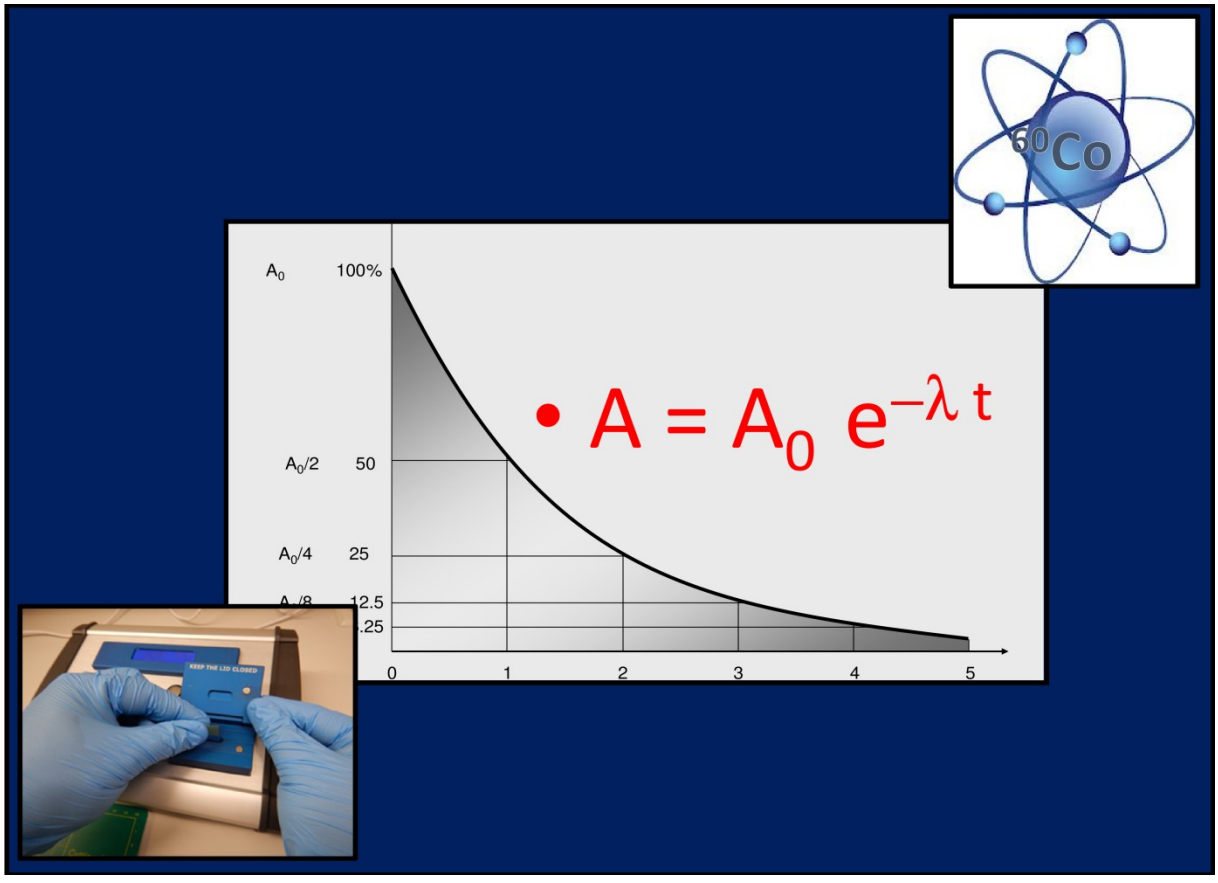
Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

DOSIMETRY FOR SIT: STANDARD OPERATING PROCEDURE FOR GAFCHROMIC™ FILM DOSIMETRY SYSTEM FOR GAMMA 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 gamma 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 590 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 gamma radiation emitted by either ^{60}Co or ^{137}Cs [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 low energy X radiation [11]. A companion manual on the use of Gafchromic™ film for dose mapping using scanning is also available [12]. This manual is available from the IAEA web site together with the associated Excel workbook [13].

The original *Dosimetry System for SIT: Manual for Gafchromic® film* was developed by Dr Kishor Mehta under IAEA contract 2000CL9124 in 2004. This revised edition was developed by Dr Yeudiel Gómez-Simuta under contract TAL-NAFA20150922-001 and Mr Andrew G. Parker under contract TAL-NAFA20210531-003. The 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 gamma 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, 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.

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 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
- A to B type USB 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 button under "Select" (the FILM button) and then use the "Cycle" button 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).

Figure 6. Blank measurement message.

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

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

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 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.

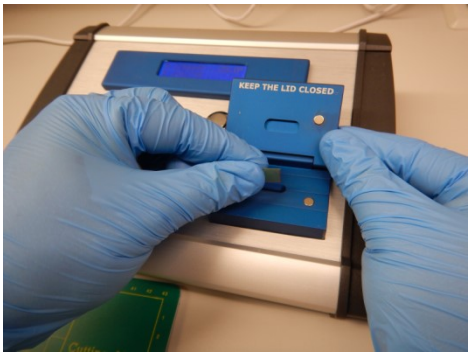


Figure 8. Inserting Gafchromic film into the DR4. The film should be handled with gloves or forceps.

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 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 expected.

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) and 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 might 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 [14]. The wavelength to be used for the present application is 590 nm. Variations in the thickness of the

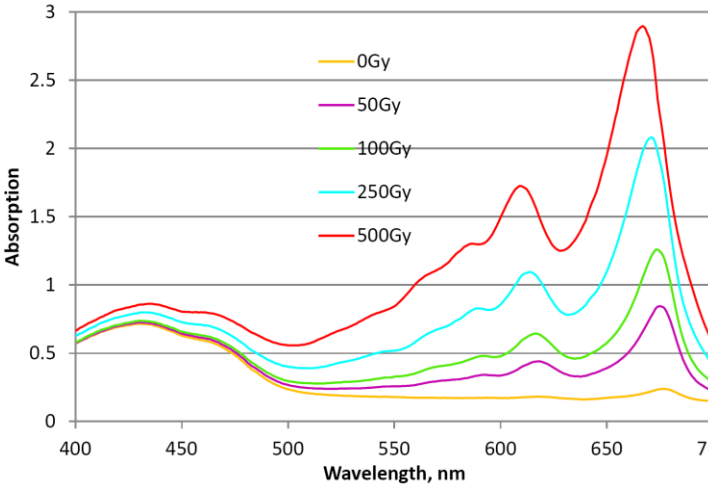


Figure 11. Absorption spectrum of Gafchromic™ HD-V2 film at various doses.

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 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.

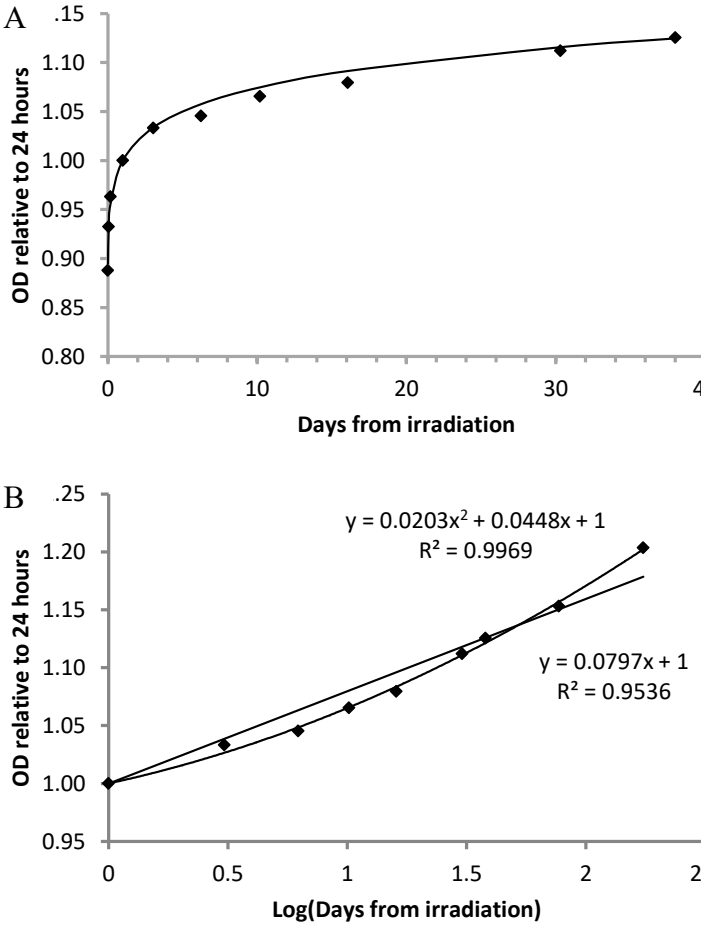


Figure 12. Change in OD of Gafchromic™ HD-V2 film with time. A: linear time up to 38 days; B: Log time to 174 days

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 [15]. 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. [16] 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 keep the dosimeter free of any dust or other contamination. Also, 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.

2.3.1. 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

The reliability of dose measurement using the Gafchromic™ dosimetry system depends mainly 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. The most often used transfer-standard dosimeter is alanine; for a list of possible suppliers see the Appendix A (see section 3.4). Other suitably calibrated dosimeters can be used, such as an ion chamber of Fricke but these are outside the scope of this SOP.

If there is more than one irradiator available, 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 a cobalt-60 irradiator can be used for a cesium-137 irradiator and vice-versa, but cannot be used for low energy X-rays (up to 300 kVp). Conversely, a calibration in low-energy X-ray cannot be used for ^{60}Co or ^{137}Cs.

3.2 Reference radiation field

When gamma rays from ^{60}Co strike a container of insects in the irradiation chamber, many of the γ-photons (1.2 MeV) 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 (about 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 γ-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

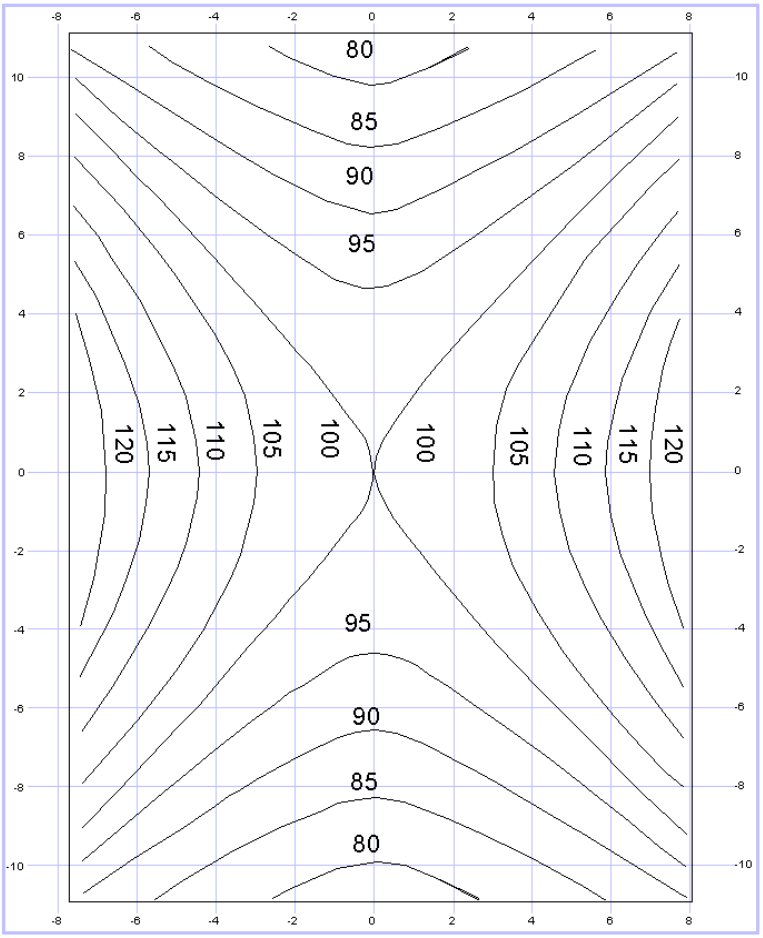


Figure 14. Typical dose-rate distribution in the irradiation chamber of a Nordion Gammacell-220. The values are normalised to 100 in the centre of the gamma field. Note that the field is most uniform in the centre. (Grid is at 2 cm intervals from the centre of the chamber). Re-drawn from Nordion data.

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 higher or lower dose than expected. For ^{60}Co the equilibrium distance is about 4mm in water or plastic, such as PMMA, and this amount of material must be provided around every dosimeter and sample to be irradiated..

There are two main types of isotopic irradiators that are used for the SIT, either for research or commercial irradiation. For both types, it is important that the dose is as uniform as possible at the reference point where the dose rate is to be established, and later where the Gafchromic™ dosimeters are irradiated for calibration.

Self-contained irradiators: In this case, the radioactive source pencils or elements are generally arranged around the circumference of a cylinder and the sample to be irradiated is located within this cylindrical volume. For such a case, the sample/dosimeter receives radiation from all directions and thus the radiation field in the centre of this volume is quite uniform. The Nordion or Sheppard Gammacell and Husman irradiators fall into this category.

The Gammacell has several ^{60}Co pencils and thus the radiation field is more symmetrical and uniform compared to that for the Husman irradiator which has source pencils only at three locations around the circumference. Fig. 14 shows a typical dose-rate distribution in air in the irradiation chamber of a Nordion Gammacell-220. The new models of self-contained irradiators such as the Foss Therapy Services Model 812, have the source pencils on one side of the cylindrical sample container which is rotating in its own axis during the irradiation process. In this case the sample/dosimeter receives radiation over the complete surface of the container but the dose rate at the edge of the container is higher than at the centre.

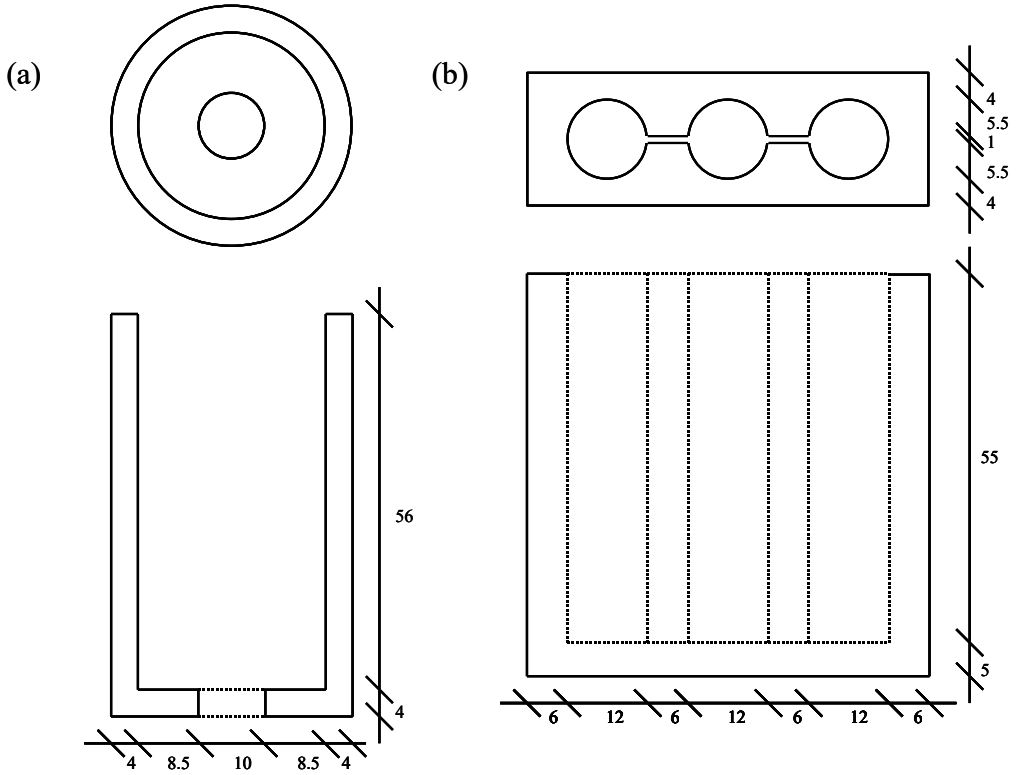


Figure 15. Two dosimeter holder designs for use with different types of irradiators. Recommended material is PMMA. (a) for self-contained irradiators, note hole in the bottom that facilitates natural air circulation; (b) for panoramic irradiators. All dimensions are in mm.

Panoramic irradiators: The source generally consists of several radioactive pencils arranged in a plane or as a single rod. For routine irradiation, either the sample is located stationary in front of this source, or it passes by or around the source. For this type of irradiator, the sample receives radiation from one side at a time. The spatial uniformity of dose for a stationary sample may be improved by either continuously rotating it during irradiation or turning it through 180º after half of the total irradiation time.

3.3. Reference irradiation conditions

3.3.1. Irradiation geometry

The placement of the dosimeters at a fixed reference location (within the reference radiation field) should be consistent to achieve reproducible results. This can be achieved by (i) using a specially designed dosimeter holder, and (ii) arranging a set of reference marks in the irradiation chamber so that the holder can be placed in exactly the same position each time.

Self-contained irradiators: Figures 15a and 16a show a dosimeter holder designed for this type of irradiator. It is made of PMMA (any polymeric material is acceptable except halogenated ones) and is an open cylinder (like a cup) with the inside diameter (~ 26 mm) just

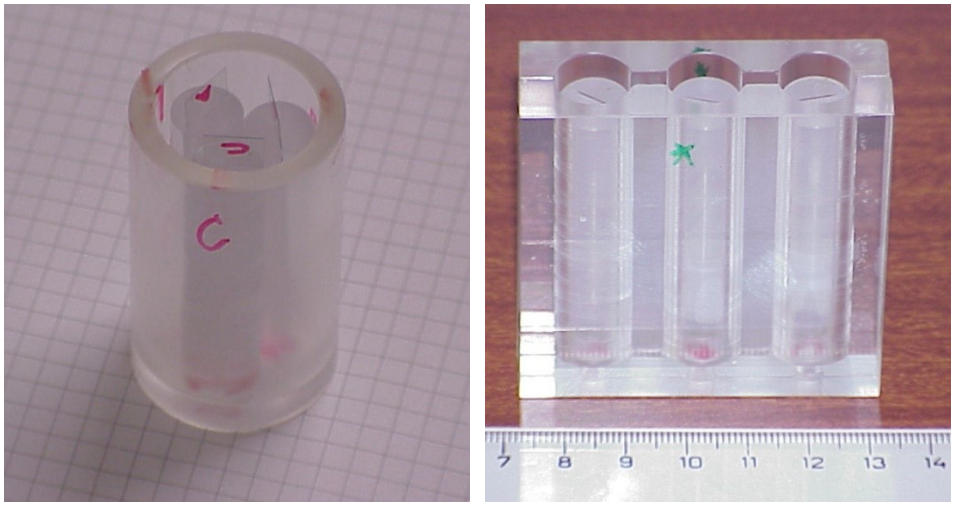


Figure 16. Two types of dosimeter holders to accommodate three dosimeters for simultaneous irradiation: (a) this cylindrical (open cup) type is suitable for irradiation in self-contained irradiators like Gammacell and Husman-type, where the gamma source surrounds the dosimeters and the field is isotropic, and (b) this flat holder is suitable for panoramic irradiators which have a plane or a rod source and the gamma field is unidirectional. These holders are made of PMMA.

large enough to accommodate three dosimeters, each being about 12 mm in diameter. The wall thickness (4 mm) of the holder is selected to provide the optimum amount of material for achieving electron equilibrium for ^{60}Co gamma rays. This standard design is recommended for use in all Gammacell-220 irradiators. Such a holder can also be used for Hussman irradiators containing ^{137}Cs by modifying the design of the base to fit within the irradiation chamber. For both types of irradiators, the dosimeter holder should be located in the irradiation chamber so that the dosimeters are at the centre of the radiation field, where the dose rate is most uniform (Fig. 14). Also, some method should be available to position this holder reproducibly at the same location in the reference field; Figs 17 and 18 show a standard support design for the Gammacell-220. For irradiation in a Gammacell-220, place this stand in the irradiation chamber and then place the dosimeter holder (Fig. 16a) securely on top of this. This ensures that the dosimeters placed in the holder are always at the same location in the radiation field, and if the dimensions are correct the centre of the dosimeters is at the centre of the radiation field.

Panoramic irradiators: Even though the sample (pupae container) may be moving past the radiation source for routine irradiation, it may be necessary in some cases that the dosimeters are *stationary* for the dose-rate measurement and also for calibration irradiations (Section 4.1). Figures 15b and 16b show a dosimeter holder designed for this type of source. It should preferably be located at approximately the same distance from the source as the sample generally is during routine irradiation (to experience similar dose rate). As mentioned above (Section 3.2), the holder should be rotated continuously during irradiation. Alternatively, it should be turned through 180º around the vertical axis after half the irradiation time. In this case, care should be taken to position the holder at the same location after rotation.

3.3.2. Irradiation temperature

Because the response of nearly all dosimeters depends on the dosimeter temperature during irradiation, measure or estimate the temperature of the transfer-standard dosimeters during irradiation. Generally, the temperature should be determined within 2-3°C, and preferably it should be controlled.

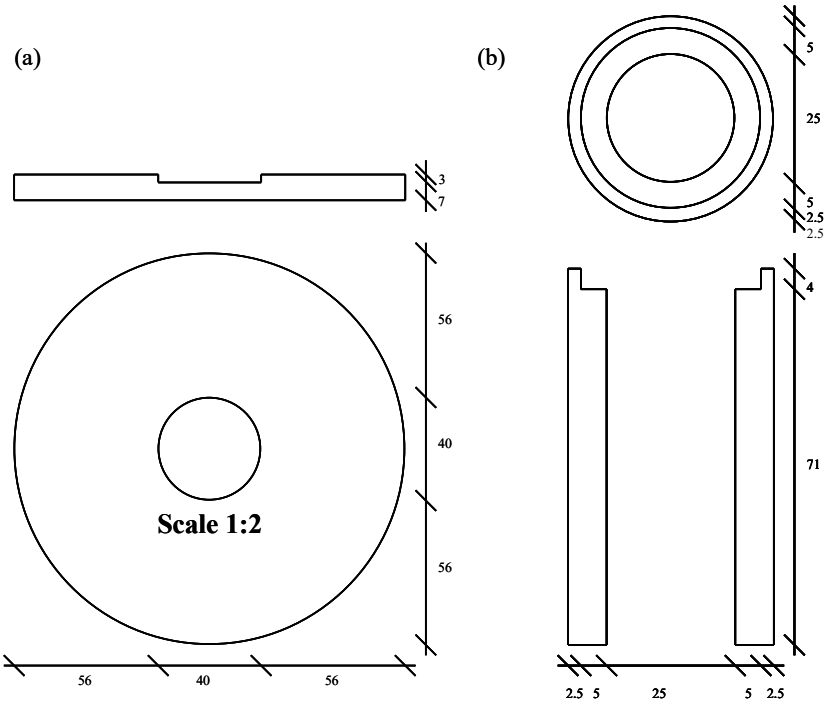


Figure 17. Typical support design (stand) for dosimeter holder for use in a Gammacell. Recommended material is PMMA. All dimensions are in mm.

3.4. Transfer-standard dosimeter

There are several dosimetry laboratories that will issue and analyze traceable transfer-standard dosimeters suitable for the purpose. These are either primary-standard dosimetry laboratories or other accredited dosimetry calibration laboratories. Some examples of such laboratories are given in the Appendix A.

Usually these are liquid dosimeters contained in 12-mm-diameter ampoules or alanine pellets in holders. For the procedure in this manual, it is assumed that a set of three such dosimeters will be irradiated together for dose-rate measurement. If alanine pellets are used, the standards laboratory supplying the dosimeters should be requested to provide a suitably shaped dosimeter holder to fit the cup used for calibration. If the transfer dosimeters are of different dimensions, it may be necessary to redesign the dosimeter holders illustrated in Figs 15 and 16.

The irradiation time for these transfer-standard dosimeters should be adjusted for each facility depending on the dose rate, transit dose and the expected temperature rise. The objective would be to make the transit dose negligible (less than 0.5% of the dose given to the transfer dosimeters) without too much (<5°C) rise in the temperature of the dosimeter during irradiation.

Ensure that the timer used for time measurement is calibrated with traceability. (See the manufacturer's documentation on how to check the timer accuracy.)

If possible, control the dosimeter temperature during irradiation at 25ºC (or ask the standards laboratory if it has a preference). Alternatively, measure the dosimeter temperature during irradiation. If an easy method (for example a thermocouple) for measuring the temperature during irradiation is not available, measure the temperature of the dosimeters just before irradiation (minimum temperature) and immediately after irradiation (maximum temperature)

Figure 18. A cylindrical dosimeter holder (as shown in Fig. 15a is firmly placed on a PMMA stand for irradiation in a Gammacell. This stand consists of a circular base plate that just fits in the irradiation chamber of the Gammacell. In the centre of this plate is a tube on which the dosimeter holder is placed. The height of this tube should be such that, when the device is placed in the Gammacell, the centre of the dosimeters coincides with the geometric centre of the irradiation chamber. A mark may be placed on the base plate so that it is always placed in the same orientation in the irradiation chamber of the Gammacell. Also, a mark may be placed on the cylindrical dosimeter holder for reproducible positioning. A similar device must be used for a Hussman irradiator so that the dosimeters (in the cylindrical dosimeter holder) can be consistently placed at the same position in the gamma field.

by temporarily introducing a standard thermometer inside the dosimeter holder next to the dosimeters. Record both of these temperature values, and enter the information in the data sheet to be sent to the standards laboratory along with the irradiated dosimeters. If the dosimeter temperature was measured continuously, attach that information to the data sheet.

The standards laboratory will analyze the irradiated transfer dosimeters and return the results in the form of a certificate containing the dose value as measured by the dosimeters, and also information regarding uncertainty in this value. Record all the data in Form-SIT-3.

3.5. Dose rate

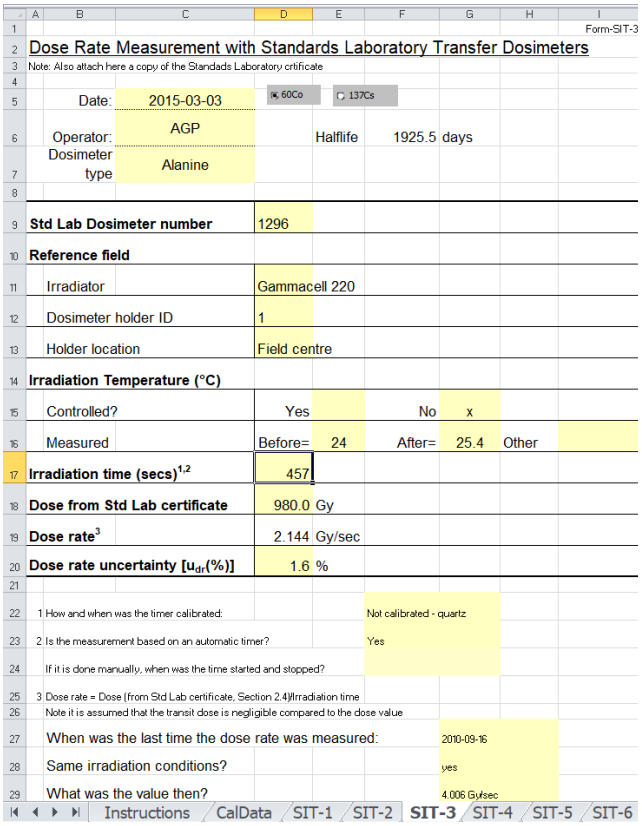
Each laboratory then should calculate the dose rate from the dose value given in this certificate and the irradiation time (assuming that the transit dose is negligible), as follows:

> Dose rate = Dose / Irradiation time; the dose rate may be expressed in kGy/hour, Gy/min or Gy/s.

Record this value of dose rate in Form-SIT-3 (Fig. 19). This value is valid for the specific irradiation conditions employed and for the day of irradiation. However, it is independent of the irradiation temperature. Ensure the correct isotope (^{60}Co or ^{137}Cs) corresponding to your irradiator is selected at the top of Form-SIT-3.

3.6. Frequency of dose rate measurement

For ^{137}Cs sources, which comprise a variable mixture of two isotopes with different half-lives, the dose rate should be measured every three years or sooner if any relevant part of the irradiation system is altered, such as replenishment of the source, or modification to movement mechanism or irradiation set up that can affect the dose rate. For ^{60}Co sources, which contain only one isotope and hence the decay rate can be calculated with high precision, re-measurement of the dose rate is only necessary following alteration to the system.



Form-SIT-3

Dose Rate Measurement with Standards Laboratory Transfer Dosimeters

Note: Also attach here a copy of the Standads Laboratory crtificate

Date:	2015-03-03	◉ 60Co	○ 137Cs		
Operator:	AGP		Halflife	1925.5	days
Dosimeter type	Alanine				
Std Lab Dosimeter number	1296				
Reference field					
Irradiator	Gammacell 220				
Dosimeter holder ID	1				
Holder location	Field centre				
Irradiation Temperature (°C)					
Controlled?	Yes		No	x	
Measured	Before=	24	After=	25.4	Other
Irradiation time (secs)[1,2]	457				
Dose from Std Lab certificate	980.0	Gy			
Dose rate[3]	2.144	Gy/sec			
Dose rate uncertainty [u_{dr}(%)]	1.6	%			

1 How and when was the timer calibrated: Not calibrated - quartz

2 Is the measurement based on an automatic timer? Yes

If it is done manually, when was the time started and stopped?

3 Dose rate = Dose (from Std Lab certificate, Section 2.4)/Irradiation time

Note it is assumed that the transit dose is negligible compared to the dose value

When was the last time the dose rate was measured: 2010-09-16

Same irradiation conditions? yes

What was the value then? 4.006 Gy/sec

Instructions | CalData | SIT-1 | SIT-2 | **SIT-3** | SIT-4 | SIT-5 | SIT-6

Figure 19. Form-SIT-3 for recording the dose rate calibration information.

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 a lot, and
- determination of total uncertainty in the measured dose value.

Procedure for each of these is described below.

The various characteristics of the current dosimeter lot are summarised on Form-SIT-9 while the calibration data is entered in Form-SIT-4 and CalData.

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. Preparing films

- Cut ten 10 × 10 mm dosimeters from the Gafchromic sheet for measuring the background OD.
- Cut three strips 10 × 50 mm for each calibration dose (18 in total).
- Cut three strips 10 × 50 mm for each of the two transit dose measurements (total 6).
- Cut nine 10 × 10 mm dosimeters for measuring the film homogeneity.

Store each set of films separately in paper envelopes.

4.1.2. Background OD

A measure of the OD value of the unirradiated film for each dosimeter lot is required.

If the lot lasts longer than 6 months, this measurement should be repeated and the OD(bkgd) value updated. Measure a new set of ten 10 × 10 mm dosimeters using the DR4 onto a blank sheet, then copy the three columns for the background films and overwrite the values in C12:E21 of the sheet CalData.

4.1.3. Calibration doses

Calibration irradiation should be performed at 6 dose levels. 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

	A	B	C	D	E	F	G
1							Form-SIT-4A
2	Gafchromic Dosimetry System Calibration: Irradiation						
3							
4	Date:	2016-06-29					
5							
6	Reference field and dosimeter holder:			Field centre holder 1			
7	(should be the same as those used for the dose rate measurement with transfer dosimeter (Form-SIT-3))						
8							
9	Dose rate of today (from section 3.1):			1.802			
10							
11	Operator:	ANGE					
12	Filter:	590nm/458nm					
13							
14	Dose (Gy)	Calculated Irrad	Actual Irrad.	Nominal	Start	Finish	Temp(eff)[3]
15		time (sec)	time (sec)[1,2]	Dose	Temp	Temp	
16	50	28	24	43.2	21.3	22.4	22.0
17	70	39	35	63.1	23.0	23.3	23.2
18	90	50	46	82.9	24.0	24.0	24.0
19	110	61	57	102.7	24.0	23.8	23.9
20	130	72	68	122.5	24.0	24.1	24.1
21	150	83	79	142.3	24.0	24.3	24.2
22						T(cal)=	23.6
23	1 When and how was the timer calibrated			Not calibrated			
24							
25	2 Is this measurement based on an automatic timer?			Yes			
26							
27	If it is done manually, when was the timer started and stopped?						

Figure 20. Completing calibration details on Form SIT-4

(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 the selected calibration doses in the first column of Form-SIT-4A (Fig. 20, cells A16:A21). The required irradiation time (in seconds) is displayed in column B so long as Form-SIT-3 has been completed and the date of the calibration has been entered in cell G4 of CalData. The time is calculated as:

Irradiation time = Dose / Dose rate (of today)

The dose rate used here is supplied by the spread sheet but can be calculated from the most recent value measured (Section 3.5) and corrected for radioactive decay from that day till 'today' (ensure the correct isotope has been selected on Form-SIT-3). It is calculated as: Dose rate (of today) = Dose rate (Section 3.5) $e^{-\lambda\Delta t}$, where, Δt = decay time (in days), $\lambda(^{60}Co)$ = 3.5991×10^{-4} d^{-1} and $\lambda(^{137}Cs) = 6.3097 \times 10^{-5}$ d^{-1}. These decay constants are based on half-lives of 1925.5 days for ^{60}Co, and 30.07 years for ^{137}Cs.

Enter the actual times used for the exposures in C16:C21 if these differ from the calculated values for any reason.

4.1.4. Film exposure

Irradiate Gafchromic™ dosimeters at the same reference location where the dose rate was determined, and with the same irradiation geometry using the same dosimeter holder. Figures 21 and 22a show a standard design of PMMA cylindrical film holder that is compatible with the geometries of dosimeter holders of Figs 15a and 15b. There are three such film holders; identify them by writing A, B or C at the bottom (uncut end) of the holders with a felt pen. For each dose in the calibration label three 10 × 50 mm strips with the dose and identify them by writing A, B or C at one end of each film with a felt pen.

Figure 21. Three film holders with Gafchromic™ dosimeters are placed in a cylindrical dosimeter holder for irradiation in a Gammacell. Note that each film holder is placed so that the film is parallel (tangential) to the curved surface of the dosimeter holder. For a flat dosimeter holder, the film holders should be placed so that the films are parallel to the longer face of the dosimeter holder.

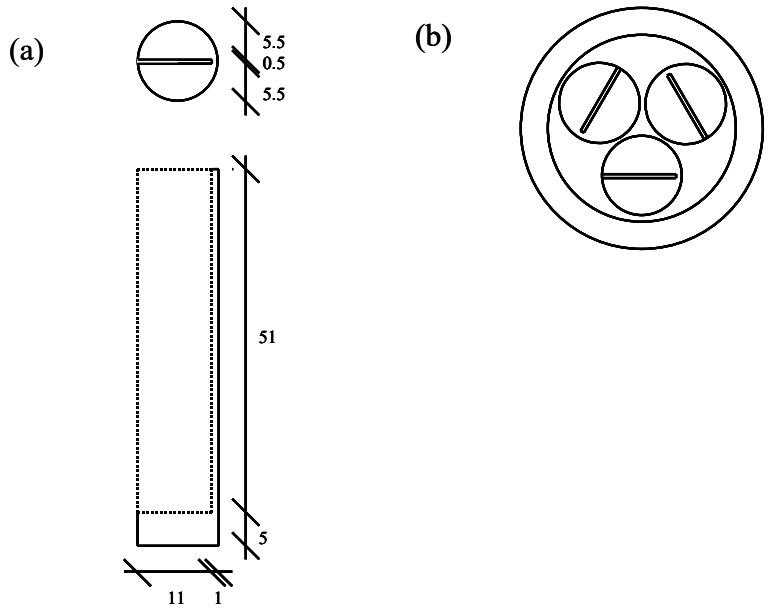


Figure 22. (a) Gafchromic™ film holder and (b) the arrangement of three such holders in the cylindrical dosimeter holder. Note that all the three films are parallel (tangential) to the curved surface of the dosimeter holder. All dimensions are in mm.

Starting with the lowest dose, insert the film strip (holding it with a pair of tweezers at the marked end) in the slot in the film holder. Then insert three such film holders in the dosimeter holder (either Fig. 15a or 15b) for simultaneous irradiation similar to three transfer-standard dosimeters. Arrange these film holders so that each film is parallel to the adjacent wall of the dosimeter holder as shown in Fig. 22b (also see Fig. 21). To keep the film holders from rotating within the dosimeter holder, you may place a small piece(s) of paper between them. For a flat dosimeter holder, the film holders should be placed so that the films are parallel to the longer face of the dosimeter holder. Mount the dosimeter holder on the stand at the reference position in the irradiator and expose for the indicated time. Store each set of films after exposure in a separate labelled envelope.

Figure 23. Three dosimeters in a cylindrical dosimeter holder on a stand are prepared for irradiation in a Gammacell. Thermocouples are used to measure the temperature throughout the irradiation, where the thermocouple junction is located inside the dosimeter holder next to the dosimeters. A black tape is used to hold the wires firm in position. The wires leave the irradiation chamber through the central access tube to the recording device situated outside the Gammacell.

4.1.5. Temperature measurement

Measure the dosimeter temperature throughout irradiation (Fig. 23). If this is not possible, measure the minimum temperature (just before starting irradiation) and the maximum

temperature (immediately after irradiation) of the dosimeters (see Section 3.4 for details of how to measure these). Enter the temperatures for each exposure in E16:F21. The effective temperature, T_{eff} is calculated as follows:

For continuous measurements: T_{eff} = average of all measurement values,
For before/after measurements: $T_{eff} = T(before) + 2/3\ (\Delta T)$,
where, $\Delta T = T(after) - T(before)$.

If possible, control the temperature so that T_{eff} for all irradiations is within 2°C. The calibration temperature, T_{cal} is the average of the six T_{eff} values. Routine dosimetry must be carried out within ±5°C of the T_{cal} (see 2.3.5.).

4.1.6. Lot homogeneity

The homogeneity of the film is measured by exposing nine randomly selected 10 × 10 mm dosimeters simultaneously in a single paper dosimeter envelope to the same dose and then measuring the responses.

4.1.7. Transit dose and Transit time

Transit dose is defined as the dose a sample or dosimeter receives while either the source is moving or the sample/dosimeter is moving. Transit time is then defined as:

Transit time = Transit dose / dose rate,

where, dose rate refers to its value at the stationary irradiation position.

Transit time is not the physical transit (or movement) time of the dosimeters (or source), which is to say the actual time the dosimeters take to go up and down. As an approximation, the transit time is one quarter of the actual time the dosimeters take to go up and down. If the transit dose is significant compared to the minimum dose of interest (namely, 40 Gy for SIT), it is essential that this value be added to the nominal dose values (40, 80, etc. Gy, see Section 4.1.3) before the calibration relation is determined. We will assume here that if the transit time is less than 0.5% of the minimum irradiation time (i.e., 40 Gy/dose rate), then the transit time (dose) may be ignored. For Gammacell-220 (Nordion), transit time is approximately 4 s, thus transit time(dose) may be ignored for those irradiators which have a dose rate less than about 3 Gy/min.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
84		9	0.7493	0.6395	28.5	1.1717	0.7493	0.6395						
85	Transit dose 1	A1	0.5699	0.6039	28.6	0.9437	0.9521	0.9291						
86	N1=	A2	0.5667	0.5952	28.6	0.5699	0.5667	0.5529						
87	1	A3	0.5529	0.5951	28.6	0.6039	0.5952	0.5951						
88		B1	0.5669	0.5977	28.6	0.9485	0.9369	0.9392						
89	7 sec *	B2	0.5613	0.5991	28.6	0.5669	0.5613	0.5515		<= * Select a time in seconds between 15 and 29				
90	plus 1 x 1 sec	B3	0.5515	0.5872	28.6	0.5977	0.5991	0.5872						
91		C1	0.558	0.5909	28.6	0.9443	0.9421	0.936						
92		C2	0.5518	0.5857	28.6	0.558	0.5518	0.5399						
93		C3	0.5399	0.5768	28.6	0.5909	0.5857	0.5768						
94	Transit dose 2	A1	0.6163	0.6014	28.6	1.0248	1.0143	1.0185						
95	N2=	A2	0.6032	0.5947	28.7	0.6163	0.6032	0.6045						
96	2	A3	0.6045	0.5935	28.6	0.6014	0.5947	0.5935						
97		B1	0.6159	0.6013	28.7	1.0243	1.0313	1.0103						
98	6 sec	B2	0.6158	0.5971	28.7	0.6159	0.6158	0.5983						
99	plus 2 x 1 sec	B3	0.5983	0.5922	28.7	0.6013	0.5971	0.5922						
100		C1	0.6169	0.6026	28.7	1.0237	1.025	1.0049						
101		C2	0.6156	0.6006	28.7	0.6169	0.6156	0.5998						
102		C3	0.5998	0.5969	28.7	0.6026	0.6006	0.5969						
103		ND0.5	0.4804	0.5533	28.7	0.4804	0.9792	2.0301						
104		ND1.0	0.9792	1.0821	28.7									
105		ND2.0	2.0301	2.2408	28.7									

Figure 24. CalData Transit dose setup.

To measure this, two extra sets of three strips are exposed to the same total time but with the time divided into several parts. Select a time not less than the time for the minimum dose of your calibration sequence and enter the value in CalData cell A89 (Fig. 24); the recommended range is indicated to the right. Next, select two small numbers (say 1 and 2) and enter these in CalData A87 (N1) and A96 (N2). The first extra film set is exposed first for the time in A89 and for one second the number of times in A90, the second set first to the time in A98 then for one second the number of times in A99. The total exposure time is, therefore, the same (7 + 1 and 6 + 1 + 1 seconds)but with additional transit doses (1 and 2 in this example). Label the two sets of transit dose film strips with the time for the initial exposure (7 and 6 seconds in this example) and the number of additional exposures of 1 second (1 and 2) plus A, B and C to distinguish the three strips. Expose the films as in 4.1.4.

If it is already known that the transit dose is insignificant at the expected treatment dose the calculation of the transit dose can be turned off using the radar button at the top of Form-SIT-4C.

4.1.8. Reading the films

Ensure the DR4 is correctly connected and the driver and RGwedge software installed (Section 2.2.). Plug the DR4 into a USB port on the computer and follow the instructions in the DoseReader manual to determine the COM port to which it is attached. Open the Excel workbook and select the appropriate sheet, CalData. Open the RGwedge program, select the COM port to which the DR4 is attached, select Write to window, click Connect and immediately select the bright yellow cell near the top of the work sheet (labelled Start here>). Clicking Connect causes the DR4 to reboot and send the header information to the COM port. RGwedge will direct the data to the active cell in the Excel workbook (Fig. 10).

Now enter the appropriate details of date, operator and Gafchromic™ film Lot No. in the pale yellow cells. Switch to sheet SIT-4 and enter the data needed in the yellow cells, 1) calibration dose targets, 2) actual irradiation time, 3) start and finish temperatures (Fig. 20) and transit dose numbers (Fig. 24). Change back to the CalData sheet and make sure the correct cell (Fig. 10, cell C9) is still selected.

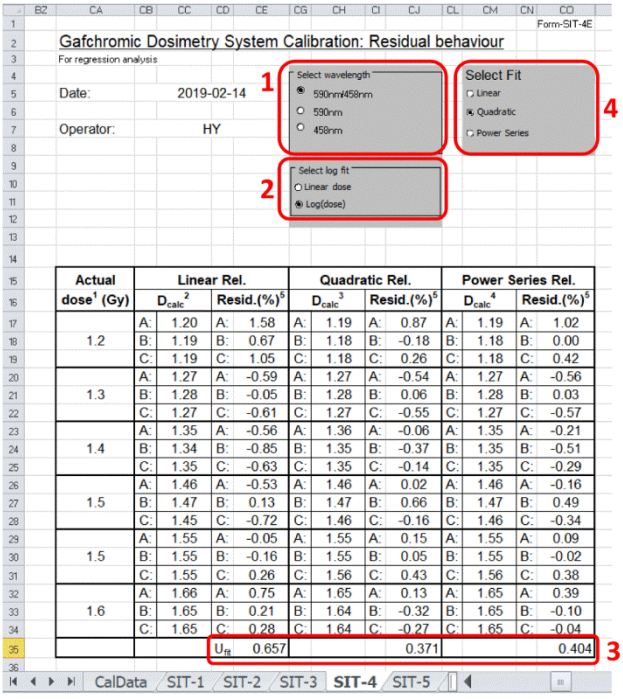
Starting with the ND films, read all the films following the sequence in the first column. For the 10 × 50 mm strips, cut three 10 × 10 mm pieces from each strip and read them in sequence. When one strip has been read remove the third film and close the DR4 lid to allow it to take a blank reading. Do not open the lid until the reader bleeps and you see the background measurement on the display (Fig. 7). Then continue with the next films. After the calibration pieces read the nine homogeneity films, then the two transit dose sets, and finally the ND filters once again. The data is automatically transferred to the calibration sheet (SIT-4). Replace the sets of dosimeters in their respective envelops so that they may be identified for rereading if necessary.

4.1.9. Selection of the calibration relationship

Once all the films have been read the final relationship can be selected. The calculations are all shown in the spread sheet SIT-4. Examine the data, and in particular the CV% values (Form-SIT-4B) to look for any errors in data entry, and faulty or damaged films. The CV% values should mostly be less than 1% and the three R values within one dose should be close.

The transit dose calculation is shown on Form-SIT-4C and the following graph. The two transit dose points should be equally spaced above the lowest calibration dose. The transit time is shown at the foot of Form-SIT-4C. For a GC220 this value will be close to 4 seconds but may differ significantly for other irradiator designs.

The response curves and residual plots follow Form-SIT4D. Linear, quadratic and power series plots are provided. Ideally the value of the residuals should be small and show no specific trend. The residual data is summarized on Form-SIT4E to the right of the graphs.


Gafchromic Dosimetry System Calibration: Residual behaviour

For regression analysis

Form-SIT-4E

Date: 2019-02-14

Operator: HY

1 Select wavelength: 590nm/458nm; 590nm; 458nm

2 Select log fit: Linear dose; Log(dose)

4 Select Fit: Linear; Quadratic; Power Series

Actual dose[1] (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]
1.2	A: 1.20	A: 1.58	A: 1.19	A: 0.87	A: 1.19	A: 1.02
	B: 1.19	B: 0.67	B: 1.18	B: -0.18	B: 1.18	B: 0.00
	C: 1.19	C: 1.05	C: 1.18	C: 0.26	C: 1.18	C: 0.42
1.3	A: 1.27	A: -0.59	A: 1.27	A: -0.54	A: 1.27	A: -0.56
	B: 1.28	B: -0.05	B: 1.28	B: 0.06	B: 1.28	B: 0.03
	C: 1.27	C: -0.61	C: 1.27	C: -0.55	C: 1.27	C: -0.57
1.4	A: 1.35	A: -0.56	A: 1.36	A: -0.06	A: 1.35	A: -0.21
	B: 1.34	B: -0.85	B: 1.35	B: -0.37	B: 1.35	B: -0.51
	C: 1.35	C: -0.63	C: 1.35	C: -0.14	C: 1.35	C: -0.29
1.5	A: 1.46	A: -0.53	A: 1.46	A: 0.02	A: 1.46	A: -0.16
	B: 1.47	B: 0.13	B: 1.47	B: 0.66	B: 1.47	B: 0.49
	C: 1.45	C: -0.72	C: 1.46	C: -0.16	C: 1.46	C: -0.34
1.5	A: 1.55	A: -0.05	A: 1.55	A: 0.15	A: 1.55	A: 0.09
	B: 1.55	B: -0.16	B: 1.55	B: 0.05	B: 1.55	B: -0.02
	C: 1.55	C: 0.26	C: 1.56	C: 0.43	C: 1.56	C: 0.38
1.6	A: 1.66	A: 0.75	A: 1.65	A: 0.13	A: 1.65	A: 0.39
	B: 1.65	B: 0.21	B: 1.64	B: -0.32	B: 1.65	B: -0.10
	C: 1.65	C: 0.28	C: 1.64	C: -0.27	C: 1.65	C: -0.04
		U_{fit} 0.657		0.371		0.404

3

CalData SIT-1 SIT-2 SIT-3 SIT-4 SIT-5

Figure 25. SIT-4E Selecting wavelength and fit.1: Wavelength 2: Log/linear 3: Uncertainty of fit 4: Fit equation.

The objective is to get the best fit (= smallest residuals) (Fig. 25). By trial, examine the U_{fit} values (3) for different combinations of wavelength (1) and log/linear (2). With the combination that gives the lowest U_{fit} value, select the radio button of the fit (column) with the smallest U_{fit} in the box (4). In Fig. 25 the ratio of wavelengths 590nm/458nm and log(dose) give a U_{fit} of 0.371 with the quadratic relationship. Quadratic is selected in the Select Fit radar button box (4). U_{fit} values less than 1 indicate a good fit. Values greater than 2 indicate a problem with the fit, and the data in the Form-SIT-4B should be examined carefully to try to ascertain the source of the problem.

4.1.10. Manual calculation

To facilitate manual processing of the data and to explain what the work book is calculating, a description follows. All of these calculations are performed by the workbook.

The objective 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 'Rmean' on the y-axis vs 'Actual dose' on the x-axis as given in Form-SIT-4D. Draw a smooth curve through all the six points. This curve may be slightly non-linear. If it is significantly non-linear, try plotting the Rmean values against log(dose).

If regression analysis is employed, use the three 'Rcorr' values (as y-parameter) for each 'Actual dose' value (x-parameter). The relationship is almost linear, but quadratic or power fit may be better. The calibration relationships may be described as:

Linear function: $\quad$ Response = a + b (Dose)

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

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

The selection between the three can be made by observing the distribution of the percentage residuals for the three cases following the procedure given below (use Form-SIT-4E):

1. Calculate D_{calc} for each of the three response values (R_{corr}) for all six irradiations (as given in column 3 of Form-SIT-4D):

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

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

Power function: $D_{calc} = Exp((Log_e(Response)-f)/g)$

Enter these values in Form-SIT-4E, column 2, 4 or 6.

2. Determine the percentage residual for each point as:

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

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

3. Record these values of 'Residual(%)' in Form-SIT-4E (column 3, 5 or 7).
4. Plot 'Residual(%)' (on y axis) vs 'Actual dose' (on x axis) for the linear as well as for the quadratic and power fits.
5. Select the relationship that yields random distribution of the residual values as a function of dose. If each shows similarly random distribution, select the linear function as the calibration relationship.

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). Enter the date of calibration, the calibration irradiation temperature, T_{cal} and the calibration relationship in Form-SIT-9.

Calculate the root-mean-square residual (u_{fit}) value for the selected calibration relationship, as follows:

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

Where, n is the total number of residual values (18 in this case), and the summation to be carried over all these n (=18) values. Record this value in Form-SIT-9. This value represents the uncertainty arising from the fitting procedure and will be used later in Section 4.3.

4.1.11. Frequency of calibration

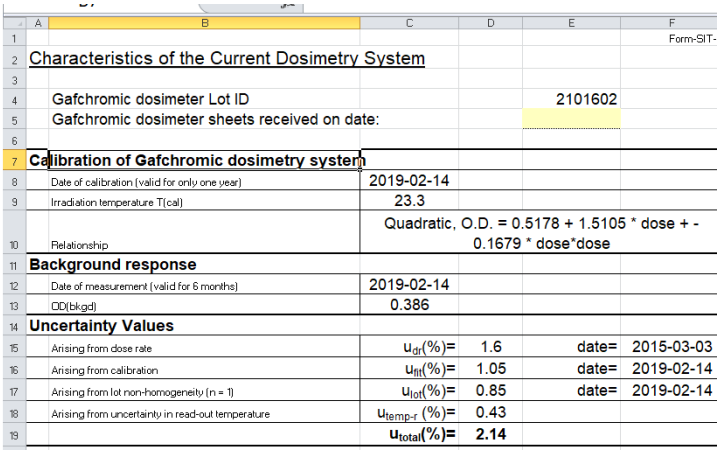
The dosimetry system should be calibrated once a year or sooner if any part of the dosimetry system is changed, such as, a new dosimeter lot or repairs to the reader.

4.2. 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 [17].

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 a 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. These calculations are presented on Form-SIT-9 (Fig. 26). It is only necessary to enter manually the date of receipt of the batch of dosimeters.



	A	B	C	D	E	F
1						Form-SIT-
2		Characteristics of the Current Dosimetry System				
3						
4		Gafchromic dosimeter Lot ID			2101602	
5		Gafchromic dosimeter sheets received on date:				
6						
7		**Calibration of Gafchromic dosimetry system**				
8		Date of calibration (valid for only one year)	2019-02-14			
9		Irradiation temperature T(cal)	23.3			
10		Relationship	Quadratic, O.D. = 0.5178 + 1.5105 * dose + - 0.1679 * dose*dose			
11		**Background response**				
12		Date of measurement (valid for 6 months)	2019-02-14			
13		OD(bkgd)	0.386			
14		**Uncertainty Values**				
15		Arising from dose rate	u_{dr}(%)=	1.6	date=	2015-03-03
16		Arising from calibration	u_{fit}(%)=	1.05	date=	2019-02-14
17		Arising from lot non-homogeneity (n = 1)	u_{lot}(%)=	0.85	date=	2019-02-14
18		Arising from uncertainty in read-out temperature	u_{temp-r} (%)=	0.43		
19			**u_{total}(%)=**	**2.14**		

Figure 26. Form-SIT-9 showing the summary of uncertainty components.

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

- u_{dr} arising from uncertainty in the dose rate value at the reference location (from certificate from the standards laboratory, see Section 3.4),
- u_{fit} arising from uncertainty in the calibration relationship (see Section 4.1.9),
- u_{lot} arising from lot non-homogeneity (= CV(%) value from Form-SIT-5, see Section 4.1.5). If n dosimeters are used at one location to measure dose, the uncertainty in the mean value of the measured dose value is reduced by $\sqrt{n}$. Thus, this component of uncertainty for n dosimeters = CV(%)/$\sqrt{n}$.
- u_{temp-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, u_{temp-r} = 0.7x5/$\sqrt{3}$ 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 [17].

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

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

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 $D_{measured} \pm 2u_{total}$.

4.3. Use of the calibration relationship

4.3.1. Point measurement

To measure dose at a point, follow the procedure given below. Use Form-SIT-7 for this procedure when a single dosimeter is used at each location and Form-SIT-8A when 2-3 dosimeters are used at each location.

Irradiation:

1. Place one 1cm x 1cm dosimeter (or several) from the calibrated lot at each point of interest. Use a small envelope for the dosimeter(s) and write the relevant identification and information on the envelope. For gamma radiation, more than one dosimeter may be placed in one envelope.
2. Irradiate the sample (with the dosimeters).

3. Estimate the temperature (T_{eff}) of the dosimeter during irradiation (Section 4.1.4).
4. Turn the reader ON, by connecting the DR4 to the PC, the reader should have about 5 minutes to stabilize. (Note: These measurements are made 20 to 28 hours after irradiation)
5. Measure the OD following the instruction given in the section 2.2.4. (Routine operation for OD measurement) starting the DR4 in cell P4 of Form-SIT-6 for individual dosimeters or X5 of Form-SIT-8a for multiple dosimeters.
6. Measure the OD of the three ND filters before starting the measurements with the dosimeter films. Compare these OD values with those measured during the calibration of the dosimetry system. Different values indicate a problem with the reader (Note: the last digit may differ, which is acceptable).
7. Remove the dosimeter(s) from the envelope and measure its OD (Section 2.2.5).
8. Insert the date of exposure (T4), Target dose (F9), description of the dosimeters (column O, e.g. location, purpose of measurement), and additional remarks (column F) when using Form-SIT-6.
9. Insert date (D4), Batch/run ID (D7), operator (D9), and description of the dosimeters (column W, e.g. location, purpose of measurement), when using Form-SIT-8a.

4.3.2. Process control

Form-SIT-8A is for process control and is used in conjunction with Form-SIT-8B. Form-SIT-8A accepts up to three dosimeter readings from one location, providing a mean and uncertainty estimate for each location. If only two dosimeters are used at a location leave one line blank following the procedure in section 4.3.1. Complete the additional information on Form-SIT-8B. For further details see section 6.

These forms would typically be used when insects are being supplied to an outside customer. Print these two forms for inclusion with the shipment.

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 sample is acceptable for the application on hand. This should be done before useful irradiation is carried out. If the distribution is wider than acceptable, it points out the need for modifying the irradiation procedure or the container 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 sample [5]. See Section 6.3 and Form-SIT-8B for examples of process parameters.

5.2. Procedure

Cut 10 × 10 mm dosimeters from an appropriate Gafchromic™ film sheet. Place at least three together in a dosimeter envelope. Fill the container to be dose mapped with the product normally irradiated, or a suitable dummy material, and arrange envelopes of dosimeters through the load, being sure to place envelopes at the expected location of maximum and minimum dose. Read the dosimeters after 24 hours on the DR4 using the calibration performed with the instructions above and record the mean and sd of the measured doses against the location of the dosimeter envelope. Use Form-SIT-7 for recording data.

In loads up to 20 × 25 cm, dose mapping can also be achieved by irradiating sheets of film and scanning them. Instructions for this are available in *Dose Mapping by Scanning Gafchromic Film to Measure the Absorbed Dose of Insects during Their Sterilization* [12].

5.3. Research application

If pupae are irradiated for research purpose, such as to establish the relationship between dose and its effect, it is inherently 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 container. The dosimeters should be protected in paper (envelopes) against contact with pupae.

5.4. 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 container 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 [12]. 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 irradiation is done.

5.5. Dose monitoring location

For process control during routine irradiation, it is sometimes necessary to place dosimeters in or on the pupae container (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, a dosimeter(s) may be placed at a monitoring location on the product container that is convenient. During the dose mapping exercise, select such a monitoring location and establish the relationship between the dose at this point 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.

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, use of radiation-sensitive indicators assists in streamlining the inventory process and gives confidence that each container 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 one envelope) at the location where the dose is expected to be a 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: container size, any specific arrangement of the pupae within the canister, positioning of the canister, irradiation time and rotation speed of the container (if applicable).

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 unirradiated 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.

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[2]

ISO/ASTM 51275 Practice for Use of a Radiochromic Film Dosimetry System
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
ISO/ASTM 52116 Practice for Dosimetry for a Self-Contained Dry-Storage Gamma-Ray Irradiator
ASTM E-1026 Practice for Using the Fricke Reference Standard Dosimetry System

[2] 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 – PROVIDERS OF TRANSFER-STANDARD DOSIMETERS

Examples of standards laboratories from where traceable transfer-standard dosimeters can be obtained. This is not an exhaustive list and does not constitute a recommendation by the IAEA.

Primary Standard Dosimetry Laboratories

Centre for Ionizing Radiation Metrology
National Physical Laboratory
Teddington, Middlesex
United Kingdom, TW11 0LW
Tel: +44 208 943-6647
Fax: +44 208 943-6680
E-mail: peter.sharpe@npl.co.uk or david.crossley@npl.co.uk
http://www.npl.co.uk/ionrad/services/mail.html

Ionizing Radiation Division
National Institute of Standards and Technology
Gaithersburg MD
U.S.A. 20899-8460
Stephen M. Seltzer
Tel: 301/975–555, E–mail: stephen.seltzer@nist.gov
Marc F. Desrosier
Tel: 301/975–5639, E-mail: marc.desrosiers@nist.gov
James M. Puhl
Tel: 301/975–5581, E–mail: james.puhl@nist.gov

Accredited Dosimetry Calibration Laboratories

Risø High Dose Reference Laboratory
Risø National Laboratory
Building NUK-201
Frederiksborgvej 399,
P.O. 49, DK-4000 Roskilde, Denmark
Tel: +45 46 774677,
Fax: +45 46 775688,
risoe@risoe.dk

MDS Nordion
Ion Technologies Customer Service Department
447 March Road
Ottawa, Ontario, K2K 1X8
Canada
Tel: +1 613 592 2790
Tel: +1 800 465 3666 (North America Only)
Fax: +1 613 592 6937
E-mail: ion.sales@mds.nordion.com

Aérial
Centre de Ressources Technologiques,
Rue Laurent FRIES – Parc d'innovation,
BP 40443 – 67412 Illkirch Cedex,
France,
Tel: +33 3 88 19 15 15 - Florent Kuntz
Fax: +33 3 88 19 15 20
www.aerial-crt.com

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** (MeVcm^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	1.853	1.844	1.005