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Shielded Gamma-Ray Detector*

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R. C. Byrd

CALCULATIONS AND MEASUREMENTS OF THE ENERGY-DEPENDENT RESPONSE OF A SHIELDED GAMMA-RAY DETECTOR

by

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ABSTRACT

Instruments designed to record high-intensity gamma-ray flashes must have fast time response, wide dynamic range, and good rejection of photon backgrounds at lower energies. In principle, plastic scintillators can easily provide the necessary time response and dynamic range; like other photon detectors, however, they must be carefully shielded to reduce their low-energy sensitivity. This shielding is often complicated by the need to use different optical sensors to cover the full dynamic range, with each sensor requiring a separate opening through the shielding. In our detector, a high-sensitivity photomultiplier tube handles low-intensity signals, and a silicon photodiode covers high intensities. These electronic components, particularly the diode, may also respond directly to incident radiation, so localized shielding must be provided. To reduce the detector's total mass, the scintillator and photodiode are enclosed in a relatively thick, tight-fitting inner shield, which is surrounded by a thin outer shield to reduce the leakage through any gaps. Although efficient, this arrangement demands careful design and testing. This report describes such an analysis, which uses Monte Carlo simulations to develop a comprehensive model of the detector at photon energies from threshold to above 10 MeV. Included are discussions of the fundamental responses of the unshielded silicon diode and plastic scintillator, explanations of the effectiveness of different shielding materials, studies of calibration sources, and comparisons with laboratory tests. Our results indicate that the shielding for the scintillator is probably adequate, but the radiation response of the photodiode is almost an order of magnitude greater than its optical signal. This situation significantly complicates the instrument's behavior as a function of incident energy, angle, and intensity, and its analysis requires extensive detector calibrations and computer simulations.

1. INTRODUCTION: PROBLEM STATEMENT

Overview. This report continues the study of a series of instruments designed to detect intense bursts of gamma rays with incident energy densities of $1\text{--}10^8$ MeV/cm².

An earlier report¹ covered calibrations of the dynamic range, and a subsequent paper will describe the time dependence of the input and output signals. The present study focuses on the energy dependence of the detection efficiency, particularly the very high ratio needed between the responses to MeV-range gamma-ray signals versus keV-range x-ray backgrounds. In the detector's intended mode of operation, the only radiation sensor is a plastic scintillator; to cover the full dynamic range, its light output is viewed by both a photomultiplier tube and a silicon photodiode. Unfortunately, photodiodes are also radiation sensitive, particularly at low energies, so achieving the desired background rejection requires careful arrangement of high-Z shielding around both the scintillator and the diode. For our report, the evaluation of this shielding is handled by the LANL Monte Carlo radiation-transport code² MCNP, along with a detailed specification of the detector's geometry and materials. This approach is benchmarked using selected data on the unshielded responses of the active elements, and detailed calculations of the shielded responses are compared with additional laboratory measurements. The conclusions are discussed in terms of the performance of the detector and the effectiveness of possible changes in its design.

Fig. 1.1. Cutaway view of the gamma-ray instrument, showing the scintillator, photodiodes, and photomultipliers.

Detector Geometry. In Fig. 1.1 we show a sectional view of the complete instrument, which illustrates most of its important components. The central feature is the detector's principal active element, a large ($7.2 \times 9.9 \times 7.4 \text{ cm}^3$) plastic scintillator. For redundancy, there are two independent readout channels, each with a high-sensitivity photomultiplier tube and a low-sensitivity photodiode. Figures 1.2a,b show detailed views of portions of the detector that are important to our discussions. First, Fig. 1.2a shows an upper corner of the detector, sliced vertically through one of the diodes. Included is

Fig. 1.2a. MCNP geometry for the upper corner of the detector, showing the photodiode assembly and the overlapping lead and tantalum shielding.

Fig. 1.2b. Geometry for the photomultiplier region (not to scale), showing the leakage path around the lead-glass light guide.

part of the inner shielding, which surrounds the scintillator on 5 of 6 sides with 30-mil lead sheet that is fitted inside the 125-mil aluminum instrument housing. Many of the dimensions in this report are given in mils (1 mil = 0.001 inch), because these have been the units conventionally employed¹ for our instrument. As indicated in the figure, the lead sheet is omitted at the top of the scintillator and is replaced by a removable calibration plate, which permits measurements of the scintillator response to be made almost unobstructed. When installed, this 20-mil tantalum plate overlaps the lead and completes the inner shielding. Examination of the overlap region, however, reveals a potential leakage path (circled) between the inner lead sheet and the outer tantalum plate, that is, obliquely through the 125-mil aluminum housing. A similar gap appears at the top of the detector on the photomultiplier side. Because the calibration plate completely overlaps the lead sheet on the left and right sides of the scintillator, the two gaps at the front and back are probably the most important. Although each gap has a maximum area of 3 cm², hand fitting of the lead shielding and the addition of two small lead shims, one of which is shown in Fig. 1.2a, can reduce the leakage significantly.

Leakage Measurements. Using the current detector in the series, Instrument 9, we investigated the possibility of leakage through the overlap region by removing the outer cover and then scanning a collimated x-ray beam across the detector with the inner calibration plate still in place. The notation "Top" in Fig. 1.3 refers to the edge of the calibration plate shown in Fig. 1.2a, "Front" indicates the extended instrument housing that contains the diode assembly, and "Corner" gives the location of the suspected gap in the shielding. The vertical scale shows the instrument's logarithmic output, with each increase of 14.25 digital levels corresponding to a 10-fold change in magnitude. Although a complete discussion must wait until Chap. 7, the increase of 1-2 orders of magnitude near the corner confirms the existence of a significant leakage path through the shielding.

Fig. 1.3. Measured low-energy leakage at the gap between two shielding sections at the corner of the detector.

Diode and LED Openings. A second set of possible leakage paths is through three openings in the lead sheet on the diode side of the scintillator. As seen in Fig. 1.1, two

0.7-cm² openings are for the photodiodes; the third is a 1.3-cm² opening for a pair of LED flashers that are used to stimulate the scintillator during testing. All three openings pass through the aluminum housing and lead sheet, with the LEDs and diodes mounted on the outer aluminum surface. As indicated in Fig. 1.2a, the diodes are placed under cylindrical shields made of 20-mil tantalum, which leaves a 1-mm gap through a nylon mounting flange. Examination of the diode's internal structure and the mounting hardware reveals that the active surface is aligned edge-on with this gap, which leaves a narrow opening all around the diode. Also, on at least some instruments the two LEDs are enclosed under a small cover made of aluminum, not tantalum. However, as shown in Fig. 1.2a, all the diode-side components are mounted inside an extended 95-mil aluminum housing, whose outer face is covered by a 20-mil tantalum plate. Any low-energy leakage must therefore pass through the aluminum sides and then obliquely through the openings in the lead sheet, which restricts the range of angles where the scintillator can be illuminated. In Fig. 1.3, the broad shoulder on the response at the front of the detector may be an indication of leakage through one of these openings.

Photomultiplier Leakage Path. A third potential leakage path into the scintillator is on the photomultiplier side. Figures 1.1 and 1.2b show the two large (3.9-cm) openings in the lead sheet that admit the photomultipliers, which are silicon-bonded to the scintillator through lead-glass light guides to improve both the shielding and light collection. Between the light guide and lead sheet, however, there exists a small gap (circled) that provides the clearance needed for assembling the components. We estimate the width of this annular gap to be about 70 mils, which leads to a total opening around both light guides of over 4 cm². These gaps, however, are surrounded by significant amounts of material, and several tests failed to detect either leakage or photocathode sensitivity at these points. In short, adding together the openings at the corners, diodes, LEDs, and light guides, we arrive at a maximum leakage area of 13 cm², or about 5–6% of the total scintillator surface area. Each of these openings is fully shielded over most of the angular range, with the remainder at least partially shielded by low-Z materials such as aluminum or nylon. Furthermore, around the entire detector there is an outer cover made of 25-mil aluminum plated with at least 3 mils of gold, which provides significant shielding at all angles. If greater leakage reduction is needed, an attractive possibility would be replacing this outer cover with one made of 20-mil tantalum, as discussed in Chaps. 4–7. This approach is mechanically simple and addresses all leakage paths in a straightforward manner.

MCNP Assumptions. At this point it is useful to discuss some of the calculational techniques employed in the present analysis. For reference, one of the MCNP input files is included in the **Appendix**. The detail in Figs. 1.2a,b indicates the level of complexity in the model, particularly in regions that might affect leakage paths or active elements. In contrast, the electronics box, which is shown below the detector in Fig. 1.1, is simply given enough distributed low-Z mass to reasonably approximate its bulk photon scattering at higher energies. Because we have no interest in studying interactions with the larger platform on which the instrument is mounted, all our calculations will illuminate the detector head from above the horizon, that is, above the plane of the electronics box. In general, we will also use an incident angular distribution that randomly averages the response over different directions. Because the shielding's effectiveness increases dramatically at low energies, the detector calculations use weight windows² to obtain good statistical precision, with different weighting coefficients for different problems. In addition to these calculations, special input files are used to address peripheral issues such as shielding effectiveness

and response functions for bare scintillators and diodes. Finally, selected MCNP calculations are benchmarked against measurements, against calculations with other simulation programs, or against widely accepted tables of attenuation parameters, and details of these tests will be provided as necessary.

Dynamic-Range Calibrations. Although the gaps in the shielding were initially expected to be the focus of this report, subsequent studies confirmed a problem that is more enigmatic—and potentially more serious. As explained in Ref. 1, the responses of the photomultiplier and photodiode must be overlapped to cover the full 10^8 dynamic range, and proper operation of the instrument depends on accurate matching of the two channels. A major result of Ref. 1 is the demonstration of this absolute alignment, as summarized in Fig. 1.4. For the x -axis, the model developed for describing the source behavior allows us to determine the energy density E_S incident on the detector using various source parameters. For the y -axis, the instrument model allows us to assign a measured value E_0 to the same energy density on the basis of the detector's digital output level L in either the photomultiplier (PM) or photodiode (PD) range. In the figure, the small dots are 325 individual measurements, and the open circles are logarithmically binned average values. The dotted line shows the expected logarithmic relationship, which agrees well with the measurements.

Fig. 1.4. Linearity of the detector response for increasing incident energy density, adapted from Ref. 1.

Diode Radiation Response. Measurements like those shown in Fig. 1.4 are made by removing the detector's outer cover and the calibration plate and then orienting the instrument so that the unshielded scintillator faces the x-ray source and the photodiodes face downward. Because the low-energy beam then illuminates the diodes' active areas edge-on through the nylon flange, it should not be surprising that they must be shielded to avoid a radiation response. Traditionally, therefore, the calibrations are carried out with

the diodes shadowed behind a 0.32-cm lead block. The effect of removing this shielding block is shown in Fig. 1.5. Here, the x -axis has been converted to give the energy E_D deposited in the scintillator (to be discussed in Chap. 7), not to the incident energy density E_S used in Fig. 1.4. Also, the y -axis is given in terms of the digital output J for the instrument, which has been adjusted in a simple way to connect the PM and PD intensity ranges. The dotted line at $J = 64$ indicates the PM-to-PD crossover, and the diagonal line shows the average logarithmic response. With the diodes unshielded, the low-energy response (solid rectangles) follows the predicted line until about $J = 52$, where it prematurely switches to the PD range and continues along the same slope. This abrupt jump implies that the diode's response to the radiation source is significantly greater than its response to the light produced in the scintillator, that is, its response with the lead block in place. Because the diode's radiation sensitivity decreases rapidly with increasing photon energy, it had been assumed that such behavior might exist at the relatively low photon energies of the calibration source (a few tens of keV), but it would disappear for MeV-range gamma rays. The other measurements in the figure, however, show that this assumption is false. Here, a Scandiflash source,³ with x-ray energies up to 1.2 MeV, is used to perform the same type of measurement as the lower-energy Febetron source,⁴ and the results are almost the same. For confirmation, a straightforward diode measurement was also made using a detector mockup and an intense ^{60}Co radiation source, which provides an average gamma-ray energy of 1.25 MeV. In these tests the output from the scintillator-plus-diode combination was only slightly greater than the output from the diode by itself. This simple experiment confirms that even at high energies the diode's dominant response is radiation-induced, not optical.

Fig. 1.5. Measured detector response with unshielded photodiodes, showing the effect of the direct photodiode response for two different calibration sources.

Significance of the Diode and Leakage Results. The two major issues in this chapter, shielding leakage and diode response, combine to create a major problem in understanding the instrument's behavior. The traditional detector calibrations, those made using the lead shield to observe the response to energy deposited in the scintillator,

are almost irrelevant unless they can be modified to account for the diode's radiation response, which dominates the behavior in actual operation. In Fig. 1.5, it appears that the step is about 12 digital levels for the low Febetron energies and a slightly greater 13–14 levels for the higher Scandiflash range. Fortunately, there is no loss in signal continuity because a unique input exists for every output value. However, because the maximum digital level of 127 is reached with a lower input signal, the missing 12–14 output levels represent almost an entire decade (14.25 levels) of lost dynamic range. More troubling, however, is the uncertainty about the connection between the input and output signals at other energies and angles, which can only be addressed by finding an explanation for the unexpected diode response. Possible mechanisms include (1) gamma-ray interactions at high energies, where shielding becomes ineffective, (2) low-energy leakage through gaps in the high-Z shielding, which allows gamma rays to reach the diode almost directly, and (3) Compton scattering of high-energy gamma rays in the low-Z scintillator, producing lower-energy gamma rays that pass through the diode aperture. In particular, the latter two mechanisms involve both shielding leakage and diode response, so they probably have energy and angle dependences very different from those expected. Given that the diode channel overrides that for the photomultiplier if the PD threshold is reached, the detector output could switch unpredictably between the PM and PD channels as the time-dependent signal intensity varies, with a step size that depends on the unknown energy spectra of both the signal and background. Thus, the instrument could be almost useless for quantitative measurements unless a reasonable model for its operation can be developed.

Analysis and Results. Our explanation begins with the first principles of photon interactions. Chapters 2 and 3 describe the responses of the detector's two active elements, the silicon diode and plastic scintillator. These discussions and comparisons between measurements and calculations rely on data taken from the literature; our goal is to explain the physical basis of the responses and establish benchmarks for the MCNP calculations. Chapter 4 then describes the energy-dependent effectiveness of different shielding materials and thicknesses. In Chap. 5 the basic principles from Chaps. 2–4 are applied to the actual detector by using MCNP calculations for a detailed model of the shielding geometry. Included are investigations of weaknesses in the shielding and evaluations of possible improvements. Chapter 6 compares the calculated scintillator and diode responses with laboratory measurements to evaluate the reliability of the calculations, with a focus on the pulsed x-ray sources used for the detector calibrations. Chapter 7 brings the measurements and calculations together in a comprehensive examination of the scintillator and diode responses. The issue of leakage into the scintillator is addressed by examining one of the most serious cases, which occurs at the gap between the calibration plate and the inner shielding. Even this leakage, however, is negligible compared with the total scintillator response; it also decreases rapidly at the lower energies of typical backgrounds and can easily be eliminated by additional outer shielding. The issue of the diodes' radiation response is much more complex. At low energies, the sensitivity results from a combination of leakage through a gap in the high-Z shielding and the very high energy-absorption efficiency of the silicon. At the highest energies, the response is simply the interaction of photons with the silicon as the shielding becomes transparent, which cannot be prevented. Using the analyses in the previous chapters, however, we can show that the additional outer shielding needed to reduce the gap leakage into the scintillator also eliminates the leakage that causes the low-energy diode response, which allows a simple correction to be employed regardless of the energy and angle dependences of the signal and background. Thus, a straightforward change in the shielding for future detectors would recover their quantitative response, and our analysis allows us to estimate a correction for instruments that have already been deployed. These conclusions are summarized in Chap. 8.

2. SILICON PHOTON RESPONSE

Overview. As described in the Introduction, the detector's principal active element is a plastic scintillator that is coupled to both a photomultiplier tube and a silicon photodiode in order to cover the desired dynamic range. In this view, the photomultiplier and photodiode are optical sensors that convert light levels into electrical signals, but they are not themselves radiation detectors. However, the measurements described in the Introduction suggest that the diode actually has significant radiation sensitivity, so our analysis must address the photon responses of both active elements. Because the discussion of gamma-ray interactions in silicon provides a good introduction to the general photon-transport problem, we will consider the diode first and then address the scintillator in Chap. 3. We begin with spectra that show the energy depositions produced by individual photons, and then we use various integrals over these spectra to define different detection efficiencies, including those for both photon counting and energy absorption. Our final goal is the comparison between results from empirical models, MCNP calculations, and tables of attenuation coefficients published by Storm and Israel⁵ (referred to here as "S&I").

Fig. 2.1a. Calculated energy-deposition spectrum for 20-keV photons incident on a 3-mm silicon detector. The large peak is from complete photoelectric absorption; its low-energy tail comes from escaping fluorescence x-rays. The zero-energy contribution represents essentially complete escape of the incident photon, and the few counts at 2 keV come from Compton scattering.

Pulse-Height Spectra. The basic detector response is illustrated in Figs. 2.1a,b, which show energy spectra produced by single photons incident on bare silicon. The results were calculated as an MCNP pulse-height tally (an f8 tally, for those familiar with MCNP notation) with a normally incident photon beam uniformly illuminating a silicon disk of thickness 3 mm and area 1 cm², which is typical of the detector elements described in the literature. Figure 2.1a shows results for a 20-keV beam energy, and the counts in the 20-keV bin are the photopeak response. The tail on the low-energy side of the peak signifies incomplete energy absorption, which is caused by the partial escape of fluorescence

photons produced near the detector surface. Together, the peak and tail contain 93.8% of the incident photons. The 5.7% of the photons that are tallied in the very lowest pulse-height bin are either transmitted through the detector or scattered out of the beam with almost no loss in energy. Compton scattering, which at this energy results in a maximum energy transfer of only 1.45 keV, just barely contributes (<1%). Figure 2.1b shows the results for incident photons at 50 keV. Here, only 15.6% of the photons appear in the photopeak, and 78.2% deposit essentially no energy. The remaining 6.2% of the spectrum comes from Compton scattering. At this energy a single Compton collision can deposit 8.2 keV, which produces the pronounced peak in the spectrum. Because the scattered photon can reinteract and deposit more energy, there also exists a multiple-scattering distribution that extends well above the Compton edge. Thus, as the incident energy increases, the energy deposition in the detector becomes increasingly complicated.

Fig. 2.1b. Energy-deposition spectrum for incident photons at 50 keV. The maximum energy deposited in a single Compton collision is 8.2 keV, which corresponds to the peak at low energies. The shoulder above the Compton edge is from multiple photon scattering.

Photopeak Efficiencies for a Bare Diode. The energy dependence of the photopeak magnitude is particularly important for photon spectroscopy,⁶ and it provides a good starting point for arriving at the integral efficiencies needed for our detector study. At the lowest energies, below about 16 keV for the 3-mm detector shown here, this efficiency is nearly 100%, but at higher energies it drops rapidly. This energy-dependent probability is shown in Fig. 2.2a, which compares our MCNP results with those obtained using two other approaches. First, the photon attenuation coefficients⁵ tabulated by S&I allow us to calculate the photopeak efficiency $\eta_{\tau,a}(E)$ using the transmission relationship

$$\eta_{\tau,a}(E) = 1 - e^{-x (\mu/\rho)_{\tau,a}}, \quad (2.1a)$$

where x is the detector thickness in g/cm² and $(\mu/\rho)_{\tau,a}$ is the tabulated photoelectric absorption coefficient. The S&I results (dotted curve) are in very good agreement with

MCNP calculations (dashed curve) over the full energy range. Second, because actual detectors often have unknown compositions or thicknesses, an empirical technique has been developed to characterize their efficiencies on the basis of a limited number of calibration measurements. As mentioned by Knoll⁷ and discussed in detail in the original reference,⁸ the assumption is that the attenuation coefficients vary roughly as $\mu \sim E^\delta$ with $\delta \approx -3.0$, so that the empirical efficiency $\eta_{\tau,e}(E)$ becomes

$$\eta_{\tau,e}(E) \propto 1 - e^{-\gamma E^\delta}, \quad (2.1b)$$

where the detector thickness and density have been absorbed into the normalization constant $e^{-\gamma}$. This empirical function allows the δ and γ parameters to be determined by a simple linear fitting procedure, namely,

$$\ln(\ln(1 - \eta)) = \delta \ln E + \ln(-\gamma). \quad (2.2)$$

For the case shown, the fitted parameters are $\gamma = 4.0 \times 10^6$ and $\delta = 4.42$, which give excellent results. This empirical parameterization for describing photoelectric absorption will be used later in the report.

Fig. 2.2a. Photopeak efficiencies from different calculations for interactions in a bare 3-mm silicon diode.

Photopeak Efficiencies for a Covered Diode. In most measurements, and for the instrument described in this report, silicon detectors are used with various layers of shielding that limit their sensitivity to photons at the lowest energies. For the example in Fig. 2.2a, the actual detector included a 0.5-micron silicon dead layer, a 40- $\mu\text{g}/\text{cm}^2$ gold contact, a 0.5-mil beryllium window, and a 0.5-mil Mylar window. Figure 2.2b shows the photopeak efficiencies calculated for this arrangement. The high-energy results are unchanged from those in Fig. 2.2a, but there is now a low-energy cutoff and, with the finer resolution of the S&I absorption, a slight dip in the efficiency at the silicon *K*-edge energy of 1.8 keV. The MCNP results and the empirical fit are again in good agreement.

Fig. 2.2b. Photopeak efficiencies as in Fig. 2.2a, but for a detector covered with several shielding layers that limit the low-energy response. There is good agreement among the different calculations.

To account for the covering layers, the empirical fitting function now has an additional term,

$$\eta_{\tau,e}(E) = e^{-\alpha E^\beta} (1 - e^{-\gamma E^\delta}) . \quad (2.3)$$

As with δ and γ in Eq. 2.1b, β should have a value near -3.0 and α absorbs any normalization factors. The fitted parameters for the curve shown are $\alpha = 7.0$ and $\beta = -2.8$. As with the bare detector, the S&I coefficients and empirical fitting functions will be useful for extrapolating the efficiency of our own detector to lower energies.

Total Photon Efficiencies. Although photopeak efficiencies are important for spectroscopy detectors, our instrument has no energy discrimination, so in principle it responds to all photon interactions that produce nonzero energy deposition E_D by either photoelectric absorption or Compton scattering. Its total efficiency η_N can be calculated by summing over the distribution of energy depositions (dN/dE_D), as in

$$\eta_N = \int_{E_D > 0} (dN/dE_D) dE_D . \quad (2.4a)$$

The energy dependence of the result is shown in Fig. 2.3a along with the photopeak efficiency from Fig. 2.2b. The MCNP values (solid curve, open circles) are slightly below those from the S&I coefficients (dotted curve), at least partly because of the minimum 1-keV photon energy in our MCNP calculation. For our detector, however, the important issue is not the number of photons interacting, but the fraction of the incident energy that is absorbed. In terms of our MCNP energy spectra, we can calculate this fraction by simply integrating $E_D \times dN/dE_D$ to get the total energy loss and then dividing by the incident energy E_γ , as

$$\eta_E(E) = 1/E_\gamma \int E_D (dN/dE_D) dE_D . \quad (2.4b)$$

Fig. 2.3a. Photopeak versus total efficiencies for photon interactions in a covered 3-mm detector.

Fig. 2.3b. Photon-interaction versus energy-absorption efficiencies for a covered detector. Once the total and photoelectric cross sections diverge, scattering effects cause the energy-absorption and photon-counting integrals to give different efficiency values.

In Fig. 2.3b we show both the total photon efficiency η_N (solid curve) and the energy-absorption efficiency η_E (dashed curve) for the MCNP calculations. Also shown are the corresponding S&I values calculated from the photon- and energy-absorption coefficients. Note that the energy-absorption efficiencies are greater than the photopeak absorption, which neglects Compton scattering, but they are less than the total interaction probability, which counts all scattered photons equally. Because the scattered photons generally give low energy depositions, their contribution to the energy-absorption integral is usually

Fig. 2.4. Energy-deposition spectrum for the 300-micron (0.03-cm) photodetector used in our instrument.

small; this weighting accounts for the excellent agreement between the MCNP and S&I energy-absorption efficiencies when compared with that for the total photon-interaction values in Fig. 2.3a.

Present 300-micron Detector. We now turn to similar calculations for the slightly thinner silicon photodetector used in our instrument. Figure 2.4 shows the energy-deposition spectrum at 50 keV, which resembles that in Fig. 2.1b for the thicker detector. Because the interaction probability is relatively small, that is, within the linear range of the exponential function, decreasing the detector thickness by a factor of 10 has reduced both the photopeak area and the total efficiency by the same factor.

Absorption Efficiency and Heating Tallies. As with the 3-mm detector, we can calculate an energy-absorption spectrum at each photon energy and then use a weighted integral to calculate the absorption efficiency. Alternatively, we can forego the spectral information provided by the MCNP pulse-height tally (f8) and instead use a heating tally (f6). This approach considerably reduces the calculation time, because all photon tracks that pass through the diode volume, whether interacting or not, contribute to the tally, thereby making it reasonable to perform calculations for thinner detectors at higher energies. The energy-deposition efficiencies for a beam at normal incidence are shown in Fig. 2.5a. With the thinner detector, the characteristic transition between photoelectric absorption and Compton scattering now occurs at a lower energy, near 10 keV instead of 20 keV, and the Compton-scattering plateau at high energies is almost two orders of magnitude lower. Also shown in this figure are two versions of the S&I coefficients, referred to here as "heating" and "absorption," which make different assumptions about the contribution from fluorescence x-rays. As defined here, heating (μ_h) assumes the escape of all secondary photons (Compton-scattered gamma rays and fluorescence x-rays); absorption (μ_a) assumes that the x-rays are absorbed, which gives slightly higher efficiencies (lower coefficients). The two results differ only slightly, especially for low-energy photons on low-Z materials such as silicon, so the energy-deposition curves are barely distinguishable and tend to bracket the MCNP values. Most important, however, is the nonzero Compton-

scattering absorption at incident energies above 100 keV, whose near-constant magnitude varies strongly with diode volume.

Fig. 2.5a. Energy-absorption efficiencies as obtained from an MCNP photon heating tally and from two different sets of S&I coefficients.

Effective Areas. We now discuss an important concept that was originally developed for studies of neutron detectors.^{9,10} It is convenient to multiply the detector's physical area times its efficiency and to consider the result $A_{\text{eff}} = \eta \times A$ as the "effective" area of an equivalent detector that is perfectly absorbing. This quantity is shown as the solid curve in Fig. 2.5b; because the beam is at normal incidence and our detector's frontal area is 1 cm², the A_{eff} values are numerically identical to the efficiencies in Fig. 2.5a. However, there is a second important feature of effective areas. The A_{eff} values can be calculated not only by multiplying the efficiency by the projected area, but by multiplying the MCNP heating per unit mass (ϵ_m from an f6 tally) by the mass of the detector ($m = 0.7$ g), which gives the energy deposition per photon (E_D in MeV). This quantity is then divided by the average energy fluence Φ_E (in MeV/cm²) at the detector location. In simple cases, this fluence can be calculated as the product of the photon energy E_γ and the photon fluence ϕ_γ . For more complicated energy and angle distributions, a convenient approach is a separate calculation that uses an energy-fluence tally (*f4 in MCNP) for the identical source and detector geometry but turns off all photon interactions using an MCNP void card. The result is

$$A_{\text{eff}} = E_D / \Phi_E = \frac{m \epsilon_m}{E_\gamma \phi_\gamma}, \quad (2.5)$$

which gives an effective energy-absorbing area expressed in cm². For normal incidence on simple detectors, this alternative approach reduces to the original area-efficiency product. However, the alternative method also allows calculations to be made for more complex source and detector geometries, as illustrated in Fig. 2.5b for a random incident angular distribution or for edge-on incidence through the diode's curved surface. For the high absorption at low energies, the values for normal and edge-on incidence reach the geometric limits of the corresponding projected areas, with the random case located between these

two values. At high energies, however, all three curves become identical because the efficiency is proportional to the detector's volume, not its area. Finally, an important aspect of the effective-area approach is the simplicity that it brings to calculations of the detector's response to an incident energy fluence expressed in MeV/cm^2 . Simply multiplying the fluence by the effective area immediately gives the energy deposited in the detector, $E_D = \Phi_E A_{\text{eff}}$. The use of effective areas and the fluence-normalization technique for their calculation will be essential for the complex geometry of our actual detector.

Fig. 2.5b. Effective areas for photons at normal, random, and edge-on incidence to a 300-micron detector.

Summary and Discussion. This chapter has explained the basic energy-loss mechanisms for photon interactions with silicon. Our focus has been on comparisons between different calculational techniques, principally the convenient but approximate approach of the attenuation coefficients published by Storm and Israel versus the more general but time-consuming calculations possible with the MCNP code. The major issues have been

- (1) the transition between photoelectric absorption at low energies (<10 keV) and Compton scattering at higher energies (>100 keV);
- (2) the difference between efficiencies calculated using photon attenuation versus energy absorption;
- (3) the comparison between MCNP tallies, S&I coefficients, and empirical fitting functions such as $\eta \propto 1 - \exp(-\gamma E^\delta)$;
- (4) the technique of using effective areas to generalize the efficiency calculations for arbitrary source and detector geometries; and
- (5) the nonzero diode effective area at high energies.

These results will find application in the next chapter, which describes similar calculations for the case of plastic scintillators, and in our later analyses of the response of the detector's silicon photodiodes to incident photon radiation. The fifth item, however, immediately addresses one of our most important questions. For the 0.3-mm thickness of our silicon diode, the nonzero energy absorption above 100 keV may be at least partly responsible for the high-energy diode response described in the Introduction.

3. SCINTILLATOR PHOTON RESPONSE

Overview. This chapter discusses the response of the detector's primary sensor, a BC400 plastic scintillator, for photons at energies from a few hundred keV to a few MeV. In this energy range, photon interactions in low-Z materials are dominated by Compton scattering, as opposed to the simpler photoelectric absorption emphasized in the preceding diode chapter. The response of plastic scintillators to individual photons is difficult to measure, because their inefficient energy-to-light conversion leads to resolution effects caused by poor photon-counting statistics. As a result, no useful single-photon spectra can be obtained for our detector, and the present discussion relies heavily on published data for a similar scintillator. We begin with comparisons between spectra calculated with different simulation codes, including the present MCNP approach. As in the diode chapter, we then switch to the integral responses for the plastic scintillator used in our own detector.

Fig. 3.1a. Published¹¹ comparison between measurements with a plastic scintillator and a ^{22}Na source versus DEMONS calculations that assume perfect resolution.

Previous Scintillator Studies. The initial data set for our scintillator calculations was obtained with a detector made from a long BC408 bar measuring 3.8 cm on a side and 50 cm in length.¹¹ By combining light outputs from photomultipliers at both ends, the optical attenuation could be cancelled, and pulse-height distributions with good resolution were obtained. The original paper¹¹ discusses the measurements in detail; it also describes the DEMONS simulation code, which handles both photon and neutron interactions in plastic scintillators. Figures 3.1a,b show the published results for a ^{22}Na source placed about 10 cm outward from the midpoint of the scintillator bar. The gamma-ray energies for this source are 511 and 1275 keV; the corresponding Compton edges are at 341 and 1062 keV_{ee}. Here keV_{ee} stands for “keV electron equivalent,” which indicates a light-output scale calibrated in terms of electron energies. The calculations in Fig. 3.1a show the original perfectly resolved spectrum; as in the diode calculations, multiple scattering

Fig. 3.1b. Comparison between measurements and DEMONS calculations as in Fig. 3.1a, but now including estimated resolutions.

causes the distributions to extend well beyond the Compton edges. When the instrumental resolution and threshold effects are included (Fig. 3.1b), the agreement between the measurements and calculations is excellent. The only similar comparison for a plastic scintillator appears to be that of Ref. 12, which used the Stanford code EGS4.¹³ As explained in the DEMONS paper, however, the agreement in both cases is to some extent contrived, because the light-output scales and resolution functions were varied to provide the best fits. Thus, such calculations are not truly predictions but merely consistency checks.

Original DEMONS versus Current Calculations. Because the published 1992 results in Figs. 3.1a,b were not obtained with the final DEMONS code, for this report we have repeated the calculations using the current version of the program. The major change concerns the replacement of simple minimum-ionizing electron ranges with energy losses derived from tables.¹⁴ To investigate an alternative transport model, we have also produced an EGSDEM code that combines the DEMONS geometry with the EGS4 cross sections and energy losses.¹³ This approach allows a more realistic representation of the random-walk nature of electron transport, as opposed to a simple range model. The new DEMONS and EGSDEM calculations are compared with the original 1992 results in Fig. 3.2a. Although the agreement is good, the systematic differences between the predictions indicate the overall uncertainty in the simulations. Figure 3.2b compares these results with those obtained using version 4A of the MCNP code. The MCNP and DEMONS values are in essentially perfect agreement, but the EGSDEM values appear to be slightly (~6%) higher at the lowest light outputs. Note that the MCNP calculation does not include the threshold cutoff near 65 keV_{ee}. Because the EGSDEM and DEMONS codes are normally operated in "list" mode, which produces an interaction-by-interaction output file, in those cases it is straightforward to apply a threshold test in subsequent processing. Although the current MCNP version supports this option as a PTRAC file,⁹ it remains more convenient to include approximate threshold and resolution effects directly in the spectral calculation, as described below.

Fig. 3.2a. Comparison between previous DEMONS values for the ^{22}Na gamma-ray response and two current calculations, both with perfect detector resolution.

Fig. 3.2b. Calculated spectra as in Fig. 3.2a, but for comparisons between current DEMONS and EGSDEM values versus the corresponding results from MCNP.

Other Gamma-Ray Sources. For added confirmation, Figs. 3.3a,b show comparisons between MCNP, DEMONS, and EGSDEM results for two lower-energy measurements included in the previous paper.¹¹ Because the photoelectric and Compton effects vary strongly with energy, this approach provides a strenuous test of the calculations. First, Fig. 3.3a shows distributions for the 662-keV gamma ray from a ^{137}Cs source. Again, multiple-scattering contributions beyond the Compton edge at 478 keV_{ee} are conspicu-

Fig. 3.3a. Calculations for a lower-energy gamma-ray source, in this case a 662-keV ^{137}Cs source.

Fig. 3.3b. Gamma-ray spectrum as in Fig. 3.3a, but for a ^{208}Hg source at 279 keV.

ous, but the three calculations are in very good agreement above the threshold cutoff. Figure 3.3b shows results for a 279-keV ^{208}Hg source, whose 145-keV_{ee} Compton edge is just above the instrumental threshold near 65 keV_{ee}. Note that the higher-resolution MCNP binning in Fig. 3.3b reveals a 279-keV photopeak; its absence in the MCNP spectra at higher energies provides another indication of the relative energy dependence of the photoelectric and Compton interactions.

Resolutions and Thresholds in DEMONS and MCNP. Making further comparisons between the MCNP and DEMONS analyses—and especially comparisons with measurements—requires including instrumental effects such as detector thresholds and resolutions. The DEMONS analyses¹¹ developed a resolution function expressed as a three-term polynomial,

$$(\Delta L/L)_D = 2.35 (a^2/L^2 + b_2/L + c^2)^{1/2}, \quad (3.1a)$$

where the parameter values $a = 2 \text{ keV}_{ee}$, $b_2 = 1.15/b$, $b = 0.188/\text{keV}_{ee}$, and $c = 0.051$ can be empirically interpreted in terms of physical effects such as electronic noise (a), photoelectron statistics (b), and nonuniform light collection (c). To maintain consistency with previous versions of MCNP, which used a two-term resolution function, the current MCNP code uses three parameters in a less physical form,

$$(\Delta L/L)_M = (x + y(L + zL^2)^{1/2})/L. \quad (3.1b)$$

Because of this difference, we can at best obtain MCNP resolutions that are only similar to those originally developed for DEMONS. The coefficients $x = 0.011$, $y = 0.1566$, and $z = 0.717$ give resolutions that agree within a few percent, with the largest discrepancies occurring in the 200- to 500-keV region. Also, although MCNP allows specification of a minimum photon energy, this cutoff is not equivalent to the light-output threshold employed in an actual detector. Thus, unless a photon-by-photon output file is constructed and processed, for MCNP we should not expect exact agreement with spectral measurements or predictions made using other codes.

Resolution-Broadened Spectra. Adding resolutions and thresholds to the ideal spectra in Figs. 3.2b and 3.3a,b leads to the three resolution-broadened distributions shown in Figs. 3.4a–c. The first panel shows the ^{22}Na case along with the original measurements. Except at the lowest channels, all three predictions are in good agreement with the data. As expected from the ideal spectra, the MCNP and DEMONS results are identical except for differences in resolution and threshold effects. The EGSDEM values are different, but only slightly. Similar behavior is seen in the ^{137}Cs and ^{208}Hg cases in Figs. 3.4b,c. The systematic underestimate of the measured spectra at low light outputs probably indicates an unsubtracted scattering contribution from the detector surroundings; a similar effect was observed in the measurements for Ref. 12. This undersubtraction was largely hidden in the original DEMONS analysis (Fig. 3.1b) because of an underestimate in the electron energy losses, which is corrected in the new version of DEMONS (see Fig. 3.2a). On the whole, therefore, we conclude that the MCNP calculations of light outputs produced by individual photons interacting with plastic scintillators agree well with results from other simulation codes (DEMONS and EGS4, for example) and with published measurements for sources at different energies.

Integral Efficiency for the Present Scintillator. The first part of this chapter has followed the pattern of our photodiode discussion in Chap. 2, using differential responses to examine gamma-ray interactions and compare calculations. Thus benchmarked, the MCNP code can be confidently used to calculate responses for our own $7.2 \times 9.9 \times 7.4 \text{ cm}^3$ scintillator made of nearly identical BC400 material. Because our electronics respond only to the total light output, not to individual photons, we can ignore the effect of resolutions and thresholds, and we can employ the calculational techniques of heating tallies and effective areas developed in the previous chapter. Figure 3.5 shows the results of MCNP calculations and S&I estimates for photons incident either randomly or along each of

Fig. 3.4a. As in Fig. 3.2b, calculated spectra for a ^{22}Na source, but including instrumental effects and comparing with measurements.

Fig. 3.4b. Resolution-broadened light-output spectra for a ^{137}Cs source.

the scintillator axes. (In Fig. 1.1, the x -axis is along the photomultipliers; the z -axis is vertical.) As in the diode case, at low energies the effective areas approach the projected areas of 53–74 cm^2 , but at energies above 0.1–1.0 MeV the areas converge to a single volume-dependent value near 9–15 cm^2 . The S&I coefficients reproduce the MCNP results very well, except perhaps for incidence along the detector's long y -axis. Note also that the largest effective area for our relatively compact detector corresponds to random angular incidence, a result opposite from that obtained for the thin silicon detector in the previous chapter.

Fig. 3.4c. Resolution-broadened light-output spectra for a ^{208}Hg source.

Fig. 3.5. Calculated effective areas for the present $7.2 \times 9.9 \times 7.4 \text{ cm}^3$ scintillator with photons incident from different directions.

Discussion. This chapter has demonstrated that the MCNP code provides accurate predictions of the detailed response of plastic scintillators to individual photons at energies throughout the range where Compton-scattering processes are dominant. The results are comparable with those obtained with the EGS4 code in Ref. 12 and with the DEMONS code in Ref. 11. Because the response is simpler at the lower energies where total photoelectric absorption dominates, and because the MCNP-derived effective areas for energy absorption agree with those calculated using the S&I coefficients, we are confident that MCNP simulations are completely adequate for addressing the present detector problem.

Again, we point out that our own detector response is integrated over all light outputs, so the issues of resolution functions and thresholds are not directly relevant. We conclude this chapter with Fig. 3.6, which compares the angle-averaged effective areas for the bare diode and scintillator. Both efficiencies reach unity at low energies, so the areas there are simply geometrical. Both efficiencies also make the transition from photoelectric absorption to Compton scattering over the energy range from 10 keV to 100 keV, and both are relatively constant at typical gamma-ray energies of 0.2–5 MeV. But there are also important differences. At low energies, the areas differ by slightly more than two decades, and at high energies this ratio increases to almost four decades. This behavior suggests that the diode response should always be less than the scintillator response, and the difference should increase at higher energies, just as intended. Nevertheless, in the measurements the diode response is the largest, and the diode-to-scintillator ratio is almost the same at low and high energies, that is, the PM-to-PD step in Fig. 1.5 appears to be the same for both the Febetron and Scandiflash sources. Thus, although the calculations in Chap. 2 showed that a radiation response should exist for unshielded diodes, this chapter shows that the energy deposited in the bare scintillator should nevertheless be much greater.

Fig. 3.6. Effective areas of the bare scintillator and diode active elements for total energy absorption of randomly incident photons at different energies.

4. SHIELDING EFFECTIVENESS

Overview. The previous two chapters have described the intrinsic photon responses of the sensor's two active elements, a large plastic scintillator and a small silicon photodiode. Operated without shielding, both elements would be so sensitive to photon backgrounds at low energies—tens of keV—that gamma-ray signals above a few hundred keV would be lost. This energy dependence is an unavoidable consequence of the relative cross sections for the photoelectric effect and Compton scattering in low-Z materials like plastic and silicon. This chapter discusses the third component of the basic detector response, the high-Z shielding that is responsible for reducing the response to photon backgrounds at

low energies. Again, our emphasis will be on comparisons between predictions from Storm and Israel energy-attenuation coefficients and results obtained using MCNP calculations. In later chapters we will combine the shielding results with the effective areas of the bare diode and scintillator to estimate the spectral response of the complete instrument.

Fig. 4.1. Attenuation lengths in mils for energy fluences passing through aluminum (Al), gold (Au), and tantalum (Ta) at different energies.

Attenuation Lengths. A useful measure of the effectiveness of different shielding materials is the attenuation length $T(E)$, which is defined by the relation

$$I(E) = I_0 e^{-t/T(E)}, \quad (4.1a)$$

where t is the material thickness used to reduce the incident intensity I_0 to the transmitted intensity I at the energy E . This expression is directly related to the efficiency relations in Eqs. 2.1b and 2.3, that is,

$$T_h(E) = 2.54 \times 10^{-3} (\mu/\rho)_h^{-1} / \rho \quad T_a(E) = 2.54 \times 10^{-3} (\mu/\rho)_a^{-1} / \rho, \quad (4.1b)$$

where $(\mu/\rho)_h$ and $(\mu/\rho)_a$ are the tabulated S&I heating and absorption coefficients (in cm^2/g) discussed in Chap. 2. The additional factors convert the attenuation length in cm to a value in mils (0.001 inch), which are the units conventionally employed¹ for our instrument. Figure 4.1 compares the effectiveness of the three dominant shielding materials in our instrument—aluminum, gold, and tantalum—over the most important range of energies. When plotted on double-logarithmic axes, the attenuation lengths appear to be almost linear with a roughly 3:1 slope, which indicates an approximately third-order power-law dependence on energy, that is, $T(E) \sim E^{-\delta}$ with $\delta \approx -3$, in agreement with Eqs. 2.1a,b. Because the $T(E)$ values are the thicknesses needed to reduce the transmitted energy by the factor $1/e$, the shielding effectiveness of the materials is inversely related to the plotted values. Thus, the shielding thickness required for tantalum is usually 40–50% greater than for gold, and the equivalent thickness for aluminum would be more than 200

times greater. Also, the effectiveness changes rapidly with energy; at 10 keV an attenuation factor of 100 requires less than 1 mil of gold, but at 100 keV about 20 mils would be required. Note that aluminum of reasonable thickness is effective only at low energies; 125 mils provides only 3% attenuation at 100 keV, but even 25 mils is 99% effective at 10 keV. Finally, the major point of the figure is the good agreement between the MCNP and S&I results. In general, the MCNP values for beams at normal incidence lie between the two S&I curves—the T_h (upper) and T_a (lower) values—depending somewhat on the material thickness used in the particular MCNP calculation. The ranges listed in the MCNP legend indicate these thicknesses, with the largest values being used at the higher energies.

Present Energy Attenuations. The attenuation lengths in Fig. 4.1 can immediately be used to estimate the energy-dependent shielding provided by the outer cover on the present detector, which consists of 25 mils of aluminum plated with a minimum thickness of 3 mils of gold (4 mils nominal). Figure 4.2a shows the results of these calculations, with S&I values represented by curves and MCNP results given as individual data points. The upper, slightly heavier curves are the T_h values; the MCNP values tend to follow these curves except at energies just above absorption edges. The single dotted line is for aluminum, which is effective only at low energies. The dashed curves are for gold, and the solid lines show the combined effect of both materials. The MCNP calculations for the combined shield generally lie between the two S&I curves.

Fig. 4.2a. Energy attenuations obtained for normal incidence on the different layers of material that make up the outer cover of our instrument.

Equivalent Thicknesses for Different Covers. As pointed out in the Introduction, one approach to improving the shielding on the detector is replacing the existing outer aluminum-and-gold (Al + Au) cover with one made of tantalum (Ta). Given the 40–50% lower effectiveness of tantalum, we can expect the minimum cover thickness to rise from 3 mils of gold to 4–5 mils of tantalum. Including the existing 25 mils of aluminum may increase this value somewhat. Figure 4.2b shows the results of a more detailed analysis.

First, the open diamonds and solid curves repeat the Al + Au results from Fig. 4.1. Next, the closed circles and dotted curves show the S&I and MCNP results for a Ta cover that is 4.4 mils in thickness. Finally, the results at the far right show calculations for a proposed 20-mil Ta cover. Again, the S&I and MCNP results are in excellent agreement, except at energies just above the absorption edges. Clearly, replacing the existing Al + Au cover with one made of 20-mil tantalum would provide greatly enhanced shielding against background photons at low energies. At 20 keV, for example, the estimated improvement is 15–16 orders of magnitude.

Fig. 4.2b. Comparison between attenuations for the existing Al + Au cover and proposed Ta covers 4.4 mils and 20 mils in thickness.

Summary. This chapter has established several important points about the effectiveness of the shielding on the existing and proposed detectors:

- (1) the energy attenuations obtained from MCNP calculations and S&I coefficients are in good-to-excellent agreement;
- (2) the existing Al + Au cover could be replaced with a tantalum cover of thickness 4.4 mils that would provide equivalent or greater shielding; and
- (3) replacing the existing cover with a 20-mil Ta cover would provide an improvement in shielding estimated as 15–16 orders of magnitude at 20 keV.

Of course, the predicted improvement assumes a beam at normal incidence to a cover of uniform thickness with no mechanical seams or pinholes. Even a one-micron gap would cause far greater leakage, so at very low energies these simple estimates must be supplanted by a more sophisticated analysis based on the actual detector's construction. This analysis is addressed in the next chapter, which will combine the diode, scintillator, and shielding discussions with a realistic MCNP model of the detector to allow more definitive statements about shielding effectiveness and the resulting energy-dependent detector efficiency.

5. MCNP INSTRUMENT ANALYSIS

Overview. We now turn to the heart of this report: the quantitative analysis of the energy-dependent response of the actual scintillator and diode elements and the effect of possible modifications to the shielding. We begin with the main detector element, the plastic scintillator, by describing the existing inner and outer layers of shielding. We then attempt to identify particular weaknesses in the shielding and examine possible improvements. These suggestions lead to proposals for replacing the existing Al + Au outer cover with one made of tantalum, and we examine different options. We also show results from a separate series of calculations that evaluate the effect of the existing and proposed shielding on the radiation response of the silicon diodes. Finally, we use a combination of MCNP calculations and Storm and Israel coefficients to extrapolate the results to lower energies, and we summarize the relevance of the calculations for the instrumental problems described in the Introduction. Our discussion emphasizes that the response of the complete detector depends on the energy dependences of both the sensor efficiency and the shielding attenuation.

Fig. 5.1a. Energy-dependent effective area of the bare plastic scintillator compared with its response when surrounded by only the inner layer of shielding and with the response including the outer Al + Au cover.

Basic Scintillator Shielding. Our concern in Chap. 3, and the motivation behind the shielding discussion in Chap. 4, was the high sensitivity of the bare scintillator for photons at low energies. To address this problem, it is convenient to divide the detector's shielding into two components, the complex, overlapping lead and tantalum sections that make up the inner layer of shielding (see Figs. 1.2a,b) versus the simple outer cover that completely encloses the top half of the detector (see Fig. 1.1). At the tops of Figs. 5.1a,b we show the original results from Chap. 3 for the bare scintillator. The next step in the analysis investigates the effectiveness of the inner shielding alone by removing the instrument's outer Al + Au cover and illuminating the top half of the detector with a random incident angular distribution. The lower half is considered to be shielded by the

Fig. 5.1b. Low-energy detail of the effective areas in Fig. 5.1a, emphasizing the structure introduced by the absorption edges in gold, tantalum, and lead.

mounting framework, which is not included in our calculations. These results are shown in Figs. 5.1a,b as the $\times$'s and the connecting dotted line. In comparing the upper two curves in Fig. 5.1a, it is seen that the inner shielding is essentially transparent to photons at energies above 1 MeV, but its effectiveness approaches a factor of 10^4 at 20 keV and increases rapidly at lower energies. The structure near 80 keV is caused by the K -edges in tantalum and lead. Finally, the bottom curve shows the effect of adding the outer Al + Au cover to the inner shielding. This outer cover was designed to provide significant shielding only at the very lowest x-ray energies, but it shifts the detector threshold upward in energy by more than 10 keV. This set of calculations is one of the major results of this report, because it represents our best determination of the existing scintillator's energy-absorption efficiency as a function of incident photon energy.

Gaps versus Transmission. Part of the difficulty of estimating the detector's low-energy response is illustrated by Figs. 5.2a,b. Figure 5.2a shows the lowest-energy portion of Fig. 5.1b, but now including another calculation that separates the photon penetration into two components, one for transmission through the shielding and another for leakage around it, that is, through the gaps between different sections. The dashed line with closed circles shows the result of taking the MCNP model for the complete detector and making only the inner high- Z shielding impenetrable (in MCNP, we set $\text{imp}=0$ for the tantalum and lead sections). The outer cover and any structures made of low- Z materials such as aluminum and nylon were unchanged. At higher energies, the difference between this curve and that for the actual detector (solid line) indicates the penetration through the high- Z shielding, which can be reduced only by increasing the thickness of the material. More importantly, the convergence of the two curves at energies below 30 keV indicates that the detector's low-energy response consists entirely of leakage through gaps in the inner shielding. If we are to improve the background rejection at these energies, it is important to identify the locations of these gaps. Furthermore, by understanding the different contributions to the detector response, we may be better able to evaluate different techniques for extrapolating the response to lower energies.

Fig. 5.2a. Study of leakage through the inner detector shielding, showing the effect of making all high-Z materials completely impenetrable.

Fig. 5.2b. Detailed examination of the convergence region in Fig. 5.2a, showing the effect of various attempts to improve the inner shielding.

Gap Sealing. To examine the sources of shielding leakage suggested in the Introduction, in Fig. 5.2b we show an enlarged section of the response curves around the region where the normal and imp=0 results converge. First, on the photomultiplier side of the detector we apply an obvious fix by plugging the annular openings around the lead-glass light guides. The result is shown by the small diamonds, which indicate a typical shielding improvement by a factor of ~ 2 -2.5. The two other calculations show the effect of replacing the aluminum LED cover with one made of tantalum and then adding lead glass to the openings for the two photodiodes. Neither of these diode-side changes provides a sig-

nificant shielding improvement, suggesting that the light-guide gaps are among the most important leakage paths. Further calculations confirmed this assumption by revealing that the remaining leakage is through the multiple paths where the Ta calibration plate overlaps the inner lead shielding at the top of the scintillator. However, in an existing detector none of these areas, neither around the calibration plate nor the light guides, could be sealed without complete disassembly of the detector, which is an unlikely option.

Fig. 5.3a. Comparison between the effective area of the original detector and the areas obtained by replacing the outer Al + Au cover with a new Ta cover, allowing for the option of removing or keeping the small inner Ta calibration plate.

Replacement Covers. Because there is no convenient detector fix that significantly reduces the leakage around the inner shielding, we now investigate the alternative of replacing the entire outer Al + Au cover with a more effective 20-mil tantalum cover, as suggested in Chap. 4. Two different configurations have been studied. First, because the outer Ta cover essentially replaces the 20-mil calibration plate, eliminating the inner plate provides nearly equivalent shielding in the old and new designs. Second, by instead leaving the inner plate in place, we can improve the shielding at the top of the detector with little added weight, although the detector's energy and angle response changes somewhat. Figure 5.3a provides a basis for evaluating these options by comparing the two responses with that for the existing arrangement, an outer Al + Au cover with an inner Ta calibration plate. Replacing the outer cover and removing the inner calibration plate leaves the response almost unchanged above 0.2 MeV, but it reduces the leakage and shifts the low-energy threshold upward by about 10 keV at 30 keV, a significant improvement. Leaving the inner plate in place, as shown by the lower curve, reduces the response near 0.1 MeV by another two orders of magnitude and shifts the low-energy threshold upward by another 7–8 keV, an even greater improvement. Thus, removing the inner plate has the advantages of closely reproducing the existing shielding over much of the energy and angle range and slightly reducing the detector mass. Conversely, retaining the inner plate improves the shielding, albeit with a slight additional increase in mass and a likely change in the response. These options will be evaluated in detail in Chap. 7. Given the likelihood

that several of the detectors may be retrofitted with the proposed covers, the modified response functions are another significant result of our study.

Fig. 5.3b. Investigation of potential shielding improvements obtainable by sealing gaps in the inner shielding. The effects are similar for both types of outer covers.

Residual Leakage. As with the original cover, we have attempted to identify further improvements obtainable by plugging suspected gaps in the detector's inner shielding. Figure 5.3b repeats the evaluation from Fig. 5.2b for the existing shielding and adds the corresponding analyses for a detector that uses both the inner plate and the outer Ta cover. First, the light dashed line and upright triangles show the effect of setting all inner high-Z materials to $\text{imp}=0$, which indicates that the detector response above 50 keV is associated mainly with transmission through the shielding. At lower energies, sealing the gaps around the light guides (dotted line) would again provide a 50% improvement, with the remaining leakage being associated mainly with the spaces around the calibration plate. These results are consistent with those encountered in the previous analysis with the original cover, and they support the view that replacing the outer cover provides by far the simplest and most effective means of reducing the leakage through the numerous gaps in the detector's inner layer of shielding.

Shielded Diode Response. Our discussion now shifts to the issue of the diode's radiation response. In Fig. 5.4 we begin with the effective-area calculation from Chap. 2 for the bare diode, which is shown at the top of the figure. Next, the $\times$'s and the dotted line show the effect of the detector's inner shielding; as seen in Fig. 1.2a, for the diode this shielding consists of the lead sheet around the scintillator and either one or two layers of 20-mil tantalum, depending on angle. As explained in the Introduction, this arrangement leaves a small gap between the Ta diode cover and the lead lining, that is, through the nylon flange and nearby aluminum. More detailed calculations confirm that most of the low-energy leakage is near this gap, which could not be sealed in an existing detector without a complete reconstruction. The two remaining curves in the figure show the effect

Fig. 5.4. Calculated radiation response for the bare diode, for the inner shielding only, and for the addition of two different outer covers.

of adding the outer covers, either the existing Al + Au cover or the proposed 20-mil Ta cover. Each of these changes significantly improves the diode's low-energy threshold, with the total increase reaching about 30 keV for the Ta cover.

Diode versus Scintillator Responses. In Figs. 5.5a,b we collect the final results from most of this chapter. Figure 5.5a shows the bare scintillator and diode responses and the effect of the existing Al + Au outer cover. For the scintillator, the bare and shielded effective areas are the same above 0.5 MeV, about 13 cm², indicating no loss of signal at the most likely gamma-ray energies. For the diode, the high-energy values are a few times 10⁻³ cm², that is, about 10⁴ below the scintillator areas. Note that the areas for the shielded diodes are actually higher than those for the bare diodes, an indication of scattering from nearby low-Z materials, particularly the plastic scintillator. Below the high-Z *K*-edges, the shielded responses both begin to drop, at 25 keV falling to about 10⁻⁶ cm² and 10⁻⁹ cm² for the scintillator and diode, respectively. The factor of 10³ between these areas indicates that the ratio between the scintillator and diode responses is narrowing toward low energies, a potential disadvantage. Figure 5.5b shows the corresponding results for the proposed Ta cover with the inner calibration plate removed. When compared with the existing cover, the proposed cover's major effect is a considerable improvement in the position of the low-energy threshold, both for the scintillator and for the diode. In addition, the ratio between the scintillator and diode areas remains at least 10⁴ down to the lower limit of the calculations, an important advantage.

Low-Energy Extrapolations. Throughout this chapter, different techniques have been used to provide the curves shown in the figures. In cases where yields are high, most of the curves are simple spline fits. For cases with poor statistics, the attenuation models developed in Chaps. 2 and 4 were used to provide reasonable extrapolations of the calculated values. For example, ratios were calculated between the MCNP results for the fully

Fig. 5.5a. Scintillator and diode responses, bare and with the existing Al + Au outer cover. The two slightly different curves for the scintillator's low-energy response are different extrapolations of the calculations.

Fig. 5.5b. Scintillator and diode responses, bare and with the proposed tantalum outer cover but with the inner calibration plate removed. The curves from Fig. 5.5a for the existing cover are included for comparison.

shielded and bare diodes, which represent average attenuations through the outer shielding. Using an effective cover thickness, these ratios can be fitted using either the empirical $\exp(-\alpha E^\beta)$ function from Chap. 2 or the S&I and MCNP attenuations from Chap. 4. The resulting continuous transmission function is then multiplied by the bare-diode calculations and interpolated to produce a smooth curve through the calculated efficiencies for the shielded detector. Similar interpolations can be used for the scintillator by taking the ratio between the MCNP results for the fully shielded detector and those obtained with the outer cover removed. These approaches are used for the diode at all energies and for the scintillator at energies below the K -edge cutoff. In some cases the empirical and S&I approaches give noticeably different results, as illustrated by the alternative low-energy scintillator extrapolations shown in Fig. 5.5b. In such cases the difference between the two curves indicates the uncertainty in the low-energy extrapolations.

Angular Responses for the Existing Detector. As with the bare detector elements, it is important to compare the efficiencies for photons from random incident angles with those obtained for beams incident from specific directions. We cannot, of course, consider all possibilities, but by investigating three orthogonal axes we can illustrate the range of variation. Figure 5.6 shows the results for beams incident on the existing detector along its $-x$ -, $-y$ -, and $-z$ -axes. (In Fig. 1.1, the x -axis is along the photomultipliers; the z -axis is vertical.) The curves are the same ones shown in Fig. 5.5a. As expected, at high energies the beam direction is unimportant. At lower energies, there is more variation, particularly for the diodes, which have areas that are systematically lower than the random case because the three orthogonal directions are comparatively well shielded. The behavior for the detector with the proposed Ta cover would be similar because the outer covers are relatively symmetric when compared with the inner shielding. We conclude that the gamma-ray response of the detector is almost independent of angle except for the diode response to particular directions at very low energies.

Fig. 5.6. Angular dependence of the scintillator and diode responses, bare and with the existing Al + Au outer cover, as calculated for parallel beams incident from three orthogonal directions.

Shielding Evaluation. This chapter has presented the heart of our report, an investigation of the detector's energy-dependent effective areas and the impact of different shielding options on these responses. The responses of the scintillator and diode have been extended downward in energy to the limit of the Monte Carlo techniques, and they have been extrapolated to even lower energies by using empirical functions and the S&I attenuation coefficients. A key feature of our analyses is the division between the inner and outer layers of shielding. The inner shielding consists of overlapping sections that closely surround the active diode and scintillator elements; the outer layer is the one-piece cover that encloses the entire top half of the detector. Even the small thickness of high-Z material in this cover is very successful at reducing the effect of gaps in the inner shielding, which nevertheless dominate the detector's response below 40 keV. Because sealing the inner gaps in existing instruments would be impossible without almost complete refabrication, further improvements must be obtained by increasing the shielding in the outer layer by substituting a 20-mil Ta cover for the existing Al + Au one. This change shifts the threshold upward in energy and increases the background rejection by many orders of magnitude.

Summary. The following list itemizes the major results from this chapter and identifies the remaining issues:

- (1) The use of two-layer shielding effectively separates the leakage problem into transmission at high energies versus gaps at low energies.
- (2) The major leakage paths into the scintillator are around the light guides and at the overlap for the calibration plate; both vary from detector to detector, and neither can be conveniently sealed in an assembled instrument.
- (3) Because a relatively thin layer of outer shielding is very effective at reducing the gap leakage, substituting a Ta cover for the existing Al + Au one greatly reduces the leakage and raises the detector's low-energy threshold, particularly for the diode.
- (4) Except for the diode response at energies near threshold, the total detector efficiency is almost angle-independent, and its uniformity improves as the outer shielding is increased.
- (5) Complete energy-absorption efficiencies are available for several important detector configurations, including those with the existing and proposed outer covers.
- (6) Several empirical methods exist to reliably extrapolate the calculated efficiencies to very low energies.

In the case of the diode response, few of our calculations indicate any complicated conversion process such as downscattering of the incident high-energy gamma rays in low-Z materials to produce low-energy photons that then interact with the diode in its high-efficiency region. Instead, it appears that the diode's radiation response results mainly from simple gamma-ray transmission, either penetrating through the shielding at high energies or passing through the gaps between shielding sections at low energies. Thus, at this point the effective area calculated for the shielded scintillator at any energy still appears to be 3-4 orders of magnitude greater than that for the diode, so the apparent dominance of the diode response remains unexplained. Our emphasis in the next two chapters therefore shifts squarely to efforts to compare the detector's calculated response with the measured diode and scintillator responses at different energies. One difficulty is the lack of a convenient and consistent set of calibration sources, as discussed next.

6. SOURCE ENERGY DEPENDENCE

Overview. A major problem in comparing our calculations with laboratory measurements is that the detector responds only to intense energy bursts, not to individual gamma rays, which eliminates the possibility of using spectral measurements like those in Chaps. 2 and 3. In the absence of calibrated sources of pulsed high-energy photons, the next option is pulsed x-ray generators, which can provide high energy densities, but only for photons at lower energies. Our dynamic-range study¹ attempted to deduce energy and intensity parameters for two such sources by analyzing calibrations made using tantalum filters with different thicknesses. Such measurements form the bulk of the available data for our instrument, and they exist for every detector in the series. Basically, the intent is to examine the source's energy spectrum by converting a set of response measurements $I(t)$ for filters with different thicknesses t into attenuation lengths $T(t)$, using a version of Eq. 4.1a given by

$$T(t) = -t/\ln(I(t)/I_o) , \quad (6.1)$$

where I_o is the response measured with all filters removed. For a thin filter and a monoenergetic beam, $T(t)$ would be a constant. For thick filters or a broad energy spectrum, each thickness increment introduces more scattering and removes more of the lower energies, so $T(t)$ takes on progressively larger values. We can test a candidate energy spectrum by comparing its calculated attenuation lengths with the measured thickness dependence. In our previous analysis,¹ a major approximation was the use of total photon attenuations instead of energy transmissions, whose distinction was discussed in Chap. 2. This report continues these analyses using an approach that should provide greater fidelity between the measurements and calculations. Recognizing the importance of Compton scattering for both the beam attenuation in the filters and the energy deposition in the detector, we first use the realistic MCNP detector model from Chap. 5 to simulate the experiments more accurately. Second, to obtain more complete information about the Febetron's energy spectrum, we investigate measurements that combine different filter materials (tantalum and copper) with the different energy responses of the scintillator and diode sensor elements. Third, these new approaches are used to test the suitability of simple Gaussian source distributions as well as a calculated energy spectrum suggested by the source's manufacturer. Finally, we examine recent calibrations that suggest that the source spectra may be changing over time. In addition to the differential information provided by the attenuation analyses, this chapter also includes our first data on the magnitude of the diode's radiation response. The results are discussed in terms of the detector calculations and measurements to be presented in the next chapter.

Previous Results. In Fig. 6.1 we summarize the results from the previous analysis and introduce the approach used in the present work. The $\times$ and $+$ symbols show the measured attenuation lengths¹ for two different pulsed x-ray sources, a low-energy Golden source¹⁵ and a higher-intensity Febetron source.⁴ The difference between the two data sets indicates the generally harder spectrum for the Febetron source. The dashed lines and open squares show the final MCNP results from the previous analysis, which modeled the x-ray transmission using photon tallies from a combination of three Gaussian energy functions, with one component being by far the most important. Because these were photon and not energy tallies (see Chap. 2), it is difficult to evaluate their relevance for the actual measurements. As a simple check, the solid lines in Fig. 6.1 show the best results obtained by fitting the data with analytical calculations that use Gaussian input spectra weighted by the energy-dependent product of the S&I energy transmission and the scintillator's effective area. Although the overall S&I estimates are reasonable, they deviate from the measurements at the lowest thicknesses.

Fig. 6.1. Measurements of the energy-attenuation lengths for two x-ray sources, compared with photon-counting results from a previous MCNP analysis and the present values obtained using S&I energy-absorption coefficients from Chaps. 2 and 4.

Revised MCNP Analyses. The analysis of the data for Fig. 6.1 suggested a likely limitation in the simple S&I approach. The *K*-edge for the tantalum filters falls at almost the same energy as the structure produced by bremsstrahlung on the source's tungsten anode, and in Chap. 4 we showed that the S&I results are particularly suspect near such transition energies. As a result, small changes in the assumed source distribution can give large changes in the calculated attenuation lengths. Figure 6.2a shows an example for the Golden source. The measured data are shown at the center of the figure; the dotted lines at the top and bottom are attenuations calculated for monoenergetic sources at 65 and 70 keV, which are to either side of the Ta *K*-edge at 67.4 keV.⁵ For the energy below the *K*-edge (65 keV), absorption is large and scattering is small, so a nearly constant attenuation length is obtained. At the 70-keV energy, however, scattering causes even a monoenergetic beam to produce a complicated thickness dependence. A simple suggestion is to average the two results by proposing a distribution with a finite width; accordingly, the curve shown just above the data uses a 69-keV Gaussian with a 5-keV width ("69/5" or "*Ga*" in the figures). An alternative approach is to use the dominant component from the previous analysis, a 48-keV Gaussian with an 18-keV width (48/18, or *Gb*), which gives a result that lies just below the data. Finally, the curve labelled "*Ga* + *Gb*" combines the two Gaussians, with a result that passes almost perfectly through the measurements. Thus, each of the three Gaussian functions (*Ga*, *Gb*, or *Ga* + *Gb*) gives a reasonable result, and the differences in shape reflect the different weightings for energies near the sharp *K*-edge structures. As shown by the analyses in Fig. 6.2b, similar behavior is encountered for the higher-intensity Febetron source. The 90-keV results (*G0*, 90/28) are the current version of the previous analysis; the other curve combines a broad 88-keV Gaussian (*G1*, 88/33) with a narrow 70-keV peak (*G2*, 70/5) to reproduce the other extreme of the measurements. In principle, basing our analyses on energy absorptions should be an improvement in technique, but the existing attenuation data and analyses are apparently not sufficient to constrain the results.

Fig. 6.2a. Reanalysis of the previous attenuation measurements for the Golden source, using the present MCNP approaches.

Fig. 6.2b. Reanalysis as in Fig. 6.2a, but for the Febetron measurements.

Alternative Approaches. Because attenuation measurements made with the Febetron source have been our instrument's traditional calibration standard, to improve our analysis we have explored a new approach for determining its energy spectrum. We first made attenuation measurements that use the diode and scintillator elements to emphasize the low- versus high-energy portions of the spectrum, and we supplemented our measurements for tantalum filters with data for copper filters, which should eliminate the interference between competing *K*-edge structures from the source and filters. Second, we adapted the calculated 300-kV source distribution from Refs. 16 and 17 for the case of our nominally 150-kV source, and we developed a technique for varying this spectrum in a reasonable manner. The results are discussed in the following paragraphs.

Fig. 6.3a. Measured and calculated attenuation lengths for tantalum filters as obtained for the Febetron source with a silicon diode. The calculations use simple Gaussian energy distributions.

Fig. 6.3b. Silicon diode measurements and calculations as in Fig. 6.3a, but for attenuation with copper filters.

New Attenuation Data. In Figs. 6.3a,b we show attenuation lengths measured with the unshielded diode and filters made of tantalum (5–20 mils) and copper (6–250 mils). For these measurements, the sensor was a bare silicon photodiode identical to the ones in the instrument, which was mounted in a spare detector housing and connected to an external charge-sensitive preamplifier. The basic measurements consist of the peak voltage (in mV) produced by the preamplifier when the diode is illuminated by a Febetron pulse. The upper, dotted curves show the results calculated using the 90-keV Gaussian distribution

Fig. 6.3c. Attenuation-length analyses for copper filters using the Febetron source and the main scintillation detector.

Fig. 6.3d. As in Fig. 6.3c, but for tantalum filters and the main scintillation detector.

(90/28) suggested by the previous analyses;¹ the lower, dashed lines that pass through the data use an optimized 58-keV Gaussian with a 32-keV width (58/32). For reference, the solid line is obtained by combining the two Gaussians with equal weighting. Clearly, the 90-keV distribution differs greatly from the new diode measurements, but the agreement for 58 keV could scarcely be better. Continuing along this path, in Figs. 6.3c,d we show the corresponding results using the scintillator element as installed in the detector, which should emphasize higher photon energies. In this case the attenuations are calculated from differences in the instrument's digital output levels, and the large error bars in Fig. 6.3c are

a consequence of the relatively small attenuation produced by the copper when compared with the differential nonlinearity in the electronics' logarithmic response. The values shown are an average of several sets of $T(t)$ values obtained using different separation distances to sample different portions of preamplifier curve. With this caveat, the 58-keV assumption that fits the diode data also adequately describes the copper-plus-scintillator measurements, but only the original 90-keV assumption agrees with the tantalum-plus-scintillator results in Fig. 6.3d. Although this conflict reinforces our concern about overlapping structures from the tungsten anode and the tantalum filters, it also indicates that a single Gaussian distribution cannot adequately represent the entire energy spectrum.

Candidate Source Spectrum. As an alternative to a set of Gaussian spectra, in Fig. 6.4 we show an estimated energy spectrum for our nominally 150-kV Febetron source. Beginning with the calculated spectrum for a 300-kV source from Refs. 16 and 17, we removed the absorption discontinuities near 10 and 70 keV, compressed the resulting 300-kV continuum spectrum by a factor of 2 in energy, and then reintroduced the discontinuities. As shown in the figure, the result is a distribution with three continuum regions (low f_l , medium f_m , and high f_h , with boundaries at the discontinuities) and a single characteristic peak (f_p) near 60 keV. The relative weightings for the 4 components are those of the original 300-kV spectrum: $f_l = 33$, $f_m = 53$, $f_h = 7$, and $f_p = 7$. Most of the spectrum is at relatively low energies, where even the aluminum shielding around the scintillator and diode is very effective. Starting with these coefficients, our analysis can now vary the ratios in an attempt to better describe the different measurements.

Fig. 6.4. Estimated Febetron source spectrum obtained by adapting the 300-kV calculation of Ref. 16 for the 150-kV nominal voltage for our source.

Spectral Adjustments. In Figs. 6.5a-d we show the results of our multicomponent spectral analysis, beginning with curves for the individual spectral components, which are given as light lines. No low-energy components are shown, because only for the copper-plus-diode case was the result nonzero. For copper (Figs. 6.5b,c), the mid-energy component (dashed) always gives the greatest attenuations and smallest lengths, and the high-energy

Fig. 6.5a. Measured and calculated attenuation lengths for tantalum filters and a silicon diode. The calculations use variations on the spectrum in Fig. 6.4.

Fig. 6.5b. Silicon diode measurements and calculations as in Fig. 6.5a, but for copper filters.

component (dotted) always has the largest lengths and least attenuations, just as expected for an absorption cross section that decreases with energy. However, for tantalum (Figs. 6.5a,d) the order of the peak and high-energy components is reversed because of the K -edge structure. Not surprisingly, none of the individual components comes close to the data, although the dashed mid-energy distribution shows the best dependence on thickness. Next, the heavy chain-dotted curve shows the results for the original spectral weighting, with $h:p:m = 1:1:8$. Only for the large errors of the scintillator-plus-copper

Fig. 6.5c. Spectral analyses for copper filters using main scintillation detector.

Fig. 6.5d. As in Fig. 6.5c, but for tantalum filters with the scintillation detector.

data is this spectrum reasonable; otherwise, the weighting for the middle energies appears to be much too high. Accordingly, the heavy solid line shows the results obtained with a weighting of $h:p:m = 2:5:3$, which works very well for the diode measurements and gives reasonable results for the scintillator data. By far the most serious difficulty occurs for the tantalum-plus-scintillator case in Fig. 6.5d, which suggests that changes in the assumed distribution's high-energy tail may be required. This discrepancy may be related to the Marx-generator design of the source, which allows the endpoint energy to vary from 120 kV (at 20 kV anode voltage) to 180 kV (at 30 kV).¹⁷ In the end, the new analyses

Fig. 6.6a. Variation in tantalum attenuation-length results for different scintillator measurements made with the Febetron source.

Fig. 6.6b. As in Fig. 6.6a, variation in tantalum attenuation-length results for different scintillator measurements, but for the Golden source.

demonstrate that the Febetron spectrum has components at both low and high energies, which affect measurements made with different filters and sensor elements. In particular, overlap between the *K*-edge structures at high energies makes a differential analysis very difficult for the scintillator data.

Source Variability. Further attempts at understanding the two calibration sources must be balanced against the analysis of additional data obtained during the continuing program of measurements with Instrument 9, the detector used for the studies in Ref. 1. In Figs. 6.6a,b we compare the original attenuation-length data from Fig. 6.1 with sub-

sequent measurements using the two x-ray sources. Here the power-law fitting exploits the nearly logarithmic behavior of the attenuation lengths discussed in Chaps. 2 and 4 (see Fig. 4.1). Over time, it appears that the Febetron values show considerable variation at low filter thicknesses; as suggested by Fig. 6.5d, such variations are a strong indication of changes in the source spectrum at low energies. Although these changes do not significantly affect dynamic-range calibrations such as those in Ref. 1, they are a serious issue for the differential measurements needed to test calculations of low-energy responses like those in this report. In contrast, the few available measurements for the Golden source suggest somewhat greater stability, which will be exploited in our later analyses.

Shielded Diode Response. One example of calibrations with the Golden source is provided by measurements of the diode's radiation response by using a collimated beam to illuminate the diode edge-on through the side or top of the instrument (see Fig. 1.1). Slight movements of the collimator to either side resulted in sharp falloffs in the response, confirming that the diode's active surface is located between its tantalum cover and the lead sheet around the scintillator, as shown in Fig. 1.2a. Figure 6.7 shows these measurements along with calculations for the simple 48-keV and 70-keV Gaussian functions proposed at the beginning of this chapter (Fig. 6.2a), but now for edge-on illumination. With the diode installed in the instrument, its response can be measured only over the PD part of the dynamic range, so only a limited set of filter thicknesses is available. The results, however, clearly favor the narrow 70-keV Gaussian, and this assumption will be followed in the next chapter of our report.

Fig. 6.7. Attenuation-length analyses for illuminating one of the silicon diodes from the side with a collimated beam.

Absolute Normalizations. Because the attenuation calculation in Eq. 6.1 deliberately cancels out the source intensity, none of the above analyses specifically addresses the magnitudes of the scintillator or diode direct responses. In Ref. 1, the Febetron-plus-scintillator data were used to establish the absolute energy density of the Febetron output pulses. In this chapter, the Febetron-plus-diode measurements can be used to transfer this normalization to the diode. To investigate air scattering, the attenuation data taken

for Figs. 6.5a,b included preamplifier outputs measured with the bare diode either covered or uncovered by the 0.32-cm lead block. The difference between the two preamplifier readings, $V_d = 27.5$ mV ($\pm 10\%$), is a measure of the diode's radiation response; this value can be converted into a deposited energy by using the formula $E_D = V_d C_V w_{Si}$, where $C_V = 220$ pC/V is the calibration constant for the external preamplifier and $w_{Si} = 3.62$ eV is the energy required to create a charge pair in silicon.⁷ The result, $E_D = 140$ MeV ($\pm 10\%$), gives a measurement for the deposited energy as derived from the detector output. Alternatively, for the source input we can combine the Febetron intensity calibration from Ref. 1 (see Fig. 1.4) with the energy spectra from this chapter to obtain calculated energy-deposition values, as follows. At an anode voltage of 18 kV and a source-to-detector distance of 193 cm, the source model gives an incident energy density at the detector of $E_S = 4940$ MeV/cm² ($\pm 20\%$). The total energy depositions E_D for the different spectra can be calculated from the corresponding effective areas, using $E_D = E_S A_{\text{eff}}$. As in Eq. 2.5, the A_{eff} values can be obtained by dividing the calculated energy deposition per photon by the mean energy fluence for the incident spectrum. For the best-fit (2:5:3) case, the A_{eff} value is 0.027 cm²; the other estimates range from 0.02 to 0.08 cm² for the 58-keV Gaussian and the manufacturer's original spectrum. The resulting E_D values of 130 MeV (for the 2:5:3 case) and 100–400 MeV (for the alternative spectra) are in very good agreement with the measured 140-MeV value. This agreement confirms that the diode's radiation response exists and suggests that it can be determined with roughly 50% accuracy.

Source Discussion. The present attenuation analyses include several improvements in technique over those in Ref. 1, including (1) using the energy responses of the actual instrument instead of photon transmission through a set of filters, (2) using different sensor elements and filter materials to sample the response over a wider energy range, and (3) using physically reasonable spectra as a basis for fitting the measurements. The results are somewhat improved over those from the previous analysis, although there are still large uncertainties at both low and high energies and the final spectrum remains somewhat unphysical. Additional spectral analyses could be pursued using approaches described in the literature,^{6,18} such as choosing combinations of filters to select narrow sections of the spectrum and then using specialized fitting routines to construct a source distribution that is consistent with all available measurements. It may also be possible to develop MCNP calculations of a candidate source spectrum from first principles. Most disturbing, however, are the measurements that suggest that the Febetron spectrum apparently changes over time, an effect not obvious for the Golden source or in our previous Febetron study.¹ We emphasize that these uncertainties affect mainly analyses of the detector's differential response, as used in the present study; they do not cause difficulties for the integral response, which is the issue for the calibrations in Ref. 1. For the moment, therefore, we will continue to approximate the two sources as simple 70-keV (Golden) and 90-keV (Febetron) Gaussian distributions. Unfortunately, these energies are too high for realistic backgrounds, and they are too low for likely gamma-ray signals. Thus, measurements using the calibration sources must be combined with simulations in order to predict the detector's signal and background responses. Finally, our most important result is an implicit one. In the course of this chapter, we have shifted from an analysis of the scintillator response alone to a study of the relative radiation responses of both the scintillator and the photodiode, producing the first comparison between calculations and measurements of the magnitude of the diode response. When these results are combined with those in Ref. 1, the agreement suggests that the absolute normalizations for the scintillator and diode can be determined to perhaps 20% and 50%, respectively.

7. COMPLETE DETECTOR RESPONSE

Overview. Chapter 5 above provided detailed calculations of the detector response, both with the original aluminum-and-gold cover and with the proposed tantalum replacement. The major results were the effective areas of the detector's two active elements and the identification of multiple low-energy leakage paths that could be addressed only by improving the detector's outer shielding. Chapter 6 used some of these results to repeat the source analyses of Ref. 1 with a more realistic model, which provided solid values for the effective areas of the diode and scintillator. In this chapter we combine the detector calculations with the source model to address two major issues, shielding leakage and diode response, which were originally raised in the Introduction. To establish a basis for our analysis, we begin by reexamining the expressions from Ref. 1 for the detector's response to energy deposited in the plastic scintillator by the calibration sources. Included are the relation between the incident and deposited energies, the connection between measured outputs and Monte Carlo calculations, and the detector's logarithmic conversion between input signals and digital outputs. We then investigate the shielding leakage at the overlap region identified in the Introduction, which turns out to be insignificant at the low energies of typical backgrounds. Next, the most important part of this chapter—and perhaps this report—discusses the different components of the detector's scintillator and diode responses, particularly the diode radiation response, and develops techniques for properly interpreting the instrument's output in different situations. The results show that the electronic signal produced in the diode by the direct interaction of gamma rays with silicon is in fact far larger than the corresponding signal produced by optical stimulation from the scintillator. We conclude with further measurements that explain and support this conclusion and an extensive summary of the entire chapter.

7.1. RESPONSE FORMALISM

Summary of Previous Work. We begin by describing the previous model¹ for the detector operating in its intended mode, where the scintillator is the only active element and the photomultiplier and photodiode are simply electronic sensors that respond to the scintillation light. One result is an empirical expression for the input energy density produced by the calibration sources, which can be summarized as

$$E_S = Ke^{-t/T(t)}(V - V_o)/R^2, \quad (7.1)$$

where E_S is the energy density at the detector (MeV/cm²), t is the filter thickness (mils), $T(t)$ is the attenuation length (in mils, from Chap. 6), R is the source-to-detector separation in cm, and K is the normalization constant $K = 4.6 \times 10^8$ MeV/kV. The voltage parameters V and V_o are used to normalize the different source intensities; for an offset voltage $V_o = 17.6$ kV, V is set to either the anode voltage (in kV) for the Febetron, to a fixed 19.2 kV for the Golden source, or to 196.5 kV for the Scandiflash source. The other important result is the expression for the output produced by the instrument when stimulated by the calibration sources. With the diodes shielded from the beam, the scintillator response is given in logarithmic digital levels L for either the PM or PD channel as

$$L_{PM} = 14.25 \log_{10} E_S + 1.5H \quad (\text{for } L < 64), \quad (7.2a)$$

$$L_{PD} = 14.25 \log_{10} E_S + 8 \quad (\text{for } L > 64). \quad (7.2b)$$

Here H is the PM high-voltage step (0–7), which is usually placed at $H = 7$ during testing but is set to the midrange value $H = 3$ for an operational instrument. As indicated by the two equations, the electronics switches between the PM and PD channels as the level changes, but both outputs actually originate from the energy deposited in the scintillator, not the diode. Equations 7.1 and 7.2a,b represent the final expressions from Ref. 1 for the connection between the input energy density from the calibration sources and the scintillator's resulting output in digital levels. Again, the expressions are valid only for these sources, and only with the diodes shielded by the lead block.

Reformulation of the Response Equations. To simplify the response equations as much as possible, we first combine the outputs from the two channels into a single expression. For the detector operating at high-voltage step $H = 3$ with a calibration source and shielded diodes, the procedure in Ref. 1 provides a smooth logarithmic response through the crossover between the maximum PM output level at $L_{\text{PM}} = 63$ and the minimum PD level at $L_{\text{PD}} = 68$. The missing levels 64–67 at the bottom of the PD range are omitted because of their poor signal-to-noise characteristics. For convenience, we will therefore assume PM operation at this voltage step and subtract the 4 unused PD levels, thereby defining a continuous digital variable J^s for the scintillator response as

$$J_{\text{PM}} = L_{\text{PM}} + 4.5 - 1.5H \quad (7.3a)$$

$$J_{\text{PD}} = L_{\text{PD}} - 4 \quad (7.3b)$$

$$J_{\text{PM}} \approx J_{\text{PD}} \equiv J^s = 14.25 \log_{10} E_S + 4.25 . \quad (7.3c)$$

This formulation explicitly recognizes the continuity of the response across the boundary and will simplify the analyses below. Again, these expressions are valid only for calibration sources and shielded diodes.

Energy Density versus Energy Deposition. Although Eqs. 7.1 and 7.3c reliably describe the instrument's digital output during calibrations, it is clear that the scintillator's fundamental response is to the deposited energy E_D^s , not the input energy density E_S . To obtain a more general formulation, we can exploit the relation between the deposited energy E_D and an arbitrary incident energy density E_I (as opposed to the specific E_S values for the calibration sources). For the scintillator effective area A_{eff}^s , we have

$$E_D^s = E_I \times A_{\text{eff}}^s . \quad (7.4)$$

Because the calibration in Eq. 7.3c is based on an average of measurements with the Golden and Febetron sources, the appropriate A_{eff}^s value for the conversion is an average of the areas at the estimated mean energies of the two sources. We will therefore use $A_{\text{eff}}^s = 8.8 \text{ cm}^2$, which combines the unshielded scintillator areas at 70 keV (8.0 cm²) and 90 keV (9.5 cm²). We can then rewrite Eq. 7.3c in terms of the deposited energy E_D^s as

$$J^s = 14.25 \log_{10} E_D^s - 9.2 . \quad (7.5)$$

Equation 7.5 is valid for all incident energies, whereas Eq. 7.3c applies only for the calibration sources. Also important for comparing measurements and calculations is a similar expression that relates the measured E_D^s value for the entire scintillator to the calculated MCNP energy deposition ϵ_D^s for a single incident photon. If E_γ is the average beam energy and A is the projected area at the scintillator, then

$$E_D^s = \epsilon_D^s (E_I / E_\gamma) A , \quad (7.6)$$

where the quantity in parentheses is simply the incident fluence in photons/cm². This relation allows us to convert the macroscopic form of Eq. 7.5 into its microscopic equivalent,

$$J^s = 14.25 \log_{10}(\epsilon_D^s(E_I/E_\gamma)A) - 9.2, \quad (7.7)$$

which provides a vital connection between the measured detector calibrations and the MCNP calculations. The two important expressions in Eqs. 7.5 and 7.7 specify the scintillator's generalized response to arbitrary energy inputs, and they provide the basis for much of our analysis. Although no longer restricted to calibration sources, they still assume the diodes to be electronic sensors that respond only to light from the scintillator, that is, the diode's radiation response must be avoided by using the lead shielding block. We also point out that these equations are examples of the general logarithmic conversion $J = B \log_{10} I + C$, where C is a normalization constant and B is the conversion slope between the output variable J and the input variable I . For our electronics, this slope is always fixed at $B = 14.25$, so different conversions vary only in their value of C , an issue that will be important in our later discussions.

Summary. This section has described the conversion of the detector's response formalism from its original focus on calibration sources and incident energy densities E_S to the more general case of the energy E_D deposited in the scintillator from any source. When written in its microscopic form, the conversion can also be used for different energies and detector configurations, which will be necessary throughout the remainder of this chapter.

7.2. SHIELDING LEAKAGE

Scintillator Gap Response. The first application of our reformulated response equations is provided by a study of the radiation leakage through the gap between the scintillator's inner lead liner and the tantalum calibration plate, as discussed in the Introduction. To examine this leakage, the Golden source was used to illuminate the scintillator through a long, narrow slit (0.5 cm by 7.0 cm), which was aligned parallel with the gap and scanned across it in a plane tilted at 30° to the top face of the detector. The results are discussed in terms of Fig. 7.1. The source position indicated along the x -axis gives the distance of the slit from an arbitrary origin near the corner of detector. The open circles are the measurements taken with the Golden source; the solid curve connects MCNP calculations for the collimated response. Referring to Fig. 1.2a, the "Top" of the detector is the face shielded by the calibration plate, the "Front" is the boxlike photodiode housing with its tantalum shielding, and the "Corner" is the location of the presumed gap between the front and top faces. The agreement between the shapes of the measurements and calculations is good except at the shoulder just below the gap, where the precise arrangement of the inner lead shielding is uncertain because of the small hand-fitted shim shown in Fig. 1.2a. A surprising result is the large rise in the region of the diode housing. A check on the location of this feature is provided by the calculations that remove the two sections of tantalum at the top and front of the detector. As suggested in the Introduction, this rise appears to be associated with leakage into the scintillator through the small aluminum cover over the two calibration LEDs. Unfortunately, no measurements were made in this region because of its proximity to the diodes and their large active response. The additional calculations shown here indicate that the leakage could be greatly reduced if the LED cover were replaced with a tantalum version or if a piece of lead glass were placed in the opening—or if the proposed Ta outer cover were installed. Thus, a major result is the large (~15-fold) rise in the response at the gap, which confirms the existence of a weak point in the shielding. A secondary result is the possibility of significant leakage through the LED opening, which would also be eliminated by replacing the outer cover.

Fig. 7.1. Comparison between measured and calculated responses for a linear scan of a collimated Golden source of 70-keV x-rays across a gap in the shielding at the corner of the detector.

Variations in Gap Response. To provide a check on the calculations, two changes were made in the experiment. First, as shown in Fig. 7.2a, a “softer” x-ray tube was used to repeat the scan. Because this spectrum is unknown, we have simply compared the two measurements against the 70-keV (“hard source”) and 48-keV (“soft source”) Golden calculations described at the end of the previous chapter. Within the scatter in the data, the soft-source results reflect the lowering of the beam energy, and the comparison supports our assumption of a 70-keV centroid for the normal (hard) source. Next, in Fig. 7.2b we show the effect of placing a 20-mil tantalum sheet over the slit in the lead collimator. The agreement between the measurements and the 70-keV results provides additional support for the reliability of the calculations and the use of the higher mean source energy. The results also illustrate the effect of the proposed 20-mil tantalum cover at these energies.

Collimated versus Uncollimated Measurements. Figures 7.1 and 7.2a,b allow a check on the conversion between the source output E_S , the deposited energy E_D , and the scintillator output J^s as expressed in Eqs. 7.1–7.5. First, a test was made using the uncollimated detector to verify the basic relationships. Filters of thickness $t = 0$ and $t = 20$ mils were inserted with the Golden source placed at a separation $R = 200$ cm and the detector set at high-voltage step $H = 7$. The measured results of $J^s = 64$ with no filter and $J^s = 42$ with the 20-mil filter agree perfectly with the values calculated from the equations. Next, the 5-mm collimation slit was inserted and the beam was scanned across the top of the detector. Instead of the 20-fold reduction in output expected from the ratio of the collimator and detector areas, the observed drop was only a factor of 8 (12 instead of 18 levels). The missing factor of 2.5 (6 levels) may be associated with a nonuniform x-ray beam profile, possibly because of air scattering near the source aperture. To maintain consistency with the more general case of an uncollimated source, we will henceforth shift all collimated measurements downward by this same factor.

Absolute Response Magnitudes. The comparisons in Figs. 7.1 and 7.2a,b also test the relation between the calculated energy depositions per incident photon ϵ_D^s and

Fig. 7.2a. Scan as in Fig. 7.1, but for 70-keV and 48-keV beams moving across the same region.

Fig. 7.2b. Linear scan as in Fig. 7.2a, but comparing measurements made with an additional 20-mil tantalum filter placed in the beam.

the detector's corrected response J^s . Based on MCNP calculations made specifically for this geometry, we used Eq. 7.7 to transform the resulting ϵ_D^s values by using the incident energy density $E_I = E_S = 18\,400 \text{ MeV/cm}^2$ from Eq. 7.1 and assuming a beam energy $E_\gamma = 0.07 \text{ MeV}$, a scintillator area $A = 70 \text{ cm}^2$, and a collimator area $A = 3.5 \text{ cm}^2$. For the uncollimated case, the agreement between the measurements and calculations was again reasonable. As shown in the three figures, the magnitudes of the collimated responses are also in good agreement, with only the above 6-level correction. These results provide an important end-to-end check on our understanding of the scintillator response.

Fig. 7.3a. Energy dependence of the effective area of the detector at the center of the scintillator gap and the effect of different shielding options.

Energy Dependence of the Gap Leakage. On the basis of Figs. 7.1 and 7.2a,b, we can now use Eq. 7.7 to extend the analysis to a wider energy range, which is important for estimating the energy dependence of the gap leakage and the effectiveness of shielding modifications at low energies. To begin, in Fig. 7.3a we show the leakage as an effective area for the range of energies below 150 keV. As in Chap. 5, these A_{eff} values are obtained by dividing the calculated heating tallies by the incident energy fluences. For reference, recall that the detector's total effective area is on the order of 10 cm², so leakage at the level of 0.1–1 cm² is not serious unless it extends to very low energies. The upper points, which represent the effect of collimation on the bare detector, were obtained by reducing the A_{eff} values from Fig. 3.5 for the full scintillator by the factor of 20 between the detector and collimator areas. The curve through these points is simply a spline fit. All remaining symbols are MCNP calculations made specifically for the gap region, and the remaining curves are estimates using S&I coefficients. For the inner shielding, the S&I curve was obtained by assuming the nominal Al thickness of 125 mils and then including an empirical reduction to account for the narrow gap in the lead lining. Similarly, the curves for the Al + Au and Ta covers were obtained by applying S&I coefficients to the curve for the inner shielding, again using thicknesses that were increased slightly from the minimum values. The resulting energy dependences are in good agreement with the MCNP calculations.

Leakage Normalization. Next, the conversion function in Eq. 7.7 was used to express the energy depositions calculated for Fig. 7.3a in terms of digital levels J^s instead of effective areas. In Fig. 7.3b, the large symbols are measurements like those in Figs. 7.2a,b, with the addition of a data point for the existing Al + Au cover. Again, the only correction is the downward shift by 6 levels to account for the presumed beam nonuniformity. It is clear that the *K*-edge structures for gold and tantalum greatly complicate the comparison, just as discussed in Chap. 6. For example, although the symbols are plotted at 70 keV, similar agreement could be obtained at any energy from 60–80 keV. The major purpose of these figures, however, is the straightforward comparison of the leakage contribution with

Fig. 7.3b. Energy dependence of the gap response in Fig. 7.3a, but expressed in terms of digital levels. The large symbols are measured values that have been shifted to match the calculations.

the overall detector response in this worst case. Especially with the addition of the tantalum cover, the leakage area is orders of magnitude below the total detector area of about 10 cm^2 , and its size decreases rapidly at lower energies. We conclude that gap leakage, which accounts for at most 10% of the instrument's total effective area even at 100 keV, is not a serious problem in either the original or modified instrument. According to the analysis in Chap. 5, a similar statement should apply to other sites such as the lead-glass light guide, where the leakage was in fact too small to measure in the case of Instrument 9.

Summary. For the scan of a collimated beam across the gap region at the corner of the detector, the shapes of the measured and calculated detector responses are in good agreement, which supports the fidelity of our computer simulations. Furthermore, there is also good agreement for the magnitudes of the uncollimated and collimated responses, which supports the response formalism developed in the previous section. The comparisons demonstrate that leakage at the gap and presumably at other shielding locations makes up only a fraction of the total detector response at calibration energies, and replacement of the existing cover provides even greater rejection at the lower background energies.

7.3. DIODE RESPONSE

Diode versus Scintillator Responses. The discussions in Secs. 7.1 and 7.2 address only the detector's scintillation response, with the diode acting simply as a photosensor. In this mode, energy deposited in the scintillator is converted to light that results in photoelectron production in the photomultiplier and photodiode, which feed separate logarithmic preamplifiers to provide digital outputs for the PM and PD channels. Based on our results in previous chapters, however, it is clear that the detector's actual operation also involves the diode's direct response to incident radiation. In the Introduction, we briefly described calibration measurements for the Febetron and Scandiflash sources, with results expressed equivalently as the shift between the detector outputs with the diodes

shielded and unshielded or as the abrupt step that occurs when the PM-to-PD crossover is triggered prematurely. When measured using a bare detector (one with the outer cover and calibration plate removed), this shift is 13 ± 1 levels for all the sources, that is, the diode's radiation response is larger than its scintillator response by a factor of 8.2 ± 1.4 , essentially an order of magnitude. This factor is supported by additional diode measurements made using the detector mockup described at the end of Chap. 6. In that case, inserting a thin sheet of black paper between the scintillator and diode had no effect on the diode output, but inserting a few copper filters revealed an attenuation curve consistent with photon scattering at roughly the original source energy. Thus, there appears to be *no* observable optical signal from the diode, and thus its calibrated response with the lead block in place consists mainly of a small number of photons that have scattered from the scintillator. For the moment, we will therefore assume that the detector's PM or PD output in the calibration mode, that is, with the diodes shielded, is simply the scintillator response J^s . In actual operation, that is, with the diodes unshielded, the output switches between the scintillator response J^s in the PM channel and the diode response J^d in the PD channel. At the conclusion of our analysis, we will be able to confirm that the diode's optical signal is far smaller than its radiation response, although probably nonzero, and the observed magnitudes of both the radiation and optical responses are entirely reasonable. Although this insight establishes a useful basis for our discussion, it cannot provide the analyses needed to assure an accurate detector calibration. Our immediate task is therefore to develop a quantitative connection between the calibrated scintillator response J^s and the calculated diode response J^d .

Collimated Diode Response. We will address the calibration of the diode's radiation response by two different methods, both of which normalize energy-dependent calculations to measurements made at single energies. The first method relies on a set of measurements that use the well-behaved Golden source to investigate the radiation response of the diode as installed in the detector. Using an arrangement similar to that for the gap analysis, we illuminated the diode from the side by placing a thin slit between the source and the detector. As discussed in Chap. 6, this edge-on orientation emphasizes the diode response by taking advantage of the location of the diode's active surface in the narrow space between its tantalum shielding and the scintillator's lead liner (see Fig. 1.2a). In this geometry the collimated photon beam passes through only the instrument's aluminum housing, the nylon flange, and the diode's copper enclosure, all low-Z materials. Figure 7.4a shows MCNP effective areas calculated specifically for this arrangement, including comparisons for the areas of the edge-on bare diode, the diode with the Al + Au cover added, and the diode with the tantalum cover added. The curves for the bare diode and the inner detector are spline fits; those for the Al + Au and Ta covers were obtained by applying S&I coefficients to the curve for the inner shielding, using the nominal values for the thicknesses of the Al + Au and Ta covers. As with the instrument's gap response, these calculations show that the shielded diode's energy dependence is steep enough that the large output levels observed at the calibration energies do not indicate an inevitable problem with backgrounds at lower energies. Although the different materials (Al, Cu, nylon, etc.) make an exact calculation impossible without a precise specification of the diode's internal structure, the shielded response is certainly very small at energies below 30 keV.

Normalization of the Collimated Response. As in the gap analysis, the next step is to calibrate the effective-area values in Fig. 7.4a against the measured digital levels, as shown in Fig. 7.4b. As pointed out in Sec. 7.1, because the same type of logarithmic preamplifier is used in both the PM and PD channels, the expression for the instrument's

Fig. 7.4a. Calculated energy dependence of the collimated diode's radiation response, expressed as an effective area.

Fig. 7.4b. Collimated diode response as in Fig. 7.4a, but converted to digital output levels for normalizing to the measurements.

diode response J^d can differ only by a scale factor from its calibrated scintillator response J^s . For the scintillator case, in Eq. 7.5 we obtained $J^s = 14.25 \log_{10} E_D^s + C_s$, with $C_s = -9.2$. The corresponding expressions for the diode response J^d can therefore be written as

$$J^d = 14.25 \log_{10} E_D^d + C_d, \quad (7.8a)$$

$$J^d = 14.25 \log_{10} (\epsilon_D^d (E_I/E_\gamma) A_d) + C_d, \quad (7.8b)$$

where A_d is the diode area and C_d is a normalization constant. By using Eq. 7.8b to match the calculations to the two measurements shown in Fig. 7.4b, we can obtain an estimated

value of 54.3 for C_d . Note that this normalization again depends on the mean energy assumed for the Golden source, and similar agreement with different C_d values could be obtained at other nearby energies. Furthermore, the normalization relies heavily on a single experiment performed in a unique detector configuration. Nevertheless, Eqs. 7.8a,b are the first step toward the diode equivalent of the scintillator expressions in Eqs. 7.5 and 7.7, which is an extremely important result. In the overall view, the C_s and C_d factors in these equations are the two arbitrary normalizations that connect the calculated diode and scintillator outputs with the calibrated source input.

General Diode Normalizations. An important extension of the collimated calibration in Figs. 7.4a,b is provided by the accumulated measurements for the shift ΔJ between the detector's PM and PD responses. This shift can be obtained either from the observed offset between the diode's shielded and unshielded calibrations or from the abrupt PM-to-PD step in the detector's unshielded response. In contrast to the above collimated measurements, the offset data set is broadly relevant because it includes calibrations for different energies and detector configurations, several of which are supported by calculated responses. We now come to a critical point in our derivations. Because J^d and J^s both share the logarithmic form $J = 14.25 \log_{10} E_D + C$, their difference ΔJ translates to a ratio between E_D^d and E_D^s , which in turn connects to the ratio between the calculated diode and scintillator effective areas A_{eff}^d and A_{eff}^s . Equations 7.7 and 7.8b were specifically arranged to emphasize this relationship, and we can easily rearrange them to exploit their common logarithmic form, giving

$$\Delta J = J^d - J^s = 14.25 \log_{10} (E_D^d / E_D^s) + 63.5 \quad (7.9a)$$

$$\Delta J = J^d - J^s = 14.25 \log_{10} \left(\frac{28400 A_{\text{eff}}^d}{A_{\text{eff}}^s} \right). \quad (7.9b)$$

These equations are an alternative to the expression for the diode response in Eqs. 7.8a,b, and they connect the calculated MCNP effective areas to ΔJ values that can be easily measured in terms of the PM-to-PD step in the unshielded detector response. The factor of 28400 in Eq. 7.9b, which is equivalent to the difference between the normalization factors C_d and C_s , finally confirms the diode's far greater sensitivity to direct stimulation (A_{eff}^d) than to indirect energy deposition in the scintillator (A_{eff}^s). This factor is exactly the magnitude needed to more than cancel out the difference of 3–4 decades between the scintillator and diode effective areas, so that the diode response dominates the PD output by almost an order of magnitude. Significantly, by connecting the normalization factor to the effective areas, Eq. 7.9b also allows us to extend the limited calibration in Fig. 7.4b to provide normalized, energy-dependent response functions for the detector.

Diode Responses and PM-to-PD Steps. A crucial test of the relation in Eq. 7.9b is its reliability in predicting the measured offsets ΔJ between the diode and scintillator responses J^d and J^s for different detector configurations and calibration conditions. The results shown in Fig. 7.5a are the values with the inner calibration plate present, as in the existing shielding; those in Fig. 7.5b are with the inner plate removed, as in the proposed design. The curves were obtained from the interpolated A_{eff} values. Also shown are various measurements collected from different calibrations using the Golden, Febetron, and Scandiflash sources. Significantly, the measurements for all configurations at all energies agree well with the predicted values. When presented in this form, it is clear that the size of the ΔJ step varies with energy because of the difference between the scintillator and diode effective areas. As a result, the inclusion or removal of the inner calibration plate becomes an important issue for the overall detector response. With

Fig. 7.5a. Difference between the diode and scintillator responses for the detector with Al + Au and tantalum covers, assuming that the inner calibration plate is present.

Fig. 7.5b. As in Fig. 7.5a, difference between the diode and scintillator responses for the detector with the proposed tantalum cover, but assuming that the inner calibration plate is removed.

the plate included, as in Fig. 7.5a, changing the outer cover has little effect on the ΔJ step because it affects the scintillator and diode equally, except at energies very near the threshold (below about 50 keV). In contrast, removing the inner plate as in Fig. 7.5b increases the scintillator response at low energies and thereby decreases the ΔJ values. Thus, addressing the problem of the diode's radiation response requires both an increase in the outer shielding, which seals the leakage paths at the extreme low energies, and removing the inner calibration plate, which provides a better match between the energy dependences

of the diode and scintillator effective areas at higher energies. This more uniform energy response with the inner plate removed provides our strongest reason for recommending this option for the modified detector. Although nothing can be done to avoid the large ΔJ values at low energies for the existing detector, this problem exists only below 200 keV, which is presumed to be much lower than typical gamma-ray energies.

Instrumental Areas. The discussion of the energy dependence of the ΔJ offsets supports a major revision of the original view of the detector's scintillator and diode responses. Instead of treating the scintillator as the detector's only active element and the photomultiplier and diode simply as photosensors for two different output ranges, we instead have an instrument with two active elements, the scintillator and the diode, whose energy-dependent responses should be matched as closely as possible to avoid discontinuities at the crossover between the PM and PD ranges. In this view, the analysis for Eq. 7.9b provides scintillator and diode efficiencies that include both the effective energy-absorbing areas and the coupling to the electronics for the subsequent signal processing. With the factor of 28 400 included, we regard these detector responses not simply as effective areas but as "instrumental" areas, which are proportional to A_{eff}^d and $A_{\text{eff}}^s/28\,400$. To illustrate, Figs. 7.6a,b show instrumental areas for detectors with the two major shielding options, that is, the existing Al + Au outer cover with the Ta calibration plate versus the proposed Ta outer cover with no inner plate. In both cases, the responses above 200 keV are dominated by Compton scattering, and the diode-to-scintillator ratios converge to a nearly constant factor of 10. For the proposed shielding (Fig. 7.6b), the ratio remains almost constant for all energies down to the *K*-edge region, and then it drops to zero at 30 keV. In contrast, for the existing shielding (Fig. 7.6a), the rapid rise in the diode's low-energy efficiency at energies below 100 keV causes the ratio to increase by another factor of 10 before both responses finally fall toward zero near 20 keV. Accordingly, the ΔJ values for the existing shielding vary greatly with energy, but those for the proposed detector are relatively constant.

Scandiflash Measurements. The data obtained with the high-energy Scandiflash x-ray generator³ have been shown several times in this report. In particular, these values are the only MeV-range check on the predictions in Figs. 7.5a,b, and we now provide a few of the experimental details. As in Ref. 1, to cover a wide dynamic range the Scandiflash measurements used a combination of $1/r^2$ variations and attenuations, this time with a 2-inch lead brick as a filter. For source distances greater than 200 cm, the PM values can be normalized to those from the model for the Febetron and Golden sources in Eq. 7.1, with the lead attenuation length set to 520 mils and the source voltage parameter set to $V = 196.5$ kV. Some results were shown in Fig. 1.5 in the Introduction; as seen in Figs. 7.5a,b, they provide an important detector calibration at high photon energies, where the detector shielding becomes almost transparent.

Corrected Energy Depositions. Unfortunately, understanding the basis for the detector's scintillator and diode responses does not immediately provide a method for reversing its effects. The results in Figs. 7.5a,b, however, suggest a possible approach for recovering most of the linearity described in the Introduction. We first consider only the case of laboratory calibrations, where the incident photons are known a priori to be either at high (Scandiflash) or low (Febetron and Golden) energies. In Fig. 7.7a, which is a more detailed version of Fig. 1.5, the PM output levels (open and closed squares) are plotted just as measured. Because we now know that any measurement in the PD range ($J \geq 64$) is actually a radiation response from the diode, to match the calibrated PM values we must immediately subtract the appropriate offset shown in Figs. 7.5a or 7.5b. Thus, for high energies we subtract 13.6 levels, which is the average ΔJ value

Fig. 7.6a. Calculated instrumental areas that show the diode and scintillator responses for the existing combination of an Al + Au cover with an inner tantalum calibration plate.

Fig. 7.6b. As in Fig. 7.6a, diode and scintillator instrumental responses, but with the proposed tantalum cover present and the inner calibration plate removed.

for the Scandiflash data, giving the J^c results shown by the open circles. For the low-energy Febetron source, the ΔJ correction depends on whether the Ta calibration plate is present, as for the existing instrument ($\Delta J = 29$ from Fig. 7.5a), or absent, as for the proposed shielding ($\Delta J = 12$ from Fig. 7.5b). As hoped, the resulting responses show fairly good agreement between the deposited energy E_D and the corrected digital output level, that is, $J^c = 14.25 \log_{10} E_D - 9.2$. As seen in the figure, however, slight changes in the Febetron spectrum cause the low-energy PD corrections to vary from the expected value

Fig. 7.7a. Corrected Scandiflash and Febetron data for a detector with the existing and proposed shielding, expressed in terms of the deposited energy E_D in the scintillator.

(the solid line), even in calibration tests. Basically, however, for the proposed shielding this ΔJ correction recovers the simple relationship between deposited energy E_D and digital output level J^c by simply shifting the PM-to-PD crossover from $J = 64$ to $J^c = 50$, a loss of almost one decade in dynamic range. For the existing shielding, the shift is downward by 29 levels to $J^c = 35$, a loss of two decades.

Corrected Energy Densities. There remains a problem, however. For a deployed instrument, the important relationship is not between the corrected digital output J^c and the deposited energy E_D , but between J^c and the incident energy density $E_I = E_D/A_{\text{eff}}$. In such cases, the incident energy distribution is essentially unknown, so both the step correction ΔJ and the effective area A_{eff} are uncertain. Because the gamma-ray signals are presumed to exist mainly at high energies, it makes sense to assume a conversion between deposited energy and incident energy that is based on the high-energy values $\Delta J = 13.6$ and $A_{\text{eff}} = 13.5 \text{ cm}^2$. Figure 7.7b illustrates the effect of this assumption by using the Febetron and Scandiflash measurements to represent the extreme contributions from the lower and upper limits of an unknown energy spectrum. The desired conversion between J^c and E_I is simply the transformed version of the basic relation between J^c and E_D from Fig. 7.7a, that is, $J^c = 14.25 \log_{10} E_D - 9.2$. For high energies, the conversion is obtained by inserting $E_D = E_I A_{\text{eff}}$ and $A_{\text{eff}} = 13.5 \text{ cm}^2$, giving $J^c = 14.25 \log_{10} E_I + 6.9$. Similarly, the low-energy relation uses $A_{\text{eff}} = 8.8 \text{ cm}^2$ and obtains $J^c = 14.25 \log_{10} E_I + 4.3$. These ideal conversions are shown in Fig. 7.7b as solid and dashed lines. As intended, for the high-energy Scandiflash source (open symbols), both the PM and PD measurements agree perfectly with their ideal values (solid line). For the low-energy Febetron data (filled symbols), the overestimate of A_{eff} (using 13.5 cm^2 instead of 8.8 cm^2) shifts the energy densities $E_I = E_D/A_{\text{eff}}$ downward by 50% from the ideal values (dashed line), as shown by the Febetron data in the PM range (solid squares). In the PD range with the proposed

shielding, further subtracting the assumed ΔJ shift of 13.6 levels (instead of $\Delta J = 12$) leads to a slight overestimate of the ideal E_I values (solid circles). Finally, for existing instruments the assumption of $\Delta J = 13.6$ instead of $\Delta J = 29$ causes a significant PD undercorrection, as shown by the filled diamonds. Thus, with the proposed shielding the almost energy-independent ΔJ value in Fig. 7.5b ensures acceptable results regardless of the incident energy distribution, that is, the error in the incident energy density is at most 50%. With the existing shielding, however, a spectrum with a large low-energy component would cause errors of more than an order of magnitude and the loss of not one but two decades of dynamic range. We stress, however, that the deviations shown in Figs. 7.7a,b are the extreme cases. Because predominantly low-energy fluences should be relatively rare for gamma-ray spectra, our ΔJ correction procedure should provide reasonable PM-to-PD linearity even with the existing shielding.

Fig. 7.7b. Scandiflash and Febetron measurements as in Fig. 7.7a, but expressed in terms of the energy density E_I . See the text for a complete discussion.

Summary. The analyses in this section are based on the assumption that the diode's optical response is negligible compared with its direct radiation sensitivity, which is supported by several measurements earlier in this report. As a result, the detector's output in the PM range is simply the scintillator response J^s , while the PD output can be either the scintillator response J^s or the diode response J^d , depending on whether the diode shielding block is in place, that is, whether the measurement is a calibration or actual operation. As a first step, the collimated results provide a diode normalization for a particular detector arrangement at a single energy. They are important for providing a clear demonstration of the diode's response to the calibration sources, and they also indicate that the detector's response to backgrounds at lower energies should be insignificant. In contrast, measured ΔJ values exist for many different situations, several of which represent typical operating conditions. When these measurements are compared with the

energy-dependent ratios between the calculated diode and scintillator effective areas, their systematic behavior becomes clear. The result is a set of instrumental areas and a simple prescription for recovering most of the linearity of the original detector response. For the proposed shielding, incident energy densities for high-energy gamma-ray fluences can be accurately calculated from the expression $J^c = 14.25 \log_{10} E_I + 6.9$, with $J^c = J^s$ in the PM range and $J^c = J^d - 13.6$ in the PD range. The same expression applies for the existing shielding, but with $J^c = J^d - 29$. Thus, by the end of the section, the original assumptions about the diode response have been supported by the consistency between results for many different energies and detector configurations.

7.4. ADDITIONAL MEASUREMENTS

Calibration Checks. Because the results developed in Sec. 7.3 for the diode's radiation response are crucial to our analysis, we have investigated alternative measurements that might verify our conclusions. One such test was included at the end of Chap. 6 as the absolute normalization for the Febetron source and the unshielded diode. On one hand, the measured preamplifier output of 27.5 mV led to an energy deposition of 140 MeV. On the other, the values predicted based on the calibrated source intensity from Ref. 1 and the calculated effective areas from the various source spectra were 100–400 MeV, with 130 MeV corresponding to the best-fit spectrum and providing excellent agreement. A similar comparison can be obtained for the diode when installed in the detector, as follows. At the diode output, the fixed threshold for switching from the PM to the PD channel is $V_0^d = 0.7$ mV. Given the instrument's preamplifier conversion $C_V^d = 1000$ pC/V and the silicon charge-separation energy $w_{Si} = 3.62$ eV per pair, this threshold corresponds to an energy deposition $E_D^d = V_0^d C_V^d w_{Si} = 16$ MeV. For the Febetron source with the lead shielding block removed, the PD crossover at $J^s = 64$ shifts downward by $\Delta J = 12$ to $J^s = 52$; according to Eq. 7.3c, this shifted level corresponds to an incident energy density of 2240 MeV/cm². From Fig. 5.4, for a shielded diode our best-fit effective area with the Febetron source is about 0.0027–0.0045 cm². Together, these E_I and A_{eff} values give predicted E_D^d values of $E_I A_{eff}^d = 6$ –10 MeV, which is within 50% of the observed 16-MeV result. (For later reference, this comparison also suggests that $A_{eff}^d = 0.0072$ cm² is the best value for the effective area of the shielded diode when illuminated by the Febetron source.) These two calibrations and their 50% uncertainties are typical of our absolute diode comparisons.

⁶⁰Co Source Verification. A second, very straightforward test mentioned in the Introduction involved a measurement made using an intense ⁶⁰Co source at a radiation exposure facility. The facility's calibrated source dose rate $dD/dt = 264$ R/min can be converted to an energy fluence Φ_E in MeV/cm² by using the definition of 1 R; for a mean ⁶⁰Co gamma-ray energy of 1.25 MeV, the resulting conversion factor C_R between dose in R and energy fluence in MeV/cm² is given numerically as $C_R = 2.07 \times 10^9$ MeV·cm⁻² per R. The dose rate $dD/dt = 264$ R/min therefore corresponds to an incident energy flux $\Phi_E = 9.1 \times 10^9$ MeV·cm⁻²·s⁻¹. Using the calculated diode effective area of 1.65×10^{-3} cm² for random incidence at 1.25 MeV, we obtain a predicted energy deposition rate $dE_D^d/dt = 1.5 \times 10^7$ MeV/s. For the experimental data with the diode mounted in the detector housing but with the scintillator removed, the recorded diode current of 1.04 μ A corresponds to a measured dE_D^d/dt value of 2.4×10^7 MeV/s, which is only 50% higher than the predicted value. Also important, however, is the measurement obtained with the scintillator inserted in the housing. In this case the recorded current of 1.13 μ A is only 9% greater than that for the diode alone. As indicated in Fig. 5.4, more than half of this increase (6%) can

be attributed to Compton scattering of photons from the scintillator through the diode aperture, as opposed to optical stimulation. These results suggest that the response of the diode at 1 MeV consists of at most 5% optical signal, 5–10% photons and electrons scattered from the scintillator, and 85–90% direct stimulation, whose calculated magnitude is within 50% of the measured value.

Optical Transport. As a final step toward understanding the nature of the diode response, we conclude this section with a discussion of the diode's optical behavior. Recall that measurements made with the detector mockup indicated that the diode's low-energy response was almost all radiation response, with the remainder apparently attributable to scattering from the scintillator, not optical signal. The high-energy ^{60}Co measurements just described led to the same conclusion. It is therefore reasonable to explore the reason for the apparent absence of the diode's optical response. To begin this investigation, measurements were made of the photodiode's response to pulses from a 450-nm blue-light pulser. At an incident power $P = 28 \mu\text{W}$, the measured diode output current I_d was $3.4 \mu\text{A}$. Because 100% photon conversion would give $I_\gamma = P\lambda e/(hc) = 10.1 \mu\text{A}$, the measured quantum efficiency at this wavelength is $I_d/I_\gamma = 34\%$. We can combine this value with the previous Febetron measurements to estimate the light production, transport, and detection probabilities for the scintillator and photodiode. For the measured value $\Delta J = 12$, the ratio between the induced charge for the diode's radiation versus its optical-plus-scattering components is $10^{12/14.25} = 7$; that is, only about 1/7 or 14% of the measured signal is not radiation-induced. We can interpret this result as follows. For the effective area of the diode as installed in the detector, we use the measured A_{eff}^d value of 0.0072 cm^2 obtained in the PD threshold analysis above, which indicates that a 1-MeV/cm² unit energy fluence would produce 2000 electrons directly in the diode. For the scintillator, our A_{eff}^s value of 8.8 cm^2 can be combined with a typical photon production of 5000–7000 photons/MeV and a total scintillator volume of about 530 cm^3 to yield 400–600 photons within the $0.7 \times 7.2 \text{ cm}^3$ region viewed by the diode area of 0.7 cm^2 . With perfect light collection, the diode's 34% quantum efficiency would result in an optical charge production of 140–200 photoelectrons, which makes up only 7–10% of the likely radiation production of 2000 electrons. Given that the measured 14% nonradiation fraction also includes scattering, this 7–10% optical estimate is quite reasonable. We also point out that the ^{60}Co experiment obtained a similar result at much higher energies, with the nonradiation component making up only 8% of the total scintillator-plus-diode value. Thus, the diode's optical output is in fact entirely reasonable; it only appears to be low when compared to the unexpected radiation response. Most important, the observed ratio between the diode's radiation and optical sensitivities seems to have a completely physical basis.

Summary. This short discussion presents several cases where the measured charge production in the diode can be compared with predictions based on calibrated incident energy densities, calculated effective areas, and standard charge-separation energies. The general agreement between the measurements and predictions provides additional support for the dominance of the diode's radiation response. In addition, the brief discussion of the mechanism for the diode's optical response provides a physical basis for our observation that the radiation response dominates the detector output by almost an order of magnitude.

7.5. RESPONSE SUMMARY

Collected Equations. It is useful to close this chapter by bringing together most of the important equations in one place. The results are of two main types: (1) relationships

between the instrument's digital outputs J or L and the desired input energy density E_I , and (2) relationships between the scintillator and diode responses, both shielded and unshielded. First, the addition of measurements for the Scandiflash source to those for the Febetron and Golden sources leads to a slight extension of the previous model. The source-output formula in Eq. 7.1 can be made to include the Scandiflash data if the voltage parameter V is set to the anode voltage (in kV) for the Febetron, to 19.2 kV for the Golden, or to 196.5 kV for the Scandiflash. Also, if lead bricks are used to attenuate the Scandiflash beam, the appropriate attenuation length appears to be about 520 mils. Second, for an incident gamma-ray fluence E_I with energies mainly above 200 keV, the digital output L for an operating detector (that is, without the lead shielding block covering the diodes) is related to the input energy fluence as

$$E_I = 10^{J/14.25} / K_E \quad (7.10a)$$

$$J = J_{PM} \approx J_{PD} \quad (7.10b)$$

$$J_{PM} = L_{PM} + 4.5 - 1.5H \quad (\text{for } L = L_{PM} < 64) \quad (7.10c)$$

$$J_{PD} = L_{PD} - K_c \quad (\text{for } L = L_{PD} > 64) . \quad (7.10d)$$

Here H is the PM high-voltage step (0–7), which should be set to the midrange value $H = 3$ for an operational instrument. For gamma-ray energies in the MeV range, we use $K_E = 3$ and $K_c = 17.6$. For calibration sources in the range of 50–100 keV, the appropriate values are $K_E = 2$ and $K_c = 33$ or 17.6, depending on the presence ($K_c = 33$) or absence ($K_c = 17.6$) of the inner calibration plate. The K_E divisors of 3 (high energies) or 2 (low energies) account for the 50% change in the scintillator's effective area between these two ranges. Using relationships developed at various points in this chapter, we can also write end-to-end expressions for the diode's radiation and optical responses to an incident fluence E_I . For the radiation response,

$$E_D^d = A_{\text{eff}}^d E_I \quad (7.11a)$$

$$V_D^d = (E_D^d / w_{Si}) / C_V^d \times 2 \quad (7.11b)$$

$$J^d = 14.25 \log_{10}(V_D^d / V_0^d) + 50.4 , \quad (7.11c)$$

where $w_{Si} = 3.62$ eV is the silicon charge-separation energy, $C_V^d = 1$ pC/mV is the preamplifier constant, and $V_0^d = 0.7$ mV is the diode channel's electronic threshold. The factor of 2 roughly accounts for scattering from the diode's surroundings. For the optical response,

$$E_D^s = A_{\text{eff}}^s E_I \quad (7.12a)$$

$$V_D^s = E_D^s \eta_{Sc} f_V q_e / C_V^d \times 2 \quad (7.12b)$$

$$J^s = 14.25 \log_{10}(V_D^s / V_0^d) + 50.4 , \quad (7.12c)$$

where $\eta_{Sc} = 6000$ photons/MeV is the energy-to-light conversion efficiency, f_V is the light-collection efficiency (1%), q_e is the photodiode's quantum efficiency (34%), $C_V^d = 1$ pC/mV is the diode's preamplifier constant, and $V_0^d = 0.7$ mV is the diode channel's electronic threshold. The factor of 2 in Eq. 7.12b assumes approximately equal optical and scattered contributions. These end-to-end expressions are accurate to about 50%.

Discussion. This chapter has brought together material from all previous chapters to obtain the following results:

- (1) The detector response was generalized from a dependence on incident energy density E_I to deposited energy E_D at both the macroscopic and microscopic levels, culminating in the central expressions $E_D^s = A_{\text{eff}}^s E_I$ and $J^s = 14.25 \log_{10} E_D^s - 9.2 = 14.25 \log_{10} (\epsilon_D^s (E_I/E_\gamma) A) - 9.2$. The latter expression allows the single-photon energy losses ϵ_D to be compared with measured J^s values.
- (2) Specific measurements and calculations were compared to demonstrate that leakage at the corner gap, and presumably at other points, is significant only at the relatively high energies of the calibration sources, and even then it makes up less than 10% of the total detector response.
- (3) Measurements and calculations for a collimated x-ray beam were used to establish an initial normalization for the diode's radiation sensitivity and to study the effect of different shielding options on the detector's low-energy response.
- (4) The scintillator and diode electronics use the same preamplifiers, so their response functions can be written with the relative sensitivities appearing as normalization factors, which then reduce to an energy-dependent offset between the detector's logarithmic responses in the PM and PD ranges.
- (5) The size of the offset is affected by either removing or retaining the inner calibration plate, with the conclusion that removing the plate provides more uniform energy dependence.
- (6) Combining the measured PM-to-PD offset with the calculated diode and scintillator effective areas provides energy-dependent instrumental areas for both the existing and proposed shielding.
- (7) Replacing the outer cover is important mainly for sealing leakage paths around the inner high-Z shielding at very low energies, which raises the diode and scintillator energy thresholds and gives a more uniform angular response.
- (8) Supplementary measurements using Scandiflash and ^{60}Co sources were analyzed to confirm the calculated areas at high energies, and a procedure was developed to recover most of the desired detector linearity at the inevitable cost of one decade of dynamic range.
- (9) For the proposed shielding, the incident energy densities for high-energy gamma-ray fluences can be obtained from the expression $J^c = 14.25 \log_{10} E_I + 6.9$, with $J^c = J^s$ in the PM range and $J^c = J^d - 13.6$ in the PD range. This expression also applies for the existing shielding, but with $J^c = J^d - 29$.
- (10) The energy-to-light conversion and optical transport from the scintillator to the photodiode were examined to show that the diode's optical and scattered signals together make up less than 15% of the total diode output, with the optical response being essentially unobservable. The difficulty is not that the nonradiation components are unusually small, but that the direct radiation response is unexpectedly large. All signals actually have physically reasonable magnitudes.

8. SUMMARY AND CONCLUSIONS

Introduction. Following a physical description of the detector and its system of two-layered shielding, we examined the evidence for leakage through suspected gaps between sections of high-Z shielding. Our focus was on the gap between the inner lead liner and the outer tantalum calibration plate, the openings around the photodiodes and LEDs,

and the space around the photomultipliers' lead-glass light guides. We also discussed the previous calibrations of the detector's linearity and dynamic range, and we showed new measurements that indicate that the photodiode's direct radiation response is much larger than its optical response to light produced in the scintillator, even for incident gamma rays in the MeV energy range. Because this operating mode for the diode was not expected in the design and calibration of the instrument, in this report we have devoted considerable effort to understanding and compensating for its effects.

Diode Response. Using calculated pulse-height distributions of the energy losses for photons incident on silicon detectors, we discussed the energy dependence of the photoelectric and Compton-scattering interactions and developed definitions for photon-counting versus energy-absorption detector efficiencies. By comparing efficiency calculations from the general-purpose MCNP code with those from the familiar but more limited Storm and Israel coefficients, we were able to benchmark the MCNP calculations and develop several empirical efficiency expressions. Most important, however, was the formulation of detection efficiency in terms of effective energy-absorbing areas, a concept adapted from previous work with neutron detectors and used extensively throughout this report.

Scintillator Response. Following the pattern of the diode discussion, we used measured light-output distributions to compare calculations using the DEMONS, EGS4, and MCNP codes, all of which produced equivalent results. Although detector thresholds and resolution functions were necessary for these comparisons, they are not important in applications that do not employ single-photon counting, such as our burst-mode detector. By again using effective energy-absorption areas, we were able to obtain simple MCNP detection efficiencies that were compared with the values obtained from the Storm and Israel coefficients. Using these results, we established that the scintillator's effective area at gamma-ray energies is 3-4 orders of magnitude greater than that for the diode, which left the unexpectedly large diode response unexplained.

Shielding Effectiveness. Because photoelectric absorption guarantees 100% detection efficiency for the bare scintillator and diode at low energies, the only way the instrument's response could be tailored to accept high-energy gamma rays while rejecting low-energy x-ray backgrounds is through careful shielding. This chapter compared the attenuation lengths obtained using Storm and Israel coefficients with those produced by MCNP calculations. Included were discussions of the relative shielding effectiveness of different materials and the determination of the minimum tantalum thickness equivalent to the detector's existing Al + Au cover. Substituting a thicker cover made of 20-mil tantalum should eliminate any low-energy background response, assuming the material is uniform. Because even the thickest shielding becomes transparent at high energies, however, changing the cover design does not affect the efficiencies at high energies and cannot resolve the problem of the diodes' radiation response.

MCNP Instrument Calculations. By emphasizing the different roles of the detector's inner and outer shielding layers, we readily developed calculations for the detector's energy-dependent absorption efficiency. At energies above a few hundred keV, the shielding becomes almost transparent, but toward lower energies its effectiveness increases rapidly. Below about 20-30 keV, even calculations using potent variance-reduction techniques were unable to penetrate the shielding in computer runs with 10^9 incident photons. By examining changes in shielding design, we were able to show that the scintillator's low-energy response is associated solely with leakage through gaps between shielding sections. Careful analysis confirmed that this leakage was essentially along the paths discussed in the Introduction, more or less equally around the photomultipliers' light guides and the tantalum

calibration plate. These gaps cannot be sealed in an existing detector without its complete reconstruction, nor can their exact size be predicted for a particular instrument. However, replacing the existing Al + Au outer cover with a 20-mil tantalum cover would simply and effectively eliminate the leakage through all such openings. Such a replacement cover would be even more effective at dealing with the radiation response of the diode, which was not expected to require heavy shielding in the original instrument design. With the existing shielding, the diode's high efficiency at low energies allows even a small amount of leakage through gaps in the shielding to produce large excursions in the detector's energy and angle response, which the proposed cover effectively reduces. Nothing in this chapter, however, explained the diode's apparent dominance at high energies or suggested a straightforward correction for its effect on the detector output.

Source Models. Testing our calculations against measured detector responses is made difficult by the instrument's designed sensitivity primarily to intense bursts of photons at gamma-ray energies. Many of our calibrations depend on information about the spectra produced by pulsed x-ray generators, and the major tool for estimating these spectra has been the attenuation-length analysis developed in Ref. 1. For this report, improvements in technique included using different filter materials, exploiting the different energy ranges for the diode and scintillator efficiencies, and basing our analyses on spectra from a reasonable physical model. The results confirmed that the diode response is strongly influenced by low-energy components in the beam, but measurements with an unshielded detector mockup were able to confirm the absolute efficiencies calculated using a best-fit energy spectrum. Unfortunately, these studies also indicated that the spectrum from the Febetron source that has been our calibration standard may vary significantly over time.

Actual Detector. Our final analyses used the results developed throughout the report to deal with the problems identified in the Introduction, specifically the leakage through gaps in the shielding and the diode's unexpected radiation response. First, it was necessary to rewrite the calibration expressions from Ref. 1 in terms of the energy E_D deposited in the scintillator or diode, as opposed to E_S , the incident energy density in the beam from a calibration source. This revision allowed us to connect the calibrated E_D values to the the calculated MCNP quantities. This more general expression was then combined with measurements and calculations that were aimed specifically at investigating leakage at the gap around the edge of the calibration plate. The calculations were able to reproduce both the shapes and magnitudes of the measurements, in the process providing a strong test of the detector model and the MCNP approach. The energy dependence of the calculated response showed that this leakage is serious only at the relatively high energies of the calibration sources, and even the existing Al + Au cover might be sufficient to limit the background response at lower energies. By extension, leakage through other gaps in the detector shielding should also be manageable. Next, a similar approach to the issue of diode response established our ability to calculate its absolute magnitude with an accuracy of about 50%. More important for the calibration of an actual detector was the reformulation of the response equations in terms of the relative diode and scintillator responses, whose ratio cancels out many of the instrumental unknowns and allows the detector's logarithmic response to be determined to within a single additive offset. Measurements at different energies and in different detector configurations were used to calibrate this constant, which was in turn connected to our effective-area calculations in order to establish the complete energy dependence of the diode and scintillator responses. Finally, a correction procedure was devised to recover most of the detector's original linearity, although not its complete dynamic range. Because the correction was firmly based on a comprehensive analysis of

the detector's basic physical principles, not a simplistic renormalization of its output, the results should be easily adaptable to other instruments in the series.

Discussion. Although the present study of detector response opened with an investigation of shielding leakage, most of our emphasis has been on the more complex problem of the diode radiation response. In the Introduction we speculated about the possible origins of this sensitivity, and it now appears that the response is primarily high-energy Compton interactions in the diode itself or in the nearby scintillator. No evidence of complicated coupling between photon downscattering and the diode's low-energy efficiency was ever observed. However, all our measurements were obtained with a single instrument, and small variations in shielding can potentially have large effects. In particular, much of the detector's background response at low energies is connected to either leakage through shielding gaps or to the unintentional placement of the diode's active surface precisely in the gap between the scintillator's lead liner and the diode's tantalum cover. Both of these circumstances can vary from instrument to instrument, but both can be effectively addressed by replacing the instrument's existing outer cover. Fortunately, the efficiency for signals at high energies is largely a consequence of Compton scattering in the plastic scintillator or the silicon diode, which is largely determined by their active volumes, not the surrounding shielding. As a result, with the modified shielding, the signal and background characteristics for all instruments in the series should be essentially the same. Nonetheless, any future design should consider replacing the existing silicon photodiode with an alternative active element. For example, our tests of vacuum photodiodes indicate a complete absence of radiation response but a comparable quantum efficiency and larger sensitive area.

Future Work. Much of the analysis that remains is a follow-up study to test our predictions about the replacement covers and their effect on the diode response. For all available instruments, plans are being made to remove the original inner plate and outer cover, install the replacement Ta outer cover, and recheck the dynamic range and crossover behavior for several angles at both Febetron and Scandiflash energies. This set of consistent tests for different instruments can then be analyzed as a group to provide much better estimates of the reliability of our calibrations. In addition, a major study is needed to address the question of the instrument's time response, which makes up its other important capability.

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Appendix: MCNP Input File

For readers familiar with the MCNP program, this listing gives an example of the input decks used for the detector with the aluminum-plus-gold outer cover. The first section specifies the cell parameters, which consist of (1) an index number; (2) the material number, or 0 for a void, or empty, cell; (3) the material density, in g/cm³, for nonvoid cells; (4) the cell's combinatorial definition, using the surface specifications given in the second section; (5) the cell importance, which is set to 1 for active cells and 0 to terminate a photon track; and (6) a brief comment. If possible, the cell boundaries are listed in the order x, y, z . The next section specifies the surfaces used to build the detector, along with comments, and the final section includes the source, material, and tally cards.

C	INSTRUMENT W/ AL+AU COVER; RANDOM UPPER ILLUMINATION									
C	CELL CARDS									
01	1	-1.032	+01 -03	+05 -06	+02 -04					IMP:P=1 \$SCINT
02	2	-11.35	+23 -25	+34 -36	+22 -24					IMP:P=1 \$PB BOT
03	0		+55 -58	+05 -06	+26 -28					IMP:P=1 \$AIR (VOID) TOP
04	0		+21 -23	+17 -18	+153 -152					IMP:P=1 \$PB HOLE FOR LED
05	2	-11.35	+25 -27	+33 -59	+22 -28	+57	VOL=2.0316			IMP:P=1 \$PB BCK LFT
06	2	-11.35	+23 -25	+33 -34	+22 -45					IMP:P=1 \$PB LEFT
07	2	-11.35	+23 -25	+36 -35	+22 -45					IMP:P=1 \$PB RIGHT
08	0		+23 -25	+34 -36	+24 -02					IMP:P=1 \$GAP BOT
09	1	-1.032	+55 -58	+05 -06	+04 -26					IMP:P=1 \$TOP SCINT SLICE
10	0		+23 -01	+34 -36	+02 -28					IMP:P=1 \$GAP FRNT
11	0		+03 -25	+34 -59	+02 -28	+80				IMP:P=1 \$GAP BCK LEFT
12	0		+01 -03	+34 -05	+02 -28					IMP:P=1 \$GAP LEFT
13	0		+01 -03	+06 -36	+02 -28					IMP:P=1 \$GAP RIGHT
14	3	-2.7	+38 -39	+52 -53	+43 -44					IMP:P=1 \$AL BOT
15	3	-2.7	+38 -39	+52 -53	+49 -50					IMP:P=1 \$AL TOP
16	0		+37 -38	+17 -18	+19 -20					IMP:P=1 \$LED HOLE IN AL
17	3	-2.7	+41 -42	+29 -07						IMP:P=1 \$AL PLUG LEFT TUBE
18	3	-2.7	+41 -42	+30 -08						IMP:P=1 \$AL PLUG RIGHT TUBE
19	3	-2.7	+39 -41	+57 -47						IMP:P=1 \$AL SLEEVE LEFT
20	0		+23 -25	+33 -34	+45 -28					IMP:P=1 \$ABOVE PB VOID LEFT
21	0		+23 -25	+36 -35	+45 -28					IMP:P=1 \$ABOVE PB VOID RIGHT
22	0		+38 -39	+52 -53	+44 -22					IMP:P=1 \$GAP BOT
23	0		+38 -39	+52 -53	+28 -49					IMP:P=1 \$GAP TOP
24	3	-2.7	+39 -41	+56 -46						IMP:P=1 \$AL SLEEVE RIGHT
25	0		+38 -21	+52 -53	+22 -28					IMP:P=1 \$FRONT VOID
26	0		+27 -39	+52 -59	+22 -28	+57				IMP:P=1 \$REAR VOID LEFT
27	0		+21 -27	+52 -33	+22 -28					IMP:P=1 \$LEFT VOID
28	0		+21 -27	+35 -53	+22 -28					IMP:P=1 \$RIGHT VOID
29	0		+83 -37	+133 -134	+140 -139					IMP:P=1 \$LED HOUS VOID
30	0		+40 -42	+62 -63	+50 -66					IMP:P=1 \$TOP VOID
31	0		+40 -42	+62 -52	+43 -50					IMP:P=1 \$LEFT VOID
32	0		+40 -42	+53 -63	+43 -50					IMP:P=1 \$RIGHT VOID
33	0		+85 -87	-82						IMP:P=1 \$LEFT TUBE VOID
34	0		+85 -87	-93						IMP:P=1 \$RIGHT TUBE VOID
35	3	-2.7	+37 -40	+51 -52	+43 -50					IMP:P=1 \$AL LEFT
36	3	-2.7	+37 -40	+53 -54	+43 -50					IMP:P=1 \$AL RIGHT
37	0		+41 -42	-29						IMP:P=1 \$PLUG HOLE LEFT TUBE
38	0		+41 -42	-30						IMP:P=1 \$PLUG HOLE RIGHT TUBE
39	3	-2.7	+39 -40	+52 -59	+43 -50	+47				IMP:P=1 \$BASEPLATE LEFT
40	3	-2.7	+39 -40	+59 -53	+43 -50	+46				IMP:P=1 \$BASEPLATE RIGHT
41	0		+40 -41	+52 -59	+43 -50	+47				IMP:P=1 \$VOID FRONT LEFT
42	0		+40 -41	+59 -53	+43 -50	+46				IMP:P=1 \$VOID FRONT RIGHT
43	4	-16.654	+67 -68	+60 -61	+65 -66					IMP:P=1 \$TOP TANT
44	0		+67 -68	+62 -60	+43 -64					IMP:P=1 \$SUBTANT VOID LEFT
45	0		+67 -68	+61 -63	+43 -64					IMP:P=1 \$SUBTANT VOID RIGHT

46	4	-16.654	+67 -68	+62 -60	+64 -66	IMP:P=1 \$TANT LEFT
47	4	-16.654	+67 -68	+61 -63	+64 -66	IMP:P=1 \$TANT RIGHT
48	0		+67 -68	+60 -51	+43 -65	IMP:P=1 \$AIR GAP LEFT
49	0		+67 -68	+51 -54	+50 -65	IMP:P=1 \$AIR GAP TOP
50	0		+67 -68	+54 -61	+43 -65	IMP:P=1 \$AIR GAP RIGHT
51	0		+37 -67	+62 -63	+50 -66	IMP:P=1 \$VOID LEFT TOP
52	0		+68 -40	+62 -63	+50 -66	IMP:P=1 \$VOID RIGHT TOP
53	0		+37 -67	+62 -51	+43 -50	IMP:P=1 \$VOID FRONT LEFT
54	0		+37 -67	+54 -63	+43 -50	IMP:P=1 \$VOID FRONT RIGHT
55	0		+68 -40	+62 -51	+43 -50	IMP:P=1 \$VOID BACK LEFT
56	0		+68 -40	+54 -63	+43 -50	IMP:P=1 \$VOID BACK RIGHT
57	0		+112 -37	+79 -78	+126 -74	IMP:P=1 \$SI VOID TOP
58	0		+112 -37	+79 -78	+75 -127	IMP:P=1 \$SI VOID BOT
59	3	-2.7	+70 -37	+77 -76	+72 -75	IMP:P=1 \$HOUSING BOT
60	3	-2.7	+70 -37	+77 -76	+74 -73	IMP:P=1 \$HOUSING TOP
61	4	-16.654	+71 -70	+77 -76	+72 -73	IMP:P=1 \$TANT COVER
62	0		+71 -94	+62 -63	+73 -66	IMP:P=1 \$TOP VOID
63	0		+94 -37	+62 -63	+73 -66	IMP:P=1 \$VOID FRONT TOP
64	0		+71 -37	+62 -77	+72 -73	IMP:P=1 \$VOID FRONT LEFT
65	0		+71 -37	+76 -63	+72 -73	IMP:P=1 \$VOID FRONT RIGHT
66	3	-2.7	+70 -37	+77 -79	+75 -74	IMP:P=1 \$HOUSING LEFT
67	3	-2.7	+70 -37	+78 -76	+75 -74	IMP:P=1 \$HOUSING RIGHT
68	2	-11.35	+25 -27	+59 -35	+22 -28	+56 VOL=2.0316 IMP:P=1 \$PB BACK RIGHT
69	0		+84 -86		+110 -57	IMP:P=1 \$GAP BELOW HOLDER LEFT
70	0		+84 -86		+111 -56	IMP:P=1 \$GAP BELOW HOLDER RIGHT
71	9	-1.700	+25 -88		-81	IMP:P=1 \$LIGHT GUIDE LEFT
72	9	-1.700	+25 -88		-92	IMP:P=1 \$LIGHT GUIDE RIGHT
73	0		+25 -84		+81 -57	IMP:P=1 \$HOLE ARND GUIDE LEFT
74	0		+25 -84		+92 -56	IMP:P=1 \$HOLE ARND GUIDE RIGHT
75	7	-8.0	+84 -89		+81 -80	IMP:P=1 \$MAG SHIELD LEFT
76	7	-8.0	+84 -89		+92 -91	IMP:P=1 \$MAG SHIELD RIGHT
77	0		+27 -39	+59 -53	+22 -28	+56 IMP:P=1 \$REAR VOID RIGHT
78	8	-2.2	+87 -89		-81	IMP:P=1 \$TUBE BACK LEFT
79	8	-2.2	+87 -89		-92	IMP:P=1 \$TUBE BACK RIGHT
80	0		+84 -86		+80 -110	IMP:P=1 \$GAP BELOW HOLDR LEFT
81	0		+84 -86		+91 -111	IMP:P=1 \$GAP BELOW HOLDR RIGHT
82	5	-1.18	+86 -41		+80 -57	IMP:P=1 \$HOLDER OUT LEFT
83	5	-1.18	+86 -41		+91 -56	IMP:P=1 \$HOLDER OUT RIGHT
84	5	-1.18	+89 -90		+31 -80	IMP:P=1 \$HOLDER BACK LEFT
85	5	-1.18	+89 -90		+32 -91	IMP:P=1 \$HOLDER BACK RIGHT
86	0		+90 -41		-80	IMP:P=1 \$VOID ELEC LEFT
87	0		+90 -41		-91	IMP:P=1 \$VOID ELEC RIGHT
88	8	-2.2	+84 -85		-81	IMP:P=1 \$TUBE FRONT LEFT
89	8	-2.2	+84 -85		-92	IMP:P=1 \$TUBE FRONT RIGHT
90	8	-2.2	+85 -87		+82 -81	IMP:P=1 \$TUBE WALL LEFT
91	8	-2.2	+85 -87		+93 -92	IMP:P=1 \$TUBE WALL RIGHT
92	0		+03 -25	+59 -36	+02 -28	+91 IMP:P=1 \$GAP BCK RIGHT
93	6	-2.33	+03 -25		-80	IMP:P=1 \$SI COOKIE LEFT
94	6	-2.33	+03 -25		-91	IMP:P=1 \$SI COOKIE RIGHT
95	0		+41 -42	+52 -59	+43 -50	+07 IMP:P=1 \$VOID BACK LEFT
96	0		+41 -42	+59 -53	+43 -50	+08 IMP:P=1 \$VOID BACK RIGHT
97	2	-11.35	+01 -55	+05 -06	+04 -28	IMP:P=1 \$PB SHIM FRONT
98	2	-11.35	+58 -03	+05 -06	+04 -28	IMP:P=1 \$PB SHIM BACK
99	0		+112 -37	+79 -119	+127 -126	IMP:P=1 \$SI VOID LEFT
100	0		+112 -120	+119 -129	+127 -126	+122 IMP:P=1 \$SI OUT LEFT
101	0		+112 -120	+130 -128	+127 -126	+123 IMP:P=1 \$SI OUT RIGHT
102	3	-2.7	+42 -101	+105 -102	+43 -137	IMP:P=1 \$REAR COVER
103	3	-2.7	+37 -38	+52 -17	+43 -50	+11 IMP:P=1 \$AL FRONT LEFT
104	3	-2.7	+37 -38	+18 -53	+43 -50	+12 IMP:P=1 \$AL FRONT RIGHT
105	3	-2.7	+37 -38	+17 -18	+20 -50	IMP:P=1 \$AL CENTER UP
106	3	-2.7	+37 -38	+17 -18	+43 -19	IMP:P=1 \$AL CENTER DOWN
107	0		+117 -38		-11	IMP:P=1 \$FRONT LEFT AL HOLE
108	0		+117 -38		-12	IMP:P=1 \$FRONT RIGHT AL HOLE
109	2	-11.35	+21 -23	+33 -17	+22 -28	+11 VOL=2.366 IMP:P=1 \$PB FRNT LEFT

110	2	-11.35	+21 -23	+18 -35	+22 -28	+12	VOL=2.366	IMP:P=1 \$PB RONT RIGHT
111	2	-11.35	+21 -23	+17 -18	+152 -28			IMP:P=1 \$PB CENTER UP
112	2	-11.35	+21 -23	+17 -18	+22 -153			IMP:P=1 \$PB CENTER DOWN
113	0		+21 -23		-143			IMP:P=1 \$FRONT LEFT PB HOLE
114	6	-2.33	+21 -23		-144			IMP:P=1 \$FRONT RIGHT PB HOLE
115	6	-2.33	+48 -118		-09			IMP:P=1 \$LEFT DIODE
116	6	-2.33	+48 -118		-10			IMP:P=1 \$RIGHT DIODE
117	0		+142 -71	+103 -104	+107 -66			IMP:P=1 \$FRONT VOID
118	0		+94 -42	+103 -62	+43 -66			IMP:P=1 \$LEFT TOP VOID
119	0		+94 -42	+63 -104	+43 -66			IMP:P=1 \$RIGHT TOP VOID
120	0		+94 -101	+105 -102	+108 -43			IMP:P=0 \$VOID BOX TO INSTR
121	3	-2.7	+94 -101	+105 -102	+109 -108			IMP:P=1 \$SELEC BOX TOP
122	3	-2.7	+98 -101	+105 -102	+100 -109			IMP:P=1 \$SELEC BOX BACK
123	3	-2.7	+96 -98	+105 -102	+100 -99			IMP:P=1 \$SELEC BOX BOT
124	3	-2.7	+95 -96	+105 -102	+100 -106			IMP:P=1 \$SELEC BOX FRONT
125	3	-2.7	+95 -94	+105 -102	+106 -107			IMP:P=0 \$SELEC SHELF FRON TOP
126	3	-2.7	+97 -94	+105 -102	+109 -106			IMP:P=0 \$SELECT SHL REAR
127	3	-2.7	+96 -97	+105 -103	+99 -106			IMP:P=1 \$SELEC SHELF LEFT
128	3	-2.7	+96 -97	+104 -102	+99 -106			IMP:P=1 \$SELECT SHELF RIGHT
129	3	-2.7	+97 -98	+105 -103	+99 -109			IMP:P=1 \$SELECT BOX LEFT
130	3	-2.7	+97 -98	+104 -102	+99 -109			IMP:P=1 \$SELECT BOX RIGHT
131	0		+71 -94	+103 -104	+107 -72			IMP:P=1 \$VOID BOT FRONT
132	5	-0.45	+97 -98	+103 -104	+99 -109			IMP:P=1 \$BOX INSIDE VOID REAR
133	5	-0.45	+96 -97	+103 -104	+99 -106			IMP:P=1 \$BOX INSIDE VOID FRONT
134	0		+89 -90		-31			IMP:P=1 \$TUBE HOLDER VOID LEFT
135	0		+89 -90		-32			IMP:P=1 \$SS LG INSERT LEFT
136	7	-8.0	+88 -84		-81			IMP:P=1 \$SS LG INSERT RIGHT
137	7	-8.0	+88 -84		-92			IMP:P=1 \$SI VOID RIGHT
138	0		+112 -37	+128 -78	+127 -126			IMP:P=1 \$TA HOUSING LEFT
139	4	-16.654	+113 -120		+11 -122			IMP:P=1 \$TA HOUSING RIGHT
140	4	-16.654	+113 -120		+12 -123			IMP:P=1 \$CU HOUSING BACK LEFT
141	10	-8.96	+116 -117		-13			IMP:P=1 \$CU HOUSING BACK RIGHT
142	10	-8.96	+116 -117		-14			IMP:P=1 \$VOID INSIDE BACK LEFT
143	0		+118 -116		-13			IMP:P=1 \$VOID INSIDE BACK RIGHT
144	0		+118 -116		-14			IMP:P=1 \$OUT FLA SUPP LEFT
145	0		+15 -121	+119 -129	+127 -126 +131			IMP:P=1 \$OUTER FLA SUPP LEFT
146	0		+15 -121	+130 -128	+127 -126 +132			IMP:P=1 \$VOID INSIDE FRNT LEFT
147	0		+115 -48		-13			IMP:P=1 \$VOID INSIDE FRNT RIGHT
148	0		+115 -48		-14			IMP:P=1 \$CU HOUSING FRONT LEFT
149	10	-8.96	+114 -115		-124			IMP:P=1 \$CU HOUSING FRONT RIGHT
150	10	-8.96	+114 -115		-125			IMP:P=1 \$CU-TA GAP LEFT
151	0		+113 -114		-124			IMP:P=1 \$CU-TA GAP RIGHT
152	0		+113 -114		-125			IMP:P=1 \$TA CAP LEFT
153	4	-16.654	+112 -113		-122			IMP:P=1 \$TA CAP RIGHT
154	4	-16.654	+112 -113		-123			IMP:P=1 \$VOID FRONT
155	0		+94 -37	+62 -63	+43 -72			IMP:P=1 \$VOID IN FRNT SI HOUS
156	0		+70 -112	+79 -78	+75 -74			IMP:P=1 \$CU SIDE HOUSING REAR
157	10	-8.96	+16 -117	+13 -124				IMP:P=1 \$CU SIDE HOUSING REAR
158	10	-8.96	+16 -117	+14 -125				IMP:P=1 \$CU FLANGE LEFT
159	10	-8.96	+15 -16	+13 -131				IMP:P=1 \$CU FLANGE RIGHT
160	10	-8.96	+15 -16	+14 -132				IMP:P=1 \$INNER FLANGE SUPP LEFT
161	5	-1.18	+16 -37	+124 -131				IMP:P=1 \$INNER FLANGE SUPP RIGHT
162	5	-1.18	+16 -37	+125 -132				IMP:P=1 \$OUTER FLA SUPP LEFT
163	5	-1.18	+121 -37	+119 -129	+127 -126 +131			IMP:P=1 \$OUTER FLA SUPP RIGHT
164	5	-1.18	+121 -37	+130 -128	+127 -126 +132			IMP:P=1 \$CU SDE HOUS FRNT LEFT
165	10	-8.96	+115 -15	+13 -124				IMP:P=1 \$CU SDE HOUS FRNT RIGHT
166	10	-8.96	+115 -15	+14 -125				IMP:P=1 \$HOUSING VOID LEFT
167	0		+113 -15	+124 -11				IMP:P=1 \$HOUSING VOID RIGHT
168	0		+113 -15	+125 -12				IMP:P=1 \$TA FLANGE LEFT
169	4	-16.654	+120 -15	+119 -129	+127 -126 +11			IMP:P=1 \$TA FLANGE RIGHT
170	4	-16.654	+120 -15	+130 -128	+127 -126 +12			IMP:P=1 \$VOID IN AL LEFT
171	0		+37 -117	+124 -11				IMP:P=1 \$VOID IN AL RIGHT
172	0		+37 -117	+125 -12				IMP:P=1 \$CENTRAL SI VOID LEFT
173	0		+48 -118	+09 -13				

174	0	+48 -118	+10 -14		IMP:P=1 \$CENTRAL SI VOID RIGHT
175	0	+71 -94	+103 -62	+72 -66	IMP:P=1 \$LEFT VOID
176	0	+71 -94	+63 -104	+72 -66	IMP:P=1 \$RIGHT VOID
177	0	+112 -69	+129 -130	+127 -126	IMP:P=1 \$LED HOUS VOID FRONT
178	0	+69 -37	+129 -135	+127 -126	IMP:P=1 \$LED HOUS VOID LEFT
179	0	+69 -37	+136 -130	+127 -126	IMP:P=1 \$LED HOUS VOID RIGHT
180	3 -2.7	+94 -42	+105 -103	+43 -137	IMP:P=1 \$LEFT TOP OUTER SHLD
181	3 -2.7	+94 -42	+104 -102	+43 -137	IMP:P=1 \$RIGHT TOP OUTER SHLD
182	3 -2.7	+69 -83	+135 -136	+140 -139	IMP:P=1 \$LED HOUSING FRONT
183	3 -2.7	+83 -37	+135 -133	+140 -139	IMP:P=1 \$LED HOUS LEFT
184	3 -2.7	+83 -37	+134 -136	+140 -139	IMP:P=1 \$LED HOUS RIGHT
185	3 -2.7	+69 -37	+135 -136	+139 -126	IMP:P=1 \$LED HOUS TOP
186	3 -2.7	+69 -37	+135 -136	+127 -140	IMP:P=1 \$LED HOUS BOT
187	3 -2.7	+141 -42	+103 -104	+138 -137	IMP:P=1 \$TOP COVER
188	0	+142 -42	+103 -104	+66 -138	IMP:P=1 \$TOP VOID
189	0	+95 -146	+148 -149	+107 -145	IMP:P=1 \$FRONT VOID
190	3 -2.7	+141 -142	+103 -104	+107 -138	IMP:P=1 \$FRONT COVER
191	3 -2.7	+141 -94	+105 -103	+107 -137	IMP:P=1 \$LEFT COVER PIECE
192	3 -2.7	+141 -94	+104 -102	+107 -137	IMP:P=1 \$RIGHT COVER PIECE
193	2 -11.35	+21 -23		+143 -11	IMP:P=1 \$FRNT LEFT PB HLE BUSH
194	2 -11.35	+21 -23		+144 -12	IMP:P=1 \$FRNT RGHT PB HLE BUSH
195	11 -19.31	+141 -101	+105 -102	+137 -145	IMP:P=1 \$TOP GOLD
196	11 -19.31	+146 -141	+105 -102	+107 -145	IMP:P=1 \$FRONT GOLD
197	11 -19.31	+101 -147	+105 -102	+100 -145	IMP:P=1 \$BACK GOLD
198	11 -19.31	+146 -147	+148 -105	+107 -145	IMP:P=1 \$LEFT GOLD
199	11 -19.31	+146 -147	+102 -149	+107 -145	IMP:P=1 \$RIGHT GOLD
200	11 -19.31	+146 -147	+148 -105	+108 -107	IMP:P=1 \$LEFT AU LOWER
201	11 -19.31	+146 -147	+102 -149	+108 -107	IMP:P=1 \$RIGHT AU LOWER
202	0	+95 -147	+148 -105	+100 -108	IMP:P=1 \$LEFT AU LOWER VOID
203	0	+95 -147	+102 -149	+100 -108	IMP:P=1 \$RIGHT AU LOWER VOID
204	0	+95 -146	+148 -105	+108 -107	IMP:P=1 \$LEFT FR AU VOID
205	0	+95 -146	+102 -149	+108 -107	IMP:P=1 \$RIGHT FR AU VOID
998	0	-999 #(+95 -147 +148 -149 +100 -145)			IMP:P=1 \$SURROUND
999	0	+999			IMP:P=0

C SURFACE CARDS NO

01	PX	-3.575		\$SC FR
02	PZ	-3.702		\$SC BOT
03	PX	+3.575		\$SC BACK
04	PZ	+3.664		\$SC TOP
05	PY	-4.972		\$SC LEFT
06	PY	+4.972		\$SC RIGHT
07	C/X	-2.35 0. 2.301		\$BACK FLANGE OUT RADIUS LEFT
08	C/X	+2.35 0. 2.301		\$BACK FLANGE OUT RADIUS RIGHT
09	C/X	-2.73 1.484 0.564		\$SI DI LEFT
10	C/X	+2.73 1.484 0.564		\$SI DI RIGHT
11	C/X	-2.73 1.484 1.295		\$DIODE TA COVER ID LEFT
12	C/X	+2.73 1.484 1.295		\$DIODE COVER ID RIGHT
13	C/X	-2.73 1.484 1.256		\$DIODE CASE INNER LEFT
14	C/X	+2.73 1.484 1.256		\$DIODE CASE INNER RIGHT
15	PX	-4.338		\$SI BACK/HO FRONT/TA FLANGE REAR
16	PX	-4.237		\$SI HOLDER REAR
17	PY	-0.508		\$LED WINDOW LEFT
18	PY	+0.508		\$LED WINDOW RIGHT
19	PZ	+0.073		\$LED WINDOW BOTTOM
20	PZ	+2.893		\$LED WINDOW TOP
21	PX	-3.701		\$PB SHIELD FRN OUTER
22	PZ	-3.823		\$PB SHIELD BOT OUTER
23	PX	-3.620		\$PB SHIELD FRN INNER
24	PZ	-3.742		\$PB SHIELD BOT INNER
25	PX	+3.620		\$PB SHIELD BCK INNER
26	PZ	+3.740		\$PB SHIELD TOP INNER
27	PX	+3.701		\$PB SHIELD BCK OUTER

28	PZ	+3.745	\$PB SHIELD TOP OUTER
29	C/X	-2.35 0. 1.483	\$BACK FLANGE IN RADIUS LEFT
30	C/X	+2.35 0. 1.483	\$BACK FLANGE IN RADIUS RIGHT
31	C/X	-2.35 0. 1.219	\$PLAS TUBE HOLDER INNER RAD L
32	C/X	+2.35 0. 1.219	\$PLAS TUBE HOLDER INNER RAD R
33	PY	-5.063	\$PB SHIELD LFT OUTER
34	PY	-4.992	\$PB SHIELD LFT INNER
35	PY	+5.063	\$PB SHIELD RGT OUTER
36	PY	+4.992	\$PB SHIELD RGT INNER
37	PX	-4.064	\$OUTER AL SHIELD FR OUT
38	PX	-3.746	\$OUTER AL SHIELD FR IN
39	PX	+3.746	\$OUTER AL SHIELD BCK IN
40	PX	+4.064	\$OUTER AL SHIELD BCK OUT
41	PX	+11.720	\$OUTER AL SHIELD FAR BACK INNER
42	PX	+12.395	\$OUTER AL SHIELD FAR BACK OUTER
43	PZ	-3.939	\$OUTER AL SHIELD BOT OUT
44	PZ	-3.863	\$OUTER AL SHIELD BOT IN
45	PZ	+3.33	\$SIDE PB UPPER
46	C/X	+2.35 0. 2.176	\$OUTER TUBE SHIELD RADIUS RIGHT
47	C/X	-2.35 0. 2.176	\$OUTER TUBE SHIELD RADIUS LEFT
48	PX	-4.318	\$DIODE ACTIVE SURFACE (300MU)
49	PZ	+3.795	\$OUTER SHIELD TOP IN
50	PZ	+4.113	\$OUTER SHIELD TOP OUT
51	PY	-5.398	\$OUTER SHIELD LFT OUT
52	PY	-5.080	\$OUTER SHIELD LFT IN
53	PY	+5.080	\$OUTER SHIELD RGT IN
54	PY	+5.398	\$OUTER SHIELD RGT OUT
55	PX	-3.064	\$SCINT SHIM NOTCH FRONT
56	C/X	+2.35 0. 2.100	\$INNER TB SHIELD RADIUS RIGHT
57	C/X	-2.35 0. 2.100	\$INNER TB SHIELD RADIUS LEFT
58	PX	+3.258	\$SCINT SHIM NOTCH REAR
59	PY	0.0	\$DIVIDER
60	PY	-5.417	\$TANT LEFT INNER
61	PY	+5.417	\$TANT RIGHT INNER
62	PY	-5.467	\$TANT LEFT OUTER
63	PY	+5.467	\$TANT RIGHT OUTER
64	PZ	+2.564	\$TANT LOWER
65	PZ	+4.138	\$TANT TOP LOWER
66	PZ	+4.189	\$TANT TOP UPPER
67	PX	-3.144	\$TANT FRONT
68	PX	+3.398	\$TANT BACK
69	PX	-4.445	\$LED COVER FRONT
70	PX	-5.779	\$SI HOU TA FRONT INNER
71	PX	-5.829	\$SI HOU TA FRONT OUTER
72	PZ	-0.802	\$SI HOU LOWER OUTER
73	PZ	+3.770	\$SI HOU UPPER OUTER
74	PZ	+3.529	\$SI HOU UPPER INNER
75	PZ	-0.561	\$SI HOU LOWER INNER
76	PY	+4.699	\$SI HOU RIGHT OUTER
77	PY	-4.699	\$SI HOU LEFT OUTER
78	PY	+4.458	\$SI HOU RIGHT INNER
79	PY	-4.458	\$SI HOU LEFT INNER
80	C/X	-2.35 0. 1.949	\$MAG SHIELD OUTER LEFT
81	C/X	-2.35 0. 1.930	\$MAG SHIELD INNER LEFT
82	C/X	-2.35 0. 1.83	\$TUBE INNER LEFT
83	PX	-4.343	\$LED COVER INNER
84	PX	+4.0763	\$MAG SHIELD FRNT/TUBE FACE OUTER
85	PX	+4.2477	\$TUBE FACE INNER
86	PX	+8.5026	\$TUBE HOLDER FRONT
87	PX	+10.268	\$TUBE REAR INNER
88	PX	+4.0636	\$LIGHT GUIDE REAR (SS)
89	PX	+10.433	\$TUBE REAR OUTER
90	PX	+10.585	\$TUBE HOLDER REAR
91	C/X	+2.35 0. 1.949	\$MAG SHIELD OUTER RIGHT

92	C/X	+2.35	0.	1.930	\$MAG SHIELD INNER RIGHT
93	C/X	+2.35	0.	1.83	\$TUBE INNER RIGHT
94	PX	-5.385			\$SELECT SHELF REAR OUT
95	PX	-8.5014			\$SELECT SHELF FRONT OUT
96	PX	-8.4379			\$SELECT SHELF FRONT INSIDE
97	PX	-5.4358			\$SELECT SHELF REAR INSIDE
98	PX	+12.396			\$SELECT BOX REAR INSIDE
99	PZ	-13.032			\$SELECT BOX BOTTOM INS
100	PZ	-13.0826			\$SELECT BOX BOTTOM OUTS
101	PX	+12.4586			\$SELECT BOX REAR OUT
102	PY	+10.0838			\$SELECT BOX RIGHT OUT
103	PY	-10.033			\$SELECT BOX LEFT IN
104	PY	+10.033			\$SELECT BOX RIGHT IN
105	PY	-10.0838			\$SELECT BOX LEFT OUT
106	PZ	-1.4238			\$SELECT BOX SHELF TOP IN
107	PZ	-1.373			\$SELECT BOX SHELF TOP OUT
108	PZ	-3.964			\$SELECT BOX TOP OUT
109	PZ	-4.0148			\$SELECT BOX TOP INS
110	C/X	-2.35	0.	2.082	\$TUBE HOLDER INNER RAD L
111	C/X	+2.35	0.	2.082	\$TUBE HOLDER INNER RAD R
112	PX	-4.920			\$TA HOUS FRONT OUT
113	PX	-4.869			\$TA HOUS FRONT INNER
114	PX	-4.775			\$CU HOUS FRONT OUT
115	PX	-4.755			\$CU HOUS FRONT IN
116	PX	-3.876			\$DIODE CU INNER BACK
117	PX	-3.856			\$DIODE CU OUTER BACK
118	PX	-4.2880			\$SI DIODE FRONT
119	PY	-4.343			\$TA FLANGE OUT LEFT
120	PX	-4.389			\$TA SI CAP FLANGE FRONT
121	PX	-4.318			\$SI PLAS FLANGE FRONT
122	C/X	-2.73	1.484	1.3458	\$TA SI CAP OUTER RAD LEFT
123	C/X	+2.73	1.484	1.3458	\$TA SI CAP OUTER RAD RIGHT
124	C/X	-2.73	1.484	1.2764	\$SI BUSHING ID/DIODE CASE LEFT
125	C/X	+2.73	1.484	1.2764	\$SI BUSHING ID/DIODE CASE RIGHT
126	PZ	+3.097			\$TA FLANGE UPPER
127	PZ	-0.129			\$TA FLANGE LOWER
128	PY	+4.343			\$TA FLANGE OUT RIGHT
129	PY	-1.117			\$TA FLANGE INNER LEFT
130	PY	+1.117			\$TA FLANGE INNER RIGHT
131	C/X	-2.73	1.484	1.492	\$SI BUSHING ID LEFT
132	C/X	+2.73	1.484	1.492	\$SI BUSHING ID RIGHT
133	PY	-0.851			\$LED HOUS INNER LEFT
134	PY	+0.851			\$LED HOUS INNER RIGHT
135	PY	-1.080			\$LED HOUS OUTER LEFT
136	PY	+1.080			\$LED HOUS OUTER RIGHT
137	PZ	+4.6574			\$AL BOX TOP OUT
138	PZ	+4.5939			\$AL BOX TOP IN
139	PZ	+2.867			\$LED HOUS INNER UP
140	PZ	+0.099			\$LED HOUS INNER BOT
141	PX	-6.7438			\$AL HOUSING FRONT OUT
142	PX	-6.6803			\$AL HOUS FRONT INNER
143	C/X	-2.73	1.484	0.476	\$HOLE IN PB/AL FOR SI DI LEFT
144	C/X	+2.73	1.484	0.476	\$HOLE IN PB/AL FOR SI DI RIGHT
145	PZ	+4.6676			\$AU LAYER TOP
146	PX	-6.7540			\$AU LAYER FRONT OUT
147	PX	+12.4688			\$AU LAYER REAR OUT
148	PY	-10.0940			\$AU LAYER LEFT OUT
149	PY	+10.0940			\$AU LAYER RIGHT OUT
152	PZ	+2.33			\$PB HOLE DIODE TOP
153	PZ	+1.06			\$PB HOLE DIODE BOT
999	S	2	0	-4.2 17.1	

C DATA CARDS
 CUT:P 1E9 .001
 PHYS:P 10 1
 MODE P
 SDEF SUR=999 NRM=-1 ERG=.056 DIR=D1 \$SOURCE
 SI1 0 1
 SP1 0 1
 M1 1000 1.104 6000 1. \$SCINTILLATOR
 M2 82000 1. \$LEAD
 M3 13000 1. \$ALUMINUM
 M4 73000 1. \$TANTALUM
 M5 1000 8. 6000 5. 8000 2. \$PLASTIC
 M6 14000 1. \$SILICON
 M7 14000 .01 24000 .19 25000 .02 \$STEEL
 26000 .68 28000 .10
 M8 14000 1. 8000 2. \$GLASS
 M9 14000 1. 8000 2. 82000 1. \$LEAD GLASS
 M10 29000 1. \$COPPER
 M11 79000 1. \$GOLD
 NPS 15E5 \$NUMBER OF PHOTONS
 F16:P (115 116) \$DIODE HEATING TALLY
 F6:P (1 9) \$SCINTILLATOR HEATING TALLY
 PRDMP 0 -5 0 2 \$DUMP TAPE
 WWG 6 998 0 0 0 0 \$WEIGHT-WINDOW GENERATOR