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Low Energy Photon Filter Box Optimization Study for the Gamma Irradiation Facility (GIF)

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ABSTRACT

As a follow-up to results presented at the 16th International Symposium on Reactor Dosimetry, a new set of low energy photon filter box designs were evaluated for potential testing at the Gamma Irradiation Facility in Sandia National Laboratories' Technical Area V. The goal of this filter box design study is to produce the highest fidelity gamma ray test environment for electronic parts. Using Monte Carlo coupled photon/electron transport, approximately a dozen different designs were evaluated for the effectiveness in reducing the dose enhancement in a silicon sensor. The completion of this study provides the Radiation Metrology Laboratory staff with a starting point for experimental test plans that could lead to improvement in the gamma ray test environment at the Gamma Irradiation Facility.

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1. INTRODUCTION

Experimenters in Sandia National Laboratories photon and mixed (neutron/gamma) field test facilities rely on the calibrated thermoluminescent dosimeters (TLDs) to provide accurate measurements of the photon dose. One of the principal means of reducing the gamma dose measurement uncertainty in Sandia National Laboratories' (SNL) reactor environments is careful calibration of the CaF_2:Mn TLDs used in the test environment [1]. Almost all Co-60 gamma fields used for TLD calibration have a low energy photon component that hampers the ability to obtain high quality calibrations, and the Gamma Irradiation Facility (GIF) at SNL is no different. The scattered photons that make up the low energy photon component are a principal source of measurement error for the TLD calibration. The low energy photon component also contributes significantly to the difficulty in accurately translating results provided by dosimetry results to the radiation dose experienced by the devices under test. ASTM E1249, Standard Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronics Devices Using Co-60 Sources, describes a method that utilizes photon spectrum filter boxes to enclose devices under test that can reduce the measurement error during TLD calibration as well as during normal radiation testing of electronic components in the gamma field [2].

1.1. Background

The dosimetry error created by low energy photon dose enhancement is minimized by the use of a lead/aluminum (Pb/Al) filter box [2]. The dose enhancement reduction is accomplished by photon spectrum hardening, and the spectrum hardening is accomplished by irradiating the TLDs (or device under test) in filter boxes that have an outer layer of between 1.5 mm and 2.0 mm of Pb and an inner of between 0.7 mm and 1.0 mm of Al [2]. When dosimetrists at the Radiation Metrology Laboratory (RML) noted that the standard Pb/Al filter boxes in use at the GIF (1.6 mm of Pb, 3.2 mm of Al) were outside the guidelines of the standard, an optimization study was performed to determine if the current filter boxes might be improved [3]. The optimization study used a silicon sensor that is representative of a CMOS-7 technology, and the stack-up of materials for the silicon sensor is found in Table 1.

1.2. Previous Results

After extensive calculations with MCNP6 [4], three-layer filter box designs performed no better than two-layer designs [3]. Thus, the future work portion of the optimization paper highlighted a series of additional filter box design options that were based on two-layer designs. This report is a follow-up to the calculations performed at 1 meter from the GIF Cell 3 single pin source. As with other studies, the previous work on Co-60 filter boxes at the GIF defined the dose enhancement factor (DEF) as the ratio of the absorbed dose to the electronic equilibrium dose (that is, kerma) at the location or material of interest [3], [5] – [7]. Building on DePriest *et al.* [3], the filter box effectiveness metric for this study will be the silicon DEF in the active silicon layer. The DEF values obtained during the optimization study at 1 meter from the source are found in Table 2.

The previous work suggested examining lead/copper, bismuth/copper, tantalum/aluminum, and tantalum/copper filter box designs as well as additional lead/aluminum and tungsten/copper designs. This document provides a description and summary of the examination of these filter box designs.

Table 1 – Stack-up of Materials for CMOS-7 Silicon Sensor

Disc Number	Material Layer	Disc Thickness (cm)
1	Tin/Lead (63/37) solder	0.06
2	Copper	0.0015
3	Nickel	0.0005
4	Gold	0.00007
5	BT-Epoxy Laminate	0.036
6	Copper	0.0015
7	Nickel	0.0005
8	Gold	0.00007
9	Ablebond 8361J	0.003
10	P-type Silicon	0.03
11	Silicon Oxide (SiO_2)	0.00002
12	Active Silicon Layer	0.000025
13	Tungsten	0.000085
14	Silicon Oxide (SiO2) Passivation Layer	0.000838
15	Plastic Encapsulation Layer	0.0866

Table 2 – GIF Cell 3 Dose Enhancement Factors Reported in Reference [3]

Filter Box Details	Density Thickness (g/cm^2)	DEF in Active Silicon Layer	Dose Reduction Ratio
None	0.00	2.02	---
*1.59 mm Pb / 3.18 mm Al	2.66	1.34	0.57
1.52 mm W / 1.60 mm Al	3.37	1.43	0.59
1.27 mm W / 1.25 mm Cu	3.57	1.27	0.52
1.52 mm W / 0.75 mm Cu	3.61	1.23	0.50
1.25 mm Cu / 3.18 mm Al	1.98	1.60	0.75
3.18 mm Cu / 3.18 mm Al	3.70	1.52	0.67
***This is the current filter box utilized by the RML.**			

2. CALCULATION DESCRIPTION

Over the past 17 years, staff members in the Applied Nuclear Technologies organization in Tech Area V (TA-V) at SNL have developed and improved a MCNP radiation transport model of GIF Cell 3. Using the latest version of the transport model, Filter box designs were placed at a location 1.0 meter from the location used for the single pin source of GIF Cell 3. Figure 1 shows an overhead view of the radiation transport model while Figure 2 displays the side view. Figure 3 provides an enlarged view to show the source pin details and the relationship between the source and the filter box. The filter box design is a 10 cm cube of air with the filtering materials of the appropriate thickness layered around the cube. The low atomic number material is the first layer around the air followed by the high atomic number material.

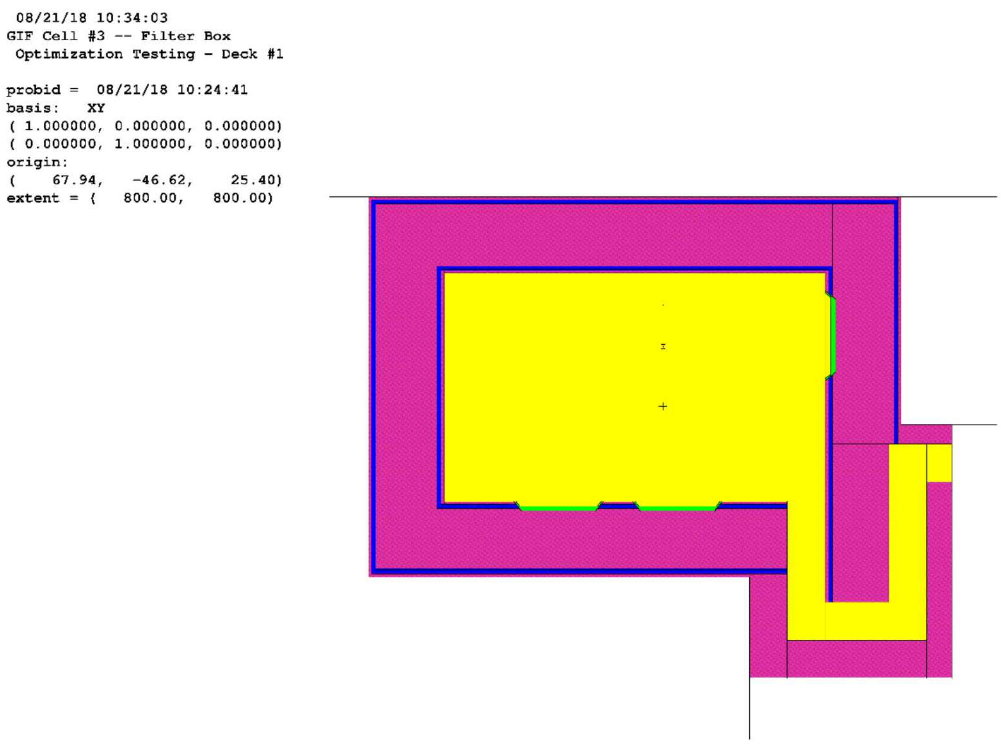

Figure 1 – Overhead View of GIF Cell 3 MCNP Model

The silicon sensor based on CMOS-7 technology was modeled and placed inside the filter box. The silicon sensor was oriented such that the tungsten layer closest to the active silicon layer faced the source pin based on the recommendations found in ASTM E1249 [2]. In addition to the silicon sensor, a 1 cm radius sphere of air was modeled inside the filter box to tally the energy spectrum of the photons that are transported through the box.

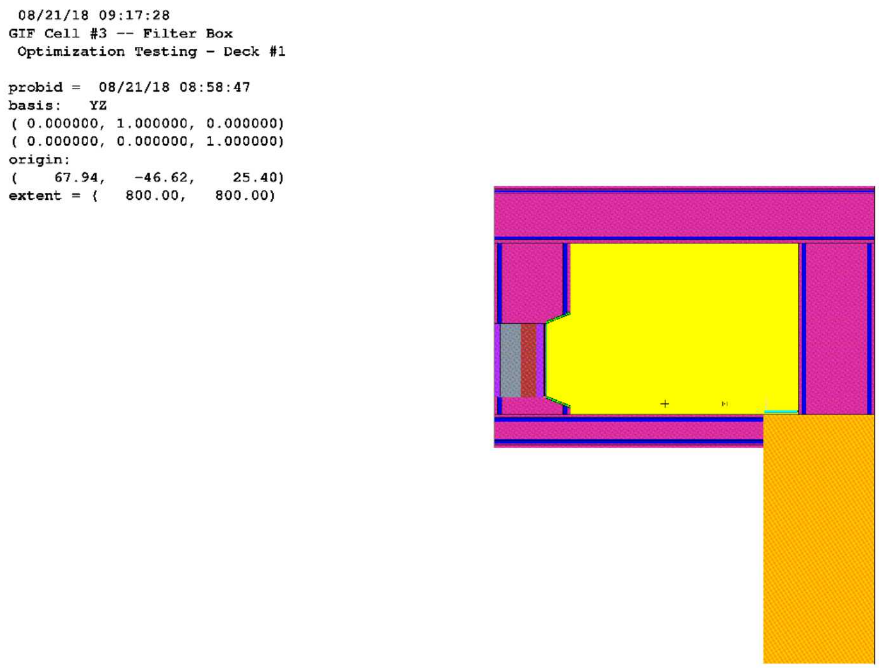

Figure 2 – Side View of GIF Cell 3 MCNP Model

Once the modeling was completed, a full 3D coupled photon/electron transport calculation was performed with MCNP6 using the Serrano High Performance Computing (HPC) platform at SNL. To assess the DEF in the silicon sensor (and other metrics), the following quantities were tallied for each of the filter boxes under study:

- Average silicon photon kerma in the active silicon region
- Energy deposition (collision heating) in the active silicon region
- Energy-dependent photon fluence in the scoring sphere

The Monte Carlo simulations were run until the energy deposition tally (dose tally) obtained a relative error of between 4 to 6%. The relative errors for the other tallies were typically less than 1% as the dose tally had the most difficulty in convergence. The filter box configurations examined in this report are found in Table 3.

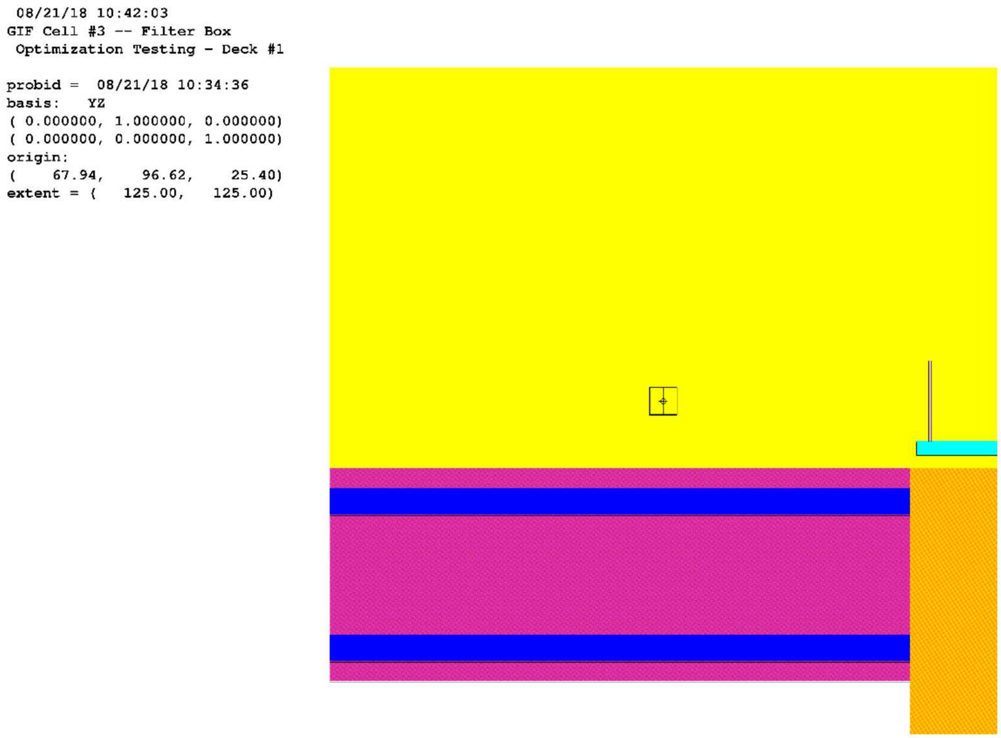

Figure 3 – Enlarged Side View of GIF Cell 3 MCNP Model with Filter Box

Table 3 – Filter Box Details

Filter Box Details	Density Thickness (g/cm^2)
1.587 mm Pb / 0.686 mm Cu	2.42
1.587 mm Pb / 0.813 mm Cu	2.53
1.587 mm Pb / 1.016 mm Cu	2.71
1.981 mm Pb / 0.813 mm Cu	2.98
2.387 mm Pb / 0.813 mm Cu	3.44
3.175 mm Pb / 0.813 mm Cu	4.33
1.5875 mm Bi / 0.813 mm Cu	2.28
3.175 mm Bi / 0.813 mm Cu	3.82
4.7625 mm Bi / 0.813 mm Cu	5.37
1.016 mm Ta / 0.813 mm Cu	2.39
1.270 mm Ta / 0.813 mm Cu	2.81
1.524 mm Ta / 0.813 mm Cu	3.23
2.032 mm Ta / 0.813 mm Cu	4.06
1.524 mm W / 2.540 mm Al	3.63
1.524 mm W / 3.175 mm Al	3.80
1.524 mm W / 4.064 mm Al	4.04
1.524 mm W / 0.686 mm Cu	3.56
1.524 mm W / 0.813 mm Cu	3.67
1.524 mm W / 1.016 mm Cu	3.85

3. FILTER BOX CALCULATION RESULTS

The results of the GIF Cell 3 filter box calculations are found in Table 4. The values for the DEF in the active silicon layer are consistent with the previous work. The data in the table clearly suggests that copper is a better low atomic number filter material than aluminum. Additionally, the 20-gauge copper (that is, 32 mil or 0.813 mm) appears to be the optimum thickness to use whether it is coupled with lead or tungsten. [*NOTE: The lead and tungsten filters were completed first, so the 20-gauge copper was the only thickness used for the bismuth and tantalum filter box designs.*]

Table 4 – GIF Cell 3 Dose Enhancement Factors for Various Filter Boxes

Filter Box Details	Density Thickness (g/cm^2)	DEF in Active Silicon Layer	Dose Reduction Ratio
1.587 mm Pb / 0.686 mm Cu	2.42	1.25	0.53
1.587 mm Pb / 0.813 mm Cu	2.53	1.22	0.52
1.587 mm Pb / 1.016 mm Cu	2.71	1.27	0.53
1.981 mm Pb / 0.813 mm Cu	2.98	1.24	0.51
2.387 mm Pb / 0.813 mm Cu	3.44	1.22	0.49
3.175 mm Pb / 0.813 mm Cu	4.33	1.27	0.49
1.5875 mm Bi / 0.813 mm Cu	2.28	1.32	0.57
3.175 mm Bi / 0.813 mm Cu	3.82	1.31	0.52
4.7625 mm Bi / 0.813 mm Cu	5.37	1.33	0.49
1.016 mm Ta / 0.813 mm Cu	2.39	1.25	0.54
1.270 mm Ta / 0.813 mm Cu	2.81	1.23	0.52
1.524 mm Ta / 0.813 mm Cu	3.23	1.25	0.52
2.032 mm Ta / 0.813 mm Cu	4.06	1.19	0.48
1.524 mm W / 2.540 mm Al	3.63	1.32	0.54
1.524 mm W / 3.175 mm Al	3.80	1.40	0.57
1.524 mm W / 4.064 mm Al	4.04	1.36	0.55
1.524 mm W / 0.686 mm Cu	3.56	1.20	0.49
1.524 mm W / 0.813 mm Cu	3.67	1.20	0.49
1.524 mm W / 1.016 mm Cu	3.85	1.22	0.50

To understand the effects of the filter materials on the photon spectrum inside a filter box, the photon spectrum inside a subset of the boxes was calculated along with a spectrum for a bare (or unfiltered) silicon sensor. The photon spectrum for the bare silicon sensor is found in Figure 4. In the spectrum, the "notch" or bump around 0.20 MeV represents the backscatter peak (Compton edge) for the Co-60 gammas. The Compton scatter peak as a function of scattering angle for Co-60 gamma energies is found in Figure 5. The photon spectrum inside the 1.524 mm W / 0.813 mm Cu filter box is found in Figure 6, and it is plotted with the unfiltered spectrum. The photon spectra inside the 1.587 mm Pb / 0.813 mm Cu and 2.032 mm Ta / 0.813 mm Cu filter boxes are found in

Figure 7 and Figure 8, respectively. These figures provide some insight into why the DEF is improved from an electronic testing perspective compared to the unfiltered environment.

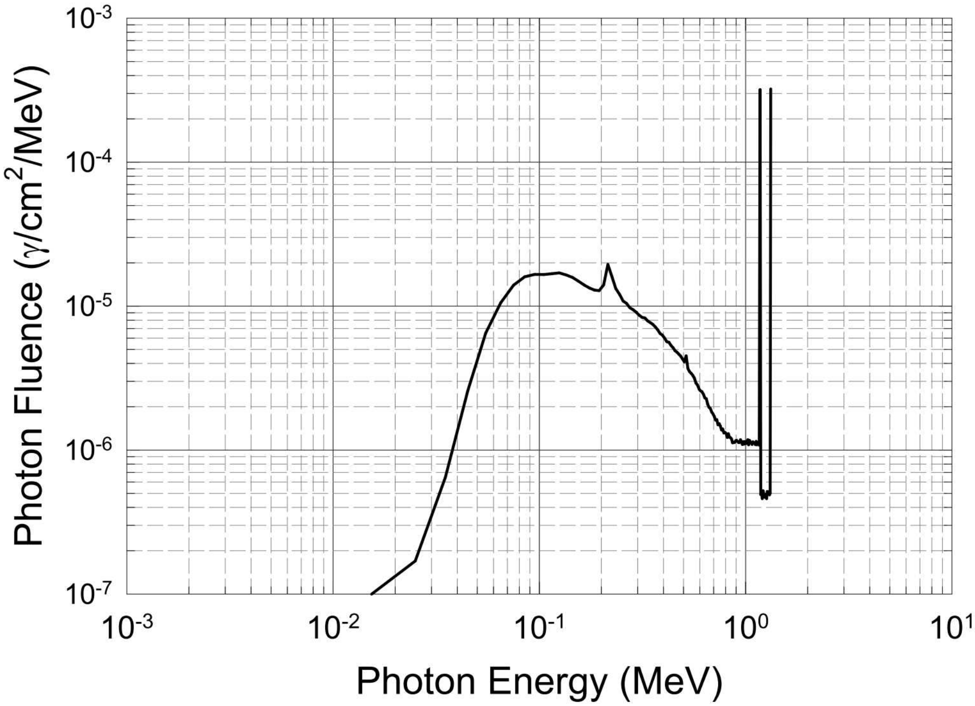

Figure 4 – Unfiltered Photon Spectrum @ 1 m from Single Pin Source in Cell 3

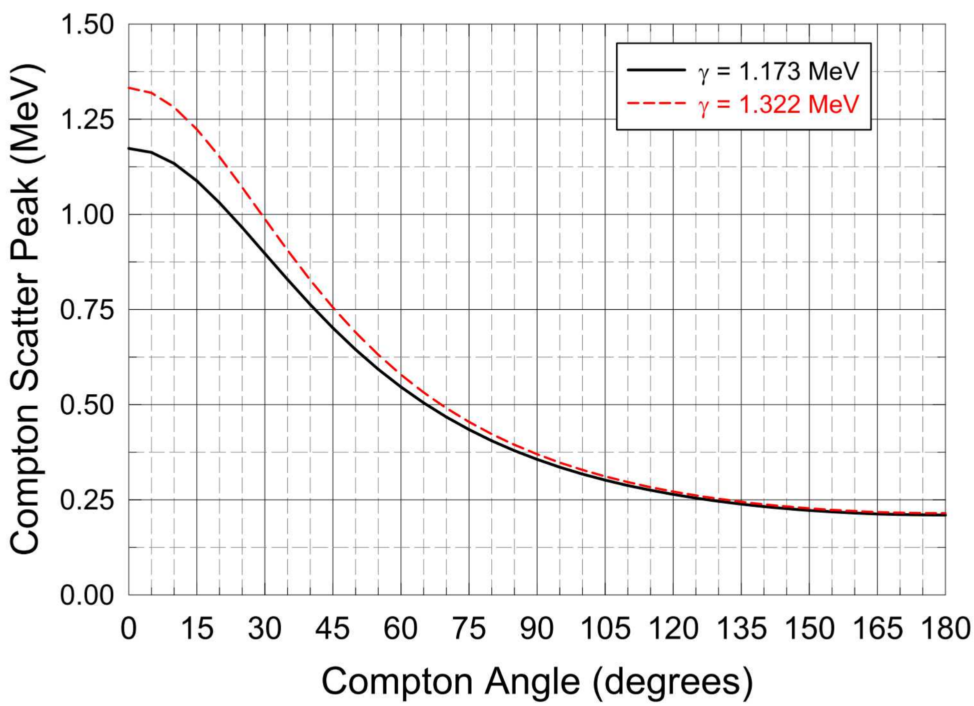

Figure 5 – Compton Edge as a Function of Scattering Angle

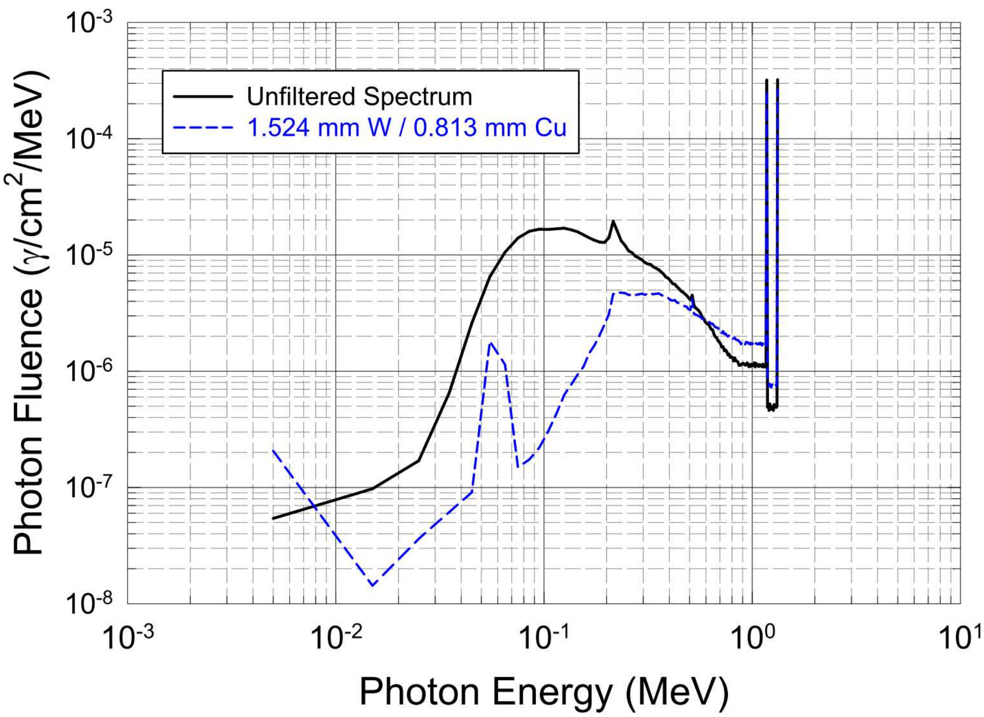

Figure 6 – Photon Spectrum with 1.524 mm W / 0.813 mm Cu Filter

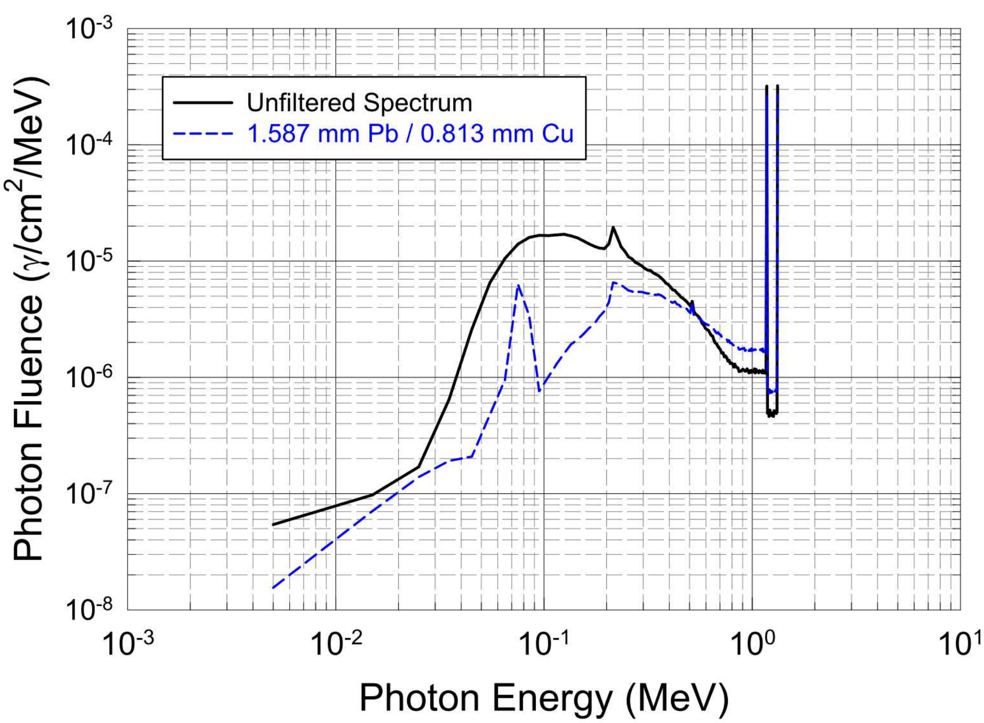

Figure 7 – Photon Spectrum with 1.587 mm Pb / 0.813 mm Cu Filter

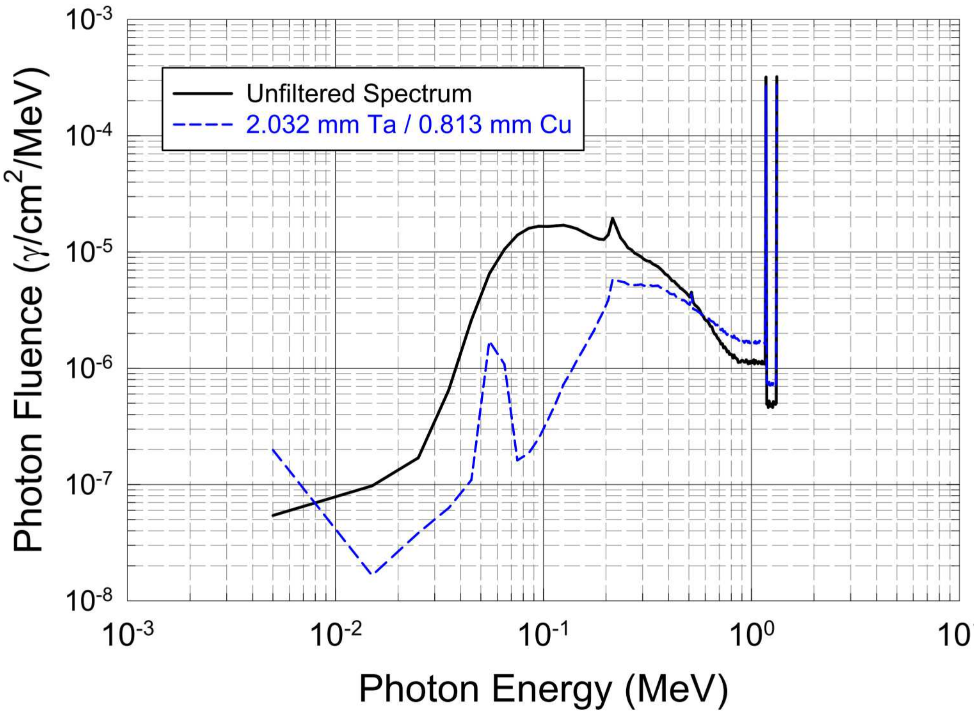

Figure 8 – Photon Spectrum with 2.032 mm Ta / 0.813 mm Cu Filter

From the figures above, it appears that suppression (or filtering) of photons with energy less than ~300 keV is responsible for the improvement (that is, reduction) in the DEF in the active silicon layer. Research into photon spectrum hardening metrics revealed that the most (if not all) are related to x-ray machines and medical linear accelerators rather gamma sources. Given the lack of metrics for photon spectrum hardness, the integral ratio of photon fluence below a photon energy cutoff to the total photon fluence were examined for the spectra discussed above. Three different cutoff energies ($h\nu < 100$ keV, $h\nu < 200$ keV, and $h\nu < 300$ keV) were selected to evaluate their correlation to the DEF in the active silicon layer of the silicon sensor. These ratios are displayed in Table 5 for the unfiltered spectrum as well as three of the filter boxes considered.

Table 5 – Photon Spectral Parameters

Filter Box Details	DEF in Active Silicon Layer	$\frac{\Phi_{h\nu<100\text{ keV}}}{\Phi_{Total}}$	$\frac{\Phi_{h\nu<200\text{ keV}}}{\Phi_{Total}}$	$\frac{\Phi_{h\nu<300\text{ keV}}}{\Phi_{Total}}$
None	2.02	0.0547	0.1772	0.2784
1.524 mm W / 0.813 mm Cu	1.20	0.0047	0.0190	0.0734
1.587 mm Pb / 0.813 mm Cu	1.22	0.0125	0.0293	0.0907
2.032 mm Ta / 0.813 mm Cu	1.19	0.0045	0.0217	0.0834

Examining the table, there is very little difference between the DEF in the active silicon layer and the ratios for the 1.524 mm W / 0.813 mm Cu filter box and the 2.032 mm Ta / 0.813 mm Cu filter box. The unfiltered spectrum ratios are very different from the ratios for the spectra inside the filter boxes.

The guidance in ASTM Standard E1249-15 states that, by using an appropriate filter box and correct device under test orientation, the DEF contributes no more than 20% to the dosimetry error [2]. Given the uncertainties in the tallies, there is little to no difference in the DEF in the active silicon layer for any of the three filter boxes in Table 5. Thus, a "good" filter box configuration for Co-60 gammas will produce integral metric ratios like these filters – particularly when compared to the DEF in the active silicon layer computed for the current filter box configuration used by the RML (see Table 2).

To understand the shape of the photon spectra inside the filter boxes at a deeper level, the photon attenuation cross sections for lead and tungsten are plotted with the spectra from their respective filter boxes in Figure 9. A quick look at the figure reveals that the shapes of the photon spectra have features that can be explained by the k-edges of the total photon attenuation cross sections for both lead and tungsten. While it may seem counter-intuitive, the lower k-edge energy (69.5 keV) for tungsten seems to provide better filtering than the more energetic k-edge energy (88.0 keV) of lead. However, the greater density of tungsten (19.3 g/cm^3) as compared to lead (11.35 g/cm^3) may be a more significant factor in the filtering of lower energy photons.

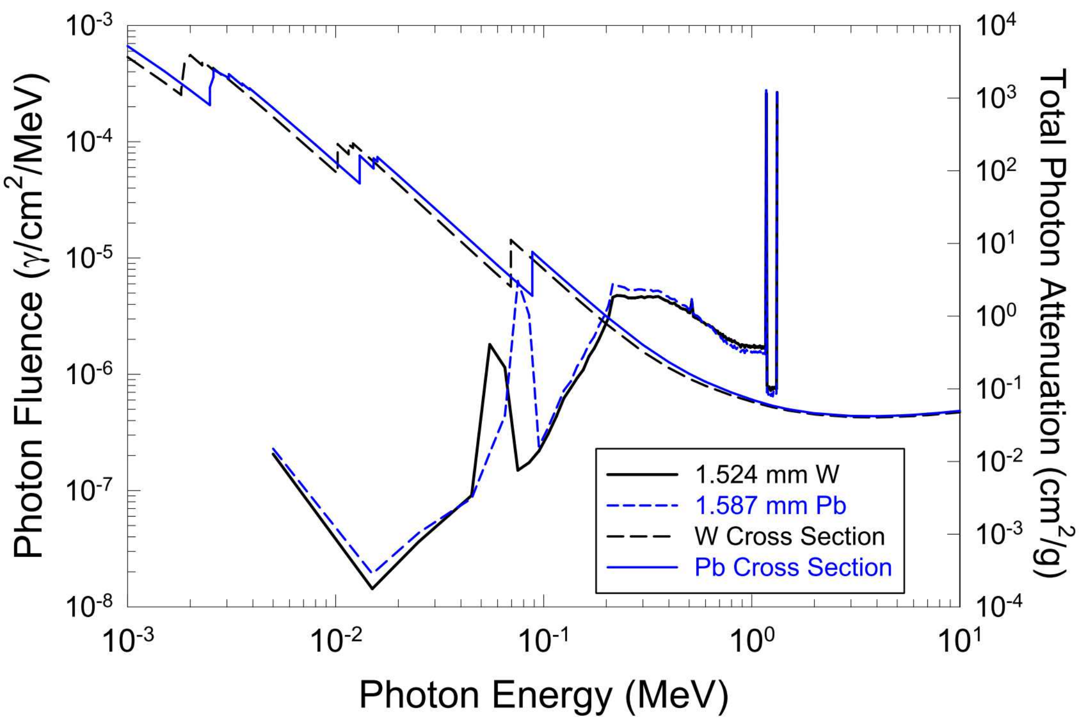

Figure 9 – Filter Box Spectra with Photon Attenuation Cross Sections

4. SUMMARY AND CONCLUSIONS

Based on a previous study [3] and the work presented above, the low energy photon filter box in use at the GIF can be improved. DePriest *et al.* suggested that adding lead to the current design while substituting copper for aluminum may improve the performance of the filter box. Both suggestions were found to improve the DEF in the active silicon layer of the sensor. This work shows that tungsten and tantalum both provide a reasonable alternative to the current lead design. While there is a desire to move away from lead in the filter box design due to its general toxicity, the potential issues with the machinability of tungsten and the expense of tantalum mean that lead should be included in any experimental study. The results for the filter boxes with bismuth did not really show improvement over the current lead/aluminum design.

This work has completed the planned radiation transport calculations to examine additional tungsten/copper, lead/copper, tantalum/copper, and bismuth/copper filter box designs called for at the 16th International Symposium on Reactor Dosimetry. The completion of this study means that filter box designs can be finalized and constructed for a set of experimental measurements. The experimental series should determine the effectiveness the various photon filters in the GIF using the method described in ASTM Standard E1250-15 [8]. The test method uses an ionization chamber technique (known as the Kerris chamber method) to determine a figure of merit for the Co-60 radiation field under investigation. The test method recommends the iterative use of the Kerris chamber method to assess the effectiveness of filter box designs to produce an irradiation environment with a suitable figure of merit for silicon electronic parts testing in a Co-60 field.

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APPENDIX A: SAMPLE GIF CELL 3 MODEL

```
GIF Cell #3 -- Filter Box Optimization Testing
C
C ***************************************************************************
C *           MCNP input file for new GIF Cell #3 photon dosimetry.         *
C *=========================================================================*
C *  Versions:                                                              *
C *    Ver   Update   Programmer               Description                  *
C *    ---  --------  ----------  ----------------------------------------  *
C *   v1.0  10/03/01  R DePriest   Model of GIF Cell #3 for dosimetry calcs  *
C *   v1.1  10/04/01  R DePriest   Add pool under the source                 *
C *   v1.2  10/05/01  R DePriest   Add Shutters to N and E Walls             *
C *   v1.3  10/15/01  R DePriest   Add "Viewing slices" to N and E Walls;    *
C *                                Adjusted width of pool; Add Elevator      *
C *                                Volume source in Steel Casing             *
C *   v1.4  10/24/01  R DePriest   Divided Main Cell so that photon imp's are *
C *                                increased closer to the detectors         *
C *   v1.5  11/01/01  R DePriest   More changes to importances of cells      *
C *   v2.0  11/07/01  R DePriest   IMP:P=1 in most cells; Source biasing     *
C *   v3.0  11/15/01  R DePriest   Point Detectors; no source bias           *
C *   v4.0  03/31/03  R DePriest   12" source; lead boxes @ 13.75, 40.75, and *
C *                                 176 inches from source                   *
C *   v4.1  04/01/03  R DePriest   12" source; ion chambers @ 13.75, 40.75,  *
C *                                 and 176 inches from source               *
C *   V4.2  04/06/06  SNJ & KRD    Modified to run w/ WWG for dose tallies   *
C *                                  outside Cell3 Walls                     *
C *                                Added Cell Door (w/o windows) of          *
C *                                   2(1/8" SS) +(1/8 Pb) thick             *
C *   V4.3  09/28/06  R DePriest   Ceiling in the maze changed to correct    *
C *                                 height (243.84 cm). Ion chamber detectors *
C *                                 and cylindrical men removed.  Detectors  *
C *                                 placed at location as of 9/28/06, in the *
C *                                 "old" location, and throughout the maze. *
C *   V5.0  02/17/17  R DePriest   Detectors all removed. New detectors based *
C *                                on silicon sensor in various filter box   *
C *                                designs.                                  *
C *                                 - Co-60 Filter Box Optimization (Cont.)  *
C *                                 - 0.1524 W / 0.0686 Cu                   *
C *                                                                         *
C *=========================================================================*
C *  CONFIGURATION:                                                         *
C *    - 5.48 W x 9.14 L x 4.11 H (m) with origin at Center-floor of Cell    *
C *    - Cell 3 orientation: -X(south), +X(north), -Y(east), +Y(west)       *
C *    - maze on north-east corner of Cell 3 with 4.11m ceiling throughout   *
C *    - Co-60 Cylindrical Source (made of Co, but density is mix of SS/Co)  *
C *    - Source bottom is located 2" from front of elevator at x= 67.945    *
C *        y=231.5 z=10.16 (R=0.56642, H=30.48);                            *
C *    - Cell, surface, detector Conventions:                               *
C *                   MCNP Cells       # 1-299                              *
C *                   X-plane (s-n)    # 100-199                            *
C *                   Y-plane (e-w)    # 200-299                            *
C *                   Z-plane (d-u)    # 300-399                            *
C *                   Angular surfaces # 400-499                            *
C *                   Tally/detectors  # 500-599                            *
C *                   Macrobodies      # 600-699                            *
C *                   Void             # 900-999                            *
C *=========================================================================*
C
C ***************************************************************************
C *                                CELL CARDS                               *
C ***************************************************************************
C ---+----+---------+---------+---------+---------+---------+-----------------------
```

```
C  Irradiation Cell #3 and MAZE
   1   2  -1.0245e-3  110 -100  210 -200  310 -300
                      610  650  1503               IMP:P=1  $Main component
   2   2  -1.0245e-3  121 -100 -210  224  310 -340
                                                   IMP:P=1  $Inner hall of MAZE
C
2002   1  -2.27600    121 -100 -210  224  340 -300  IMP:P=1  $Lower ceiling level--
cell 2
C
   3   2  -1.0245e-3  100 -123  224 -223  310 -340
                                                   IMP:P=1  $East hall of MAZE
C
2003   1  -2.27600    100 -123  224 -223  340 -300  IMP:P=1  $Lower ceiling level--
cell 3
C
   4   2  -1.0245e-3  122 -123  223 -221  310 -340
                                                   IMP:P=1  $Outer hall of MAZE
C
2004   1  -2.27600    122 -123  223 -221  340 -300  IMP:P=1  $Lower ceiling level--
cell 4
C
   5   2  -1.0245e-3  123 -125  222 -221  310 -340  IMP:P=1  $Entrance
C
2005   1  -2.27600    123 -125  222 -221  340 -300  IMP:P=1  $Lower ceiling level--
cell 5
C
  80  16  -9.0326667  125 -124  222 -221  310 -340  IMP:P=1  $Door to Entrance
C
2080   1  -2.27600    125 -124  222 -221  340 -300  IMP:P=1  $Lower ceiling level--
cell 80
C
C  Shutters
   6   2  -1.0245e-3 -400 -401 -210  216 -410 -411  IMP:P=1  $Air Cutout(N window)
   7   LIKE 6   BUT TRCL=5                                   $Air Cutout(S window)
   8   2  -1.0245e-3  100 -106 -402 -403 -412 -413  IMP:P=1  $Air Cutout(N wall)
   9   3  -7.82100   -404  400 -210  216 -410 -411  IMP:P=1  $Left Steel (N window)
  10   LIKE 9   BUT TRCL=5                                   $Left Steel (S window)
  11   3  -7.82100    401 -405 -210  216 -410 -411  IMP:P=1  $Right Steel (N window)
  12   LIKE 11  BUT TRCL=5                                   $Right Steel (S window)
  13   3  -7.82100    100 -106  402 -406 -412 -413  IMP:P=1  $Left Steel (N wall)
  14   3  -7.82100    100 -106  403 -407 -412 -413  IMP:P=1  $Right Steel (N wall)
  15   3  -7.82100   -404 -405 -216  217 -410 -411  IMP:P=1  $Shutter (N window)
  16   LIKE 15  BUT TRCL=5                                   $Shutter (S window)
  17   3  -7.82100    106 -107 -406 -407 -412 -413  IMP:P=1  $Shutter (N wall)
  18   3  -7.82100   -404 -405 -210  217  410 -414  IMP:P=1  $Bottom Steel (N window)
  19   LIKE 18  BUT TRCL=5                                   $Bottom Steel (S window)
 106   3  -7.82100   -404 -405 -210  217  411 -415  IMP:P=1  $Top Steel (N window)
 107   LIKE 106 BUT TRCL=5                                   $Top Steel (S window)
 108   3  -7.82100    100 -106 -406 -407  412 -416  IMP:P=1  $Bottom Steel (N wall)
 109   3  -7.82100    100 -106 -406 -407  413 -417  IMP:P=1  $Top Steel (N wall)
C  "Viewing Slices"
  90  10  -2.50000    130 -131 -217  218  330 -331  IMP:P=1  $Glass behind shutter
  91   LIKE 90 BUT TRCL=5
  92   2  -1.0245e-3  130 -131 -218  219  330 -331  IMP:P=1  $Air behind glass
  93   LIKE 92 BUT TRCL=5
  94  10  -2.50000    130 -131 -219  226  330 -331  IMP:P=1  $Glass behind air
  95   LIKE 94 BUT TRCL=5
  96  12  -0.86000    130 -131 -226  227  330 -331  IMP:P=1  $Oil behind glass
  97   LIKE 96 BUT TRCL=5
  98  13  -6.20000    130 -131 -227  228  330 -331  IMP:P=1  $Pb-glass
  99   LIKE 98 BUT TRCL=5
 190  10  -2.50000    130 -131 -228  215  330 -331  IMP:P=1  $Glass to back of wall
 191   LIKE 190 BUT TRCL=5
```

```
 192  10  -2.50000    107 -132  229 -230  330 -331  IMP:P=1  $Glass behind shutter
 193   2  -1.0245e-3  132 -133  229 -230  330 -331  IMP:P=1  $Air behind glass
 194  10  -2.50000    133 -134  229 -230  330 -331  IMP:P=1  $Glass behind air
 195  12  -0.86000    134 -135  229 -230  330 -331  IMP:P=1  $Oil behind glass
 196  13  -6.20000    135 -136  229 -230  330 -331  IMP:P=1  $Pb-glass
 197  10  -2.50000    136 -105  229 -230  330 -331  IMP:P=1  $Glass to back of wall
C  South Wall Sections
  20   1  -2.27600   -110  111  211 -201  310 -300  IMP:P=1  $First concrete
  21  11  -2.55325   -111  112  212 -202  310 -300  IMP:P=1  $First rebar
  22   1  -2.27600   -112  113  213 -203  310 -300  IMP:P=1  $Second concrete
  23  11  -2.55325   -113  114  214 -204  310 -300  IMP:P=1  $Second rebar
  24   1  -2.27600   -114  115  215 -205  310 -300  IMP:P=1  $Final concrete
C  West Wall Sections
  30   1  -2.27600    110 -100  200 -201  310 -300  IMP:P=1  $First concrete
  31  11  -2.55325    111 -101  201 -202  310 -300  IMP:P=1  $First rebar
  32   1  -2.27600    112 -102  202 -203  310 -300  IMP:P=1  $Second concrete
  33  11  -2.55325    113 -103  203 -204  310 -300  IMP:P=1  $Second rebar
  34   1  -2.27600    114 -104  204 -205  310 -300  IMP:P=1  $Final concrete
C  North Wall and MAZE Sections
  40   1  -2.27600    100 -101 -201  223  310 -300
                 #8 #13 #14 #108 #109               IMP:P=1  $First concrete
  41  11  -2.55325    101 -102 -202  223  310 -300
                 #8 #13 #14 #108 #109               IMP:P=1  $First rebar
  42   1  -2.27600    102 -122 -221  223  310 -300  IMP:P=1  $Second concrete
  43   1  -2.27600    102 -103 -203  221  310 -300
                 #8 #13 #14 #17 #108 #109 #192
                 #193 #194 #195 #196                IMP:P=1  $Second concrete
  44  11  -2.55325    103 -104 -204  221  310 -300
                 #196 #197                          IMP:P=1  $Second rebar
  45   1  -2.27600    104 -105 -205  221  310 -300
                 #197                               IMP:P=1  $Final concrete
  46   1  -2.27600    105 -124  221 -220  310 -300  IMP:P=1  $Maze wall
  47   1  -2.27600    123 -124  225 -222  310 -300  IMP:P=1  $Maze wall
  48   1  -2.27600    121 -123  225 -224  310 -300  IMP:P=1  $Maze wall
  49   1  -2.27600    120 -121  225 -215  310 -300  IMP:P=1  $Maze wall
C  East Wall Sections
  50   1  -2.27600    110 -121 -210  211  310 -300
                 #6 #7 #9 #10 #11 #12 #18
                 #19 #106 #107                      IMP:P=1  $First concrete
  51  11  -2.55325    111 -121 -211  212  310 -300
                 #6 #7 #9 #10 #11 #12 #18
                 #19 #106 #107                      IMP:P=1  $First rebar
  52   1  -2.27600    112 -121 -212  213  310 -300
                 #6 #7 #9 #10 #11 #12 #15 #16 #18
                 #19 #106 #107 #90 #91 #92 #93 #94
                 #95 #96 #97 #98 #99                IMP:P=1  $Second concrete
  53  11  -2.55325    113 -121 -213  214  310 -300
                 #98 #99 #190 #191                  IMP:P=1  $Second rebar
  54   1  -2.27600    114 -121 -214  215  310 -300
                 #190 #191                          IMP:P=1  $Final concrete
C  Ceiling Sections
  60   1  -2.27600    115 -121  215 -205  300 -301  IMP:P=1  $First concrete
  61  11  -2.55325    115 -121  215 -205  301 -302  IMP:P=1  $First rebar
  62   1  -2.27600    115 -121  215 -205  302 -303  IMP:P=1  $Second concrete
  63  11  -2.55325    115 -121  215 -205  303 -304  IMP:P=1  $Second rebar
  64   1  -2.27600    115 -121  215 -205  304 -305  IMP:P=1  $Final concrete
  65   1  -2.27600    121 -105  225 -205  300 -301  IMP:P=1  $First concrete
  66  11  -2.55325    121 -105  225 -205  301 -302  IMP:P=1  $First rebar
  67   1  -2.27600    121 -105  225 -205  302 -303  IMP:P=1  $Second concrete
  68  11  -2.55325    121 -105  225 -205  303 -304  IMP:P=1  $Second rebar
  69   1  -2.27600    121 -105  225 -205  304 -305  IMP:P=1  $Final concrete
 160   1  -2.27600    105 -124  225 -220  300 -301  IMP:P=1  $First concrete
 161  11  -2.55325    105 -124  225 -220  301 -302  IMP:P=1  $First rebar
```

```
 162   1  -2.27600    105 -124  225 -220  302 -303  IMP:P=1  $Second concrete
 163  11  -2.55325    105 -124  225 -220  303 -304  IMP:P=1  $Second rebar
 164   1  -2.27600    105 -124  225 -220  304 -305  IMP:P=1  $Final concrete
 165   1  -2.27600    120 -121 -215  225  300 -305  IMP:P=1  $Concrete add-in
C  Floor Sections
  70   1  -2.27600    115 -121  215 -205 -310  311
                         600                        IMP:P=1  $First concrete
  71  11  -2.55325    115 -121  215 -205 -311  312
                         600                        IMP:P=1  $First rebar
  72   1  -2.27600    115 -121  215 -205 -312  313
                         600                        IMP:P=1  $Second concrete
  73  11  -2.55325    115 -121  215 -205 -313  314
                         600                        IMP:P=1  $Second rebar
  74   1  -2.27600    115 -121  215 -205 -314  315
                         600                        IMP:P=1  $Final concrete
  75   1  -2.27600    121 -105  225 -205 -310  311  IMP:P=1  $First concrete
  76  11  -2.55325    121 -105  225 -205 -311  312  IMP:P=1  $First rebar
  77   1  -2.27600    121 -105  225 -205 -312  313  IMP:P=1  $Second concrete
  78  11  -2.55325    121 -105  225 -205 -313  314  IMP:P=1  $Second rebar
  79   1  -2.27600    121 -105  225 -205 -314  315  IMP:P=1  $Final concrete
 170   1  -2.27600    105 -124  225 -220 -310  311  IMP:P=1  $First concrete
 171  11  -2.55325    105 -124  225 -220 -311  312  IMP:P=1  $First rebar
 172   1  -2.27600    105 -124  225 -220 -312  313  IMP:P=1  $Second concrete
 173  11  -2.55325    105 -124  225 -220 -313  314  IMP:P=1  $Second rebar
 174   1  -2.27600    105 -124  225 -220 -314  315  IMP:P=1  $Final concrete
 175   1  -2.27600    120 -121 -215  225 -310  315  IMP:P=1  $Concrete add-in
C
C
C
C  Pool, sources, and elevator
C
 600   8  -1.00000    -600                          IMP:P=0.25  $Pool under source
 610   9  -8.36050    -610                          IMP:P=1  $Co-source
 650   5  -2.70000    -650                          IMP:P=1  $Aluminum elevator
C  Voids
 920   0   -900      -115      -205  215 -305  315  IMP:P=1  $Void Outside S wall
 930   0   -900                 205      -305  315  IMP:P=1  $Void Outside W wall
 940   0   -900       105       220 -205 -305  315  IMP:P=1  $Void Outside N wall
 941   0   -900       124      -220  225 -305  315  IMP:P=1  $Void Outside N wall
 950   0   -900       120      -225      -305  315  IMP:P=1  $Void Outside E wall
 951   0   -900      -120      -215      -305  315  IMP:P=1  $Void Outside E wall
 960   0   -900                           305       IMP:P=1  $Void Above ceiling
 970   0   -900                           600 -315  IMP:P=1  $Void Below Floor
C
C  Detectors (1500-2000)
C
C
1501   2  -1.0245e-3    -1501  1504  1510  1511  1512
                   1513  1514  1515  1516  1517  1518
                   1519  1520  1521  1522  1523  1524  IMP:P=1  $Air box
C
1502   29  -8.96      -1502  1501                      IMP:P=1  $Cu - 0.0686 cm
C
1503  209  -19.3      -1503  1502                      IMP:P=1  $W - 0.1524 cm
C
1504  2  -1.0245e-3    -1504                           IMP:P=1  $Sphere Box 5
C
C
C CMO7 Stack for Box 6 - Solder on "bottom"
C
1510  201   -8.67    -1510                           IMP:P=1 $Solder
1511  202   -8.94    -1511                           IMP:P=1 $Cu - 1
1512  203   -8.90    -1512                           IMP:P=1 $Ni - 1
```

```
1513  204   -19.3    -1513                            IMP:P=1 $Au - 1
1514  205   -1.31    -1514                            IMP:P=1 $BT Laminate
1515  202   -8.94    -1515                            IMP:P=1 $Cu - 2
1516  203   -8.90    -1516                            IMP:P=1 $Ni - 2
1517  204   -19.3    -1517                            IMP:P=1 $Au - 2
1518  206   -3.40    -1518                            IMP:P=1 $Ablebond 8361 J
1519  207   -2.33    -1519                            IMP:P=1 $Si (p-type)
1520  208   -2.196   -1520                            IMP:P=1 $SiO2
C
1521  207   -2.33    -1521                            IMP:P=1 $Si Active - 1
C
1522  209   -19.3    -1522                            IMP:P=1 $W
1523  208   -2.196   -1523                            IMP:P=1 $SiO2 passivation
1524  210   -0.92    -1524                            IMP:P=1 $Plastic Encapsulation
C
C
 999   0    900                                     IMP:P=0

C ******************************************************************************
C *                               SURFACE CARDS                                *
C ******************************************************************************
C  X-planes for NORTH WALL
 100   px   457.00                     $North wall (use on MAZE too)
 101   px   464.50                     $Distance to rebar in N wall
 102   px   474.50                     $Rebar depth 10cm~4inches
 103   px   621.50                     $Second rebar
 104   px   631.50                     $Rebar depth 10cm~4inches
 105   px   639.00                     $Outside N wall
 106   px   512.88                     $Depth of shutter
 107   px   515.42                     $Shutter is 1"=2.54 cm thick
C  X-planes for SOUTH WALL
 110   px  -457.00                     $South wall
 111   px  -464.50                     $Distance to rebar in S wall
 112   px  -474.50                     $Rebar depth 10cm~4inches
 113   px  -621.50                     $Second rebar
 114   px  -631.50                     $Rebar depth 10cm~4inches
 115   px  -639.00                     $Outside S wall
C  X-planes for MAZE
 120   px   275.00                     $Outside of MAZE wall (S)
 121   px   366.00                     $S end of inner MAZE wall
 122   px   609.00                     $S wall of MAZE entrance
 123   px   700.00                     $N end of inner MAZE wall
 124   px   760.96                     $Outside of MAZE wall (N)
C
 125   px   760.0075                   $ Effective thickness of Personnel Door (1/8
ss=1/8Pb+1/8SS)
C  X-planes for "viewing slices"
 130   px    45.25                     $Edge of glass
 131   px   160.49                     $Edge of glass
 132   px   517.96                     $Glass is 1"=2.54 cm thick
 133   px   520.83                     $Air layer 2.87 cm thick
 134   px   538.61                     $Glass is 7"=17.78 cm thick
 135   px   576.20                     $Oil is 14.8"=37.59 cm thick
 136   px   624.46                     $Pb-glass 19"=48.26 cm thick
C ---+----+---------+---------+---------+------------------------------------
C  Y-planes for WEST WALL
 200   py   274.00                     $West wall
 201   py   281.50                     $Distance to rebar in W wall
 202   py   291.50                     $Rebar depth 10cm~4inches
 203   py   438.50                     $Second rebar
 204   py   448.50                     $Rebar depth 10cm~4inches
 205   py   456.00                     $Outside W wall
C  Y-planes for EAST WALL
```

```
 210   py  -274.00                      $East wall (use on MAZE too)
 211   py  -281.50                      $Distance to rebar in E wall
 212   py  -291.50                      $Rebar depth 10cm~4inches
 213   py  -438.50                      $Second rebar
 214   py  -448.50                      $Rebar depth 10cm~4inches
 215   py  -456.00                      $Outside E wall
 216   py  -329.88                      $Depth of shutter
C  Y-planes for "viewing slices"
 217   py  -332.42                      $Shutter is 1"=2.54 cm thick
 218   py  -334.96                      $Glass is 1"=2.54 cm thick
 219   py  -337.83                      $Air layer 2.87 cm thick
 226   py  -355.61                      $Glass is 7"=17.78 cm thick
 227   py  -393.20                      $Oil is 14.8"=37.59 cm thick
 228   py  -441.46                      $Pb-glass 19"=48.26 cm thick
 229   py    65.25                      $Edge of glass
 230   py   180.52                      $Edge of glass
C  Y-planes for MAZE
 220   py   -91.00                      $Outside of MAZE wall (W)
 221   py  -136.72                      $W wall of MAZE entrance
 222   py  -227.72                      $W end of outer MAZE wall
 223   py  -517.00                      $W end of inner MAZE wall
 224   py  -608.00                      $E end of MAZE
 225   py  -699.00                      $Outside of MAZE wall (E)
C ---+----+---------+---------+---------+--------------------------------------
C  Z-planes for CEILING
 300   pz   411.00                      $Ceiling
 301   pz   418.50                      $Distance to rebar in ceiling
 302   pz   428.50                      $Rebar depth 10cm~4inches
 303   pz   530.50                      $Second rebar
 304   pz   540.50                      $Rebar depth 10cm~4inches
 305   pz   548.00                      $Outside of ceiling
C  Z-planes for FLOOR
 310   pz     0.00                      $Floor
 311   pz    -7.50                      $Distance to rebar in floor
 312   pz   -17.50                      $Rebar depth 10cm~4inches
 313   pz   -62.50                      $Second rebar
 314   pz   -72.50                      $Rebar depth 10cm~4inches
 315   pz   -80.00                      $Outside of floor
C  Z-planes for "viewing slices"
 330   pz    42.90                      $Bottom of glass
 331   pz   218.64                      $Top of glass
C  Z-planes for maze ceiling
 340   pz   243.84                      $Ceiling in the maze section
C  Angular planes for shutters
 400   p     0.00 -274.00   0.00    0.00 -274.00  50.00
              45.25 -329.88   0.00
 401   p   205.74 -274.00   0.00  205.74 -274.00  50.00
             160.49 -329.88   0.00
 402   p   457.00   20.00   0.00  457.00   20.00  50.00
             512.88   65.25   0.00
 403   p   457.00  225.74   0.00  457.00  225.74  50.00
             512.88  180.52   0.00
 404   p    -5.08 -274.00   0.00   -5.08 -274.00  50.00
              40.17 -329.88   0.00
 405   p   210.82 -274.00   0.00  210.82 -274.00  50.00
             165.57 -329.88   0.00
 406   p   457.00   14.92   0.00  457.00   14.92  50.00
             512.88   60.17   0.00
 407   p   457.00  230.82   0.00  457.00  230.82  50.00
             512.88  185.60   0.00
 410   p     0.00 -274.00  20.32   50.00 -274.00  20.32
               0.00 -329.88  42.90
 411   p     0.00 -274.00 241.22   50.00 -274.00 241.22
```

```
              0.00 -329.88 218.64
 412   p   457.00    0.00  20.32  457.00   50.00  20.32
            512.88    0.00  42.90
 413   p   457.00    0.00 241.22  457.00   50.00 241.22
            512.88    0.00 218.64
 414   p   0.00 -274.00  15.24   50.00 -274.00  15.24
              0.00 -329.88  37.82
 415   p   0.00 -274.00 246.30   50.00 -274.00 246.30
              0.00 -329.88 223.72
 416   p   457.00    0.00  15.24  457.00   50.00  15.24
            512.88    0.00  37.82
 417   p   457.00    0.00 246.30  457.00   50.00 246.30
            512.88    0.00 223.72
C
C
C  Detectors
C
C
1501   RPP  62.945   72.945   126.50    136.50    20.4     30.4      $Air box 1 meter
from source
1502   RPP  62.8764  73.0136  126.4314  136.5686  20.3314  30.4686   $0.0686 Cu box
1503   RPP  62.72400 73.16600 126.27900 136.72100 20.17900 30.62100  $0.1524 W box
C
1504   S    70.0000  131.500000   25.400     1.0      $Detector sphere
C
1510   RCC  66.0000  131.500000   25.400
            0.000000   0.060000    0.000     1.128371  $Solder
1511   RCC  66.0000  131.560000   25.400
            0.000000   0.001500    0.000     1.128371  $Cu layer - 1
1512   RCC  66.0000  131.561500   25.400
            0.000000   0.000500    0.000     1.128371  $Ni layer - 1
1513   RCC  66.0000  131.562000   25.400
            0.000000   0.000070    0.000     1.128371  $Au layer - 1
1514   RCC  66.0000  131.562070   25.400
            0.000000   0.036000    0.000     1.128371  $BT Laminate
1515   RCC  66.0000  131.598070   25.400
            0.000000   0.001500    0.000     1.128371  $Cu layer - 2
1516   RCC  66.0000  131.599570   25.400
            0.000000   0.000500    0.000     1.128371  $Ni layer - 2
1517   RCC  66.0000  131.600070   25.400
            0.000000   0.000070    0.000     1.128371  $Au layer - 2
1518   RCC  66.0000  131.600140   25.400
            0.000000   0.003000    0.000     1.128371  $Ablebond 8361J
1519   RCC  66.0000  131.603140   25.400
            0.000000   0.030000    0.000     1.128371  $Si (p-type)
1520   RCC  66.0000  131.633140   25.400
            0.000000   0.000020    0.000     1.128371  $SiO2 layer
1521   RCC  66.0000  131.633160   25.400
            0.000000   0.000025    0.000     1.128371  $Active Si layer
1522   RCC  66.0000  131.633185   25.400
            0.000000   0.000085    0.000     1.128371  $W layer
1523   RCC  66.0000  131.633270   25.400
            0.000000   0.000838    0.000     1.128371  $SiO2 passivation layer
1524   RCC  66.0000  131.634108   25.400
            0.000000   0.086600    0.000     1.128371  $Plastic Encapsulation
C
C
C
C  Macrobody for pool, source, and elevator
C
C
 600   rpp    -135.89  135.89  189.00  456.00
               -600.00    0.00                    $Pool depth 6.0 m
```

```
 610   rcc  67.945 196.62  10.16  0 0 30.48 0.56642  $Source
 650   rpp     2.54  133.35   191.54  271.46
                   5.08   10.16                     $Elevator
C
 900   RPP  -1638 1638 -1698 1698 -1600  1600

C ****************************************************************************
C *                               DATA CARDS                                 *
C ****************************************************************************
MODE P E
PHYS:P  100.0 0
NPS      5.0e10
RAND    GEN=2 STRIDE=352917
PRDMP  j  1.0E9 j 2 1.0e9
C ********************
C *  SOURCE CARDS    *
C ********************
SDEF  CEL=610 ERG=D1 POS=67.945 196.62 25.4 AXS=0 0 1
       RAD=D2 EXT=D3
SC1   Cobalt-60 Single Pin Source
SI1   L  1.173  1.322
SP1   D  1.0   1.0
SI2   0  0.56642
SI3   15.24
C
C  MPLOT TAL=126  FREQ=250000 FREE F XLIMS=0 52 PLINEAR
C
C ********************
C * TRANSFORMATIONS  *
C ********************
TR5  -285.74     0.00   0.00
C
C ********************
C *  MATERIAL CARDS  *
C ********************
M1     8000.84p  -0.503507     14000.84p  -0.320735     $Concrete
      13000.84p  -4.74581e-2   26000.84p  -1.99938e-2   $Boldt's model with
      20000.84p  -6.83329e-2    6000.84p  -9.51764e-4   $Kr->Fe
      11000.84p  -1.52287e-2   19000.84p  -1.23728e-2   $Zn->Ca
       1000.84p  -9.51619e-3   12000.84p  -1.90351e-3
C
M11    8000.84p  -0.417606     14000.84p  -0.266016     $Reinforced concrete
      13000.84p  -3.93610e-2   26000.84p  -0.165085     $Values obtain from
      20000.84p  -5.66749e-2    6000.84p  -2.28933e-2   $Excel sheet concrete.xls
      11000.84p  -1.26306e-2   19000.84p  -1.02619e-2
       1000.84p  -7.89267e-3   12000.84p  -1.57876e-3
C
M2     7000.84p   0.784484      8000.84p   0.210722     $N & O  components of air
       6000.84p   0.000165     18000.84p   0.004629     $C & Ar components of air
C
M3    26000.84p  -0.990001      6000.84p  -0.009999     $Carbon Steel from KENO
C
M5    13000.84p   1.000000                              $Al
C
M8     1000.84p   0.666667      8000.84p   0.333333     $Water in pool
C
M9    27000.84p   1.000000                              $Cobalt source
C
M10    8000.84p   0.666667     14000.84p   0.333333     $Si[O2] -> Glass
C
M12    1000.84p   0.654310      6000.84p   0.345690     $BC-517H Mineral Oil (Bicron)
C
M13    8000.84p   0.531667     14000.84p   0.063333
```

```
      82000.84p   0.405000                              $Pb-glass (concrete.xls)
C
M14   82000.84p   1.000000                              $Pb for box
C
M15   14000.84p   1.000000                              $Si for dose measurement
C
M16   82000.84p  -0.4188513   26000.84p  -0.58114835    $ 1/3 thickness Pb, 2/3
thickness Fe ...M10=9.032667g/cc
C
C
C
C
C  Copper @ 8.96 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Cu-63        0.691500           0.684792          0.0515083
C  Cu-65        0.308500           0.315208          0.0229795
C
C  The total compound atom density (atom/b-cm):  0.0744878
C
M29     29000.84p   1.000000
C
C
C
C
C   Tantalum from Nuclear Wallet Cards - Electronic Version
C    Isotope   atomic abundance    delta (MeV)
C    Ta-180m       0.01201          -48.8594
C    Ta-181       99.98799          -48.4419
C
C   Atomic Weight:  180.94788 g/mol
C         Density:  16.4 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Ta-180       0.000120           0.000119          0.0000066
C  Ta-181       0.999880           0.999881          0.0545744
C
C  The total compound atom density (atom/b-cm):  0.0545810
C
M73     73000.84p   1.000000
C
C  To convert a particle flux to rad[Material]
C  use FM  5.3316296E-11 73   -4  1 for neutrons
C   or FM  5.3316296E-11 73   -5 -6 for photons.
C
C
C
C
C   Bismuth from Nuclear Wallet Cards - Electronic Version
C    Isotope   atomic abundance    delta (MeV)
C    Bi-209        100.0%          -18.2593
C
C   Atomic Weight:  208.98040 g/mol
C         Density:  9.747 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Bi-209       1.000000           1.000000          0.0280877
```

```
C
C  The total compound atom density (atom/b-cm):  0.0280877
C
M83     83000.84p   1.000000
C
C  To convert a particle flux to rad[Material]
C  use FM  4.6164478E-11 83   -4  1 for neutrons
C   or FM  4.6164478E-11 83   -5 -6 for photons.
C
C
C
C  Solder - Sn/Pb - 63/37
C
C   Material extracted from CMOS7 stack-up
C   Atom fractions in the stack-up deck from C. D. Peters
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Sn-112       0.007258           0.005760          0.0002688
C  Sn-114       0.004938           0.003989          0.0001829
C  Sn-115       0.002544           0.002073          0.0000942
C  Sn-116       0.108792           0.089431          0.0040287
C  Sn-117       0.057464           0.047645          0.0021280
C  Sn-118       0.181221           0.151540          0.0067109
C  Sn-119       0.064273           0.054203          0.0023801
C  Sn-120       0.243772           0.207306          0.0090272
C  Sn-122       0.034643           0.029952          0.0012829
C  Sn-124       0.043322           0.038072          0.0016043
C  Pb-204       0.003525           0.005099          0.0001305
C  Pb-206       0.060677           0.088642          0.0022470
C  Pb-207       0.055642           0.081681          0.0020605
C  Pb-208       0.131929           0.194605          0.0048855
C
C  The total compound atom density (atom/b-cm):  0.0370314
C
M201    50000.84p   0.748227
        82000.84p   0.251773
C
C  To convert a particle flux to rad[Material]
C  use FM  6.8424849E-11 201  -4  1 for neutrons
C   or FM  6.8424849E-11 201  -5 -6 for photons.
C
C
C   Copper from Nuclear Wallet Cards - Electronic Version
C    Isotope   atomic abundance    delta (MeV)
C     Cu-63       69.15%            -65.5792
C     Cu-65       30.85%            -67.2633
C
C   Atomic Weight:  63.546 g/mol
C         Density:  8.94 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Cu-63        0.691500           0.684792          0.0585858
C  Cu-65        0.308500           0.315208          0.0261370
C
C  The total compound atom density (atom/b-cm):  0.0847227
C
M202     29000.84p   1.00000
C
C  To convert a particle flux to rad[Material]
```

```
C  use FM  1.5181860E-10 202  -4  1 for neutrons
C   or FM  1.5181860E-10 202  -5 -6 for photons.
C
C
C
C
C   Nickel from Nuclear Wallet Cards - Electronic Version
C    Isotope   atomic abundance    delta (MeV)
C     Ni-58       68.077%          -60.2281
C     Ni-60       26.223%          -64.4725
C     Ni-61       1.1399%          -64.2212
C     Ni-62       3.6346%          -66.7458
C     Ni-64       0.9255%          -67.0984
C
C   Atomic Weight:  58.6934 g/mol
C         Density:  8.902 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Ni-58        0.680770           0.671978          0.0621799
C  Ni-60        0.262230           0.267759          0.0239515
C  Ni-61        0.011399           0.011834          0.0010412
C  Ni-62        0.036346           0.038349          0.0033198
C  Ni-64        0.009255           0.010080          0.0008453
C
C  The total compound atom density (atom/b-cm):  0.0913376
C
M203    28000.84p   1.000000
C
C  To convert a particle flux to rad[Material]
C  use FM  1.6437075E-10 203  -4  1 for neutrons
C   or FM  1.6437075E-10 203  -5 -6 for photons.
C
C
C
C   Gold from Nuclear Wallet Cards - Electronic Version
C    Isotope   atomic abundance    delta (MeV)
C    Au-197        100.0%          -31.1409
C
C   Atomic Weight:  196.966569 g/mol
C         Density:  19.3 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Au-197       1.000000           1.000000          0.0590087
C
C  The total compound atom density (atom/b-cm):  0.0590087
C
M204    79000.84p   1.000000
C
C  To convert a particle flux to rad[Material]
C  use FM  4.8980243E-11 204  -4  1 for neutrons
C   or FM  4.8980243E-11 204  -5 -6 for photons.
C
C
C
C  BT Laminate from CMOS7 Stack
C
C   Material extracted from CMOS7 stack-up
C   Based on atomic data in the stack-up
C
```

```
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   H-1         0.360518           0.042790          0.0334951
C   H-2         0.000041           0.000010          0.0000039
C   C-12        0.486645           0.687742          0.0452133
C   C-13        0.005263           0.008060          0.0004890
C   N-14        0.070427           0.116144          0.0065433
C   N-15        0.000257           0.000455          0.0000239
C   O-16        0.076661           0.144407          0.0071224
C   O-17        0.000029           0.000058          0.0000027
C   O-18        0.000158           0.000334          0.0000146
C
C  The total compound atom density (atom/b-cm):  0.0929083
C
M205    01000.84p   0.360560
        06000.84p   0.491908
        07000.84p   0.070684
        08000.84p   0.076848
C
C  To convert a particle flux to rad[Material]
C  use FM  1.1361758E-09 205  -4  1 for neutrons
C   or FM  1.1361758E-09 205  -5 -6 for photons.
C
C
C  Ablebond 8361 J from CMOS7 Stack
C
C   Material extracted from CMOS7 stack-up
C   Based on atomic data in the stack-up
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   H-1         0.396713           0.016453          0.0334265
C   H-2         0.000046           0.000004          0.0000038
C   C-12        0.333858           0.164865          0.0281305
C   C-13        0.003611           0.001932          0.0003043
C   O-16        0.092832           0.061103          0.0078219
C   O-17        0.000035           0.000025          0.0000030
C   O-18        0.000191           0.000141          0.0000161
C  Cl-35        0.002844           0.004093          0.0002397
C  Cl-37        0.000910           0.001384          0.0000767
C  Ag-107       0.087587           0.385321          0.0073800
C  Ag-109       0.081373           0.364678          0.0068564
C
C  The total compound atom density (atom/b-cm):  0.0842587
C
M206    01000.84p   0.396759
        06000.84p   0.337469
        08000.84p   0.093058
        17000.84p   0.003754
        47000.84p   0.168960
C
C  To convert a particle flux to rad[Material]
C  use FM  3.9700715E-10 206  -4  1 for neutrons
C   or FM  3.9700715E-10 206  -5 -6 for photons.
C
C
C
C  To convert a particle flux to rad[Material]
C  use FM  6.6316874E-10 1    -4  1 for neutrons
C   or FM  6.6316874E-10 1    -5 -6 for photons.
C
```

```
C   Silicon at 2.33 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Si-28        0.922230           0.918665          0.0460749
C  Si-29        0.046850           0.048336          0.0023406
C  Si-30        0.030920           0.032999          0.0015448
C
C  The total compound atom density (atom/b-cm):  0.0499603
C
M207      14000.84p   1.000000
C
C  To convert a particle flux to rad[Material]
C  use FM  3.4350364E-10 207  -4  1 for neutrons
C   or FM  3.4350364E-10 207  -5 -6 for photons.
C
C
C
C  SiO2 from CMOS7 Stack
C
C   Material extracted from CMOS7 stack-up
C   Based on atomic data in the stack-up
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   O-16        0.665047           0.531122          0.0439132
C   O-17        0.000253           0.000215          0.0000167
C   O-18        0.001367           0.001228          0.0000902
C  Si-28        0.307410           0.429416          0.0202984
C  Si-29        0.015617           0.022594          0.0010312
C  Si-30        0.010307           0.015425          0.0006806
C
C  The total compound atom density (atom/b-cm):  0.0660303
C
M208    08000.84p   0.666667
        14000.84p   0.333333
C
C  To convert a particle flux to rad[Material]
C  use FM  4.8169663E-10 208  -4  1 for neutrons
C   or FM  4.8169663E-10 208  -5 -6 for photons.
C
C
C
C  Tungsten at 19.3 g/cc
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   W-180       0.001200           0.001175          0.0000759
C   W-182       0.265000           0.262271          0.0167537
C   W-183       0.143100           0.142406          0.0090470
C   W-184       0.306400           0.306582          0.0193710
C   W-186       0.284300           0.287567          0.0179738
C
C  The total compound atom density (atom/b-cm):  0.0632214
C
M209    74000.84p   1.000000
C
C  To convert a particle flux to rad[Material]
C  use FM  5.2477033E-11 209  -4  1 for neutrons
C   or FM  5.2477033E-11 209  -5 -6 for photons.
```

```
C
C
C  ABS Plastic from CMOS7 Stack
C
C   Material extracted from CMOS7 stack-up
C   Based on atomic data in the stack-up
C
C   Summary of MatMCNP (Version 3.0) Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   H-1         0.515091           0.081073          0.0445688
C   H-2         0.000059           0.000019          0.0000051
C   C-12        0.449686           0.842750          0.0389096
C   C-13        0.004864           0.009877          0.0004208
C   N-14        0.030190           0.066022          0.0026122
C   N-15        0.000110           0.000258          0.0000095
C
C  The total compound atom density (atom/b-cm):  0.0865261
C
M210    01000.84p   0.515150
        06000.84p   0.454550
        07000.84p   0.030300
C
C  To convert a particle flux to rad[Material]
C  use FM  1.5066821E-09 210  -4  1 for neutrons
C   or FM  1.5066821E-09 210  -5 -6 for photons.
C
C
C
C ********************
C *  PHOTON TALLIES  *
C ********************
C
F4:P   1504
FC4    Photon Fluence in the Detector Sphere (Photons/cm**2)
C
F14:P   1504
FC14    Silicon Kerma in Detector Sphere (Rad[Si])
FM14    3.4350364E-10 207  -5 -6
C
C
F104:P  1521
FM104   3.4350364E-10 207   -5 -6
FC104   Average Silicon Kerma in Si Active Region (Rad[Si])
C
C
C  The collision heating tally (+F6) always applies to all particles
C   in a problem according to the MCNP6 User's Manual.
C
+F106    1521
FC106    Energy Deposition in Si in Box 1 (MeV/g)
C
+F746    1522
FC746    Energy Deposition in W (MeV/g)
C
+F756    1520
FC756    Energy Deposition in SiO2 (MeV/g)
C
C
C
C
C
```

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