TECHNICAL MEMORANDUM

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DOSIMETRY FOR LOW ENERGY ELECTRON BEAM

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Please refer to GEX Technical Memorandum #100-203, *Dosimetry System Calibration,* for general information on the dosimetry system calibration process. Information herein is additional and specific to low energy electron beam applications.

LOW ENERGY ELECTRON BEAM DOSIMETRY – GENERAL INFORMATION

Industrial radiation process applications using low energy electrons (80-300 keV) are well established with a large installed base. Low energy electron beam users have historically utilized dosimetry primarily as an internal quality tool although a small but increasing number of low energy electron beam installations are now being used for surface sterilization applications where traceable, accurate dose measurement is mandated.

In addition to sterilization, other new applications involving the curing of inks and coatings for food packaging now use dosimetry to monitor the radiation process. Others use dosimetry in low energy processing applications as a quality tool to satisfy their ISO quality standards commitments and they too demand a reliable means of obtaining dose measurement results within expected accuracy limits.

- Thin radiochromic film dosimeters remain the standard for low energy dosimetry where dosimeter thickness is critical to success.
- An international guidance standard (ISO/ASTM 51818) exists that provides instruction and examples to assist users in facility characterization and routine dosimetry practices for low energy applications.
- A method of calibration based on a surface dose concept called Dµ (average dose measured in the first micron of transfer standard dosimeters) provides the means to establish doses traceable to a national standard through an unbroken chain of calibration comparisons.

Low energy dosimetry system considerations or requirements can typically be universally applied for in-vacuum electron energies between 80 and 300 keV. The ISO/ASTM 51818 document *Standard Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 80 and 300 keV* provides industry accepted dosimetry guidance. The most recently approved version of the document points to the need to consider the impact of dose gradients within the dosimeter when calibrating dosimetry systems.

DOSIMETRY SYSTEM CALIBRATION CONSIDERATIONS

The dosimetry calibration requirements and practices for low energy are the same as those used for high energy e-beam and gamma irradiation applications. The ISO/ASTM 51261 document *Standard Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing* provides guidance on calibration. For example, separate dosimetry system calibrations are required for each so called “irradiation pathway” where differences in process energy, dose rate or environmental factors can significantly affect dose outcomes.

The influence of the electron beam window composition and thickness and the air gap from window to product surface impact dose measurement outcomes at electron energies between 80-300 keV. Therefore, to avoid significant variance and bias, their effects at different energy settings must be known and accounted for in the dosimetry system calibration process.

Factors Impacting Dosimetry Results at Low Electron Energies
The low energy user must take a number of factors into account when performing a dosimetry system calibration for use with each new batch of dosimeters. For instance, the lower penetration associated with low energy electrons requires accounting for effects on dosimeter response due to beam window composition and thickness, air gap from window to product, and the dosimeter thickness.

The dosimetry challenges to a low energy electron beam user are also further complicated because low energy e-beam irradiation systems typically allow the user to change the process energy. Different set energies on a system are equivalent to separate “irradiation pathways” that likely may require separate dosimetry system calibrations to be performed. Even small changes in energy can have significant impact on dose outcomes due to the combined contribution of window, air gap, and dosimeter thickness on dosimeter response.

To avoid possible bias, the effects of these factors at different energy settings must be known and accounted for in the dosimetry system calibration process. Thus, calibrating the dosimetry system at multiple energy settings may be required to more accurately account for the influence on the dosimeter response.

Another factor impacting dose measurement accuracy in low energy electron beam applications is the thickness of the dosimeter. At energies over the 80-300 keV range absorbed dose gradients within the dosimeters can lead to significant dose measurement error.

A ‘dose gradient’ is a situation in which the absorbed dose is not uniformly distributed through the thickness of the dosimeter material. These dose gradients are more significant at very low energies where the dosimeter becomes fully absorbing (for the B3 dosimeter, this would occur at machine set energies of 125 keV or less, typically).

These gradients can vary dramatically in dosimeters as energy decreases because energy determines the penetration range of the electrons. Thus, the impact of the dose gradient is more significant for a thicker dosimeter than for a thinner dosimeter.

The absorbed dose in the dosimeter is measured as an absorbance or response value. This value that is measured is an average value representing the portion of dose actually absorbed in the dosimeter. An optimal thickness dosimeter can minimize the impact of gradients over a range of energies. For example, a nominal 17 micron thickness film dosimeter such as the B3 can be used over a range of electron energies without introducing significant dose error (see Figure 2 below on page 6).

CALIBRATION OF DOSIMETRY SYSTEMS FOR USE IN LOW ENERGY ELECTRON BEAM APPLICATIONS

Gamma Calibration Method
Originally, low energy users calibrated dosimetry systems by sending their batch specific representative dosimeter samples to a national standards lab or otherwise accredited lab for irradiation in a well characterized gamma source at a fixed temperature (typically 25°C).

This method has an apparent comfort of being able to state that your calibration was performed at a calibration lab with the doses directly traceable to a national standard. Unfortunately, when attempting to use such a calibration in a low energy electron beam process, the chain of traceability to a national standard is broken. This is because this method does not take the influence of temperature changes during irradiation and other environmental factors into account that have a significant impact on the response of the dosimeters being calibrated.

In addition, the fixed temperature gamma calibration method has no means of resolving absorbed dose gradients encountered in the dosimeters when they are used in low energy processing.

High Energy Electron Beam Calibration Method
Later, performing a high energy (typically in 5-10 MeV) calibration in electron beam irradiators was introduced as a more advanced method of calibration for low energy applications. This approach eliminated the temperature influence bias of the earlier gamma process and offered improved dose measurement accuracy for the low energy user. Figure 1 on page 5 shows the temperature influence on the calibration response function for dosimeters irradiated with 10 MeV electrons versus a gamma source. Results are shown for B3 dosimeters but results are typical of those expected to be found with any dosimetry system.

The calculated response differences between the two calibration methods can be considered insignificant (<1.0%) up to approximately 20 kGy. As dose increases and the near-adiabatic temperature rise in the dosimeter becomes significant, the result is an over-estimation of dose. Unfortunately, the temperature influence continues to grow larger with higher and higher doses resulting in a growing over estimation of dose that approaches 10% at only 40 kGy, nears 20% at 60 kGy, and finally exceeds 30% at 80 kGy and above.

High energy electron calibrations have been demonstrated to provide a more accurate dosimetry calibration method than the original gamma method by eliminating the temperature influence bias. However, the high energy calibration approach still causes a break in the calibration traceability chain and begs the question of how to transfer a calibration function derived in a high energy electron beam to a low energy electron beam.

This question was partially answered with investigations carried out and published in 2005 by Miller, Helt-Hansen and Sharpe, et al from Risø and NPL[Refs 2-3] which developed and used low energy calorimeters for dose comparison with thin film radiochromic dosimeters calibrated with 10 MeV electrons to be in agreement at approximately ±10 percent (k=2).

Surface Dose Calibration Method

This work finally led to development of a “Dµ” calibration method that provides a source of transfer dosimeters with doses traceable to a national standard through an unbroken chain of traceability. The method is based on a surface dose concept called Dµ which is used by the calibration laboratory to calculate the average dose measured in the first micron of their traceable transfer-standard dosimeters. The Dµ calibration method is based on the same principles used for in-situ or in-plant calibration under the expected conditions of use as has been used successfully for more than 20 years in gamma and high energy electron beam facilities (see ISO/ASTM 51261).

The Dµ calibration method evolved over 7 years with a significant amount of technical research needed to resolve the complexities associated with dosimetry system calibration for use in a low energy electron irradiation environment. Although it is not essential that a user possess a technical understanding of Dµ in order to use it effectively, the references provide discussion of technical information. Most routine dosimetry users can simply enjoy the accuracy and simplicity of Dµ without concern for how the doses are arrived at by the calibration laboratory, but only that the laboratory is properly accredited to certify doses traceable to a national standard.

The Dµ method allows the calibration laboratory to account for the impact of the accelerator window and air gap of a user’s specific irradiator system as well as to correct for their transfer alanine dosimeter thickness to arrive at average surface dose. By irradiating routine thin film dosimeters alongside these transfer laboratory dosimeters, a user can establish a relationship in the response of their routine dosimeters to these traceable Dµ doses reported to the user by the laboratory.

Some Dµ Calibration Process Specifics

Risø National Laboratory supplies GEX with the transfer dosimeters (130 micron nominal thickness alanine films) which are sent to customers who irradiate them alongside their routine B3 radiochromic dosimeters using protocols specified by Risø and GEX. The customer returns the alanine film dosimeters to Risø who measure the alanine films and corrects the measured doses for the specific in-plant conditions of the user’s machine.

The transfer alanine dosimeter results are corrected to account for the actual beam energy penetration at the dosimeter surface as actually measured in a depth/dose stack. Other correction factors are used by the laboratory to account for the user’s stated distance between the external surface of the accelerator window and dosimeter surface (air gap) as well as the accelerator window material composition and its thickness. Additionally, the laboratory makes a temperature correction based on an estimated average temperature in the alanine dosimeters during irradiation.

The calculated surface dose in the transfer alanine dosimeters is designated as the Dµ dose and is considered to be the average dose in the first micron of the transfer alanine dosimeter. The customer measures the routine dosimeter samples, such as GEX B3 dosimeters, and GEX relates the reported customer’s B3 batch calibration dosimeter measurements with the Risø reported Dµ doses to develop a calibration response function for the routine dosimeters.

The combined overall uncertainty associated with Dµ doses is nearly twice that of other transfer dosimetry systems used for in-process calibration in gamma and high energy electron beam applications. This is due to the higher variability associated with thin alanine film dosimeters and the added uncertainty components involved with the corrections applied by Risø.

COMPARING Dµ WITH 10 MEV DOSE ESTIMATES IN LOW ENERGY ELECTRONS
Transfer standard Dµ calibration dosimeters were used to audit batch specific calibrations of dosimeters using a high energy 10 MeV electron calibration source. The results shown in the Figure 1 below demonstrate good agreement between the 10 MeV calibration and the national standard traceable Dµ doses.

The plots also demonstrate the clear temperature influence bias associated with the use of a gamma calibration in a low energy electron beam process, as mentioned earlier.

FIGURE 1

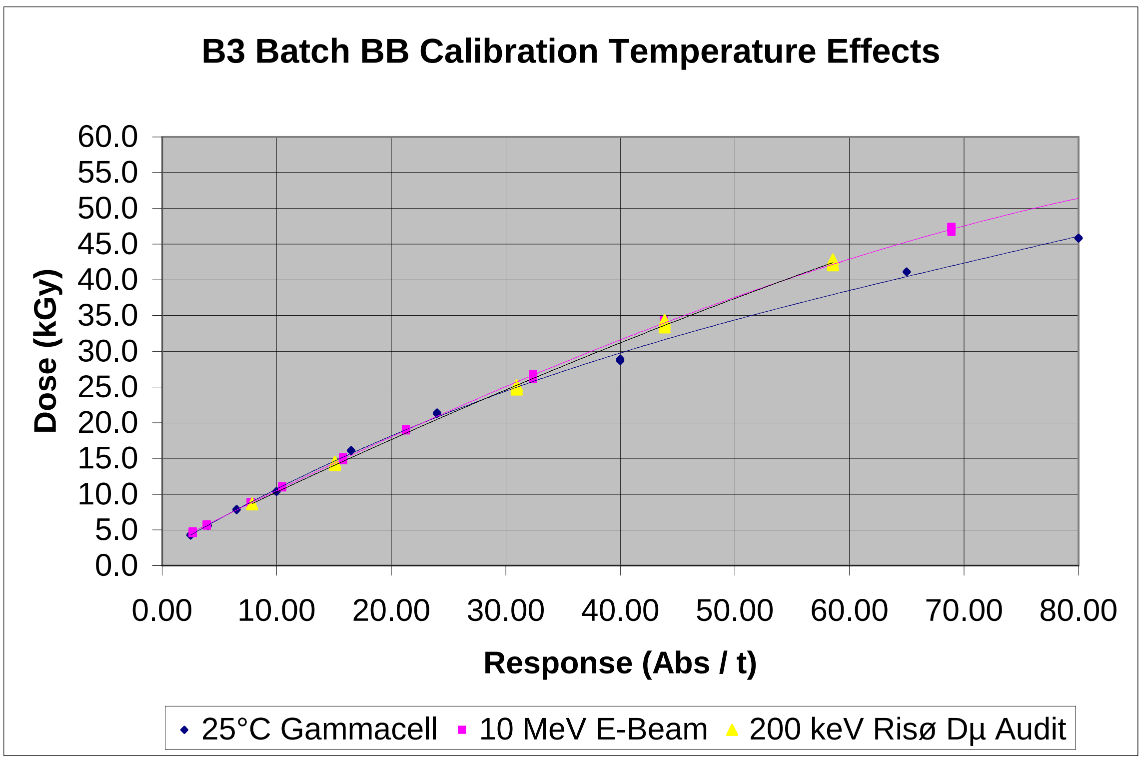

Figure 2 below is a comparison summary of Dµ calibration audit results versus doses estimated using 10 MeV B3 and FWT-60 dosimeter batch calibrations over five different energy settings on a single accelerator using constant speed with the machine's current varied to achieve specific dose targets. Contact GEX for a copy of the Dµ audit data.

FIGURE 2

10 MeV Calibration Agreement with Dµ Audit Doses					
Voltage Set Point	100 kV	125 kV	150 kV	200 kV	300 kV
Product Surface Energy	65 keV	90 keV	115 keV	165 keV	265 keV
B3 BB Cal ID# 2719	-30.9%	-2.9%	-5.4%	-4.2%	0.0%
B3 BA Cal ID# 2621	-33.4%	-4.5%	-5.0%	-4.3%	-1.4%
FWT-60 Cal ID# 2621	-60.7%	-21.9%	-13.9%	-7.0%	-0.6%

The results reflect the differences from Dµ doses that are found when using a single 10 MeV calibration related to changes in energy. Results for the thicker 43.5 micron FWT-60s reflect more severe gradient conditions than observed with the thinner 17 micron B3 and are in agreement with Monte Carlo calculated gradient estimates based on dosimeter thickness and material composition.

CONCLUSIONS

Low energy electron beam in-situ calibrations using the Dµ method have been demonstrated to eliminate several sources of calibration bias by accounting for the impact of window, air gap, and dosimeter thickness in the calibration process. New Dµ traceable doses can be used to verify use of a 10 MeV calibration in low energy electron beam irradiators. Results indicate an approximate ±7.0% or better agreement with Dµ doses at surface energies down to approximately 90 keV (~125 kV accelerator energy set point) when using a thin B3 dosimeter that is nominally 17 microns thick. The data indicates that dosimetry calibration for dosimeter surface energies below 90 keV (~125 kV accelerator energy set point) require a full in-situ calibration using the Dµ method to obtain any degree of dose measurement accuracy.

The new Dµ calibration method resolves the historical inability to establish calibration traceability to a national standard through an unbroken chain of calibration events for dosimetry systems used in low energy electron beam applications. It should be noted that not all low energy applications may require such accuracy, but it should also be noted that this new calibration method may impact how we are able to use dosimetry in low energy applications that require only dosimetry measurement reproducibility.

At this time only limited field testing has been carried out in an effort to broadly evaluate the new method. These Dµ comparative results were also presented formally by Risø at the September 2008 International Meeting on Radiation Processing (IMRP) and will be subsequently published. Additional activities have included peer review discussions with open presentations made at the past two meetings of the ASTM E10.01 Sub-Committee on Dosimetry as well as at the Gamma and Electron Radiation Panel workshop on Advanced Dosimetry Techniques immediately following the IMRP 2008 meeting. The initial rounds of field tests involving the new Dµ doses have provided reproducible results.

At this time, extensive testing above 60 kGy has not been conducted using the Dµ calibration method for any web processing accelerators, and more work is necessary to determine what benefits this new calibration method may have for higher dose applications on such machines.

New Dµ traceable doses can be used to verify use of a 10 MeV calibration for use in low energy electron beam irradiations. It can be demonstrated that a generic 10 MeV calibration may be used with an approximate ±7.0% or better agreement with Dµ doses at surface energies down to approximately 90 keV (~125 kV accelerator energy set point) when using a thin B3 dosimeter that is nominally 17 microns thick. The data indicates that dosimetry calibration for dosimeter surface energies below 90 keV (~125 kV accelerator energy set point) require a full in-situ calibration using the Dµ method to obtain any degree of dose measurement accuracy.

REFERENCES

1.) Helt-Hansen, J., Miller, A., 2004. RisøScan—a new dosimetry software. Radiat. Phys. Chem. Volume 71, Issues 1-2, p. 361–364.

2.) Helt-Hansen, J., Miller, A., McEwen, M., Sharpe, P., Duane, S., 2004. Calibration of thin-film dosimeters irradiated with 80–120 keV electrons. Radiat. Phys. Chem. Volume 71, Issues 1-2, p. 355-359

3.) Helt-Hansen, J., Miller, A., Duane, S., Sharpe, P., McEwen, M., Clausen, S., 2005. Calorimetry for dose measurement at electron accelerators in the 80–120 keV energy range. Radiat. Phys. Chem. Volume 74, Issue 5, p. 354-371

4.) Janovsky, I., Miller, A., 1987. A calorimeter for measuring energy deposition in materials and calibrating the response of dosimeters irradiated by low-energy industrial electron accelerators. Appl. Radiat. Isot. 38 (11), 931–937.

5.) Kawrakow, I., Rogers, D.W.O., 2000. The EGSnrc code system: Monte Carlo simulation of electron and photon transport. Technical Report PIRS-701,NationalResearch Council of Canada, Ottawa, Canada.

6.) Zeng, G.G., McCaffrey, J.P., 2005. The response of alanine to a 150 keV X-ray beam. Radiat. Phys. Chem. Volume 72, p. 537–540.

7.) Sharpe, P., Miller, A., 1999. Guidelines for the calibration of dosimeters for use in radiation processing. CIRM 29, National Physical Laboratory, Teddington, England

8.) Pending Publication – Presented September 2008 IMRP London Meeting – “Dμ - a new concept in low energy electron dosimetry” Helt-Hansen, et al