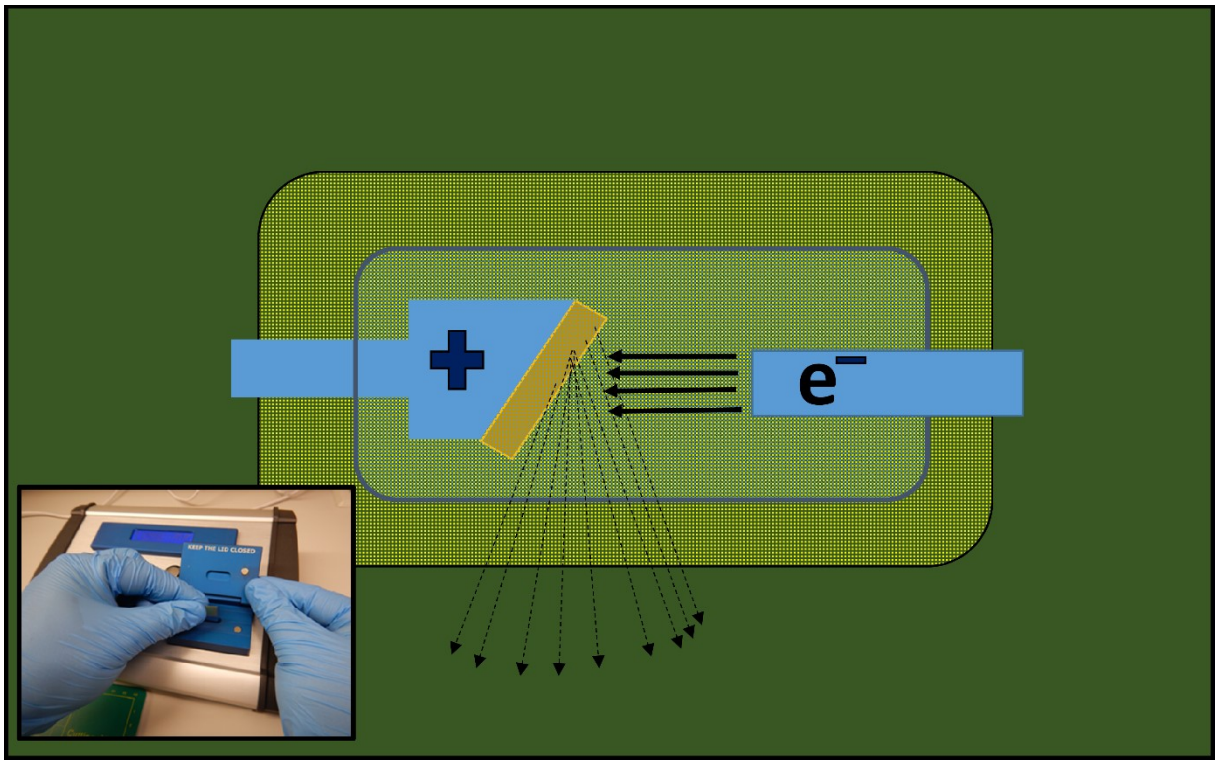
Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

DOSIMETRY FOR SIT: STANDARD OPERATING PROCEDURE FOR GAFCHROMIC™ FILM DOSIMETRY SYSTEM FOR LOW ENERGY X RADIATION

Version 1.0



Food and Agriculture Organization of the United Nations
International Atomic Energy Agency
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Dosimetry for SIT:

Standard Operating Procedure for Gafchromic™ film dosimetry system for low energy X radiation

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Foreword

The International Atomic Energy Agency (IAEA) and the Food and Agriculture Organization of the United Nations (FAO) support the development of the sterile insect technique (SIT) [1]. The SIT utilizes ionizing radiation to induce sterility in insectary-reared insects which can then be released in the wild to control a pest population. The SIT has been successfully employed against several insect pests for more than 40 years, and is constantly being developed for new pests. Ionizing radiation as a means of inducing sterility has several advantages over the alternative of chemical sterilization, and currently is universally used in operational area-wide integrated pest management (AW-IPM) programmes incorporating an SIT component [2, 3]. An incorrect dose of radiation, however, will reduce the impact of the released insects. Control of dose is therefore important in all stages from the initial research to operational programmes, and this requires an accurate, reliable dosimetry system. Species targeted by the SIT are typically major pests affecting agriculture or human health, so the assurance by standardized dosimetry that insects have been properly irradiated is of crucial importance to agricultural growers, agricultural regulators, public health officials and the public [4].

Examination of the available literature indicates that there is no one dosimetry system in common use for the SIT, and indeed dosimetry is often neglected completely [5]. There is a clear need for a dosimetry system that is simple enough to be operated without special laboratory facilities, provides adequate precision and is cheap enough to be used routinely for quality control as well as research [6].

Selection of a suitable dosimetry system depends on several considerations, including dose range of interest, ease of measurement, the expertise available, environmental factors that can be important at the location of use, cost and uncertainty [7] that is consistent with the process [8, 9]. Considering these factors, the Gafchromic™ dosimetry system offers SIT practitioners and their clients a relatively simple, low cost and accurate means of assessing absorbed dose [5]. The dosimeter is a small (1 × 1 cm square), thin (~100 micron) film that changes colour when irradiated. This colour change, which depends on the absorbed dose, is then measured by a photometric reader. This SOP manual describes the operation of the DoseReader4, but any photometric reader capable of measuring around 460 and 600 nm can be used with appropriate modifications to the procedures. Like almost all dosimetry systems, the performance of the Gafchromic™ system is affected by environmental factors, such as temperature and time of analysis. The quality of dosimetry and hence the success of the sterilization process thus depend on rigorously following the described procedures.

This SOP brings together in one place a description of the components of the Gafchromic™ dosimetry system, the procedure for its characterization, and its application to process validation and process control [6], together with references to the relevant standards. It provides a readily available source of information that can be accessed by both research workers and production facility managers. Even though this dosimetry system can be used for various types of radiation, including electrons, the procedures described are limited to low energy X radiation (150-225 keV) [8]. Due to a significant difference in photon energy between low energy (150-225 keV) X radiation and gamma radiation from ^{60}Co or ^{137}Cs, many dosimetry procedures are different [10]. There is a companion document specifically for gamma radiation [11]. A companion manual on the use of Gafchromic™ film for dose mapping using scanning is also available [12]. This manual with its associated Excel workbook is available from the IAEA web site [13].

This Standard Operating Procedure was adapted for low energy X radiation from *Dosimetry System for SIT: Manual for Gafchromic® film* developed by Dr. Kishor Mehta under IAEA contract 2000CL9124 in 2004. The adaptation was carried out by Dr Yeudiel Gómez-Simuta under contract TAL-NAFA20150922-001 and Mr Andrew G. Parker under contract TAL-NAFA20210531-003. The Agency staff member responsible is Ms Hanano Yamada.

Mention of a commercial product or of an organization does not constitute a recommendation by the IAEA.

1. INTRODUCTION

This document is divided into three parts:

The first part (Section 2.- Description of the Gafchromic™ dosimetry system), describes the two main components of the dosimetry system, namely the DoseReader 04 and the Gafchromic™ film dosimeters. It includes information about handling the film, its optical absorption behaviour and influence quantities (environmental parameters) that affect the performance of these film dosimeters. Also, it describes the procedure for set up and for routine optimal operation of the reader.

The second part (Sections 3 and 4, Traceability and Characterization), describes the procedures for establishing traceability to the international measurement system and for characterization of the dosimetry system. Characterization includes:

- Calibration of the dosimetry system,
- Determination of the dosimeter lot homogeneity, and
- Determination of uncertainty in the measured dose.

The third part (Sections 5 and 6.- Use of this dosimetry system for SIT), describes the use of this calibrated dosimetry system for X-ray irradiators likely to be used for irradiating insects either for research or commercial purposes. It reviews the procedures for carrying out dose mapping for process validation, as well as process control.

There is also an accompanying workbook in Microsoft Excel format available from the IAEA web site [13], containing all the forms, with formulas to do the necessary calculations automatically (the file contains no macros). Brief instructions are included in a sheet within the workbook. All the data forms for the procedures described in this document can be printed from the Excel file.

For more information about this dosimetry system for use in low energy X radiation, see Ref [14].

2. DOSIMETRY SYSTEM

2.1. General

The dosimetry system consists of DoseReader 04, Gafchromic™ film dosimeters, Excel workbook, and accessories.

2.2. DoseReader 4[1]

The DoseReader 4 (DR4) is a small, light-weight, easily portable densitometer for measuring the response of radiochromic film, such as the Gafchromic™ film used in this manual. The purpose is to calculate the applied radiation for insect sterilization in sterile insect programmes and other insect irradiation applications. The measurements range from 1 mGy to 10 kGy depending on the film used.

The DR4 measures the optical density (OD) of 10 x 10 mm radiochromic film dosimeters at up to four fixed wavelengths. The results are automatically transferred to the computer using a USB connection (which also powers the reader) together with the temperature of the reader. If automatic data transfer is not needed, the reader can also be powered by an external supply. This means the reader would not be connected to the computer.

The DR4 normally defaults to reading two wavelengths, 458 nm and 590 nm (appropriate for Gafchromic™ film) but this can be changed to other combinations at start-up and other defaults can be set by the manufacturer on request.

2.2.1. System components

The DR4 system consists of the following components:

- DR4 unit
- External power supply
- USB 2.0 A-B cable
- CD with software
- Neutral density filters with 0.5, 1.0 and 2.0 nominal OD
- User's Guide and Service Manual
- Carry case
- Forceps to handle film

2.2.2. Structure of the system

The system consists of 3 parts:

- The DR4 instrument (including hardware and software)
- The program used to transmit measurement data between the DR4 and the PC
- A personal computer (PC)

In order to install the drivers and software, administrator rights on the PC will be needed.

2.2.3. Required environment

- PC running Windows 7 or later
- Free USB 2.0 connector on the PC
- USB A to B type cable to connect the DR4 and the PC
- Suitable free COM port on the PC (see later)
- External power supply (optional: an external power supply is only required if the DR4 is to be used without a computer connection)

[1] Supplied by Radiation General Ltd., 1118 Budapest, Sasadi út 36, Hungary. www.rad-gen.com

- Spread sheet program such as Excel®
- RGwedge software used to transfer data from the DR4 to the PC

2.2.4. Routine operation for OD measurement

As soon as the DR4 is connected to the PC (or any other kind of external power supply), it turns on automatically. The DR4 does not have a separate POWER switch. Sometimes it might be necessary to restart the DR4. This is achieved by unplugging and re-plugging the USB cable or by clicking Disconnect then Connect from the RGwedge program. For detailed information on connecting the software of the DR4 with the PC, please refer to the DoseReader 4 Manual.

After connecting the DR4 to the PC, the reader should have about 5 minutes to stabilize. When the DR4 is turned on three beeps sound and the LCD panel shows the following message (Fig. 1):

Figure 1. Schematic view of the Dose Reader 4 at boot up.

Explanation of the screen:

- The number following "Version" is the software version number.
- The number following "S/N" is the device serial number
- The number following "Typ" is the device type:
  - 2T: two colour model
  - 4T: four colour model

After several seconds the display changes to Fig. 2.

Figure 2. Selection of wavelengths.

If the "Select" button is not pressed within about 5 seconds the displayed option is selected. To select different wavelengths press the "Cycle" button repeatedly to run through the options, and select your choice with the "Select" button. Several options are indicated by the type of film (as in the above GAF MD-HD), others indicating the reading wavelength ("B" for blue (458 nm), "G" for green (522 nm), "A" for amber (585 nm) and "R" for red (625 nm)).

Once the wavelength(s) are selected (or it times out) the DR4 sends the serial number of the device and column headers giving the measurement colours to the serial port.

Important: Before the transmission and processing of the measurement data can begin launch the following software:

- Excel workbook running on the PC (for instructions please see the sheet Instructions in the Excel Workbook for Data Recording and section 2.2.7)
- Data transmission software, RG wedge.

Important: Make sure the DR4 is connected to the USB socket and operating before starting the data transmission software (RGwedge) so that the software can identify the port to which the DR4 is attached. Start the RGwedge program as soon as the DR4 boots up.

After a short time the message of the DR4 appears on the display (Fig. 3).

Figure 3. Preparation for blank measurement.

When this message appears on the display make sure that there is no film in the slot, close the lid and push either of the two pushbuttons.

WARNING: DO NOT OPEN THE LID while the blank measurement is in progress. If you do, the device will have to be reset.

The blank value measurement can be repeated at any time during the measurement process by pushing the BLANK (left) button on the reader. However, keep in mind that the new blank value will be used after that point.

The DR4 attempts to detect the presence of a film in the reader and may display a warning message (Fig 4). If a film is present, press the "N" (right) button, remove the film and close the lid then press the "Y" (left) button. The display becomes blank until the measurement is finished.

Figure 4. Film detected message.

WARNING: This message may also be displayed even if the film has been removed or if the DR4 has been left with a film inside (preventing the automatic taking of blank readings) and the temperature has changed significantly. If the user insists on accepting the measured value as blank (the left button is pushed) when a film is actually present it will lead to unpredictable results.

If the temperature change exceeds a threshold a blank measurement is forced. This can happen in automatic mode if films are inserted one after another and there is no opportunity to measure the blank (Fig. 5).

Figure 5. Forced blank read

If the pushbutton labelled FILM (the right button) is pushed when no blank value is available the "Measure blank!" screen appears. This happens when the DR4 forces a blank measurement due to temperature change but the user pushes the FILM button (Fig. 5).

When the reader is handled correctly, the blank measurement starts and a message will appear on the

Figure 7. Blank values. A = amber (590 nm); B = blue (458 nm); temperature is in Celsius.

screen (Fig. 6). A symbol in the lower right corner will indicate the progress of the measurement. When the symbol decreases from top to bottom the first colour is being measured, when the symbol decreases from bottom to top the second colour is being measured and so on for more colours.

When the blank measurements are finished a beep sounds and a message is displayed (Fig. 7). The letters on the left side of the display are the first letters of the measuring colours (B for blue and A for amber).

The numbers following the letters are the blank measurement values and the number in the upper right corner is the temperature inside the reader head in degrees Celsius. If more than two wavelengths are being measured they will appear on the right and the temperature is not displayed. Blank measurements are not sent to the serial port.

If no button is pushed and the lid is not opened the DR4 will repeat the blank measurement about every 20 seconds and the display will be refreshed. A beep sounds at the end of each measurement. If the DR4 should get into a state where it is not correctly measuring the blank, a blank reading can be forced by pressing the BLANK button when no reading operation is in progress.

2.2.5. Measuring irradiated film

After measuring the blank value, measurement of the optical density of irradiated films can begin. Ensure that the temperature of the film has reached room temperature. The film should be inserted vertically into the slot, as can be seen in Fig. 8.

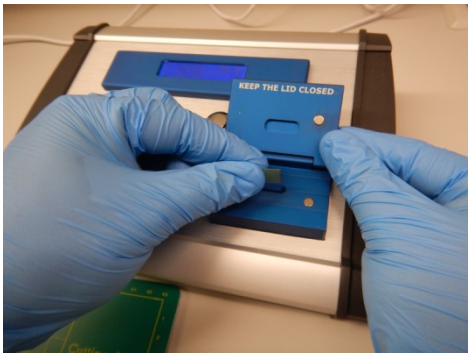


Figure 8. Inserting Gafchromic film into the DR4. The film should be handled with gloves or forceps.

The DR4 operates automatically. The user simply inserts the films and closes the lid. The DR4 recognizes the presence or absence of the film. In the absence of a film the blank value is measured. When a film is present in the slot the film value is measured. It is advisable to let the device measure the blank value between measuring two film values. The optical density is calculated as:

$$\log_{10}(I_0/I)$$

I_0= the blank density value

I = non-blank density value

The DR4 transmits the optical density for the two colours and the temperature to the PC via the RGwedge program. The fields are separated by tabulator (TAB) characters and the temperature is followed by a carriage return character.

WARNING: ***It is very important to have the Excel sheet accepting the measurement data selected during the whole measurement process!*** The Excel window must be the active window and the cell that is to accept the data must be selected. Don't switch to other tasks while the measurement is in progress and don't move the cursor.

Excel must be set up properly (for instructions, please see 2.2.7. Excel Workbook for Data Recording *et seq.*) to move the cursor when special characters arrive from the DR4. The cursor should move horizontally to the next cell when a tabulator character arrives and the cursor should move to the next line when an end of line character (CR/LF) arrives. This is the default setting.

Some principles applying to all measurements:

1. DR4 measures only when the lid is closed.
2. The end of a successful blank measurement is signalled by a beep. The end of successful film measurement is signalling by a longer beep. A measurement is successful if it is not interrupted by opening the lid.
3. If the lid is opened while a measurement is in progress the measurement is interrupted and the reading ignored.
4. The BLANK and FILM buttons are only active when there is no measurement going on.
5. The LCD display will be refreshed after each successful measurement.
6. If a film is left in the slot the measured film value will be transmitted only once to the PC. (If the lid is opened and closed without removing the film and inserting a new one or the FILM button is pressed the DR4 will transmit the next measured value again once).
7. If the DR4 is not connected to a PC measurement results will appear only on the display.
8. The read OD value of the film changes with temperature. If the film has been kept in a place at a different temperature from the DR4, allow time for the film to reach the same temperature as the DR4 before starting reading.

As mentioned in the previous section, if the measurements are conducted correctly, the data will appear on the screen (Fig. 9).

Figure 9. Film OD values.

The letters on the left side of the display are the first letters of the measuring colours. In this case A stands for amber (590 nm) and B for blue (458 nm). The numbers following the letters are the OD values and the number in the upper right corner is the temperature in degrees Celsius. If more than two colours are being measured they will appear on the right of the display and the temperature will not be displayed but is still transmitted to the PC.

The measured OD values and the temperature are transmitted to the PC automatically. Erroneous OD values must be deleted on the PC. Following any deletions, the cursor should be positioned in the cell where the next OD value is required.

WARNING: If the cursor is placed in a cell already containing data, the data will be overwritten in that cell and the two cells to the right (or more if more than two colours are being read).

As mentioned in the previous section, Routine Operation for Optical Density (OD) Measurement, if no button is pushed and the lid is not opened the DR4 will repeat the film measurement about every 20 seconds and the display will be refreshed. A long beep sounds at the end of every measurement. Only the first measurement results will be transmitted automatically to the serial port. If a second reading from the same film is required, press the FILM button to send the next reading data to the serial port. To turn off the sound signals, hold down both buttons (BLANK and FILM) when starting the DR4.

2.2.6. Checking reader operation

The DR4 is supplied with a set of three neutral density (ND) filters for checking the operation of the reader. The nominal OD of the films is 0.5, 1.0, and 2.0, but the true OD will differ somewhat from the nominal values but be stable over time. The neutral density films should be read at the start and end of each session using the DR4; the values of each ND filter should not differ between sessions or during a session by more than 2-3 in the last decimal place. Keep a record of the ND filter readings to confirm the continued correct operation of the DR4.

2.2.7. Excel Workbook for Data Recording

An Excel workbook is available designed to simplify the capture of dosimetry data using a DoseReader radiochromic film reader. The workbook contains eleven sheets, six of which are for the calibration procedures (CalData and forms SIT-1 to SIT-5), three for routine dosimetry (SIT-6, -7 and -8), one to summarize the characteristics of the dosimetry system (SIT-9) and one to correct for reading times other than 24 hours (Time). There is also a sheet containing simplified instructions. The workbook calculates the relationship between response and applied dose for linear, quadratic and power series regressions, against either dose or log(dose), selectable on sheet SIT-4D.

	A	B	C	D	E	F	G	H
1			**Data entry form**					
2			Use this form to collect readings automatically from a DoseReader film reade					
3			Place cursor in yellow cell before starting the DoseReader					
4			**Start here>** S/N: 12348			Date read:		
5			Film type	GAF MD-HD		Operator:		
6			Colour	Amber	Blue		Lot No.:	
7	Target		Wavelength	590nm	458nm			
8	Dose		Film	OD	OD	Temp C		
9			ND0.5	0.4847	0.5634	24.9	0.4847	0	0
10			ND1.0					
11			ND2.0					
12	0		1				0	0
13	(Background)		2				0	0

Figure 10. Data entry form with the headers and the first ND filter reading. The DR4 should be started as above and the cursor placed in the bright yellow cell (C4).

These instructions assume the use of this workbook. The workbook is available from the IPCS. If desired, the blank spreadsheets can be printed to provide forms to manually record the values and perform the calculations.

When the DR4 is started as above, the cursor should be placed in the bright yellow cell (C4 in this example) to capture the data in the correct cells (Fig. 10). All the calibration films should be prepared and read in sequence into the CalData sheet. Pale yellow cells require manual entry of additional data.

2.2.8. Advice on Excel:

Data entry in an Excel sheet can be controlled in several ways. The default movement of the cursor is down, but this can be changed to up, left or right in the File, Options, Advanced, Editing Options menu (in Excel 2003 or 2010). Data can also be entered into a range of cells by highlighting the range. The first value will go into the top left cell and then down the column (if down is the default movement) or right across the row (if right is the default movement) then continue at the top of the next column or beginning of the next row.

2.3. Gafchromic™ Dosimetry Film (HD-V2 and MD-V3).

2.3.1. Description

The HD-V2 film consists of two parts, the active layer and the polyester substrate. The active layer is 8µm thick and consists of the active component, marker dye, stabilizers and other components which are responsible for the film reacting to the radiation. The polyester substrate is 97µm thick and has a clear consistency. Depending on the batch, the thickness of the polyester substrate may vary.

Due to the asymmetrical cross section of the Gafchromic™ HD-V2 film the response of the scanner or densitometer may vary. Looking at the film from both sides, you may notice that one side is shiny (laminated side), while the other (active side) is not. Using either side is acceptable. However, in order to have consistent measurements, it is best to always measure the film from the same side.

In order to distinguish the sides, the laminated and the active side, there is a little help. The sheets of Gafchromic™ HD-V2 film have a small slit near one corner. When the film is in a landscape orientation with the slit in the upper right corner the active side of the film is facing you.

The following table shows in detail the specification of the film.

Table 1: Structure and composition of Gafchromic™ HD-V2 film[1]

Material	**Thickness** (microns)	**Density** (g/cm^3)	**Composition (atom%)** C	H	O	N
Polyester film base	97	1.35	45.5	36.4	18.2	0
Active layer	8	1.08	31.5	56	5	7.5

[1]Supplied by Ashland, Bridgewater, NJ.

The Gafchromic™ MD-V3 film is chemically identical but has a 20µm active layer between two 97µm polyester sheets. The film is, therefore, symmetrical and can be used either way around. MD-V3 film is usable for doses from 1 - 100 Gy but is best up to about 50Gy, whilst the HD-V2 film is suitable for 10-1000 Gy. Either MD-V3 or HD-V2 can be used with this SOP.

2.3.2. Absorption spectrum

The absorption spectra for the Gafchromic™ dosimeter material for the wavelength region of relevance (400 – 700 nm) are shown in Fig. 11 for unirradiated as well as irradiated film at various doses [15]. The wavelength to be used for the present application is 590 nm. Variations in the thickness of the

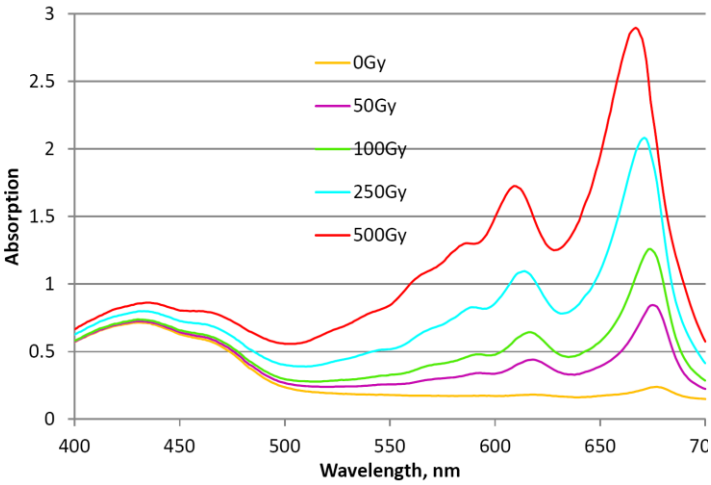


Figure 11. Absorption spectrum of Gafchromic™ HD-V2 film at various doses.

active layer cause variations in the response of the film. The active layer incorporates a yellow marker dye; simultaneously measuring the film density in the blue part of the spectrum (458nm) provides an estimate of the active layer thickness that can be used to correct the response.

2.3.3. Response

Response, as used in this SOP, means the difference in OD between an exposed film and an unexposed film.

The film is yellowish and transparent before irradiation, and it turns green almost instantaneously upon exposure to ionizing radiation. The intensity of the green colour (OD) is a function of the radiation dose. However, the OD of the film increases (the green colour deepens) slightly with time after exposure; the rate of change decreases with time. After about 24 hours, the OD value becomes relatively stable at a value approximately 12% over its initial value (measured within a few minutes after exposure). This behaviour is illustrated from just after irradiation to 38 days in Fig. 12A for a dose of about 100 Gy (data from Seibersdorf laboratories), with the final OD approximately 12.5% higher than at 1 day. The relationship between OD and time is approximately logarithmic (Fig. 12B) and a quadratic fit gives a close approximation to the data points. A sheet (Time) is provided in the Excel workbook to correct the OD reading from any time up to more than 100 days to the reading at 24 hours. Follow the instructions on the spread sheet, but it should be recognized that this will add additional uncertainty to the overall result.

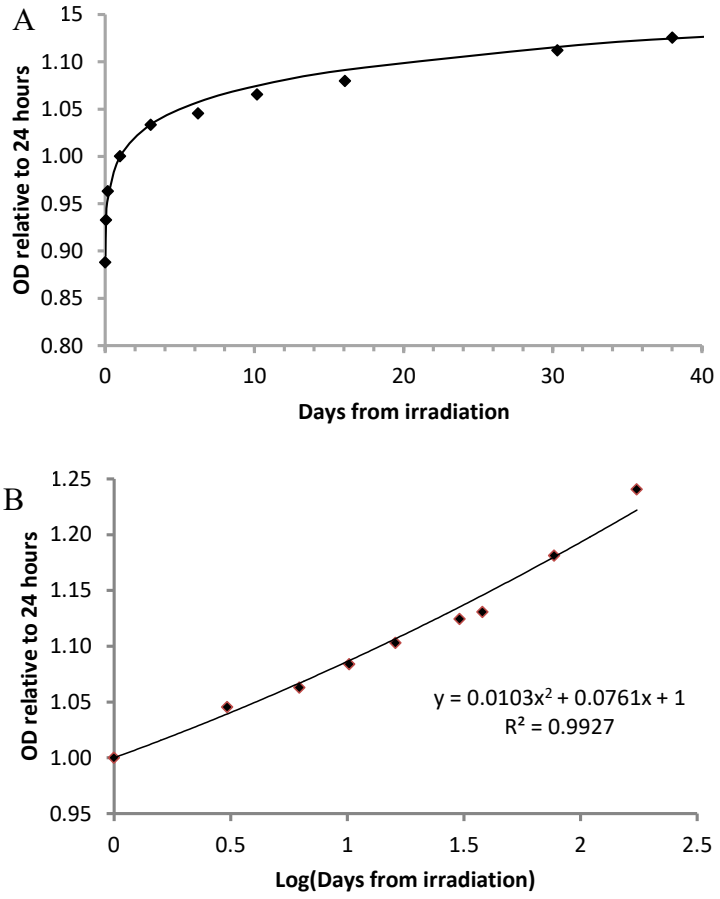


Figure 12. Change in OD of Gafchromic™ HD-V2 film with time. A: linear time up to 38 days; B: Log time to 174 days

Note: If samples are to be irradiated in a reduced oxygen environment (nitrogen, hypoxia or anoxia), the calibration must be made in nitrogen, hypoxia or anoxia, or the dosimeters placed in a reference location outside the container in ordinary air.

2.3.4. UV light

There are no extreme measures to be taken to protect the dosimeter film against UV light. However, do not expose the films to direct sunlight, and keep exposure to room lights (especially fluorescent lights) to the minimum required to handle the films and for the measurements. Store the large film sheet in its envelope in a dark place when not handling it.

2.3.5. Temperature dependence

The OD of the irradiated dosimeter film (for the same dose) varies little with temperature at the time of irradiation in the range from 5 to 40 °C [16]. Over that range the maximum variation is about ± 2%, which is normally less than the uncertainty on the dosimetry system, but the effect of temperature seems to vary with dose and reading wavelength. It is recommended, therefore, that for exposures within ± 5 °C of the calibration temperature that no correction is required but for differences greater than ± 5 °C a separate calibration should be constructed at the relevant temperature.

The dependence of the OD on the dosimeter temperature during its read-out was determined by Li et al. [17] for an earlier version of the film. However, such effects quite often vary from lot to lot. Some limited experiments carried out in the IAEA Laboratory, indicate that the read-out temperature coefficient is about 0.7%/°C for the tested dosimeter lot in the room-temperature range of 20-25°C. Because of this, it is essential that the ambient room temperature where the reader is located stays fairly constant throughout the year.

2.3.6. Handling

Handle the film with a pair of forceps/tweezers (preferably with fine points) or with gloves so as not to leave any finger-prints on the film (Fig. 8). Finger-prints, scratches on the film surface, dirt or dust can affect the light absorption of the film. Also, the tweezers tips should touch only the edges or corners of the film, away from the centre portion through which the analysing light passes.

The dosimeter film is purchased as a sheet (about 20 x 25 cm for HD-V2, 12.5 x 12.5 for MD-V3). However, the size that the dosimeter holder of the reader can accommodate is about 1 x 1 cm, and thus the film needs to be cut to this size prior to taking readings. The film may be cut with a paper guillotine or a sharp utility knife (or single-edged razor blade) and ruler. In addition to this, using a rotary paper cutter will achieve the same result with less effort and greater precision (but care has to be taken when using a rotary cutter with Gafchromic™ MD-V3 film).

It is convenient to make the correct size by placing the film sheet on a grid paper or cutting mat while cutting it. Wear thin disposable gloves for this activity to avoid leaving fingerprints on the film (Fig. 13). To easily insert the film into the DR4, the film can be cut slightly smaller, about 0.9 x 0.9 cm. Store the remainder of the sheet in its envelope when not in use. Do not store it for a long time in the room where the irradiator is located.

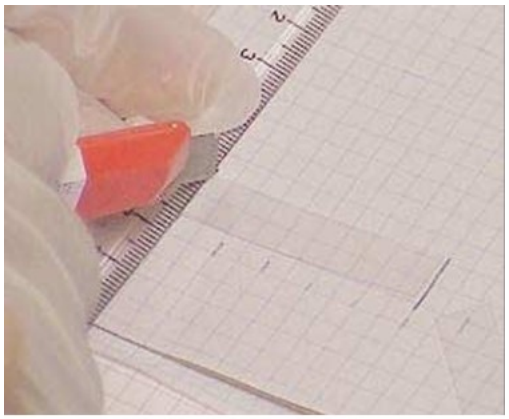


Figure 13. A sharp utility knife, a plastic ruler and a grid under the film help to cut it conveniently into desirable lengths.

Use a small paper envelope to store each film dosimeter. Place the dosimeter in it and remove it only for OD measurement. It is recommended that you *irradiate the dosimeter in the envelope* when it is placed in the canister with the pupae to provide adequate build-up material and keep the dosimeter free of any dust or other contamination. Record relevant information on the envelope, such

as dosimeter identification, irradiation location, exposure time, conditions and date of irradiation. Do not write on the envelope with the film inside, as this may damage the film.

2.3.7. Background OD

Measure the OD value of the un-irradiated film for each dosimeter lot. Cut 10 dosimeters from the dosimeter sheet. Measure the OD of each dosimeter following the procedure of Section 2.2.5.

If the lot lasts longer than 6 months, this measurement should be repeated and the OD(bkgd) value updated.

3. RELIABILITY THROUGH TRACEABILITY

3.1. General

Reliability of dose measurement using the Gafchromic™ dosimetry system mainly depends on:

1) Consistently following the procedure described in this standard operating procedure, and

2) Having the dose-rate measurement at a reference point that is traceable to a nationally or internationally recognized standard.

Traceability is an ability to demonstrate by means of an unbroken chain of comparisons all having stated uncertainties, known as a traceability chain, that a measurement is in agreement within acceptable limits of uncertainty with comparable nationally or internationally recognized standards. Thus, such traceability for the dose rate at a reference point is achieved by measuring it with a transfer-standard dosimeter that is traceable to these standards. This section describes the procedure for these measurements.

The commonest way to measure dose rate in X-ray is with an ion chamber. Both free air and sealed chambers are available. Free air chambers often incorporate temperature measurement in the stem and pressure measurement in the digitizer to provide automated correction for temperature and pressure. It is important to ensure that the small hole that allows air to move into and out of the chamber with changing temperature and pressure is not obstructed and that there is a free passage to the ambient air. Sealed chambers are also available that do not require temperature and pressure correction; the accuracy of the chamber relies on the integrity of the chamber seal and this is not easy to check but it may allow the chamber to be used in water without any further protection.

Dose, and hence dose rate, can also be measured with chemical dosimeters, such as Fricke or alanine. Alanine dosimeters are provided as part of calibration services by various dosimetry standard laboratories and these can be contacted to find out if they provide a calibration in the appropriate energy range. Chemical dosimeters are outside the scope of this standard operating procedure and it is assumed here that either a sealed ion chamber or a free to air ion chamber with automatic correction and electrometer is used.

If there is more than one irradiator available of similar energy, select the one providing the most convenient place for irradiating the dosimeters and where the temperature can be either controlled or measured more easily. The Gafchromic™ dosimetry system is then calibrated by irradiating the dosimeters at various dose levels at the reference point. Once the dosimetry system is calibrated, it is ready to be used anywhere with almost any type of irradiator with equivalent photon energy.

This process is recorded using the Excel workbook available from the IPCS.

Note: A Gafchromic™ calibration conducted in low-energy X-ray can be used to measure dose in another irradiator of similar energy (150-225 keVp) but cannot be used for measurements in ^{60}Co or ^{137}Cs irradiators. See also Appendix A for differences between X and gamma radiation.

3.2. Reference radiation field

When ionizing radiation strikes a container of insects in the irradiation chamber, many of the photons (150-225 keVp) pass through.

Some photons interact with the material of the container and the insects, dislodging high-energy electrons. Each of these in turn dislodges several lower-energy electrons, in a cascade. Finally the energy of the electrons in the cascade falls below the biologically active level (less than 100 eV). At each point that an electron is dislodged a molecular bond may be broken, including damage to the DNA of the chromosomes causing sterility. As the photons interact with the material at different depths, the cascades from each overlap, leading to the establishment of an equilibrium level of biologically active electrons (greater than 100 eV) at a distance into the material that depends on the photon energy and density, known as the electron equilibration distance. The equilibrium depends on the density and atomic composition of the material through which the radiation is passing, so that different materials will produce different equilibria. To standardize the reporting of dosimetry, dose is always expressed as dose to water, that is in an equilibrated electron field produced by water or equivalent material. See also Appendix B for a discussion of dose to air, dose to water and dose to pupae.

Both the dosimeters during calibration and the insects during irradiation must be surrounded by sufficient material of suitable atomic composition and density (build-up material) to ensure a water equivalent electron equilibrium is established before the radiation reaches the sample or dosimeter, as it is this electron field that primarily causes ionization. If this is not done, the surface of the sample may receive a significantly lower or higher dose than expected. For 150 keVp X-ray photons the equilibrium distance is about 100 µm in water or plastic, such as PMMA or the polyester backing material of the Gafchromic™ films. As the backing film is about 100 µm this provides adequate build-up material on both sides of the MD-V3 film, but due to its asymmetric construction one side of the HD-V2 film is exposed directly to the ionizing radiation. It is, therefore, very sensitive to the medium immediately in contact with the exposed side. To ensure consistent and accurate results HD-V2 film must always be placed in a suitable covering, such as cartridge paper envelopes (e.g. FWT-80 dosimeter envelopes[2]) to ensure the presence of sufficient build-up material. MD-V3 film may be used bare but it is generally better to place them in an envelope to keep them clean.

Low energy X-ray irradiators are based on one of two types of X-ray tube. The commonest type is the standard orthovoltage tube, usually with one tube facing downwards (Fig. 14a) or with two tubes vertically opposed (Fig. 14b). X-ray output from these tubes is limited by the need to remove the heat generated in the anode to prevent overheating and collapse of the tube structure. Such tubes produce a cone of radiation from the anode with an angle of about 40°, the beam varying about 10% in intensity across this area and falling rapidly outside it. These tubes also exhibit the "heel effect" whereby the intensity falls faster on the side of the beam away from the cathode due to absorption in the anode. Samples are placed on a platform under the beam and need to be centred within the cone of radiation to avoid areas of low dose rate; some systems also incorporate a turntable to reduce the impact of the heel effect. In order to have a usable circular area with a diameter of 150 mm the sample must be about 400 mm from the source of the X-rays inside the tube; due to the inverse square law this results in a

[2] Supplied by Far West Technologies Ltd, 330 South Kellogg Ave. Suite D, Goleta, CA 93117 USA, https://www.fwt.com/racm/accessory_ds.htm

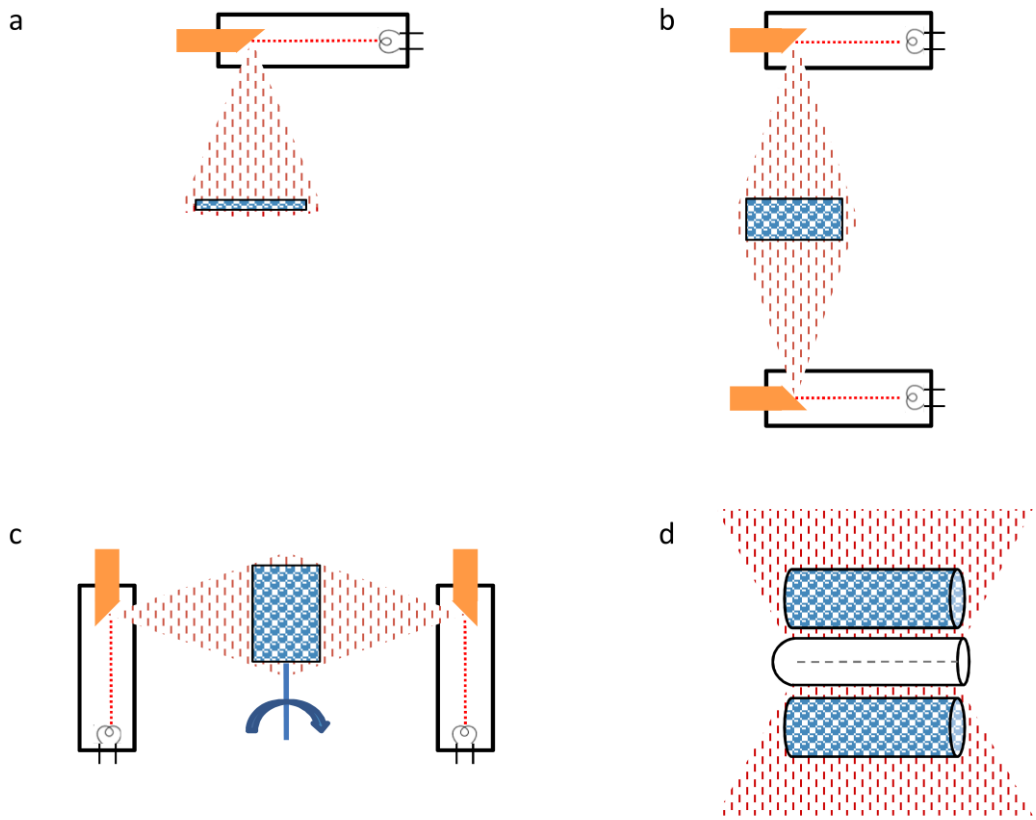


Figure 14. Various X-ray beam configurations are available. a) single vertical beam – due to the attenuation of the beam in the sample, the usable depth in the beam is limited to about 10 mm (for water equivalent); b) two vertically opposed beams greatly improve the dose distribution within the sample, allowing a much greater depth of material to be irradiated (about 50 mm water equivalent); c) single or dual horizontal beams allow the sample to be rotated about a vertical axis to improve dose uniformity, allowing a canister about 120 mm diameter and up to 150 mm tall with good DUR; d) the Rad Source Technologies tube has a cylindrical anode around an extended cathode filament, such that X-ray are produced over a large surface, emanating in all directions, giving a higher dose rate to up to six canisters placed close to the tube and rotated around the tube (only two shown for clarity).

low dose rate of 2-3 Gy•min^{-1} for a single beam. Due to the beam attenuation in water at 150-225 keV the usable depth in water is around 10 mm with a single tube and single sided irradiation. The depth uniformity is greatly improved by double sided irradiation, either with two tubes or by flipping the load over after half the dose.

A few systems designed specifically for SIT have the X-ray tubes arranged with their beams horizontal (Fig. 14c). With this configuration a cylinder about 120 mm diameter and 150 mm tall can be irradiated with acceptable DUR, even with a single tube. The load may further be divided into two parts placed one on top of the other to swap position after half the dose; this further improves the DUR.

The second type of tube is the axial cathode design of Rad Source Technology Inc., consisting of a cylindrical anode surrounding an extended cathode filament (Fig. 14d). Radiation is emitted by transmission through the anode in all directions rather than in a confined beam. Samples are held in canisters rotating around the tube so that they are irradiated from all sides, improving the dose distribution. The X-ray output from such tubes can be higher than from conventional orthovoltage tubes as the thin, cylindrical anode allows the heat created during X-ray generation to be removed more efficiently. Due to the large emission surface the

samples can be placed very close to the tube to receive a high dose rate and the tube has significant inherent filtration, increasing the effective energy of the beam and hence penetration and dose uniformity in larger diameter canisters.

3.3. Reference irradiation conditions

3.3.1. Irradiation geometry

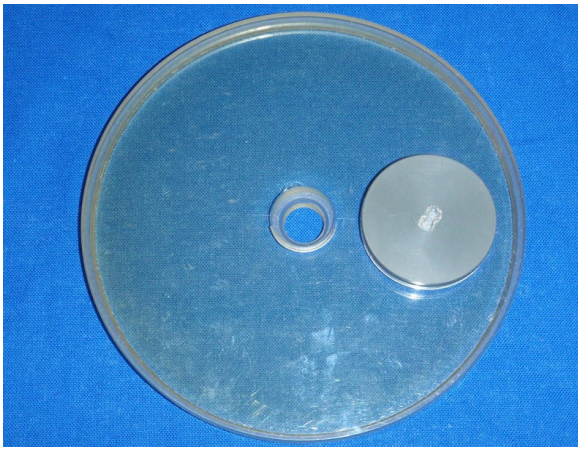
The dose rate is established by the supplier of the irradiator during the commissioning of the irradiator. Subsequent checks can be made by the user with the use of an appropriate reference standard or transfer standard dosimetry system.

The dose rate depends on the product in the canisters, the irradiation geometry, the location of the dose measurement and the tube voltage and current. The determination of the dose rate should be carried out for the irradiation conditions that are expected during routine irradiation where all the canisters are filled with insects. The measurements should be made at the same voltage and current that will be used for routine exposures; to maintain throughput it is likely that these will be the maximum permissible values. It is always desirable to use the rotational mode for making these measurements; however, it is not practical with an ionization chamber because of the lead going to the electrometer. For dose rate determination, the electrometer should be operated in 'integrated dose' mode and likewise for the Gafchromic calibration the films should not be rotated.

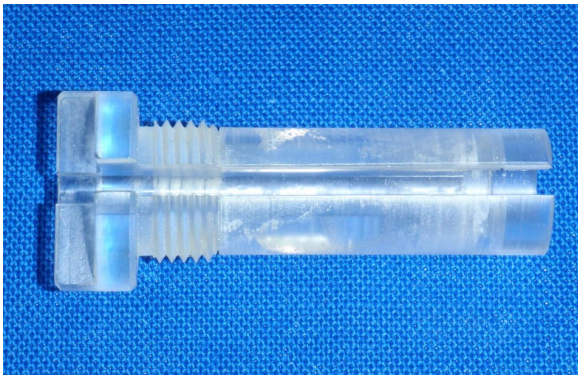
During calibration of the dosimetry system, a product that simulates insects may be used in the canisters. Instant rice seems to simulate pupae very closely with regards to radiation attenuation and scattering properties (mainly because of similar density and elemental composition) (see Appendix C). However, a simulated product cannot be used for the determination of dose rate to be used for routine insect irradiation.

It is important that the dose rate is quite uniform at the location selected as the

a



b



c

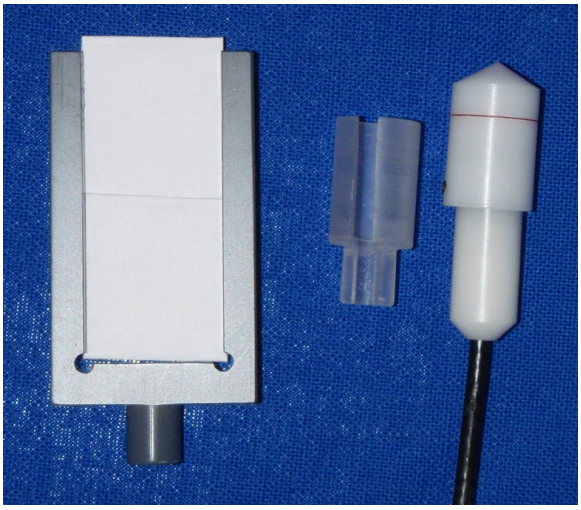


Figure 15. System for positioning the dosimeters in the canister: a Canister lid; b adaptor to centre the holders in the canister; c holders for ion chamber and dosimeter envelopes; assembled system with ion chamber.

reference location where the dose rate will be measured with the reference standard or transfer standard dosimetry system, for example in the centre of the canister for rotational mode of operation. However, since rotational mode is not practical for ionization chamber measurements, it is essential that the Gafchromic dosimeters (for calibration irradiation) are placed at the precise location where the dose rate is determined. This requires specially designed devices for holding these dosimeters and ensuring positioning the canister containing them in a fixed, reproducible position.

Figure 15 shows an arrangement for irradiating the ionization chamber in the RS2400 irradiator. It is designed to fulfil the following requirements of the specific ionization chamber described in Appendix D:

- the ionization chamber should be directly in contact with the irradiated material (pupae or instant rice),
- the leads have to be connected to an electrometer that is situated outside the irradiator,
- the ionization chamber, being a free-air type, has to be protected against any particulates or powder in the surrounding material entering the cavity, and
- being a fee-air type also requires that the ionization chamber cavity is 'open' to atmosphere such that temperature and pressure within the cavity represent the ambient conditions.

Figure 15a shows the specially designed canister lid which is used for irradiation of both types of dosimeters, the ionization chamber as well as Gafchromic film, for the calibration purpose. It has a central threaded hole which accommodates an adapter for the dosimeter holders. It also has another, off-centre hole for introducing the product in the canister after the lid is in place. Figure 15b shows an adapter which is screwed to the lid on one end and at the other end takes a dosimeter holder for either ionization chamber or Gafchromic dosimeter films. Figure 15c shows the holders for the ionization chamber as well as for Gafchromic film dosimeters such that they are precisely at the same location (in the centre of the canister). All these devices are made of PMMA (acrylic, Plexiglas®, Lucite® etc.). Also, to protect the ionization chamber from any particulates, it is recommended to envelop it within a thin cover; the best is to use part cut from a rubber surgical glove (either a finger or the thumb). This protective cover should be placed such that a free passage to the ambient air is maintained to ensure pressure equalization.

3.3.2. Irradiation temperature

The response of the ionization chamber (for a given dose) is directly proportional to the air mass in the cavity, which depends on the pressure and temperature. It is thus recommended to operate the electrometer in temperature and pressure compensation mode. If the compensation is available, it is not necessary to measure separately the temperature or pressure.

3.4. Transfer-standard dosimeter

At present the only reference standard dosimetry system that fulfils the necessary conditions is an ionization chamber; thus, the following procedures are specific to ionization chamber measurements. It is recommended to use a Farmer type 0.18-cm^3 (such as the 10×6-0.18 thimble ion chamber[3]) or 0.6-cm^3 (10×6-0.6) free-air ionization chamber in conjunction with

[3] Supplied by RadCal 426 West Duarte Road, Monrovia, California 91016, USA. www.radcal.com

an electrometer for these measurements (see Appendix D). It must be calibrated for the relevant photon energies with traceability to a national or international standard.

The accompanying spread sheet in Microsoft Excel format, available from the IAEA web site, contains all the forms with formulas to do the necessary calculations automatically (the file contains no macros). This spread sheet should be used for the following procedures. Forms for manual calculations can be printed from the workbook.

Starting with sheet Form-SIT3A, enter the information required in the yellow cells in rows 4 to 21 including model and serial number of all the components used in the calibration (Fig. 16). As the ion chamber is filled with air and dose is conventionally expressed as dose to water it is necessary to correct the ion chamber reading with the ratio of the energy absorption coefficients for air and water, available from NIST [18]. The ratio depends on the effective energy of the X-ray beam (not the maximum energy). The effective energy is approximately one third of the maximum energy, but this depends on the amount of hardening filtration used. For the RS2400 the effective energy is about 60 keV [14]. The energy absorption ratio of water to air can be estimated from Fig. 17 for effective energies from 20 to 200 keV (maximum energies of approximately 60 – 600 keV), giving a value of 1.05 for the RS2400, and must be entered in cell G19. See also Appendix D.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Characterization of the irradiator**												Form-SIT-3A
2	**Dose Rate (DR) Measurement with Reference Dosimetry**												
3			**System (Ionization Chamber)**										
4				Date:	2020-11-20								
5				Operator:	YGS								
6	**Irradiator type and serial number**						Raycell MK2 s/n 163						
7	**Irradiator location**						IPCL, Seibersdorf						
8	**Reference dosimetry system**												
9			Ionization Chamber and ser. No.				10-6-0.18 01-0005						
10			Digitizer				9660A 01-2557						
11			Electrometer				Accu Dose 27-0016						
12			Settings				Automatic						
13			Calibration date				2015-08-01						
14			Ion chamber calibration factor				1						
15			Reference system uncertainty U_{Ref}(%)				1.6						
16	**Reference irradiation conditions**												
17			Operating voltage		kV		160						
18			Operating current		mA		25						
19			Energy absorption ratio		water/air		1.05						
20			Product in all canisters				None						
21			Ionization chamber location				Center of canister						

Figure 16. Form-SIT3A

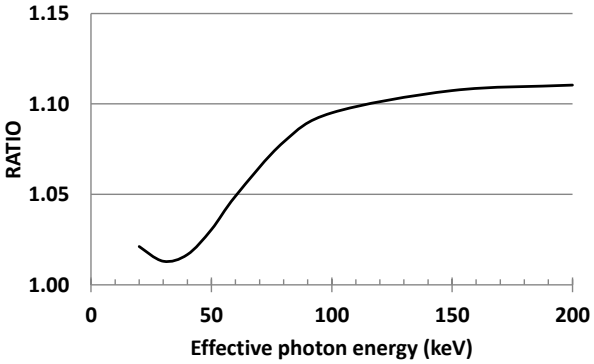


Figure 17. Ratio of the water and air energy absorption coefficients against effective photon energy.

Preparation of the canister

1). Connect the ionization chamber (to be located within the irradiator) to the electrometer located outside the irradiator.

2). Thread the ionization chamber through the central hole in the lid and place the cables in the slot in the adaptor provided for the purpose.

3). Screw the adapter to the lid.

4). Mount the ionization chamber holder on to the adapter and attach the ionization chamber to the holder.

5). Fix the nylon protective layer around the ionization chamber and attach it to the adapter such that there is a clear air passage between the ionization chamber cavity and the outside atmosphere.

3). Fill the canister with pupae or instant rice to about half way and then close the lid assuring that the ionization chamber is in the centre of the canister.

4). Secure the lid to the canister with 3 or 4 tapes.

5). Fill the remaining canister through the off-centre hole in the lid assuring that the canister is tightly packed.

6). Close the hole in the lid.

7). Place the canister in position on the rotor making sure that the ionization chamber wires are clear of obstruction.

Irradiation run

8). Set the operating parameters of irradiator to the maximum possible, (150 kV 45 mA for the RS2400), with an irradiation time of 5 min / 300 s and stationary (rotation off).

9). Set the electrometer for 'integrated dose' mode. Record the calibration factor, pressure and temperature on Form-SIT-3A (Fig. 18). Start the measurements.

10). Start the irradiator immediately.

Dose rate in air

Irradiation Time[1]		From electrometer			Measured					Dose Rate
min	sec	cal	kPa	T °C	T °C	min	sec	$Dose_{air}$ (Gy)	$Dose_W$ (Gy)	Gy/min
6.0		1.00	101.3	22.0	22.0	6.0		47.75	50.14	8.34
9.0		1.00	101.3	22.0	22.0	9.0		70.74	74.28	8.24
12.0		1.00	101.3	22.0	22.0	12.0		94.31	99.03	8.25
15.0		1.00	101.3	22.0	22.0	15.0		118.00	123.90	8.25
18.0		1.00	101.3	22.0	22.0	18.0		141.10	148.16	8.22
21.0		1.00	101.3	22.0	22.0	21.0		163.70	171.89	8.17
21.0		1.00	101.3	22.0	22.0	21.02		163.60	171.78	8.17
27.0		1.00	101.3	22.0	22.0	27.03		211.40	221.97	8.21
									Mean[1]	8.23
									Uncertainty [u_{sdr}(%)]	0.66

When was the last time the DR was measured:
Same irradiation conditions?
What was the value then?
Any other remarks:

[1] Time can be entered in minutes and decimal (2.1), minutes and seconds or seconds (up to 999 seconds)

Figure 18. Form-SIT-3A

11). Soon after the irradiation has been completed (after the set time), stop the electrometer dose accumulation.

12). Record the dose from the electrometer (Gy to air) and the time on Form-SIT-3A (Fig. 18). Dose to water is then calculated by multiplying the dose to air value by 1.05 for 150/160 kV. The correction factor for other energies can be estimated from Fig. 17.

13). The dose rate is then calculated as the ratio between dose to water and the irradiation time.

14). Repeat steps 9 to 13 several times (minimum of five).

15). Calculate the mean and standard deviation for the dose rate values.

16). The coefficient of variation (100 x std dev/mean) represents the uncertainty in the value of dose rate. This value is entered in SIT-FORM-9 as u_{dr}. This value should be less than 1%.

The mean value is the dose rate for the irradiator for these operating conditions and for the particular product in the canisters.

3.5. Frequency of dose rate measurement

The dose rate should be measured annually or sooner if any relevant part of the irradiation system is altered, such as replacement of the X-ray tube, or irradiation set up that can affect the dose rate.

4. CHARACTERIZATION OF GAFCHROMIC™ DOSIMETRY SYSTEM

Characterization of a dosimetry system consists of:

- calibration of the dosimetry system,
- determination of the homogeneity of the dosimeter response for the current dosimeter lot, and
- determination of total uncertainty in the measured dose value.

Procedure for each of these is described below.

The information about the current dosimetry system is then listed in Form-SIT-9.

4.1. Calibration

Calibration of a dosimetry system consists of irradiating several dosimeters at specified dose levels, measuring the OD and determining the response for each dosimeter, and establishing a relationship between dosimeter response and dose. Each of these steps is discussed below.

4.1.1. Irradiation

Irradiate Gafchromic™ dosimeters at the same reference location where the dose rate was determined and under the same irradiation conditions. The range of the secondary electrons that are generated by the low energy photons is extremely short, about 0.1 mm in water. Thus, the electrons reaching the sensitive region of the dosimeter film are much influenced by the material of the envelop it is placed in during irradiation (see Appendix E). It is, therefore, important that the dosimeter should be used in the same type of envelop for making routine dose measurements as used during calibration. One such envelope is the small (2.5cm x 2.5cm) white paper envelop supplied by FWT Technology, Inc., however, any paper envelopes are acceptable. Also, more than one dosimeter should not be placed together in one envelope. For calibration irradiation, use two such envelopes each containing one 2cm x 2cm film. Place these two envelops in the dosimeter holder (Fig. 15c) and attach it to the adapter (Fig. 15b) replacing the ionization chamber holder.

	A	B	C	D	E	F	G
1							Form-SIT-4A
2	Gafchromic Dosimetry System Calibration: Irradiation						
3							
4	Date:	2020-11-30					
5							
6	Operator:	YGS					
7							
8	Reference irradiation conditions:				Centre of canister		
9	(should be the same as those for the dose energy ratio measurement (Form-SIT-3A))						
10							
11							
12							
13	Dose Rate in air (from Form-SIT-3):					8.23	Gy per minute
14	Anode voltage					160.0	kV
15	Set Current					25.0	mA
16							
17							
18							
19							
20	Filter	590nm					
21							
22	Required	Calculated time[1]		Actual time[2]		Dose (Gy)	
23	Dose (Gy)	min	sec	min	sec		
24	50	6.1	364	6.1		50.2	
25	60	7.3	437	7.3		60.1	
26	80	9.7	583	9.7		79.9	
27	100	12.1	729	12.1		99.6	
28	120	14.6	875	14.6		120.2	
29	150	18.2	1093	18.2		149.9	

Figure 19. Form SIT-4A

As the response of Gafchromic™ film is approximately logarithmic, six calibration doses should be selected in an approximately geometric sequence. The final uncertainty of the calibration will be affected by the span of doses used for the calibration. For the smallest uncertainty a span of approximately 3× should be used, e.g. if the routine irradiation dose is 100 Gy select 6 doses from 50 to 150 Gy in an approximate geometric sequence (50, 60, 80, 100, 120, 150). Using a logarithmic fit this range can be expanded to 5× or 6× and a reasonable uncertainty will still be obtained. For F1 sterility where higher doses are required or for mosquitoes where lower doses are required, adjust the intervals appropriately. Enter

these values in column 1 in Form-SIT-4A (Fig. 19). It calculates the corresponding time values as:

Calculated time (min) = Dose (Gy to water) / Dose rate (Gy/min)

For the irradiator operating parameters, select the same voltage and current used for the determination of the dose rate, and turn off rotational mode if your irradiator supports this mode.[4]

Irradiate each pair of 2 x 2 cm dosimeters for the indicated time. Record the actual time values in Form-SIT-4A should they differ from the predicted times for any reason.

After irradiation, cut each 2cm x 2cm film into 4 pieces (each 1cm x 1cm) and place them into an envelope for safekeeping. Since the colour develops over some time, measure the OD of the dosimeters *between 20 and 28 hours after irradiation* (Section 2.3.3).

Measure the OD of each dosimeter film following the procedure given in Sections 2.2.4. and 2.2.5. For each dose point, there will be two sets of 4 values of OD. Record all the OD values on sheet CalData. First, measure the OD of the three ND filters before starting the read-out of the dosimeters. Then read the OD of 10 unirradiated 1 x 1 cm dosimeters to record the background reading. Read each set of dosimeters in sequence and finally repeat the reading of the ND filters.

The OD_{mean}, $OD_{std\ dev}$ and CV(%) for each set of four OD values are calculated by the spread sheet. Also calculated is response (R) for each OD_{mean} as:

$$R = OD_{mean} - OD(bkgd)$$

where, OD(bkgd) is the mean value of the

Form-SIT-4B

Gafchromic Dosimetry System Calibration: Response Determination

Film reader s/n: S/N: 12348 Film batch ID: 08252001

Date: 2020-11-30

Analysed by: YGS

	ND0.5	ND1.0	ND2.0
Start	0.494	0.969	2.036
Finish	0.493	0.981	2.039

Dose (Gy)		OD (4 values for each 2 x 2 dosimeter)				OD (mean)	OD (std dev)	CV(%)	Resp.[1] (R)	R(mean)[2]
26	A:	0.370	0.380	0.369	0.371	0.372	0.0054	1.4%	0.154	0.152
26	B:	0.362	0.367	0.380	0.365	0.368	0.0083	2.3%	0.150	
51	A:	0.484	0.488	0.478	0.498	0.487	0.0085	1.8%	0.269	0.269
51	B:	0.498	0.477	0.485	0.487	0.487	0.0087	1.8%	0.269	
77	A:	0.581	0.562	0.577	0.588	0.577	0.0108	1.9%	0.359	0.360
77	B:	0.586	0.570	0.582	0.577	0.579	0.0070	1.2%	0.361	
102	A:	0.658	0.645	0.635	0.661	0.650	0.0122	1.9%	0.432	0.435
102	B:	0.662	0.659	0.649	0.658	0.657	0.0059	0.9%	0.439	
128	A:	0.715	0.732	0.708	0.722	0.719	0.0102	1.4%	0.501	0.500
128	B:	0.725	0.710	0.722	0.715	0.718	0.0067	0.9%	0.500	
153	A:	0.790	0.781	0.781	0.750	0.776	0.0175	2.3%	0.558	0.558
153	B:	0.752	0.789	0.779	0.788	0.777	0.0170	2.2%	0.559	

Figure 20. Form SIT-4B

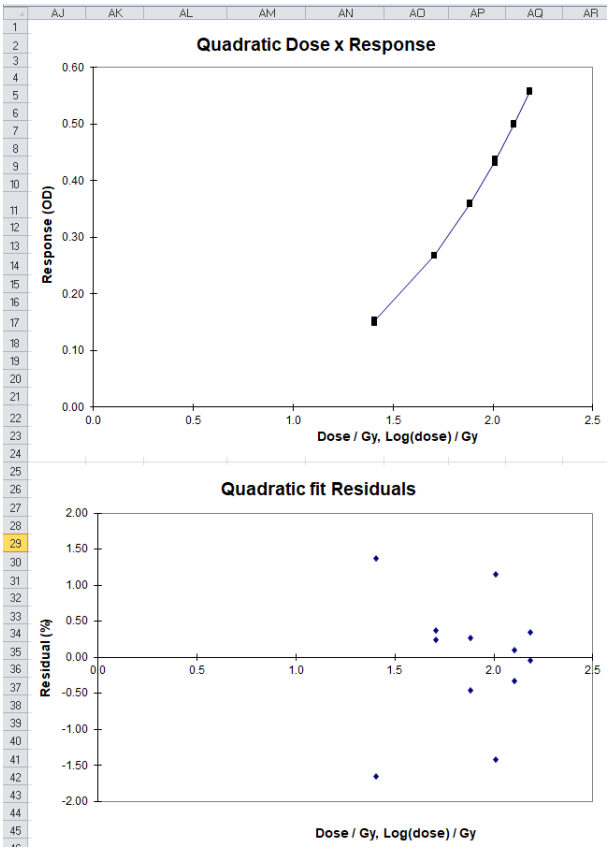


Figure 21. Example of the residual plot. Above is the regression curve (quadratic in this case against log(dose)) with the residual plot below.

[4] Where rotation is available this improves dose uniformity but must not be used during this calibration step as it can change the dose rate from that measured by the ion chamber.

OD of the un-irradiated film (Form-SIT-2) which is valid for the entire dosimeter lot (see Section 2.3.7). R_{mean} is the mean value for the two R values for each dose point (Form-SIT-4B) (Fig. 20).

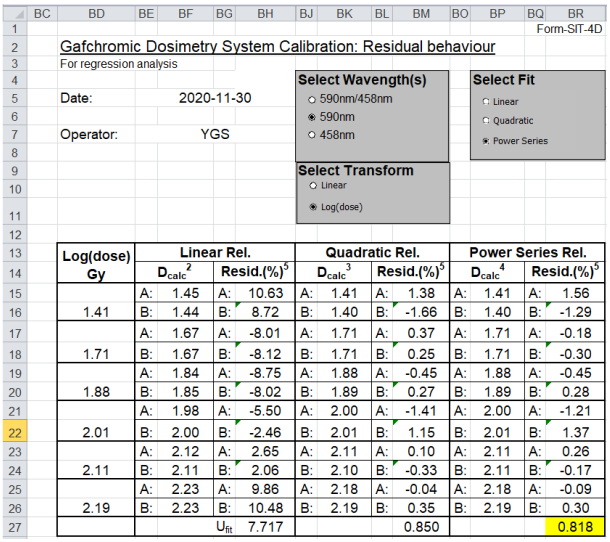
4.1.2. Calibration relationship

The values of Dose, R and R_{mean} are transferred from Form-SIT-4B to Form-SIT-4C.

The objective here is to determine the relationship between the dosimeter response and the dose. This can be done graphically or with regression analysis.

For graphical analysis, plot R_{mean} on the y-axis vs Dose on the x-axis as given in Form-SIT-4C. Draw a smooth curve through all the six points. This curve may be slightly non-linear.

For regression analysis, the spread sheet uses the two R values (as y-parameter) for each Dose value (x-parameter, Fig. 21). The relationship is almost linear, but quadratic or power series fit may be better. The calibration relationships may be described as:



Form-SIT-4D

Gafchromic Dosimetry System Calibration: Residual behaviour

For regression analysis

Date: 2020-11-30

Operator: YGS

Select Wavength(s): ○ 590nm/458nm ◉ 590nm ○ 458nm

Select Fit: ○ Linear ○ Quadratic ◉ Power Series

Select Transform: ○ Linear ◉ Log(dose)

Log(dose) Gy	Linear Rel. D_{calc}^2	Linear Rel. Resid.(%)[5]	Quadratic Rel. D_{calc}^3	Quadratic Rel. Resid.(%)[5]	Power Series Rel. D_{calc}^4	Power Series Rel. Resid.(%)[5]
	A: 1.45	A: 10.63	A: 1.41	A: 1.38	A: 1.41	A: 1.56
1.41	B: 1.44	B: 8.72	B: 1.40	B: -1.66	B: 1.40	B: -1.29
	A: 1.67	A: -8.01	A: 1.71	A: 0.37	A: 1.71	A: -0.18
1.71	B: 1.67	B: -8.12	B: 1.71	B: 0.25	B: 1.71	B: -0.30
	A: 1.84	A: -8.75	A: 1.88	A: -0.45	A: 1.88	A: -0.45
1.88	B: 1.85	B: -8.02	B: 1.89	B: 0.27	B: 1.89	B: 0.28
	A: 1.98	A: -5.50	A: 2.00	A: -1.41	A: 2.00	A: -1.21
2.01	B: 2.00	B: -2.46	B: 2.01	B: 1.15	B: 2.01	B: 1.37
	A: 2.12	A: 2.65	A: 2.11	A: 0.10	A: 2.11	A: 0.26
2.11	B: 2.11	B: 2.06	B: 2.10	B: -0.33	B: 2.11	B: -0.17
	A: 2.23	A: 9.86	A: 2.18	A: -0.04	A: 2.18	A: -0.09
2.19	B: 2.23	B: 10.48	B: 2.19	B: 0.35	B: 2.19	B: 0.30
		U_{fit} 7.717		0.850		0.818

Figure 22. Form-SIT-4D with the optimal U_{fit} highlighted and selected above.

Linear function: $\text{Response} = a + b\,(\text{Dose})$

Quadratic function: $\text{Response} = c + d\,(\text{Dose}) + e\,(\text{Dose})^2$

Power function: $\text{Log}_e(\text{Response}) = f + g\,\text{Log}_e(\text{Dose})$

The selection between the three can be made by observing the distribution of the percentage residuals for the three cases as shown in Form-SIT-4D (Fig. 22), where the residuals are calculated as follows:

1. Corresponding to each of the two response values (R), D_{calc} is calculated for all six irradiations (as given in column 2 of Form-SIT-4C):

   Linear function: $D_{calc} = (R - a) / b$

   Quadratic function: $D_{calc} = (1/2e)\,[-d \pm \{d^2 - 4e\,(c - R)\}^{1/2}]$

   Power function: $D_{calc} = \text{Exp}((\text{Log}_e(\text{Response})-f)/g)$

   These values are shown in Form-SIT-4D, column 2, 4 and 6.

2. From these values, the percentage residual for each point is determined as:

   $\text{Residual}(\%) = 100 \times (D_{calc} - D) / D$

   where, D is the actual value of the delivered dose (as given in column 1 of Form-SIT-4D Fig. 22.). Note: Residual(%) value may be positive or negative.

3. These values of Residual(%) are shown in Form-SIT-4D (column 3, 5 and 7).

4. The plots of Residual(%) (on y axis) vs Dose (on x axis) are shown in the spreadsheet for the linear as well as for the quadratic and power fits. Check the distribution of points in the plots to identify any outlier residual(%) values (Fig. 21).

   The uncertainty arising from the fitting procedure (u_{fit}) is calculated as the root-mean-square residual value for the selected calibration relationship, as follows:

   $$u_{fit} = \{\Sigma(\text{Residual}(\%))^2 / n\}^{1/2},$$

   where n is the total number of residual values (12), and the summation is carried over all these values. The U_{fit} values are shown for each relationship on Form-SIT-4D.

While observing the U_{fit} values at the foot of the table on Form-SIT-4D test the different radio buttons in the Select Wavelength(s) and Select Transform boxes to find the combination giving the lowest value of U_{fit}. Select the corresponding radio button in the grey "Select Fit" area for the relationship that yields the lowest value of U_{fit}. This value is also entered in Form-SIT-9 and will be used later in Section 4.3

This calibration relationship is valid for the specific dosimeter lot for one year, and for the temperature employed for the irradiations, T_{cal} ± 5 °C The following information is then entered in Form-SIT-9: the date of calibration, the calibration irradiation temperature, T_{cal} and the calibration relationship.

4.1.4 Frequency of calibration

The dosimetry system should be calibrated once a year or sooner if any part of the dosimetry system is changed, such as new dosimeter lot or repairs to the reader.

4.2. Dosimeter lot homogeneity

It is important to determine the degree of homogeneity of response for dosimeters belonging to a lot since it affects the overall precision of the measured dose value. For each lot, this is determined by irradiating several dosimeters selected randomly from the lot to the same dose, following the procedure given below:

1. Cut two pieces 2 x 2 cm from the dosimeter film sheet (current lot).
2. Place each piece in a separate small envelope for irradiation.
3. Place these envelopes together at a location inside a container full of pupae (or instant rice) where the dose is expected to be uniform (for example, at the centre of the canister).
4. Irradiate them at about 100 Gy dose. The exact value of dose is not important. However, it is very important that they all receive the *same* dose.
5. Cut each piece into four 1 x 1 cm dosimeters and determine the response of each dosimeter following Section 2.2.5. Ensure the values are entered into the correct place on the sheet CalData.
6. Mean and standard deviation of these eight response values are calculated. Subsequently, coefficient of variation is determined as:

   $$\text{CV}(\%) = (\text{standard deviation/mean value}) \times 100.$$

This CV value is for dosimeter response; however, since the relationship between dosimeter response and absorbed dose is nearly linear, the CV value for dose can be assumed to be the same as that for the response. This value of CV(%) is entered in Form-SIT-9 as u_{lot}. The lower the CV(%) value the higher (better) the precision of the measured dose value.

4.3. Uncertainty

In general, the result of any measurement is only *an approximation or estimate* of the value of the quantity being measured (for example, absorbed dose), and thus is complete only when accompanied by a statement of the uncertainty of that estimate. Uncertainty (of measurement) may be defined as a parameter, associated with the quantity that characterises the distribution of the values that could reasonably be attributed to it. Thus, uncertainty reflects the degree of accuracy in the measured value.

Uncertainty in any measurement is a fact of life and unavoidable. First, the sources of uncertainty should be identified, and their effects minimised as much as possible. And then the remaining sources of uncertainty should be evaluated. This is most easily done by considering in turn each step in the calibration and use of the dosimetry system, and assessing what uncertainties are likely to be associated with each step. The uncertainty associated with a dose measurement can then be calculated by combining the individual components together. The philosophy used is to ascribe to each component of uncertainty an effective standard deviation, known as a standard uncertainty, and these standard uncertainties are then combined to produce the total uncertainty.

The total uncertainty in the measured dose value using the Gafchromic dosimetry system consists of several components (all these component values are in %):

- u_{ref}: of reference dosimetry system (ionization chamber)
- u_{dr}: arising from uncertainty in the measurement of the dose rate of the irradiator,
- u_{fit}: arising from uncertainty in the calibration relationship (see Section 4.1.2.),
- u_{lot}: arising from lot non-homogeneity (= CV(%) value from Form-SIT-6, see Section 4.2). If n dosimeters are used at one location to measure dose, the uncertainty in the mean value of the measured dose is reduced by $\sqrt{n}$. Thus, this component of uncertainty for n dosimeters = CV(%)/$\sqrt{n}$.
- $u_{temp\text{-}r}$: arising from uncertainty in the dosimeter temperature during OD read-out procedure. Assuming that the dosimeter temperature during read-out is within ±5°C of the temperature during calibration, the uncertainty in the measured value of the dosimeter response (and hence dose) is $u_{temp\text{-}r} = 0.7x5/\sqrt{3}$ (~ 1%) where, 0.7%/°C is the read-out temperature coefficient as estimated in the IAEA Laboratory. The factor of $\sqrt{3}$ is based on the assumption that the dosimeter temperature has rectangular probability distribution within the two limits [3]. Calculate this value and record it in Form-SIT-9.

The total uncertainty, u_{total} (%) is then given by adding these components in quadrature:

$$u_{total} = (u_{ref}^2 + u_{dr}^2 + u_{fit}^2 + u_{lot}^2 + u_{temp\text{-}r}^2)^{1/2}$$

All these values of u are for 1 standard deviation (σ). However, to imply a higher level of confidence that the 'true' value lies within the reported range, u_{total} should be multiplied by a factor of 2 (called a 'coverage factor'). Thus, one can state with about 95% confidence that the 'true' dose value lies within $D_{measured} \pm 2u_{total}$.

4.4. Characteristics of the current dosimetry system

Enter the values determined above for the following characteristics in Form-SIT-9:

- ID of the dosimeter lot (this is on the dosimeter box received from Ashland),
- calibration of the dosimetry system (relationship, date and temperature),
- background response, and
- uncertainty values.

4.5. Use of the calibration relationship

To measure dose at a point, follow the procedure given below. Use Form-SIT-6 for this procedure.

1. Place one 1cm x 1cm dosimeter from the calibrated lot in a paper envelope and place it at the point of interest. Write the relevant information on the envelope. Several such envelops may be placed at a location to reduce the uncertainty in the measured dose value. More than one dosimeter should not be placed in one envelope; however, one larger piece (for example, 2x2 cm) of film may be placed in one envelope and cut into four dosimeters after irradiation.
2. Irradiate the sample (with the dosimeters).
3. Measure the OD of the dosimeters following the procedure of section 2.2.4. above. Ensure that the cursor is in the dark yellow cell of Form-SIT-6 (cell P4) so that the reader data is entered into the sheet. (Note: These measurements should be made 20 to 28 hours after irradiation):

5. DOSE DISTRIBUTION MEASUREMENT (DOSE MAPPING)

5.1. Objective

The primary purpose of performing dose mapping is to verify that the dose variability in the irradiated insects is acceptable for the application on hand. This should be done before useful irradiation is carried out. If the dose variation is greater than acceptable, it points out the need for modifying the irradiation procedure or the canister size/shape. This activity is generally referred to as 'Performance Qualification' since it establishes values of all process parameters necessary to achieve the specified dose in the insects [4]. See Section 6.3 and Form-SIT-8B for examples of process parameters.

Use Form-SIT-7 for recording data.

If instant rice was used for calibration of the Gafchromic dosimetry system and thus for determination of the dose rate (DR), it is essential to determine DR again for the insects before 'Performance Qualification' is performed.

5.2. Research application

If insects are irradiated for research purposes, such as to establish the relationship between dose and its effect, it is essential that the dose is as uniform as possible across the irradiated sample. To measure the dose distribution in the sample, place several dosimeters (or a strip of dosimeter film) in the sample. The dosimeters should be protected in paper envelopes against contact with pupae.

5.3. Commercial application

For commercial applications, generally larger volumes are irradiated, and thus dose is not as uniform as for small volumes used for research applications. Dose variation is unavoidable, and the main objective of dose mapping is to determine the maximum and minimum dose in the canister and the regions where these occur. Carry out detailed dose determination by carefully placing several dosimeters throughout the irradiated volume. Place dosimeters in a specific regular grid pattern; however, place more dosimeters in regions where extreme doses are expected from previous experience or from theoretical analysis. Alternately, long strips or sheets of Gafchromic film may be used. If some portion of the pupae is receiving too high or too low a dose for the application at hand, some changes need to be carried out before large-scale routine irradiation is done.

The dose distribution depends on the load configuration (quantity and distribution of the insects and canisters) within the irradiator. Separate dose mapping has to be performed for each load configuration that is used.

5.4. Dose monitoring location

For process control during routine irradiation, it is sometimes necessary to place dosimeters in or on the insect canister (see Section 6.2). They are preferably placed at a point where the dose is expected to be at a minimum. However, it is not always convenient to do so. Alternatively, one or more dosimeters may be placed at a monitoring location on the canister that is convenient. During the dose mapping exercise, select such a monitoring location and establish the relationship between the dose at this location and the minimum dose in the product. This relationship depends strongly on the load configuration and should be determined for each configuration used. To reduce uncertainty in the process, the dose gradient at this location should not be significant.

5.5. Dose mapping using scanning

A separate document is available describing the procedure for mapping dose using a scanner [12].

6. PROCESS CONTROL

6.1. General

Carry out routine irradiation as per information gathered during the dose mapping exercise; that is, ensure that the values of all the process parameters are the same as established during performance qualification (Section 5.). Thus, it is expected that the dose distribution would be acceptable. On the other hand, it is necessary to have in place some measures of process control to show with a high degree of confidence that the entire process was carried out as specified. This is accomplished through two independent procedures: a) routine dosimetry, and b) monitoring of process parameters. In addition, the use of radiation-sensitive indicators assists in streamlining the inventory process and gives confidence that each container[5] was irradiated. These process control measures should be supported by periodic assays of the level of sterility achieved where appropriate.

6.2. Routine dosimetry

For each irradiation batch, place at least three dosimeters (in three envelopes) at the location where the dose is expected to be minimum or at the monitoring location identified during performance qualification (Section 5.4). Thus, if the dose value (mean of the three values) measured by these dosimeters is acceptable (as established during performance qualification), then it can be concluded that the particular irradiation batch has received the expected dose. Use Form-SIT-8A for recording data. Each facility should determine for itself what constitutes an irradiation batch and how many such measurements should be performed per batch.

6.3. Process parameter monitoring

Control, monitor and document the values of all process parameters that can affect dose. Such parameters include: canister size, any specific arrangement of the pupae within the canister, positioning of the canister, irradiation time, rotation speed of the canisters and the power level values (kV and mA).

Use Form-SIT-8B for recording data.

6.4. Radiation-sensitive indicators

Appropriate radiation-sensitive indicators should be placed on each packaging container before irradiation. Check the state of the indicator before and immediately after irradiation. Use of these indicators assists in keeping irradiated and un-irradiated packaging containers apart. However, there should also be administrative procedures in place to identify the irradiated packaging containers.

These indicators are not replacement for routine dosimeters. Routine dosimeters are absolutely essential as discussed in Section 6.2.

[5] *packaging container* is a container such as a paper cup with lid, plastic bag, or plastic bottle that is used to hold factory-reared insects during irradiation and, typically, during subsequent shipment from the irradiation facility to the release site. On the other hand, *canister* is the durable, reusable carbon fibre container used to hold packaging containers of factory-reared insects in the irradiator during the irradiation process.

7. DOCUMENTATION

Document all information collected during the various procedures described above and file these documents together at an easily accessible location. This is necessary for research applications as well as for commercial applications. Prepare and use appropriate forms to make this consistent, such as those printed from the supplied Excel workbook. Operators should sign and date these forms and file them as an integral part of quality assurance for audit purposes.

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Standards[6]

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ISO/ASTM 51539 Guide for Use of Radiation-Sensitive Indicators
ISO/ASTM 51900 Guide for Dosimetry in Radiation Research on Food and Agricultural Products
ISO/ASTM 51940 Guide for Dosimetry for Sterile Insect Release Programs
ASTM E-1026 Practice for Using the Fricke Reference Standard Dosimetry System

Other publications

INTERNATIONAL ATOMIC ENERGY AGENCY, Dosimetry for food irradiation, Technical Reports Series no. 409, IAEA, Vienna, Austria (2002). http://www-pub.iaea.org/MTCD/publications/PDF/TRS409_scr.pdf

[6] For ASTM and ISO/ASTM Standards referred to here, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. These standards are generally updated about every five years; please refer to the latest version.

Appendix A

X radiation vs. gamma radiation

A.1 General

X radiation and gamma radiation are both part of the electromagnetic radiation spectrum, which also includes radio waves, infrared, visible and UV light. Just as we say that matter is made up of atoms, electromagnetic radiation is 'made up' of photons. The difference between the various components of electromagnetic radiation, e.g. radio waves, visible light and gamma radiation, is only their wavelength; the shorter the wavelength, the higher the energy level. The energy associated with gamma radiation and X radiation is high enough to break atomic and molecular bonds (that is, to ionize atoms), producing changes in matter including living cells. This high-energy end of the spectrum is therefore referred to as 'ionizing radiation'.

A.2 Absorbed dose and RBE

The amount of radiation energy absorbed in a medium is expressed as absorbed dose. The unit of absorbed dose (sometimes referred to simply as 'dose') is gray (Gy), where

$$1 \text{ Gy} = 1 \text{ J/kg}$$

Thus, absorbed dose is the measure of the radiation energy absorbed in a unit mass. The unit used earlier was rad, where 100 rads = 1 Gy.

Equal absorbed dose from different types of radiation may not produce similar biological effects. For example, 1 Gy of X-radiation would have less biological effect than 1 Gy of neutrons or protons. The key characteristic which creates this difference is the distribution of the energy deposition by these different types of radiation in the exposed medium (such as tissues). This characteristic can be described by linear energy transfer (LET) (see description below).

When comparing the biological effectiveness of the different types of radiation, traditionally X radiation (250 keV) is used as the standard against which other radiation types are compared. The relative biological effectiveness (RBE) of a test radiation (r) may be defined as:

$$\text{RBE (r)} = \text{D250} / \text{Dr}$$

where, D250 and Dr are the doses of X radiation (of 250 keV) and the test radiation, respectively, required for the same biological effect.

The RBE can be different depending on the tissues/cells under consideration, and also on the biological effect selected for this comparison.

A.3 Linear Energy Transfer (LET)

Linear energy transfer (LET) represents the amount of energy transferred from radiation to a medium (for example, tissues) per unit length of the path travelled by the radiation (sometimes referred to as 'track'). The commonly used unit is keV/μm. LET is defined as:

The linear energy transfer (LET) of a medium for charged particles is the quotient of dE/dl, where dE is the energy lost by a charged particle due to electronic collisions in traversing a distance dl.

Since energy transfer to the medium is principally via ionization, LET is related to the density of ionization along the track. LET gives an indication of the 'radiation quality'.

Note that LET is related to energy lost by charged particles. Thus, for X radiation and gamma radiation, the energy of interest is the energy lost by the secondary electrons generated by these photons.

Typical LET values for the types of radiation that are commonly used for industry or medicine are listed in the table below.

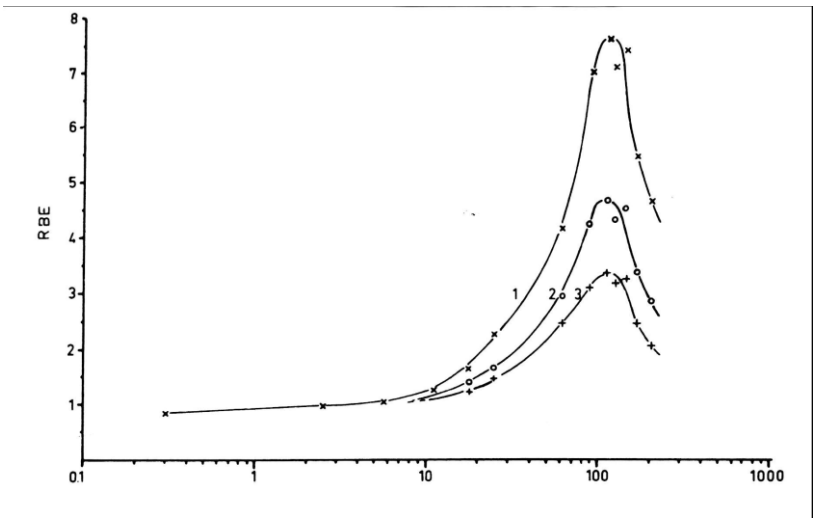
LINEAR ENERGY TRANSFER (LET) VALUES FOR DIFFERENT TYPES OF RADIATION

Type of Radiation	**LET (keV/μm)**
Cobalt-60 gamma radiation	0.2
250 keV X radiation	2.0
10 MeV protons	4.7
2.5 MeV α particles	166

A small value of LET means that there are few ionization events along the radiation track. Thus, X radiation, gamma radiation and fast electrons are considered sparsely ionizing radiation, unlike neutrons, protons and α particles.

The figure below shows the relation between RBE and LET; it shows three curves for three different biological effects. As mentioned above, RBE depends on the biological effect being considered. From this it is clear that the RBE for cobalt-60 gamma radiation (which would be similar for caesium-137 gamma radiation) is only slightly less than that for 250 keV X radiation.

All curves in the figure exhibit maximum RBE around LET of about 100 keV/μm. The average spacing between ionization events for this LET value coincides approximately with the diameter of the DNA double helix, resulting in maximizing the radiation effect. Radiation with a higher LET has more densely located ionization events than necessary for the biological effect, and thus the energy is ‘wasted’. This is manifested as a lowering of the RBE after this optimum value of LET.



Dependence of RBE on LET for survival of mammalian cells of human origin.
Curves 1, 2 and 3 refer to cell survival levels of 0.8, 0.1 and 0.01, resp. This illustrates that the value of RBE depends on the biological effect selected for comparison[6] (from [19]*)*

Appendix B

Dose to pupae

The following procedure describes how to give the same *dose to pupae* in X-ray field as well as in Co-60 gamma-ray field.

1). The dose measured by the calibrated dosimetry system (either in a Co-60 field or in an X-ray field) is 'dose to water' (that is energy absorbed in unit mass of water), and NOT 'dose to pupae'.

2). Since the radiation effect on pupae depends on the energy absorbed by them (and not water) and this depends on the photon energy, for comparisons between the effect of gamma and X radiation it is necessary to calculate 'dose to pupae'.

3). Dose to pupae, D_p, can be calculated from the measured dose, D_w, as follows:

$$D_p = D_w \left[(S/\rho)_p / (S/\rho)_w\right] \equiv D_w \left[S_{ratio}\right]$$

where,

D = dose,

Subscripts 'p' and 'w' refer to pupae and water, respectively, and

S/ρ = mass collision stopping power for electrons (MeV cm^2/g), which is a function of energy.

4). Thus, dose to pupae, D_p is:

In Co-60 field: $D_p^{60} = D_w^{60} \left[S_{ratio}\right]^{60}$

In X-ray field: $D_p^{x} = D_w^{x} \left[S_{ratio}\right]^{x}$

If we want to give the same dose to pupae in both radiation fields, that is $D_p^{60} = D_p^{x}$

$$D_w^{60} \left[S_{ratio}\right]^{60} = D_w^{x} \left[S_{ratio}\right]^{x}$$

$$D_w^{x} = D_w^{60} \left\{ \left[S_{ratio}\right]^{60} / \left[S_{ratio}\right]^{x} \right\}$$

That means that to give the same dose to pupae in the two fields, the two measured dose values (dose to water) must be related as shown above.

See the following table for the value of S_{ratio} as a function of electron energy.

We should take S_{ratio} value for the energy of the secondary electrons. For the 150 keV X-rays, the electron energy could be 30-100 keV. And for Co-60 gamma rays, the energy could be about 300-500 keV. However, it can be seen from the table that S_{ratio} is quite constant in the relevant range of the electron energy, namely 1.0 (±0.4%). Thus, the second term in the above equation is 1.0.

Thus, $D_w^{x} = D_w^{60}$. That is, when the dosimeter measures the same dose in the two fields, we are giving the same dose to the pupae. Also, since the S_{ratio} is unity, the 'dose to water' and 'dose to pupae' are the same for both radiation fields.

Since LET is different for X-rays and Co-60 gamma rays their RBE could also be different, albeit it is expected to be a very small difference. Thus, the same (physical) absorbed dose could have different biological effects (sterilization and effect on quality) in the two fields. This can be determined only by biological/entomological experiments.

MASS COLLISION STOPPING POWER FOR ELECTRONS FOR WATER AND PUPAE (*data from ICRU Report 37, 1984*)

Energy (MeV)	**Pupae** (MeV cm^2/g)	**water** (MeV cm^2/g)	**Pupae/water**
0.03	9.688	9.653	1.004
0.035	8.619	8.592	1.003
0.04	7.799	7.777	1.003
0.045	7.149	7.130	1.003
0.05	6.618	6.603	1.002
0.055	6.179	6.166	1.002
0.06	5.807	5.797	1.002
0.07	5.215	5.207	1.001
0.08	4.763	4.757	1.001
0.09	4.406	4.402	1.001
0.1	4.117	4.115	1.001
0.125	3.591	3.591	1.000
0.15	3.236	3.238	0.999
0.175	2.980	2.984	0.999
0.2	2.789	2.793	0.999
0.25	2.522	2.528	0.998
0.3	2.348	2.355	0.997
0.35	2.226	2.233	0.997
0.4	2.138	2.145	0.997
0.45	2.073	2.079	0.997
0.5	2.022	2.028	0.997
0.55	1.983	1.988	0.998
0.6	1.953	1.956	0.998
0.7	1.909	1.910	1.000
0.8	1.881	1.879	1.001
0.9	1.864	1.858	1.003
1.0	1.853	1.844	1.005

Appendix C

Properties of 'instant' rice

C.1 Selection requirements for a simulated product

For dosimetry purpose it is essential that we select a material that can 'simulate' insects as closely a possible. To be realistic, the simulated material/product should have radiation attenuation and scattering properties (that is photon mass energy absorption coefficient) similar to those of the insects, at least in the energy range of interest (30-150 keV). Generally this can be achieved by having similar density and elemental composition. Several materials such as cereals and different types of rice were investigated to simulate insect pupae. Eventually, a particular brand of 'instant rice' was selected for the purpose. Its properties are given here.

C.2 Density

The density of pupae is about 0.46 g/cm3.

The measured density of the particular instant rice that was used for all the dosimetry experiments was about 0.44 g/cm3. However, we noticed that with time the value changed due to evaporation of water. This rice was purchased in the USA. The density of 'minute rice' purchased in the UN commissary in Vienna is about 0.4 g/cm3.

C.3 Elemental composition

Samples of instant rice and tsetse pupae were analysed on a contractual basis by the Microanalysis Laboratory, Chemistry Department, University of Vienna. Table below shows the results from their Report 0408/0316.

ELEMENTAL COMPOSITION OF 'INSTANT RICE' AND TSETSE PUPAE

Element	Instant rice	Tsetse pupae
C	40.98 ±0.28	22.86 ±0.3
H	6.46 ±0.05	10.05 ±0.1
N	1.44 ±0.17	3.76 ±0.1
S	0.086 ±0.01	0.170 ±0.03
O	50.54 ±0.06	63.09 ±0.2
Cl	0.033 ±0.003	0.148 ±0.01
Other (residual ashes)	0.163 ±0.03	0.854 ±0.03
SUM	99.62 ±0.5	100.78 ±0.5

C.4 Photon mass energy absorption coefficient

The photon mass energy absorption coefficient for pupae and rice can be calculated from the above data and from the values of this coefficient for various elements, namely C, H, N and O[5] . For these calculations, S and Cl were omitted.

The results are shown in figures below for this coefficient for pupae and rice as a function of photon energy. Coefficient for water is also included for comparison [5].

Appendix D

Ionization chamber at the Insect Pest Control Laboratory

A Farmer type 0.18-cm^3 free-air ionization chamber (supplied by RadCal Corporation, Monrovia, CA, USA) in conjunction with an electrometer was used as a reference standard dosimetry system to measure the dose rate and dose (for establishing dose energy ratio) at a reference position. It was calibrated in the photon energy range 50-1300 keV by the supplier with traceability to NIST, with the quoted uncertainty in the calibration factor of 5% over this range[7]. This value was also checked at the Austrian Primary Standards Laboratory (BEV), Seibersdorf by comparing it against their reference standard ionization chamber. Since such calibrations are performed in an un-scattered photon field (incident normally on the ionization chamber), it was also confirmed that there was no significant variation in the response of the ionization chamber up to about 30° angle of incidence from the normal.

An ionization chamber measures air kerma or air kerma rate. However, what we need is dose to water (Gy) or dose-rate to water (Gy/min) and not air kerma. Dose (in air) is related to kerma (in air) as follows:

$D_{air} = K_{air}$ (1-g), where g is the fraction of energy converted into bremsstrahlung.

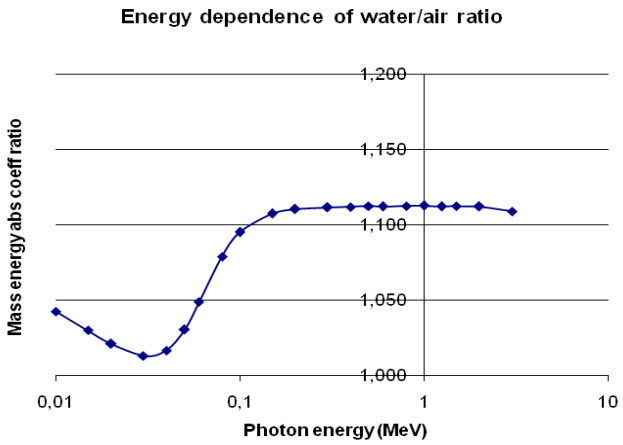
However, at the photon energy we are concerned with here, and for materials of low atomic number, g is insignificant. Thus, $D_{air} = K_{air}$.

Now, D_{water} can be calculated from D_{air} as follows:

$D_{water} = D_{air} \times$ photon mass energy absorption coefficient ratio

where, this ratio = $(\mu_{en}/\rho)_{water}$ / $(\mu_{en}/\rho)_{air}$.

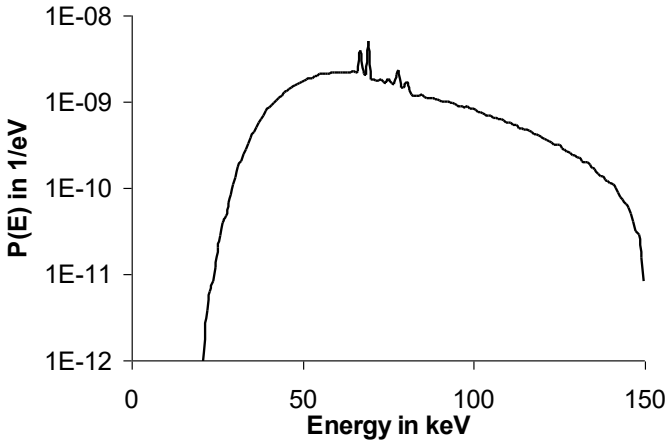
This ratio must be calculated for the effective photon energy at the location of the ionization chamber measurements. Its variation with photon energy is shown in the figure below.



Dependence of the photon mass energy absorption coefficient ratio for water-to-air on photon energy [5]

[7] 5% value is for 2 standard deviations. Thus, standard uncertainty is 2.5%, which may be designated as u_{ref}.

The reference position selected was the centre of a canister, with all canisters filled with instant rice to simulate radiation conditions normally used. The dose rate (and dose) measured by the ionization chamber was converted to dose rate (and dose) to water by multiplying it by a factor of 1.05, which is the ratio of water to air photon mass absorption coefficients weighted for the photon spectrum at this location. Following figure shows the photon spectrum at this location as determined by Monte Carlo simulation using the Penelope code by R. Uribe (personal communication).



Photon spectrum at the centre of the canister for 150 keV determined by MC simulation (all canisters filled with instant rice) (personal communications, R. Uribe).

Prior to starting the ionization chamber measurements, the linearity of its response was checked to ensure that it was operated below the saturation level. This was done by making the dose rate determinations at the centre of the canister as the tube current was increased, while holding the tube voltage constant at 150 kV. If there is no saturation, the dose rate should linearly increase with the tube current. Any bending of the curve at higher current would suggest saturation. The data showed that the ionization chamber is within its linear range when operated under these conditions and below 45 mA tube current (maximum possible at this time).

An ionization chamber measures dose or dose rate in the cavity air. Being a free-air chamber, the measured value needs to be corrected for the temperature and the pressure of the cavity air during the measurements. This is conveniently done automatically when the electrometer is operated in 'compensation' mode. The temperature is monitored in the ionization chamber and the pressure in the digitizer.

The electrometer associated with the ionization chamber can be operated in two modes: it measures either air dose rate (Gy/min) or integrated air dose (Gy). Both the modes were very useful in the characterization of the irradiator and the Gafchromic dosimetry system.

Appendix E

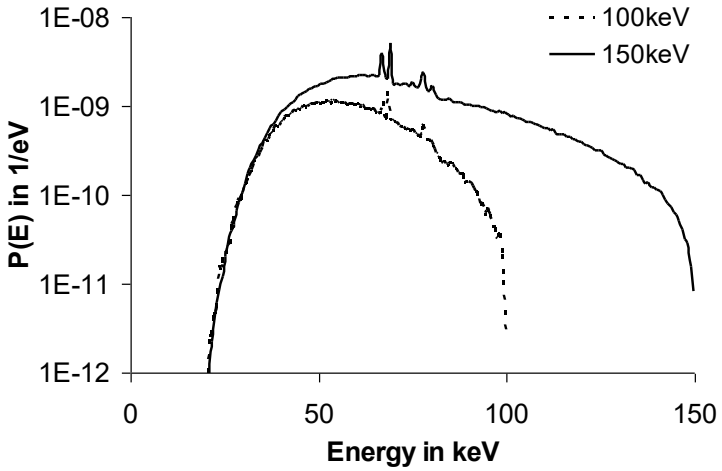
Parameters affecting Gafchromic film dosimeter response for low-energy X radiation

E.1 General

It is well known that irradiation temperature affects the response of the Gafchromic dosimeters [2]; however, for the low doses that we are concerned with the temperature does not rise much (by less than 1 degree Celsius), and generally the calibration and routine use temperatures are very similar. However, several experiments were carried out to study the effect of other influence quantities on the dosimeter performance, namely the photon energy and the material in contact with the dosimeter film.

E.2 Photon energy

To change the photon energy spectrum at the centre of a canister (at the location of the dosimeters), the tube was operated at 100 and 150 keV (following figure shows the two computer-calculated photon energy spectra determined by R. Uribe). The dose rate (or dose) was measured with the ionization chamber as well as with the Gafchromic dosimetry system (calibrated for 150 keV spectrum). When exposed to the same field (based on ionization chamber measurements), the dose measured by the two sets of Gafchromic dosimeters differed by less than 3%, comparable with the uncertainty in the Gafchromic dosimetry system as well as the ionization chamber system. Thus, it can be concluded that the response of the Gafchromic film is energy independent in this photon energy range.



Photon energy spectrum for 100 and 150 keV X-radiation in the centre of the canister filled with instant rice determined by MC simulations (personal communications, R. Uribe).

E.3 Material surrounding the dosimeter

In another set of experiments, the Gafchromic film (2x2 cm square) was sandwiched between different materials and placed at the canister centre. The sandwiched film was completely surrounded by and in contact with instant rice. Table below shows the net OD values for these different materials for the same dose.

DEPENDENCE OF THE GAFCHROMIC FILM DOSIMETER RESPONSE ON THE SURROUNDING MATERIAL

Material	Dosimeter response (OD, net)	Normalized response
Bare dosimeter film	0.332 ± 1.3%	1.0
Black PE [a]	0.341 ± 0.3%	1.03
FWT paper envelope [b c]	0.393 ±0.6%; 0.379 ±1.2%	1.18 – 1.14
Printer paper [d]	0.416 ±0.7%	1.25
3-mm PVC	0.608 ±0.6%	1.83
2-mm PVC	0.619 ±0.6%	1.86
1-mm PVC	0.672 ±0.7%	2.02

[a] ~ 100 μm; b ~ 150 μm; d ~ 110 μm

[c] FWT paper envelops supplied by Far West Technologies, Inc., California, USA.

This clearly shows that the response of the Gafchromic film depends significantly on the material in contact. Thus, the dosimeters should always be used for dose measurement as they were during calibration. It is recommended to use the 1x1-inch FWT paper envelope, during calibration of the dosimetry system as well as during dose measurements.

However, this holds only when the absolute value of the dose is needed. In the case of relative values, such as measuring dose uniformity, this is not necessary; any convenient material may be used. For example, all the axial and radial dose distribution measurements were carried out using long (1-cm wide) dosimeter film strips sandwiched between either PVC or PMMA plates.

E.4 Multiple dosimeters

Often it is desirable to irradiate more than one dosimeter at a particular location (generally to improve the precision of the measurement). Thus, the question is: referring to the effect of the surrounding material mentioned above, can several dosimeters be placed together without affecting each other?

When three dosimeters were irradiated together in one FWT envelope, it was very clear that they affected each other. Thus, ONLY one dosimeter film can be placed in one envelop; that is, films should not be in contact with each other.

Another experiment was carried out where nine envelopes were used, each containing only one (2x2 cm) dosimeter film. All these were tightly placed together in the centre of a canister and exposed in a run: 150 kV, 35 mA, 5 rpm, 600 s. After irradiation, each 2x2-cm film was cut into four 1x1-cm dosimeters and the OD measured. The values of these nine sets of dosimeters are listed in the table below.

RESPONSE OF NINE FILMS PLACED TOGETHER, EACH IN ITS OWN ENVELOPE.

Film ID	OD, net
1	0.506 ±1.1%
2	0.479 ±0.6%
3	0.508 ±0.1%
4	0.504 ±1.3%
5	0.505 ±0.7%
6	0.508 ±1.3%
7	0.509 ±1.0%
8	0.504 ±1.0%
9	0.504 ±0.7%

- average of 9 films = 0.503 ±1.8%

- average of 8 films = 0.506 ±0.4% (ignoring the 2nd film)

Assuming that the 2nd film was defective, it is very clear that the other eight are reading the same dose. Thus, several such envelopes can be placed together.

E.5 Dosimeter orientation

The Gafchromic film dosimeter is a 2-dimensional dosimeter, being a thin film. The question is: does the measured value of the dose depend on the orientation of the film with respect to the primary beam direction?

The following experiment was carried out:

- Irradiator parameters: 150 kV, 35 mA, stationary, 390 s

- Two (2x2 cm) dosimeter films (in two separate FWT envelopes) were placed at the centre of a canister; one flatly facing the X-ray tube, and another facing the tube edge-wise (and perpendicular to the sides of the canister). The results are given below:

Response (net OD) values: flat dosimeter – 0.243 ± 0.9%

edge wise dosimeter – 0.239 ± 6.3%

This shows that both sets of dosimeters read almost the same dose, independent of the orientation. Note that there is dose gradient in the direction of the edge wise dosimeters, and hence a large variation in dose. Of course, this experiment was done in the centre of the canister, which is far away from the radiation source (X-ray tube). If a similar experiment were carried out close to the tube, the two values would be different. However, in a real-life situation, the canisters are rotated and the dosimeters will go through different orientations as well as different distances, depending on where the dosimeters are placed.