*Dynamic-Range Tests for a
Gamma-Ray Sensor*

R. C. Byrd

J. L. Longmire

C. E. Moss

MASTER

Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

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DYNAMIC-RANGE TESTS FOR A GAMMA-RAY SENSOR

by

R. C. Byrd, J. L. Longmire, and C. E. Moss

ABSTRACT

The task of detecting and characterizing intense bursts of nuclear radiation requires an instrument capable of operating reliably over wide extremes of signal intensity. Developing techniques for testing and calibrating such a detector involves a combination of experimental measurements, data analyses, and computer simulations. The results of these efforts provide important insight into the instrument's behavior in the laboratory and in its eventual application. For the present case, such studies not only verify the proper operation of the existing detector, but they also provide the basis for future improvements in its performance.

1. INTRODUCTION: DYNAMIC RANGE

Basic Instrument Linearity. An important feature of instruments designed to detect intense bursts of gamma rays is the large dynamic range required. **Figure 1.1** shows an illustration that summarizes the present work. The x -axis shows the input radiation level, which varies over about seven orders of magnitude; the y -axis shows the radiation level indicated by the instrument. As shown by the close agreement between the data and the dotted line, the output level accurately tracks the varying input intensity.

Instrument Features. Designing, producing, and demonstrating linearity over such a wide range is not a simple task; for example, our detector uses two overlapping transducers, each covering a range of approximately 10^4 in signal. As shown in the cutaway view of **Fig. 1.2**, a single block of plastic scintillator is viewed by two independent pairs of sensors, with each pair consisting of a photomultiplier tube and a silicon photodiode. The high-sensitivity photomultiplier tubes, which are coupled directly to the scintillator, cover the lower half of the intensity range; the low-sensitivity, air-coupled photodiodes cover the upper half. Even at its most basic level, the operation of the instrument therefore involves many different features. This report is devoted to explaining the measurements and analyses that connect the physical detector shown in **Fig. 1.2** with the demonstrated linearity shown in **Fig. 1.1**.

Contents. Section 2 describes the experimental arrangement for the measurements and explains the technique used to analyze the results for previous instruments. This technique provides calibrations that confirm that all delivered instruments have essentially the same response; however, further inspection suggests that this response covers a dynamic

Fig. 1.1. Linearity of the detector output for an input signal intensity that varies over almost seven orders of magnitude. The circles are obtained from the measurements described in this report; the dotted line shows the desired unit slope.

Fig. 1.2. Cutaway view of the gamma-ray sensor, showing the pairs of high-sensitivity photomultipliers and low-sensitivity photodiodes. The use of two pairs of active elements provides redundancy.

range of a little more than a factor of 10^5 , not 10^8 . In Sec. 3 we therefore investigate an alternative calibration procedure, which reveals that the apparent range limitation is actually an effect of the calibration technique, not a problem associated with the instrument itself. Because the analysis needed to provide this alternative calibration is admittedly complicated, Sec. 4 develops a phenomenological model that allows the calibration to be simplified and also provides an absolute detector normalization. Section 5 explains the "fine-tuning" of the detector response using the instrument's adjustable photomultiplier gain, and Sec. 6 illustrates the effect of these adjustments on the maximum dynamic range. Section 7 summarizes the analyses and discusses areas that require further study.

2. EXPERIMENTAL SETUP AND STANDARD ANALYSIS

Overview. The calibration of the instrument involves two operations: a set of laboratory measurements and their subsequent analysis. The measurements consist of irradiations using flash x-ray generators whose intensities cover most of the desired 10^8 range and whose energies represent the signals and background typical of operating sensors. The analysis then undertakes to convert the raw data into the form shown previously in Fig. 1.1. This section describes the measurements and analyses that have traditionally been performed for all delivered instruments. In the course of the discussion, we also explain many of the instrument's important features.

Experimental Setup. Figure 2.1 shows a schematic layout common to all the measurements covered in this report. For tests using a Febetron pulsed x-ray source,¹ the source head and the instrument are placed on a laboratory bench at separation distances of 25–200 cm. Alternatively, tests using a Golden portable x-ray generator² are made in

Fig. 2.1. Schematic layout of the experimental setup for the detector calibrations. A pulsed x-ray source is placed a variable distance away from the instrument. The beam intensity can be reduced by increasing the separation or adding attenuation filters, and the source and beam monitors are used to normalize the results.

a long subbasement tunnel, where the separation can be varied over a larger range, from 25 to 1340 cm. These changes in separation distance and hence detector solid angle are used to vary the fluence incident on the instrument by factors of about 60–3000. Because the measurements at the largest distances (smallest solid angles) are always made with filters inserted, corrections for air attenuation can generally be neglected. For the Febetron, the source voltage can also be increased to provide some additional range in beam intensity. In either case, filters made of stacks of tantalum foils with thicknesses up to about 200 mils (5 mm) are used to attenuate the beam intensity. (For clarity, many of the values in this report will be given in both metric and engineering units.)

Normalization. As indicated in Fig. 2.1, monitor detectors are employed to normalize the instrument response to the beam intensity. A *source* monitor is usually placed next to the source; because it is unaffected by the addition of filters or changes in separation distance, this normalization compensates for random variations in source output or intentional changes in accelerating voltage. In contrast, a *beam* monitor is placed next to the detector and is moved along with it, so its output reflects both separation and filter effects. In general, determining the effect of changes in separation distance is more straightforward than estimating the effect of different filter thicknesses or source voltages, which usually change the beam’s energy spectrum as well as its intensity. On the other hand, changes in separation distance can affect the relative amounts of direct and scattered flux, and hence the measured intensity may not correspond precisely to the calculated solid angle. These possibilities are considered in the calibrations described later in this report.

Monitor Values. Figure 2.2 shows the raw measurements for a Febetron run that was intended to be Instrument 9’s final calibration before delivery. The results illustrate the information provided by the detector and the complications of performing a calibration that spans a large dynamic range. First, the *horizontal* scale gives the relative signal level from a beam monitor placed a short distance to the side of the instrument. Each of the three sets of data corresponds to a range of beam intensities measured using a single setting for the monitor sensitivity (that is, bias voltages of 300, 450, or 715 V). At each setting, the monitor output spans about two decades, from 20 to 2000 mV. At the limit of this range, the bias voltage is changed, and the previous measurement is repeated to normalize the results at the two settings, as indicated by the dotted lines. Typically, data for the two lowest intensity scans are obtained by varying the filter thickness, and data for the third scan are measured by increasing the source voltage after all filters have been removed.

Sensor Outputs. Second, the *vertical* scale in Fig. 2.2 shows the observed instrument response on a logarithmic scale expressed in “digital levels.” Nominally, each decade of sensitivity is digitized into 16 levels; the full 128 levels should therefore correspond to 8 orders of magnitude in total intensity. As explained in the Introduction (Sec. 1), to span this range the instrument uses a plastic scintillator viewed by two different sensor elements. The lower four decades (digital levels 0–63) are those for the photomultiplier—hence, the “PM” range. The upper four decades (levels 64–127) are covered by the photodiode (“PD”) sensor. The dashed line at level 64 in Fig. 2.2 indicates the division between the two ranges. Actually, at the bottom of the PD range there is a deliberate four-level gap (levels 64–67); for simplicity, we have therefore shifted all the PD output levels downward by four levels to produce a continuous response. Because levels 0 and 127 (shifted to 123) are null and overflow channels, the useful data range therefore covers levels 1–122.

Overlapping Ranges. The next step in the data analysis interconnects the three sets of measurements at the different monitor voltages to provide the single continuous calibration shown in Fig. 2.3. As stated, we have simply normalized the output-to-monitor ratios at the end of each set to the corresponding point from the next set. Three observations emerge. First, the results in the PD range (above level 64) have a slope that is much different

Fig. 2.2. Calibration data normalized to a beam monitor. Because the monitor detector has a maximum range of about two orders of magnitude, three separate scans are required, each using a different monitor voltage.

Fig. 2.3. Interconnected monitor calibrations from Fig. 2.2. A continuous result is obtained by internormalizing the overlapping values from the three ranges in Fig. 2.2.

from that for the PM data (below level 64). Second, although the slope for the PM range appears to be reasonable, that for the PD range is much too steep to cover the desired four decades of monitor variation. Finally, even with the uncertainties in the interconnection of the data sets, it appears there is a slight amount of systematic, nonlinear structure in the PM response.

Previous Calibrations. Before speculating about the possibility of an instrumental problem in the PD range, in Fig. 2.4a we include results from two previous calibrations of Instrument 9, each normalized to a slightly different monitor scale in order to match the expected PM calibration slope. Qualitatively, the behaviors of the three measurements are very similar, although the apparent onset of the sharp PD increase occurs at slightly different points relative to the PM data. Furthermore, Fig. 2.4b shows the analysis of a similar calibration for Instrument 2, using measurements that were made several years earlier. Comparison of the measurements in Figs. 2.4a,b with the dotted line, which shows the slope appropriate for spanning 8 decades in 128 digital levels, shows that (1) the responses of Instruments 2 and 9 are consistent with one another but (2) both responses are inconsistent with a desired dynamic range that approaches 10^8 .

Electronics Calibration. The most obvious explanation for the restricted range, an incorrect conversion gain in the PD electronics, can be dismissed by examining the electronics calibration (C_E) shown in Fig. 2.5. Each amplifier/digitizer section (PM or PD) is calibrated separately with a pulser. The heavy curves show the actual digital responses; the light dotted lines indicate the ideal slope, that is, a gain of 4 decades over 64 levels. As suggested by the dashed line connecting the two ranges, simple electronics calibrations cannot determine the absolute normalization between the PM and PD channels, which involves differences between the energy conversion, light collection, and electrical responses for the two active elements. The calibrations do, however, indicate that the coverage should be about 4.6 decades (a factor of 40,000) for the PM range and about 4 decades for the PD range, even with the 4 lowest PD levels (64–67) removed. Thus, the electronics cannot be the source of the suspicious PD response in the x-ray measurements shown in Figs. 2.2–2.4. On the other hand, the amplifier’s slight deviation from a purely logarithmic transform in Fig. 2.5 may explain the apparent deviations seen in the PM range. (The present deviations are much smaller than those observed in previous instruments.)

Discussion. Other possible explanations for an incorrect PD range abound. For example, there could be direct stimulation of the active silicon element in the photodiode—except that a thick lead shield is placed over the photodiode during all calibrations. Also, one could argue that measurements at the low 300-V monitor setting are the problem, except that close inspection of Figs. 2.4a,b shows several 300-V measurements with apparently normal results. Finally, it appears that most of the discrepant PD measurements were made not by removing filters, but by increasing the source voltage. However, sorting the data according to source voltage reveals that some of the distorted measurements at levels 68–83 were obtained at the standard 20-kV source voltage, which argues against a systematic source problem. Thus, the available measurements with the standard calibration technique appear to indicate that all instruments behave the same but that none achieves the desired dynamic range.

(a)

(b)

Figs. 2.4a,b. Previous calibrations. Part a: Adding results from two previous measurements for Instrument 9 to those in Fig. 2.3 shows that the anomalous behavior in the PD range was also present in earlier tests. Part b: Measurements for an earlier instrument show behavior similar to that seen for Instrument 9 in part a.

Fig. 2.5. Electronics calibration C_E . The dotted lines show the ideal logarithmic conversion; the solid curves connect the measured values. The systematic deviations from the ideal case are an expected characteristic of the existing amplifiers.

3. SCANS OVER SEPARATION DISTANCE

Overview. The difficulties with the standard calibration could be associated with the changes in filter thickness and source voltage, which increase the average beam energy and hence the penetration through the instrument shielding. It therefore seemed reasonable to attempt measurements using the alternative technique of changing only the separation distance. This approach varies mainly the detector's solid angle, not the energy spectrum, so the intensity should vary predictably as the inverse square of the separation distance. This section describes the results of these tests.

Technique. The alternative measurements were made with source-to-instrument separations that varied from 25 to 200 cm (see Fig. 2.1). Upon reaching the maximum separation, this intensity factor of 64 was repeated in steps after changing the filter thickness or the source voltage, while taking care to provide several overlapping digital levels for normalization. In this approach, small changes in intensity (usually by factors of 4) are made by gradually decreasing the separation, and larger changes are made by varying the filter thickness or source voltage. Thus, even if the energy spectrum is affected by the few large changes, any effect should be absorbed into the normalization. Although a source monitor was also included to correct for long-term source drifts, no such effects were observed.

Solid-Angle Scans. Figure 3.1 shows one set of individual $1/r^2$ scans normalized as a function of relative solid angle. The large overlaps in output level are used to ensure reliable connection of the different scans. It is immediately clear that the two highest PD ranges have slopes similar to those in the PM data, which is a result very different from that in the previous monitor-voltage scans. A clearer picture emerges in Fig. 3.2, which connects the individual segments to cover the complete range. The overall dynamic range is approximately correct, as indicated by comparison with the straight line that spans 7

Fig. 3.1. Individual $1/r^2$ scans, with each point showing measurements at a different separation distance and each line using a different filter thickness or source voltage. The slopes in the PD and PM ranges are essentially the same.

Fig. 3.2. Interconnected $1/r^2$ scans, with overlapping segments normalized together by eye. The overall dynamic range appears to be correct, but the crossover region shows a clear discontinuity.

decades in 112 levels, just as required. However, there now appears to be a pronounced “shelf” between the PM and PD ranges. Note in particular that a single $1/r^2$ scan (shown by the solid line and inverted triangles) extends across the PM/PD electronics boundary from level 57 to level 72. Within this scan two measurements at solid angles that differ by a factor of 4 both result in an output level of 63. Also, the suggestion of a systematic nonlinearity in the PM range is now unmistakable. Thus, the problem of a restricted PD response appears to have been replaced by two lesser questions about the overlap between the two ranges and the possibility of nonlinearities within the ranges.

Accumulated Results. To verify the observed behavior without relying on interconnecting so many solid-angle ranges, wide $1/r^2$ scans were made in the subbasement tunnel using the portable Golden x-ray generator to cover distances of 25–1340 cm (a solid-angle factor of almost 3000). When combined with the Febetron tests, the remarkably complete and consistent data set seen in Fig. 3.3a emerges. Here, comparison with the dotted line clearly shows that the slopes in the two ranges are essentially correct and the offset between the PM and PD ranges is a consistently reproducible feature. For clarity, these 186 measurements were compressed into 4 logarithmic energy bins per decade; the result is shown in Fig. 3.3b. This figure also includes the electronics calibration curves C_E from Fig. 2.5, whose arbitrary PM/PD horizontal offset has now been adjusted to match the measured offset between the two sensor ranges across level 64. The suggestion of nonlogarithmic structure in the PM and PD data is now clearly seen to be an effect of the structure in the electronics calibration. At first glance, it appears that the instrument covers 8 decades with less than 112 digital levels; in fact, however, the offset causes a missing half-decade of response at the center of the range. This issue will be addressed in Sec. 5.

Comparison between Techniques. Contrasting the inverse-square measurements of this section with the monitor-normalized analyses of the previous one suggests that the instrument is in fact operating correctly but that the beam monitor is suspect. If, at its lowest voltage setting, the monitor output ceased to increase linearly just as the incident intensity (coincidentally) crossed into the PD range, then the normalized results would indeed display too large a slope and too restricted a range, just as observed. Subsequent tests at the lowest voltage setting showed that the monitor output indeed failed to vary properly with separation distance, thereby confirming the saturation hypothesis. With the recognition that some of the measurements normalized to the monitor at its 300-V setting might be anomalous, the apparent discrepancy between the two techniques is resolved. In fact, the accumulated results shown in Figs. 3.3a,b include measurements using both $1/r^2$ variations and monitor normalizations (omitting those at the 300-V setting).

Interpretation. Within each PM or PD range, the solid-angle results show that the instrument seems to cover 4 decades of input intensity with 64 digital levels, just as desired. The small variations from the ideal logarithmic response appear to be a predictable (and correctable) consequence of the electronics calibration. The offset between the PM and PD ranges is a consequence of the relative gains of the two electronics channels. Because of differences in the optical responses of the PM and PD sensors, this relative gain cannot be determined in bench testing without great difficulty. With the x-ray source, however, the offset in the instrument output is clearly measurable. We will return to this discussion in Sec. 5.

(a)

(b)

Figs. 3.3a,b. Collected response calibrations. Combining measurements using variations in separation distance, filter thickness, and source voltage provides a consistent set of data. Part a shows the complete data set; part b shows the average in quarter-decade bins, which reveals a systematic behavior that matches the electronics calibration C_E from Fig. 2.5.

4. X-RAY SOURCE MODEL

Motivation. The solid-angle analysis in Sec. 3 demonstrates that Instrument 9 covers the desired dynamic range with a linearity consistent with that expected from the electronics calibration. However, the complexity of the overlay analyses required for both the $1/r^2$ and monitor-normalized approaches precludes their routine use for calibrations of future instruments. Worse, these results provide only limited confidence in the performance of previous instruments, for which measurements were made at only a single separation distance. For these reasons, this section develops yet another approach to the calibration analysis, one that does not require the use of a monitor detector but estimates the radiation intensity at the detector using only source voltages, filter thicknesses, and separation distances. Four important steps are involved. First, an empirical source model is developed to describe the input intensity at the detector. Second, this model is justified by comparisons with calculations and the systematics of the measurements. Third, particular examples from the measurements are reanalyzed to illustrate the usefulness of the model. And last, calibrations with a monitor detector are used to normalize the sensor's absolute intensity scale.

Model Assumptions. We will represent the major parameters for each i^{th} measurement as the source voltage V_i in kV, the tantalum filter thickness T_i in mils, and the separation distance R_i in cm. Based on the analyses in the previous section, the detector solid angle $\Delta\Omega$ varies according to the relation

$$\Delta\Omega = A/R^2, \quad (4.1)$$

where A is the detector's frontal area ($3 \times 4 \text{ in}^2$ or 77.42 cm^2). For changes in source voltage, we simply assume that the intensity I_i varies linearly as

$$I_i \propto (V_i - V_o), \quad (4.2)$$

where V_o is an empirical source offset voltage. As shown later, this assumption appears to be successful for source voltages from 20 to 30 kV.

Filter Transmission. In the measurements, the source intensity is reduced by adding filters, with the nominal relation

$$I_i \propto e^{-T_i/T_o}, \quad (4.3)$$

where T_o is an empirical attenuation length that reflects the energy-dependent effect of the tantalum absorption. Because our filter thicknesses span the range from 1 mil to 166 mils (0.0254 to 4.22 mm), it should be expected that a single T_o value is not sufficient to cover the full range. This prediction is explained by reference to **Fig. 4.1**, which shows a set of energy-dependent transmissions estimated using the MCNP code³ for tantalum filters of different thicknesses (in mils). Clearly, the attenuation produced by adding filters is not simply a fractional absorption of photons at all energies; it also essentially includes complete removal of all photons below a certain cutoff energy. As more and more low-energy photons are removed, additional filtering provides less and less attenuation per unit thickness because of the low absorption at high energies. Thus, the effective attenuation length is expected to increase with filter thickness. We have allowed for this possibility by replacing the constant T_o value with the thickness-dependent expression

$$T_S(t_i) = c_1 + c_2 t_i + c_3 t_i^2, \quad (4.4)$$

where for convenience the thickness T_S is expressed in terms of the dimensionless ratio $t_i = T_i/200$ (for T_i in mils).

Fig. 4.1. Energy-dependent filter transmission. Using the MCNP code and a flat energy spectrum, we have estimated the transmission of photons at different energies through tantalum filters with thicknesses from 1 mil to 200 mils (shown by the small numbers).

Initial Parameter Determination. Measurements using both filter and solid-angle variations are required to determine the offset voltage V_o and the c_k coefficients. In the first stage of the analysis, the parameters and normalizations were varied to fit each set of measurements, hence a *single-scan* analysis. The value for the Febetron offset V_o was obtained by matching the effect of voltage variations with that for changes in the filter thickness or separation distance, with the result $V_o = 17.6 \pm 1$ kV. Figure 4.2 shows the results for all available measurements (326 points, open circles) and their logarithmic average (solid circles). The few outliers correspond to measurements with the very thickest filters. The sets of attenuation lengths $T_S(t)$ used to predict the input intensities are shown in Fig. 4.3a. In terms of Eq. (4.4), very different c_k coefficient sets are required to describe the attenuation of the Febetron and Golden x-ray beams, which is reasonable in view of the likely differences between the two energy spectra. The Febetron data can be fitted using $c_1 = 5.8$, $c_2 = 9.4$ to 11.5, and $c_3 = -6$ to +1. The Golden data used $c_1 = 3.5$, $c_2 = 25$, and $c_3 = 42$. In practice, the c_1 values are used to minimize the overall offset between sets of measurements that employed solid-angle or thickness variations, the c_2 value determines the overall slope of the response, and c_3 controls the relative curvature at the highest t values (lowest intensities). At least empirically, the source-model approach provides reasonable response characteristics without the need for monitor normalizations. The successful parameterization of the source intensity for each measurement in terms of R_i , V_i , and T_i values is the first step in our development of an alternative calibration approach.

MCNP Comparisons. Our focus now shifts from establishing an empirical source model to supporting its assumptions. Qualitatively, the variation of the attenuation lengths with thickness is explained by reference to Fig. 4.1. For a quantitative basis, we first refer to the three curves in Fig. 4.3b, which show the thickness dependence of the attenuation lengths calculated using the MCNP code for Gaussian energy distributions in three different

Fig. 4.2. Single-scan analyses. The input intensities come from source fitting; the digital levels are the same as those used previously. The open circles show the individual measurements; the solid circles are quarter-decade averages. Each set of measurements is allowed its own normalization value and attenuation coefficients.

Fig. 4.3a. Single-scan attenuation lengths. The Febetron and Golden parameters for individual measurements are shown by the cross and plus signs, respectively.

Fig. 4.3b. Single-scan attenuation lengths from Fig. 4.3a compared with the thickness dependences calculated using the MCNP code for three Gaussian energy distributions centered at 45, 95, and 125 keV.

bands. The lowest curve, $g_1(E)$, is for a Gaussian with a centroid $E_0 = 45$ keV and a width $\sigma = \pm 15$ keV; the middle curve (g_2) uses $E_0 \pm \sigma = 95 \pm 25$ keV; the top curve is for $g_3 = 125 \pm 50$ keV. Even with these relatively narrow energy distributions, the progressive removal of low-energy photons produces calculated attenuation lengths that increase significantly with increasing filter thickness. The three beam energy regions in Fig. 4.3b—low, middle, and high—roughly correspond to energies above the cutoffs for low-, middle-, and high-thickness filters.

Fitting Results. Although none of the three Gaussian distributions describes the observed thickness variation for either of the sources, appropriate combinations with relative areas (a_1, a_2, a_3) provide remarkably good results, as shown in Fig. 4.3c. The measurements at low thicknesses were used to constrain the ratio between the areas of the two lower-energy distributions (g_1, g_2), and the measurements at higher thicknesses were used to fix the ratio for the two higher energies (g_2, g_3). For the Golden data, the single set of attenuation coefficients (c_1, c_2, c_3) gives a single set of relative areas (a_1, a_2, a_3) = (0.79, 0.18, 0.03). The range of attenuation coefficients for the Febetron data causes the two higher-energy a_k areas to vary: (a_1, a_2, a_3) = (0.171, 0.822 ± 0.002 , 0.015 ± 0.010). These small variations result in the three different Febetron curves shown in Fig. 4.3c. Only the central curves for each source, referred to as T_F and T_G , will be used in the remainder of our calculations, henceforth described as our “standard” source model.

Source Energy Spectra. The energy distributions that result from the fitting procedure are shown by the combined Gaussian distributions in Fig. 4.4. The differential probabilities $P(E)$ (per keV) have been multiplied by the energies so that the resulting $E \times P(E)$ function indicates relative probability on a logarithmic energy scale, that is, $E \times P(E) = E \times dN(E)/dE = dN(E)/d(\ln E)$. There is also the issue of the relative intensity of the two sources. As normalized to the digital levels obtained with no filters,

Fig. 4.3c. MCNP calculations vs. single-scan attenuation values. The Febetron and Golden data from Fig. 4.3a are compared with calculated values obtained from a weighted combination of a three-component spectral model.

Fig. 4.4. Estimated energy distributions $E \times P(E)$ for the Febetron and Golden sources.

the output of the Golden source is about 30% lower than that for the Febetron operated at the same distance and at the standard 20-kV source voltage. When compared with the offset voltage $V_o = 17.6$ kV, this decrease leads to the equivalent operating voltage of $V_i = 19.2$ kV for the Golden source. Of course, operating the Febetron at its maximum 30-kV voltage would provide an additional intensity factor of 4, for a maximum factor of 6 increase over the Golden source operated in the same geometry.

Source-Model Validation. The MCNP calculations shown in Fig. 4.3c provide a clear justification for our assumption of exponential filter attenuation; two additional steps are needed to verify the assumptions of linear dependence on source voltage and source-to-detector solid angle. First, by correcting the source predictions for all but the $1/r^2$ factor and then dividing by the observed sensor output intensity, we obtain the plot shown in Fig. 4.5a for the relative source output vs. solid angle. The small dots show 405 individual measurements; the open circles are averages over logarithmic energy bins. The agreement with the dashed line confirms the expected validity of the solid-angle assumption. More debatable, however, is the assumption of a linear variation in Febetron output with anode voltage, but this parameterization is justified by the similar analysis shown in Fig. 4.5b. These tests, along with the MCNP predictions of the attenuation lengths, complete our justification of the source-model assumptions.

Comparisons with Original Distributions. The utility of adopting the standard source model—with no adjustable parameters—to estimate the x-ray source intensities is illustrated by the next four figures. First, Fig. 4.6a shows the predictions for the three runs made with the Golden source, including the intensity factor. The only significant discrepancies are at the largest filter thicknesses, as seen also in the differences between the measured and calculated attenuation values in Fig. 4.3c. Next, Fig. 4.6b shows the Febetron test that covers the widest range of filters and solid angles (also shown previously in Fig. 3.2); except for a few outliers (those seen also in Fig. 4.2), the results from the standard set of coefficients are quite good. Third, and perhaps most important, the same coefficients also allow the monitor to be ignored and the three original Instrument 9 calibrations to be recovered (see Fig. 2.4a), as shown in Fig. 4.6c. Finally, Fig. 4.7 shows the predictions for the complete set of 326 measurements from Fig. 4.2, but this time using the standard model, not the adjustable single-scan parameters. Given the lack of free parameters, the overall description is unquestionably impressive.

Absolute Fluence. Having developed a procedure for estimating the relative beam intensity as a function of source voltage, filter thickness, and separation distance, we can now take the final step of establishing an absolute scale for this intensity. In our case this calibration is based on the beam monitor measurements made with the Febetron source. In the standard setup, at a monitor voltage of 715 V the observed monitor output level is 10 mV for a 0.662-MeV ^{137}Cs gamma-ray source. This value can be used to convert the output level produced by a Febetron pulse into an absolute energy deposition; for example, 1.18 V would give $(1.18 \text{ V}/10 \text{ mV}) \times 0.662 \text{ MeV} = 78.1 \text{ MeV}$ of deposited energy. Dividing by the monitor's frontal area of $1.5 \times 1.5 \times 2.54^2 \text{ cm}^2$ then provides the energy density E of 5.38 MeV/cm^2 at the monitor and (presumably) at the detector. The accumulated result of many such measurements fixes the normalization K for the energy-density equation:

$$E_i = K e^{-T_i/T_S(t_i)} (V_i - V_o) / R_i^2, \quad (4.5)$$

where E_i is the energy density for the i^{th} measurement in MeV/cm^2 , T_i is its filter thickness in mils, $T_S(t_i)$ is the corresponding calculated attenuation length for either the Febetron ($S = F$) or Golden ($S = G$) source, V_i is the source voltage in kV (set to the constant value $V_i = 19.2$ kV for the Golden source), V_o is the offset voltage of 17.6 kV, R_i is the separation distance in cm, and K is the normalization constant of $4.6 \times 10^8 \text{ MeV/kV}$.

(a)

(b)

Figs. 4.5a,b. Source-model validation. Part a provides confirmation of the $1/r^2$ solid-angle variation, and part b confirms that the source output varies approximately linearly with anode voltage. Similarly, the earlier Fig. 4.3c confirms the filter attenuation model.

Fig. 4.6a. Predicted response for tests using the Golden x-ray source. The input intensities are calculated from the standard source model.

Fig. 4.6b. Predicted response for a Febetron test using variations in source voltage, filter thickness, and $1/r^2$ separation distance (see Fig. 3.2). The input intensities are calculated from the source model.

Fig. 4.6c. Predicted response for the three original Febetron calibrations using the standard combination of filters and source voltages (see Fig. 2.4a). The input intensities are calculated from the source model.

Fig. 4.7. Accumulated results for all measurements at different source voltages, filter thicknesses, and separation distances. These points are the same measurements shown in Fig. 4.2, but now using the standard source model to provide the relative input intensities.

Fig. 4.8. Absolute energy densities. The measurements in Fig. 4.7 have been averaged over logarithmic bins, and the horizontal scale is now given in MeV/cm² based on normalization to a calibrated monitor detector.

For our sample measurement, the Febetron source voltage was $V_i = 20$ kV, the filter thickness was 84 mils ($T_F = 9.75$ mils), and the detector was at $R_i = 196$ cm, for which Eq. (4.5) predicts $E_i = 5.41$ MeV/cm², in good agreement with the measured monitor value of 5.38 MeV/cm². The accumulated plot of digital levels vs. energy densities, after converting the measurements in Fig. 4.7 and averaging over quarter-decade steps, is given in Fig. 4.8. Although the exponential transmission could be calculated more fundamentally by integrating the transmission curves in Fig. 4.1 over the probability distributions $P(E)$ from Fig. 4.4, the present approach is far more convenient.

Discussion. This section began by developing an empirical model for the output intensities of the calibration sources, with each set of measurements allowed to have a separate normalization and thickness dependence. Based on the observed systematics, we next used MCNP calculations to justify the attenuation model and estimate possible energy distributions for the sources. These standard source parameters were used to confirm the systematics of the original assumptions. Finally, the filter and source parameterizations were used to predict the absolute source intensities for the different measurements. Although the approximations in this approach prevent its use for documenting fine details of the response, the convenience should simplify testing of the dynamic range and PM/PD offset for any of the instruments. It is especially important to note that the MCNP calculations and the resulting energy spectra are only supporting analyses—the empirical attenuation lengths, source-voltage dependence, and solid-angle variation are sufficient on their own to explain the input energy densities. In practice, we expect that a combination of the source-model approach (Figs. 4.6–4.8) and the single-scan analyses of Fig. 4.2 will be suitable for establishing calibrations for both previous and future instruments.

5. PM GAIN VARIATIONS AND ABSOLUTE OUTPUT

Overview. The previous section established an absolute calibration for the input source intensity and the systematics of the instrument's relative response expressed in digital output levels 1–128. Armed with the tools required to systematically analyze particular sections of the data, we now return to the issues discussed at the end of Sec. 3, which concerned the nonlinearities in the electronics calibrations and the effect of changes in the PM high voltage on the size of the PM/PD offset. This discussion focuses on the vertical axis in our plots and converts the instrument's output in digital levels to readings in absolute energy densities. We conclude by illustrating the effects of different gain choices on a hypothetical instrument response, which completes our studies of dynamic range.

PM High-Voltage Settings. All measurements presented thus far were made with the PM high voltage (HV) set at its maximum gain, that is, at step 7 of steps 0–7. Referring now to Fig. 5.1a, we see that lowering the HV step reduces the PM gain and decreases the digital level for a given input signal, thereby shifting the previous C_7 electronics calibration curve downward across the entire PM range. Equivalently, a decrease in gain can be represented by increasing the input signal needed to provide a fixed digital level, that is, by shifting the C_7 calibration curve to the right, toward larger input levels. For outputs expressed in digital levels, this latter approach is more appropriate because the distortion in the electronics is associated with its output, not input, level. In effect, the source intensities are shifted instead of the output levels. To illustrate, Fig. 5.1a shows the previous step-7 data along with the results from several scans made at the lower voltage steps of 3 and 0. The open circles are the average step-7 data; the triangles are the individual step-3 and step-0 measurements. In the figure, the data at these reduced settings can be described by shifting the PM portion of the C_7 calibration curve to the right by factors of $1.275^4 = 2.64$ (for C_3) and $1.275^7 = 5.48$ (for C_0). Such shifts result in more smoothly joining the PM and PD responses and thereby eliminating the missing decade of dynamic range. This point is emphasized by the expanded view in Fig. 5.1b, which shows the three response curves near the crossover. Considering that the actual measurements fall somewhat below the shifted curves, it appears that the step-0 measurements (as opposed to the step-0 curve) show a vertical break that is almost as large as the horizontal break seen in the step-7 values. Within the straggling in the measurements, it can be seen that the step-3 measurements connect almost continuously across the crossover.

Corrected Responses. Knowing the PM electronics calibration and the gain shifts for different HV settings allows us to horizontally shift the measured PM digital levels in Figs. 5.1a,b to correct for differences in gain at steps 0 and 7. The results are shown in Fig. 5.2a, along with an approximate conversion from step-3 digital levels to energy density (and its inverse) given by

$$E_i = 10^{(L_i - 4)/14.25} , \quad (5.1)$$

$$L_i = 14.25 \log_{10} E_i + 4 , \quad (5.2)$$

where E_i is the shifted energy density in MeV/cm^2 for the i^{th} measurement and L_i is the instrument's digital output level. We can also use the electronics calibrations from Fig. 5.1 to provide look-up tables that shift the digital levels vertically by correcting for the non-logarithmic deviations in the electronics; the results are shown in Fig. 5.2b along with the same conversion function.

Input/Output Energy Densities. Given the voltage corrections, response data, and estimated function shown in Figs. 5.2a,b, it is only necessary to convert the vertical scale from digital levels to energy density to obtain the linear relation between input and output densities shown in Fig. 5.3. Here the input values come from Eq. (4.5); the output

(a)

(b)

Figs. 5.1a,b. Voltage step variations. Reducing the PM high voltage shifts the data and the calibration curves to lower values of the output/input ratio. Part b, which is an expanded section of part a, shows that the step-3 measurements (not the curves) provide the smoothest connection across the PM/PD boundary.

(a)

(b)

Figs. 5.2a,b. Voltage-step corrections. By shifting the PM measurements at step 7 and step 0 to match the step-3 values, a single response curve can be obtained. Part a shifts the source intensities; part b shifts the digital levels. The reference line shows the estimated function for conversion between step-3 digital levels and energy densities.

Fig. 5.3. Conversion of instrument output in digital levels to absolute results in MeV/cm².

values come from Eq. (5.2). Close inspection shows that the corrected responses are now remarkably logarithmic except for points immediately around the crossover region. In fact, the compressed version of this plot, with results for all the voltage levels combined, was used to introduce this report in Fig. 1.1.

Accumulated Results. Equations (5.1) and (5.2) provide the fundamental connection between the input signal and the instrument output. At voltage step 3, the instrument's ideal response to an energy deposition E_i in MeV/cm² is given in logarithmic digital levels L_i as

$$E_i = 10^{L_i/14.25} , \quad (5.1)$$

$$L_i = 14.25 \log_{10} E_i + 4 . \quad (5.2)$$

These ideal relations include the absolute monitor normalization but not two corrections needed to obtain the actual reported digital output. First, the PD channel is triggered if the energy density is greater than about 1.5×10^4 MeV/cm². In this case an offset of 4 levels is added to the ideal L_i value to give the reported L_i^{PD} value:

$$L_i^{PD} = L_i + 4 , \quad L_i = L_i^{PD} - 4 , \quad (5.3)$$

$$L_i^{PD} = 14.25 \log_{10} E_i + 8 . \quad (5.4)$$

Second, if the energy density is below the PD range, then the reported PM output level L_i^{PM} for high-voltage steps $H = 0-7$ varies from the standard L_i value for $H = 3$ as

$$L_i^{PM} = L_i + 1.5 \times (H - 3) . \quad (5.5)$$

For the PM range, Eq. (5.2) then become approximately

$$L_i^{PM} = 14.25 \log_{10} E_i + 1.5H . \quad (5.6)$$

Inverting Eqs. (5.4) and (5.6) gives energy densities E_i in MeV/cm^2 for instrument outputs in actual digital levels L_i^{PM} (<64) or L_i^{PD} (>64):

$$E_i = 10^{(L_i^{PM}-1.5H)/14.25} \quad (L_i^{PM} < 64) , \quad (5.7a)$$

$$E_i = 10^{(L_i^{PD}-8)/14.25} \quad (L_i^{PD} > 64) . \quad (5.7b)$$

Equations (5.7a) and (5.7b) are the final conversions between the instrument's output in digital levels and the original input energy density.

Summary. This section has completed our final version of the instrument calibration. The source model of Sec. 4 has allowed us to reasonably predict the absolute energy density produced by the Golden or Febetron sources as functions of source voltage, filter thickness, and separation distance. The absolute instrument response to this energy density can then be fixed in terms of its electronics calibration, the high-voltage step used for the PM range, and a single overall normalization. The only important tuning of individual instrument responses is expected to be the gain-matching that sets the overall scale and that minimizes the offset across the boundary between the PM and PD ranges. The analyses developed in this section should allow these parameters to be easily determined by using a few laboratory measurements.

6. DYNAMIC-RANGE ILLUSTRATION

Ideal Response. We now present a hypothetical illustration of the instrument's dynamic range and the effect of different choices on gain-matching across the PM/PD boundary. First, Fig. 6.1 shows an adaptation of the plot of digital levels vs. energy densities from Fig. 5.1, but now emphasizing the electronics calibrations over the full range rather than just the range appropriate for comparison with the measurements. Because of the increase

Fig. 6.1. Expected instrument output for different voltage steps.

in gain with increasing PM voltage step, operating at higher voltages should provide a lower detection threshold. However, once the maximum PM level of 63 is reached, all information about the changing input level is lost until the PD threshold is exceeded. Because changing the PM voltage step has little effect on the PD sensitivity, all three response curves coincide above this point.

Output Inversion. An illustration of the effect of different voltage steps on the overall range can be obtained by attempting to invert the instrument response, that is, to recover the input information from the digital output, assuming that the calibration curves are known. The results are shown in Fig. 6.2a. First, beyond the highest digital level all information is lost at any voltage setting. Second, raising the voltage step lowers the instrument's minimum threshold by as much as a factor of 6. Third, however, is the fact that much of this increase in low-end range comes from the loss of information at the crossover. This loss is more clearly seen in the enlarged view shown in Fig. 6.2b. Here, the step-7 results, which were "locked" in digital level 63, provide essentially no resolution over the same half-decade that was gained at the lower end of the range. The step-3 curve shows less of an effect, and the step-0 values change smoothly across the entire region. Thus, any voltage reduction below step 3 provides an insignificant gain in resolution at the cost of an unnecessary loss in dynamic range.

7. CONCLUSIONS

Instrument Certification. The first goal of this report was to demonstrate that the existing instrument provided a desired dynamic range approaching 7-8 orders of magnitude. As discussed in Sec. 2, this certification could not be provided based on the available measurements and analysis; in fact, the likely conclusion would be that the instrument in fact did *not* meet expectations because of a severe nonlinearity in the PD range. With this problem identified and isolated as a failure of the calibration monitor, not the sensor, the analyses in the remaining sections convincingly support a dynamic range in excess of that desired.

Calibration Procedures and Results. Our analyses have replaced the monitor ratios of the original calibration, first with a cumbersome interconnected $1/r^2$ approach, then with an empirical source model embodied in Eq. (4.5):

$$E_i = K e^{-T_i/T_S(t_i)} (V_i - V_o) / R_i^2, \quad (7.1)$$

where E_i is the energy density (MeV/cm²), T_i is the filter thickness (mils), $T_S(t_i)$ is the attenuation length (mils, from Fig. 4.3c), V_i is the Febetron source voltage (in kV, or set to 19.2 kV for the Golden source), V_o is an offset voltage (17.6 kV), R_i is the separation distance (cm), and K is the normalization constant (4.6×10^8 MeV/kV). The instrument's actual response to this energy deposition is given in logarithmic digital levels L_i by Eq. (5.7a) (for the PM range) and Eq. (5.7b) (for the PD range):

$$E_i = 10^{(L_i^{PM} - 1.5H)/14.25} \quad (L_i^{PM} < 64), \quad (7.2a)$$

$$E_i = 10^{(L_i^{PD} - 8)/14.25} \quad (L_i^{PD} > 64). \quad (7.2b)$$

Equations (7.1) and (7.2) represent the complete calibrations and conversions between the source's input energy density and the instrument's output in digital levels.

Advanced Topics. In the process of developing the source model, useful information was also obtained about (1) shielding effectiveness, (2) source spectra, and (3) absolute calibrations. This information, while contributing to the analyses in this report, also provides the basis for future work on instrument shielding and the relative response to the gamma-ray signal and x-ray background from intense bursts of radiation.

(a)

(b)

Figs. 6.2a,b. Inversion of the digital responses in Fig. 6.1 to recover the original input signal. Part b is an enlargement of the crossover section of part a.

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