a new absorption band in the 600-700 nm region of the spectrum. The darkening is measured in terms of optical density increase by means of a spectrophotometer. Having established a calibration curve of optical density vs. dose, the material can be used in the range from 1×10^6 to 5×10^6 rads. The response is independent of dose rate up to 10^7 rad/s, and from there it fells by 6% on increasing the dose rate to 10^8 rad/s.

Optical density measurements are done at a wavelength in the region from 630-640 nm. This wavelength does not correspond to the maximum absorption wavelength (615 nm). The reason to choose the higher wavelength in the range is that the optical density measurements are somewhat dependent on the time delay between irradiation and read-out. Postirradiation intensification occurs to wavelengths in the 600-640 nm range, whereas in the 640-700 nm interval some post-irradiation fading occurs. In the optimum read-out region (630-640 nm) the two post-irradiation effects cancel each other.

Among the factors which influence the dose determination are:

a) Error in readout wavelength: it is observed that a change greater than 1 nm in the wavelength causes a change of 1-2%/nm in the readout dose.

b) Band width: it has been found that readout errors become significant (> 1%) if the band width of the readout light is greater than 5 nm.

c) Drying out: when the dosimeters are exposed to very dry air a change in the slope of the absorption coefficient vs. dose is observed. The absorption coefficient is defined as:

$$K = \frac{\Delta \ OD}{t}$$

with t the thickness of the Perspex sheet. This effect can be reduced by storing the unused dosimeter in sealed containers, as the change does not amount to more than 1% in a 3-month period. This effect is negligible for an exposure to dry air of a few days during irradiation and readout.

EXPERIMENTAL

The purpose of this section is to provide illustrations of the topics discussed and to attain familiarity with the systems mentioned above. It is not intended to give precise dosimetry methods and present accurate results, which can with appropriate care be obtained with these systems. These methods are fully described in the references given earlier. However, this section provides some useful comments and gives some light as to which of the topics discussed above need further consideration.

G VALUE DETERMINATION FOR SOME CHEMICAL DOSIMETERS

The purpose of this experiment was to determine the G value from the calibration curve for the following systems: Fricke, "super" Fricke, ferrous-cupric, and ceric sulfate dosimeters.

The dosimeters were prepared as follows:
For the Fricke dosimeter, as described in ref. 2a, 0.4$\underline{M}$ H_2SO_4, $10^{-3}\underline{M}$ Fe^{2+}. For the "super" Fricke, the santard Fricke solution was bubbled with O_2 for half an hour, producing an increment in the H_2O_2 concentration. The ferrous-cupric dosimeter was prepared dissolving 196 mg $(NH_4)_2 \cdot Fe(SO_4)_2 \cdot 6H_2O$ and 1.25 g $CuSO_4 \cdot 5H_2O$ in 500 ml of 0.005$\underline{M}$ H_2SO_4. This composition may be improved, thus extending the useful dose range by dissolving 196 mg $(NH_4)_2 \cdot Fe(SO_4)_2 \cdot 6H_2O$, 2.5 g $CuSO_4 \cdot 5H_2O$ and 24 mg $NH_4 \cdot Fe(SO_4)_2$ in 0.002$\underline{M}$ H_2SO_4.

To prepare the ceric-sulfate dosimeter a stock solution was made by dissolving 1.616 g $Ce(SO_4)_2$ in 200 ml of 0.4$\underline{M}$ H_2SO_4 solution containing 0.1$\underline{M}$ H_2O_2. This solution will be $10^{-2}\underline{M}$ Ce^{3+}, $10^{-2}\underline{M}Ce^{+4}$, 0.4$\underline{M}$ H_2SO_4, and 0.1$\underline{M}$ H_2O_2. From these two solutions were made: one with 0.25m$\underline{M}$ Ce^{3+}, 0.25m$\underline{M}$ Ce^{4+}, 0.4m$\underline{M}$ H_2SO_4 for the low-dose range; the other with 2.5m$\underline{M}$ Ce^{3+}, 2.5m$\underline{M}$ Ce^{4+}, 0.4$\underline{M}$ H_2SO_4 for the high-dose range.

All dosimeters were prepared with analytical grade reagents in glassware, washed and heated to 540°C.

For their irradiation the solutions were placed in small glass ampoules and sealed. Irradiations were made with a 10,000 Ci ^{60}Co facility of the Danish Atomic Energy Commission Research Establishment, Risø(12).

Doses were determined from a previous calibration of the ^{60}Co facility made by means of a calorimeter(13) and rechecked when the source was reloaded in January 1973(12).

After the irradiation the absorption spectrum of each type of irradiated sample was measured. The wavelength of maximum absorption was determined. The optical density of irradiated and unirradiated solutions was then measured in a Cary 15 spectrophotometer. In the case of the ceric sulfate dosimeter the irradiated solution was read against a 0.4$\underline{M}$ H_2SO_4 solution because of the instability of this system.

CALIBRATION OF RADIOCHROMIC DYE FILM

The purpose of this experiment is to derive a suitable method for calibrating radiochromic dye films.

The system consists of 5m$\underline{M}$ (hexahydroxy) ethyl pararosaniline cyanide in 2-methoxy ethanol and 1 ml 100% glacial acetic acid dissolved in a plastic matrix and dried on a flat surface to form a uniform film sheet. Optical density measurements were performed in a spectrophotometer specially adapted for this purpose(14).

First the response of the spectrophotometer was checked by means of optical density measurements with a photographic film step wedge calibrated by the National Bureau of Standards (N.B.S).

For irradiation the films were placed in plastic envelopes which protected them from UV ligth. Irradiations were carried out in the ^{60}Co facility property of the Danish Atomic Energy Commission Research Establishment (Risø)(12), in the dose range 0.5 to 3 Mrad. An absorption spectrum was run for an irradiated film to determine the maximum absorption wavelength in a Cary 15 spectrophotometer, which gave a value of 600 nm.

Finally a calibration curve of Δ OD/mm vs. dose was obtained. The optical density change per unit thickness (ΔOD/mm) is used to correct for small variations in thickness of the films.

DETERMINATION OF THE SENSITIVITY OF A LIQUID DYE DOSIMETER

The purpose of this experiment was to determine the sensitivity of a liquid dye dosimeter made from pararosaniline dye cyanide dissolved in 2-methoxy ethanol containing a small amount of weak acid.

The dosimeter was prepared as follows: 0.3144 g of pararosaniline was dissolved in 200 ml 2-methoxy ethanol containing 200 µl 100% glacial acetic acid. This makes a 5m<u>M</u> dye solution. This solution was stirred for a half hour and filtered through ordinary filter paper.

For its irradiation the solution was placed in sealed glass ampoules. The ampoules were placed in a wooden holder thick enough to approximate electronic equilibrium conditions. During handling, the ampoules were protected from ultraviolet light.

Irradiations were performed in the ^{60}Co Gammacell of the Danish Atomic Energy Commission (Risø)(12), in the dose range 5 to 25 Krad, as measured with Fricke solution.

After each irradiation the change in optical density was determined by means of a Cary 15 spectrophotometer in a 5 mm optical pathlength cell. All values were determined at the maximum absorption wavelength of 550 nm.

DOSE DISTRIBUTION IN THE GAMMACELL CHAMBER

The purpose of this experiment was to determine the dose distribution in a vertical plane through the center axis of the Gammacell chamber described in ref. 12. The chamber is cylindrical in shape, 220 mm in height and 122 mm in diameter.

As radiation sensor a sheet of Red Perspex 400 from ICI Ltd. was placed between two 15 mm thick wooden plates to approximate electronic equilibrium conditions. The sheet was irradiated to a dose of 5×10^6 rads, as measured with Fricke solution, and the change in optical density determined by means of a scanning spectrophotometer(14) at a wavelength of 640 nm, in which a 1 cm wide strip of Perspex was measured each time. Optical density measurements were translated to dose values by means of a calibration curve(8) and by this procedure it was possible to generate the isodoses profiles inside the chamber.

RESULTS AND DISCUSSION

Chemical Dosimeters.- Figure 1 shows the change in optical density (ΔOD) vs. dose (D) for each of the systems discussed. The spectrophotometric readings of optical density were taken at the respective maximum absorption wavelengths, and from these readings were subtracted values of optical density of unirradiated solutions. The values of Δ OD/D determined from the figures and the corresponding values of ε are given in Table 2. These values could then be substituted in equation 1 to obtain the corresponding G values for each of the dosimetric solutions, also listed in Table 2.

G values obtained from figure 1 are not as accurate as they might be under highly controlled conditions. To get the traditional values documented in the references, a more elaborate procedures and better familiarization with each of the systems mentioned would be required. This familiarization implies an extremely precise and accurate practice in the preparation of the dosimeter. This is especially evident in the case of the ceric sulfate dosimeter, for which the preparation of techniques require a lot of practice. Figure 1d reflects this fact, since unreliable results were obtained from the 2.5$\underline{M}$ Ce^{3+}, 2.5m$\underline{M}$ Ce^{4+} solution.

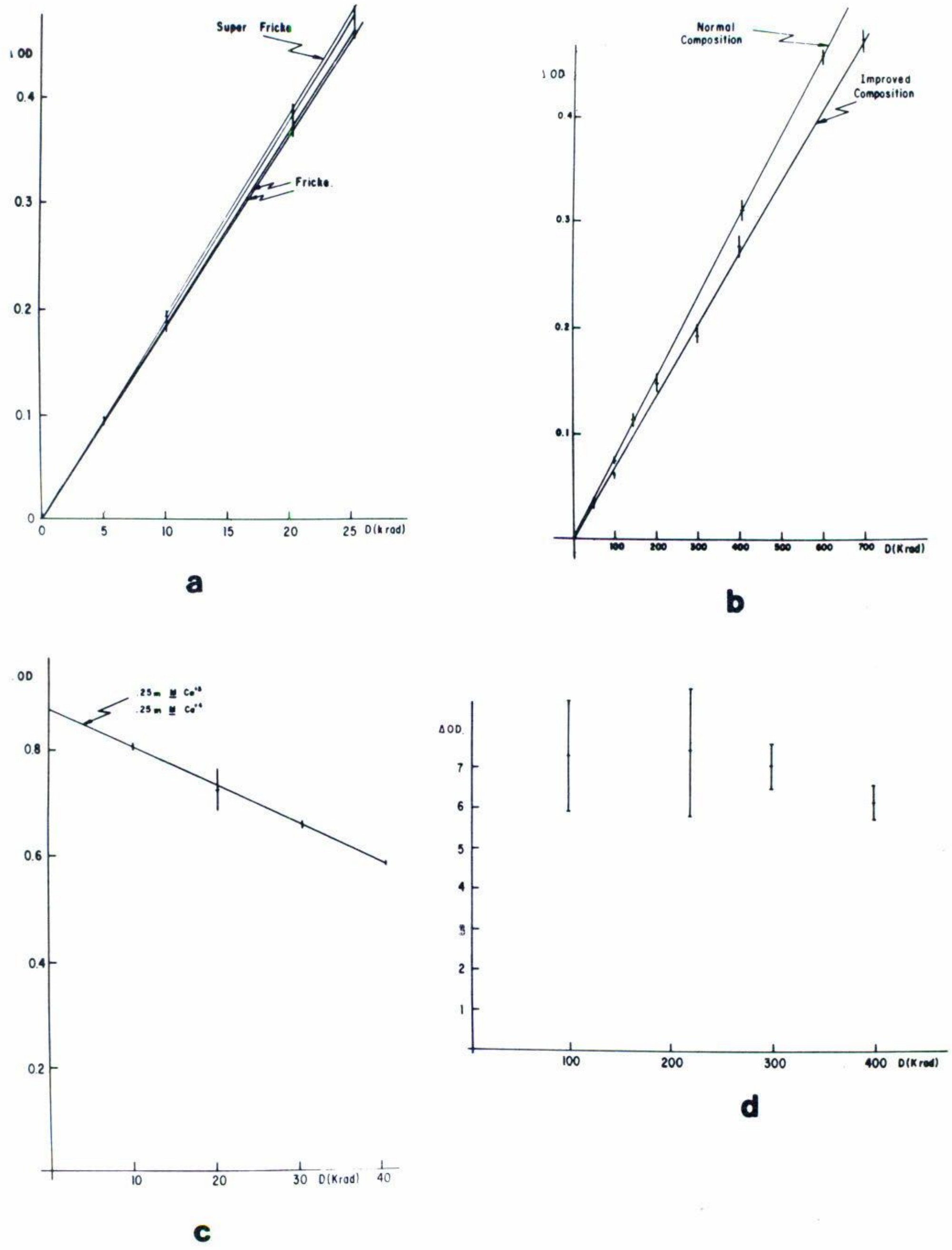

Fig. 1. Calibration curve for the change in optical density vs. dose for Fricke and "super" Fricke solutions (a), ferrous-cupric solutions; (b), ceric-sulfate dosimeter (0.25mM in Ce^{3+} and Ce^{4+}), (c), and ceric-sulfate dosimeter (2.5mM in Ce^{3+} and C^{4+}), (d), irradiated with ^{60}Co gammas.

TABLE 2.- Useful dosimetric parameters for the aqueous chemical dosimeters discussed in this work

System	$\varepsilon(\ell\ M^{-1}cm^{-1})$	λ(nm)	Reference^{+}	$(\overline{\Delta OD}/D)$*(rad)$^{-1}$	G^{++}
Fricke	2197	302	Fricke	1.8×10^{-5}	G(Fe^{3+})=15.4
Super Fricke	2197	302	Super Fricke	1.9×10^{-5}	G(Fe^{3+})=16.4
Ferrous-cupric	2167	305	Ferrous-cupric	7.5×10^{-7}	G(Fe^{3+})=.667
Ferrous-cupric (Improved solution)	3167	305	Ferrous-cupric (Improved solution)	6.8×10^{-7}	G(Fe^{3+})=.603
Ceric-sulfate 0.25m$\underline{M}$ Ce^{3+} 0.25m$\underline{M}$ Ce^{4+}	5610	320	H_2SO_4	-7.26×10^{-6}	G(-Ce^{4+})=2.34

+ All reference solution are unirradiated

* As determined from figure 1.

++ Obtained from this work.

From the experiments it is possible to estimate the response of the dosimeters in the different dose ranges. Table 3 presents the range in which each dosimeter response is linear with dose. Exception is made for the ferrous-cupric dosimeter since in this systems G(Fe^{3+}) value depends slightly on dose$^{(2b)}$.

It must be pointed out that modified solution concentrations must be used whenever one wishes to extend the dose range.

TABLE 3.- Useful dose range for the dosimetric systems discussed in this text.

System	Dose Range (krad)	Uncertainty (%)
Fricke	4-40	1-2
Super Fricke	4-100	1-2
Ferrous-cupric	50-1000	1-2
Ferrous-cupric (Improved solution)	50-1000	1-2
Ceric-sulfate		
0.25m$\underline{M}$ Ce^{3+}, 0.25m$\underline{M}$ Ce^{4+}	10-100	1-2
2.5m$\underline{M}$ Ce^{3+}, 2.5m$\underline{M}$ Ce^{4+}	100-1000	1-2
Pararosaniline dye film		
520 nm	500-2000	3-5
600 nm	100-2000	3-5
Pararosaniline dye liquid	1-200	1-3

Radiochromic dyes.- Figure 2 shows the variation of the change in optical density per mm (Δ OD/mm) vs. dose for the radiochromic dye film type used in this work. Spectrophotometric readings were taken at two different wavelengths, 600 and 520 nm. As can be seen from the figure when the lower wavelength is used, the useful dose range of the dosimeter is extended over that for wavelengths close to the absorption maximum.

The use of radiochromic dye in low-energy accelerator dosimetry shows promise, because these films can be made thin enough and their composition can be varied, so as to match the effective atomic number and electron stopping power of the material irradiated in practical radiation processing.

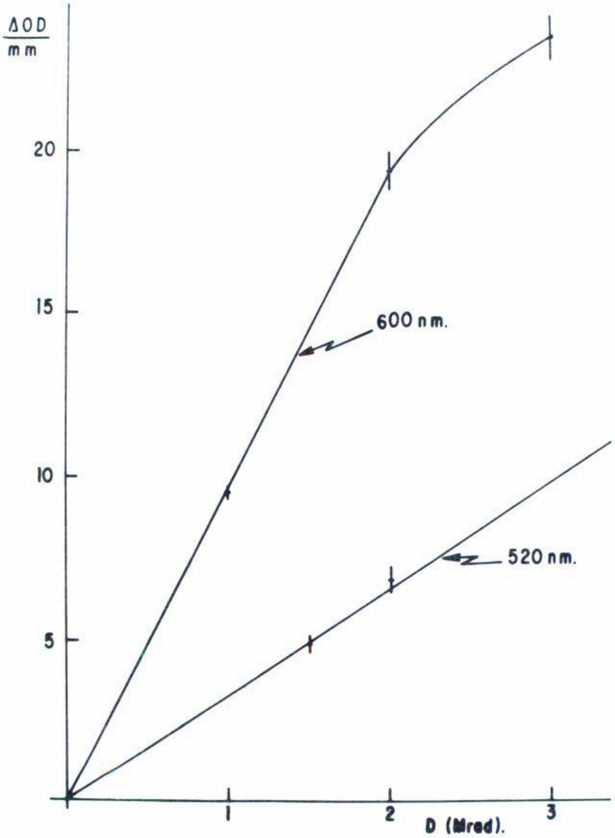

Fig. 2. Calibration curve of the change in optical density per mm. vs. dose for the pararosaniline dye film irradiated with ^{60}Co gammas. The upper curve as determined at a wavelength of 600 nm. The lower one at 520 nm.

Figure 3 shows the calibration curve for the radiochromic dye liquid based on Fricke dosimeter solution dose readings. To compute the sensitivity of the dosimeter from the figure we have to:

i) Determine the slope of the linear Δ OD vs. dose response curve.

ii) Correct this value from different absorption characteristics of the dye system and the Fricke solution which was used to calibrate the ^{60}Co gammacell. This last correction can be computed from:

$$D_{dye} = D_{Fricke} \frac{\overline{(Z/A)}_{dye}}{\overline{(Z/A)}_{Fricke}}$$

So from figure 3 we have:

$$\Delta\ OD = 0.0188\ D_{Fricke}$$

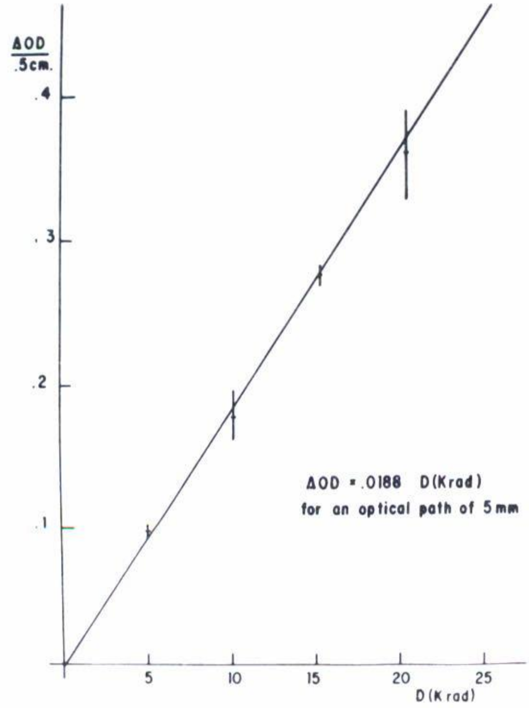

Fig. 3. Calibration curve of the change in iptical density vs. dose for the liquid dye system. Optical density measurements were determined in 0.5 cm optical path cuvettes. Irradiations were carried out in a ^{60}Co Gammacell.

Substituting from D_{Fricke} in the above equation:

$$D_{dye} = \frac{\Delta\ OD}{0.0188}\ (0.9939)$$

and thus

$$\Delta\ OD = 0.0189\ D_{dye}\ \text{(in krad)}$$

So the sensitivity of the dosimeter is

$$0.0378\ \frac{\Delta\ OD}{\text{krad}}$$

for 1 cm optical path.

From this value it can be seen that this system can be used in the same dose range as the Fricke solution, with the advantage that its preparation technique and ingredients donot have to be as clean as for the Fricke dosimeter. However, it must be remembered that these radiochromic dye systems are sensitive to UV light.

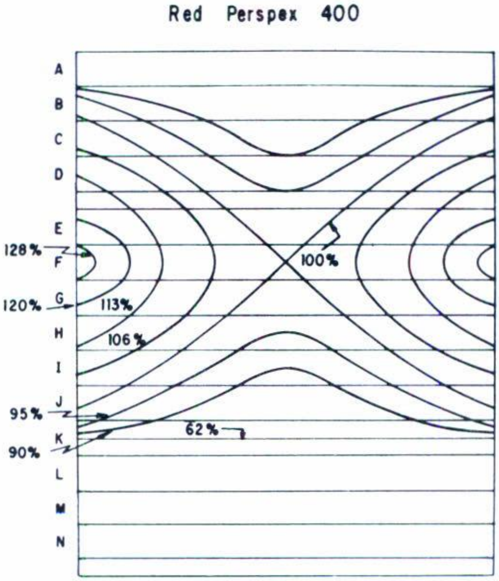

Fig. 4. Relative dose distribution in the irradiation chamber of the 3000 Ci ^{60}Co Gammacell. Measurements were done with red Perspex 400.

Isodose pattern inside the irradiation chamber.- Figure 4 shows the isodose profiles inside the irradiation chamber of the ^{60}Co Gammacell at Risø(12), as determined by means of Red Perspex 400 dosimeter strips from ICI Ltd. The change in optical density values were converted to absorbed dose values by means of a calibration curve, since the relation between the optical density and dose is not linear for this system.

ACKNOWLEDGEMENTS

The authors greatefully acknowledge the Accelerator Department Staff from the Danish Atomic Energy Commission Research Establishment, Risø, for all their help in supporting the experiments and especially to E. Bjergbakke , A. Miller and K. Sehested for their guidance during the development of this work. Also, the support of Consejo Nacional de Ciencia y Tecnología is acknowledged.

REFERENCES

1. Holm, N.W., "Dosimeter for industrial irradiation", IAEA/SM 123/41 (STI/PUB/236) (1969).

2a. Sehested, K., "Manual on Radiation Dosimetry", Holm, M.W. and Berry R.J. (Eds), Marcel Dekker Inc. N.Y. (1970) pp. 313-317.

2b. Bjergbakke, E., "Manual on Radiation Dosimetry", Holm, N.W. and Berry, R.J. (Eds), Marcel Dekker Inc. N.Y. (1970) pp. 319-321.

2c. Bjergbakke E., "Manual on Radiation Dosimetry", Holm, N.W. and Berry R.J. (Eds), Marcel Dekker Inc. N.Y. (1970) pp. 323-326.

3. Sehested L., Bjergbakke E., Holm N.W. and Fricke H., "The reaction mechanism of the ferrous sulfate dosimeter at high dose rates", in Dosimetry in Agriculture, Industry, Biology and Medicine, IAEA-SM-160/30 (1973) pp. 397.

4. Spinks, J.W.T. and Woods, R.J., "An Introduction to Radiation Chemistry", John Wiley & sons Inc. N.Y. (1964) Ch. 8

5. Sehested K., Rasmussen O.L. and Fricke H., "Rate constant of OH with HO_2, O_2^- and $H_2O_2^+$ from hydrogen peroxide formation in pulse-irradiated oxygenated water", J. Phys. Chem. 72 (1968) 2,626.

6. Brynjolfsson A., "A significant correction factor in gamma ray dosimetry", Advan. Chem. Ser. 81 (1968) 550.

7; McLaughlin, W.L., Hjortenberg P.E. and Radak B.B., "Absorbed dose measurements with thin films", IAEA-SM-160/32 (1973) pp. 577.

8. Miller A., Bjergbakke E. and McLaughlin W.L.,"Some limitations in the use of plastic dosimeters", Int. J. Appl. Rad. Isot. 26 (1975) 611-620.

9. Hjortenberg P.E. and McLaughlin W.L., "Use of radiochromic dye systems for dosimetry", Proceedings of the regional conference on radiation protection, Jerusalem 5-8 March 1973, pp. 122-140 Israel Atomic Energy Commission, Soreq Nuclear Research Centre, Yavne, 1973.
10. McLaughlin W.L., Miller A., Fidan S., Pejtersen K. and Batsberg Pedersen W., "Radiochromic plastic films for accurate measurements of radiation absorbed dose and dose distributions", Radiat. Phys. Chem. 10 (1977) 119-27.
11. Whittaker B., "Manual on Radiation Dosimetry", Holm, N.W. and Berry R.J., (Eds), Marcel Dekker Inc. N.Y. (1970) pp. 363-369.
12. Bjergbakke E. and Engholm Larsen E., "The 10,000 Ci ^{60}Co facility and the 3,000 Ci ^{60}Co Gammacell, Risø report M-1651 (Sept. 1973).
13. Holm, N.W., Brynjolfsson A. and Maul J.E., "Absolute measurements on the ^{60}Co Irradiation facility at Risø", in "Selected Topics on Radiation Dosimetry", IAEA, Vienna (1960) pp. 371-376.
14. Miller A., McLaughlin W.L. and Lynggård B., "A scanning spectrophotometer for reading thin-film dosimeters", Risø Report M-1525 (Aug. 1972).
15. American Society of Testing and Materials "Absorbed gamma radiation dose in the Fricke dosimeter", American Standard Method of Test D1671-63, ASTM Standard K65, 15-1965, 1965 Book of ASTM Standards, Part 27, ASTM, Philadelphia, PA. 1965, p. 529.