Sources of Dose Variability and a Dose Prediction Model Benchmark for Low Energy Electron Beams

Douglas E. Weiss, 3M Company, St. Paul, MN

Abstract. In this PowerPoint presentation, the types of dose variability observed in a low voltage electron beam are characterized. Sharp gradients at low voltage make direct measurement of the true surface dose (first micron) difficult since the thin film dosimeters that must be used capture a gradient dose that represents only an average through a thickness of at least 10 microns. A method for calculating a surface dose at low voltage is illustrated using a model of the problem and Monte Carlo code (ITS). Such model predictions must always be benchmarked against dosimetry. This brings into play a variety of issues associated with dosimetry measurement, model building and the characteristics of a specific piece of equipment that all must come together in order to achieve agreement. This is demonstrated using an example to illustrate the value that these predictions provide when operating at voltages in the range of 80 – 120 kV.

Introduction.

A world of uncertainties is a key driver of radiation processing standards. There are over 30 ISO/ASTM and ASTM standards on this topic in print today. These include only two standards specific to low voltage equipment[1,2]. For electron beam, most of the focus has been on high voltage, especially where sterilization is involved and there are now five standards specific to high voltage applications. Low voltage has, in the past, been viewed in more simplistic terms where robust and forgiving industrial applications are governed more by machine parameters (mA, kV) in lieu of dosimetry. Also, low voltage is not amenable to many types of dosimeters and measurement methods on account of the limited electron penetration and the narrow passages of their self-shielded chambers. However, the user-base is large and the growth area is the trend to ever lower voltage. This has introduced the need for better understanding and better methods of control as dose precision and beam parameters now become more critical. This has proven to be as challenging as the dose-mapping and characterization of high voltage operations. The purpose of this presentation is to outline an evolving approach to better process understanding and control for practitioners, who develop and manufacture products.

There are roughly about 1,400 industrial electron accelerators in the world, of which about half of those are low voltage. Until the early 1990's, low voltage was defined by the range of 150 – 300 kV, as manufacturers increased the high end from 200 kV upward to the practical maximum of 300 kV for a single-gap accelerator. In the mid-1990's, improved understanding and equipment design enabled the bottom end to be lowered into the range of 100-120 kV. In the first few years of this new century, the use of thinner windows enabled the bottom end to be moved down to as low as 80 kV. This ever-evolving movement to lower voltage is being driven by the need for smaller, more compact, more efficient equipment for cost savings and improved properties. If it were practical to run a process without a window at all (vacuum), then voltages as low as 50 kV might define the true practical bottom for industrial radiation processing.

This shift to ever lower voltage introduces steep dose gradients, defined in ever thinner cross-sections, and this is now redefining routine dosimetry (**Figure 1**). The new definition of a surface dose will likely become the first micron, but there is no dosimeter that thin. Hence, this is a dose that cannot be measured directly and the need for simulation technology modeling to define the gradient is clearly evident. For this application, the use of a Monte Carlo code provides a quick, easy and precise method for partitioning a dosimeter into thinner sections to allow dose calculation to the first micron of depth. It can often be applied in its simplest and most user-friendly form, the 1-D slab geometry model, when properly benchmarked against dosimetry. These models are critical to process control, for setting the voltage range and for calculating a precise dose for increments of depth within a product, especially in the sub-100 kV range.

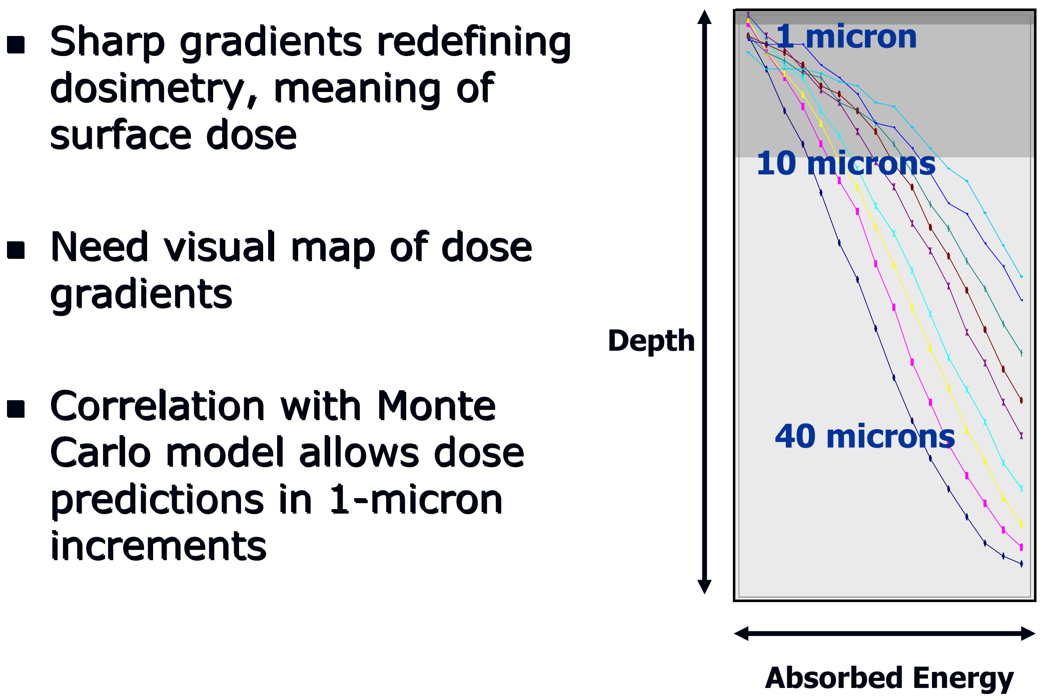

Figure 1. Energy deposited by the beam drops sharply with increasing depth at low voltage. Dosimeters measure only the average value as dose and this value changes greatly with thickness. Hence, the meaning of 'surface dose' depends on the thickness of the dosimeter. Voltages in the range of 70-86 kV are shown here, after passing through a 25 micron Kapton window.

In the remainder of this paper, the complex interplay of uncertainties in surface dose measurement, equipment variability and model building are described by examples, detailing our effort to achieve understanding and a benchmark. The equipment used in these examples is of the older style ESI Electrocurtain™ type with a single filament running transverse to the web path. Newer cathode designs having multiple filaments will likely have less variability than what is being described here. Also, this equipment was run at voltages below their original design limit. The Monte Carlo code used for the electron-photon transport simulations is the Integrated Tiger Series (ITS), available from the Radiation Safety Information Computational Center (RSICC). Information on the use and application of this code and others can be found in ASTM E-2232-02[3]. Dosimeters supplied by Far West Technologies, Inc. (FWT 60-00) and GEX Corporation (B-3) were used for dosimetry measurements with calibration traceable to RISO National Laboratories, Denmark. Dose is stated in units of Mrads (1 Mrad = 10 kGy) throughout this paper as this older unit is in common usage among low voltage users. The electron beam was equipped with a real-time radiation monitor (RTRM) Monitorad ™ available from Trygon, Inc. and uses X-ray detection as a means to gauge dose when calibrated against dosimetry.

Results and Discussion.

Sources of Surface Dose Variability. Crossweb Measurement. The older style, single filament electron beams typically have +/- 10% dose variability across the web and this can vary with voltage and over time. Hence, center-point measurement alone may not accurately indicate total beam output. Measurement at other locations across the web will show the variability in dose and the true measure of beam output will be the average dose measured across the full width of the cathode. It is that number that will correlate with Monte Carlo code predictions since they are based on the beam current supplied to the whole cathode. **Beam Output.** Many users establish a single value for the machine constant ‘k’ to express the beam output, often at 175 kV where it is usually at a maximum or at the single voltage where they use the machine most of the time. The value of ‘k’ is derived from a dosimetry measurement (D) in combination with the web speed (S in units of choice) and beam current (I in units of mA) in the simple KI=DS equation. Others who make multiple uses of the beam for different applications will characterize ‘k’ over the whole operating range of voltage where it can vary widely. Usually this is done just once when a machine is commissioned and the values are assumed to remain constant. However, this may not be true and every electron beam should periodically be re-characterized with dosimetry to redraw the k-curve and evaluate the consistency of the beam output over a long period of time. Over a period of several years, the repetitive collection of data for our electron beam, shown in **Figure 2**, sweeps out an area that represents both the periodic variations in real machine output and measurement error, typically a combined variability in the range of +/- 10%.

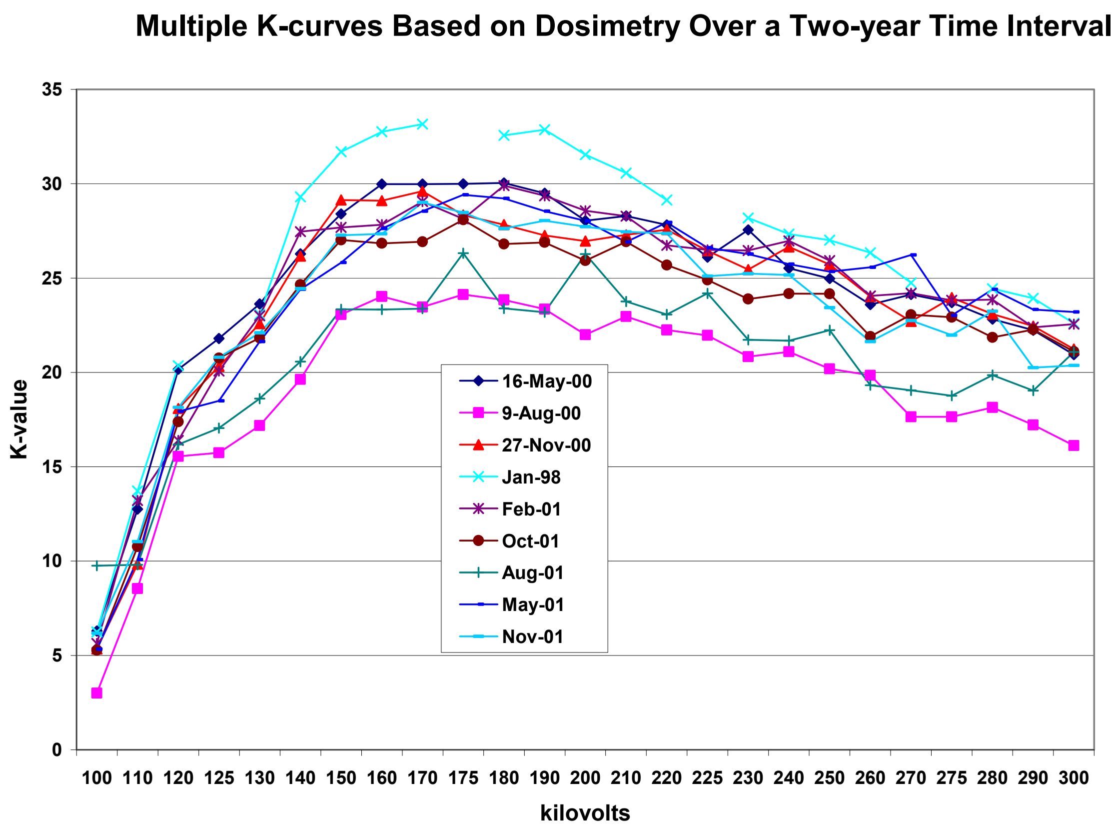

Figure 2. Series of repeat dose measurements for every 10 kV from 100 to 300 kV, expressed here as 'K' over a long period of time.

This information, when averaged over time, expresses the true output of the machine, with uncertainty limits, and correlates well with the Monte Carlo code prediction (**Figure 3**). It is this statistically averaged K-value that is the best indicator of true beam output. These numbers can be programmed into a real-time radiation monitor (RTRM) for tracking machine performance over time. The RTRM offers the ability to monitor and control the beam, by adjustment to the current, to maintain a narrow specified dose range over long periods of operation. Given the high precision of the instrument (+/- 1%), any deviations over time are likely attributed to variations in machine output, not measurement error and can be corrected in real time. Initial instabilities in the machine at cold start-ups are always apparent and stabilize quickly. Differences between the targeted dose and the actual dose can then be corrected by changes to the current setting (mA) during operation.

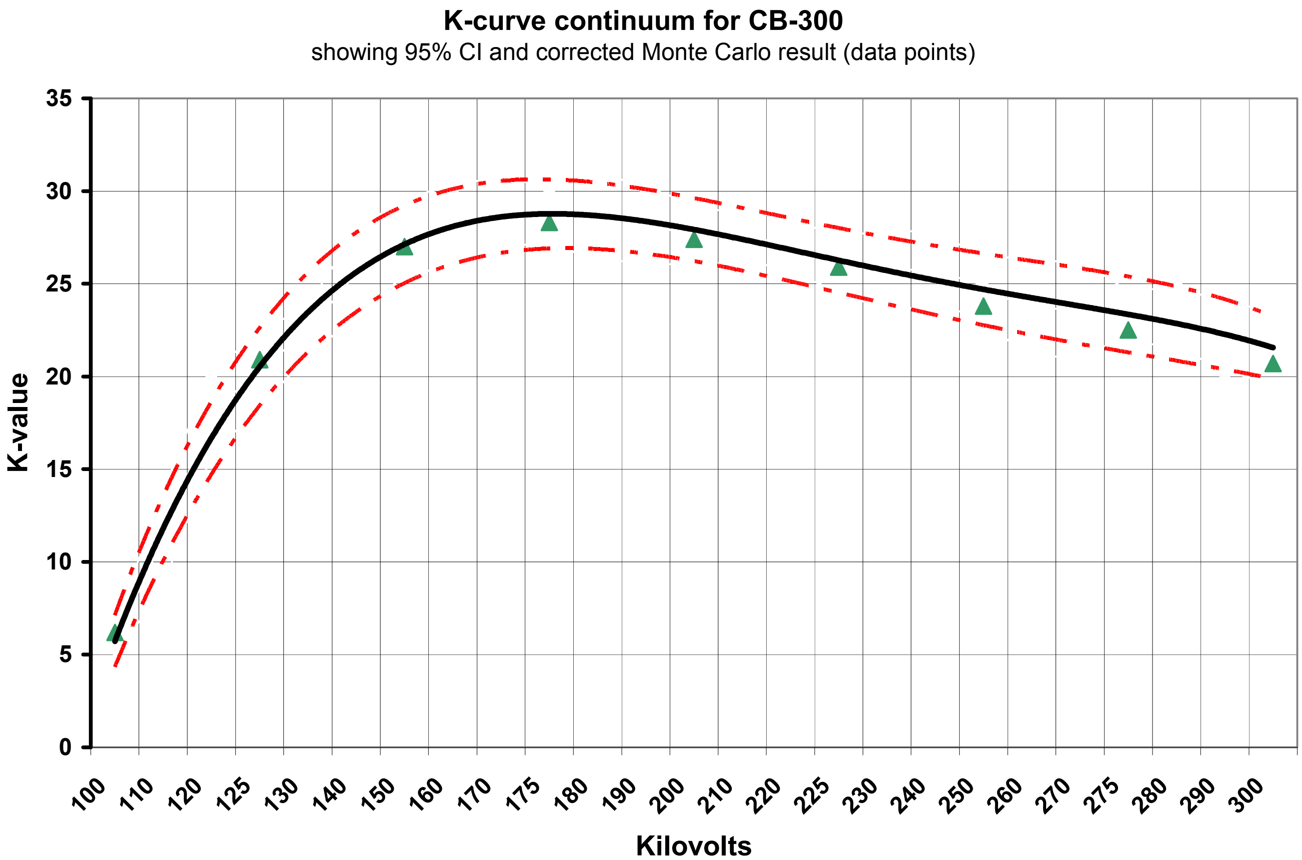

Figure 3. Data from Figure 1, averaged to show k-curve (solid line) with 95% confidence intervals (dashed lines) and 1-D Monte Carlo calculation results (triangles) corrected for beam blockage.

Variation in beam output at selected voltages (100, 175, 300 kV) should be monitored and accessed on a weekly/monthly basis and charted. Over a span of about 4 years, dosimetry and RTRM readings for our electron beam show variability and fairly independently of one and other (**Figure 4**). This independence might be attributed to the fact that the RTRM is fixed at the center location across web but the dosimeters varied in location across the web depending on where they were applied to the web. When expressed as a percent deviation from the long-term average dose, values for dosimetry generally remain mostly within the expected 10% band but occasionally exceed those limits. Statistically, the RTRM shows less variability, presumably because measurement error is less of a factor. Considering that variability is still about 7%, there clearly is detectable machine variability over time that must be distinguish from dosimetry measurement error. Our dosimetry measurement error is about 3-4%, hence machine and other factors account for about 6% of the variability observed. That is also consistent with the variability seen in RTRM measurements.

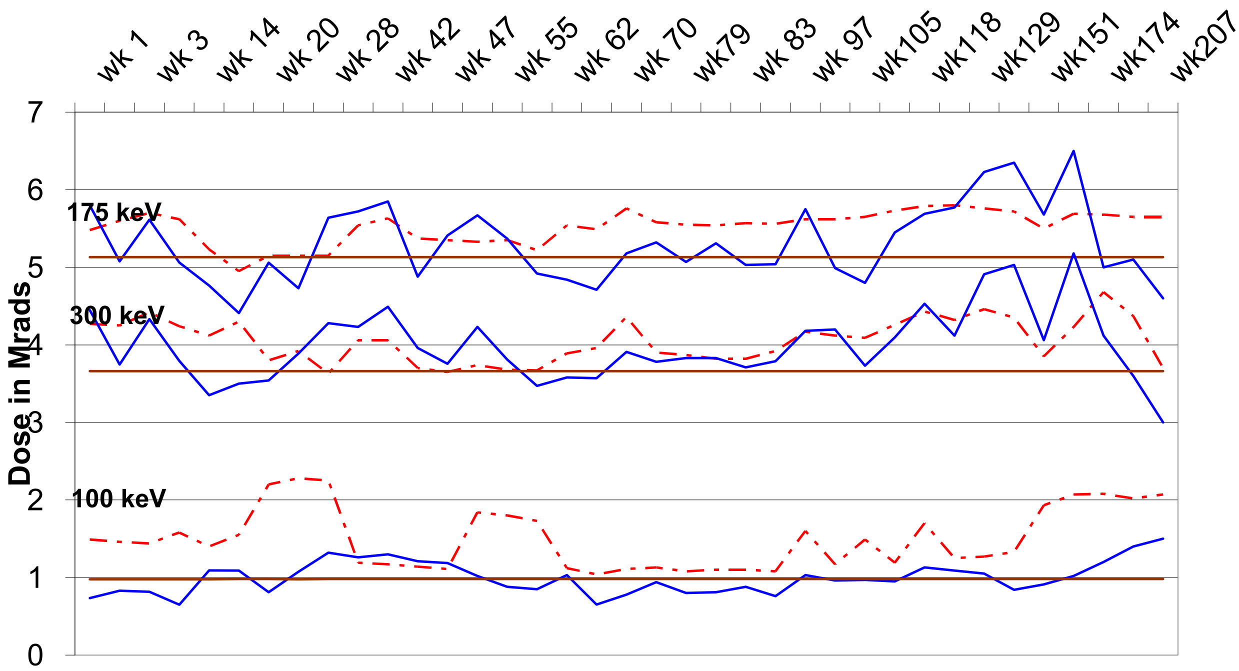

Figure 4. Weekly measurements of dose at constant current and speed at three different voltage levels. Solid line indicates dosimetry, the dashed line indicates RTRM output. The straight solid line at each voltage level indicates the average long-term value for dose as predicted by Monte Carlo code.

Chamber temperature. While beam current generally remains steady over long periods of operation, the progressive warming of the chamber over time may increase the surface dose, especially when the gap between the window and product surface is significant (more than several cm). This is illustrated in an example of an RTRM in a production unit, the cross-web output (monitored at 5 locations) from a 1980 vintage 60”-wide ESI Electrocurtain™ shows about a 10% variation (**Figure 5**). This variation in cross-web dose is very consistent from run to run for a series of nine large rolls of material, providing a lot of assurance that the dose delivered was consistently within the range of allowance. However, the overall dose slowly crept upwards over time and the current had to be adjusted downwards twice by the operator to maintain the proper dose range. This may have been a result of the lower density (lower stopping power) of the chamber gas as it heats up. A gap of nearly 5 cm, as in the case of this machine, has the same stopping power as the 12 microns of titanium window. This tool lends a lot of confidence to a manufacturing operation as the steering wheel of the process and any apparent deviation in machine output can be detected in real-time and adjusted by the beam current.

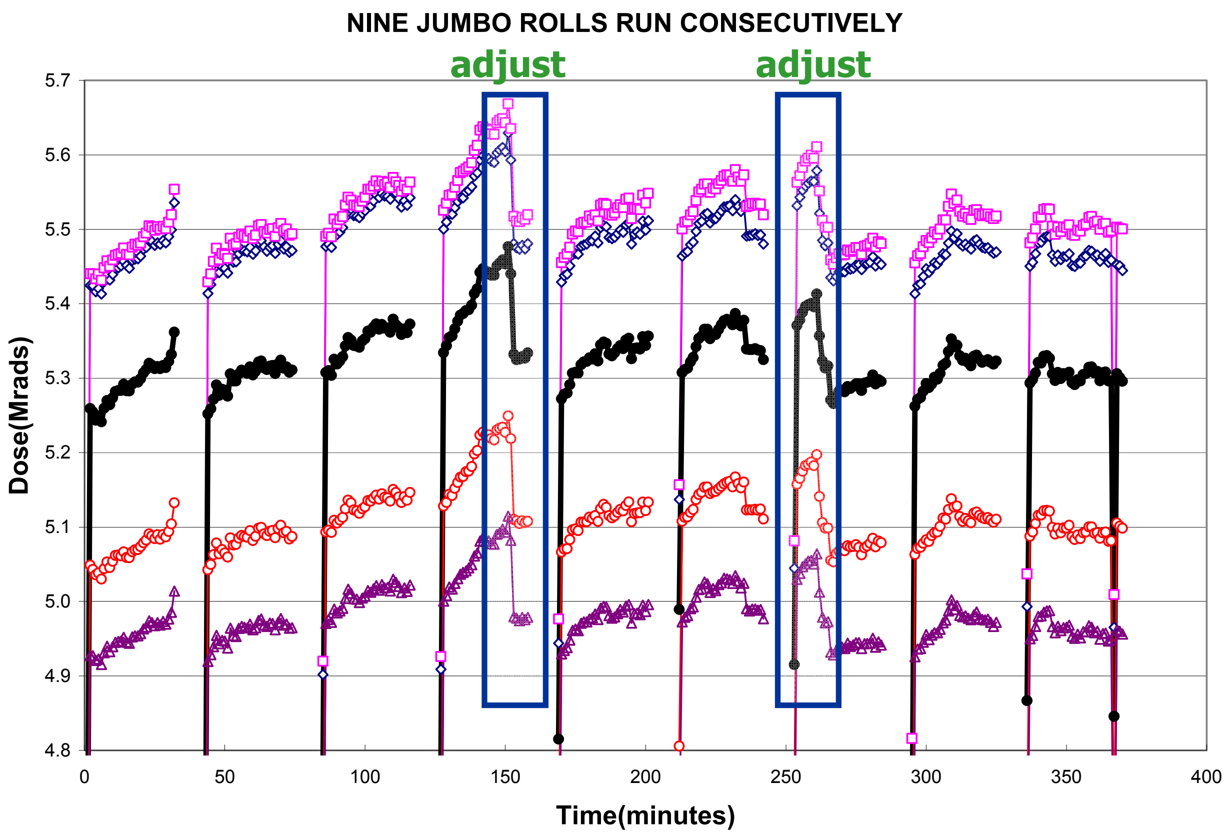

Figure 5. Cross-web dose as logged and indicated by a five-sensor RTRM during the irradiation of nine large rolls of film over the span of about 5 hours. Note the progressive upward trend in dosimetry and the two downward adjustments needed to maintain specification.

Characterization of Dose Gradients at Low Voltage. While we have mostly been concerned so far with characterization of machine output as the 'surface dose' based on unspecified dosimeter thickness, it is more of a challenge to predict a dose within a product with precision, given that voltage selection gives rise to dose gradients that can not be characterized directly using dosimeters. The definition of surface dose can vary depending on dosimeter thickness. In order to correlate voltage (dose/depth relationships) with product performance, use of a simulation tool or mathematical model is essential for defining the exact shape of the gradient in finer detail than permitted by a stack of dosimeters of 10 micron thickness or greater.

Two independent approaches to characterize beam output. In the past, there was no independent method to estimate a dose, one had to rely on dosimetry alone and established practice. As personnel changed jobs, responsibilities got passed on to others, files and traceability got lost and routines abandoned, confidence in the measurements became questionable. The use of simulation technology to calculate a dose is not a substitute for measurement but it provides a number, arrived at independently using a reliable mathematical method and a model based on physical measurements. With good dosimetry and modeling practice, both of these approaches should provide nearly the same result over the entire voltage range and serve as a check against each other. When the numbers don't agree, a learning opportunity presents itself as resolution is sought.

Both of the electron beams in this study were modeled using the ITS Monte Carlo code. More details of this study can be found in a previous publication[4]**.** Generally, the simpler 1-D TIGER calculations were used for low voltage dose/depth predictions when corrected for the 3-D beam blockage factors. For these machines, the principle blockage was the ribbed structure (hibachi) that supports the window, which blocked about 22% of the beam. On average, the blockage for this machine was determined by best-fit of the 1-D model predictions with dosimetry to be about 29%, indicating that other factors are also involved. Blockage varies from machine to machine and can be calculated directly from observation and measurements of the structure dimensions. These structures can be included in the full 3-D code (ACCEPT) but requires a much more detailed input file. The 3-D model tracks dosimetry more precisely, showing a skew in actual blockage ranging from 32% at 100 kV down to 25% at 300 kV as higher energy electrons are better able to scatter out of the blockage areas. Based on this correlation, machine output can be calculated and charted, showing the expected output of the machine as an independent approach from dosimetry, see **Figure 6**.

Direct correlation of a Monte Carlo 1-D result with dosimetry can be made by entering the beam current and web speed using an expanded KI=DS relationship to solve for D, see Equation (1). Information related to Equation (1) can be found in the appendix of ASTM E-2232.

$$\textbf{Dose (kGy)} = \mathbf{1000\ \ k'\ \ (I\ \ E)/A} \qquad\qquad \textbf{Equation 1}$$

Where **k'** corrects for beam blockage by the hibachi, **I** = current (mA), **E** = Monte Carlo result (MeV-cm2/g-electron) and **A** = beam area swept per second (width of beam in cm times speed in cm/s).

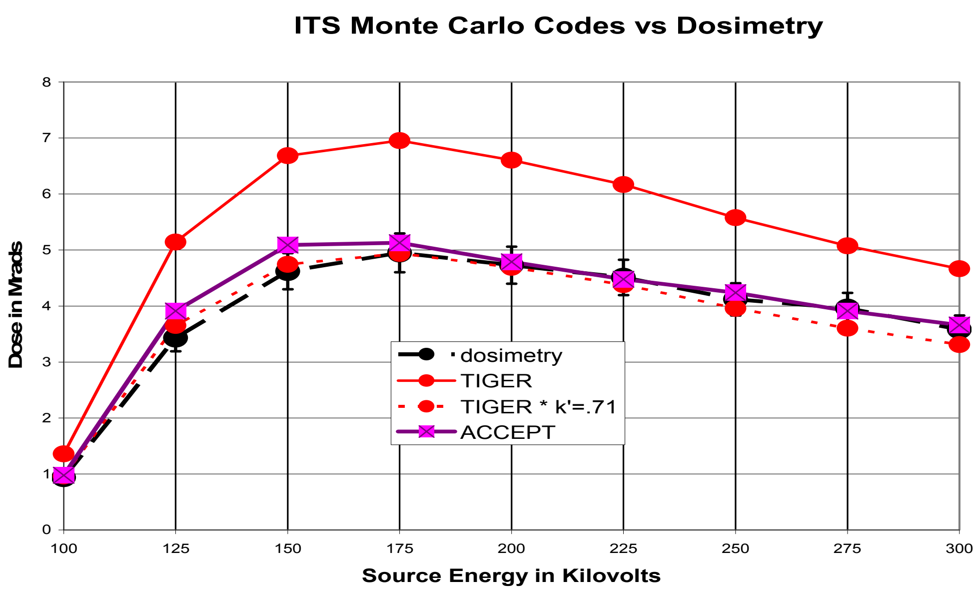

Figure 6. Results of Monte Carlo code calculations for TIGER (1-D model) and ACCEPT (3-D model) compared with dosimetry over a range of voltage at constant current and web speed. Note error bars on dose measurements.

Machine/Model building uncertainties. There are multiple sources of uncertainty associated with correlation of a Monte Carlo code prediction at low voltages. One potential source of uncertainty is that the indicated voltage may not be accurate. In the 1980 vintage ESI CB-175, the indicated voltage was 10% higher than actual, across the whole voltage range. Such a difference might not influence the surface dose in the 150-175 kV range but errors of only a few kilovolts in the range of 80-100 kV can account for significant differences in surface dose if characterized by a 20 micron thick dosimeter. Another source of uncertainty is that exact thicknesses must always be used in describing a cross-section at low voltages. The exact window thickness, while not critical in the 150 - 175 kV range, can make a big difference at 100 kV. Titanium window foil is generally provided at a stated thickness of 12 microns but can vary by several microns. The window thickness needs to be measured before being installed in the machine. The exact distance between the product plane and the window, the 'gap', needs to be measured to the nearest mm. A 5-cm gap of air has the same stopping power as a 12 micron titanium window. If the web is suspended through the chamber by web tension, it is possible that the pressure of the nitrogen blanket within the chamber can depress the web at low web tension and increase the air gap. The temperature of the chamber atmosphere affects the density of the gas and therefore stopping power. Also, the window material itself becomes an issue in terms of the energy spectrum of the electrons as they emerge (Kapton vs Ti) and this can affect the surface dose.

Tape Example. The tape in this example has a 2-mil thick layer of adhesive on a 5-mil thick tape backing. A 10 micron dosimeter (GEX) was used to benchmark the surface dose and a 40+ micron dosimeter (FWT) was used to benchmark most of what would be the entire thickness of the adhesive layer against Monte Carlo code. Neither dosimeter is able to represent the critical interface dose at voltages below 150 kV but when benchmarked against a Monte Carlo code, the code can then be used to determine the dose to the first micron (surface) and also at the interface. The interface dose is important since it sets the minimum dose necessary to bond the adhesive to the backing. Once that has been determined, and the gradients associated with voltage are characterized, then higher surface dose can be balanced against reduced dose to the backing material (degrades) by adjusting the voltage while maintaining constant interface dose. Monte Carlo code results were used to calculate the current at selected voltage/window/gap combinations to target delivery of a specific and fixed dose to the adhesive/backing interface under various operating conditions. Given the instabilities at very low voltage and low current conditions being used with this older piece of equipment, the correlations were reasonable but by no means exact. In most cases, agreement was within 20% but at the lowest voltage and current settings it was larger than that. However, the model was useful in gaining insight into the dose/depth relationships through a tape product as a function of voltage and predictions correlated well with product properties. Calculation of the surface dose and interface dose as a 1-micron thickness is made possible (2.5 micron intervals are shown in **Figure 7**) with normalization of these calculations to a minimum interface dose of 3 Mrads to show the correct target for surface dose and the degree of penetration into the backing at different voltages.

An interface dose of 3 Mrads was found to be more than enough to provide good 5-bond (adhesion to the backing). MIT Flex, an indication of backing degradation, showed no detectable degradation at voltages below 92 kV with an interface dose in the range of 2-6 Mrads. Tape holding power (adhesion to a substrate) was best in the range of 87 to 116 kV with an interface dose in the 2-4 Mrad range. More details of this particular study can be found in a previous publication.[5]

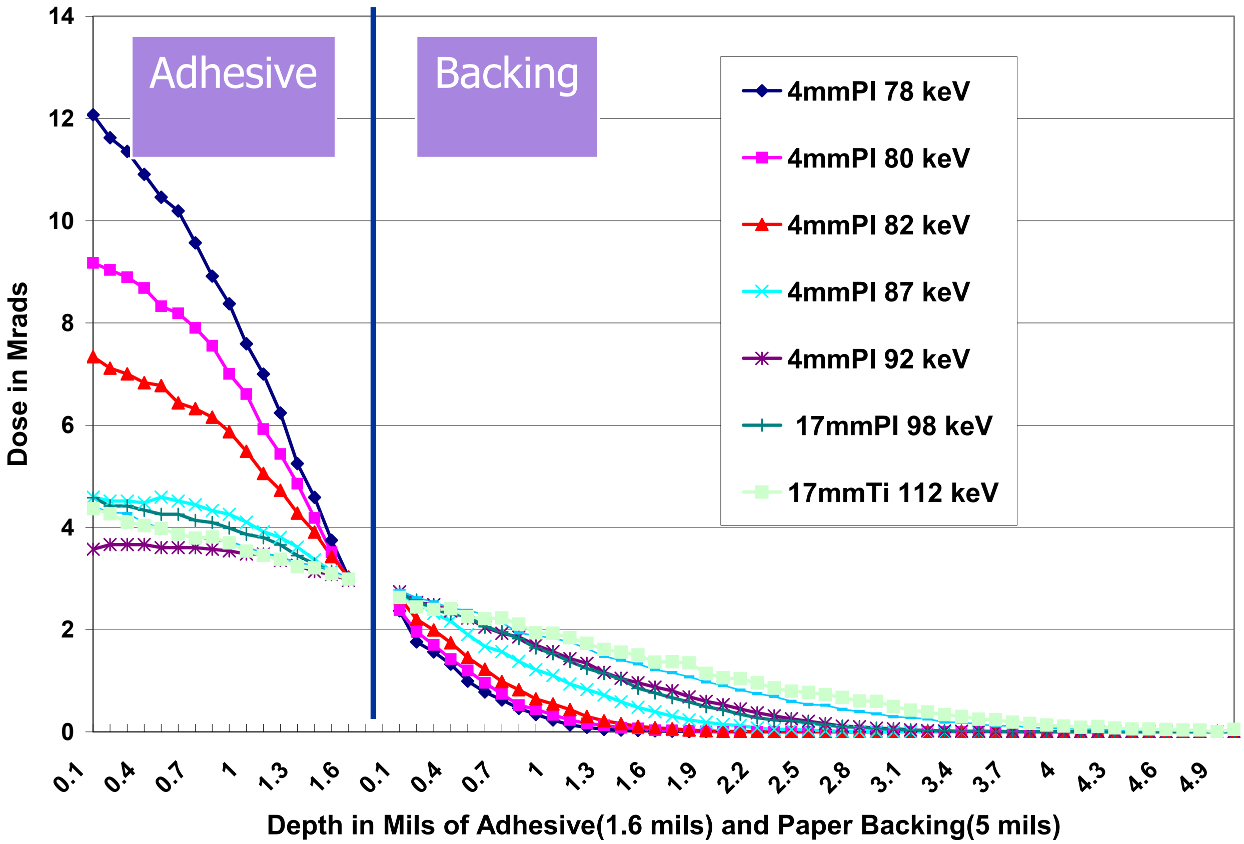

Figure 7. Results of Monte Carlo code calculations, normalized to an interface dose of 3 Mrads showing the different dose gradients through the 2-layer product that can be achieved over a narrow range of voltage.

Conclusions.

Uncertainty is inherent in dosimetry, model specification and the machine. Much of the uncertainty appears to come from the machine. While these characterizations are time consuming, they allow for a better understanding of the critical relationships between machine parameters and product performance and to bracket a specification. Once established, adjustment can be made to these parameters, based on the model, to account for changes in product density or layer thickness, window thickness or migration of the process to other equipment.

As the adoption of these tools become more common place and low voltage processing becomes more sophisticated, improvements will be made to ASTM/ISO 51818 that reflect how we do dosimetry, the definition of a surface dose and the need for and the usefulness of models (ASTM E 2232). The user needs to be aware of the inherent variability in the beam and how to separate this from dosimetry measurement error. The future reality of *in situ* calibration to a national laboratory using thin alanine dosimeters as the transfer medium will enable precise calibration of dosimeters and estimation of dose to the first micron.

References.

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5. Weiss, D. E., 'Electron Beam Tape Processing at Low Voltages,' Pressure Sensitive Tape Council TECH XXVII Global Conference Proceedings, May 12-14, 2004.