Study on Measurement Techniques for Key Metrological Parameters of Low-Energy Electron Beam Irradiation

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Abstract

Electron irradiation has become an important component in the nuclear technology application industry, with low-energy electron beams finding increasingly widespread applications in wastewater treatment, food preservation, and other fields. The metrological parameters of irradiation are crucial for irradiation quality. Since relevant dosimetry standards for electron beams below 300 keV have not yet been established, parameter measurements are all traceable to 10 MeV electron linear accelerators, and the inconsistency in measurement objects introduces systematic deviations. This paper focuses on low-energy electrons below 300 keV, conducting research on electron beam energy measurement methods that combine experimental testing and simulation calculations, developing an absorbed dose measurement device based on the calorimetric method, and investigating the relationship between absorbed dose and parameters such as beam current intensity and displacement velocity. The results demonstrate that measurement of low-energy electron energy parameters was achieved through stepped stack dosimetry experiments combined with energy deposition curve simulation, while measurement of low-energy electron absorbed dose parameters was realized through the calorimetric method, with a measurement uncertainty of 11% (k=2). This study provides reliable metrological assurance for low-energy electron irradiation processes.

Full Text

Preamble

Measurement of Metrological Parameters for Low-Energy Electron Beam (LEEB) Irradiation below 300 keV

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Abstract

Electron beam irradiation has become an important component of the nuclear technology applications industry. Low-energy electron beams are increasingly used in wastewater treatment, food preservation, and other fields, where irradiation metrological parameters are crucial for ensuring irradiation quality. Since relevant standards for electron beam dosimetry below 300 keV have not yet been established, parameter measurements are currently traced to 10 MeV electron linear accelerators, and this inconsistency in measurement objects introduces systematic bias. This paper investigates electron beam energy measurement methods for low-energy electrons below 300 keV by combining experimental testing with simulation calculations, develops an absorbed dose measurement device based on calorimetry, and explores the relationship between absorbed dose and parameters such as beam intensity and displacement velocity. The results demonstrate that low-energy electron energy parameters can be measured through step-stacking dose experiments combined with energy deposition curve simulations, while absorbed dose parameters can be measured via calorimetry with a measurement uncertainty of 11% (k=2). This study provides reliable metrological assurance for low-energy electron irradiation processes.

Keywords: Low-Energy Electron Beam (LEEB); Metrological Parameters; Quality Control; Energy Measurement; Absorbed Dose

Introduction

Electron beam irradiation technology has become a significant part of the nuclear technology applications industry, finding widespread use in sterilization, food processing, and material modification [1]. Yan Pengcheng et al. [2] introduced the main types of low-energy accelerators currently used in China and their primary application fields. In recent years, the development of low-energy electron accelerators has made industrial and medical wastewater treatment more efficient [3]. WANG J et al. [4] reported on the removal efficiency of COD, fecal coliform bacteria, and viruses from actual hospital wastewater using electron beam technology, providing valuable information for its application in hospital sewage treatment. In food processing, low-energy electron beams offer advantages of high efficiency and minimal loss compared to high-energy electrons. Research by Gryczka et al. [5, 6] demonstrated that electrons with energies of 300 keV or lower have the potential to decontaminate various food surfaces while minimizing quality loss. Yang et al. [7] investigated the effects of different energy levels of low-energy electron beams on the quality and shelf life of vacuum-packaged pork under chilled and superchilled storage conditions, showing that the oxidation and sterilization effects of electron beams can significantly improve food quality and extend shelf life. JIA Chaowei [8] described the applications and advantages of electron beam curing on material surfaces and conducted research on the relationship between curing processes and irradiation parameters.

The electron beam energy and absorbed dose parameters of low-energy electron beam irradiation directly affect irradiation quality. However, China has not yet established standards for electron beam dosimetry below 300 keV [9], and related parameters are traced to 10 MeV electron accelerators. The substantial energy difference between these systems leads to systematic measurement bias. Miller et al. [10] proposed that quality control of irradiation processes can be achieved by establishing relationships between key parameters of electron accelerator equipment (energy, beam current, beam width, and transport speed) and absorbed dose. Helt-Hansena et al. [11-13] developed a thin-film dosimeter calibration system based on a graphite calorimeter for the 80-120 keV energy range, where the calorimeter measures total energy in the electron beam and electron energy is determined through thin-film measurements and Monte Carlo calculations. They quantified heat loss effects through heat transfer modeling, characterized dose response and measurement uncertainty, and achieved deviations within 10% compared to 10 MeV electron beam irradiation calibration.

This paper presents research on metrology for low-energy electron beam irradiation, developing measurement methods for electron beam energies below 300 keV based on thin-film dosimeters, and fabricating an electron beam absorbed dose measurement device based on a graphite calorimeter. The relationship between absorbed dose and beam intensity, transport speed was established, providing reliable metrological assurance for quality control in low-energy electron beam irradiation processes.

1.1 Low-Energy Electron Beam Energy Measurement Method

For electron beams with energies above 300 keV, energy measurement can be achieved through the stacking method [14]. However, for (100-300) keV electron beams, the penetration capability is low, with a range less than 0.1 g/cm^2 (see Table 1). Typical thin-film dosimeters have thicknesses of several tens of micrometers, making it difficult for the stacking method to resolve the penetration thickness of electron beams in thin-film dosimeters. This study employs Mylar films several micrometers thick as electron stopping materials, uses thin-film dosimeters such as CTA dosimeters as dose measurement devices, and implements the step-stacking method [15] for low-energy electron energy measurement, as shown in Figure 1 [Figure 1: see original paper]. When the electron beam irradiates the thin-film dosimeter perpendicularly, it loses partial energy due to the Mylar film barrier. The more barrier layers, the greater the energy loss, resulting in a step-like dose distribution on the bottom thin-film dosimeter. This allows determination of the number and thickness of Mylar film layers when the electron energy is completely lost. By comparing the penetration thickness with the energy deposition distribution of the electron beam in materials simulated by software such as FLUKA, the electron beam energy can be determined.

1.2 Low-Energy Electron Beam Absorbed Dose

This study designed a calorimeter device suitable for measuring absorbed dose from low-energy electron beams, shown in Figures 2 [Figure 2: see original paper] and 3. The absorber thickness is 2 mm, ensuring complete deposition of electron beam energy on the absorber surface. When the electron beam strikes the graphite absorber, energy deposition causes temperature changes in the absorber, and the absorbed dose is calculated according to Equation (1). The guard ring blocks electrons scattered to the absorber side walls, reducing measurement bias. Temperature changes are sensed by an NTC thermistor (Amphenol B07 series, size $ $0.25 mm × 0.5 mm) placed on the lower surface of the absorber to avoid electron beam irradiation effects. A Wheatstone bridge measures resistance changes to determine the absorber temperature before and after irradiation. A Mylar film above the absorber prevents thermal convection between the calorimeter internal gas and ambient air. The internal gas can be replaced with inert gas, which prevents oxidation of the graphite absorber and simplifies heat transfer analysis.

The average absorbed dose within the range of low-energy electron beams based on calorimetry can be obtained from the following equation:

$$\bar{D} = \frac{c \cdot (T_2 - T_1)}{p}$$

where: - $\bar{D}$: average absorbed dose within the electron beam energy deposition range, kGy - c: specific heat capacity of graphite absorber material, kJ/(kg · °C) - T_2: temperature of absorber after irradiation, °C - T_1: temperature of absorber before irradiation, °C - p: range correction factor, the ratio of electron beam range in absorber to absorber thickness

The absorber temperature is determined by an NTC thermistor according to the H-H equation:

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \ln\left(\frac{R}{R_0}\right)$$

where: - T: temperature, °C - R: thermistor resistance, Ω - A, B: calibration constants - T_0: temperature constant, 273.15 K

2.1 Electron Beam Energy

CTA films manufactured by Fuji Japan were used as the bottom layer, and 6 m thick Mylar films from PREMIER were used as electron stopping layers. Irradiation was performed on a curtain-type low-energy electron accelerator with output energy of (120-150) keV and beam current of 0-5 mA. The film distance from the beam window was 5 cm, using dynamic irradiation to approximately 100 kGy. The results, shown in Figure 4 [Figure 4: see original paper], indicate that the beam was completely blocked after penetrating 9 layers of Mylar film, corresponding to an electron range of 54 m in Mylar film. Comparing with energy deposition depth distribution simulation results (Figure 5 [Figure 5: see original paper]), the electron beam energy was determined to be 140 keV. After increasing the accelerator energy output parameters and remeasuring, the beam was completely blocked after penetrating 12 layers of Mylar film, corresponding to a range of 72 m and an electron beam energy of 150 keV.

2.2 Absorbed Dose

Absolute absorbed dose measurements were performed using the calorimeter device on this accelerator. Dynamic irradiation was employed by varying beam intensity and transport speed to achieve different dose levels. As shown in Figure 6 [Figure 6: see original paper], the results demonstrate that the calorimeter device can measure electron beam absorbed dose in the range of (1-120) kGy, with measurement results showing a linear relationship with beam intensity I and inverse transport speed $1/V$, indicating good stability of the calorimeter device.

2.3.1 Absorber Specific Heat

The absorber material is high-purity graphite, where impurities affect the specific heat parameter. After high-dose irradiation, impurity composition changes, altering the specific heat value. To minimize irradiation effects on absorber composition, the absorber material was irradiated with ultra-high doses to fully react the impurity components. As shown in Figure 7 [Figure 7: see original paper], after 1 MGy electron irradiation, the specific heat of the absorber shows some deviation compared to the unirradiated state. Generally, the operating temperature range of the absorber is (20-60)°C, where the specific heat deviation before and after irradiation is small and can be included in the instrument's specific heat measurement uncertainty, which is 0.64%. The specific heat has a linear relationship with temperature in the (20-60)°C range, and the uncertainty due to specific heat variation during measurement is 0.37% based on the fitted equation.

2.3.1 Temperature Measurement

Temperature values are derived from thermistor resistance. Thermistor calibration results are shown in Figure 8 [Figure 8: see original paper], where the inverse temperature $1/T$ shows a linear relationship with $\ln(R)$. The uncertainty from thermistor calibration, determined by the least squares method, is 0.52%. Additionally, due to the characteristics of low-energy electron beams, the absorber cannot be well thermally insulated and contacts air directly, causing rapid heat loss. The measured temperature after irradiation cannot represent the temperature rise from irradiation and requires heat loss correction. Since the electrical signal cannot be measured during irradiation when large numbers of electrons deposit on the absorber, temperature versus time curves before and after irradiation are recorded and fitted, then extrapolated to the midpoint of irradiation (time zero) to determine temperatures before and after irradiation, as shown in Figure 9 [Figure 9: see original paper]. The uncertainty from heat loss correction, determined by the least squares method, is 4.43%.

2.3.1 Uncertainty Evaluation

The uncertainty components for 140 keV electron beam irradiation absorbed dose measurement are listed in Table 2 . The uncertainty from experimental device stability, derived from the D-$1/V$ fitting curve, is 1.12%. Six repeated measurements under the same conditions yield a repeatability uncertainty of 1.86%. Therefore, the measurement uncertainty for low-energy electron beam absorbed dose is 11% (k=2). The results indicate that heat loss correction is the dominant uncertainty source. Reducing heat loss through methods such as inert gas filling and isolation of gas heat exchange [16-18] represents a feasible approach to improve measurement accuracy.

3. Conclusions

1) Accurate measurement of electron beam energy below 300 keV can be achieved through the step-stacking method for dose distribution measurement combined with software simulation of electron beam energy deposition distribution.

2) Absolute measurement of low-energy electron beam absorbed dose was realized based on calorimetry, and device stability was verified experimentally, providing quality assurance for low-energy electron irradiation processes.

3) The measurement uncertainty of low-energy electron beam absorbed dose using this calorimeter device is 11% (k=2), with heat loss correction being the primary uncertainty source. Measurement accuracy can be improved by reducing heat loss.

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Note: Figure translations are in progress. See original paper for figures.