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DOSIMETRY PROCEDURES IN ELECTRON PROCESSING

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ABSTRACT

Dosimetry is of basic significance in the various stages of electron processing: during characterization of the irradiation facility, in process validation, and in the routine control of the irradiation process. Various reference and routine dosimetry systems of solid and liquid state are in regular use for these procedures. The paper describes the basic role of dosimetry in the course of these processes including the applicability of various dosimeters.

INTRODUCTION

Electron accelerators are widely used in radiation processing, and the main applications include:

* Cross-linking of wires and cables (100 to 200 kGy),
* Curing (10 to 200 kGy),
* Sterilization (25 to 50 kGy), and
* Food processing (0.5 to 10 kGy).

Dosimetry plays an important role in controlling these processes by providing documentation that the radiation treatment has been carried out correctly. It is essential that the uncertainty of the dosimetry system is known and the system is traceable to a national standard. There are three basic stages in electron processing where dosimetry performs a vital function through the use of various types of dosimeters. These three stages are: the characterization of an irradiation facility, the validation of the irradiation process, and the process control during production [1,2,3].

DOSIMETRY SYSTEMS AND SELECTION CRITERIA

From the variety of dosimetry systems available for electron processing, it is important that an appropriate one be selected, carefully taking into account the actual purpose of irradiation and the expected irradiation conditions, such as dose, dose-rate and environmental effects.

Energy dependence of the dosimeter response is another factor to be considered; since the energy spectrum of the radiation field is usually not known, the dosimeter and the product should have very similar energy absorption/scattering characteristics. The size of the dosimeter should be such that it yields the required spatial resolution for detailed dose distribution measurements. The most commonly used systems are the following:

1. Calorimeters: Water and graphite calorimeters, used as reference systems, are applicable in the 4 to 10 MeV energy range for practical processing applications. The most commonly used systems have been designed, built and used at Riso National Laboratory, Denmark [4], National Institute of Standards and Technology, USA [5], and Whiteshell Laboratories, AECL Research, Canada [6]. The schematic view of the Riso-type water calorimeter is shown in Fig. 1. These instruments contain a thermistor placed in the water or graphite absorber for measurement of temperature rise due to irradiation. Absorbed dose can generally be calculated as specific heat multiplied by the temperature rise.

2. Liquid-state dosimeters: These types of dosimeters are not as widely used for electron processing as for gammas because of their relatively large size. For example, spatial resolution considerations exclude their application for dose distribution measurements. According to recent studies, however, potassium dichromate (10 to 40 kGy), ceric-cerous (1 to 100 kGy) and ethanol-monochlorobenzene (1 to 400 kGy) solutions - sealed in glass ampoules - are suitable for measurement of nominal dose and for reference dosimetry [7]. The dosimeters must be placed in phantoms for these purposes.

3. Solid-state dosimeters: The following solid-state dosimeters are the most commonly used systems in electron processing [8]:

DOSIMETERS	DOSE RANGE (kGy)
Radiochromic Dye Film:	
Gafchromic	0.1 - 40
FWT-60	0.5 - 100
B3 (Riso)	5 - 100
Cellulose Triacetate Film	5 - 300
Alanine (rod and film)	0.01 - 100
PMMA:	
Gammachrome	0.1 - 3
Amber Perspex	1 - 30
Red Perspex	5 - 50
Radix	5 - 50

Among all these systems, the thin radiochromic films are the most widely used both during dose mapping and for routine process control. However, because of their dependence on environmental conditions, their use needs careful consideration.

DOSIMETRY PROCEDURES

1. Characterization of the Irradiation Facility

The purpose of this procedure is to determine the principal characteristics of the facility. For example, the relationships between the operating parameters and the absorbed dose in a reference material must be established. In an electron irradiation facility, the dose depends on a number of operating parameters. For example, variation in the electron beam current affects the absorbed dose, whereas variation in the beam energy affects electron penetration and depth dose distribution. Thus the characterization of the facility consists of the measurement of the following parameters:

* nominal dose,
* electron energy,
* beam spot size,
* scan width and dose uniformity, and
* dose distributions in reference material(s).

The characterization of the facility must be carried out after its initial commissioning and whenever changes that can influence the dose are introduced. It is also suggested that this procedure be executed at regular intervals, for example, yearly.

1.1 Measurement of nominal dose

The aim of this procedure is to determine the relationships between the operating parameters and the absorbed dose in a specific geometry [9]. When the beam current, the beam energy and the scan width are kept constant, there is an inverse relationship between the dose and the conveyor speed. When, however, the conveyor speed is kept constant, the dose and the beam current are directly proportional to each other.

In electron irradiation facilities, the nominal dose can be measured by either a calorimeter (water or graphite), or a liquid or solid dosimeter placed in a phantom (Fig. 2).

1.2 Measurement of electron energy

A change in the electron energy affects the depth dose distribution and the absorbed dose in a product; hence, the determination of the electron energy is of basic significance. The most probable energy (E_p) and the average energy (E_a) of an electron beam at the surface of the product can be determined by the following formulas [11]:

$$E_p \text{ (MeV)} = C_1 + C_2 \cdot R_p \text{ , and}$$

$$E_a \text{ (MeV)} = C_6 \cdot R_{50}$$

where, R_p and R_{50} are, respectively, the practical range and the half-value depth in a homogeneous reference material. The values of the three constants C_1, C_2 and C_6 for water and aluminum have been determined empirically and may be found in Ref 11. Relationships between R_p in water and in other low-atomic-number materials are also given in this reference.

The range parameters can be determined by using the wedge technique along with a thin film dosimeter strip, such as FWT-60, B3, or Gafchromic [p 97, 8]. The details of the experimental setup and the resulting depth dose profile are shown in Fig. 3.

1.3 Measurement of beam spot size

When using a scanned and a pulsed electron beam, it is important to know the dose distribution within a single pulse. This information will assist in ensuring the proper overlap between the pulses and scans, thus avoiding non-uniform lateral dose distribution.

Again, the dose distribution within the beam spot is measured with a film dosimetry system.

1.4 Measurement of scan width

The aim of measuring scan width is to determine the lateral extent of the radiation zone in the scanned direction with respect to dose uniformity. Film dosimeters, including radiochromic and cellulose triacetate, as well as radiation-sensitive indicators, such as PVC, are suitable for the purpose. This information can be of practical importance in determining the allowable height of a product box when irradiating from above.

1.5 Determination of dose distribution in reference product

During the characterization of an irradiation facility, the determination of the dose distribution, and especially the minimum and maximum dose regions in a reference product box, is of basic significance. The measurement is carried out by placing individual dosimeters (mainly film dosimeters) in the product box containing reference material, which is then irradiated under production conditions. A new product validation is needed if the dose distribution is significantly altered after a modification to the facility.

2. Validation of the Process

Process validation includes several components such as:

* assessment of materials compatibility,
* determination of the process dose, and
* process qualification.

In all of these activities, accurate dosimetry is of great importance.

During a materials assessment program, samples of products must be irradiated with known doses, and the properties of the product must be tested. Such an evaluation ensures not only that the product and its packaging can withstand the radiation process employed, but also that the final product will meet the manufacturer's specifications and labelling claims. The test irradiation must present a challenge to the materials at least as severe as the process. For determination of the process dose, taking sterilization of medical devices as an example, samples of products are irradiated to relatively small doses and, based on the extrapolation of

the microbiological data from these samples, a dose is chosen that is suitable for the process. A protocol for this procedure has been established by the Association for the Advancement of Medical Instrumentation [12] and has also been proposed by the International Organization for Standardization [1] and the European Committee for Standardization [2].

The last activity, namely the process qualification, is of more relevance to the facility operator. Here, all the processing parameters for a specific product box are established, so as to ensure that the product receives the required dose within the specified limits and under the specified conditions. The main steps of this procedure are as follows:

2.1 Dose mapping process

a) Identification of product (weight, size of product box, type, density, manufacturer of product);
b) Selection of dosimeters (mainly film), irradiation conditions and packaging geometry;
c) Location of dosimeters in the product box;
d) Irradiation of the product box at a nominal dose (set optionally);
e) Determination of the minimum and maximum dose values and their locations in the product box, estimation of dose uncertainties, calculation of the dose uniformity ratio; and
f) Adjustment of the processing parameters to achieve the required minimum dose and the required dose uniformity ratio.

2.2 Verification process

a) Irradiation of 8 to 10 product boxes with dosimeters located at the minimum and maximum dose locations;
b) Analysis of results, determination of the variance of D_{min} and D_{max} values; and
c) Establishment of the processing parameters based on this analysis, and selection of a reference position for routine dosimetry.

For the dose mapping procedure, extreme care should be exercised in locating the dosimeters in product units (boxes). As a guide for placing dosimeters, the information obtained during facility characterization may be useful. Special attention should be given, especially for electron processing, to those characteristics of the product unit that may influence the dose distribution. These include inhomogeneous product distribution within the unit, orientation of the products, voids present, local differences in density, and interfaces such as between product and air. It is also important to note that the results of the verification process is valid only for a specific packaging and loading arrangement, and any change in this respect may result in a dose distribution that is different than that determined earlier.

Validation must be repeated whenever the irradiation conditions, including the product, its packaging pattern or the operating parameters, are changed.

3. Routine Process Control

It is essential to demonstrate that the entire process is under control within a specified confidence level. Routine process control is applied through dosimetry and is achieved by measuring the absorbed dose at regular intervals during the production run. For this purpose, dosimeters are usually placed at pre-determined reference positions (see Section 2.2(c) above). These reference positions, as well as the relationships between the dose values at these positions and the minimum dose values in the product, must be established and documented during the validation exercise. These reference positions can be on the product box or between the boxes. For example, calorimeters, or liquid or solid-state dosimeters, placed between product boxes can be passed under the electron beam during the production run. This in fact may be the preferred method because dose gradients on the outside of the product box prevent reproducible reference dosimetry.

In the case of electron facilities, the key operating parameters (conveyor speed, beam current, beam energy and scan width) must also be monitored, controlled and recorded. This information, along with the routine dosimetry data, is used to demonstrate that the process was under control throughout the production run.

CONCLUSION

An electron processing facility must have available all the dosimetry systems that are needed for the three stages of the irradiation process described here. These systems must be calibrated and the calibration must be traceable to a national standards laboratory.

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Figures:

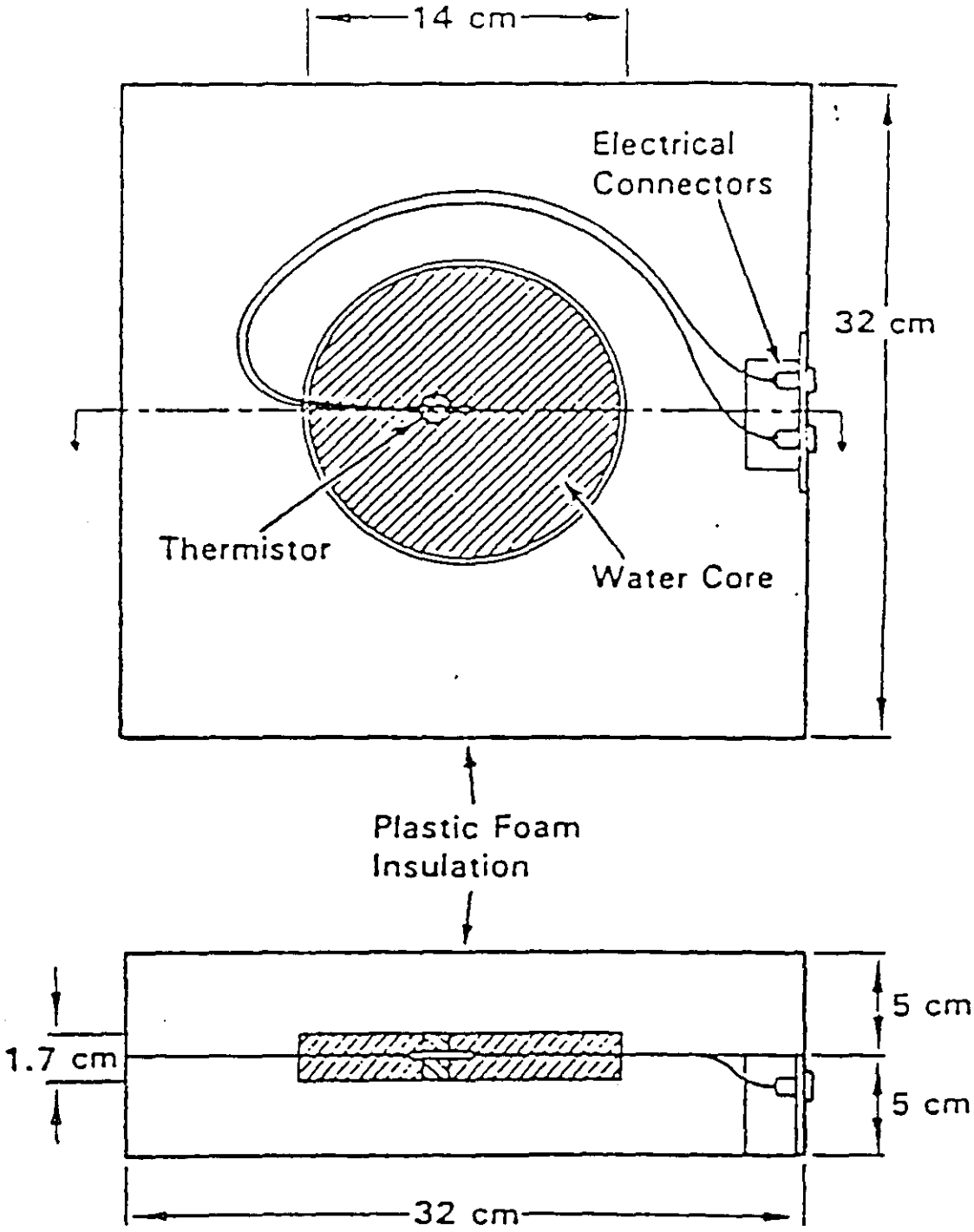

FIG.1. Riso-type water calorimeter for 10-MeV electrons

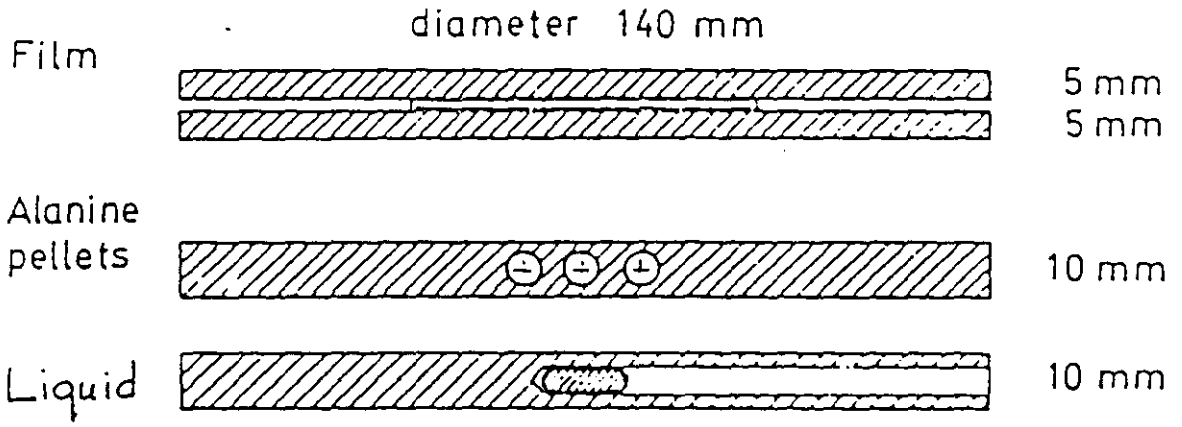

FIG.2. Liquid and solid-state dosimeters placed in graphite phantoms [10]

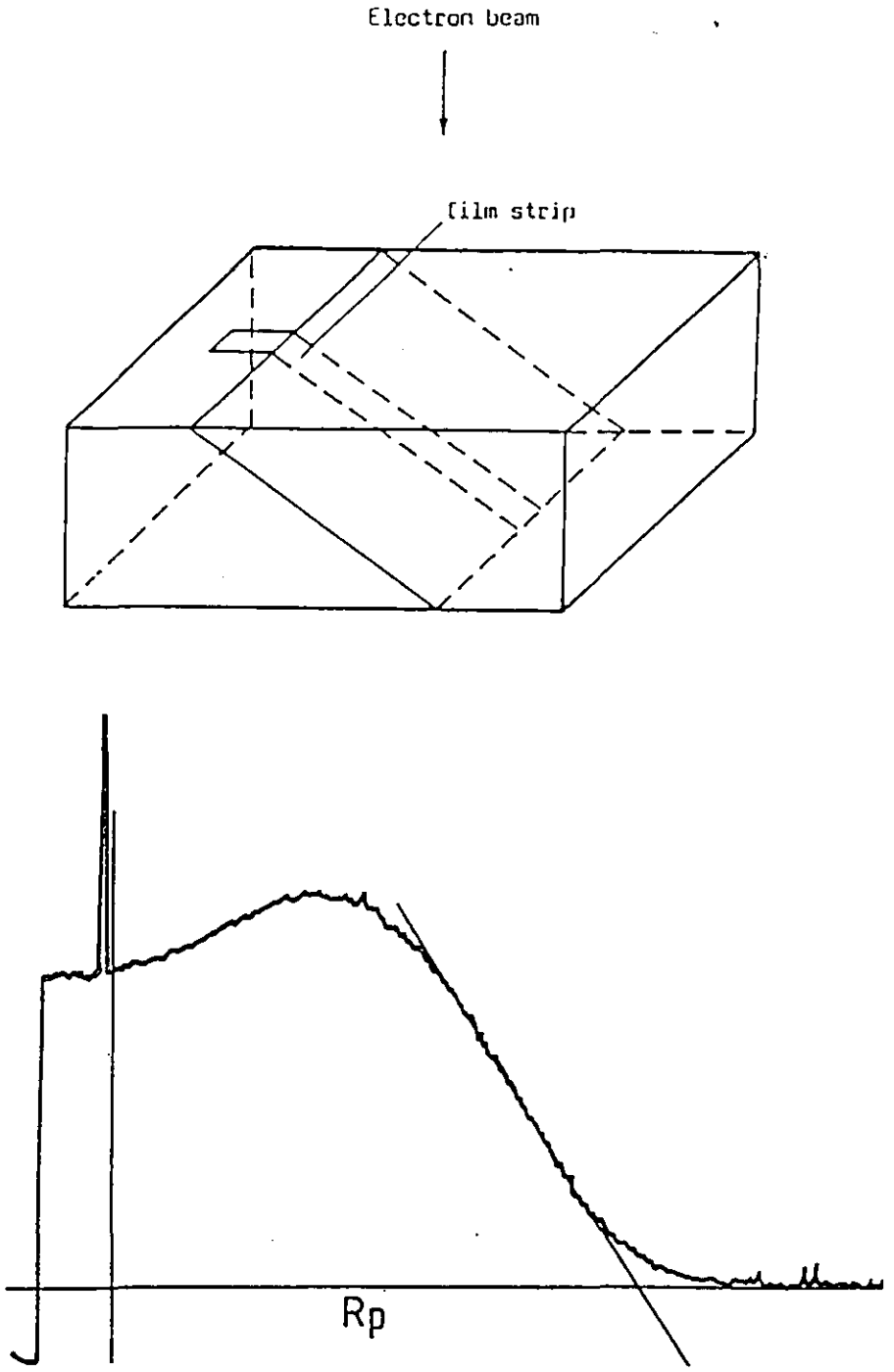

FIG.3. Determination of the most probable energy (E_p) of the electron beam by measuring the practical range (R_p) in an aluminum wedge.
$E_p(MeV) = 0.20 + 5.09 \cdot R_p(cm)$, [11].