AN ABSTRACT OF THE THESIS OF

Errol D.I. Newman for the degree of Master of Science in Radiation Health Physics presented on June 7, 2007

Title: A Comparison of Measured and Simulated Exposure Rates Near Tungsten- Based Medical Transport Pigs

Abstract approved:

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David M. Hamby

A lack of data concerning tungsten-based medical shields, specifically unit dose transport pigs, may lead to unnecessary exposure to medical personnel. Available research comparing lead to sintered tungsten shows that tungsten is approximately 1.5 – 10.0 times more effective as a radiation shield. However, this research lacks high-energy vs. low-energy photon response. It also does not examine specific isotopes used in the nuclear pharmacy industry. If an accurate set of models could be made for these pigs, then extensive shielding tests could be done in simulations, with no health hazard present. A series of physical measurements of exposure rates were done using both high-energy and low- energy gamma emitters in various transport pigs used in the radio- pharmaceutical industry. Simulation models were also constructed using Monte Carlo n-Particle version 5. There was a close correlation between the Monte-Carlo simulations and calculated values. The models appear to phsycially behave as expected and may provide a fundamental basis for more focused dose rate studies utilizing Monte-Carlo simulations. The physical experiment did not support the calculated data but could provide a methodological starting point for future experimenters who wish to perform similar measurements in a more controlled environment.

A Comparison of Measured and Simulated Exposure Rates Near Tungsten-Based Medical Transport Pigs

by
Errol D.I. Newman

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Errol D.I. Newman, Author

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A Comparison of Measured and Simulated Exposure Rates Near of Tungsten-Based Medical Transport Pigs

Chapter 1 - Introduction

Shielding is a fundamental part of radiation protection. It is the only one of the three protection factors of time, distance and shielding that can be directly improved with technology. Ideally, when dealing with radioactivity, shielding should be available to make dose negligible, even if full advantage is not taken of the other two factors. However, some practical considerations such as cost of materials, size and weight of the shielding encourage a cost-benefit balance approach. New ways of using materials, such as composites or sintering, can result in vastly material-dependant effectiveness.

The work described in this report is an analysis of the use of an older technology recently applied to shielding applications. The product is sintered tungsten, which has a number of advantages over lead, the traditional and most widely used shielding product of choice. The shields evaluated were unit-dose medical radioisotope transport shields, known as pigs, in use by the Cardinal Health[1] Corporation.

Available research comparing lead and sintered tungsten of equal thickness shows that tungsten is approximately 1.5 – 10.0 times more effective as a radiation shield [3,8,11]. However, the available research lacks detailed high-energy vs. low-energy photon response, and does not consider specific isotopes used in the nuclear pharmacy industry. If an accurate set of

[1] Cardinal Health Inc. 7000 Cardinal Place, Dublin, Ohio 43017

computer models could be created for these pigs, extensive shielding tests could be done with no health hazard present.

In this work, two sources of data were used to analyze the shielding effectiveness of the pigs. First, exposure rates were physically measured in several of the Cardinal pigs containing radiopharmaceuticals. Second, a set of computer models, using Monte-Carlo methods, was generated to closely match the physical measurements. These data were examined and compared.

Chapter 2 - Background

2.1 History

Soon after radiation was discovered, it was utilized for medical purposes. In the first quarter of the twentieth century safety was not typically a concern. However, as soon as the detrimental effects of ionizing radiation were discovered, society began to develop methods for protection. Protection standards have gone through many revisions as our understanding of the hazards of ionizing radiation has increased.

Various organizations exist that provide information and protection standards to the public and industry. The BEIR (Biological Effects of Ionizing Radiation) committee publishes risk estimates for exposure to ionizing radiation. The NCRP (National Council on Radiation Protection), ”disseminate(s) information and research data about radiation exposure and protection guidelines in the public interest”[7]. The ICRP (International Commission on Radiological Protection) also publishes reports that provide guidelines for radiation protection. Although these agencies have no way to enforce their recommendations, most nations, including the U.S., consider these publications when developing their own radiation protection standards.

2.2 Medical Physics

Today, medical physics is a major industry. A large number of medical techniques are employed which utilize radiation. The most common technique is X-ray imaging. External photon and particle radiation also are employed to destroy cancer cells. Radio-labeled pharmaceuticals are used to target specific internal organs for both information and therapy; this technique is most pertinent to this research.

For internal therapy the type of radionuclide needs to be considered carefully. Its properties are customized for the purpose of the technique. For example, in cancer therapy, an alpha emitter applied internally is appropriate due to its high linear energy transfer. For imaging, a low-energy gamma emitter is preferable because it has the least impact on living cells, as well as being easily visible to external detectors. A property of almost all medical radioisotopes is that they are relatively short lived. This, combined with radio-labeled cells, designed to accumulate in certain organs, ensures that cancerous tissue receives as much dose as possible while healthy tissue is spared. The technicians who initially separate and distribute the radiopharmaceuticals must sometimes deal with considerably large activities because of the fast decay rates of these nuclides. Strict handling and monitoring procedures for these technicians is necessitated to ensure their safety.

2.3 Cardinal Health

The experimental portion of this work was done at various Cardinal Health, Inc. facilities. Cardinal Health is the primary provider of nuclear pharmaceuticals in the United States. Cardinal Health has 130 pharmacies in the U.S. that distribute product to over seven thousand health care facilities [2]. The Nuclear Pharmacy Division of Cardinal only came into existence in 2002 when Cardinal Health bought the Syncor International Corporation for the purpose of establishing a core unit for their radiopharmacy division.

Previously, Syncor used lead-based pigs for the transport of their nuclear medicine radioisotopes. Cardinal Health is now making a transition into using almost exclusively tungsten shielding.

2.4 Medical Radioisotope Generation

Cardinal Health produces the isotopes it distributes from cyclotron facilities or from decay generators located in pharmacies. It is imperative that isotopes be produced in a location very close to their distribution hub, because of their fast decay times.

2.4.1 Molybdenum and Technecium

The isotope used in the majority of nuclear medicine procedures is Technecium-99m, abbreviated Tc-99m. Technecium-99m is a decay product of Molybdenum-99, Mo-99. A source of Mo-99 is allowed to decay and the Tc-

99m is chemically separated. Molybdenum-99 can be used as a long-term source of Tc-99m, because it has a longer half-life than Tc-99m (66.02 hours vs. 6.01 hours). Molybdenum-99 is typically produced from nuclear fission reactors. When the enriched uranium fuel fissions, it yields a variety of other nuclides, 6.1% of which are Mo-99 [6]. It is then separated chemically from the other fission products and can be used for medical purposes. One advantage to this method is a high purity product that yields high activities of Mo-99. One significant disadvantage is that it is costly due to the separation issues associated with fission waste. An alternative method for Mo-99 production is a $Mo^{98}(n, \gamma)Mo^{99}$ reaction. This method does not yield a product as pure as the fission waste separation method [12]. The most plentiful source of neutrons is from fission reactors. A common industrial alternative to neutron production is the $^{9}Be(\alpha,n)^{12}C$ reaction. Naturally abundant berylium-9 is bombarded with alpha radiation. The Be-9 absorbs the alpha particle to form Carbon-13, which decays to Carbon-12 by emitting a neutron. This method of neutron production avoids the costs and health risks associated with operation of a fission reactor, separation and fission waste disposal.

2.5 Photon Interaction with Matter

Photons are the primary radioactive particle relevant to this experiment. Photons interact with matter in several ways depending on their energy and the material they are interacting with. Low-energy photons favor an interaction known as the photoelectric effect, where incoming photons collide with bound electrons, are absorbed and eject the electron from it's orbital shell. This results in a free electron and a hole in the electron shell. This hole is quickly filled by another bound electron emitting an x-ray to lower it's energy and fill the vacant space. The probability of the photoelectric effect occurring is related to the energy of the incoming photon and the atomic number of the atom it is interacting with according to Equation [1]. Another common low-energy photon reaction is a Compton interaction. In this case the photon again interacts with an orbital electron but is not fully absorbed. The result is a free electron and a less energetic photon. The probability of Compton Interactions occurring is related to photon energy and atomic number but is not as sensitive over a range of these values when compared to photoelectric interactions. The equation describing the probability of a Compton interaction is found in Equation [2]. A third photon interaction mechanism that is important to this experiment is pair production. This interaction only occurs with photons of energy > 1.022MeV. A photon of sufficient energy has the chance of producing a positron-electron pair. The positron may then interact with another electron resulting in two annihilation photons with energy of 0.511MeV. All the steps in this chain of reactions conserve energy, momentum and quantum number.

Equation 1: Relationship of Photoelectric Effect to Photon Energy and Atomic Number[6].

$$\tau \approx \text{constant} \cdot Z^5/E^3$$

Equation 2: Relationship of Compton Interactions to Photon Energy and Atomic Number[6].

$$\sigma \approx \text{constant} \cdot Z/E$$

2.6 Tungsten Based Shielding

Tungsten used as a shielding material has advantages and disadvantages when compared to lead, but it is shown [3,8] that tungsten is an overall superior shielding material. Sintered tungsten has a density of 19.3 $g \cdot cm^{-3}$ vs. the density of lead, 11.34 $g \cdot cm^{-3}$ [3]. The result is that for equivalent radiation protection, a smaller layer of tungsten is needed than lead. Tungsten also has a greater hardness than lead, 82 GPa rigidity modulus versus 5.59 GPa, respectively, resulting in a very durable final product. Lead pigs must be replaced every few years; tungsten pigs can last indefinitely. Another advantage of tungsten is that it has a much lower bio-toxicity when compared to lead. This allows an organization to avoid the cost of hazardous waste disposal and simplifies safe handling procedures. The disadvantages of using tungsten are mainly related to its expense. Tungsten is less abundant than lead and, therefore, more costly in its raw form. In addition, a very high melting point (3410 °C) makes tungsten molds infeasible. Sintering, a more expensive process, is used in producing the Cardinal Health line of pigs. Additionally tungsten is slightly less effective than lead because its proton number is lower, lead has an atomic number of 82 versus 74 for tungsten. This makes it slightly less effective at interacting with radiation on a nuclear level but the higher density of tungsten more than overcomes this.

2.7 Sintering

Sintering is a forging process similar to ceramic firing that involves the encouragement of crystal growth and material densification. Powder sintering heats the material below its melting point under high pressure to encourage the individual particles to adhere. The sintering method can be modified to develop porous or non-porous items with varying densities. The Cardinal pigs start as a metal powder consisting of 95% tungsten, 3.5% nickel and 1.5% iron [3]. This powder is then sintered to yield a high density, low porosity material that is ideal for radiation protection. Figures [1] and [2] depict the key points of sintering, grain growth and densification, respectively. Although this report deals specifically with powder tungsten sintering, the process can be applied to a wide variety of metals for different applications. Lead can also be sintered but the hazardous aspects of the metal remain resulting in little measurable benefit from such a product for shielding applications.

Figure 1: Grain Growth: Illustration of grain growth in the sintering process. Average crystal size is increased.

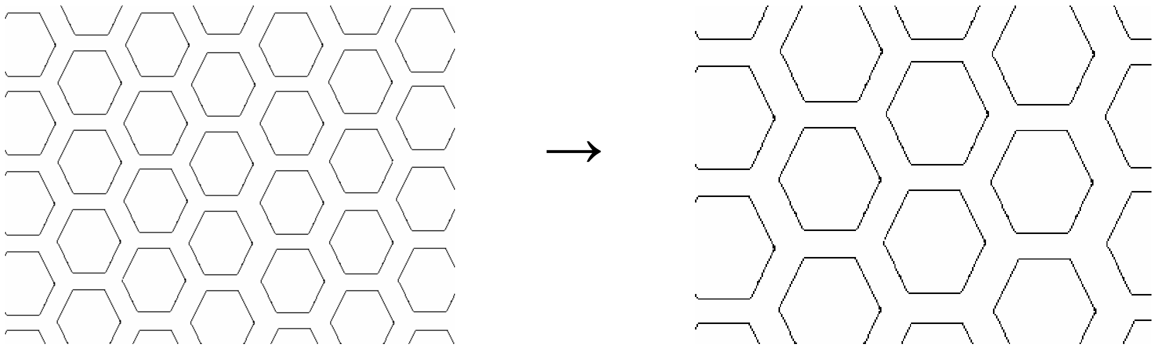
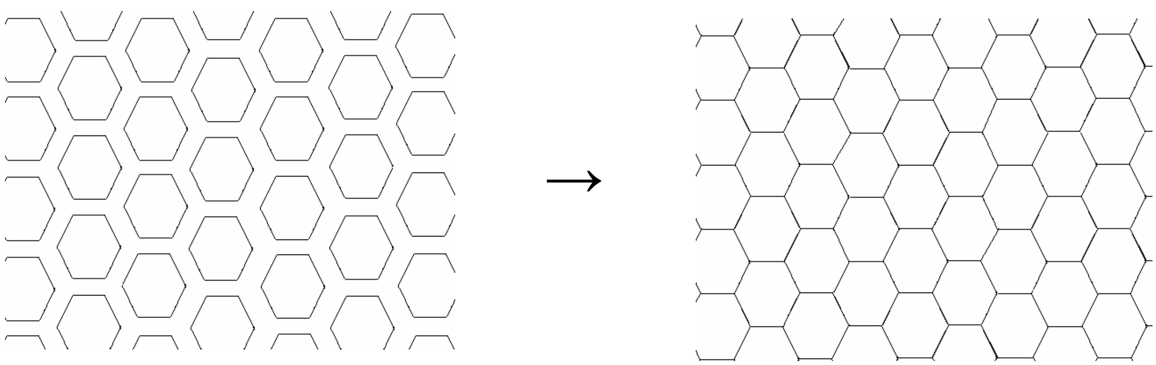


Figure 2: Densification: Illustration of densification in the sintering process. Crystal units become more densely packed.



Chapter 3 - Materials and Methods

3.1 Detector

The detector used in this experiment is the PDE-4 personal dosimeter, produced by the Science Applications International Corporation[2]. The unit is designed to work as a personal dosimeter that measures exposure from the base unit and up to four remote sensors. An available option for the PDE-4 is to display an estimated dose. This is accomplished by multiplying the exposure by an internally defined conversion factor. The detector volume of the probes and their high photon sensitivity make the SAIC PDE-4 a preferable choice for this experiment. This allowed many readings to be taken along the side of the pigs, and thus allows a smooth exposure profile to be developed.

The SAIC PDE-4 is no longer actively produced, but was intended as a long-term personal dosimetry system. Considering the advantages it offered, the PDE-4 also presented a few complications. The timing system of the PDE-4 was inflexible; the timing mechanism responds dynamically to changing exposure rates, because of its primary use as a personal dosimeter. When exposed to low intensity radiation fields the PDE-4 will measure exposure for 64 seconds between estimated dose readings. Higher exposure rates were calculated and refreshed every two seconds. The implication of this on data integrity is discussed in Chapter 6.

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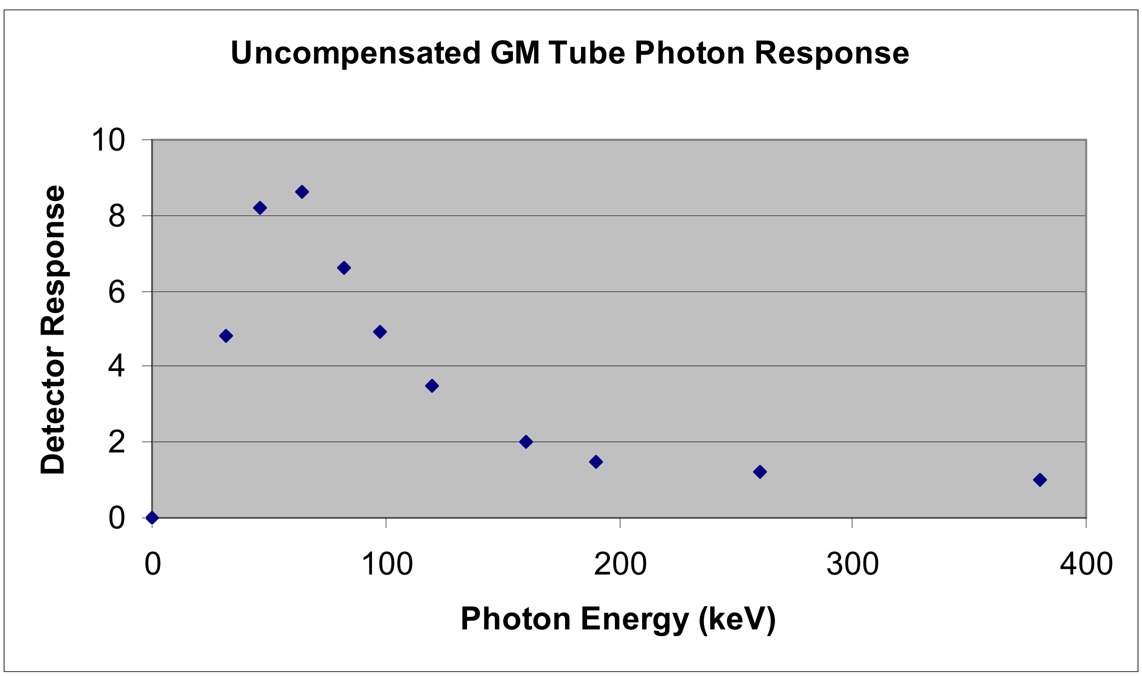
[2] SAIC Headquarters 10260 Campus Point Dr. San Diego, CA 92121

The main PDE-4 unit utilizes an energy-compensated GM tube that compensate for the over-response of low-energy photons inherent in the basic GM tube design. The probes, however, utilized standard GM probes. This has the potential to severely affect the magnitude of the dose rate because many of the photons that reached the detector are highly attenuated. Manual energy compensation is possible, by taking an MCA (Multi-Channel Analyzer) spectrum for each pig using a Sodium Iodide detector. The details of this are explained in Chapter 6. Figure [3] depicts the data points provided by the PDE-4 manual describing how the probes respond to photon energy.

Figure 3: Photon energy to dose response points for the SAIC PDE-4



3.2 Monte Carlo n-Particle Version 5

Theoretical estimates of exposure rate around shielding pigs were performed with MCNP5[10] (Monte Carlo n-Particle Version 5). Monte Carlo n-Particle Version 5 is a statistical transport code that has been under continuous development for almost 50 years. As the name implies, it does not calculate particle movement analytically, but instead uses statistics based on the energy, type of radiation and the properties of the simulated materials to "roll the weighted dice" [14] to determine the particle's ultimate fate. The statistical approach allows much more complex problems to be run because the computer processing time and memory requirements are much less significant than the set of differential equations needed to solve the problem analytically.

Monte Carlo n-Particle was originally a program that processed a text file. This required that programmers be able to clearly visualize the geometry of their problem in relation to the MCNP coding. The more complex a particle transport problem became, the greater the likelihood of minor geometry problems which prevented the simulation from running properly.

In 1992, Randy A. Schwarz and Dr. Lee Carter began developing a visual interface for MCNP geometry construction, which they aptly named MCNP Visual Editor [10]. The Visual Editor was originally intended to help them with their work in MCNP. The importance of a solidly built computer aided drafting program for MCNP quickly became clear, and Mr. Schwarz and Dr. Carter began full time development of this software. By 2001, the companies, Monte Carlo Analysis Incorporated and Visual Editor Consultants, were formed. Development of the Visual Editor is ongoing, and Dr. Carter and Mr. Schwarz continue to educate people in its use and expand its functionality.

This project was coded with a combination of basic text file editing and the use of MCNP Visual Editor. The Visual Editor was used in the early stages of development for each geometry to define materials and ensure that there were no geometrical inconsistencies. After a solid geometry was created, DOS text editing was used to define the source, photon importance, tallies and dose conversions.

Chapter 4 - Procedure

4.1 Introduction

The work herein can be separated into two components, the experiment and the simulation. The experiment involved utilizing leftover radioactive material from various Cardinal Health pharmacies to measure exposure rate at various locations on the surface of the shielding pigs. The simulation involved developing the geometric model for each class of pig in MCNP5. A number of simulations that closely approximated the experiment were processed using the MCNP5 models.

Essentially one or two radioisotope solutions (depending on the actual usage of the pig in the industry) were tested for the four pigs in question; Table [1] depicts these combinations. These choices were made with several considerations: the first being the nuclide transported in the pig; the second being which nuclides were available for the experiment; and the third being the differential attenuation of high-energy and low-energy photons by the pigs.

Table 1: Pig/Radionuclide Configurations, this table describes the nuclides that were tested in each pig based on use, gamma energy and availability.

	Photons	
	High-Energy	Low-Energy
PET Pig	F-18	N/A
30mL Dispenser	F-18	N/A
5mL Unit Dose	Ga-67	Tc-99m
Piglet	F-18	I-131

4.2 Sampling

A series of test locations were chosen on each pig. These points are shown in Tables [2]-[5] and were chosen to determine points of maximum exposure rate, typical exposure rate and to identify hot spots along the pig profile. In addition, a location 30cm from the center of where the nuclide would rest was measured. This data point was used to help estimate the dose rate a technician might receive to their trunk while transporting the pig.

The locations on the 5cc Unit Dose pig are shown in Table [2]. Data point information for the Piglet is shown in Table [3]. Information for the 10cc PET Pig is shown in Table [4], and data for the 30mL PET Dispenser is shown in Table [5]. Pictures of the pigs with the exposure test points marked are shown in Figures [4]-[8].

Table 2: 5cc Unit Dose Pig - Dose Points, quantitative depiction of dose points for the 5cc Unit Dose Pig

Point	Location	Description
1	Top	Top
2	30mm down	Just below plastic topper
3	63mm down	Bottom of sloped tungsten on top half
4	76 mm down	Coincides with the lid seam
5	85 mm down	Just under the screw lid for the base
6	40 mm down	From top of Base
7	80 mm down	From top of Base
8	Bottom	Bottom Center

Table 3: Piglet - Dose Points, quantitative depiction of dose points for the Piglet

Point	Location	Description
1	Top	Center
2	Top	Edge
3	23mm down	Coincides with the lid seam
4	48mm down	Horizontal coincidence with top of dose vial
5	73mm down	Horizontal coincidence with center of dose vial
6	Bottom	Edge
7	Bottom	Center

Table 4: 10cc PET Pig - Dose Points, quantitative depiction of dose points for the 10cc PET Pig

Point	Location	Description
1	Top	Top
2	4.76cm down	Midway down on lid
3	6.9cm down	Lid seam
4	11.21cm down	Horizontal coincidence w/ center of dose syringe
5	15.21cm down	Lower seam
6	16.81cm down	Midway between lower seam and bottom
7	Bottom	Edge
8	Bottom	Center
9	Handle	Index Finger Position

Table 5: 30mL PET Dispenser - Dose Points, quantitative depiction of dose points for the 30mL PET Dispenser

Point	Location	Description
1	Top	Top center
2	10mm down	Adjacent to the magnetic lid
3	35mm down	The lid seam
4	58mm down	Just above the primary handle
5	93mm down	Centered on the isotope vial
6	135mm down	Sloped bottom edge
7	Bottom	Bottom Center
8	Handle	Primary Handle, where the index finger would be

Figure 4: Exposure Points on 10mL PET Pig, exposure points chosen on the 10mL PET Pig to find shielding effectiveness at thin points, seals and typical human contact points.

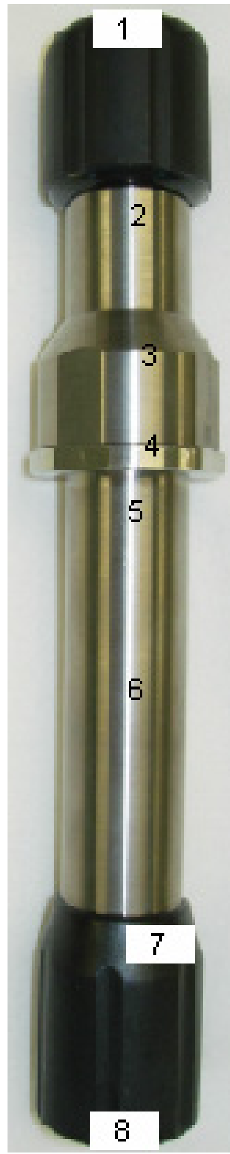


Figure 5: Exposure Points on 5mL Tungsten Pig, exposure points chosen on the 5mL Unit Dose Pig to find shielding effectiveness at thin points, seals and typical human contact points

Figure 6: Exposure Points on 30mL PET Dispenser, exposure points chosen on the 30mL PET Dispenser to find shielding effectiveness at thin points, seals and typical human contact points.

Figure 7: Exposure Points on Piglet, exposure points chosen on the Piglet to find shielding effectiveness at thin points, seals and typical human contact points.

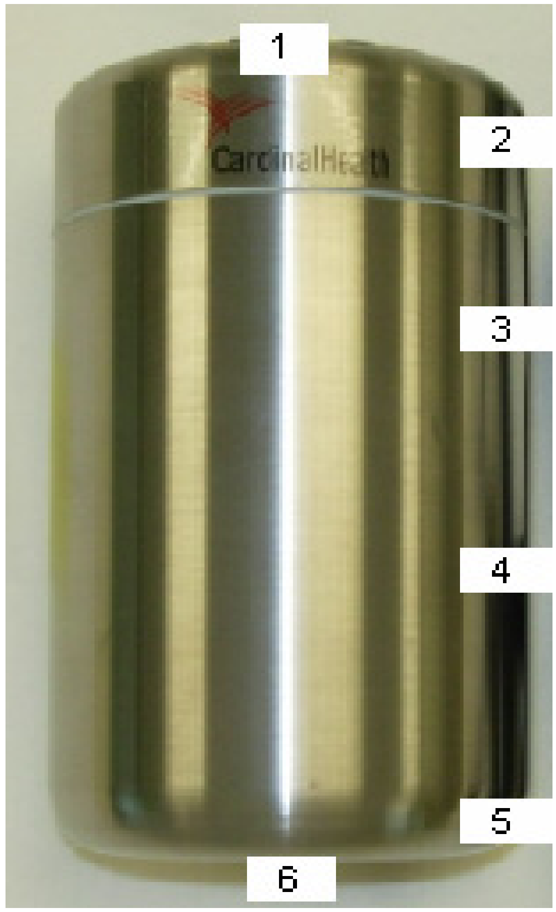


Figure 8: Exposure Points on the $Piglet_3$, exposure points chosen on the $Piglet_3$ to find shielding effectiveness at thin points, seals and typical human contact points.

4.3 Experimental Work

4.3.1 Setup

Cardinal Health pharmacists prepared the isotopes for use in this experiment. Their activities were based on the theoretical maximum that a specific pig could transport. These maximums were determined by maximum therapeutic doses and accounting for holding and transfer time between pharmacy and patient. A location was chosen to conduct the experiment that was away from generators and other radioisotopes in order to minimize background readings. The PDE-4 was setup in the lab area with a single probe attached to external port one. The MODE setting on the PDE-4 was set to display the exposure rate from the probe.

4.3.2 F-18 Testing

A therapeutic dose of Tc-99m can have a range of volumes. A therapeutic dose is a different term than a dose of radiation. A therapeutic dose refers to the radioisotope, chemical compounds and saline solution that is injected into the patient. The radiation dose is the amount of radiation energy absorbed by living tissue. The pharmacist is concerned primarily about activity. The pharmacists indicated that they tend to dispense a therapeutic dose in volumes ranging from 3 mL -7 mL. The majority of doses are dispensed in full 5 mL syringes. However a full 5.0 mL syringe, filled to capacity, spilled radionuclide into the pig when it was capped. For this reason the effective full volume in a 5 mL syringe (4.5 mL) was chosen to represent the "typical" dose volume in this experiment.

The intention of this initial phase of the experiment was to determine if smaller volumes of a typical therapeutic dose generated a higher exposure rate at the test points. This was considered because a constant radionuclide activity is used and a smaller volume would make that activity more concentrated and result in a higher dose at points physically closer to the source. A secondary objective was to identify weak spots in the shielding that may not be intuitive. Flourine-18, a positron emitter, was placed in each pig in varying volumes in order to determine the volume of radioisotope that coincided with the exposure profile that generated the point of highest radiation exposure.

Flourine-18 was chosen for this test because a nuclide was needed that would generate a clearly visible exposure profile outside all pigs. The F-18 positrons would collide with and annihilate electrons, generating two 0.511MeV photons. A concentrated volume, 937mCi in 3.0mL, of F-18 was placed in a vial or syringe, as appropriate, into each pig. The exposure was measured at each data point described in Tables [2]-[5]. The F-18 was then diluted to a slightly larger volume, about 4.5mL, and each point was tested again. A third dilution, to a volume of 9.0mL, was performed and tested in the pigs that were designed to hold up to 10mL volumes. Ultimately, either two or three exposure profiles were generated. In addition to providing a general sense of the shape for the exposure profiles, this procedure generated the numerical data needed for F-18 in the 30mL PET Dispenser and 10mL PET Pig. Note that the $Piglet_3$ was used instead of the Piglet for this aspect of the experiment; placing F-18 in the Piglet resulted in detector saturation making the results meaningless. The $Piglet_3$ has significantly heavier shielding than the Piglet, thus avoiding the detector saturation issue. An extrapolation of results, regarding leaks from container seams or weak points in shielding, from the $Piglet_3$ to the Piglet seemed reasonable because the $Piglet_3$ has essentially the same geometry as the Piglet.

Multi-Channel Analyzer (MCA) spectra using a Sodium Iodide detector were obtained for each of the F-18/Pig configurations. The purpose of this was to see how much photon energy attenuation occurred in order to manually compensate for the non-energy compensated GM probes on the PDE-4. A further examination of this method is found in the analysis chapter.

4.3.3 Tc-99m Testing

The primary nuclide transported in the 5 mL Unit Dose pig is Tc-99m. An activity of 1000mCi in 4.5 mL of saline was placed in a 5 mL syringe. The PDE-4 probe was placed at each test point and held there for three minutes. This ensured that the displayed exposure rate was within the sixty-four second integration window for the PDE-4. A five-minute MCA spectrum from a sodium iodide detector was obtained taken from the bottom point on the 5mL Unit Dose pig.

4.3.4 I-131 Capsules

The Piglet is designed to hold caplets as opposed to a liquid source solution. Four capsules of I-131 were prepared to test the Piglet. The PDE-4 was placed at each of the dose locations described in Table [3] until the PDE-4 read a stable reading for several seconds.

4.4 MCNP5 Models

MCNP5 simulations were designed to closely approximate the experiment. Some simplifications were made to the geometries in order to simplify the simulation but have a minimal impact on the estimated exposure. The materials were defined based on Cardinal Health documents and BEIR V.

The materials were defined in MCNP5 to an accuracy of a hundredth of a percent. The sintered tungsten was defined in Cardinal Health pamphlets promoting the sintering process. The stainless steel present in most of the pigs was defined as type CA-6NM as specified by The Hendrix Group [4] website. The exact type of stainless steel used in the pigs was not documented, but the physical properties and typical uses of CA-6NM made it seem an appropriate choice. The liquid sources were defined as a low concentration saline solution. The radioactive atoms were omitted from the composition because their number compared to the number of H_2O molecules was well below 0.01%. The external test locations were defined as human tissue, as defined by BEIR V. The exact compositions of all materials are described more fully in Table [6].

Table 6: Material Compositions, material compositions based off of BEIR V, Cardinal Health and Hendrix Group publications.

	Percent Composition		
Element	Stainless Steel	Human Tissue	Sintered Tungsten
Iron	80.66%		3.50%
Carbon	0.06%	18%	
Manganese	0.01%		
Phosphorus	0.05%	1%	
Sulfur	0.04%		
Silicon	1%		
Chromium	12.50%		
Nickle	4%		3.50%
Molybdenum	0.70%		
Oxygen		65%	
Hyrdrogen		10%	
Nitrogen		3%	
Calcium		1.50%	
Tungsten			95%

For coding simplicity there were a few simplifications made in the MCNP5 simulations. The ergonomic handles on the 30mL PET dispenser and the 10mL PET Pig were simplified as follows: the foundation ring was defined as an annulus, which is actually very close to its physical reality; the stem and handle were defined as simple cylinders; the handle was also coded to point along the Z-axis, instead of being slanted. This choice was made because it greatly simplified the coding without seeming to seriously affect the accuracy of the simulation. The exposure locations were defined as cylinders 2cm long with radii of 0.5cm. This is the approximate dimension of the PDE-4 probes, which were similar to the size of adult fingertips. Figures [9] – [12] are screenshots of the MCNP5 models as shown by the Visual Editor.

The number of photons followed in each simulation varied based on the pig/nuclide combination. Twenty-million photons were tracked for the 10mL PET Pig, 30mL Pet Dispenser, and the $Piglet_3$ with F-18. Five-million photons were used in the 30mL PET dispenser simulation with F-18. Four-million photons were used for the Ga-67 in the 5mL Unit Dose pig. One-billion photons were used for the I-131 capsules in the Piglet simulation. These choices allowed the automatic statistical checks executed by MCNP5 to pass with a value of less than 10%, which is the MCNP5 standard for a volume source. To further verify that the code was in fact doing what was expected, two runs were made for each pig/nuclide combination. The first simulation was executed to calculate the raw flux value in each cell. The second run used a conversion table to calculate the dose.

Figure 9: MCNP5 Piglet Model, colors represent different materials.

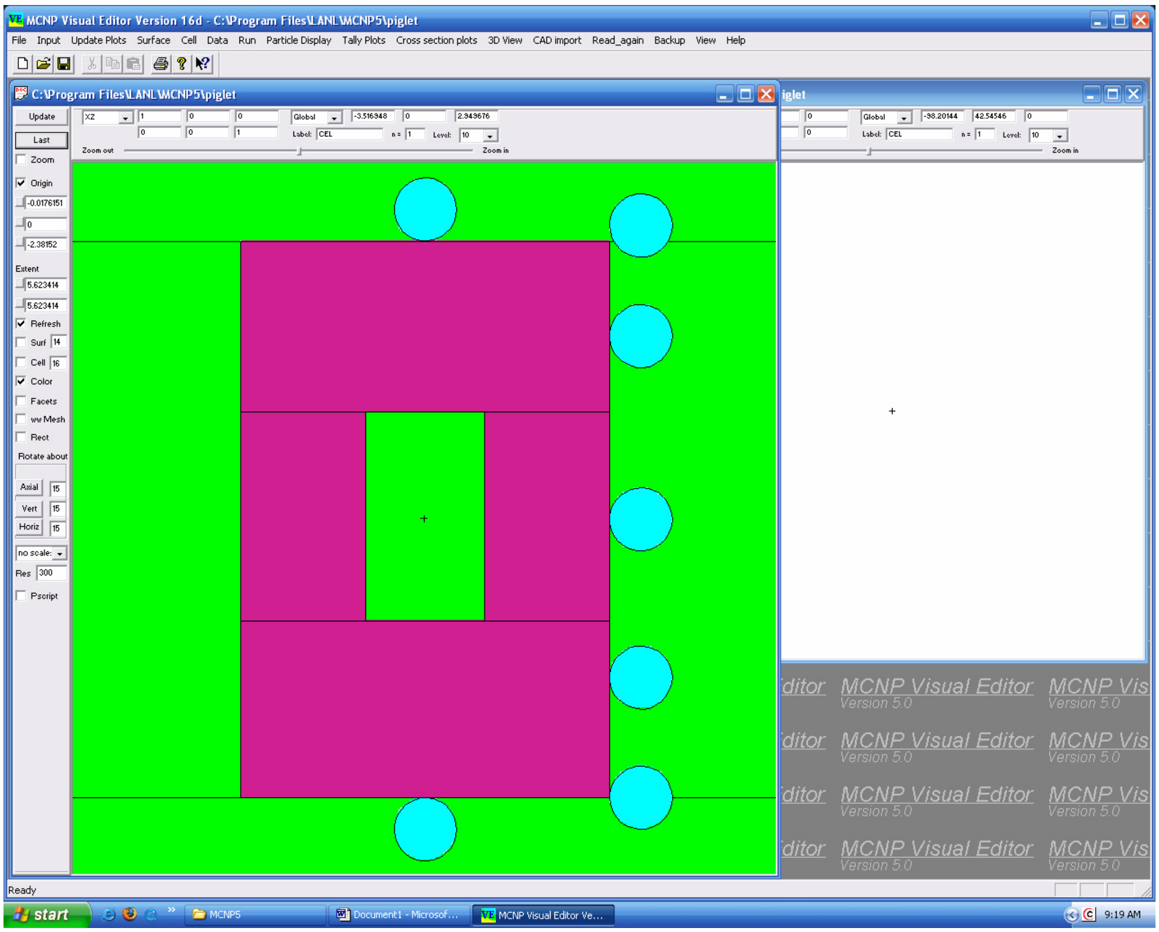


Figure 10: MCNP5 10mL PET Pig Model, colors represent different materials.

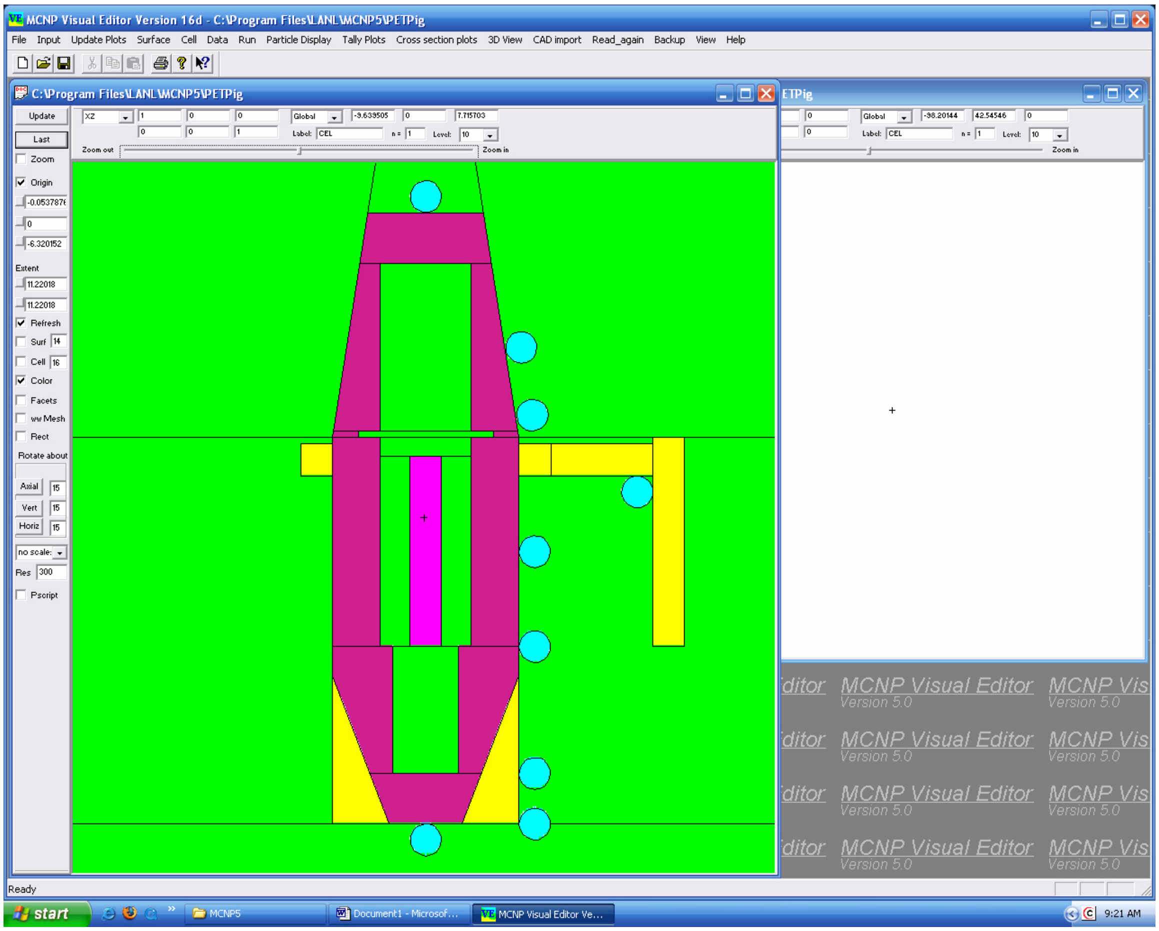


Figure 11: MCNP5 30mL PET Dispenser Model, colors represent different materials.

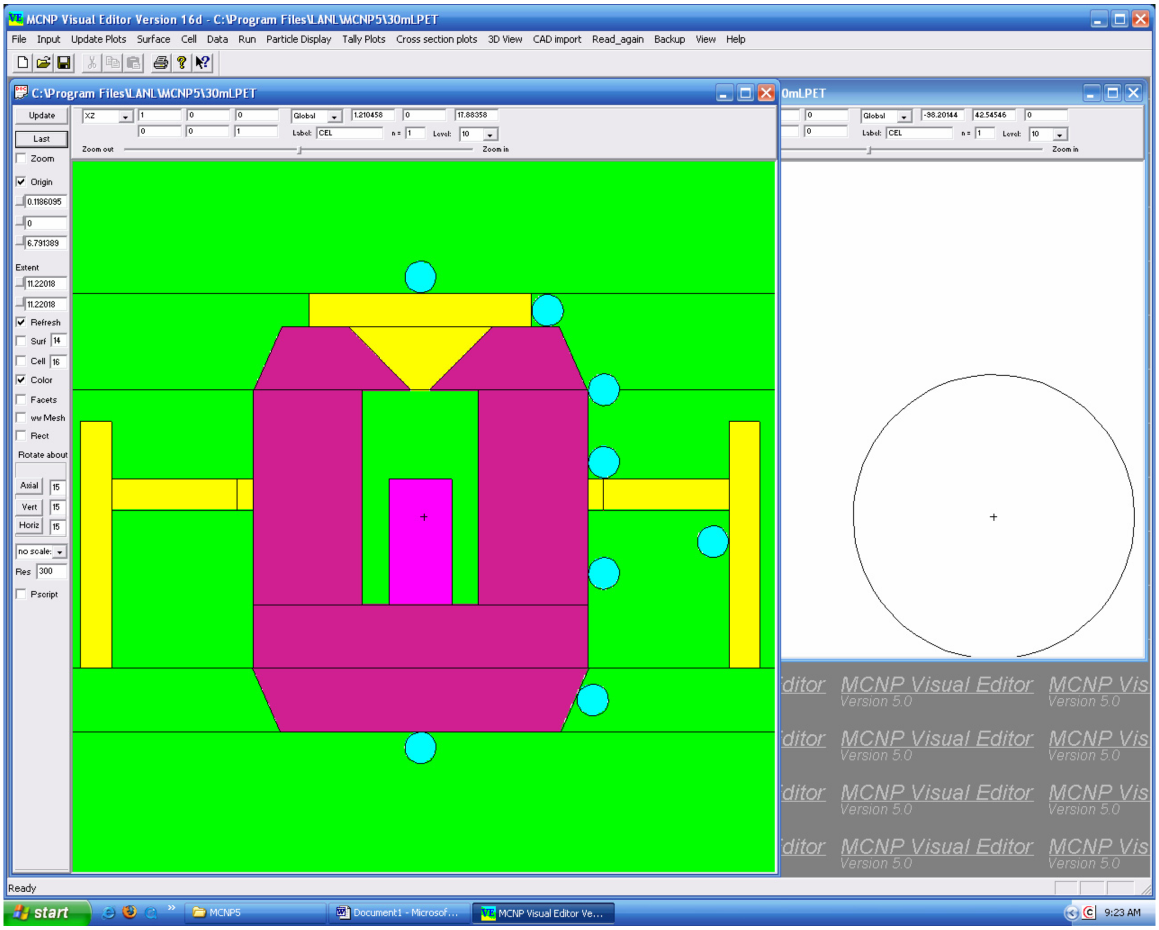
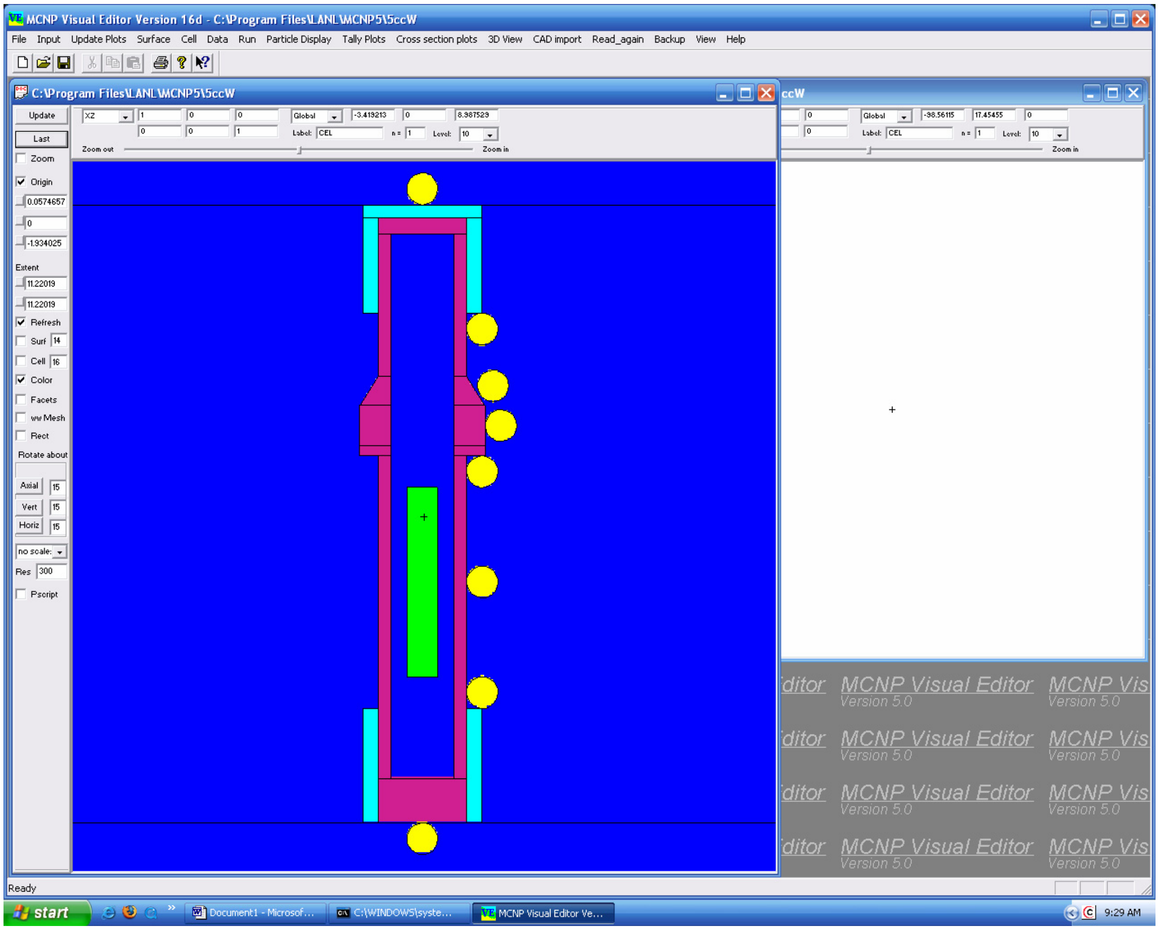


Figure 12: MCNP5 5mL Unit Dose Dispenser Model, colors represent different materials.



Chapter 5 - Results

Tables [7]-[12] contain the initial data gathered from the PDE-4. Tables [13]-[17] contain the initial flux and converted dose calculations from the MCNP5 simulations. Figures [13]-[18] depict the data from the MCA regarding photon attenuation trials.

Table 7: 10mL PET Pig, F-18(937mCi) Initial Physical Data, mrem/hr

Position	1	2	3	4	5	6	7	8	9	10
2.7mL/10mL	240	31.4	24.4	2400	650	324	105	750	620	63.6
4.5mL/10mL	231	62.7	68.4	1550	548	400	159	1000	550	48.2
9mL/10mL	125	23.8	20.7	1200	1230	290	220	780	407	22.4

Table 8: 30mL PET Dispenser, F-18(937mCi) Initial Physical Data, mrem/hr

Position	1	2	3	4	5	6	7	8	9
2.7mL/10mL	0.14	0.14	1.11	1.11	13.8	39.3	9.57	15.7	18.5
4.5mL/10mL	0.07	0.07	1.18	1.18	18	24.9	21.5	16.8	5.04
9mL/10mL	0.14	0.14	3.75	3.75	26.6	24.1	19	8.42	2.24

Table 9: $Piglet_3$, F-18 Initial Physical Data, mrem/hr

Position	1	2	3	4	5	6	7	8	9
2.7mL/10mL	203	61.4	5.04	21	490	16.9	1150	10.6	N/A
4.5mL/10mL	178	4.47	10.9	40.4	290	70.6	490	14	N/A
9mL/10mL	172	17.9	22.1	49.1	141	57	355	31	N/A

Table 10: 5mL Unit Dose Pig, Ga-67 Initial Physical Data, mrem/hr

Position	1	2	3	4	5	6	7	8	9
4.5mL/5mL	1.55	1.51	1.55	3.64	3.64	320	32.7	27.8	0.82

Table 11: 5mL Unit Dose Pig, Tc-99m Initial Physical Data, mrem/hr

Position	1	2	3	4	5	6	7	8	9
4.5mL/5mL	0.05	0.05	0.05	0.05	0.12	0.12	0.12	0.12	0.22

Table 12: Piglet, Four 100mCi I-131 Capsules, mrem/hr

Position	1	2	3	4	5	6	7	8
Dose Rate (mrem/hr)	170	168	245	330	524	52.4	96	11

Table 13: 10mL PET Pig, F-18, 1000mCi, MCNP5

Location	Dose(mrem/hour)	Flux(Particles/cm^2/sec)
1	2.83511E-01	2.64164E+05
2	7.82086E-03	1.14141E+04
3	2.10767E-02	3.63126E+04
4	1.91352E-01	2.34860E+05
5	2.04152E+00	2.19191E+06
6	5.24383E+01	5.20587E+07
7	1.42066E+02	1.29108E+08
8	5.17337E+03	4.46366E+09
9	5.84459E-01	6.86964E+05
10	1.42172E+00	1.26601E+06

Table 14: Piglet, F-18, 1000mCi, MCNP5

Location	Dose(mrem/hour)	Flux(Particles/cm^2/sec)
1	4.13376E-01	3.84711E+05
2	5.54936E-02	5.50700E+04
3	3.05811E-01	2.84317E+06
4	3.59837E+00	3.32065E+06
5	2.87816E+00	2.66677E+06
6	6.33785E-01	6.05404E+05
7	1.65434E+01	1.52885E+07
8	7.92383E-02	7.16669E+04

Table 15: Piglet, I-131 Caps, 400mCi, MCNP5

Location	Dose(mrem/hour)	Flux(Particles/cm^2/sec)
1	6.61810E-05	7.84557E+01
2	2.52944E-06	3.83379E+00
3	1.83991E-05	2.52704E+01
4	1.49014E-03	1.76501E+03
5	9.43889E-04	1.12123E+03
6	3.70273E-05	4.70388E+01
7	9.78239E-05	1.16480E+02
8	2.42774E-05	2.80929E+01

Table 16: 5mL Unit Dose Pig, Ga-67, 15mCi, MCNP5

Location	Dose(mrem/hour)	Flux(Particles/cm^2/sec)
1	1.08150E-02	1.13883E+04
2	1.65535E-03	1.84528E+03
3	1.88085E-03	2.22058E+04
4	1.39670E-02	1.78555E+05
5	1.51714E-01	2.54696E+05
6	2.17230E-01	2.54696E+05
7	2.01277E-02	2.22394E+04
8	5.75489E-04	5.94171E+02
9	1.74725E-03	2.01396E+03

Table 17: 5mL Unit Dose Pig, Tc-99m, 1000mCi, MCNP5

Location	Dose(mrem/hour)	Flux(Particles/cm^2/sec)
1	0.000	0.00000E+00
2	0.000	0.00000E+00
3	0.000	0.00000E+00
4	0.000	0.00000E+00
5	0.000	0.00000E+00
6	0.000	1.28E+03
7	0.000	0.00000E+00
8	0.000	0.00000E+00
9	0.000	0.00000E+00

Figure 13: NaI MCA Data for the 10mL PET Pig

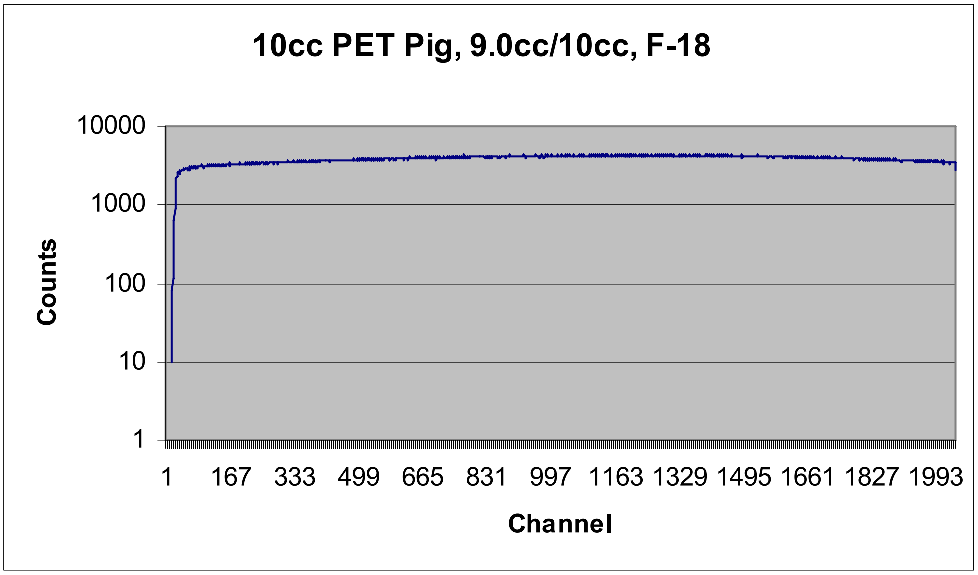


Figure 14: NaI MCA Data for the 30mL PET Dispenser

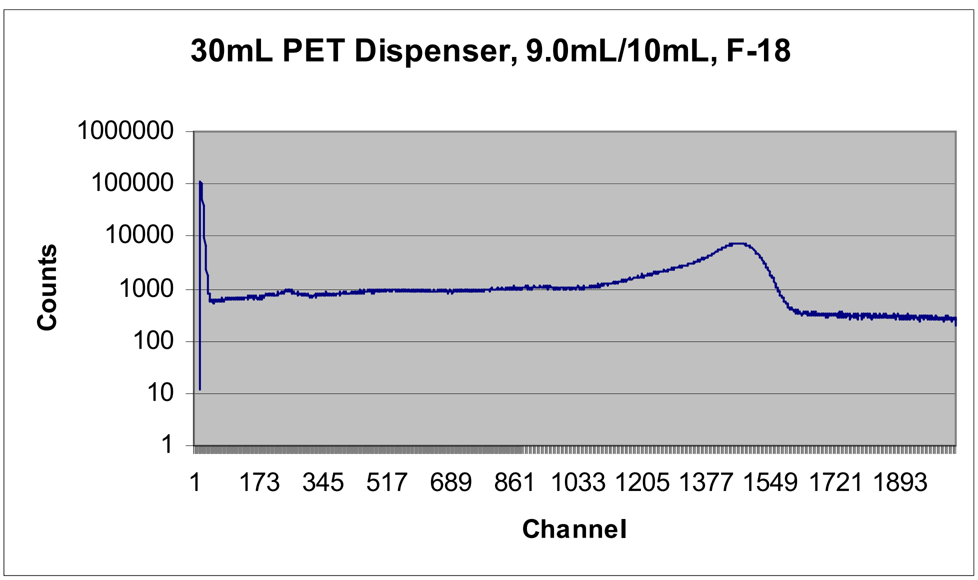


Figure 15: NaI MCA Data for the $Piglet_3$ containing F-18

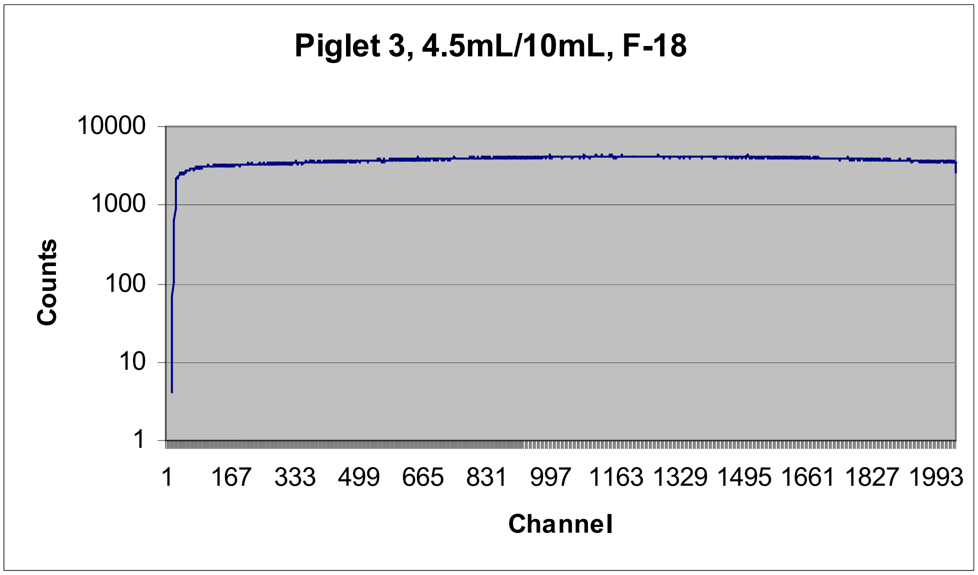


Figure 16: NaI MCA Data for the $Piglet_3$ containing I-131

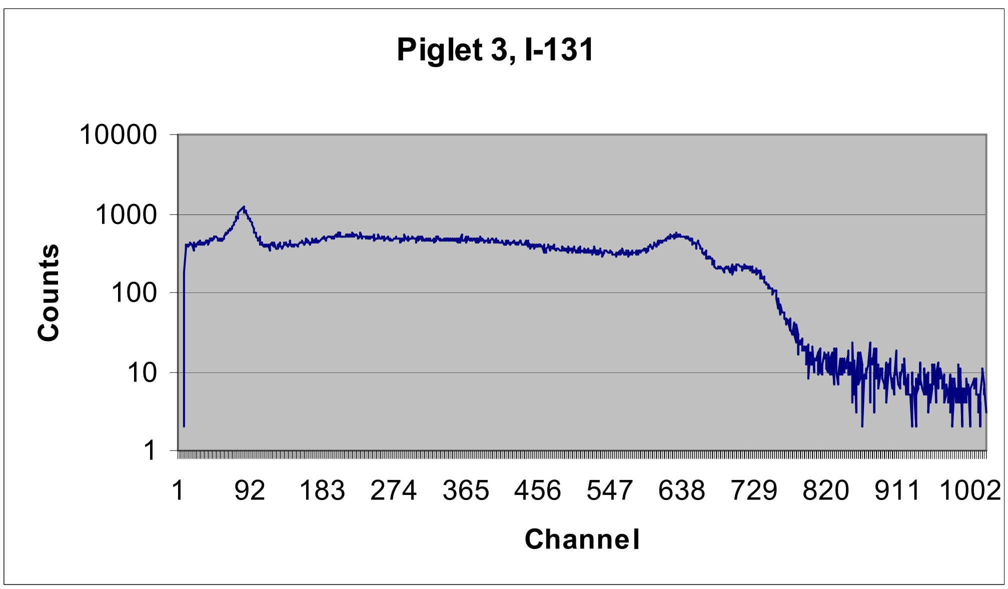


Figure 17: NaI MCA Data for the 5mL Unit Dose Pig containing Ga-67

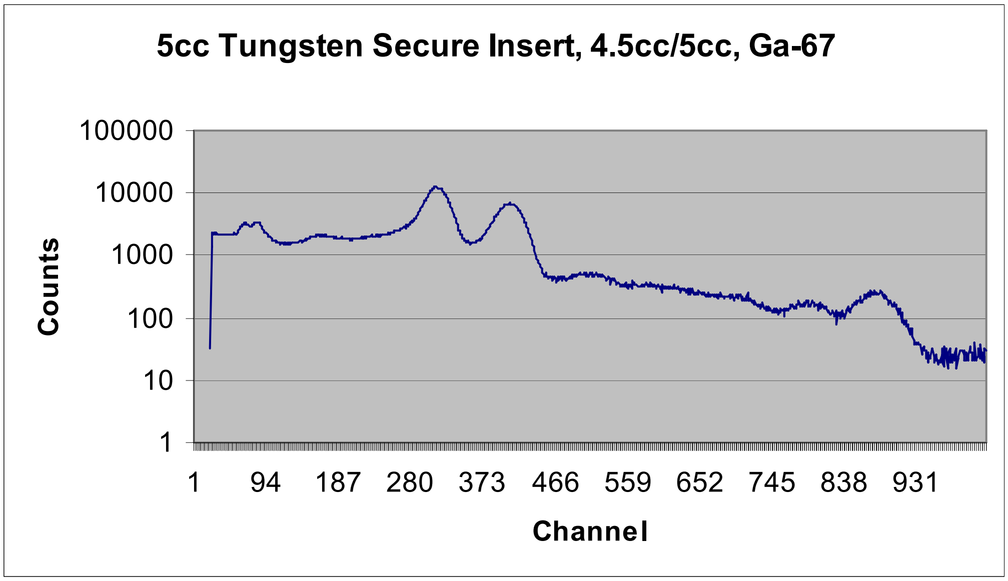
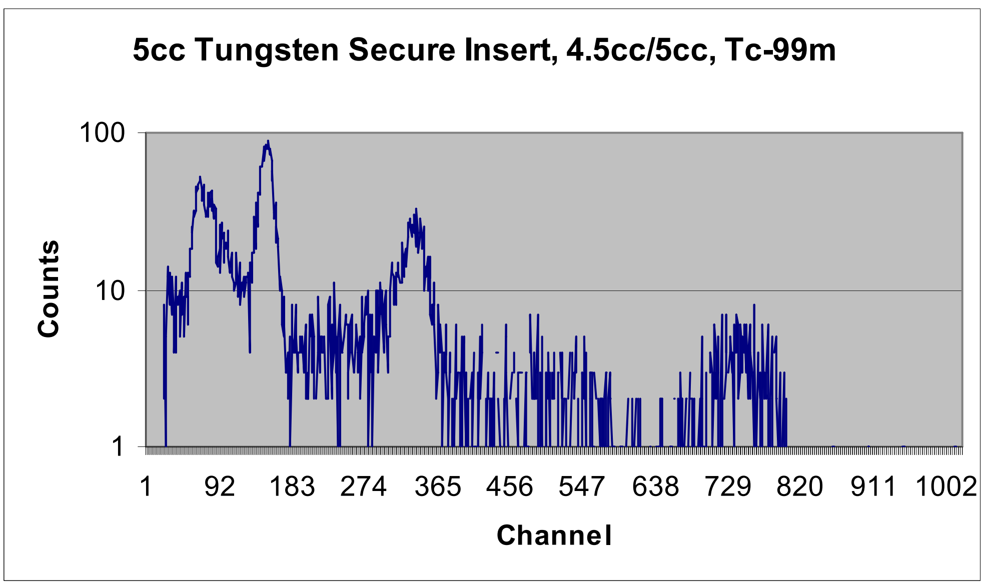


Figure 18: NaI MCA Data for the 5mL Unit Dose Pig containing Tc-99m



Chapter 6 - Analysis/Discussion

6.1 Exposure Profiles

The initial volume experiments using F-18 generally showed that smaller volumes generated points of more intense exposure. This was true in the PET Pig, 30mL PET Dispenser and $Piglet_3$. A full (4.5mL/5mL) syringe generated the maximum exposure for the 5mL Unit Dose Pig. Data points for this aspect of the experiment are found in Figure [19]-[22]. A portion of this is definitely due to the fast decay time of the F-18, but it is uncertain how much of the general trend of decreased exposure rate with fuller syringes can be attributed to this because time measurements were not taken.

What is more meaningful is the shape of the curve as the volume of the nuclide changes. In the 5mL Unit Dose pig there is a noticeable increase at exposure point three with the smaller volume. However the increase is not as significant as exposure point five in either volume. The 10mL PET Pig shows an averaging trend with higher volumes. The peak exposure at point four falls off; almost all the other exposure points rise slightly. The 30mL PET Dispenser shows a trend of more intense exposure at the top measurement points as nuclide volume increased. The shape of the $Piglet_3$ exposure profile did not change significantly as volume increased.

Figure 19: Volume Testing on 5cc Unit Dose Pig

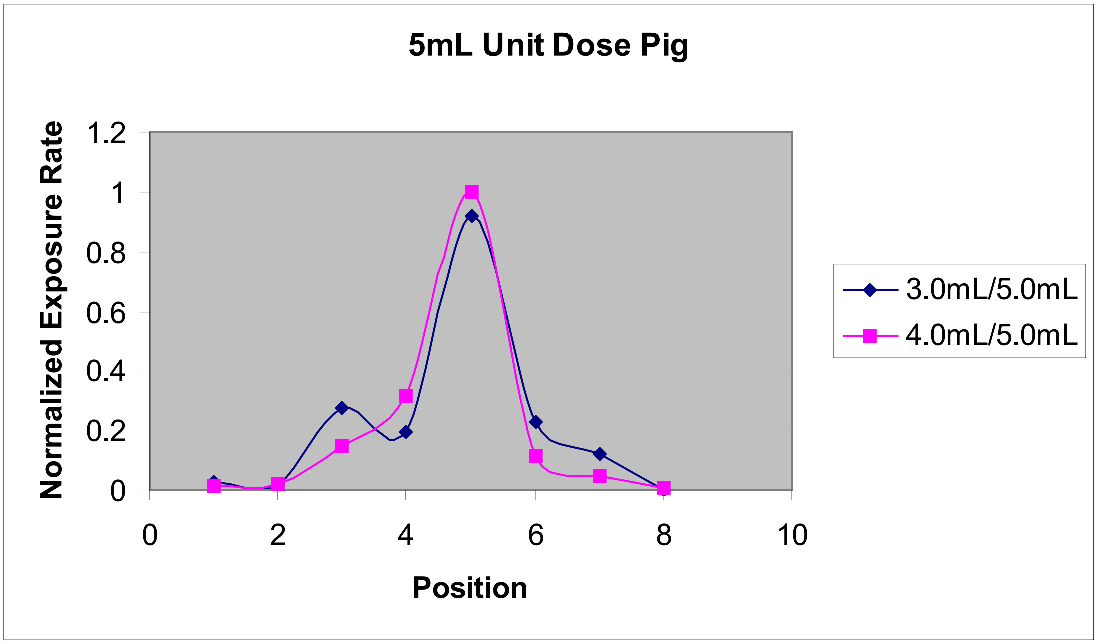


Figure 20: Volume Testing on 10mL PET Pig

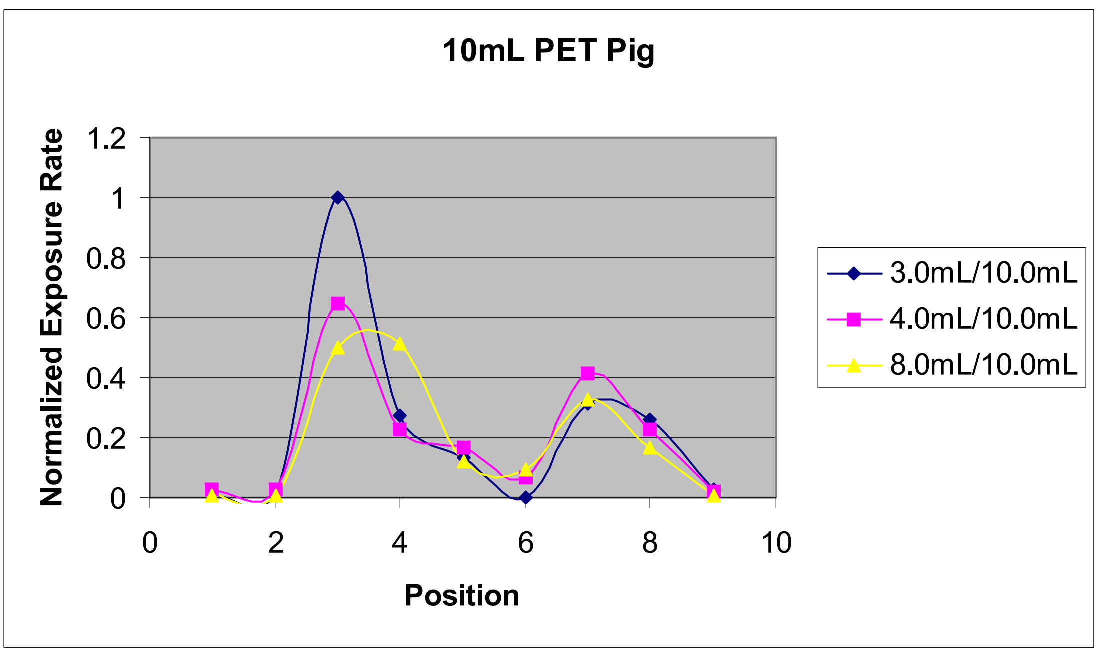


Figure 21: Volume Testing on 30mL PET Dispenser

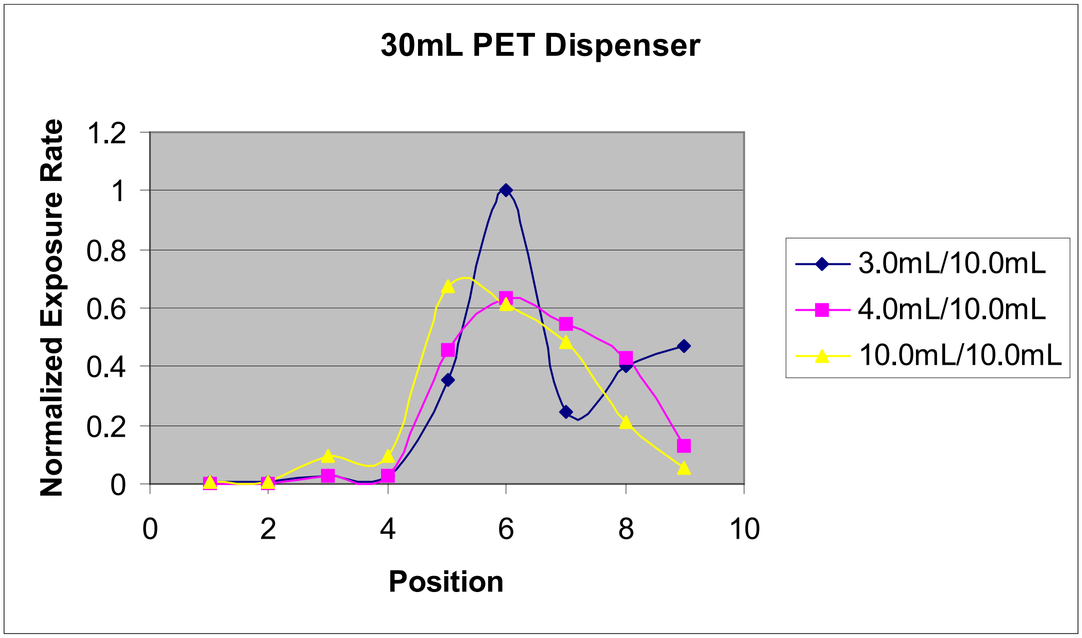
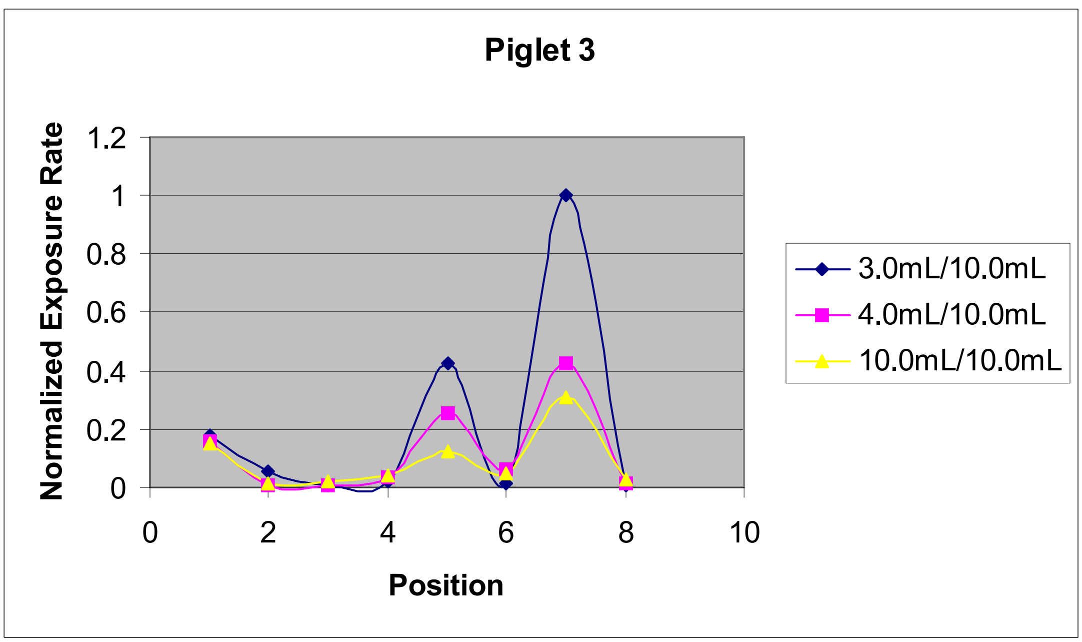


Figure 22: Volume Testing on $Piglet_3$



6.2 Experimental Data Analysis

In order to make the data gathered from the PDE-4 more accurate two significant factors need to be considered. Detector dead time is important, especially for the high exposure-rate samples. The second is that the over-response of the uncompensated GM tubes can also be accounted for manually.

6.2.1 PDE-4 Dead Time Compensation

Detector dead time can be a significant factor. This is especially true for high activity samples. The PDE-4 manual indicates that the detector automatically accounts for dead time in its internal circuitry. It uses the approximation shown in Equation [3]. The PDE-4 manual indicates that it retains an accurate reading up to 500R/hr.

Equation 3: Dead Time compensation in the PDE-4

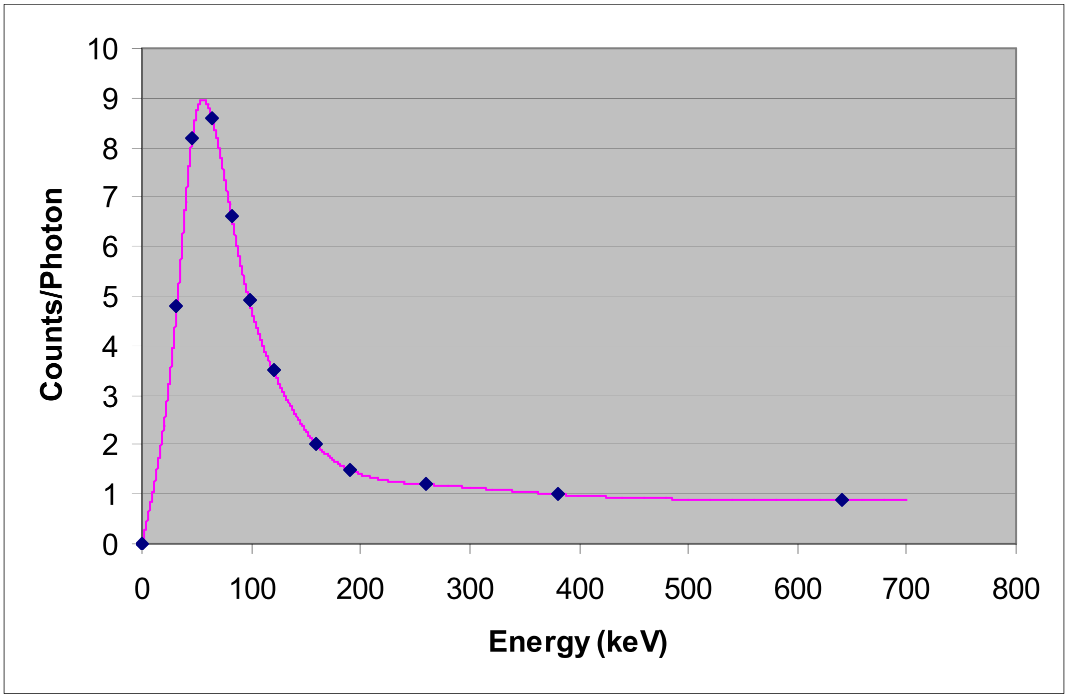
$$\frac{CountRate_{rec}}{1-CountRate_{rec}\cdot DeadTime}=CountRate_{real} \qquad [3]$$

6.2.2 GM Probe Response

The SAIC PDE-4 outputs data in either the form of accumulated exposure or an exposure rate. The primary purpose of the SAIC PDE-4 is to function as a personal dosimeter and by this design will sometimes overestimate exposure in order to be on the safe side of error. This is most prevalent in the four external probes on the PDE-4. The PDE-4 probes are standard GM tubes. This means they over-respond to photons with energies below 350keV, which results in a conservatively high exposure reading. The isotopes that were tested were often very low energy gamma emitters and they experienced a significant amount of energy attenuation from the shielding material. MCNP does not exhibit similar behavior. The over response of the uncompensated GM tubes must be taken into account. The mathematics to account for this over response are described by Equation [2].

The PDE-4 manual provides data points for the GM response vs. energy as was shown in Chapter 3, Figure [3]. By evaluating the data points provided and applying a cubic spline (a curve fitting algorithm) a more exact compensation ratio can be found. The curve for these data points is shown in Figure [23]. By relating the photon response of Figure [23] to the MCA data obtained in Figures [13]-[18] a more accurate exposure rate can be determined. Equation [4] is applied over all MCA channels, multiplying the relative contribution of each channel by an energy compensation factor given by the photon response graph.

Figure 23: SAIC PDE-4 Uncompensated GM Probe Photon Response



Equation 4: Conversion Factor for Photon Sensitivity of PDE-4

$$\frac{Exposure_{PDE}}{\sum_i MCACh_i \cdot EnergyCompFactor(E_i)} \cdot \sum_i MCACh_i = Exposure_{compensated} \qquad [2]$$

The results of applying Equation [2], if the data from Figure [23] and Figures [13]-[18] are accepted as valid, make the measured exposure rates more accurate. The compensated PDE-4 readings are described in Tables [18]-[23].

Table 18: PET Pig, F-18, Energy Compensated Data

Location	1	2	3	4	5	6	7	8	9	10
Dose Rate (mrem/hr)	98.25	18.71	16.27	943.2	966.8	227.9	172.9	613.1	319.9	17.61

Table 19: Piglet, I-131, Energy Compensated Data

Position	1	2	3	4	5	6	7	8
Dose Rate (mrem/hr)	80.28	79.33	115.7	155.8	247.4	24.74	45.33	5.195

Table 20: 5cc Unit Dose Pig, Ga-67, Energy Compensated Data

Location	1	2	3	4	5	6	7	8	9
Dose Rate (mrem/hr)	0.788	0.768	0.788	1.851	1.851	162.7	16.63	14.14	0.417

Table 21: Piglet$_3$, F-18, Energy Compensated Data

Location	1	2	3	4	5	6	7	8
Dose Rate (mrem/hr)	106.3	2.669	6.508	24.12	173.2	42.15	292.6	8.359

Table 22: 5cc Unit Dose Pig, Tc-99m, Energy Compensated Data

Location	1	2	3	4	5	6	7	8	9
Dose Rate (mrem/hr)	0.016	0.016	0.016	0.016	0.039	0.039	0.039	0.039	0.071

Table 23: 30mL PET Dispenser, F-18, Energy Compensated Data

Location	1	2	3	4	5	6	7	8	9
Dose Rate (mrem/hr)	0.04	0.04	1.06	1.06	7.516	6.809	5.368	2.379	0.633

6.3 MCNP5 Data Analysis

Tables [24]-[27] display data from the MCNP5 output file of photon population in each cell. Analysis of this data, as shown in Figures [20]-[23], shows where MCNP5 tracked photon locations. A standard visible spectrum was used to visualize this data with violet equating to 0% of the photons interacting in that cell and red equating to 100% population. White and black were also used in the graphical analysis. White depicted the hard 0% population, this was important because several cells had around 2% interaction, which was difficult to differentiate with cells with no photon interaction. Black was used for cells that interacted with more than 100% of the photons initially generated. This helped account for cells that interacted with photons generated in secondary and tertiary reactions.

Three results are expected in Figures [24]-[27]. The first is that the highest concentration of photon populations be centered around the source, diminishing radially outward. The second is that more photon interactions would be observed in the denser materials. The third is that smaller photon populations would occur in smaller volume cells.

Table [24] and Figure [24] depicts the 5mL Unit Dose Pig. This model behaved as expected. A large number of photon interactions occurred in the air cavity inside the pig and the tungsten walls that were closest to the source. Only about 88% of the photons showed up as populating the actual source. This condition may have resulted because MCNP5 only tracked photons when they changed cell borders, and the initial set of photons were not counted. The entire 88% was due to backscatter and secondary photon generation.

Table [25] and Figure [25] depict the 30mL PET Dispenser. This model does not share the source behavior evident in the 5mL Unit Dose Pig. In fact, very few interactions actually occurred inside the source. Interpretation of this figure indicates that the photons favored a more upward direction. This caused a high amount of interaction and penetration through the stainless steel magnetic cap in cell 12, leading to a high dose rate in the top data point.

Table 24: 5mL Unit Dose Pig, Ga-67, Photon Population

Cell	Photon Population	% Interactions
1	2919442	119.89
2	14418	0.59
3	75938	3.12
4	121438	4.99
5	28895	1.19
6	32878	1.35
7	9181	0.38
8	268	0.01
9	48	0.00
10	209	0.01
11	2136292	87.73
12	2435673	100.03
13	100	0.00
14	20	0.00
15	18	0.00
16	181	0.01
17	1830	0.08
18	2480	0.10
19	214	0.01
20	7	0.00
21	15	0.00
22	17865	0.73
23	23803	0.98
24	68309	2.81

Figure 24: 5mL Unit Dose Pig, Photon Population

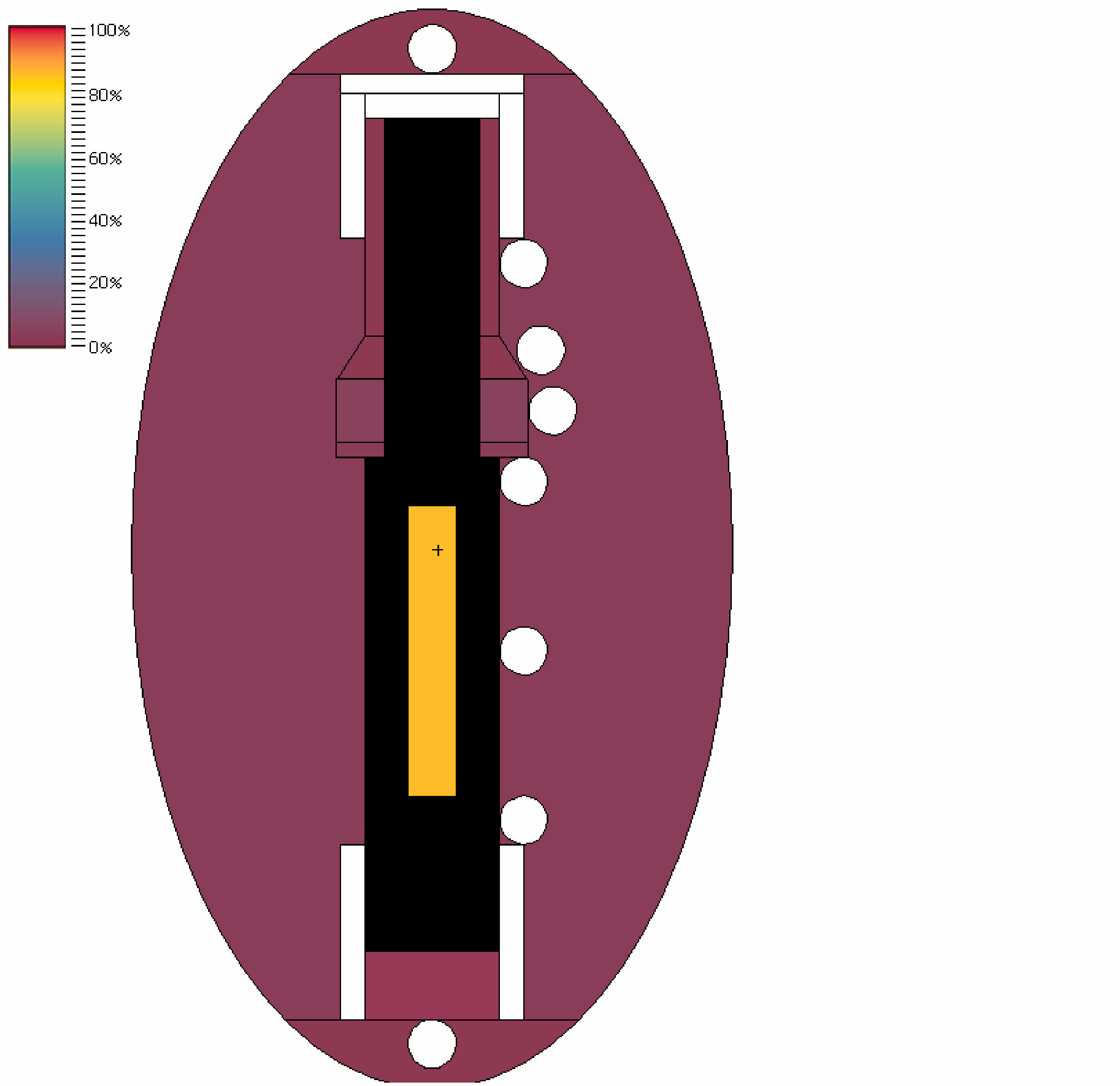
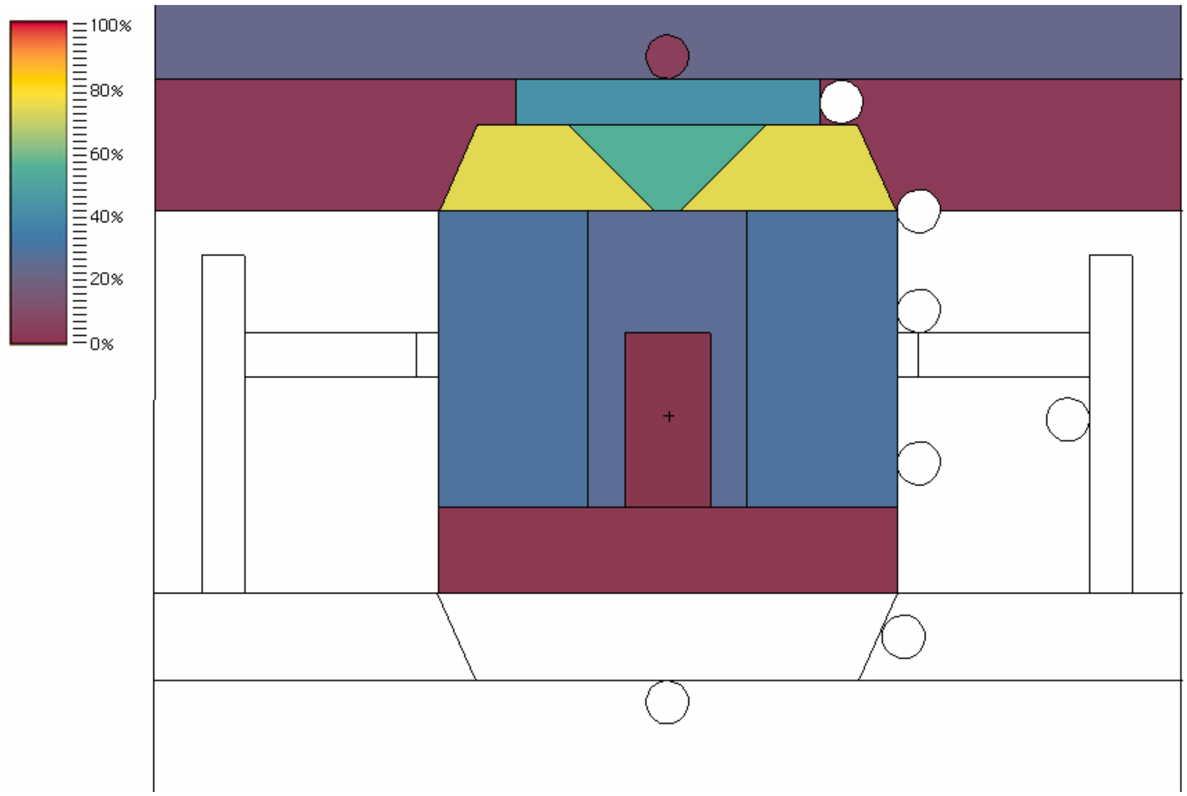


Table 25: 30mL PET Dispenser, Photon Population

Cell	Photon Population	% Interactions
1	60893	1.22
2	1436454	28.73
3	686	0.01
4	2894410	57.89
5	71643	1.43
6	1309647	26.19
7	28	0.00
8	6	0.00
9	4	0.00
10	23	0.00
11	27	0.00
12	2212908	44.26
13	3806484	76.13
14	322459	6.45
15	8709	0.17
16	18	0.00
17	4	0.00
18	0	0.00
19	1	0.00
20	0	0.00
21	1	0.00
22	17	0.00
23	1173396	23.47
24	3215	0.06
25	133828	2.68
26	4599	0.09
27	26633	0.53

Figure 25: 30mL PET Dispenser, Photon Population



In contrast to the 30mL PET Dispenser, the PET Pig, Table [26] and Figure [26], seemed to indicate a strong downward bias for the photons. Very few interactions occurred in the cells containing the nuclide and its nearest neighbors.

Table [27] and Figure [27] depict the photon population in the Piglet. This model behaved mostly as expected. The model indicated a large amount of interactions in the air cavity and the surrounding wall. Further, there is a bias toward more interactions with the bottom cell, cell 1, than the top cell, cell 3. This is consistent with photon density, and thus interaction, diminishing radially outward from the source. The one anomaly for this model is that one of the capsules had greater than 100% interaction, the other three each had less than 5%.

Table 26: PET Pig, Photon Population

Cell	Photons Entering Cell	% Interactions
1	9399276	47.00
2	589242	2.95
3	74013	0.37
4	71397	0.36
5	66473	0.33
6	284	0.00
7	55318	0.28
8	23758	0.12
9	498	0.00
10	369	0.00
11	3292	0.02
12	188	0.00
13	8	0.00
14	24	0.00
15	178	0.00
16	1586	0.01
17	37290	0.19
18	92946	0.46
19	3828595	19.14
20	482	0.00
21	845	0.00
22	711545	3.56
23	1100	0.01
24	2046768	10.23
25	8222390	41.11
26	119360	0.60
27	1959508	9.80
28	8504762	42.52
29	7732778	38.66
30	571600	2.86

Figure 26: PET Pig, Photon Population

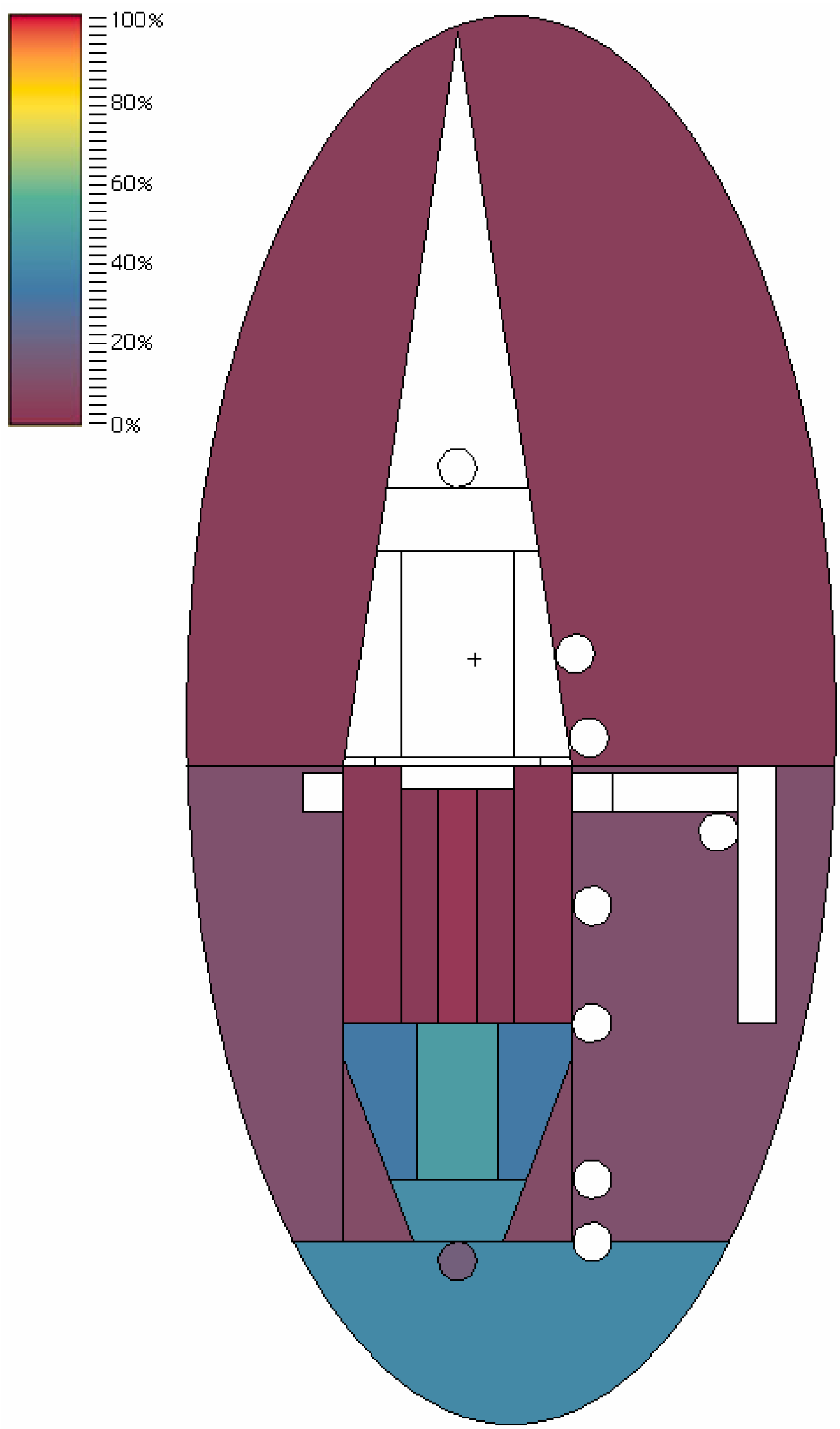
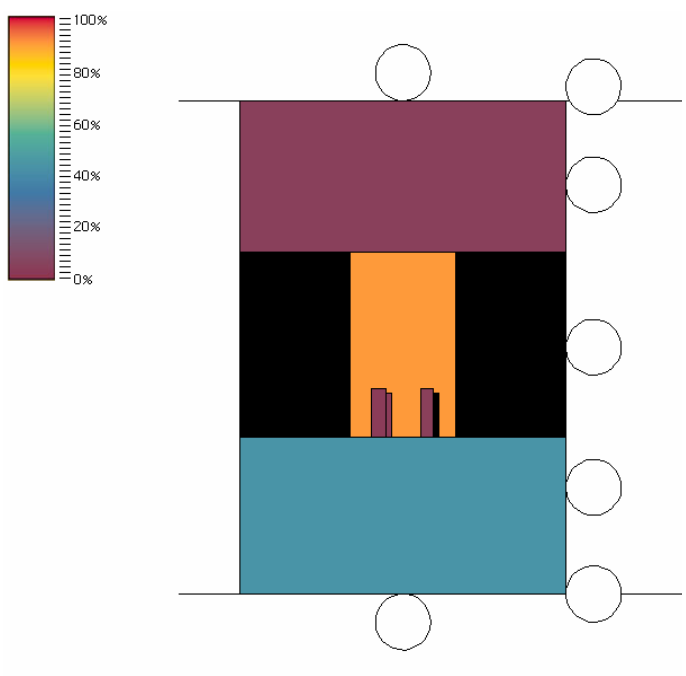


Table 27: Piglet, I-131, Photon Population

Cell	Photon Population	% Interactions
1	429745295	42.97
2	1075571533	107.56
3	50393888	5.04
4	26128923	2.61
5	47608272	4.76
6	47620979	4.76
7	1003545989	100.35
8	322	0.00
9	17	0.00
10	111	0.00
11	7638	0.00
12	4853	0.00
13	199	0.00
14	472	0.00
15	113	0.00
16	922673690	92.27
17	106196	0.01
18	280007	0.03
19	103680	0.01

Figure 27: Piglet, I-131, Photon Population



6.4 Data Comparison

Figures [28]-[33] show a comparison between the simulated (MCNP5) and experimental data. The experimental data, with few exceptions, are orders of magnitude larger than the simulation. In addition, the shapes of the curves show very little similarity. A single factor, Fisher's Analysis of Variance was used to compare the experimental and simulated data. The results of this analysis are shown in Tables [28]-[33]. Reasons for the lack of agreement between the simulation and the experimental measurements are discussed below.

6.4.1 Experimental Improvements

Several possible reasons exist for the discrepancies between the measured data and the simulation results, and are thought to be directly related to the physical experiment.

(1) One problem was time constraints. The experiment was done in an active business environment. The work needed to be done quickly not only to minimize hindrance to the business, but also because the isotopes used were decaying quickly.

(2) The detector employed was the PDE-4 which is ideal in size and portability. However interface upgrades could have greatly enhanced its effectiveness. Simultaneously positioning the probe and clearing the display in order to take new readings was difficult. The time

increment which displayed the exposure rate was inconsistent. The timing mechanism of the PDE-4 was handled automatically, ranged between 2 seconds and 64 seconds and had no visual display. A quick exposure reset button and a stopwatch may have significantly improved the readings taken.

(3) The 1.83 hour half-life of F-18 make it difficult to obtain consistent, statistically viable results from a single sample. A nuclide with a longer half-life than F-18 and a similar energy would help compensate for the nuclide decay during the experiment. A few beta emitters have a longer half-life and may be more appropriate for purely scientific purposes. These nuclides include: Chromium-48, which has a half-life of 21.6 hours and no photon emissions of higher energy than an annihilation photon; Zinc-62. It has a half-life of 9.22 hours and no primary photon emissions of significantly higher energy than the annihilation photons. Using these surrogate nuclides would allow multiple readings to be taken so that more accurate statistics could be generated from the data.

(4) For the Tc-99m measurements, a different detector should have been used. The 64-second exposure reading from the PDE-4 was not sufficient to measure the few photons that may have penetrated the tungsten on the 5mL Unit Dose Pig. This new method would require the use of a surrogate isotope that has a longer half-life but a similar

gamma spectrum. Rhenium-186 satisfies these conditions with a half-life of 200,000 years and a primary gamma emission with energy 122.6keV. Using this sample would not be practical because the long half-life would mean a large sample for a detectable amount of activity. Another alternative nuclide is In-111, which has a 2.8 day half-life. Indium-111 has primary gamma emissions of 245.4keV and 171.3keV. Using a surrogate would enable multiple measurements to be taken, further increasing statistical accuracy.

(5) An assumption was made that the positrons emitted by the F-18 quickly formed annihilation photons. If they, in fact, did not interact immediately the source definition in MCNP5 may have been inaccurate. If some of the positrons did not interact until they were outside the tungsten shielding they would have a far less proclivity of interaction, thus giving a much lower dose rate than in the physical experiment than in the MCNP5 model, where annihilation photons were used initially the start. The data analysis does not support this point.

6.4.2 Simulation Improvements

Several problems exist with the MCNP5 models.

(1) Detailed schematics for the majority of the pigs were not available. With the exception of the 10mL PET Pig all measurements on the

pigs were taken with a metric ruler, resulting in possible inconsistencies between the model and the physically recorded data. In addition, many of the internal cavities had to be estimated from documents or secondary evidence (i.e., measuring pig cavities indirectly by using reference points on vials and syringes inserted into the pig)

(2) The dose conversions used in the simulation are standards set forth by NCRP-38 ANSI/ANS 6.1.1 1977. This dose conversion listing was chosen because it was the most detailed source within MCNP5 and the PDE-4 detector did not specify the source of its own dose conversions.

The ten statistical checks in MCNP5 did not all pass. The PDF, probability distribution function, remained consistently at 0 (recommended value 3.00) for all runs and was not considered. The other nine checks seemed to be behaved within expected parameters. The implication of this on the validity of the data is unknown.

Figure 28: PET Pig, F-18 Exposure Information

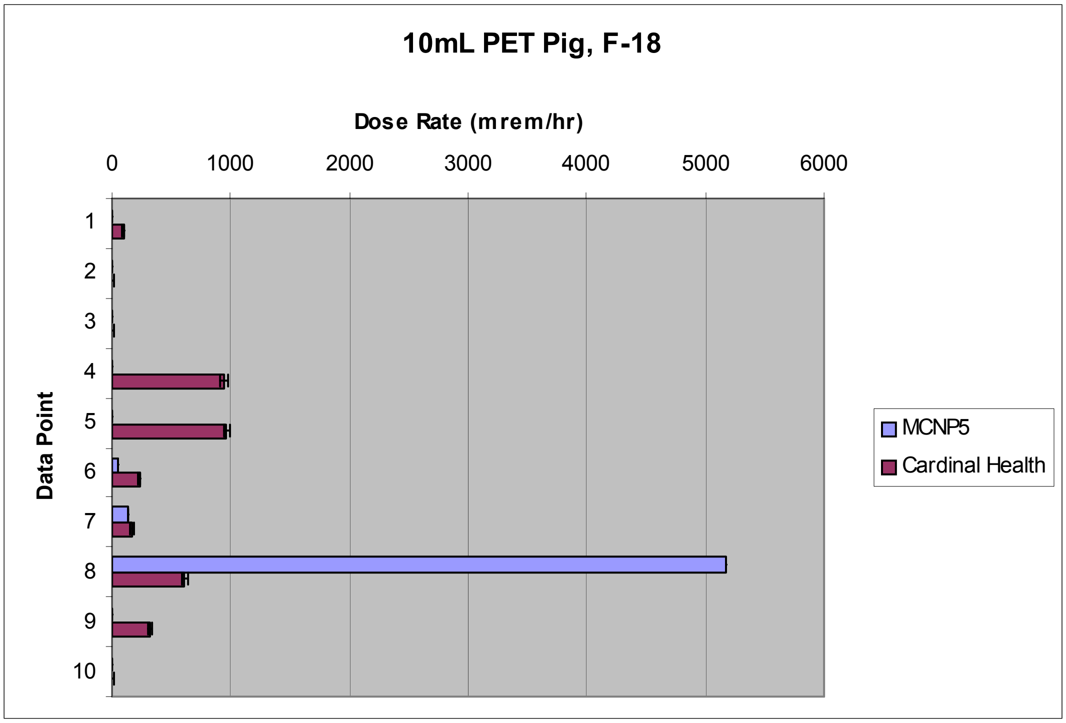


Figure 29: Piglet, I-131 Dose Information

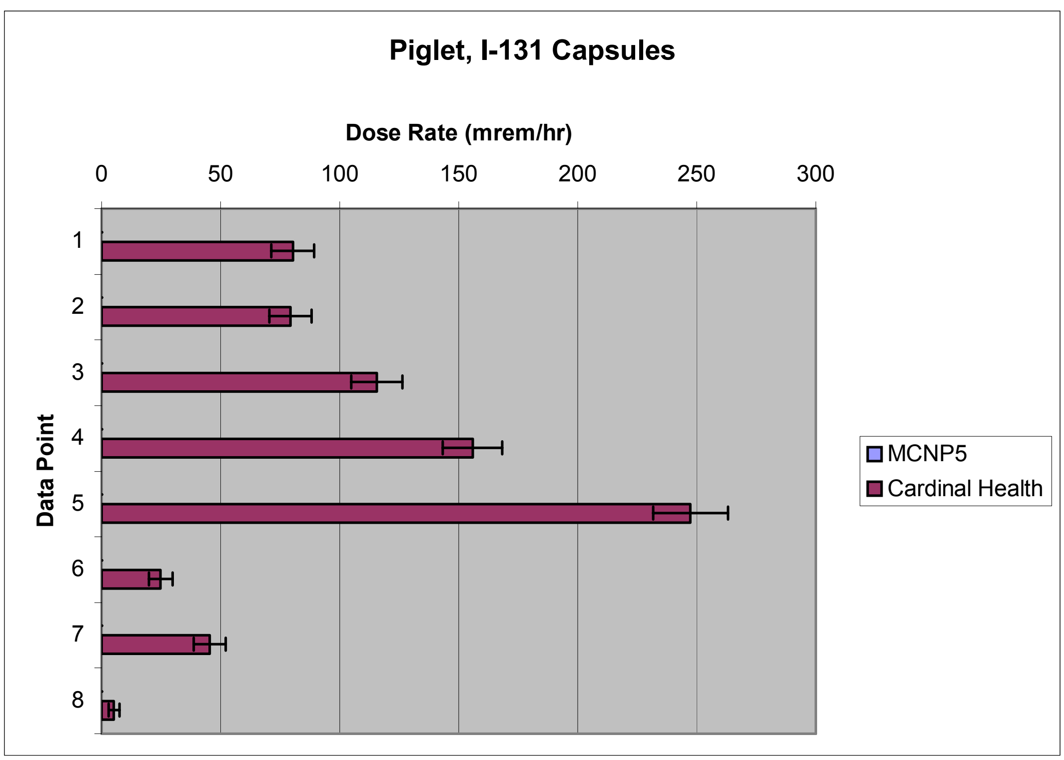


Figure 30: 5cc Unit Dose Pig, Ga-67 Dose Information

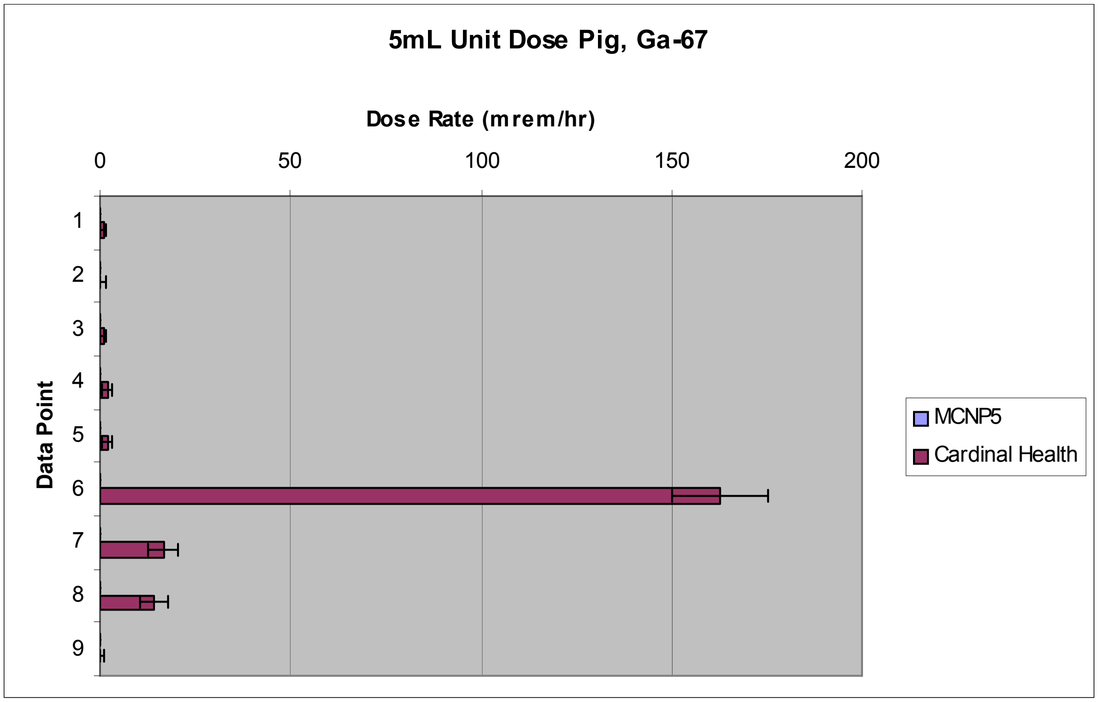


Figure 31: Piglet, F-18 Information

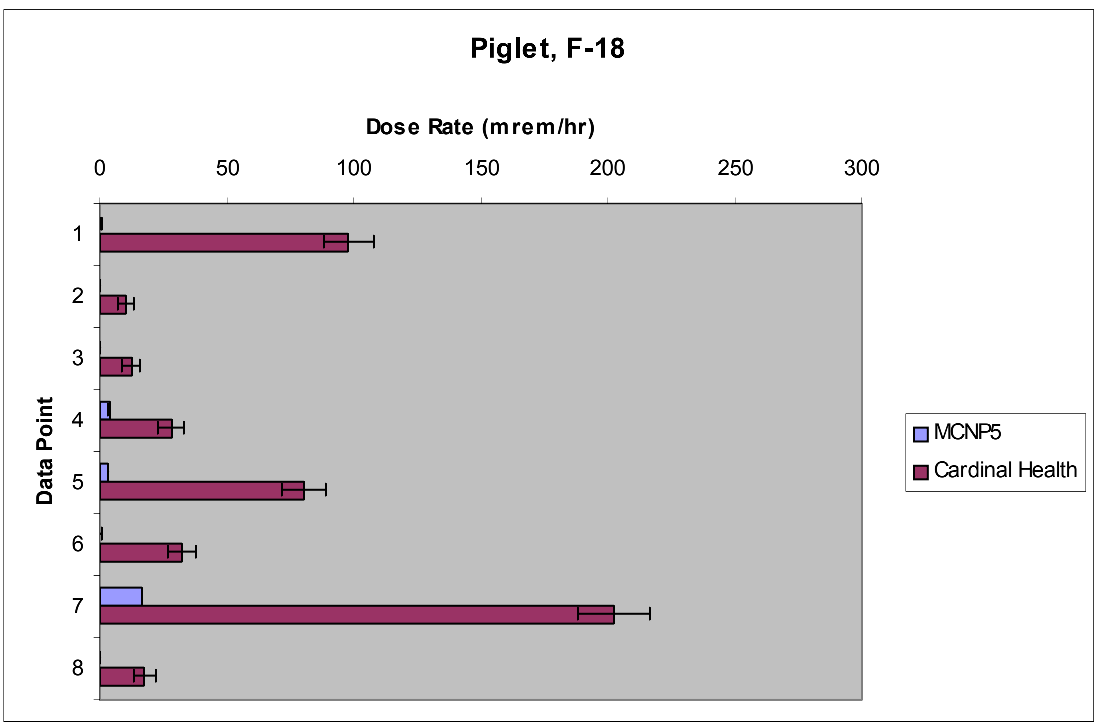


Figure 32: 5mL Unit Dose Pig, Tc-99m Dose Information

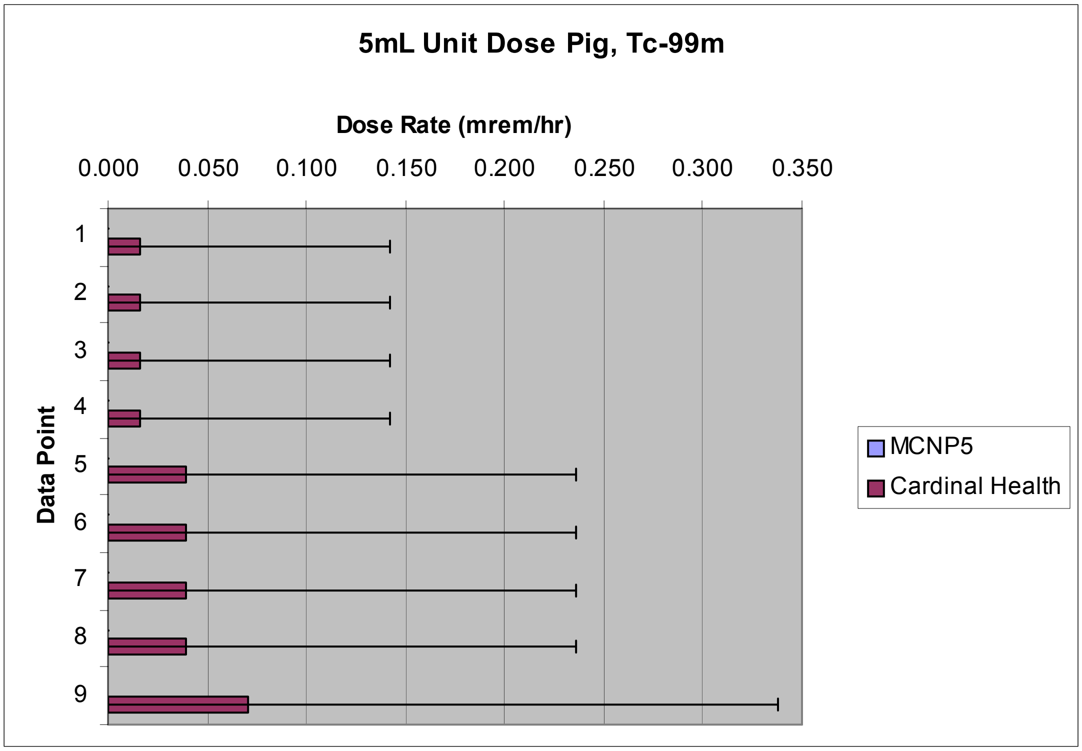
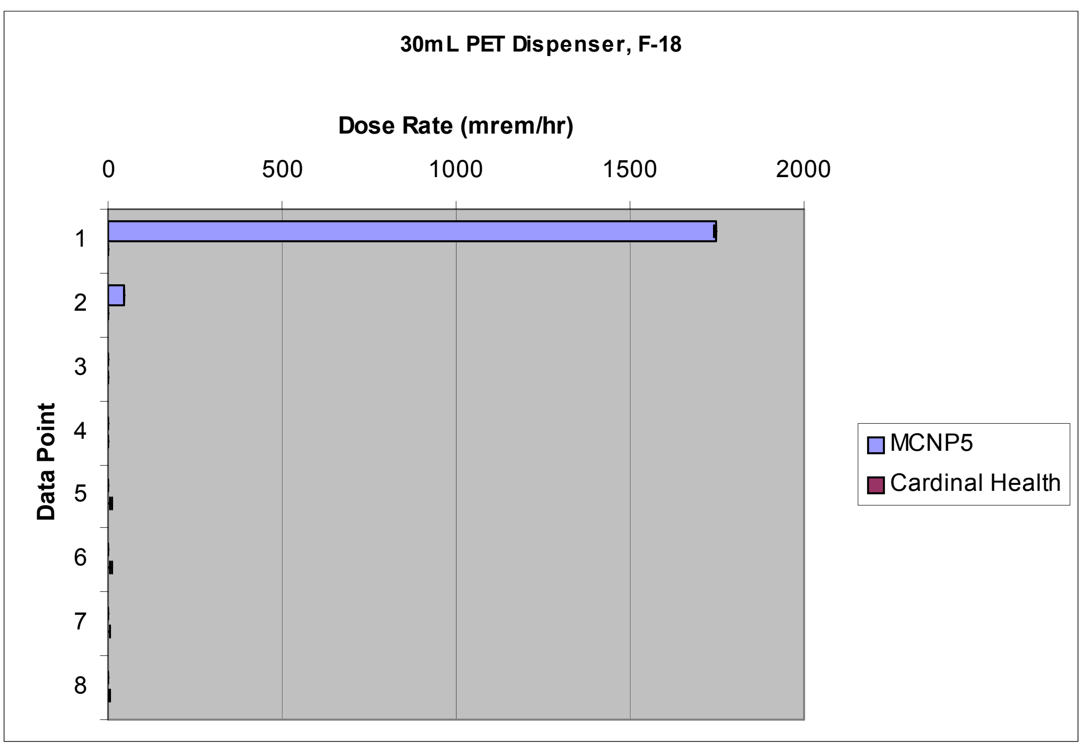


Figure 33: 30mL PET Dispenser, F-18 Dose Information



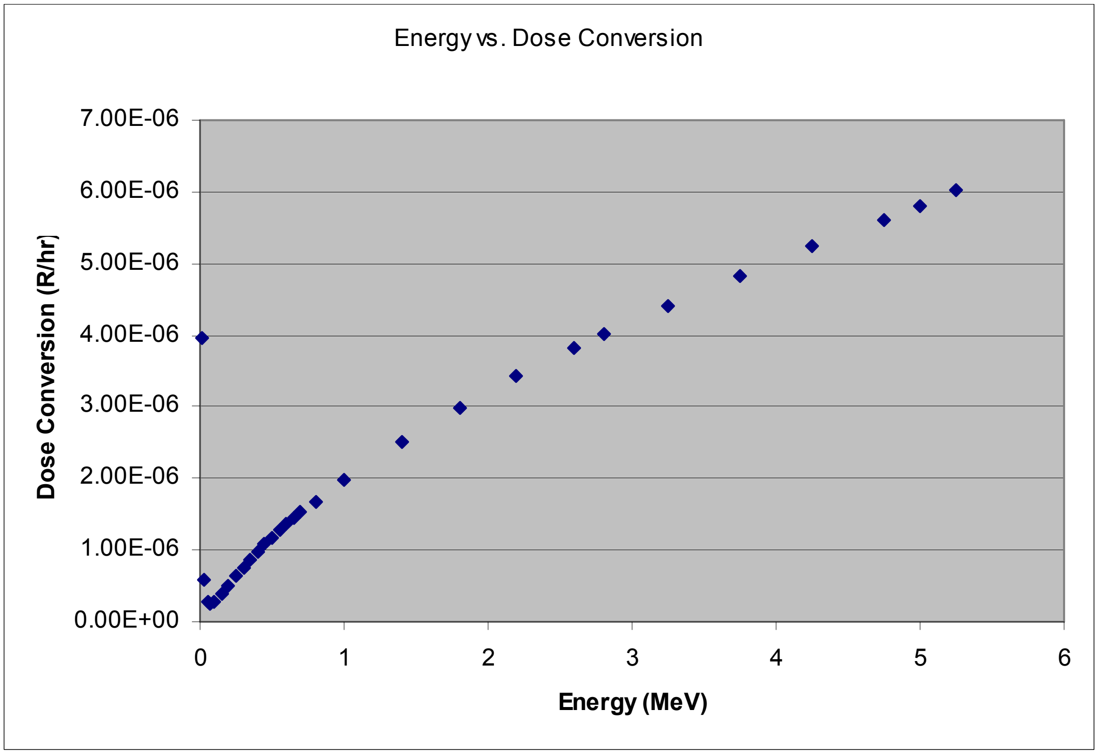
6.5 Further Improvements

In order to further improve the MCNP models for the tungsten pigs several methods can be applied. Calculating mathematical dose estimates will give another point of comparison for the models. A simplified MCNP model should theoretically be very close to the mathematical models. Continuation runs may results in better statistics for low flux cells. The application of several variance reduction techniques included in the MCNP code can improve the statistics for several dose locations. The use of additional tools in Visual Editor may give a greater understanding of the photon behavior. Once all of these additional methods are correlated the models will behave more accurately.

6.5.1 MCNP dose calculations

The flux to dose conversion is defined on the DE and DF cards. A series of conversion points are published in the MCNP5 manual. These points are shown in Figure [34]. A log-log extrapolation is calculated for energies between the explicit data points. It was noted in the MCNP5 manual that the conversion factors may differ significantly. For example the ICRP21 conversions differ by >20% for E < 0.7MeV.

Figure 34: Energy vs. Dose Conversion



6.5.2 Hand Calculations

Two equations needed to be derived to adequately represent dose estimates for the pigs. Both of these equations were based off of the following equation.

Equation 4: Gamma-factor Exposure Rate Equation for Point Sources

$$X = \Gamma \cdot A / d^2$$

Where X is exposure rate, Γ is the gamma factor describing dose rate for a specific nuclide and energy, A is activity and d is distance. This equation is valid for point sources. For the dose points directly above and below the source Equation [4] can be integrated along a length l, a distance L from the dose point. This yields Equation [5].

Equation 5: Exposure Rates for Top and Bottom Points.

$$X = (\Gamma \cdot A \cdot l) / (L^2 + l \cdot L)$$

The other equation needed is for a side dose point from a line source. This can be accomplished by integrating through the angle, ϴ, made by the dose point, a line perpendicular to the source and the line from the dose point to the edges of the source. The exposure point is a distance, d, away from the source at its midpoint. The Equation [6] is the result of this integration.

Equation 6: Side Exposure Rates for a Line Source

$$X = \Gamma \cdot A \cdot 2 \cdot \Theta / d$$

Table [28] describes the shielding thickness used in the calculations.

Table 28: Shielding Thickness Used in Hand Calculations

	Piglet	5cc Unit Dose	PET Pig	30mL PET Dispenser
Top Thickness	2.7	0.5	1.6	3.05
Bottom Thickness	2.8	1.4	1.6	4
Side Thickness	2	0.4	1.5	3.5
Top Air Thickness	3.3	8	6.1	2.8
Bottom Air Thickness	n/a	4.6	4	n/a
Side Air Thickness	.4, 1.6	1	1.2	0.425

An unattenuated exposure rate was obtained for each case using Equations [4], [5], and [6], as appropriate, and then Equation [7] was applied to factor in the shielding effect of the materials. The piglet had four capsules of I-131, 100mCi each, approximated as point sources, distributed evenly within the cavity. The 5cc Unit Dose Pig was calculated with 1Ci of Tc-99m, approximated by a line source. The PET Pig was calculated with 1Ci of F-18 and approximated by a line source. The 30mL PET Dispenser was calculated using 1Ci of F-18 approximated by a line source. Due to execution issues with the MCNP5 code, dose estimates were not obtained for this model. Instead photon flux numbers were obtained, but the method remains consistent. The numbers generated by these calculations can be found in Table [29].

Equation 7: Standard Shielding Equation Including Buildup

$$I = I_o B e^{-\mu x}$$

Table 29: Results of Hand Calculations

Dose Point	5cc Unit Dose (mrem/hr)	PET Pig (mrem/hr)	30mL Pet Dispenser (photons/cm^2/sec)	Piglet (mrem/hr)
Top	0.0019	6.248	$5.53 \cdot 10^7$	0.00265
Side	0.393	77.4803	69703	0.1389
Bottom	$7.88 \cdot 10^{-10}$	9.8588	20436	0.00843

6.5.3 Visual Editor Tools

Using several tools in Visual Editor allowed further verification that the simulated photons were acting appropriately. The particle display option helped ensure that the source particles were being generated properly and then further verified that they were interacting properly with the materials. The following figures depict the source and photon interactions of both the simplified models and the full models. Figures [35]-[43] depict the source and dispersion of a sample of particles for each simplified model and full model, when applicable.

Figure 35: 30mL PET Dispenser, Simple model

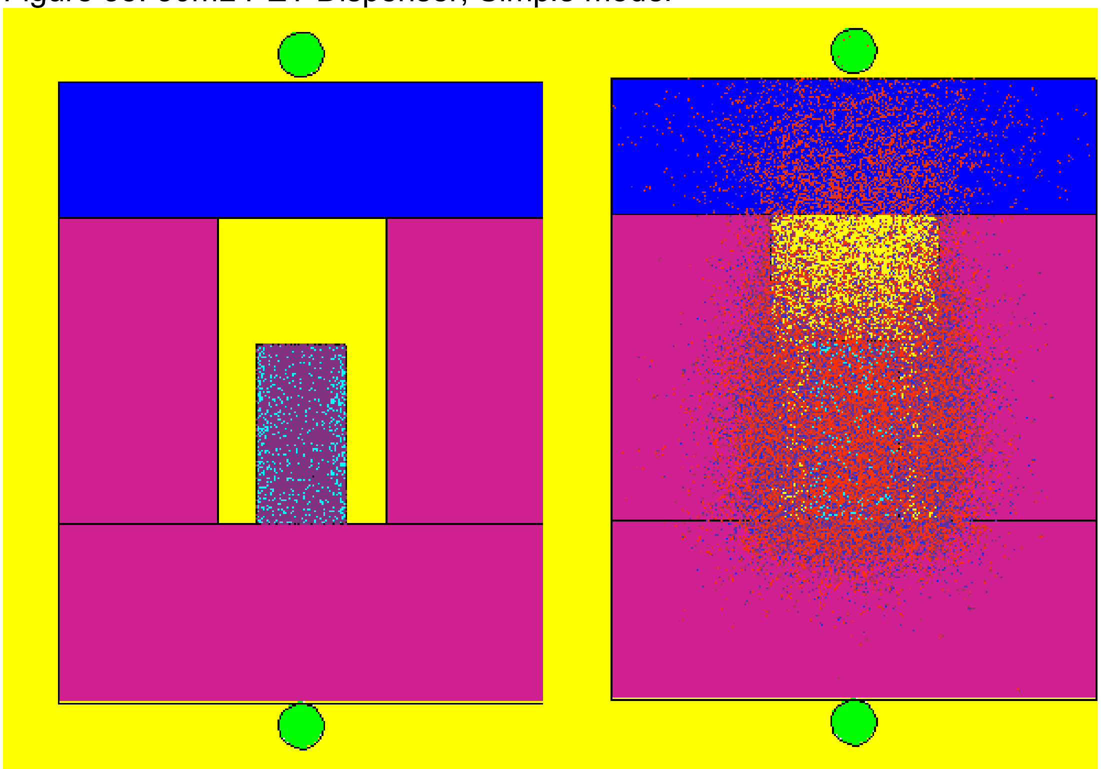


Figure 36: 30mL PET Dispenser, full model

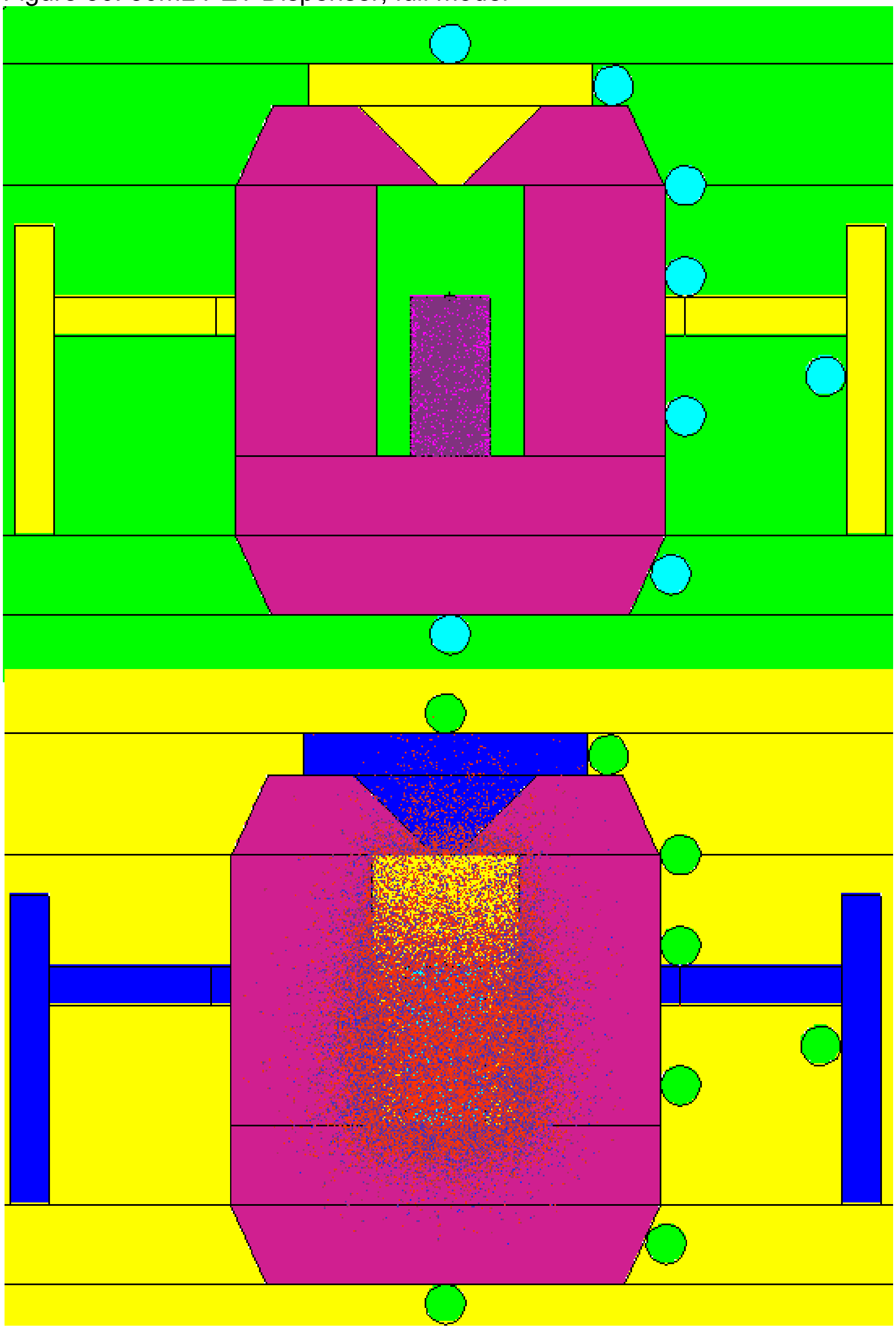
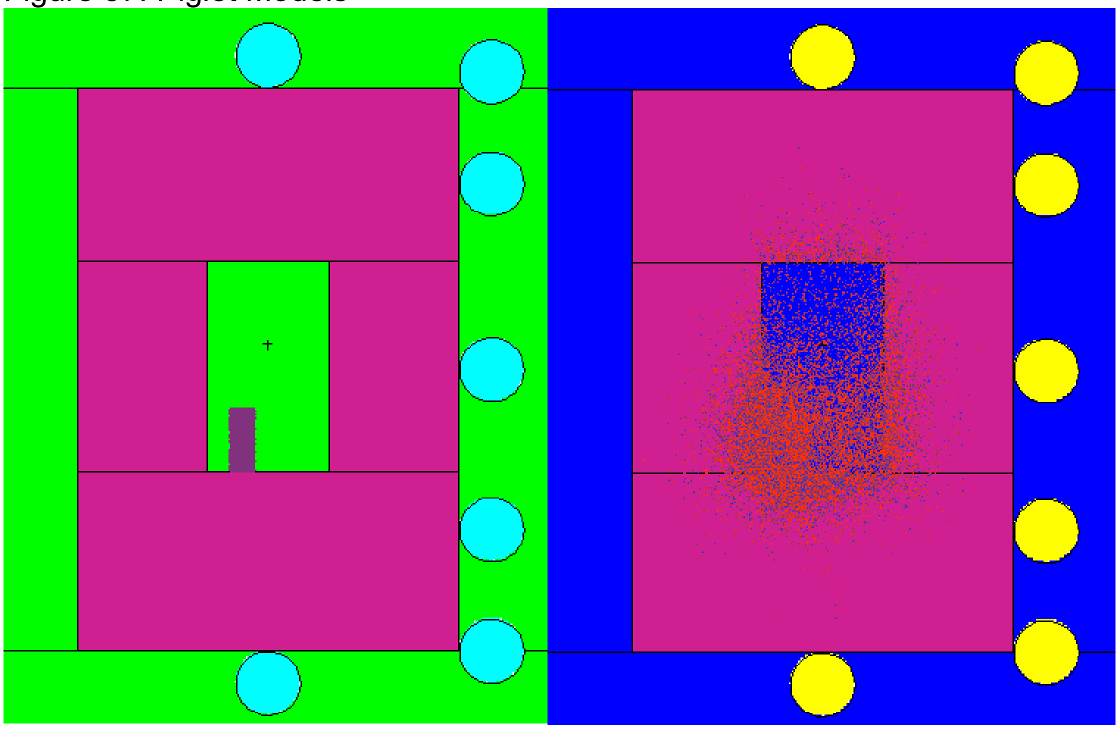


Figure 37: Piglet Models



The Piglet models did not receive a simplified version because the existing geometry could not be simplified appreciably. There was however, a problem with the source definition. The old code did not calculate three of the four source tables. To overcome this two simulations were run and then the results were added and multiplied by two because two of the tablets were perfectly symmetric with the others.

Figure 38: PET Pig, Simple Models

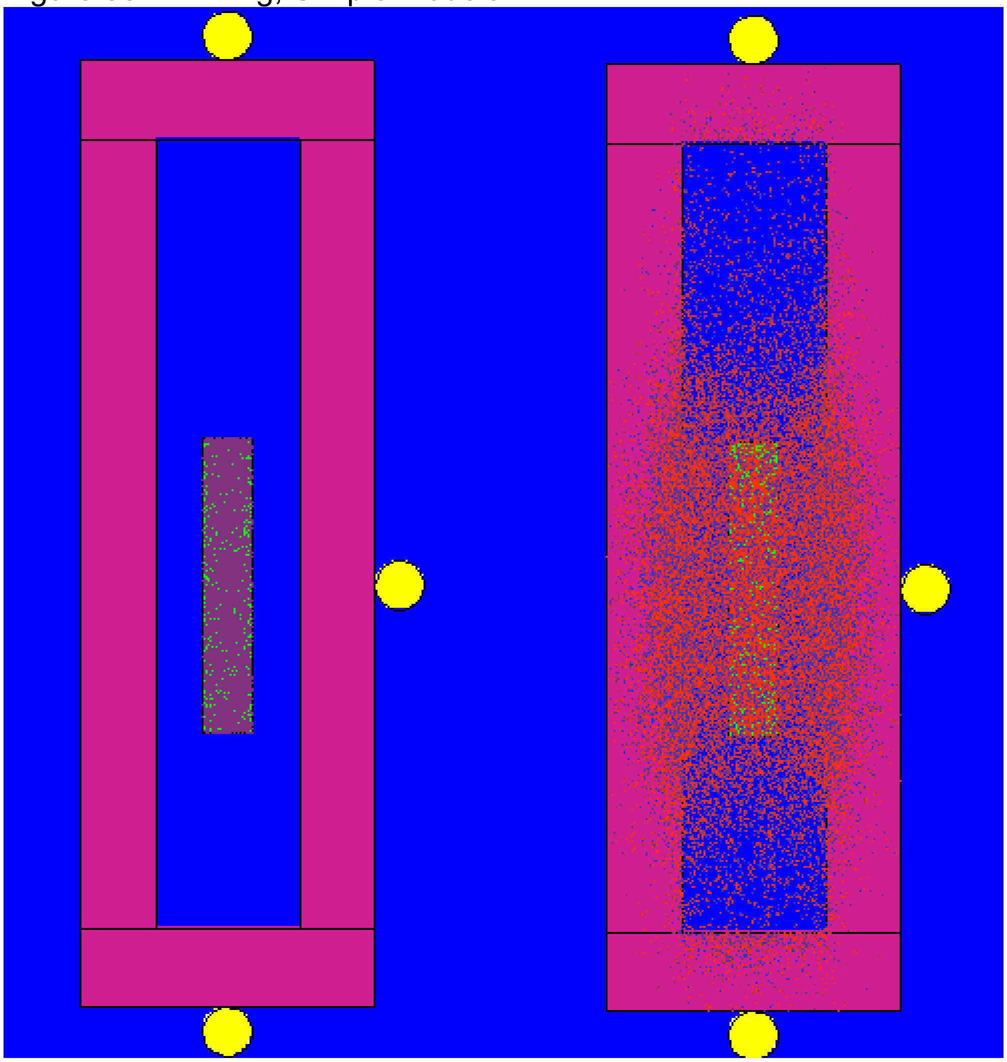
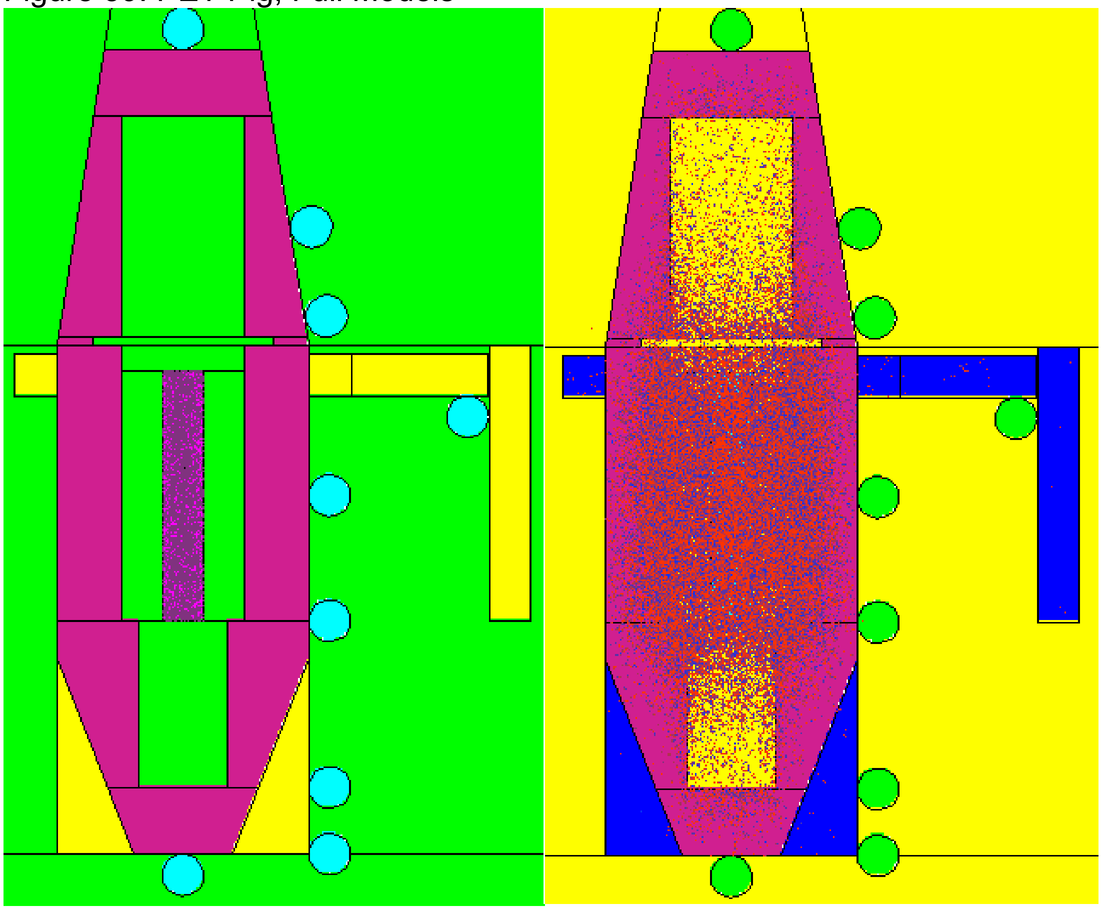
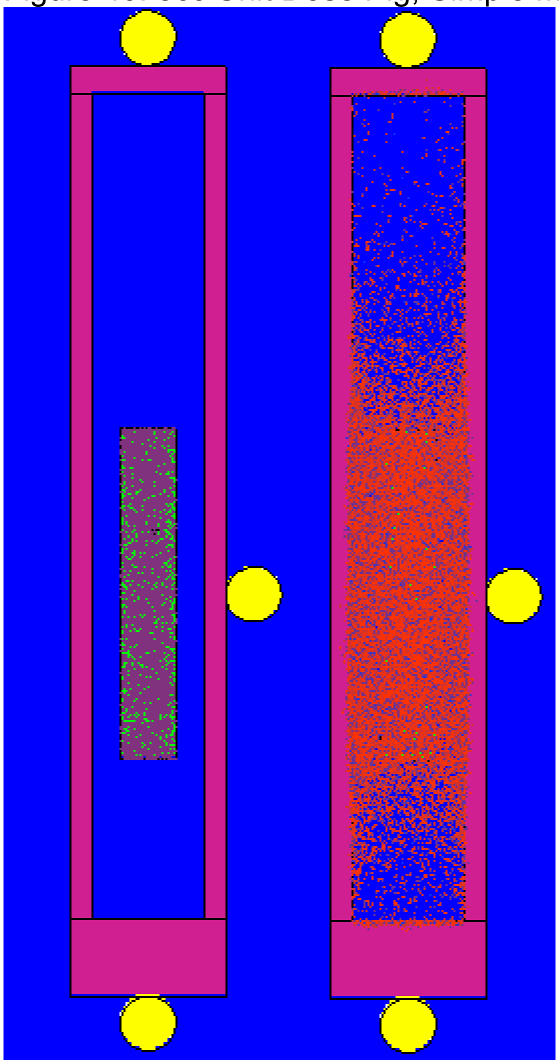


Figure 39: PET Pig, Full Models



For the 5cc Unit Dose pig the energy of the Tc-99m photons fell off too quickly to get any data in most of the dose points. To ensure that the photons were doing what was expected their positions were examined at several mid-points and continuation trials were ran from there. Figure [40] shows the initial source and dispersion particles. Figure [41] and [42] show the next stages where simulations were run.

Figure 40: 5cc Unit Dose Pig, Simple Models



The first continuation was at the top and bottom of the air cavity in the 5cc Unit Dose Pig. It is seen that the number of interactions drop off very quickly as the photons enter the tungsten. There are also appears to be a significant amount of reflection back into the air cavity. This explains the density of interactions in the air cavity in previous figures, which is counterintuitive to the cross section value. The second continuation started with an area where the flux had decreased to the order of 10^2 and an average energy of 0.09 MeV. This run results in zero flux even a short distance away from the new source. Because of the low flux and cut-off energy (0.01 MeV) issues regardless of how many particles are run or error reduction utilities used it may be impossible to get a conclusive dose estimate at most of the dose points for this model. Figure [43] shows the full model with source and 100,000 interactions. This model was not actually run to completion because the information from the simplified models was convincing enough that no additional information would be yielded.

Figure 41: 5cc Unit Dose Pig, Simple Models Phase Two

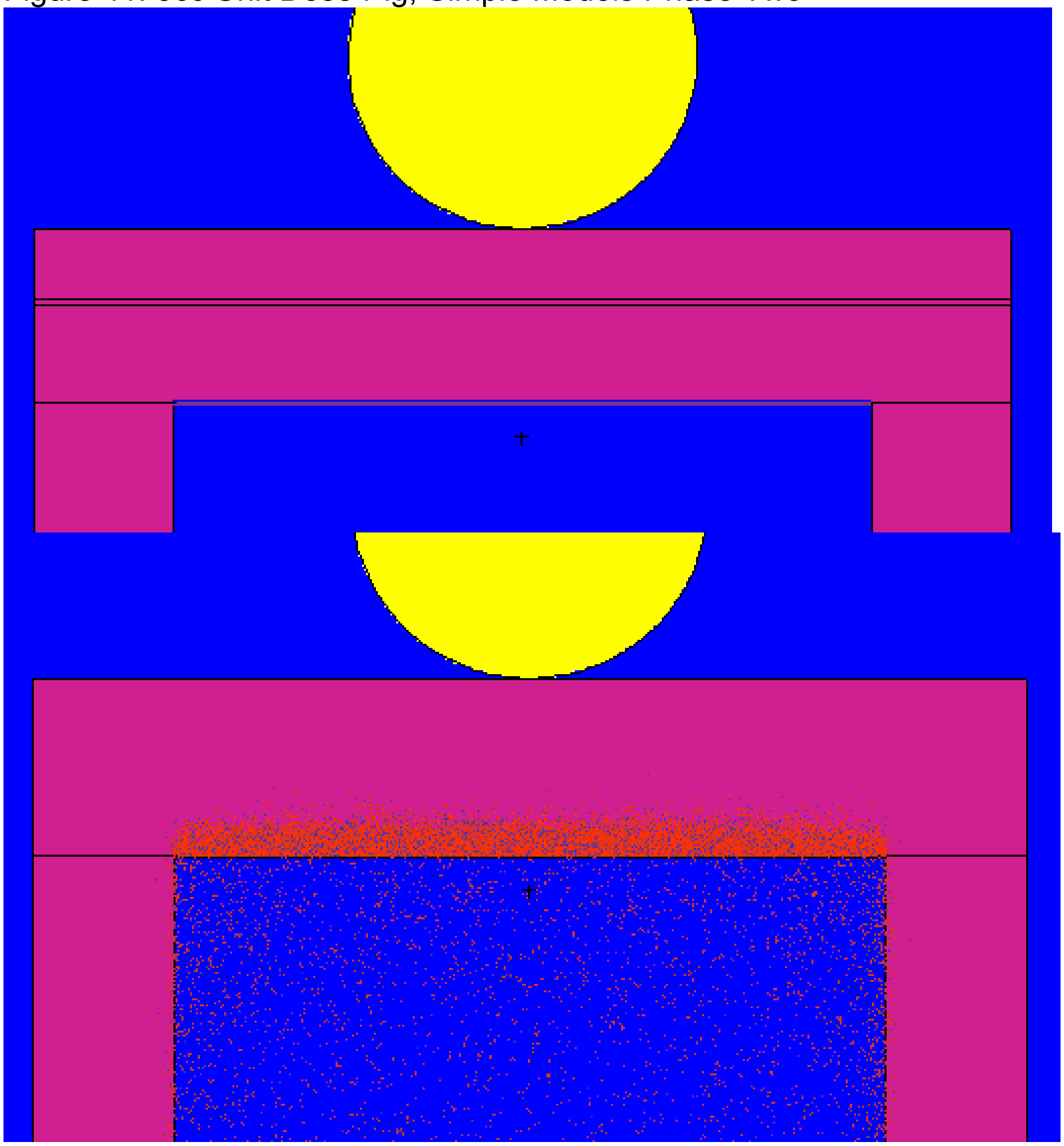


Figure 42: 5cc Unit Dose Pig, Phase Three

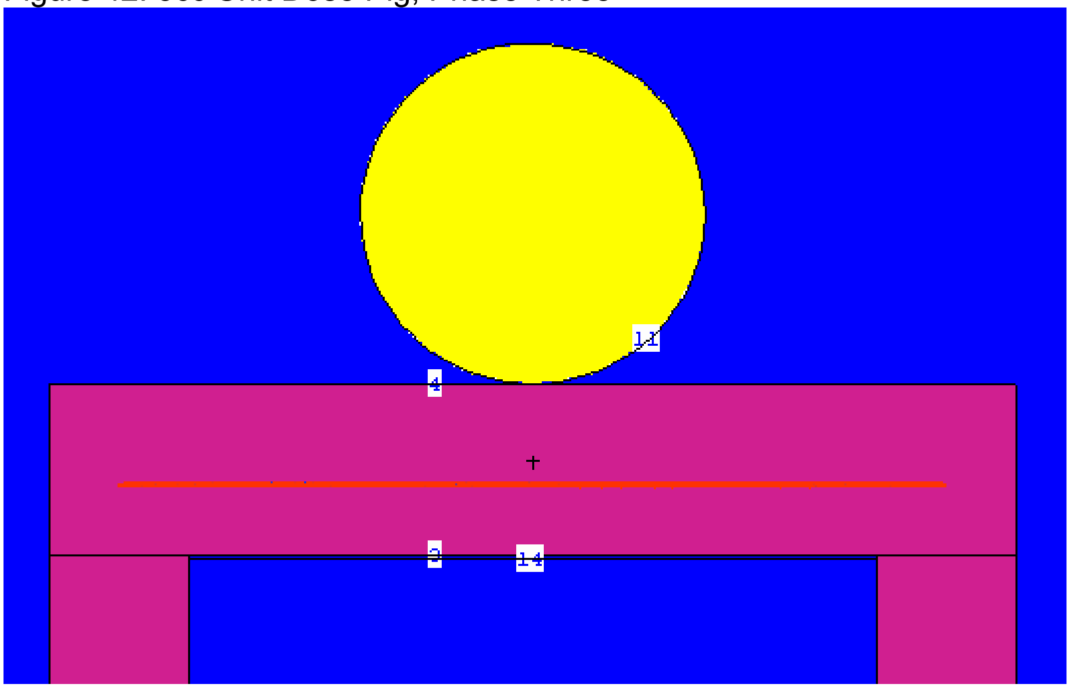
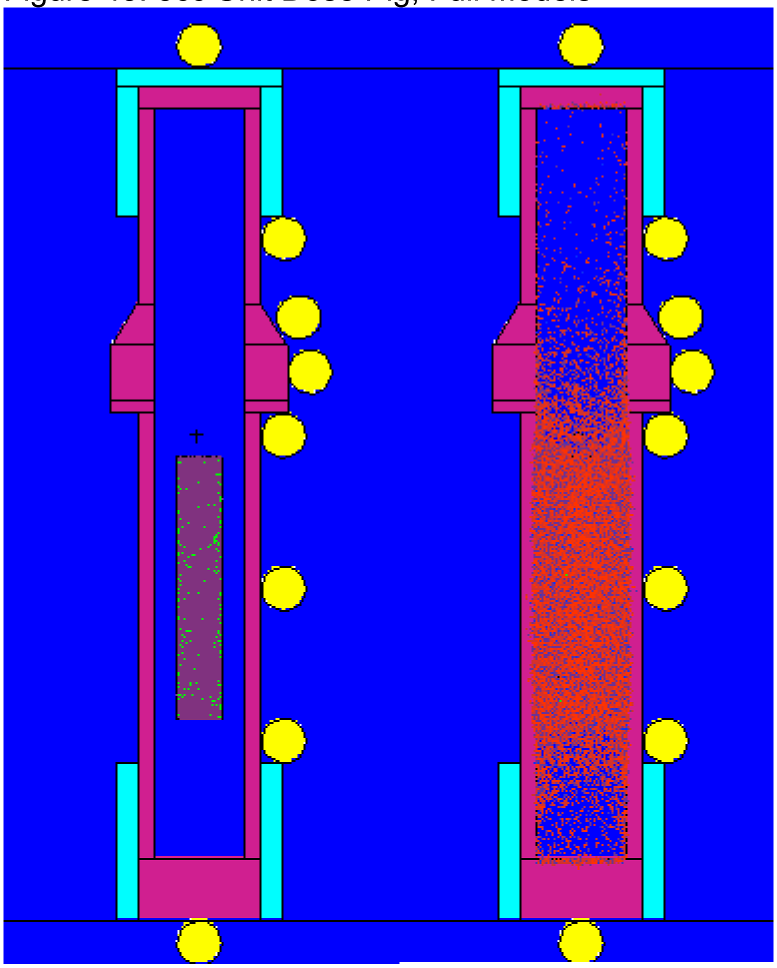


Figure 43: 5cc Unit Dose Pig, Full Models



Tables [30] – [33] depict the results from the improved MCNP models.

Table 30: 5cc Unit Dose Pig, MCNP Dose Rate Results

	5cc Unit Dose(mrem/hr)	
Dose Point	Simplified MCNP Model	Full MCNP Model
Top	0	0
Side	0.227242	0.0165
Bottom	0	0

Table 31: PET Pig, MCNP Dose Rate Results

Dose Point	PET Pig (mrem/hr)	
	Simplified MCNP Model	Full MCNP Model
1	1.39169	1.82003
2		1.6621
3		5.87906
4	11.4111	15.0471
5		8.15007
6		0.611506
7		0.296112
8	2.29519	2.90495
9		4.73421
10		0.196366

Table 32: 30mL PET Dispenser, MCNP Flux Results

Dose Point	30mL PET Dispenser (photons/cm^2/sec)	
1	Simplified MCNP Model	Full MCNP Model
2	$2.91 \cdot 10^7$	$1.24 \cdot 10^7$
3		$2.33 \cdot 10^5$
4		$1.21 \cdot 10^4$
5		$5.51 \cdot 10^4$
6	$9.23 \cdot 10^4$	$7.97 \cdot 10^4$
7		$5.25 \cdot 10^3$
8	$3.28 \cdot 10^4$	$3.47 \cdot 10^4$
9		$3.64 \cdot 10^4$
10		$2.58 \cdot 10^3$

Table 33: Piglet, MCNP Dose Rate Results

Dose Point	Piglet (mrem/hr)
1	Full MCNP Model
2	$1.43 \cdot 10^{-3}$
3	$6.72 \cdot 10^{-5}$
4	$7.07 \cdot 10^{-4}$
5	$3.06 \cdot 10^{-2}$
6	$1.69 \cdot 10^{-2}$
7	$5.40 \cdot 10^{-4}$
8	$2.16 \cdot 10^{-3}$
9	$5.58 \cdot 10^{-4}$

6.5.4 Comparison of Calculated vs. New Simulations

Figure 44: Calculated and Modeled Values for the 5cc Unit Dose Pig

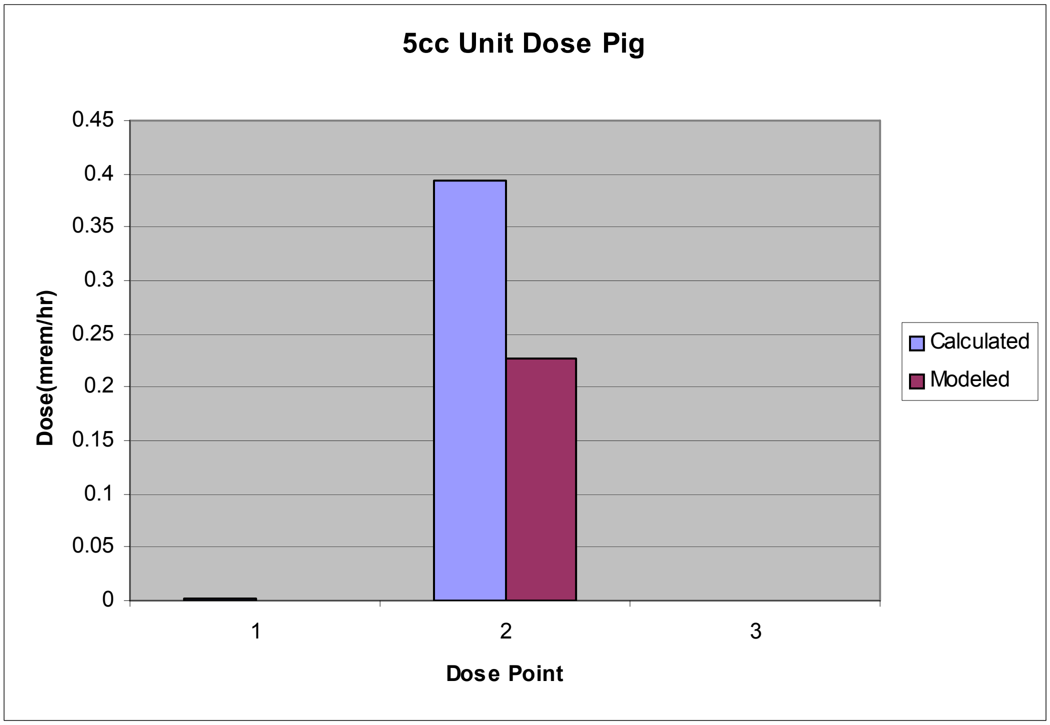


Figure 45: Calculated and Modeled Values for the PET Pig

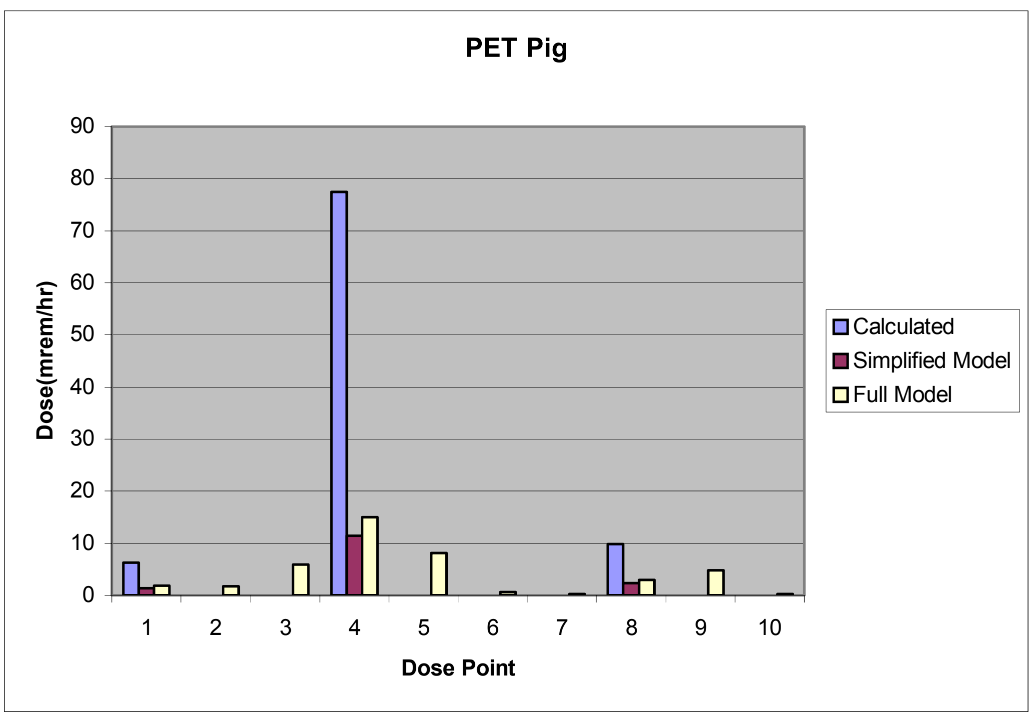


Figure 46: Calculated and Modeled Values for the 30mL PET Dispenser

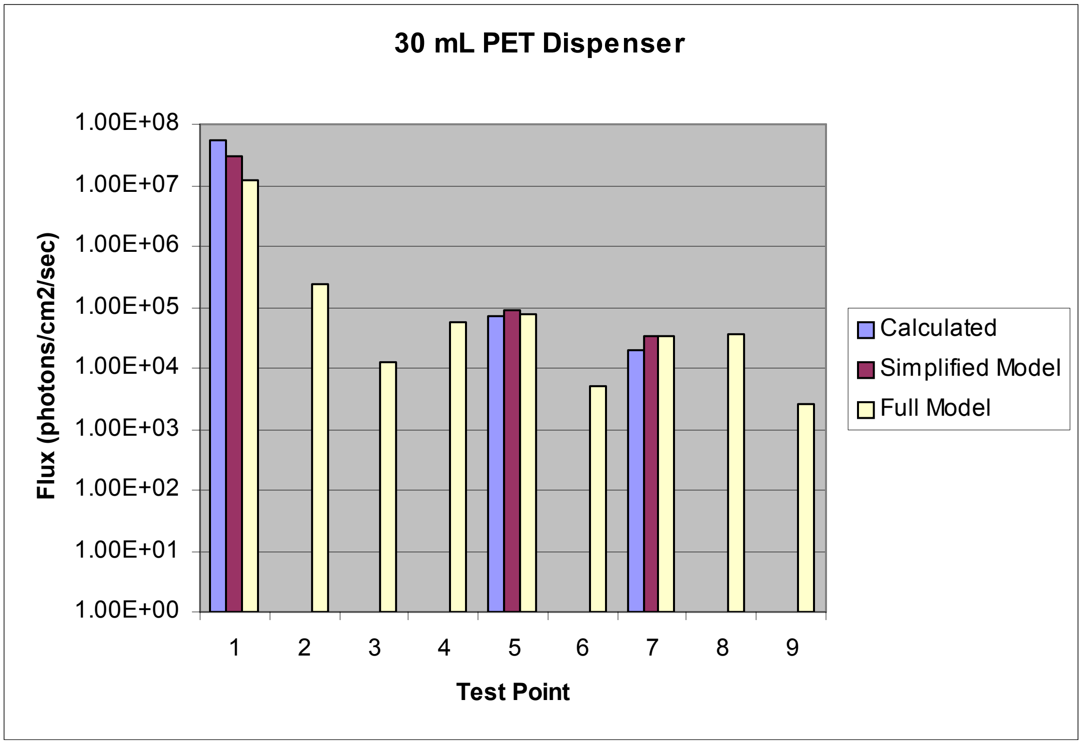
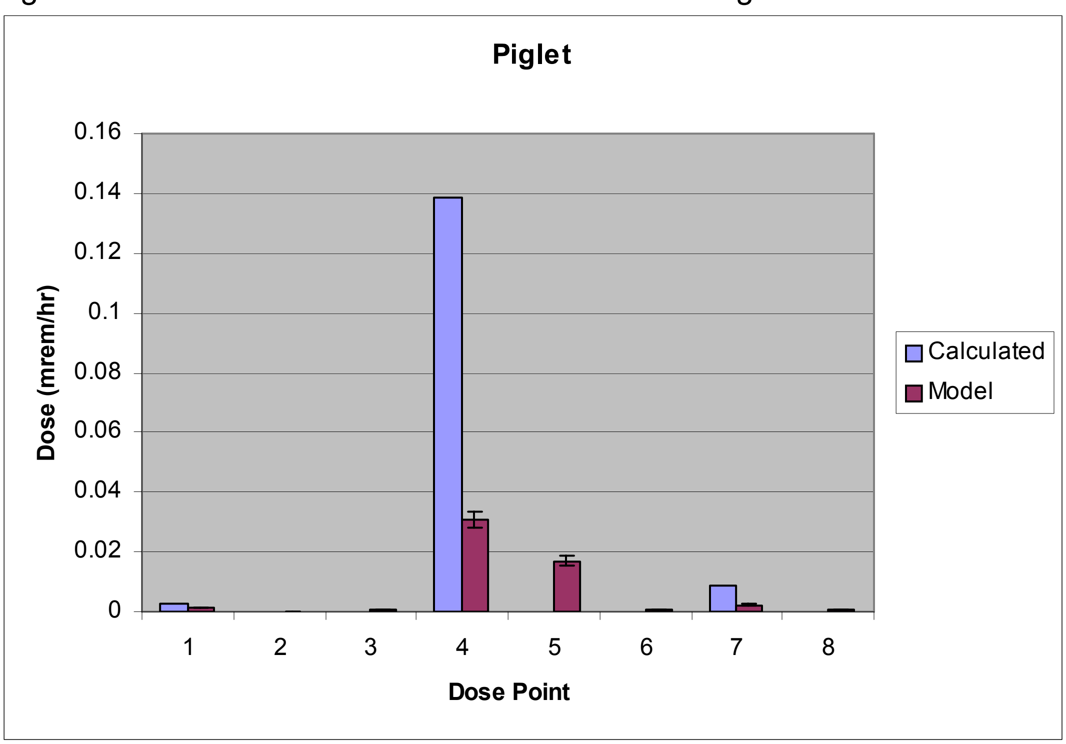


Figure 47: Calculated and Modeled Values for the Piglet



6.5.5 Discussion of the Graphs

The data for the 5cc Unit Dose Pig, the PET Dispenser and the Piglet all show a significantly higher but consistent dose rate than the MCNP models. This is likely the results of different resources used to convert between exposure and dose. The 30mL PET Dispenser has an anomaly. The other two flux points have a lower value for the calculated fluxes, but the top flux point is noticeably higher. There are several reasons this could be. When the calculations were done the photon attenuation constants for iron were used instead finding an approximation for stainless steel. A second factor is that the source was approximated as a line source. The vial that holds the source has a definite thickness to it so this approximation may not be entirely appropriate. When comparing this new data to the data obtained at Cardinal Health very little correlation is seen. The Cardinal Health numbers are orders of magnitude higher on all accounts. Their shapes relative to each other are not consistent with the calculations or the MCNP models

6.5.6 Variance Reduction Techniques

MCNP offers several variance reduction techniques. Depending on the problem different techniques may be appropriate. All of the techniques depend on a simple assumption. To gain increased knowledge about one area of the problem one needs to necessarily sacrifice information in another area when using the same amount of processing time. Because the goal of this set of models was to find information in a great many areas of interest it made the application of variance reduction techniques infeasible. For a more focused look a great number of the available techniques could be utilized. A time cutoff may have prevented wasted time for the runs that crashed. However, depending on what the specific cause of the crash was it might not have helped at all. Russian Roulette and particle splitting would help generate more particles in the low population areas. Using forced collisions would be very helpful. The simulation would not need to wait for explicit interactions and instead tally the probability of interaction for every particle that entered a region of interest. Considering that many of the points of interest had relatively low particle fluxes this method would maximize the usefulness of every particle in the region. DXTRAN and exponential transformation would be ideal for transporting particles into the low interaction regions. The shielding thickness, especially with the low energy photons, made useful data at some points nearly impossible to obtain. These methods would alleviate that. These variance reduction techniques could improve the efficiency of the runtimes for the models when focusing on a specific dose point. Even without them appropriate statistics were obtained by merely increasing the number of trials run, which is an inelegant but effective method. If more complex data needed to be obtained these methods could benefit that goal.

Chapter 7 - Conclusions

The initial data indicated very little correlation between data from Monte-Carlo Simulation or Cardinal Health. The further improvements utilizing the hand calculations, more tools in the MCNP5 Visual Editor and verification of conversions and constants support the validity of the Monte-Carlo model. The Monte Carlo models appear to behave as physically expected and comes very close to the calculated values on all accounts. These models can provide a solid starting point for improved simulations and examination of specific regions of interest around the Cardinal Health pigs. The data from the physical experiment lacks solid scientific verification but could also provide a starting point for the methodology of future experimentation utilizing similar measurements in a more controlled environment.

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APPENDICES

Appendix A: 30mL PET Dispenser, Simple MCNP Model

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        Thread Name & Version = MCNP5_RSICC, 1.30
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+-------------------------------------------------------------------+
|   This program was prepared by the Regents of the University of    |
|California at Los Alamos National Laboratory (the University) under |
|  contract number W-7405-ENG-36 with the U.S. Department of Energy  |
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+-------------------------------------------------------------------+

1mcnp     version 5     ld=06212004                 04/26/07 15:57:36
*************************************************************************                probid =  04/26/07 15:57:36
 inp=30ml_s outp=s_out

       c     Created on: Thursday, April 26, 2007 at 15:07
          1    6      -1 -7  $ isotope
          2    5      -1 -8  $ top
          3    5      -1 -9  $ middle
          4    5      -1 -10  $ bottom
          5    4 -0.001239 3 -4 -11  #1 $ air cavity
          6    1     -18 -1 2 -3  $ bottom
          7    1     -18 -1 11 3 -4  $ middle
          8    3      -8 -1 4 -5  $ top
          9    4 -0.001239 -6  #1 #2 #3 #4 #5 #6 #7 #8
         10    0        6

          1       cz 5.35
          2       pz 0.001
          3       pz 4
          4       pz 10.8
          5       pz 13.85
          6       so 40
          7      rcc 0 0 4 0 0 4 1
          8      rcc 0 -1 14.36 0 2 0 0.5
          9      rcc 5.86 -1 5 0 2 0 0.5
         10       rcc 0 -1 -0.51 0 2 0 0.5
         11        cz 1.85

       mode  p
       m1    74000.            0.95  $Impact Bonded Tungsten
             28000.           0.035 26000.           0.015
       m2    82000.               1  $Lead
 warning. material   2 is not used in the problem.
       m3    26000.          0.8066  $Stainless Steel
             6000.          0.0006 25000.            0.01 15000.          0.00045
             16000.         0.00035 14000.           0.01 24000.           0.125
             28000.            0.04 42000.           0.007
       m4    7000.              0.8  $air
             8000.              0.2
       m5    8000.             0.65  $people
             6000.             0.18 1000.             0.1 7000.             0.03
             20000.           0.015 15000.           0.01
       m6    1000.           0.6666  $ saline and tech
             8000.           0.3333
       imp:p             1 8r                 0  $ 1, 10
       sdef erg=.511 pos=0 0 0 rad=d1 ext=d2 axs=0 0 1 wgt=5.92e10
       si1 0.0 1
```

```
 43-       sp1 -21 1
 44-       si2 4 8
 45-       sp2 -21 0
 46-       nps 5000000
 47-       de0   .01 .03 .05 .07 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .8 1 1.4 1.8
 48-            2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25
 49-       df0   3.96e-6 5.82e-7 2.9e-7 2.58e-7 2.83e-7 3.79e-7 5.01e-7 6.31e-7 7.59e-7
 50-            8.78e-7 9.85e-7 1.08e-6 1.17e-6 1.27e-6 1.36e-6 1.44e-6 1.52e-6 1.68e-6
 51-            1.98e-6 2.51e-6 2.99e-6 3.42e-6 3.82e-6 4.01e-6 4.41e-6 4.83e-6 5.23e-6
 52-            5.60e-6 5.80e-6 6.01e-6
 53-       f4:p  2 3 4
```

surface 3 and surface 7.3 are the same. 7.3 will be deleted.

surface 8.2 and surface 9.2 are the same. 9.2 will be deleted.

surface 8.2 and surface 10.2 are the same. 10.2 will be deleted.

surface 8.3 and surface 9.3 are the same. 9.3 will be deleted.

surface 8.3 and surface 10.3 are the same. 10.3 will be deleted.

comment. 5 surfaces were deleted for being the same as others.

warning. 2 materials had unnormalized fractions. print table 40.

1cells print table 60

cell	mat	atom density	gram density	volume	mass	photon pieces	importance
1	1	6	1.00282E-01 1.00000E+00	1.25664E+01	1.25664E+01	1	1.0000E+00
2	2	5	4.23892E-02 1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
3	3	5	4.23892E-02 1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
4	4	5	4.23892E-02 1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
5	5	4	5.17958E-05 1.23900E-03	6.05479E+01	7.50189E-02	1	1.0000E+00
6	6	1	6.10520E-02 1.80000E+01	3.59591E+02	6.47264E+03	1	1.0000E+00
7	7	1	6.10520E-02 1.80000E+01	5.38343E+02	9.69018E+03	1	1.0000E+00
8	8	3	8.69179E-02 8.00000E+00	2.74257E+02	2.19405E+03	1	1.0000E+00
9	9	4	5.17958E-05 1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
10	10	0	0.00000E+00 0.00000E+00	0.00000E+00	0.00000E+00	0	0.0000E+00

total 1.25002E+03 1.83742E+04

minimum source weight = 5.9200E+10   maximum source weight = 5.9200E+10

```
****************************************************
* Random Number Generator  =                    1 *
* Random Number Seed       =       19073486328125 *
* Random Number Multiplier =       19073486328125 *
* Random Number Adder      =                    0 *
* Random Number Bits Used  =                   48 *
* Random Number Stride     =               152917 *
****************************************************
```

2 warning messages so far.

1cross-section tables print table 100

table length

tables from file mcplib04

table	length	description	mat	date
1000.04p	1898	ENDF/B-VI Release 8 Photoatomic Data for 1-H	mat 100	02/07/03
6000.04p	3152	ENDF/B-VI Release 8 Photoatomic Data for 6-C	mat 600	02/07/03
7000.04p	3194	ENDF/B-VI Release 8 Photoatomic Data for 7-N	mat 700	02/07/03
8000.04p	3272	ENDF/B-VI Release 8 Photoatomic Data for 8-O	mat 800	02/07/03
14000.04p	4792	ENDF/B-VI Release 8 Photoatomic Data for 14-SI	mat1400	02/07/03

```
 15000.04p    4498  ENDF/B-VI Release 8 Photoatomic Data for 15-P                 mat1500    02/07/03
 16000.04p    4654  ENDF/B-VI Release 8 Photoatomic Data for 16-S                 mat1600    02/07/03
 20000.04p    5013  ENDF/B-VI Release 8 Photoatomic Data for 20-CA                mat2000    02/07/03
 24000.04p    5682  ENDF/B-VI Release 8 Photoatomic Data for 24-CR                mat2400    02/07/03
 25000.04p    5598  ENDF/B-VI Release 8 Photoatomic Data for 25-MN                mat2500    02/07/03
 26000.04p    5718  ENDF/B-VI Release 8 Photoatomic Data for 26-FE                mat2600    02/07/03
 28000.04p    5826  ENDF/B-VI Release 8 Photoatomic Data for 28-NI                mat2800    02/07/03
 42000.04p    7592  ENDF/B-VI Release 8 Photoatomic Data for 42-MO                mat4200    02/07/03
 74000.04p    9716  ENDF/B-VI Release 8 Photoatomic Data for 74-W                 mat7400    02/07/03

 total      70605

maximum photon energy set to  100.0 mev (maximum electron energy)

                 tables from file el03

  1000.03e    2329                                                   6/6/98
  6000.03e    2333                                                   6/6/98
  7000.03e    2333                                                   6/6/98
  8000.03e    2333                                                   6/6/98
 14000.03e    2339                                                   6/6/98
 15000.03e    2339                                                   6/6/98
 16000.03e    2339                                                   6/6/98
 20000.03e    2343                                                   6/6/98
 24000.03e    2345                                                   6/6/98
 25000.03e    2345                                                   6/6/98
 26000.03e    2345                                                   6/6/98
 28000.03e    2347                                                   6/6/98
 42000.03e    2353                                                   6/6/98
 74000.03e    2367                                                   6/6/98

warning. material    1 has been set to a conductor.

warning. material    3 has been set to a conductor.

*************************************************************************************************************************
dump no.    1 on file runtpn      nps =          0     coll =            0     ctm =       0.00   nrn =               0


       4 warning messages so far.
1problem summary

     run terminated when     5000000  particle histories were done.
+                                                                04/26/07 16:01:30
     c     Created on: Thursday, April 26, 2007 at 15:07                      probid =  04/26/07 15:57:36
0
photon creation     tracks      weight       energy           photon loss        tracks      weight       energy
                             (per source particle)                                       (per source particle)

source           5000000    5.9200E+10    5.1100E-01         escape             76941    9.1098E+08    6.0288E-03
                                                    energy cutoff          0    0.          1.1925E-04
                                                    time cutoff            0    0.          0.
weight window           0    0.           0.                weight window           0    0.           0.
cell importance         0    0.           0.                cell importance         0    0.           0.
weight cutoff           0    0.           0.                weight cutoff           0    0.           0.
e or t importance       0    0.           0.                e or t importance       0    0.           0.
dxtran                  0    0.           0.                dxtran                  0    0.           0.
forced collisions       0    0.           0.                forced collisions       0    0.           0.
exp. transform          0    0.           0.                exp. transform          0    0.           0.
from neutrons           0    0.           0.                compton scatter         0    0.           1.3975E-01
bremsstrahlung    2448425    2.8989E+10    1.2439E-02         capture         13157641    1.5579E+11    4.2741E-01
p-annihilation          0    0.           0.                pair production         0    0.           0.
photonuclear            0    0.           0.                photonuclear abs        0    0.           0.
electron x-rays         0    0.           0.
1st fluorescence  4998027    5.9177E+10    4.8481E-02
2nd fluorescence   788130    9.3315E+09    1.3888E-03
    total        13234582    1.5670E+11    5.7331E-01           total        13234582    1.5670E+11    5.7331E-01
```

```
  number of photons banked                3236555       average time of (shakes)            cutoffs
  photon tracks per source particle     2.6469E+00         escape           1.2111E-01         tco   1.0000E+33
  photon collisions per source particle  3.8220E+00         capture          5.7737E-03         eco   1.0000E-03
  total photon collisions                19110039        capture or escape 6.4443E-03        wc1  -5.0000E-01
                                                 any termination   6.4443E-03         wc2  -2.5000E-01

 computer time so far in this run    3.88 minutes          maximum number ever in bank        5
 computer time in mcrun              3.85 minutes          bank overflows to backup file      0
 source particles per minute          1.2985E+06
 random numbers generated              247296624         most random numbers used was        283 in history
4084013

 range of sampled source weights = 5.9200E+10 to 5.9200E+10
1photon   activity in each cell                                                          print table 126
```

cell		tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	5062030	5006898	519567	6.1517E+09	4.8707E-01	4.8707E-01	5.9200E+10	1.0184E+01
2	2	4941	4940	397	4.7005E+06	3.7230E-01	3.7230E-01	5.9200E+10	9.9718E+00
3	3	15	15	1	1.1840E+04	4.5202E-01	4.5202E-01	5.9200E+10	1.0855E+01
4	4	8	8	2	2.3680E+04	3.9686E-01	3.9686E-01	5.9200E+10	1.0203E+01
5	5	4772642	4573627	682	8.0749E+06	4.7341E-01	4.7341E-01	5.9200E+10	8.9964E+03
6	6	1008934	1656317	3589148	4.2496E+10	4.5911E-01	4.5911E-01	5.9200E+10	3.6345E-01
7	7	4142140	6593461	14189670	1.6801E+11	4.5932E-01	4.5932E-01	5.9200E+10	3.6374E-01
8	8	242920	265045	810293	9.5939E+09	3.6006E-01	3.6006E-01	5.9200E+10	1.1827E+00
9	9	82039	77051	279	3.3034E+06	3.8504E-01	3.8504E-01	5.9200E+10	8.2480E+03
total		15315669	18177362	19110039	2.2626E+11				

```
1tally   4       nps =     5000000
          tally type 4    track length estimate of particle flux.
          tally for  photons

          this tally is modified by a dose function.

          volumes
                 cell:       2            3            4
                      1.57080E+00  1.57080E+00  1.57080E+00

 cell  2
            2.57241E+01 0.0158

 cell  3
            8.56280E-02 0.2783

 cell  4
            3.48823E-02 0.4426


=========================================================================================
==========================================

          results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally   4
```

tfc bin behavior	--mean-- behavior	---relative error--- value	decrease	decrease rate	----variance of the variance---- value	decrease	decrease rate	--figure of merit-- value	behavior	-pdf- slope
desired	random	<0.10	yes	1/sqrt(nps)	<0.10	yes	1/nps	constant	random	>3.00
observed	random	0.02	yes	yes	0.00	yes	yes	constant	random	2.03
passed?	yes	yes	yes	yes	yes	yes	yes	yes	yes	no

```
==========================================================================================
==============================================

 warning.  the tally in the tally fluctuation chart bin did not pass  1 of the 10 statistical checks.

1analysis of the results in the tally fluctuation chart bin (tfc) for tally   4 with nps =     5000000  print table 160


 normed average tally per history  = 2.57241E+01          unnormed average tally per history  = 4.04073E+01
 estimated tally relative error    = 0.0158               estimated variance of the variance  = 0.0003
 relative error from zero tallies  = 0.0142               relative error from nonzero scores  = 0.0070

 number of nonzero history tallies =        4937          efficiency for the nonzero tallies  = 0.0010
 history number of largest  tally  =     3516403          largest  unnormalized history tally = 1.01541E+05
 (largest  tally)/(average tally)  = 2.51294E+03          (largest  tally)/(avg nonzero tally)= 2.48127E+00

 (confidence interval shift)/mean  = 0.0001               shifted confidence interval center  = 2.57276E+01


 if the largest  history score sampled so far were to occur on the next history, the tfc bin quantities would change as
follows:

      estimated quantities           value at nps           value at nps+1           value(nps+1)/value(nps)-1.

      mean                          2.57241E+01             2.57370E+01                   0.000502
      relative error                1.58486E-02             1.58485E-02                   0.000000
      variance of the variance      3.26055E-04             3.26408E-04                   0.001081
      shifted center                2.57276E+01             2.57277E+01                   0.000000
      figure of merit               1.03395E+03             1.03395E+03                   0.000001

 the estimated inverse power slope of the 200 largest  tallies starting at 7.04401E+04 is 2.0271
 the empirical history score probability density function appears to be increasing at the largest  history scores:
 please examine. see print table 161.
 the large score tail of the empirical history score probability density function appears to have no unsampled regions.

 fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (1.299E+06)*( 2.822E-02)**2 = (1.299E+06)*(7.963E-04) =
1.034E+03

1unnormed tally density for tally   4            nonzero tally mean(m) = 4.092E+04   nps =     5000000  print table 161

 abscissa              ordinate   log plot of tally probability density function in tally fluctuation chart bin(d=decade,slope=
2.0)
  tally  number num den log den:d----------------------------d----------------------------d----------------------------d----------
 1.58+02      1 6.14-09  -8.212 *****************************|*****************************|**************************** |
 2.00+02      1 4.87-09  -8.312 *****************************|*****************************|*************************   |
 2.51+02      2 7.74-09  -8.111 *****************************|*****************************|*****************************|*
 3.16+02      4 1.23-08  -7.910 *****************************|*****************************|*****************************|*******
 3.98+02      4 9.77-09  -8.010 *****************************|*****************************|*****************************|****
 5.01+02      3 5.82-09  -8.235 *****************************|*****************************|***************************  |
 6.31+02      5 7.71-09  -8.113 *****************************|*****************************|*****************************|*
 7.94+02      1 1.22-09  -8.912 *****************************|*****************************|*******                |
 1.00+03      5 4.86-09  -8.313 *****************************|*****************************|************************   |
 1.26+03     10 7.72-09  -8.112 *****************************|*****************************|*****************************|*
 1.58+03      5 3.07-09  -8.513 *****************************|*****************************|*******************       |
 2.00+03     16 7.80-09  -8.108 *****************************|*****************************|*****************************|*
 2.51+03     17 6.58-09  -8.182 *****************************|*****************************|*****************************|
 3.16+03     26 8.00-09  -8.097 *****************************|*****************************|*****************************|*
 3.98+03     21 5.13-09  -8.290 *****************************|*****************************|**************************  |
 5.01+03     46 8.93-09  -8.049 *****************************|*****************************|*****************************|***
 6.31+03     42 6.47-09  -8.189 *****************************|*****************************|*****************************|
 7.94+03     71 8.69-09  -8.061 *****************************|*****************************|*****************************|**
 1.00+04     84 8.17-09  -8.088 *****************************|*****************************|*****************************|**
 1.26+04    138 1.07-08  -7.972 *****************************|*****************************|*****************************|*****
 1.58+04    160 9.82-09  -8.008 *****************************|*****************************|*****************************|****
 2.00+04    251 1.22-08  -7.912 *****************************|*****************************|*****************************|*******
 2.51+04    381 1.47-08  -7.831 *****************************|*****************************|*****************************|*********
```

```
 3.16+04    443 1.36-08  -7.866
*****************************|*****************************|*****************************|********
 3.98+04    553 1.35-08  -7.869 *****************************|*****************************|*****************************|********
 5.01+04    780 1.51-08  -7.820
mmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmm|mmmm
mmmmmmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmmmmmm
 6.31+04   1008 1.55-08  -7.809
*****************************|*****************************|*****************************|**********
 7.94+04    845 1.03-08  -7.985 *****************************|*****************************|*****************************|*****    s
 1.00+05     13 1.26-10  -9.898 *****************************|*******                  |                    |  s
 1.26+05      1 7.72-12 -11.112 *                      |                    |                    s |
  total    4937 9.87-04         d---------------------------d----------------------------d----------------------------d----------
```

1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally   result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4   missed 1 of 10 tfc bin checks: the slope of decrease of largest tallies is less than the minimum acceptable value of 3.0
missed all bin error check: 3 tally bins had   0 bins with zeros and   2 bins with relative errors exceeding 0.10

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

warning.   1 of the   1 tally fluctuation chart bins did not pass all 10 statistical checks.
warning.   1 of the   1 tallies had bins with relative errors greater than recommended.
1tally fluctuation charts

	tally 4				
nps	mean	error	vov	slope	fom
256000	2.7879E+01	0.0677	0.0059	0.0	1051
512000	2.6982E+01	0.0487	0.0030	4.6	1010
768000	2.7715E+01	0.0389	0.0019	4.0	1057
1024000	2.6824E+01	0.0343	0.0015	4.5	1033
1280000	2.5966E+01	0.0311	0.0013	3.8	1019
1536000	2.5678E+01	0.0286	0.0011	2.7	1011
1792000	2.5595E+01	0.0265	0.0009	2.8	1014
2048000	2.5552E+01	0.0248	0.0008	3.1	1018
2304000	2.5566E+01	0.0234	0.0007	3.2	1023
2560000	2.5679E+01	0.0221	0.0006	3.0	1029
2816000	2.5497E+01	0.0212	0.0006	3.0	1021
3072000	2.5444E+01	0.0203	0.0005	3.1	1019
3328000	2.5521E+01	0.0195	0.0005	3.0	1022
3584000	2.5731E+01	0.0187	0.0005	2.8	1029
3840000	2.5705E+01	0.0181	0.0004	2.6	1029
4096000	2.5751E+01	0.0175	0.0004	2.5	1032
4352000	2.5739E+01	0.0170	0.0004	2.5	1034
4608000	2.5760E+01	0.0165	0.0004	2.4	1034
4864000	2.5707E+01	0.0161	0.0003	2.2	1034
5000000	2.5724E+01	0.0158	0.0003	2.0	1034

****

dump no.   2 on file runtpn   nps =   5000000   coll =   19110039   ctm =   3.85   nrn =   247296624

7 warning messages so far.

run terminated when   5000000 particle histories were done.

computer time =   3.88 minutes

mcnp   version 5   06212004   04/26/07 16:01:30   probid = 04/26/07 15:57:36

Appendix B: 30mL PET Dispenser, Full MCNP Model

```
        Thread Name & Version = MCNP5_RSICC, 1.30
                         _
        ._ _   _ ._  ._  |_
        | | | (_ | | |_) _)
                     |
+------------------------------------------------------------------+
|   This program was prepared by the Regents of the University of   |
|California at Los Alamos National Laboratory (the University) under |
|  contract number W-7405-ENG-36 with the U.S. Department of Energy  |
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|     liability or responsibility for the use of this software.      |
+------------------------------------------------------------------+

1mcnp     version 5     ld=06212004                  04/26/07 14:57:24
*************************************************************************                    probid =  04/26/07 14:57:24
 inp=30mlpet outp=30ml_f

    1-       c     Created on: Monday, March 06, 2006 at 20:47
    2-         1     1     -18 -6 -3 2  $ bottom sloped part
    3-         2     1     -18 -6 5 -4 3  $ bottom before vial slot
    4-         3     1     -18 -8 1 -2  $ side shielding around vial
    5-         4     3      -8 -29 4 -7  $ magnet needle access
    6-         5     6      -1 -40
    7-         9     4    -1.2 3 -4 -5  #5 $ air inside cavity
    8-        10     3      -8 15 -16 -14 6  $ stainless steel ring
    9-        11     3      -8 -19 20 -21  $ stainless steel handle stem (right)
   10-        12     3      -8 -19 -22 23  $ stainless steel handle stem (left)
   11-        13     3      -8 -25 2 -24  $ handle (left)
   12-        14     3      -8 -26 2 -24  $ handle (right)
   13-        15     3      -8 -27 -28 7  $ stainless steel magnet top
   14-        16     1     -18 -9 -7 4  #4 $ top sloped part
   15-        17     5      -1 -30  $ dose point (top)
   16-        18     5      -1 -31  $ dose point
   17-        19     5      -1 -32  $ dose point
   18-        20     5      -1 -33  $ dose point
   19-        21     5      -1 -34  $ dose point
   20-        22     5      -1 -35  $ dose point
   21-        23     5      -1 -36  $ dose point (bottom)
   22-        24     5      -1 -37  $ dose point (handle)
   23-        25     5      -1 -38  $ dose point (30cm from source)
   24-        26     4 -0.001239 28 -39  #17
   25-        27     4 -0.001239 -1 -39  #23
   26-        28     4 -0.001239 4 -28 -39  #16 #4 #15 #19 #18
   27-        29     4 -0.001239 -2 1 -39  #3 #22
   28-        30     4 -0.001239 -4 2 6 -39  #10 #11 #12 #13 #14 #19 #20 #21 #24 #25
   29-        31     0         39
   30-
   31-         1       pz 0.001
   32-         2       pz 2
   33-         3       pz 4
   34-         4       pz 10.8
   35-         5       cz 1.85
   36-         6       cz 5.35
   37-         7       pz 12.8
   38-         8       kz -10 0.2 1
   39-         9       kz 22.7 0.2 -1
   40-        14        cz 5.85
   41-        15        pz 7
   42-        16        pz 8
   43-        19       c/x 0 7.5 0.5
```

```
        20        px 5.85
        21        px 9.849
        22        px -5.85
        23        px -9.849
        24        pz 9.8
        25       c/z 10.35 0 0.5
        26       c/z -10.35 0 0.5
        27        cz 3.55
        28        pz 13.85
        29        kz 10.5 1 1
        30       rcc 0 -1 14.36 0 2 0 0.5
        31       rcc 4.06 -1 13.31 0 2 0 0.5
        32       rcc 5.86 -1 10.8 0 2 0 0.5
        33       rcc 5.86 -1 8.51 0 2 0 0.5
        34       rcc 5.86 -1 5 0 2 0 0.5
        35       rcc 5.5 -1 1 0 2 0 0.5
        36       rcc 0 -1 -0.51 0 2 0 0.5
        37       rcc 9.34 -1 6 0 2 0 0.5
        38       rcc 30 -1 4.25 0 2 0 0.5
        39        so 40
        40       rcc 0 0 4 0 0 4 1

      mode  p
      m1    74000.            0.95  $Impact Bonded Tungsten
            28000.           0.035 26000.           0.015
      m2    82000.               1  $Lead
warning. material   2 is not used in the problem.
      m3    26000.          0.8066  $Stainless Steel
            6000.          0.0006 25000.            0.01 15000.          0.00045
            16000.         0.00035 14000.            0.01 24000.           0.125
            28000.            0.04 42000.           0.007
      m4    7000.              0.8  $air
            8000.              0.2
      m5    8000.             0.65  $people
            6000.             0.18 1000.             0.1 7000.             0.03
            20000.           0.015 15000.            0.01
      m6    1000.           0.6666  $ saline and tech
            8000.           0.3333
      imp:p            1 26r                   0  $ 1, 31
      sdef erg=.511 pos=0 0 0 rad=d1 ext=d2 axs=0 0 1 wgt=5.92e10
      si1 0.0 1
      sp1 -21 1
      si2 4 8
      sp2 -21 0
      nps 5000000
      de0   .01 .03 .05 .07 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .8 1 1.4 1.8
            2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25
      df0   3.96e-6 5.82e-7 2.9e-7 2.58e-7 2.83e-7 3.79e-7 5.01e-7 6.31e-7 7.59e-7
            8.78e-7 9.85e-7 1.08e-6 1.17e-6 1.27e-6 1.36e-6 1.44e-6 1.52e-6 1.68e-6
            1.98e-6 2.51e-6 2.99e-6 3.42e-6 3.82e-6 4.01e-6 4.41e-6 4.83e-6 5.23e-6
            5.60e-6 5.80e-6 6.01e-6
      f4:p  17 18 19 20 21 22 23 24 25

surface     3   and surface     40.3 are the same.     40.3 will be deleted.

surface    16   and surface     40.2 are the same.     40.2 will be deleted.

surface    30.2 and surface     31.2 are the same.     31.2 will be deleted.

surface    30.2 and surface     32.2 are the same.     32.2 will be deleted.

surface    30.2 and surface     33.2 are the same.     33.2 will be deleted.

surface    30.2 and surface     34.2 are the same.     34.2 will be deleted.

surface    30.2 and surface     35.2 are the same.     35.2 will be deleted.
```

surface 30.2 and surface 36.2 are the same. 36.2 will be deleted.

surface 30.2 and surface 37.2 are the same. 37.2 will be deleted.

surface 30.2 and surface 38.2 are the same. 38.2 will be deleted.

surface 30.3 and surface 31.3 are the same. 31.3 will be deleted.

surface 30.3 and surface 32.3 are the same. 32.3 will be deleted.

surface 30.3 and surface 33.3 are the same. 33.3 will be deleted.

surface 30.3 and surface 34.3 are the same. 34.3 will be deleted.

surface 30.3 and surface 35.3 are the same. 35.3 will be deleted.

surface 30.3 and surface 36.3 are the same. 36.3 will be deleted.

surface 30.3 and surface 37.3 are the same. 37.3 will be deleted.

surface 30.3 and surface 38.3 are the same. 38.3 will be deleted.

comment. 18 surfaces were deleted for being the same as others.

warning. 2 materials had unnormalized fractions. print table 40.

warning. 1 of the materials appear at more than one density.

1cells print table 60

	cell	mat	atom density	gram density	volume	photon mass	pieces	importance
1	1	1	6.10520E-02	1.80000E+01	1.79840E+02	3.23713E+03	1	1.0000E+00
2	2	1	6.10520E-02	1.80000E+01	5.38343E+02	9.69018E+03	1	1.0000E+00
3	3	1	6.10520E-02	1.80000E+01	1.52409E+02	2.74336E+03	1	1.0000E+00
4	4	3	8.69179E-02	8.00000E+00	1.27130E+01	1.01704E+02	1	1.0000E+00
5	5	6	1.00282E-01	1.00000E+00	1.25664E+01	1.25664E+01	1	1.0000E+00
6	9	4	5.01654E-02	1.20000E+00	6.05479E+01	7.26575E+01	1	1.0000E+00
7	10	3	8.69179E-02	8.00000E+00	1.75929E+01	1.40743E+02	1	1.0000E+00
8	11	3	8.69179E-02	8.00000E+00	3.14081E+00	2.51265E+01	1	1.0000E+00
9	12	3	8.69179E-02	8.00000E+00	3.14081E+00	2.51265E+01	1	1.0000E+00
10	13	3	8.69179E-02	8.00000E+00	6.12611E+00	4.90088E+01	1	1.0000E+00
11	14	3	8.69179E-02	8.00000E+00	6.12611E+00	4.90088E+01	1	1.0000E+00
12	15	3	8.69179E-02	8.00000E+00	4.15715E+01	3.32572E+02	1	1.0000E+00
13	16	1	6.10520E-02	1.80000E+01	1.37007E+02	2.46613E+03	1	1.0000E+00
14	17	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
15	18	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
16	19	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
17	20	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
18	21	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
19	22	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
20	23	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
21	24	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
22	25	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
23	26	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
24	27	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
25	28	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
26	29	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
27	30	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
28	31	0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0	0.0000E+00

total 1.18526E+03 1.89594E+04

minimum source weight = 5.9200E+10 maximum source weight = 5.9200E+10

****
* Random Number Generator = 1 *

```
 * Random Number Seed       =      19073486328125 *
 * Random Number Multiplier =      19073486328125 *
 * Random Number Adder      =                   0 *
 * Random Number Bits Used  =                  48 *
 * Random Number Stride     =              152917 *
 ***************************************************
       3 warning messages so far.
1cross-section tables                                                        print table 100

    table    length

                    tables from file mcplib04

  1000.04p    1898  ENDF/B-VI Release 8 Photoatomic Data for 1-H                      mat 100      02/07/03
  6000.04p    3152  ENDF/B-VI Release 8 Photoatomic Data for 6-C                      mat 600      02/07/03
  7000.04p    3194  ENDF/B-VI Release 8 Photoatomic Data for 7-N                      mat 700      02/07/03
  8000.04p    3272  ENDF/B-VI Release 8 Photoatomic Data for 8-O                      mat 800      02/07/03
 14000.04p    4792  ENDF/B-VI Release 8 Photoatomic Data for 14-SI                    mat1400      02/07/03
 15000.04p    4498  ENDF/B-VI Release 8 Photoatomic Data for 15-P                     mat1500      02/07/03
 16000.04p    4654  ENDF/B-VI Release 8 Photoatomic Data for 16-S                     mat1600      02/07/03
 20000.04p    5013  ENDF/B-VI Release 8 Photoatomic Data for 20-CA                    mat2000      02/07/03
 24000.04p    5682  ENDF/B-VI Release 8 Photoatomic Data for 24-CR                    mat2400      02/07/03
 25000.04p    5598  ENDF/B-VI Release 8 Photoatomic Data for 25-MN                    mat2500      02/07/03
 26000.04p    5718  ENDF/B-VI Release 8 Photoatomic Data for 26-FE                    mat2600      02/07/03
 28000.04p    5826  ENDF/B-VI Release 8 Photoatomic Data for 28-NI                    mat2800      02/07/03
 42000.04p    7592  ENDF/B-VI Release 8 Photoatomic Data for 42-MO                    mat4200      02/07/03
 74000.04p    9716  ENDF/B-VI Release 8 Photoatomic Data for 74-W                     mat7400      02/07/03

 total       70605

 maximum photon energy set to  100.0 mev (maximum electron energy)

                    tables from file el03

  1000.03e    2329                                                      6/6/98
  6000.03e    2333                                                      6/6/98
  7000.03e    2333                                                      6/6/98
  8000.03e    2333                                                      6/6/98
 14000.03e    2339                                                      6/6/98
 15000.03e    2339                                                      6/6/98
 16000.03e    2339                                                      6/6/98
 20000.03e    2343                                                      6/6/98
 24000.03e    2345                                                      6/6/98
 25000.03e    2345                                                      6/6/98
 26000.03e    2345                                                      6/6/98
 28000.03e    2347                                                      6/6/98
 42000.03e    2353                                                      6/6/98
 74000.03e    2367                                                      6/6/98

 warning. material    1 has been set to a conductor.

 warning. material    3 has been set to a conductor.

 ***************************************************************************************************************************
 dump no.    1 on file runtpk     nps =           0     coll =             0     ctm =        0.00   nrn =                 0


       5 warning messages so far.
1problem summary

     run terminated when     5000000  particle histories were done.
+                                                                   04/26/07 15:01:14
     c     Created on: Monday, March 06, 2006 at 20:47                          probid =  04/26/07 14:57:24
0
 photon creation     tracks      weight        energy            photon loss        tracks      weight        energy
                             (per source particle)                                          (per source particle)
```

source	5000000	5.9200E+10	5.1100E-01	escape	12291	1.4553E+08	1.0106E-03
				energy cutoff	0	0.	1.1801E-04
				time cutoff	0	0.	0.
weight window	0	0.	0.	weight window	0	0.	0.
cell importance	0	0.	0.	cell importance	0	0.	0.
weight cutoff	0	0.	0.	weight cutoff	0	0.	0.
e or t importance	0	0.	0.	e or t importance	0	0.	0.
dxtran	0	0.	0.	dxtran	0	0.	0.
forced collisions	0	0.	0.	forced collisions	0	0.	0.
exp. transform	0	0.	0.	exp. transform	0	0.	0.
from neutrons	0	0.	0.	compton scatter	0	0.	1.4611E-01
bremsstrahlung	2416152	2.8607E+10	1.2164E-02	capture	13334760	1.5788E+11	4.2742E-01
p-annihilation	0	0.	0.	pair production	0	0.	0.
photonuclear	0	0.	0.	photonuclear abs	0	0.	0.
electron x-rays	0	0.	0.				
1st fluorescence	5116143	6.0575E+10	5.0065E-02				
2nd fluorescence	814756	9.6467E+09	1.4359E-03				
total	13347051	1.5803E+11	5.7467E-01	total	13347051	1.5803E+11	5.7467E-01

number of photons banked 3230908 average time of (shakes) cutoffs
photon tracks per source particle 2.6694E+00 escape 1.2036E-01 tco 1.0000E+33
photon collisions per source particle 3.8901E+00 capture 5.8175E-03 eco 1.0000E-03
total photon collisions 19450392 capture or escape 5.9230E-03 wc1 -5.0000E-01
any termination 5.9230E-03 wc2 -2.5000E-01

computer time so far in this run 3.80 minutes maximum number ever in bank 5
computer time in mcrun 3.78 minutes bank overflows to backup file 0
source particles per minute 1.3239E+06
random numbers generated 251204203 most random numbers used was 257 in history 2207865

range of sampled source weights = 5.9200E+10 to 5.9200E+10
1photon activity in each cell print table 126

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	1021150	1656353	3563922	4.2197E+10	4.5636E-01	4.5636E-01	5.9200E+10	3.6042E-01
2	2	4113078	6462683	13846073	1.6394E+11	4.5365E-01	4.5365E-01	5.9200E+10	3.5743E-01
3	3	6214	10045	21678	2.5667E+08	4.4180E-01	4.4180E-01	5.9200E+10	3.4390E-01
4	4	31989	31004	49618	5.8748E+08	3.8396E-01	3.8396E-01	5.9200E+10	1.2403E+00
5	5	5158165	5006914	541091	6.4065E+09	4.7863E-01	4.7863E-01	5.9200E+10	1.0095E+01
6	9	4852095	4581613	732913	8.6777E+09	4.4809E-01	4.4809E-01	5.9200E+10	9.0484E+00
7	10	225	228	116	1.3734E+06	4.2071E-01	4.2071E-01	5.9200E+10	1.3309E+00
8	11	6	7	11	1.3024E+05	3.6370E-01	3.6370E-01	5.9200E+10	1.2103E+00
9	12	9	9	6	7.1040E+04	4.0558E-01	4.0558E-01	5.9200E+10	1.3212E+00
10	13	9	9	14	1.6576E+05	4.0988E-01	4.0988E-01	5.9200E+10	1.2697E+00
11	14	18	18	7	8.2880E+04	4.5363E-01	4.5363E-01	5.9200E+10	1.4117E+00
12	15	16797	17160	23525	2.7854E+08	3.5633E-01	3.5633E-01	5.9200E+10	1.1852E+00
13	16	221392	330297	671218	7.9472E+09	4.4321E-01	4.4321E-01	5.9200E+10	3.4576E-01
14	17	2143	2142	155	1.8352E+06	4.1241E-01	4.1241E-01	5.9200E+10	1.0419E+01
15	18	38	38	2	2.3680E+04	2.8023E-01	2.8023E-01	5.9200E+10	8.9684E+00
16	19	2	2	0	0.0000E+00	4.7784E-01	4.7784E-01	5.9200E+10	1.1172E+01
17	20	5	5	0	0.0000E+00	4.2980E-01	4.2980E-01	5.9200E+10	1.0650E+01
18	21	13	13	0	0.0000E+00	4.7347E-01	4.7347E-01	5.9200E+10	1.1114E+01
19	22	1	1	0	0.0000E+00	4.5612E-01	4.5612E-01	5.9200E+10	1.0964E+01
20	23	7	7	1	1.1840E+04	4.1438E-01	4.1438E-01	5.9200E+10	1.0490E+01
21	24	6	6	0	0.0000E+00	3.6318E-01	3.6318E-01	5.9200E+10	9.6649E+00
22	25	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
23	26	13411	11258	39	4.6176E+05	4.0279E-01	4.0279E-01	5.9200E+10	8.4124E+03
24	27	486	479	2	2.3680E+04	4.4665E-01	4.4665E-01	5.9200E+10	8.8031E+03
25	28	1163	1115	0	0.0000E+00	3.6538E-01	3.6538E-01	5.9200E+10	8.0690E+03
26	29	503	502	0	0.0000E+00	4.6505E-01	4.6505E-01	5.9200E+10	8.9661E+03
27	30	1404	1316	1	1.1840E+04	4.5053E-01	4.5053E-01	5.9200E+10	8.8296E+03
total		15440329	18113224	19450392	2.3029E+11				

```
1tally   4        nps =     5000000
           tally type 4    track length estimate of particle flux.
           tally for  photons

           this tally is modified by a dose function.

           volumes
                   cell:      17          18          19          20          21          22          23
                         1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00
                   cell:      24          25
                         1.57080E+00  1.57080E+00

 cell  17
                 1.22622E+01 0.0237

 cell  18
                 1.42572E-01 0.1879

 cell  19
                 1.69096E-02 0.7073

 cell  20
                 3.25798E-02 0.4709

 cell  21
                 7.91296E-02 0.2952

 cell  22
                 4.35015E-03 1.0000

 cell  23
                 4.96336E-02 0.3896

 cell  24
                 2.41377E-02 0.5259

 cell  25
                 0.00000E+00 0.0000


===========================================================================================
===========================================

           results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally   4

 tfc bin     --mean--      ---------relative error---------      ----variance of the variance----      --figure of merit--     -pdf-
 behavior    behavior      value   decrease   decrease rate      value   decrease   decrease rate       value     behavior
slope

 desired      random       <0.10      yes      1/sqrt(nps)       <0.10      yes       1/nps          constant    random      >3.00
 observed     random        0.02      yes          yes            0.00      yes        yes          constant    random       1.78
 passed?       yes          yes      yes          yes            yes      yes        yes              yes        yes          no

===========================================================================================
===========================================


 warning.  the tally in the tally fluctuation chart bin did not pass  1 of the 10 statistical checks.

1analysis of the results in the tally fluctuation chart bin (tfc) for tally   4 with nps =     5000000  print table 160


 normed average tally per history  = 1.22622E+01          unnormed average tally per history  = 1.92614E+01
 estimated tally relative error    = 0.0237               estimated variance of the variance  = 0.0007
```

```
 relative error from zero tallies  = 0.0216              relative error from nonzero scores  = 0.0097

 number of nonzero history tallies =        2139         efficiency for the nonzero tallies  = 0.0004
 history number of largest  tally  =     2628950         largest  unnormalized history tally = 1.12851E+05
 (largest  tally)/(average tally)  = 5.85892E+03          (largest  tally)/(avg nonzero tally)= 2.50645E+00

 (confidence interval shift)/mean  = 0.0003              shifted confidence interval center  = 1.22659E+01


 if the largest  history score sampled so far were to occur on the next history, the tfc bin quantities would change as
follows:

     estimated quantities          value at nps          value at nps+1          value(nps+1)/value(nps)-1.

     mean                        1.22622E+01           1.22766E+01                0.001172
     relative error              2.37140E-02           2.37151E-02                0.000048
     variance of the variance    6.97139E-04           6.99675E-04                0.003638
     shifted center              1.22659E+01           1.22659E+01                0.000001
     figure of merit             4.70830E+02           4.70785E+02               -0.000096

 the estimated inverse power slope of the 106 largest  tallies starting at 7.04899E+04 is 1.7827
 the empirical history score probability density function appears to be increasing at the largest  history scores:
 please examine. see print table 161.
 the large score tail of the empirical history score probability density function appears to have no unsampled regions.

 fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (1.324E+06)*( 1.886E-02)**2 = (1.324E+06)*(3.556E-04) =
4.708E+02

1unnormed tally density for tally   4           nonzero tally mean(m) = 4.502E+04   nps =     5000000  print table 161

 abscissa              ordinate   log plot of tally probability density function in tally fluctuation chart bin(d=decade,slope=
1.8)
  tally  number num den log den:d----------------------d----------------------d----------------------d----------------------d-
 1.26+01      1 7.72-08  -7.112 ***********************|***********************|***********************|***********************|*
 1.58+01      0 0.00+00   0.000                  |                 |                 |                 |
 2.00+01      0 0.00+00   0.000                  |                 |                 |                 |
 2.51+01      0 0.00+00   0.000                  |                 |                 |                 |
 3.16+01      1 3.08-08  -7.512 ***********************|***********************|***********************|****************      |
 3.98+01      0 0.00+00   0.000                  |                 |                 |                 |
 5.01+01      0 0.00+00   0.000                  |                 |                 |                 |
 6.31+01      0 0.00+00   0.000                  |                 |                 |                 |
 7.94+01      1 1.22-08  -7.912 ***********************|***********************|***********************|******                 |
 1.00+02      0 0.00+00   0.000                  |                 |                 |                 |
 1.26+02      0 0.00+00   0.000                  |                 |                 |                 |
 1.58+02      0 0.00+00   0.000                  |                 |                 |                 |
 2.00+02      0 0.00+00   0.000                  |                 |                 |                 |
 2.51+02      0 0.00+00   0.000                  |                 |                 |                 |
 3.16+02      2 6.15-09  -8.211 ***********************|***********************|***********************|                 |
 3.98+02      1 2.44-09  -8.612 ***********************|***********************|*************        |                 |
 5.01+02      0 0.00+00   0.000                  |                 |                 |                 |
 6.31+02      1 1.54-09  -8.812 ***********************|***********************|********             |                 |
 7.94+02      2 2.45-09  -8.611 ***********************|***********************|*************        |                 |
 1.00+03      6 5.83-09  -8.234 ***********************|***********************|********************* |                 |
 1.26+03      2 1.54-09  -8.811 ***********************|***********************|********             |                 |
 1.58+03      5 3.07-09  -8.513 ***********************|***********************|***************      |                 |
 2.00+03      6 2.92-09  -8.534 ***********************|***********************|***************      |                 |
 2.51+03      4 1.55-09  -8.810 ***********************|***********************|********             |                 |
 3.16+03      5 1.54-09  -8.813 ***********************|***********************|********             |                 |
 3.98+03     15 3.66-09  -8.436 ***********************|***********************|*****************    |                 |
 5.01+03     10 1.94-09  -8.712 ***********************|***********************|**********           |                 |
 6.31+03     19 2.93-09  -8.533 ***********************|***********************|***************      |                 |
 7.94+03     27 3.31-09  -8.481 ***********************|***********************|****************     |                 |
 1.00+04     24 2.33-09  -8.632 ***********************|***********************|************         |                 |
 1.26+04     39 3.01-09  -8.521 ***********************|***********************|***************      |                 |
 1.58+04     66 4.05-09  -8.393 ***********************|***********************|******************   |                 |
 2.00+04     76 3.70-09  -8.431 ***********************|***********************|*****************    |                 |
 2.51+04    113 4.37-09  -8.359 ***********************|***********************|******************   |                 |
```

```
 3.16+04    178 5.47-09  -8.262 ************************|************************|********************** |                  |
 3.98+04    214 5.23-09  -8.282 ************************|************************|*********************  |                  |
 5.01+04    310 6.01-09  -8.221
mmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmmmmmmmmmmmmmmmmmmmm|                  |
 6.31+04    490 7.55-09  -8.122 ************************|************************|************************|*                 |
 7.94+04    509 6.23-09  -8.205 ************************|************************|***********************|       s          |
 1.00+05     11 1.07-10  -9.971 ************************|****                    |                 |    s            |
 1.26+05      1 7.72-12 -11.112 *                       |                  |                 s                |
  total    2139 4.28-04         d-----------------------d-----------------------d-----------------------d-----------------------d-
```

1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally   result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4   missed 1 of 10 tfc bin checks: the slope of decrease of largest tallies is less than the minimum acceptable value of 3.0
missed all bin error check: 9 tally bins had   1 bins with zeros and   7 bins with relative errors exceeding 0.10

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

the tally bins with zeros may or may not be correct: compare the source, cutoffs, multipliers, et cetera with the tally bins.

warning.   1 of the   1 tally fluctuation chart bins did not pass all 10 statistical checks.
warning.   1 of the   1 tallies had bins with relative errors greater than recommended.
1tally fluctuation charts

	tally 4				
nps	mean	error	vov	slope	fom
256000	1.2679E+01	0.1016	0.0125	0.0	502
512000	1.3446E+01	0.0702	0.0060	0.0	518
768000	1.2644E+01	0.0591	0.0043	0.0	475
1024000	1.2257E+01	0.0521	0.0033	0.0	464
1280000	1.2251E+01	0.0467	0.0027	10.0	464
1536000	1.1985E+01	0.0431	0.0023	10.0	459
1792000	1.2197E+01	0.0396	0.0019	3.5	468
2048000	1.2063E+01	0.0372	0.0017	2.4	463
2304000	1.2176E+01	0.0349	0.0015	2.3	467
2560000	1.2271E+01	0.0331	0.0013	1.8	469
2816000	1.2228E+01	0.0316	0.0012	1.9	469
3072000	1.2207E+01	0.0303	0.0011	1.9	470
3328000	1.2155E+01	0.0291	0.0011	1.8	467
3584000	1.2073E+01	0.0282	0.0010	1.8	465
3840000	1.2087E+01	0.0272	0.0009	1.9	467
4096000	1.2058E+01	0.0263	0.0009	1.8	467
4352000	1.2116E+01	0.0255	0.0008	1.8	468
4608000	1.2216E+01	0.0247	0.0008	1.8	471
4864000	1.2236E+01	0.0241	0.0007	1.8	471
5000000	1.2262E+01	0.0237	0.0007	1.8	471

****

dump no.   2 on file runtpk   nps =   5000000   coll =   19450392   ctm =   3.78   nrn =   251204203

8 warning messages so far.

run terminated when   5000000 particle histories were done.

computer time =   3.80 minutes

mcnp   version 5   06212004   04/26/07 15:01:14   probid = 04/26/07 14:57:24

Appendix C: Piglet, Full MCNP Model

```
     | | |  (_  | |  |_)   _)
                  |
```



```
1mcnp     version 5     ld=06212004                 04/18/07 19:43:16
*************************************************************************                 probid =  04/18/07 19:43:16
 inp=piglet_f outp=p_f

c     Created on: Monday, March 06, 2006 at 16:08
   1    1     -18 6 -5 -2
   2    1     -18 5 -4 -2 1
   3    1     -18 -3 4 -2
   4    6    -3.4 -7  $ capsule
   5    6    -3.4 -8  $ capsule
   6    6    -3.4 -9  $ capsule
   7    6    -3.4 -10  $ capsule
   8    5      -1 -11  $ dose point (top)
   9    5      -1 -12
   10    5      -1 -13
   11    5      -1 -14
   12    5      -1 -15
   13    5      -1 -16
   14    5      -1 -17  $ dose point (bottom)
   15    5      -1 -18  $ dose point (30cm)
   16    4 -0.001239 -4 5 -1  #4 #5 #6 #7 $ air inside capsule cavity
   17    4 -0.001239 3 -19  #8 #9
   18    4 -0.001239 -19 2 -3 6  #9 #10 #11 #12 #13 #15
   19    4 -0.001239 -19 -6  #13 #14
   20    0         19

   1       cz 0.95
   2       cz 2.95
   3       pz 2
   4       pz -0.7
   5       pz -4
   6       pz -6.8
   7      rcc -0.4 -0.4 -4 0 0 1 0.2
   8      rcc 0.4 -0.4 -4 0 0 1 0.2
   9      rcc -0.4 0.4 -4 0 0 1 0.2
   10      rcc 0.4 0.4 -4 0 0 1 0.2
   11      rcc 0 -1 2.501 0 2 0 0.5
   12      rcc 3.451 -1 2.251 0 2 0 0.5
   13      rcc 3.451 -1 0.5 0 2 0 0.5
   14      rcc 3.451 -1 -2.4 0 2 0 0.5
   15      rcc 3.451 -1 -4.9 0 2 0 0.5
   16      rcc 3.451 -1 -6.8 0 2 0 0.5
   17      rcc 0 -1 -7.301 0 2 0 0.5
   18      rcc 30 -1 -2.4 0 2 0 0.5
   19       so 40

mode  p
m1    74000.            0.95  $Impact Bonded Tungsten
      28000.           0.035 26000.           0.015
m2    82000.               1  $Lead
```

```
warning. material   2 is not used in the problem.
  47-       m3    26000.           0.8066  $Stainless Steel
warning. material   3 is not used in the problem.
  48-            6000.           0.0006 25000.            0.01 15000.          0.00045
  49-            16000.          0.00035 14000.            0.01 24000.           0.125
  50-            28000.            0.04 42000.           0.007
  51-       m4    7000.              0.8  $air
  52-            8000.              0.2
  53-       m5    8000.             0.65  $people
  54-            6000.             0.18 1000.             0.1 7000.             0.03
  55-            20000.            0.015 15000.           0.01
  56-       m6    11000.            0.5  $ Iodine salt
  57-            53000.            0.5
  58-       m7    1000.          0.081616  $ polyvinyl plastic
warning. material   7 is not used in the problem.
  59-            6000.        0.648407 7000.          0.126024 8000.          0.143953
  60-       imp:p            1 18r                   0  $ 1, 20
  61-       sdef erg=.3645 pos=0 0 -1.65 rad=d1 ext=d2 axs=0 0 1 cel=4 cel=5
  62-           cel=6 cel=7 wgt=3.0155e9
  63-       si1 0.0 .95
  64-       sp1 -21 1
  65-       si2 -4 -.7
  66-       sp2 -21 0
  67-       nps 1000000000
  68-       de0   .01 .03 .05 .07 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .8 1 1.4 1.8
  69-            2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25
  70-       df0   3.96e-6 5.82e-7 2.9e-7 2.58e-7 2.83e-7 3.79e-7 5.01e-7 6.31e-7 7.59e-7
  71-            8.78e-7 9.85e-7 1.08e-6 1.17e-6 1.27e-6 1.36e-6 1.44e-6 1.52e-6 1.68e-6
  72-            1.98e-6 2.51e-6 2.99e-6 3.42e-6 3.82e-6 4.01e-6 4.41e-6 4.83e-6 5.23e-6
  73-            5.60e-6 5.80e-6 6.01e-6
  74-       f4:p 8 9 10 11 12 13 14 15

surface      5   and surface      7.3 are the same.      7.3 will be deleted.

surface      5   and surface      8.3 are the same.      8.3 will be deleted.

surface      5   and surface      9.3 are the same.      9.3 will be deleted.

surface      5   and surface     10.3 are the same.     10.3 will be deleted.

surface      7.2 and surface      8.2 are the same.      8.2 will be deleted.

surface      7.2 and surface      9.2 are the same.      9.2 will be deleted.

surface      7.2 and surface     10.2 are the same.     10.2 will be deleted.

surface     11.2 and surface     12.2 are the same.     12.2 will be deleted.

surface     11.2 and surface     13.2 are the same.     13.2 will be deleted.

surface     11.2 and surface     14.2 are the same.     14.2 will be deleted.

surface     11.2 and surface     15.2 are the same.     15.2 will be deleted.

surface     11.2 and surface     16.2 are the same.     16.2 will be deleted.

surface     11.2 and surface     17.2 are the same.     17.2 will be deleted.

surface     11.2 and surface     18.2 are the same.     18.2 will be deleted.

surface     11.3 and surface     12.3 are the same.     12.3 will be deleted.

surface     11.3 and surface     13.3 are the same.     13.3 will be deleted.

surface     11.3 and surface     14.3 are the same.     14.3 will be deleted.

surface     11.3 and surface     15.3 are the same.     15.3 will be deleted.
```

surface 11.3 and surface 16.3 are the same. 16.3 will be deleted.

surface 11.3 and surface 17.3 are the same. 17.3 will be deleted.

surface 11.3 and surface 18.3 are the same. 18.3 will be deleted.

comment. 21 surfaces were deleted for being the same as others.

warning. 1 materials had unnormalized fractions. print table 40.

1cells print table 60

	cell	mat	atom density	gram density	volume	mass	photon pieces	importance
1	1	1	6.10520E-02	1.80000E+01	7.65512E+01	1.37792E+03	1	1.0000E+00
2	2	1	6.10520E-02	1.80000E+01	8.08646E+01	1.45556E+03	1	1.0000E+00
3	3	1	6.10520E-02	1.80000E+01	7.38172E+01	1.32871E+03	1	1.0000E+00
4	4	6	2.73192E-02	3.40000E+00	1.25664E-01	4.27257E-01	1	1.0000E+00
5	5	6	2.73192E-02	3.40000E+00	1.25664E-01	4.27257E-01	1	1.0000E+00
6	6	6	2.73192E-02	3.40000E+00	1.25664E-01	4.27257E-01	1	1.0000E+00
7	7	6	2.73192E-02	3.40000E+00	1.25664E-01	4.27257E-01	1	1.0000E+00
8	8	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
9	9	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
10	10	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
11	11	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
12	12	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
13	13	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
14	14	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
15	15	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
16	16	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
17	17	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
18	18	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
19	19	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
20	20	0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0	0.0000E+00
total					2.44302E+02	4.17647E+03		

minimum source weight = 3.0155E+09 maximum source weight = 3.0155E+09

```
***************************************************
* Random Number Generator  =                  1 *
* Random Number Seed       =     19073486328125 *
* Random Number Multiplier =     19073486328125 *
* Random Number Adder      =                  0 *
* Random Number Bits Used  =                 48 *
* Random Number Stride     =             152917 *
***************************************************
```

4 warning messages so far.

1cross-section tables print table 100

table length

tables from file mcplib04

table	length			
1000.04p	1898	ENDF/B-VI Release 8 Photoatomic Data for 1-H	mat 100	02/07/03
6000.04p	3152	ENDF/B-VI Release 8 Photoatomic Data for 6-C	mat 600	02/07/03
7000.04p	3194	ENDF/B-VI Release 8 Photoatomic Data for 7-N	mat 700	02/07/03
8000.04p	3272	ENDF/B-VI Release 8 Photoatomic Data for 8-O	mat 800	02/07/03
11000.04p	3995	ENDF/B-VI Release 8 Photoatomic Data for 11-NA	mat1100	02/07/03
15000.04p	4498	ENDF/B-VI Release 8 Photoatomic Data for 15-P	mat1500	02/07/03
20000.04p	5013	ENDF/B-VI Release 8 Photoatomic Data for 20-CA	mat2000	02/07/03
26000.04p	5718	ENDF/B-VI Release 8 Photoatomic Data for 26-FE	mat2600	02/07/03
28000.04p	5826	ENDF/B-VI Release 8 Photoatomic Data for 28-NI	mat2800	02/07/03
53000.04p	8492	ENDF/B-VI Release 8 Photoatomic Data for 53-I	mat5300	02/07/03

```
 74000.04p    9716  ENDF/B-VI Release 8 Photoatomic Data for 74-W                    mat7400      02/07/03

 total       54774

maximum photon energy set to  100.0 mev (maximum electron energy)

                  tables from file el03

  1000.03e    2329                                                          6/6/98
  6000.03e    2333                                                          6/6/98
  7000.03e    2333                                                          6/6/98
  8000.03e    2333                                                          6/6/98
 11000.03e    2337                                                          6/6/98
 15000.03e    2339                                                          6/6/98
 20000.03e    2343                                                          6/6/98
 26000.03e    2345                                                          6/6/98
 28000.03e    2347                                                          6/6/98
 53000.03e    2359                                                          6/6/98
 74000.03e    2367                                                          6/6/98

warning. material    1 has been set to a conductor.

*********************************************************************************************************************
dump no.    1 on file runtpi      nps =          0     coll =            0     ctm =       0.00   nrn =              0

       5 warning messages so far.

*********************************************************************************************************************
dump no.    2 on file runtpi      nps =    19931968     coll =      64898336     ctm =      60.01   nrn =      5247426940

*********************************************************************************************************************
dump no.    3 on file runtpi      nps =    39526655     coll =     128708015     ctm =     120.03   nrn =     10403848924

*********************************************************************************************************************
dump no.    4 on file runtpi      nps =    58679811     coll =     191069513     ctm =     180.04   nrn =     15446123167

*********************************************************************************************************************
dump no.    5 on file runtpi      nps =    78670457     coll =     256152102     ctm =     240.05   nrn =     20708529613

*********************************************************************************************************************
dump no.    6 on file runtpi      nps =    98364093     coll =     320265254     ctm =     300.06   nrn =     25893445442

*********************************************************************************************************************
dump no.    7 on file runtpi      nps =   117595152     coll =     382873941     ctm =     360.07   nrn =     30956638083

*********************************************************************************************************************
dump no.    8 on file runtpi      nps =   136833489     coll =     445520522     ctm =     420.07   nrn =     36020138342

*********************************************************************************************************************
dump no.    9 on file runtpi      nps =   156065163     coll =     508139857     ctm =     480.09   nrn =     41083827706

*********************************************************************************************************************
 dump no.   10 on file runtpi      nps =   175307024     coll =     570794658     ctm =     540.09   nrn =
46148947368

*********************************************************************************************************************
dump no.   11 on file runtpi      nps =   194536223     coll =     633414736     ctm =     600.10   nrn =
```

51212137570

****
dump no. 12 on file runtpi nps = 213785359 coll = 696098907 ctm = 660.11 nrn =
56278729117

****
dump no. 13 on file runtpi nps = 233032573 coll = 758767611 ctm = 720.12 nrn =
61344813109

****
dump no. 14 on file runtpi nps = 252298311 coll = 821498667 ctm = 780.13 nrn =
66415392283

****
dump no. 15 on file runtpi nps = 271561070 coll = 884221427 ctm = 840.14 nrn =
71485424261

****
dump no. 16 on file runtpi nps = 290968320 coll = 947412228 ctm = 900.15 nrn =
76593617897

****
dump no. 17 on file runtpi nps = 310615852 coll = 1011385194 ctm = 960.15 nrn =
81768942217

****
dump no. 18 on file runtpi nps = 330405356 coll = 1075818938 ctm = 1020.17 nrn =
86976908452

****
dump no. 19 on file runtpi nps = 349628199 coll = 1138417716 ctm = 1080.17 nrn =
92037463247

****
dump no. 20 on file runtpi nps = 367973471 coll = 1198155073 ctm = 1140.18 nrn =
96866343835

****
dump no. 21 on file runtpi nps = 386768131 coll = 1259353046 ctm = 1200.19 nrn =
101814748597

****
dump no. 22 on file runtpi nps = 404741512 coll = 1317867482 ctm = 1260.20 nrn =
106545963609

****
dump no. 23 on file runtpi nps = 424234207 coll = 1381336250 ctm = 1320.22 nrn =
111675902380

****
dump no. 24 on file runtpi nps = 443633285 coll = 1444497996 ctm = 1380.22 nrn =
116781927144

****
dump no. 25 on file runtpi nps = 463389861 coll = 1508827252 ctm = 1440.22 nrn = 121982930997

****
dump no. 26 on file runtpi nps = 482745892 coll = 1571847002 ctm = 1500.22 nrn = 127078403389

****
dump no. 27 on file runtpi nps = 501763644 coll = 1633772367 ctm = 1560.23 nrn = 132085648270

****
dump no. 28 on file runtpi nps = 520773614 coll = 1695671744 ctm = 1620.24 nrn = 137091572482

****
dump no. 29 on file runtpi nps = 540492597 coll = 1759875521 ctm = 1680.25 nrn = 142283119211

****
dump no. 30 on file runtpi nps = 560011013 coll = 1823427881 ctm = 1740.25 nrn = 147419614199

****
dump no. 31 on file runtpi nps = 579307087 coll = 1886263196 ctm = 1800.25 nrn = 152498121956

****
dump no. 32 on file runtpi nps = 598608594 coll = 1949113836 ctm = 1860.26 nrn = 157578076805

****
dump no. 33 on file runtpi nps = 617904492 coll = 2011943010 ctm = 1920.27 nrn = 162657337264

****
dump no. 34 on file runtpi nps = 637262735 coll = 2074971247 ctm = 1980.29 nrn = 167752464327

****
dump no. 35 on file runtpi nps = 656878295 coll = 2138840579 ctm = 2040.29 nrn = 172915884058

****
dump no. 36 on file runtpi nps = 676343593 coll = 2202225037 ctm = 2100.31 nrn = 178040428545

****
dump no. 37 on file runtpi nps = 695336299 coll = 2264059974 ctm = 2160.31 nrn = 183040032159

****

dump no. 38 on file runtpi nps = 714806288 coll = 2327449706 ctm = 2220.31 nrn = 188165154345

****

dump no. 39 on file runtpi nps = 734838186 coll = 2392679251 ctm = 2280.32 nrn = 193438455966

****

dump no. 40 on file runtpi nps = 754819306 coll = 2457737534 ctm = 2340.33 nrn = 198699059352

****

dump no. 41 on file runtpi nps = 778510586 coll = 2534875964 ctm = 2400.34 nrn = 204936068484

****

dump no. 42 on file runtpi nps = 809334095 coll = 2635227679 ctm = 2460.35 nrn = 213046642471

****

dump no. 43 on file runtpi nps = 838769104 coll = 2731063724 ctm = 2520.35 nrn = 220797746653

****

dump no. 44 on file runtpi nps = 868293028 coll = 2827190941 ctm = 2580.35 nrn = 228570702524

****

dump no. 45 on file runtpi nps = 898993737 coll = 2927161216 ctm = 2640.35 nrn = 236654717836

****

dump no. 46 on file runtpi nps = 928203686 coll = 3022264059 ctm = 2700.36 nrn = 244344123051

****

dump no. 47 on file runtpi nps = 958197404 coll = 3119920334 ctm = 2760.37 nrn = 252240338500

****

dump no. 48 on file runtpi nps = 988954408 coll = 3220059259 ctm = 2820.37 nrn = 260338878592

1problem summary

run terminated when 1000000000 particle histories were done.

+ 04/20/07 19:38:02

c Created on: Monday, March 06, 2006 at 16:08 probid = 04/18/07 19:43:16

0

photon creation	tracks	weight (per source particle)	energy (per source particle)	photon loss	tracks	weight (per source particle)	energy (per source particle)
source	1000000000	3.0155E+09	3.6450E-01	escape	266145	8.0256E+05	9.1652E-05
				energy cutoff	1	3.0155E+00	8.7355E-05
				time cutoff	0	0.	0.
weight window	0	0.	0.	weight window	0	0.	0.
cell importance	0	0.	0.	cell importance	0	0.	0.

```
 weight cutoff           0    0.           0.                weight cutoff           0    0.           0.
 e or t importance       0    0.           0.                e or t importance       0    0.           0.
 dxtran                  0    0.           0.                dxtran                  0    0.           0.
 forced collisions       0    0.           0.                forced collisions       0    0.           0.
 exp. transform          0    0.           0.                exp. transform          0    0.           0.
 from neutrons           0    0.           0.                compton scatter         0    0.           5.2430E-02
 bremsstrahlung   345721179    1.0425E+09    7.4413E-03        capture        2499720274    7.5379E+09    3.6905E-
01
 p-annihilation          0    0.           0.                pair production         0    0.           0.
 photonuclear            0    0.           0.                photonuclear abs        0    0.           0.
 electron x-rays         0    0.           0.
 1st fluorescence 997507227    3.0080E+09    4.8350E-02
 2nd fluorescence 156758014    4.7270E+08    1.3698E-03
   total       2499986420    7.5387E+09    4.2166E-01           total       2499986420    7.5387E+09    4.2166E-01

   number of photons banked              502479193       average time of (shakes)             cutoffs
   photon tracks per source particle     2.5000E+00         escape           1.3392E-01         tco   1.0000E+33
   photon collisions per source particle  3.2560E+00         capture          2.5141E-03         eco   1.0000E-03
   total photon collisions               3256029381         capture or escape 2.5280E-03        wc1  -5.0000E-01
                                                          any termination   2.5280E-03         wc2  -2.5000E-01

 computer time so far in this run  2842.84 minutes            maximum number ever in bank        5
 computer time in mcrun            2842.80 minutes            bank overflows to backup file      0
 source particles per minute            3.5177E+05
 random numbers generated            263245669860           most random numbers used was       4439 in history
171129866

 warning. random number period exceeded.  decrease stride.

 range of sampled source weights = 3.0155E+09 to 3.0155E+09

 source efficiency = 0.0134  in cell     7
1photon   activity in each cell                                                   print table 126

              tracks     population   collisions   collisions     number       flux       average      average
      cell    entering                             * weight      weighted     weighted   track weight   track mfp
                                                (per history)    energy       energy     (relative)      (cm)

    1     1   284870577    423397504    875443773    2.6399E+09   3.3478E-01   3.3478E-01   3.0155E+09   2.2150E-
01
    2     2   727716739   1045077247   2110386479    6.3639E+09   3.3457E-01   3.3457E-01   3.0155E+09   2.2137E-
01
    3     3    31911411     47231335     98193021    2.9610E+08   3.3140E-01   3.3140E-01   3.0155E+09   2.1799E-01
    4     4    25929247     26128035      6859844    2.0686E+07   3.4241E-01   3.4241E-01   3.0155E+09   2.0999E+00
    5     5    47060345     47462175     11975672    3.6113E+07   3.4504E-01   3.4504E-01   3.0155E+09   2.1210E+00
    6     6    47068795     47470974     11986440    3.6145E+07   3.4504E-01   3.4504E-01   3.0155E+09   2.1210E+00
    7     7  1006565316   1011715503    141088033    4.2545E+08   3.5586E-01   3.5586E-01   3.0155E+09
2.2079E+00
    8     8         285          286           28    8.4434E+01   3.3669E-01   3.3669E-01   3.0155E+09   9.6649E+00
    9     9          15           15            1    3.0155E+00   2.6105E-01   2.6105E-01   3.0155E+09   8.8013E+00
   10    10         103          103           10    3.0155E+01   2.9037E-01   2.9037E-01   3.0155E+09   9.0978E+00
   11    11        7306         7302          551    1.6615E+03   3.3645E-01   3.3645E-01   3.0155E+09   9.6581E+00
   12    12        4647         4647          351    1.0584E+03   3.3554E-01   3.3554E-01   3.0155E+09   9.6430E+00
   13    13         186          186           13    3.9202E+01   3.1064E-01   3.1064E-01   3.0155E+09   9.2934E+00
   14    14         434          433           38    1.1459E+02   3.3392E-01   3.3392E-01   3.0155E+09   9.6154E+00
   15    15         112          112           10    3.0155E+01   3.4431E-01   3.4431E-01   3.0155E+09   9.7729E+00
   16    16  1034210830    901990805        93931    2.8325E+05   3.4489E-01   3.4489E-01   3.0155E+09
7.9304E+03
   17    17      100145        99860          257    7.7498E+02   3.4042E-01   3.4042E-01   3.0155E+09   7.9119E+03
   18    18      275752       263350          647    1.9510E+03   3.4778E-01   3.4778E-01   3.0155E+09   7.9869E+03
   19    19       97936        97496          282    8.5037E+02   3.3897E-01   3.3897E-01   3.0155E+09   7.8962E+03

   total     3205820181   3550947368   3256029381    9.8186E+09

1tally   4        nps =  1000000000
          tally type 4    track length estimate of particle flux.
          tally for  photons
```

this tally is modified by a dose function.

volumes
cell: 8 9 10 11 12 13 14
1.57080E+00 1.57080E+00 1.57080E+00 1.57080E+00 1.57080E+00 1.57080E+00 1.57080E+00
cell: 15
1.57080E+00

cell 8
3.52218E-04 0.0636

cell 9
1.36735E-05 0.2747

cell 10
1.03203E-04 0.1075

cell 11
8.57533E-03 0.0127

cell 12
5.45579E-03 0.0159

cell 13
2.08018E-04 0.0795

cell 14
5.41707E-04 0.0515

cell 15
1.46640E-04 0.0988

===

results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally 4

tfc bin behavior	--mean-- behavior	---------relative error--------- value	decrease	decrease rate	----variance of the variance---- value	decrease	decrease rate	--figure of merit-- value	behavior	-pdf- slope
desired	random	<0.10	yes	1/sqrt(nps)	<0.10	yes	1/nps	constant	random	>3.00
observed	random	0.06	yes	yes	0.00	yes	yes	constant	random	0.00
passed?	yes	yes	yes	yes	yes	yes	yes	yes	yes	no

===

warning. the tally in the tally fluctuation chart bin did not pass 1 of the 10 statistical checks.

1analysis of the results in the tally fluctuation chart bin (tfc) for tally 4 with nps = 1000000000 print table 160

normed average tally per history = 3.52218E-04 unnormed average tally per history = 5.53262E-04
estimated tally relative error = 0.0636 estimated variance of the variance = 0.0047
relative error from zero tallies = 0.0593 relative error from nonzero scores = 0.0228

number of nonzero history tallies = 284 efficiency for the nonzero tallies = 0.0000
history number of largest tally = 581177513 largest unnormalized history tally = 3.52266E+03
(largest tally)/(average tally) = 6.36706E+06 (largest tally)/(avg nonzero tally)= 1.80825E+00

(confidence interval shift)/mean = 0.0021 shifted confidence interval center = 3.52974E-04 if the largest history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

estimated quantities	value at nps	value at nps+1	value(nps+1)/value(nps)-1.
mean	3.52218E-04	3.54460E-04	0.006367
relative error	6.35824E-02	6.34961E-02	-0.001357
variance of the variance	4.72706E-03	4.73223E-03	0.001094
shifted center	3.52974E-04	3.52977E-04	0.000010
figure of merit	8.70121E-02	8.72487E-02	0.002720

there is not enough information in the largest history scores (usually less than 500 scores) for a reliable estimate of the slope.
the empirical history score probability density function appears to be increasing at the largest history scores: please examine. see print table 161.
the large score tail of the empirical history score probability density function appears to have no unsampled regions.

fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (3.518E+05)*(4.974E-04)**2 = (3.518E+05)*(2.474E-07) = 8.701E-02

1unnormed tally density for tally   4   nonzero tally mean(m) = 1.948E+03   nps = 1000000000 print table 161

```
 abscissa              ordinate   log plot of tally probability density function in tally fluctuation chart bin(d=decade,slope= 0.0)
  tally  number num den log den:d------------------------------------------d------------------------------------------d------
 3.16+01      1 1.54-10  -9.813 ******************************************|******************************************|*****
 3.98+01      1 1.22-10  -9.913 ******************************************|******************************************|*
 5.01+01      1 9.70-11 -10.013 ******************************************|****************************************  |
 6.31+01      0 0.00+00   0.000                                |                               |
 7.94+01      0 0.00+00   0.000                                |                               |
 1.00+02      1 4.86-11 -10.313 ******************************************|***************************            |
 1.26+02      1 3.86-11 -10.413 ******************************************|**********************                |
 1.58+02      1 3.07-11 -10.513 ******************************************|*******************                  |
 2.00+02      1 2.44-11 -10.613 ******************************************|**************                     |
 2.51+02      0 0.00+00   0.000                                |                               |
 3.16+02      1 1.54-11 -10.813 ******************************************|******                           |
 3.98+02      2 2.44-11 -10.612 ******************************************|**************                     |
 5.01+02      5 4.85-11 -10.314 ******************************************|***************************            |
 6.31+02      9 6.94-11 -10.159 ******************************************|*********************************        |
 7.94+02      7 4.28-11 -10.368 ******************************************|************************              |
 1.00+03     14 6.81-11 -10.167 ******************************************|*********************************         |
 1.26+03      8 3.09-11 -10.510 ******************************************|*******************                  |
 1.58+03     25 7.67-11 -10.115 ******************************************|***********************************       |
 2.00+03     42 1.02-10  -9.990
mmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmmmmmmmmmm
mmmmmmmmmmmmmmmmmmmmmmmmmm |
 2.51+03     82 1.59-10  -9.799
******************************************|******************************************|******
 3.16+03     81 1.25-10  -9.905 ******************************************|******************************************|*
 3.98+03      1 1.22-12 -11.913 *                              |                               |
  total     284 2.84-07         d------------------------------------------d------------------------------------------d------
```

1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally   result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4   missed 1 of 10 tfc bin checks: there is insufficient tfc bin tally information to estimate the large tally slope reliably
missed all bin error check: 8 tally bins had   0 bins with zeros and   2 bins with relative errors exceeding 0.10

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

warning. 1 of the 1 tally fluctuation chart bins did not pass all 10 statistical checks.
warning. 1 of the 1 tallies had bins with relative errors greater than recommended.
1tally fluctuation charts

tally 4

nps	mean	error	vov	slope	fom
65536000	3.4062E-04	0.2528	0.0725	0.0	7.8E-02
131072000	3.5683E-04	0.1745	0.0352	0.0	8.2E-02
196608000	3.8362E-04	0.1357	0.0218	0.0	9.0E-02
262144000	3.7754E-04	0.1191	0.0166	0.0	8.7E-02
327680000	3.6839E-04	0.1082	0.0135	0.0	8.4E-02
393216000	3.5939E-04	0.1000	0.0115	0.0	8.2E-02
458752000	3.4966E-04	0.0935	0.0102	0.0	8.0E-02
524288000	3.5221E-04	0.0871	0.0088	0.0	8.1E-02
589824000	3.7657E-04	0.0798	0.0075	0.0	8.6E-02
655360000	3.8842E-04	0.0746	0.0065	0.0	8.8E-02
720896000	3.7074E-04	0.0726	0.0062	0.0	8.5E-02
786432000	3.6649E-04	0.0702	0.0058	0.0	8.4E-02
851968000	3.5873E-04	0.0682	0.0054	0.0	8.4E-02
917504000	3.4886E-04	0.0667	0.0052	0.0	8.4E-02
983040000	3.4654E-04	0.0646	0.0049	0.0	8.5E-02
1000000000	3.5222E-04	0.0636	0.0047	0.0	8.7E-02

****

dump no. 49 on file runtpi nps = 1000000000 coll = 3256029381 ctm = 2842.80 nrn = 263245669860

9 warning messages so far.

run terminated when 1000000000 particle histories were done.

computer time = 2842.84 minutes

mcnp version 5 06212004 04/20/07 19:38:02 probid = 04/18/07 19:43:16

Appendix D: PET Pig, Simple MCNP Model

```
      | | |  (_  | |  |_)   _)
                     |
+-------------------------------------------------------------------+
|   This program was prepared by the Regents of the University of    |
|California at Los Alamos National Laboratory (the University) under |
|  contract number W-7405-ENG-36 with the U.S. Department of Energy  |
|(DoE).  The University has certain rights in the program pursuant to|
|  the contract and the program should not be copied or distributed  |
| outside your organization.  All rights in the program are reserved |
|by the DoE and the University.  Neither the U.S. Government nor the |
| University makes any warranty, express or implied, or assumes any  |
|     liability or responsibility for the use of this software.      |
+-------------------------------------------------------------------+

1mcnp     version 5     ld=06212004                    04/11/07 18:16:43
****************************************************************************                    probid =  04/11/07 18:16:43
 inp=test outp=t

    1-       c     Created on: Wednesday, April 11, 2007 at 16:35
    2-          1     1   -19.4 1 -2 -3 9  $ sides
    3-          2     1   -19.4 -2 -4 3  $ top
    4-          3     1   -19.4 -9 8 -2  $ bottom
    5-          4     6      -1 -7 -6 5  $ syringe
    6-          5     4 -0.001239 -3 9 -1  #4 $ inside air
    7-          6     5      -1 -11
    8-          7     5      -1 -12
    9-          8     5      -1 -13
   10-          9     4 -0.001239 -10  #1 #2 #3 #4 #5 #6 #7 #8
   11-         10     0         10
   12-
   13-          1       cz 1.45
   14-          2       cz 2.975
   15-          3       pz 1.7
   16-          4       pz 3.3
   17-          5       pz -10.4
   18-          6       pz -4.4
   19-          7       cz 0.5
   20-          8       pz -16
   21-          9       pz -14.4
   22-         10        so 20
   23-         11       rcc 0 -1 3.81 0 2 0 0.5
   24-         12       rcc 3.476 -1 -7.4 0 2 0 0.5
   25-         13       rcc 0 -1 -16.501 0 2 0 0.5
   26-
   27-      mode  p
   28-      m1    74000.             0.95  $Impact Bonded Tungsten
   29-           28000.           0.035 26000.            0.015
   30-      m4    7000.              0.8  $air
   31-           8000.              0.2
   32-      m5    8000.             0.65  $people
   33-           6000.            0.18 1000.              0.1 7000.              0.03
   34-           20000.           0.015 15000.            0.01
   35-      m6    1000.           0.6666  $ saline and tech
   36-           8000.           0.3333
   37-      m7    1000.         0.081616  $ polyvinyl plastic
 warning. material   7 is not used in the problem.
   38-           6000.         0.648407 7000.         0.126024 8000.         0.143953
   39-      imp:p             1 8r                0  $ 1, 10
   40-      sdef erg=.511 pos=0 0 0 rad=d1 ext=d2 axs=0 0 1 wgt=5.92e10
   41-      si1 0.0 .5
   42-      sp1 -21 1
   43-      si2 -10.4 -4.4
   44-      sp2 -21 0
   45-      nps 100000000
   46-      de0   .01 .03 .05 .07 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .8 1 1.4 1.8
```

```
 47-           2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25
 48-      df0   3.96e-6 5.82e-7 2.9e-7 2.58e-7 2.83e-7 3.79e-7 5.01e-7 6.31e-7 7.59e-7
 49-           8.78e-7 9.85e-7 1.08e-6 1.17e-6 1.27e-6 1.36e-6 1.44e-6 1.52e-6 1.68e-6
 50-           1.98e-6 2.51e-6 2.99e-6 3.42e-6 3.82e-6 4.01e-6 4.41e-6 4.83e-6 5.23e-6
 51-           5.60e-6 5.80e-6 6.01e-6
 52-      f4:p 6 7 8

 surface     11.2 and surface     12.2 are the same.     12.2 will be deleted.

 surface     11.2 and surface     13.2 are the same.     13.2 will be deleted.

 surface     11.3 and surface     12.3 are the same.     12.3 will be deleted.

 surface     11.3 and surface     13.3 are the same.     13.3 will be deleted.

 comment.    4 surfaces were deleted for being the same as others.

 warning.   2 materials had unnormalized fractions. print table 40.
1cells                                                              print table 60

               atom        gram                            photon
      cell  mat    density      density     volume       mass     pieces importance

    1     1    1  6.58004E-02 1.94000E+01 3.41318E+02 6.62156E+03     1  1.0000E+00
    2     2    1  6.58004E-02 1.94000E+01 4.44881E+01 8.63069E+02     1  1.0000E+00
    3     3    1  6.58004E-02 1.94000E+01 4.44881E+01 8.63069E+02     1  1.0000E+00
    4     4    6  1.00282E-01 1.00000E+00 4.71239E+00 4.71239E+00     1  1.0000E+00
    5     5    4  5.17958E-05 1.23900E-03 1.01631E+02 1.25921E-01     1  1.0000E+00
    6     6    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
    7     7    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
    8     8    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
    9     9    4  5.17958E-05 1.23900E-03 0.00000E+00 0.00000E+00     0  1.0000E+00
   10    10    0  0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00     0  0.0000E+00

 total                              5.41350E+02 8.35725E+03

    minimum source weight = 5.9200E+10    maximum source weight = 5.9200E+10

 *************************************************************
 * Random Number Generator  =                   1 *
 * Random Number Seed       =      19073486328125 *
 * Random Number Multiplier =      19073486328125 *
 * Random Number Adder      =                   0 *
 * Random Number Bits Used  =                  48 *
 * Random Number Stride     =              152917 *
 *************************************************************


       2 warning messages so far.
1cross-section tables                                                  print table 100

     table    length

                   tables from file mcplib04

  1000.04p    1898  ENDF/B-VI Release 8 Photoatomic Data for 1-H        mat 100     02/07/03
  6000.04p    3152  ENDF/B-VI Release 8 Photoatomic Data for 6-C        mat 600     02/07/03
  7000.04p    3194  ENDF/B-VI Release 8 Photoatomic Data for 7-N        mat 700     02/07/03
  8000.04p    3272  ENDF/B-VI Release 8 Photoatomic Data for 8-O        mat 800     02/07/03
 15000.04p    4498  ENDF/B-VI Release 8 Photoatomic Data for 15-P       mat1500     02/07/03
 20000.04p    5013  ENDF/B-VI Release 8 Photoatomic Data for 20-CA      mat2000     02/07/03
 26000.04p    5718  ENDF/B-VI Release 8 Photoatomic Data for 26-FE      mat2600     02/07/03
 28000.04p    5826  ENDF/B-VI Release 8 Photoatomic Data for 28-NI      mat2800     02/07/03
 74000.04p    9716  ENDF/B-VI Release 8 Photoatomic Data for 74-W       mat7400     02/07/03

  total      42287
```

```
maximum photon energy set to  100.0 mev (maximum electron energy)

                 tables from file el03

  1000.03e    2329                                        6/6/98
  6000.03e    2333                                        6/6/98
  7000.03e    2333                                        6/6/98
  8000.03e    2333                                        6/6/98
 15000.03e    2339                                        6/6/98
 20000.03e    2343                                        6/6/98
 26000.03e    2345                                        6/6/98
 28000.03e    2347                                        6/6/98
 74000.03e    2367                                        6/6/98

warning. material    1 has been set to a conductor.

*********************************************************************************************************************
dump no.    1 on file runtpl     nps =          0     coll =           0     ctm =       0.00   nrn =             0


      3 warning messages so far.

*********************************************************************************************************************
dump no.    2 on file runtpl     nps =   77564372     coll =   288060268     ctm =      60.01   nrn =      3734018020

1problem summary

    run terminated when   100000000  particle histories were done.
+                                                          04/11/07 19:35:10
    c     Created on: Wednesday, April 11, 2007 at 16:35                 probid =  04/11/07 18:16:43
0
photon creation     tracks      weight        energy            photon loss         tracks      weight        energy
                         (per source particle)                                        (per source particle)

source           100000000    5.9200E+10    5.1100E-01          escape             2309550    1.3673E+09    1.0868E-02
                                                               energy cutoff            0    0.           1.2219E-04
                                                               time cutoff              0    0.           0.
weight window            0    0.            0.                 weight window            0    0.           0.
cell importance          0    0.            0.                 cell importance          0    0.           0.
weight cutoff            0    0.            0.                 weight cutoff            0    0.           0.
e or t importance        0    0.            0.                 e or t importance        0    0.           0.
dxtran                   0    0.            0.                 dxtran                   0    0.           0.
forced collisions        0    0.            0.                 forced collisions        0    0.           0.
exp. transform           0    0.            0.                 exp. transform           0    0.           0.
from neutrons            0    0.            0.                 compton scatter          0    0.           1.2708E-01
bremsstrahlung    50371106    2.9820E+10    1.2912E-02          capture           265114070    1.5695E+11    4.3661E-01
p-annihilation           0    0.            0.                 pair production          0    0.           0.
photonuclear             0    0.            0.                 photonuclear abs         0    0.           0.
electron x-rays          0    0.            0.
1st fluorescence 100984719    5.9783E+10    4.9349E-02
2nd fluorescence  16067795    9.5121E+09    1.4159E-03
   total         267423620    1.5831E+11    5.7468E-01             total         267423620    1.5831E+11    5.7468E-01

  number of photons banked               66438901        average time of (shakes)              cutoffs
  photon tracks per source particle      2.6742E+00          escape            6.3017E-02          tco   1.0000E+33
  photon collisions per source particle  3.7137E+00          capture           5.5313E-03          eco   1.0000E-03
  total photon collisions                371372648           capture or escape 6.0278E-03          wc1  -5.0000E-01
                                                             any termination   6.0278E-03          wc2  -2.5000E-01

computer time so far in this run    77.72 minutes            maximum number ever in bank         6
computer time in mcrun              77.70 minutes            bank overflows to backup file       0
source particles per minute            1.2871E+06
random numbers generated               4813999180           most random numbers used was         217 in history
54042808

range of sampled source weights = 5.9200E+10 to 5.9200E+10
1photon   activity in each cell                                             print table 126
```

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	101485977	163220500	357259963	2.1150E+11	4.6180E-01	4.6180E-01	5.9200E+10	3.4003E-01
2	2	814787	1322957	2840793	1.6817E+09	4.5324E-01	4.5324E-01	5.9200E+10	3.3104E-01
3	3	1533667	2492461	5349460	3.1669E+09	4.5421E-01	4.5421E-01	5.9200E+10	3.3206E-01
4	4	100669920	100080779	5896691	3.4908E+09	4.9718E-01	4.9718E-01	5.9200E+10	1.0288E+01
5	5	104161035	100080519	18146	1.0742E+07	4.8362E-01	4.8362E-01	5.9200E+10	9.0914E+03
6	6	4461	4455	317	1.8766E+05	4.5791E-01	4.5791E-01	5.9200E+10	1.0923E+01
7	7	38164	38174	2651	1.5694E+06	4.5730E-01	4.5730E-01	5.9200E+10	1.0915E+01
8	8	7384	7389	510	3.0192E+05	4.5892E-01	4.5892E-01	5.9200E+10	1.0934E+01
9	9	2360627	2310598	4117	2.4373E+06	4.6902E-01	4.6902E-01	5.9200E+10	8.9933E+03
total		311076022	369557832	371372648	2.1985E+11				

1tally 4 nps = 100000000

tally type 4 track length estimate of particle flux.

tally for photons

this tally is modified by a dose function.

volumes

cell: 6 7 8

1.57080E+00 1.57080E+00 1.57080E+00

cell 6

1.39169E+00 0.0161

cell 7

1.14111E+01 0.0056

cell 8

2.29519E+00 0.0125

===

results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally 4

tfc bin behavior	--mean-- behavior	---------relative error--------- value	decrease	decrease rate	----variance of the variance---- value	decrease	decrease rate	--figure of merit-- value	behavior	-pdf- slope
desired	random	<0.10	yes	1/sqrt(nps)	<0.10	yes	1/nps	constant	random	>3.00
observed	random	0.02	yes	yes	0.00	yes	yes	constant	random	1.57
passed?	yes	yes	yes	yes	yes	yes	yes	yes	yes	no

===

warning. the tally in the tally fluctuation chart bin did not pass 1 of the 10 statistical checks.

1analysis of the results in the tally fluctuation chart bin (tfc) for tally 4 with nps = 100000000 print table 160

normed average tally per history = 1.39169E+00 unnormed average tally per history = 2.18606E+00

estimated tally relative error = 0.0161 estimated variance of the variance = 0.0003

relative error from zero tallies = 0.0150 relative error from nonzero scores = 0.0059

```
 number of nonzero history tallies =        4453          efficiency for the nonzero tallies  = 0.0000
 history number of largest  tally  =    41132131          largest  unnormalized history tally = 1.09172E+05
 (largest  tally)/(average tally)  = 4.99402E+04          (largest  tally)/(avg nonzero tally)= 2.22384E+00

 (confidence interval shift)/mean  = 0.0001               shifted confidence interval center  = 1.39188E+00
```

if the largest history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

estimated quantities	value at nps	value at nps+1	value(nps+1)/value(nps)-1.
mean	1.39169E+00	1.39238E+00	0.000499
relative error	1.60956E-02	1.60953E-02	-0.000018
variance of the variance	3.06080E-04	3.06416E-04	0.001099
shifted center	1.39188E+00	1.39188E+00	0.000000
figure of merit	4.96808E+01	4.96826E+01	0.000036

the estimated inverse power slope of the 142 largest tallies starting at 7.06672E+04 is 1.5738
the empirical history score probability density function appears to be increasing at the largest history scores: please examine. see print table 161.
the large score tail of the empirical history score probability density function appears to have no unsampled regions.

fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (1.287E+06)*(6.213E-03)**2 = (1.287E+06)*(3.860E-05) = 4.968E+01

```
1unnormed tally density for tally   4           nonzero tally mean(m) = 4.909E+04   nps =   100000000  print table 161

 abscissa              ordinate   log plot of tally probability density function in tally fluctuation chart bin(d=decade,slope=
1.6)
  tally  number num den log den:d---------------------------d----------------------------d---------------------------d------------
 2.00+02      1 2.44-10  -9.613 ***************************|*****************************|************************    |
 2.51+02      0 0.00+00   0.000                           |                            |                           |
 3.16+02      0 0.00+00   0.000                           |                            |                           |
 3.98+02      0 0.00+00   0.000                           |                            |                           |
 5.01+02      0 0.00+00   0.000                           |                            |                           |
 6.31+02      3 2.31-10  -9.636 ***************************|*****************************|************************    |
 7.94+02      3 1.84-10  -9.736 ***************************|*****************************|*********************      |
 1.00+03      7 3.40-10  -9.468 ***************************|*****************************|***************************|
 1.26+03      5 1.93-10  -9.714 ***************************|*****************************|*********************      |
 1.58+03      2 6.14-11 -10.212 ***************************|*****************************|*******                    |
 2.00+03      3 7.31-11 -10.136 ***************************|*****************************|*********                  |
 2.51+03      8 1.55-10  -9.810 ***************************|*****************************|*******************        |
 3.16+03     10 1.54-10  -9.813 ***************************|*****************************|*******************        |
 3.98+03     13 1.59-10  -9.799 ***************************|*****************************|*******************        |
 5.01+03     18 1.75-10  -9.758 ***************************|*****************************|********************       |
 6.31+03     21 1.62-10  -9.791 ***************************|*****************************|*******************        |
 7.94+03     35 2.14-10  -9.669 ***************************|*****************************|***********************    |
 1.00+04     53 2.58-10  -9.589 ***************************|*****************************|*************************  |
 1.26+04     64 2.47-10  -9.607 ***************************|*****************************|*************************  |
 1.58+04    103 3.16-10  -9.500 ***************************|*****************************|***************************|
 2.00+04    147 3.58-10  -9.446 ***************************|*****************************|***************************|
 2.51+04    155 3.00-10  -9.523 ***************************|*****************************|************************** |
 3.16+04    285 4.38-10  -9.358 ***************************|*****************************|***************************|***
 3.98+04    394 4.81-10  -9.318 ***************************|*****************************|***************************|****
 5.01+04    589 5.71-10  -9.243
mmmmmmmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmm
mmmmmmmmmmmmmmmmmmmmmmmmmm|mmmmmmm
 6.31+04   1152 8.88-10  -9.052
***************************|*****************************|****************************|************
 7.94+04   1357 8.31-10  -9.081
***************************|*****************************|****************************|***********s
 1.00+05     24 1.17-11 -10.933 ***************************|****************           |                    |      s
 1.26+05      1 3.86-13 -12.413 *                          |                    |                    |  s
  total    4453 4.45-05         d---------------------------d----------------------------d---------------------------d------------
```

1status of the statistical checks used to form confidence intervals for the mean for each tally bin tally result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4 missed 1 of 10 tfc bin checks: the slope of decrease of largest tallies is less than the minimum acceptable value of 3.0
passed all bin error check: 3 tally bins all have relative errors less than 0.10 with no zero bins

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

warning. 1 of the 1 tally fluctuation chart bins did not pass all 10 statistical checks.
1tally fluctuation charts

tally 4

nps	mean	error	vov	slope	fom
8192000	1.5183E+00	0.0535	0.0034	0.0	59
16384000	1.3918E+00	0.0397	0.0019	1.8	52
24576000	1.4313E+00	0.0321	0.0012	1.8	53
32768000	1.4279E+00	0.0278	0.0009	1.7	52
40960000	1.4091E+00	0.0250	0.0007	1.6	51
49152000	1.3830E+00	0.0230	0.0006	1.6	50
57344000	1.3875E+00	0.0213	0.0005	1.6	50
65536000	1.3919E+00	0.0199	0.0005	1.6	50
73728000	1.3843E+00	0.0188	0.0004	1.7	50
81920000	1.3903E+00	0.0178	0.0004	1.7	50
90112000	1.3983E+00	0.0169	0.0003	1.6	50
98304000	1.3954E+00	0.0162	0.0003	1.6	50
100000000	1.3917E+00	0.0161	0.0003	1.6	50

****

dump no. 3 on file runtpl nps = 100000000 coll = 371372648 ctm = 77.70 nrn = 4813999180

5 warning messages so far.

run terminated when 100000000 particle histories were done.

computer time = 77.72 minutes

mcnp version 5 06212004 04/11/07 19:35:10 probid = 04/11/07 18:16:43

Appendix F: PET Pig, Full MCNP Model

```
      | | | (_ | | |_)  _)
                  |
+------------------------------------------------------------------+
|   This program was prepared by the Regents of the University of    |
|California at Los Alamos National Laboratory (the University) under |
|  contract number W-7405-ENG-36 with the U.S. Department of Energy  |
|(DoE).  The University has certain rights in the program pursuant to|
|  the contract and the program should not be copied or distributed  |
| outside your organization.  All rights in the program are reserved |
|by the DoE and the University.  Neither the U.S. Government nor the |
| University makes any warranty, express or implied, or assumes any  |
|     liability or responsibility for the use of this software.      |
+------------------------------------------------------------------+

1mcnp     version 5     ld=07-10-03                    04/11/07 15:01:22
***************************************************************************                    probid =  04/11/07 15:01:22


 c     Created on: Monday, March 06, 2006 at 12:56
    1     4 -0.001239 -7 8 -1  $ needle space
    2     4 -0.001239 7 -9 -2 36  $ radioisotope
    3     4 -0.001239 9 -6 -2  $ syring space
    4     4 -0.001239 -5 6 -3  $ syring space
    5     4 -0.001239 5 -4 -2  $ syring space
    9   1     -18 -12 6 -5 3  $ tungsten, first part of cone
   10    1     -18 -12 5 -4 2  $ tungsten, next part of cone
   11    1     -18 -13 4 -12  $ tungsten, top part of cone
    13     3      -8 -16 17 -18 10  $ stainless steel ring
    14     3      -8 21 -20 -19  $ stainless steel, handle stem
    15     3      -8 -23 7 -6  $ stainless steel, handle
    16     5      -1 -24  $ dose point (top)
    17     5      -1 -25
    18     5      -1 -26
    19     5      -1 -27
    20     5      -1 -28
    21     5      -1 -29
    22     5      -1 -30
    23     5      -1 -31  $ dose point  (bottom)
    24     5      -1 -32  $ dose point (handle)
    25     5      -1 -33  $ dose point (30cm)
    26    4 -0.001239 6 12 -34  #16 #17 #18
    27    4 -0.001239 13 -12  #16
    28    4 -0.001239 -6 11 10 -34  #13 #14 #15 #19 #20 #21 #22 #24 #18 #25
    29    4 -0.001239 -11 -34  #22 #23
    31    6      -1 7 -36 -9
    32    3      -8 37 -10 11
    33    1     -18 -10 -8 11  #32 $ lower section - tungsten
    34    1     -18 -10 8 -7 1  #32 $ tungsten, next section up
    35    1     -18 -10 7 -6 2  #32 $ tungsten, next section up\
    36    0        34

     1       cz 1.05
     2       cz 1.45
     3       cz 2.15
     4       pz 1.7
     5       pz -3.6
     6       pz -3.8
     7       pz -10.4
     8       pz -14.4
     9       pz -4.4
    10        cz 2.975
    11        pz -16
    12        kz 15 0.025 -1
    13        pz 3.3
    16        pz -4
```

```
      17       pz -5
      18       cz 4
      19      c/x 0 -4.5 0.5
      20       px 7.24
      21       px 4.01
      23      c/z 7.75 0 0.5
      24      rcc 0 -1 3.81 0 2 0 0.5
      25      rcc 3.05 -1 -0.95 0 2 0 0.5
      26      rcc 3.4 -1 -3.09 0 2 0 0.5
      27      rcc 3.476 -1 -7.4 0 2 0 0.5
      28      rcc 3.476 -1 -10.4 0 2 0 0.5
      29      rcc 3.476 -1 -14.4 0 2 0 0.5
      30      rcc 3.476 -1 -16 0 2 0 0.5
      31      rcc 0 -1 -16.501 0 2 0 0.5
      32      rcc 6.749 -1 -5.51 0 2 0 0.5
      33      rcc 30 -1 -7.4 0 2 0 0.5
      34       so 40
      35       pz -5
      36       cz 0.5
      37       kz -19 0.15 1

mode  p
m1    74000.            0.95  $Impact Bonded Tungsten
      28000.           0.035 26000.           0.015
m2    82000.               1  $Lead
warning. material   2 is not used in the problem.
m3    26000.          0.8066  $Stainless Steel
      6000.           0.0006 25000.            0.01 15000.          0.00045
      16000.          0.00035 14000.            0.01 24000.           0.125
      28000.            0.04 42000.           0.007
m4    7000.              0.8  $air
      8000.              0.2
m5    8000.             0.65  $people
      6000.             0.18 1000.             0.1 7000.             0.03
      20000.           0.015 15000.            0.01
m6    1000.           0.6666  $ saline and tech
      8000.           0.3333
imp:p            1 29r                  0  $ 1, 36
sdef erg=.511 pos=0 0 0 rad=d1 ext=d2 axs=0 0 1 wgt=5.92e10
si1 0.0 .5
sp1 -21 1
si2 -10.4 -4.4
sp2 -21 0
nps 20000000
de0   .01 .03 .05 .07 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .8 1 1.4 1.8
      2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25
df0   3.96e-6 5.82e-7 2.9e-7 2.58e-7 2.83e-7 3.79e-7 5.01e-7 6.31e-7 7.59e-7
      8.78e-7 9.85e-7 1.08e-6 1.17e-6 1.27e-6 1.36e-6 1.44e-6 1.52e-6 1.68e-6
      1.98e-6 2.51e-6 2.99e-6 3.42e-6 3.82e-6 4.01e-6 4.41e-6 4.83e-6 5.23e-6
      5.60e-6 5.80e-6 6.01e-6
f4:p 16 17 18 19 20 21 22 23 24 25

surface     17   and surface     35   are the same.     35   will be deleted.

surface     24.2 and surface     25.2 are the same.     25.2 will be deleted.

surface     24.2 and surface     26.2 are the same.     26.2 will be deleted.

surface     24.2 and surface     27.2 are the same.     27.2 will be deleted.

surface     24.2 and surface     28.2 are the same.     28.2 will be deleted.

surface     24.2 and surface     29.2 are the same.     29.2 will be deleted.

surface     24.2 and surface     30.2 are the same.     30.2 will be deleted.

surface     24.2 and surface     31.2 are the same.     31.2 will be deleted.
```

surface 24.2 and surface 32.2 are the same. 32.2 will be deleted.

surface 24.2 and surface 33.2 are the same. 33.2 will be deleted.

surface 24.3 and surface 25.3 are the same. 25.3 will be deleted.

surface 24.3 and surface 26.3 are the same. 26.3 will be deleted.

surface 24.3 and surface 27.3 are the same. 27.3 will be deleted.

surface 24.3 and surface 28.3 are the same. 28.3 will be deleted.

surface 24.3 and surface 29.3 are the same. 29.3 will be deleted.

surface 24.3 and surface 30.3 are the same. 30.3 will be deleted.

surface 24.3 and surface 31.3 are the same. 31.3 will be deleted.

surface 24.3 and surface 32.3 are the same. 32.3 will be deleted.

surface 24.3 and surface 33.3 are the same. 33.3 will be deleted.

comment. 19 surfaces were deleted for being the same as others.

warning. 2 materials had unnormalized fractions. print table 40.

1cells print table 60

	cell	mat	atom density	gram density	volume	photon mass	pieces	importance
1	1	4	5.17958E-05	1.23900E-03	1.38544E+01	1.71656E-02	1	1.0000E+00
2	2	4	5.17958E-05	1.23900E-03	3.49188E+01	4.32644E-02	1	1.0000E+00
3	3	4	5.17958E-05	1.23900E-03	3.96312E+00	4.91030E-03	1	1.0000E+00
4	4	4	5.17958E-05	1.23900E-03	2.90440E+00	3.59855E-03	1	1.0000E+00
5	5	4	5.17958E-05	1.23900E-03	3.50076E+01	4.33744E-02	1	1.0000E+00
6	9	1	6.10520E-02	1.80000E+01	2.58857E+00	4.65942E+01	1	1.0000E+00
7	10	1	6.10520E-02	1.80000E+01	7.18647E+01	1.29356E+03	1	1.0000E+00
8	11	1	6.10520E-02	1.80000E+01	1.96618E+01	3.53912E+02	1	1.0000E+00
9	13	3	8.69179E-02	8.00000E+00	2.24604E+01	1.79683E+02	1	1.0000E+00
10	14	3	8.69179E-02	8.00000E+00	2.53684E+00	2.02947E+01	1	1.0000E+00
11	15	3	8.69179E-02	8.00000E+00	5.18363E+00	4.14690E+01	1	1.0000E+00
12	16	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
13	17	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
14	18	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
15	19	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
16	20	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
17	21	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
18	22	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
19	23	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
20	24	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
21	25	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
22	26	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
23	27	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
24	28	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
25	29	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
26	31	6	1.00282E-01	1.00000E+00	4.71239E+00	4.71239E+00	1	1.0000E+00
27	32	3	8.69179E-02	8.00000E+00	6.32141E+01	5.05713E+02	1	1.0000E+00
28	33	1	6.10520E-02	1.80000E+01	1.10484E+01	1.98870E+02	1	1.0000E+00
29	34	1	6.10520E-02	1.80000E+01	6.75914E+01	1.21665E+03	1	1.0000E+00
30	35	1	6.10520E-02	1.80000E+01	1.39919E+02	2.51854E+03	1	1.0000E+00
31	36	0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0	0.0000E+00
total					5.17138E+02	6.39582E+03		

minimum source weight = 5.9200E+10 maximum source weight = 5.9200E+10

```
****************************************************
* Random Number Generator  =                 1 *
* Random Number Seed       =    19073486328125 *
* Random Number Multiplier =    19073486328125 *
* Random Number Adder      =                 0 *
* Random Number Bits Used  =                48 *
* Random Number Stride     =            152917 *
****************************************************


      2 warning messages so far.
1cross-section tables                                                     print table 100

   table    length

                 tables from file mcplib04

  1000.04p    1898  ENDF/B-VI Release 8 Photoatomic Data for 1-H            mat 100     02/07/03
  6000.04p    3152  ENDF/B-VI Release 8 Photoatomic Data for 6-C            mat 600     02/07/03
  7000.04p    3194  ENDF/B-VI Release 8 Photoatomic Data for 7-N            mat 700     02/07/03
  8000.04p    3272  ENDF/B-VI Release 8 Photoatomic Data for 8-O            mat 800     02/07/03
 14000.04p    4792  ENDF/B-VI Release 8 Photoatomic Data for 14-SI          mat1400     02/07/03
 15000.04p    4498  ENDF/B-VI Release 8 Photoatomic Data for 15-P           mat1500     02/07/03
 16000.04p    4654  ENDF/B-VI Release 8 Photoatomic Data for 16-S           mat1600     02/07/03
 20000.04p    5013  ENDF/B-VI Release 8 Photoatomic Data for 20-CA          mat2000     02/07/03
 24000.04p    5682  ENDF/B-VI Release 8 Photoatomic Data for 24-CR          mat2400     02/07/03
 25000.04p    5598  ENDF/B-VI Release 8 Photoatomic Data for 25-MN          mat2500     02/07/03
 26000.04p    5718  ENDF/B-VI Release 8 Photoatomic Data for 26-FE          mat2600     02/07/03
 28000.04p    5826  ENDF/B-VI Release 8 Photoatomic Data for 28-NI          mat2800     02/07/03
 42000.04p    7592  ENDF/B-VI Release 8 Photoatomic Data for 42-MO          mat4200     02/07/03
 74000.04p    9716  ENDF/B-VI Release 8 Photoatomic Data for 74-W           mat7400     02/07/03

 total       70605

 maximum photon energy set to  100.0 mev (maximum electron energy)

                 tables from file el03

  1000.03e    2329                                               6/6/98
  6000.03e    2333                                               6/6/98
  7000.03e    2333                                               6/6/98
  8000.03e    2333                                               6/6/98
 14000.03e    2339                                               6/6/98
 15000.03e    2339                                               6/6/98
 16000.03e    2339                                               6/6/98
 20000.03e    2343                                               6/6/98
 24000.03e    2345                                               6/6/98
 25000.03e    2345                                               6/6/98
 26000.03e    2345                                               6/6/98
 28000.03e    2347                                               6/6/98
 42000.03e    2353                                               6/6/98
 74000.03e    2367                                               6/6/98

 warning. material    1 has been set to a conductor.

 warning. material    3 has been set to a conductor.

 ***************************************************************************************************************
 dump no.    1 on file runtpg     nps =          0     coll =            0     ctm =        0.00   nrn =              0


      4 warning messages so far.
1problem summary

     run terminated when  20000000    particle histories were done.
+                                                          04/11/07 15:21:27
     c     Created on: Monday, March 06, 2006 at 12:56                probid =  04/11/07 15:01:22
```

0

photon creation	tracks	weight (per source particle)	energy	photon loss	tracks	weight (per source particle)	energy
source	20000000	5.9200E+10	5.1100E-01	escape	625611	1.8518E+09	1.4509E-02
				energy cutoff	0	0.	1.2118E-04
				time cutoff	0	0.	0.
weight window	0	0.	0.	weight window	0	0.	0.
cell importance	0	0.	0.	cell importance	0	0.	0.
weight cutoff	0	0.	0.	weight cutoff	0	0.	0.
e or t importance	0	0.	0.	e or t importance	0	0.	0.
dxtran	0	0.	0.	dxtran	0	0.	0.
forced collisions	0	0.	0.	forced collisions	0	0.	0.
exp. transform	0	0.	0.	exp. transform	0	0.	0.
from neutrons	0	0.	0.	compton scatter	0	0.	1.2663E-01
bremsstrahlung	9989792	2.9570E+10	1.2806E-02	capture	52574674	1.5562E+11	4.3287E-01
p-annihilation	0	0.	0.	pair production	0	0.	0.
photonuclear	0	0.	0.	photonuclear abs	0	0.	0.
electron x-rays	0	0.	0.				
1st fluorescence	20026159	5.9277E+10	4.8923E-02				
2nd fluorescence	3184334	9.4256E+09	1.4030E-03				
total	53200285	1.5747E+11	5.7413E-01	total	53200285	1.5747E+11	5.7413E-01

number of photons banked 13174126 average time of (shakes) cutoffs
photon tracks per source particle 2.6600E+00 escape 1.3302E-01 tco 1.0000E+33
photon collisions per source particle 3.6866E+00 capture 5.4516E-03 eco 1.0000E-03
total photon collisions 73732028 capture or escape 6.9518E-03 wc1 -5.0000E-01
any termination 6.9518E-03 wc2 -2.5000E-01

computer time so far in this run 37.87 minutes maximum number ever in bank 6
computer time in mcrun 19.78 minutes bank overflows to backup file 0
source particles per minute 1.0112E+06
random numbers generated 964084640 most random numbers used was 209 in history
10801918

range of sampled source weights = 5.9200E+10 to 5.9200E+10
1photon activity in each cell print table 126

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	1629305	1545745	277	8.1992E+05	4.7588E-01	4.7588E-01	5.9200E+10	9.0191E+03
2	2	19321654	18704140	2732	8.0867E+06	4.8669E-01	4.8669E-01	5.9200E+10	9.1200E+03
3	3	2146548	2112126	134	3.9664E+05	4.8421E-01	4.8421E-01	5.9200E+10	9.0968E+03
4	4	1700582	1672233	59	1.7464E+05	4.7573E-01	4.7573E-01	5.9200E+10	9.0184E+03
5	5	1245997	1167724	289	8.5544E+05	4.6587E-01	4.6587E-01	5.9200E+10	8.9251E+03
6	9	106515	128468	139304	4.1234E+08	4.4781E-01	4.4781E-01	5.9200E+10	3.5073E-01
7	10	1609733	2511459	5306578	1.5707E+10	4.5953E-01	4.5953E-01	5.9200E+10	3.6392E-01
8	11	164218	264141	560115	1.6579E+09	4.5384E-01	4.5384E-01	5.9200E+10	3.5745E-01
9	13	73858	75447	57481	1.7014E+08	4.1239E-01	4.1239E-01	5.9200E+10	1.3104E+00
10	14	2753	2833	2582	7.6427E+06	4.0883E-01	4.0883E-01	5.9200E+10	1.3050E+00
11	15	6680	6848	4735	1.4016E+07	4.2000E-01	4.2000E-01	5.9200E+10	1.3277E+00
12	16	1255	1254	98	2.9008E+05	4.5660E-01	4.5660E-01	5.9200E+10	1.0899E+01
13	17	1109	1107	69	2.0424E+05	4.3747E-01	4.3747E-01	5.9200E+10	1.0698E+01
14	18	4082	4080	280	8.2880E+05	4.4325E-01	4.4325E-01	5.9200E+10	1.0757E+01
15	19	10078	10075	724	2.1430E+06	4.5344E-01	4.5344E-01	5.9200E+10	1.0871E+01
16	20	5436	5440	405	1.1988E+06	4.5635E-01	4.5635E-01	5.9200E+10	1.0906E+01
17	21	416	416	37	1.0952E+05	3.9445E-01	3.9445E-01	5.9200E+10	1.0240E+01
18	22	237	237	18	5.3280E+04	3.9923E-01	3.9923E-01	5.9200E+10	1.0296E+01
19	23	1873	1875	139	4.1144E+05	4.5607E-01	4.5607E-01	5.9200E+10	1.0895E+01
20	24	3069	3027	191	5.6536E+05	4.4944E-01	4.4944E-01	5.9200E+10	1.0827E+01
21	25	131	131	12	3.5520E+04	4.5264E-01	4.5264E-01	5.9200E+10	1.0856E+01
22	26	284263	278907	946	2.8002E+06	4.6107E-01	4.6107E-01	5.9200E+10	8.9242E+03
23	27	6899	5641	2	5.9200E+03	4.8252E-01	4.8252E-01	5.9200E+10	9.1086E+03
24	28	598101	550531	1273	3.7681E+06	4.6701E-01	4.6701E-01	5.9200E+10	8.9751E+03
25	29	192834	190939	351	1.0390E+06	4.5413E-01	4.5413E-01	5.9200E+10	8.8619E+03

```
   26   31   20136002    20016210     1179513    3.4914E+09   4.9710E-01   4.9710E-01   5.9200E+10
1.0287E+01
   27   32      35293       35968       26504    7.8452E+07   3.8964E-01   3.8964E-01   5.9200E+10   1.2619E+00
   28   33     166698      265459      554533    1.6414E+09   4.5517E-01   4.5517E-01   5.9200E+10   3.5897E-01
   29   34    2487121     3945775     8425816    2.4940E+10   4.6019E-01   4.6019E-01   5.9200E+10   3.6465E-01
   30   35   17146964    27186457    57466831    1.7010E+11   4.6235E-01   4.6235E-01   5.9200E+10   3.6710E-
01

    total    69089704    80694693    73732028    2.1825E+11

1tally   4       nps =    20000000
         tally type 4    track length estimate of particle flux.      units   1/cm**2
         tally for  photons

         volumes
               cell:      16          17          18          19          20          21          22
                   1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00
               cell:      23          24          25
                   1.57080E+00  1.57080E+00  1.57080E+00

 cell  16
              1.82019E+06 0.0303

 cell  17
              1.54443E+06 0.0325

 cell  18
              5.67587E+06 0.0170

 cell  19
              1.39004E+07 0.0108

 cell  20
              7.55037E+06 0.0147

 cell  21
              5.80004E+05 0.0530

 cell  22
              3.20184E+05 0.0707

 cell  23
              2.68110E+06 0.0248

 cell  24
              4.33261E+06 0.0195

 cell  25
              1.87627E+05 0.0920


===========================================================================================
===========================================

         results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally   4

 tfc bin     --mean--      ---------relative error---------      ----variance of the variance----      --figure of merit--     -pdf-
 behavior   behavior      value   decrease   decrease rate      value   decrease   decrease rate       value     behavior
slope

 desired      random       <0.10       yes      1/sqrt(nps)       <0.10       yes        1/nps          constant    random      >3.00
 observed     random        0.03       yes          yes            0.00       yes         yes          constant    random     10.00
 passed?        yes          yes       yes          yes             yes       yes         yes             yes        yes        yes

===========================================================================================
```

==

this tally meets the statistical criteria used to form confidence intervals: check the tally fluctuation chart to verify.
the results in other bins associated with this tally may not meet these statistical criteria.

----- estimated confidence intervals: -----

estimated asymmetric confidence interval(1,2,3 sigma): 1.7660E+06 to 1.8762E+06; 1.7109E+06 to 1.9313E+06; 1.6557E+06 to 1.9864E+06
estimated symmetric confidence interval(1,2,3 sigma): 1.7651E+06 to 1.8753E+06; 1.7100E+06 to 1.9304E+06; 1.6549E+06 to 1.9855E+06

1analysis of the results in the tally fluctuation chart bin (tfc) for tally 4 with nps = 20000000 print table 160

normed average tally per history = 1.82019E+06 unnormed average tally per history = 2.85915E+06
estimated tally relative error = 0.0303 estimated variance of the variance = 0.0012
relative error from zero tallies = 0.0282 relative error from nonzero scores = 0.0109

number of nonzero history tallies = 1253 efficiency for the nonzero tallies = 0.0001
history number of largest tally = 7061907 largest unnormalized history tally = 1.32587E+11
(largest tally)/(average tally) = 4.63730E+04 (largest tally)/(avg nonzero tally)= 2.90527E+00

(confidence interval shift)/mean = 0.0005 shifted confidence interval center = 1.82110E+06

if the largest history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

estimated quantities	value at nps	value at nps+1	value(nps+1)/value(nps)-1.
mean	1.82019E+06	1.82441E+06	0.002319
relative error	3.02659E-02	3.02844E-02	0.000610
variance of the variance	1.16473E-03	1.18521E-03	0.017591
shifted center	1.82110E+06	1.82110E+06	0.000004
figure of merit	5.51923E+01	5.51251E+01	-0.001219

the estimated slope of the 62 largest tallies starting at 6.61817E+10 appears to be decreasing at least exponentially.
the empirical history score probability density function appears to be increasing at the largest history scores: please examine. see print table 161.
the large score tail of the empirical history score probability density function appears to have no unsampled regions.

fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (1.011E+06)*(7.388E-03)**2 = (1.011E+06)*(5.458E-05) = 5.519E+01

1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4 passed the 10 statistical checks for the tally fluctuation chart bin result
passed all bin error check: 10 tally bins all have relative errors less than 0.10 with no zero bins

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

1tally fluctuation charts

tally 4

nps	mean	error	vov	slope	fom
1024000	1.6819E+06	0.1383	0.0220	0.0	50
2048000	1.7451E+06	0.0948	0.0105	0.0	53
3072000	1.8506E+06	0.0752	0.0065	0.0	57
4096000	1.8526E+06	0.0651	0.0049	0.0	58

5120000	1.8105E+06	0.0589	0.0040	0.0	57
6144000	1.8140E+06	0.0539	0.0035	0.0	57
7168000	1.7959E+06	0.0504	0.0033	0.0	56
8192000	1.8116E+06	0.0474	0.0030	5.2	56
9216000	1.8928E+06	0.0437	0.0025	4.0	59
10240000	1.8862E+06	0.0416	0.0022	8.1	58
11264000	1.8833E+06	0.0396	0.0020	7.2	57
12288000	1.9090E+06	0.0377	0.0018	8.0	58
13312000	1.8937E+06	0.0363	0.0017	7.1	57
14336000	1.8798E+06	0.0351	0.0016	9.6	57
15360000	1.8739E+06	0.0341	0.0015	9.7	57
16384000	1.8767E+06	0.0330	0.0014	10.0	57
17408000	1.8407E+06	0.0323	0.0013	10.0	56
18432000	1.8315E+06	0.0314	0.0013	10.0	56
19456000	1.8240E+06	0.0307	0.0012	10.0	55
20000000	1.8202E+06	0.0303	0.0012	10.0	55

```
*********************************************************************************************************************
dump no.    2 on file runtpg       nps =    20000000     coll =       73732028     ctm =       19.78   nrn =        964084640


       4 warning messages so far.


run terminated when  20000000    particle histories were done.

computer time =   37.87 minutes

mcnp     version 5     07-10-03                  04/11/07 15:21:27                  probid =  04/11/07 15:01:22
```

Appendix G: 5cc Unit Dose Pig, Simple MCNP Model

```
          Thread Name & Version = MCNP5_RSICC, 1.30
                                          _
          ._ _   _  ._   ._  |_
          | | |  (_  | |  |_)  _)
                           |
+-------------------------------------------------------------------+
|   This program was prepared by the Regents of the University of    |
|California at Los Alamos National Laboratory (the University) under |
|  contract number W-7405-ENG-36 with the U.S. Department of Energy  |
|(DoE).  The University has certain rights in the program pursuant to|
|  the contract and the program should not be copied or distributed  |
| outside your organization.  All rights in the program are reserved |
|by the DoE and the University.  Neither the U.S. Government nor the |
| University makes any warranty, express or implied, or assumes any  |
|     liability or responsibility for the use of this software.      |
+-------------------------------------------------------------------+

1mcnp     version 5     ld=06212004                    04/13/07 07:04:37
 *************************************************************************                    probid =  04/13/07 07:04:37
 inp=test2 outp=5cc

    1-       c     Created on: Wednesday, April 11, 2007 at 16:35
    2-         1    1   -19.4 1 -2 -3 9  $ sides
    3-         2    1   -19.4 -2 -4 3  $ top
    4-         3    1   -19.4 -9 8 -2  $ bottom
    5-         4    6     -1 -7 -6 5  $ syringe
    6-         5    4 -0.001239 -3 9 -1  #4 $ inside air
    7-         6    5     -1 -11
    8-         7    5     -1 -12
    9-         8    5     -1 -13
   10-         9    4 -0.001239 -10  #1 #2 #3 #4 #5 #6 #7 #8
   11-        10    0         10
   12-
   13-         1       cz 1
   14-         2       cz 1.2
   15-         3       pz 0.4
   16-         4       pz 0.9
   17-         5       pz -10
   18-         6       pz -7.4
   19-         7       cz 0.25
   20-         8       pz -16
   21-         9       pz -14.6
   22-        10        so 20
   23-        11       rcc 0 -1 1.401 0 2 0 0.5
   24-        12       rcc 1.701 -1 -8.7 0 2 0 0.5
   25-        13       rcc 0 -1 -16.501 0 2 0 0.5
   26-
   27-       mode  p
   28-       m1    74000.            0.95  $Impact Bonded Tungsten
   29-             28000.           0.035 26000.           0.015
   30-       m4    7000.              0.8  $air
   31-             8000.              0.2
   32-       m5    8000.             0.65  $people
   33-             6000.             0.18 1000.              0.1 7000.              0.03
   34-             20000.           0.015 15000.            0.01
   35-       m6    1000.            0.6666  $ saline and tech
   36-             8000.           0.3333
   37-       m7    1000.          0.081616  $ polyvinyl plastic
 warning. material   7 is not used in the problem.
   38-             6000.          0.648407 7000.          0.126024 8000.          0.143953
   39-       imp:p            1 8r                   0  $ 1, 10
   40-       sdef erg=.1405 pos=0 0 0 rad=d1 ext=d2 axs=0 0 1 wgt=3.2967e10
   41-       si1 0.0 .25
   42-       sp1 -21 1
   43-       si2 -10 -7.4
```

```
sp2 -21 0
nps 100000000
de0   .01 .03 .05 .07 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .8 1 1.4 1.8
      2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25
df0   3.96e-6 5.82e-7 2.9e-7 2.58e-7 2.83e-7 3.79e-7 5.01e-7 6.31e-7 7.59e-7
      8.78e-7 9.85e-7 1.08e-6 1.17e-6 1.27e-6 1.36e-6 1.44e-6 1.52e-6 1.68e-6
      1.98e-6 2.51e-6 2.99e-6 3.42e-6 3.82e-6 4.01e-6 4.41e-6 4.83e-6 5.23e-6
      5.60e-6 5.80e-6 6.01e-6
f4:p 6 7 8
```

surface 11.2 and surface 12.2 are the same. 12.2 will be deleted.

surface 11.2 and surface 13.2 are the same. 13.2 will be deleted.

surface 11.3 and surface 12.3 are the same. 12.3 will be deleted.

surface 11.3 and surface 13.3 are the same. 13.3 will be deleted.

comment. 4 surfaces were deleted for being the same as others.

warning. 2 materials had unnormalized fractions. print table 40.

1cells print table 60

	cell	mat	atom density	gram density	volume	mass	photon pieces	importance
1	1	1	6.58004E-02	1.94000E+01	2.07345E+01	4.02250E+02	1	1.0000E+00
2	2	1	6.58004E-02	1.94000E+01	2.26195E+00	4.38818E+01	1	1.0000E+00
3	3	1	6.58004E-02	1.94000E+01	6.33345E+00	1.22869E+02	1	1.0000E+00
4	4	6	1.00282E-01	1.00000E+00	5.10509E-01	5.10509E-01	1	1.0000E+00
5	5	4	5.17958E-05	1.23900E-03	4.66134E+01	5.77540E-02	1	1.0000E+00
6	6	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
7	7	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
8	8	5	4.23892E-02	1.00000E+00	1.57080E+00	1.57080E+00	1	1.0000E+00
9	9	4	5.17958E-05	1.23900E-03	0.00000E+00	0.00000E+00	0	1.0000E+00
10	10	0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0	0.0000E+00
total					8.11662E+01	5.74281E+02		

minimum source weight = 3.2967E+10 maximum source weight = 3.2967E+10

```
***************************************************
* Random Number Generator  =                  1 *
* Random Number Seed       =     19073486328125 *
* Random Number Multiplier =     19073486328125 *
* Random Number Adder      =                  0 *
* Random Number Bits Used  =                 48 *
* Random Number Stride     =             152917 *
***************************************************
```

2 warning messages so far.

1cross-section tables print table 100

table	length			
		tables from file mcplib04		
1000.04p	1898	ENDF/B-VI Release 8 Photoatomic Data for 1-H	mat 100	02/07/03
6000.04p	3152	ENDF/B-VI Release 8 Photoatomic Data for 6-C	mat 600	02/07/03
7000.04p	3194	ENDF/B-VI Release 8 Photoatomic Data for 7-N	mat 700	02/07/03
8000.04p	3272	ENDF/B-VI Release 8 Photoatomic Data for 8-O	mat 800	02/07/03
15000.04p	4498	ENDF/B-VI Release 8 Photoatomic Data for 15-P	mat1500	02/07/03
20000.04p	5013	ENDF/B-VI Release 8 Photoatomic Data for 20-CA	mat2000	02/07/03
26000.04p	5718	ENDF/B-VI Release 8 Photoatomic Data for 26-FE	mat2600	02/07/03
28000.04p	5826	ENDF/B-VI Release 8 Photoatomic Data for 28-NI	mat2800	02/07/03
74000.04p	9716	ENDF/B-VI Release 8 Photoatomic Data for 74-W	mat7400	02/07/03

```
 total      42287

maximum photon energy set to  100.0 mev (maximum electron energy)

                  tables from file el03

  1000.03e    2329                                        6/6/98
  6000.03e    2333                                        6/6/98
  7000.03e    2333                                        6/6/98
  8000.03e    2333                                        6/6/98
 15000.03e    2339                                        6/6/98
 20000.03e    2343                                        6/6/98
 26000.03e    2345                                        6/6/98
 28000.03e    2347                                        6/6/98
 74000.03e    2367                                        6/6/98

warning. material    1 has been set to a conductor.

*************************************************************************************************************************
dump no.    1 on file runtpm      nps =          0     coll =            0     ctm =       0.00   nrn =              0


      3 warning messages so far.

*************************************************************************************************************************
dump no.    2 on file runtpm      nps =    95249223     coll =    238320136     ctm =      60.01   nrn =       3253210206

1problem summary

    run terminated when   100000000  particle histories were done.
+                                                          04/13/07 08:08:39
    c     Created on: Wednesday, April 11, 2007 at 16:35                 probid =  04/13/07 07:04:37
0
photon creation     tracks     weight       energy          photon loss       tracks     weight       energy
                        (per source particle)                                     (per source particle)

source          100000000    3.2967E+10    1.4050E-01         escape             56321    1.8567E+07    7.1087E-05
                                                    energy cutoff           0    0.           3.0561E-05
                                                    time cutoff             0    0.           0.
weight window            0    0.           0.                weight window           0    0.           0.
cell importance          0    0.           0.                cell importance         0    0.           0.
weight cutoff            0    0.           0.                weight cutoff           0    0.           0.
e or t importance        0    0.           0.                e or t importance       0    0.           0.
dxtran                   0    0.           0.                dxtran                  0    0.           0.
forced collisions        0    0.           0.                forced collisions       0    0.           0.
exp. transform           0    0.           0.                exp. transform          0    0.           0.
from neutrons            0    0.           0.                compton scatter         0    0.           2.7387E-03
bremsstrahlung    10188275    3.3588E+09    1.1555E-03         capture         221493111    7.3020E+10    1.8802E-01
p-annihilation           0    0.           0.                pair production         0    0.           0.
photonuclear             0    0.           0.                photonuclear abs        0    0.           0.
electron x-rays          0    0.           0.
1st fluorescence  95718195    3.1555E+10    4.7828E-02
2nd fluorescence  15642962    5.1570E+09    1.3784E-03
   total         221549432    7.3038E+10    1.9086E-01           total         221549432    7.3038E+10    1.9086E-01

  number of photons banked                25831237       average time of (shakes)             cutoffs
  photon tracks per source particle     2.2155E+00          escape           6.1241E-02        tco   1.0000E+33
  photon collisions per source particle  2.5021E+00         capture          3.2036E-03        eco   1.0000E-03
  total photon collisions               250208141        capture or escape 3.2184E-03        wc1  -5.0000E-01
                                                    any termination   3.2184E-03        wc2  -2.5000E-01

computer time so far in this run    63.17 minutes            maximum number ever in bank         4
computer time in mcrun              63.14 minutes          bank overflows to backup file       0
source particles per minute           1.5837E+06
random numbers generated              3415477954          most random numbers used was         161 in history
38646806
```

range of sampled source weights = 3.2967E+10 to 3.2967E+10

1photon activity in each cell print table 126

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	109476346	124679315	243057646	8.0129E+10	1.1552E-01	1.1552E-01	3.2967E+10	2.3774E-02
2	2	316798	389691	706459	2.3290E+08	1.1458E-01	1.1458E-01	3.2967E+10	2.3621E-02
3	3	807917	988855	1777236	5.8590E+08	1.1372E-01	1.1372E-01	3.2967E+10	2.3477E-02
4	4	101418233	100019667	4638689	1.5292E+09	1.3773E-01	1.3773E-01	3.2967E+10	6.4663E+00
5	5	112010060	100099507	27382	9.0270E+06	1.2820E-01	1.2820E-01	3.2967E+10	5.6234E+03
6	6	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
7	7	4483	4475	563	1.8560E+05	1.2333E-01	1.2333E-01	3.2967E+10	6.5941E+00
8	8	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
9	9	60929	56468	166	5.4725E+04	1.2583E-01	1.2583E-01	3.2967E+10	5.5850E+03
total		324094766	326237978	250208141	8.2486E+10				

1tally 4 nps = 100000000

tally type 4 track length estimate of particle flux.

tally for photons

this tally is modified by a dose function.

volumes

cell:	6	7	8
	1.57080E+00	1.57080E+00	1.57080E+00

cell 6

0.00000E+00 0.0000

cell 7

2.27242E-01 0.0165

cell 8

0.00000E+00 0.0000

there are no nonzero tallies in the tally fluctuation chart bin for tally 4

1status of the statistical checks used to form confidence intervals for the mean for each tally bin

tally result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins

4 no nonzero tallies were made in the tally fluctuation chart bin

passed all bin error check: 3 tally bins had 2 bins with zeros and 0 bins with relative errors exceeding 0.10

the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

the tally bins with zeros may or may not be correct: compare the source, cutoffs, multipliers, et cetera with the tally bins.

warning. 1 of the 1 tally fluctuation chart bins did not pass all 10 statistical checks.

1tally fluctuation charts

tally 4

nps	mean	error	vov	slope	fom
8192000	0.0000E+00	0.0000	0.0000	0.0	0.0E+00
16384000	0.0000E+00	0.0000	0.0000	0.0	0.0E+00
24576000	0.0000E+00	0.0000	0.0000	0.0	0.0E+00

```
   32768000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   40960000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   49152000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   57344000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   65536000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   73728000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   81920000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   90112000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   98304000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
  100000000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00

 ***********************************************************************************************************************
 dump no.    3 on file runtpm       nps =   100000000     coll =      250208141     ctm =       63.14   nrn =
3415477954


        4 warning messages so far.


 run terminated when   100000000  particle histories were done.

 computer time =   63.17 minutes

 mcnp     version 5     06212004                    04/13/07 08:08:39                    probid =  04/13/07 07:04:37
```

Appendix H: 5cc Unit Dose Pig, Full MCNP Model

```
 ._ _   _ ._  ._  |_
 | | | (_ | | |_) _)
              |
```



```
1mcnp     version 5     ld=06212004                04/18/07 12:26:17
 *************************************************************************                    probid =  04/18/07 12:26:17
 inp=5ccw outp=5ccw_f

       c     Created on: Monday, March 06, 2006 at 14:51
          1    1     -18 -2 3 1 -5  $ W bottom
          2    1     -18 -3 4 -5  $ W side shields
          3    1     -18 1 -8 2 -9  $ W bottom part of screw top
          4    1     -18 9 -10 -8 1  $ W top part of screw top
          5    1     -18 1 -11 10 -12  $ W sloped part
          6    1     -18 -6 12 -5 1  $ W top shield
          7    1     -18 6 -7 -5  $ W cap
          8    7   -1.25 -14 5 -15 4  $ bottom plastic sheath
           9    7   -1.25 -14 5 16 -7  $ top plastic sheath (1)
          10    7   -1.25 -14 7 -17  $ top plastic sheath (2)
          11    6      -1 18 -19 -20  $ radioisotope
          12    4 -0.001239 3 -6 -1  #11 $ air in pig
          13    5      -1 -21  $ dose point (top)
          14    5      -1 -22  $ dose point
          15    5      -1 -23  $ dose point
          16    5      -1 -24  $ dose point
          17    5      -1 -25  $ dose point
          18    5      -1 -26  $ dose point
          19    5      -1 -27  $ dose point
          20    5      -1 -28  $ dose point (bottom)
          21    5      -1 -29  $ dose point (30cm from source)
          22    4 -0.001239 17 -30  #13 $ air space
          23    4 -0.001239 -4 -30  #20
          24    4 -0.001239 5 -30 -17 4  #8 #9 #10 #3 #4 #5 #14 #15 #16 #17 #18 #19
                 #21
          25    0        30

           1       cz 1
           2       pz 0.001
           3       pz -10.2
           4       pz -11.6
           5       cz 1.4
           6       pz 7
           7       pz 7.5
           8       cz 2
           9       pz 0.3
          10       pz 1.6
          11       kz 4.72 0.4 -1
          12       pz 2.5
          14       cz 1.9
          15       pz -8
          16       pz 4.5
          17       pz 7.9
          18       pz -7
          19       pz -1
```

```
  47-        20       cz 0.5
  48-        21      rcc 0 -1 8.42 0 2 0 0.5
  49-        22      rcc 1.91 -0.999 3.99 0 2 0 0.5
  50-        23      rcc 2.26 -0.998 2.2 0 2 0 0.5
  51-        24      rcc 2.51 -0.997 0.95 0 2 0 0.5
  52-        25      rcc 1.91 -1.001 -0.51 0 2 0 0.5
  53-        26      rcc 1.91 -1.002 -4 0 2 0 0.5
  54-        27      rcc 1.91 -1.003 -7.49 0 2 0 0.5
  55-        28      rcc 0 -1.004 -12.11 0 2 0 0.5
  56-        29      rcc 30 -0.996 -4 0 2 0 0.5
  57-        30       so 40
  58-
  59-       mode  p
  60-       m1    74000.          0.95  $Impact Bonded Tungsten
  61-            28000.         0.035 26000.          0.015
  62-       m4    7000.           0.8  $air
  63-            8000.            0.2
  64-       m5    8000.           0.65  $people
  65-            6000.           0.18 1000.            0.1 7000.            0.03
  66-            20000.          0.015 15000.          0.01
  67-       m6    1000.          0.6666  $ saline and tech
  68-            8000.          0.3333
  69-       m7    1000.         0.081616  $ polyvinyl plastic
  70-            6000.        0.648407 7000.        0.126024 8000.        0.143953
  71-       imp:p           1 23r                  0  $ 1, 25
  72-       sdef erg=.1405 pos=0 0 0 rad=d2 ext=d3 axs=0 0 1 wgt=3.2967e10
  73-       si2 0.0 .5
  74-       sp2 -21 1
  75-       si3 -7 -1
  76-       sp3 -21 0
  77-       nps 90000000
  78-       f4:p 13 14 15 16 17 18 19 20 21

 warning.   2 materials had unnormalized fractions. print table 40.
1cells                                                                print table 60

                 atom        gram                            photon
     cell  mat    density     density     volume       mass     pieces importance

    1    1    1  6.10520E-02 1.80000E+01 3.07655E+01 5.53779E+02     1  1.0000E+00
    2    2    1  6.10520E-02 1.80000E+01 8.62053E+00 1.55170E+02     1  1.0000E+00
    3    3    1  6.10520E-02 1.80000E+01 2.81801E+00 5.07242E+01     1  1.0000E+00
    4    4    1  6.10520E-02 1.80000E+01 1.22522E+01 2.20540E+02     1  1.0000E+00
    5    5    1  6.10520E-02 1.80000E+01 5.31150E+00 9.56071E+01     1  1.0000E+00
    6    6    1  6.10520E-02 1.80000E+01 1.35717E+01 2.44290E+02     1  1.0000E+00
    7    7    1  6.10520E-02 1.80000E+01 3.07876E+00 5.54177E+01     1  1.0000E+00
    8    8    7  6.30520E-02 1.25000E+00 1.86611E+01 2.33263E+01     1  1.0000E+00
    9    9    7  6.30520E-02 1.25000E+00 1.55509E+01 1.94386E+01     1  1.0000E+00
   10   10    7  6.30520E-02 1.25000E+00 4.53646E+00 5.67057E+00     1  1.0000E+00
   11   11    6  1.00282E-01 1.00000E+00 4.71239E+00 4.71239E+00     1  1.0000E+00
   12   12    4  5.17958E-05 1.23900E-03 4.93230E+01 6.11112E-02     1  1.0000E+00
   13   13    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   14   14    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   15   15    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   16   16    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   17   17    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   18   18    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   19   19    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   20   20    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   21   21    5  4.23892E-02 1.00000E+00 1.57080E+00 1.57080E+00     1  1.0000E+00
   22   22    4  5.17958E-05 1.23900E-03 0.00000E+00 0.00000E+00     0  1.0000E+00
   23   23    4  5.17958E-05 1.23900E-03 0.00000E+00 0.00000E+00     0  1.0000E+00
   24   24    4  5.17958E-05 1.23900E-03 0.00000E+00 0.00000E+00     0  1.0000E+00
   25   25    0  0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00     0  0.0000E+00

 total                              1.83339E+02 1.44287E+03
```

```
   minimum source weight = 3.2967E+10    maximum source weight = 3.2967E+10

 ***************************************************
 * Random Number Generator  =                    1 *
 * Random Number Seed       =       19073486328125 *
 * Random Number Multiplier =       19073486328125 *
 * Random Number Adder      =                    0 *
 * Random Number Bits Used  =                   48 *
 * Random Number Stride     =               152917 *
 ***************************************************


        1 warning message so far.
1cross-section tables                                                                   print table 100

     table    length

                       tables from file mcplib04

   1000.04p    1898  ENDF/B-VI Release 8 Photoatomic Data for 1-H                       mat 100     02/07/03
   6000.04p    3152  ENDF/B-VI Release 8 Photoatomic Data for 6-C                       mat 600     02/07/03
   7000.04p    3194  ENDF/B-VI Release 8 Photoatomic Data for 7-N                       mat 700     02/07/03
   8000.04p    3272  ENDF/B-VI Release 8 Photoatomic Data for 8-O                       mat 800     02/07/03
  15000.04p    4498  ENDF/B-VI Release 8 Photoatomic Data for 15-P                      mat1500     02/07/03
  20000.04p    5013  ENDF/B-VI Release 8 Photoatomic Data for 20-CA                     mat2000     02/07/03
  26000.04p    5718  ENDF/B-VI Release 8 Photoatomic Data for 26-FE                     mat2600     02/07/03
  28000.04p    5826  ENDF/B-VI Release 8 Photoatomic Data for 28-NI                     mat2800     02/07/03
  74000.04p    9716  ENDF/B-VI Release 8 Photoatomic Data for 74-W                      mat7400     02/07/03

  total      42287

 maximum photon energy set to  100.0 mev (maximum electron energy)

                       tables from file el03

   1000.03e    2329                                                       6/6/98
   6000.03e    2333                                                       6/6/98
   7000.03e    2333                                                       6/6/98
   8000.03e    2333                                                       6/6/98
  15000.03e    2339                                                       6/6/98
  20000.03e    2343                                                       6/6/98
  26000.03e    2345                                                       6/6/98
  28000.03e    2347                                                       6/6/98
  74000.03e    2367                                                       6/6/98

 warning. material    1 has been set to a conductor.

 ******************************************************************************************************************
 dump no.    1 on file runtpg      nps =          0     coll =             0     ctm =       0.00   nrn =               0


        2 warning messages so far.

 ******************************************************************************************************************
 dump no.    2 on file runtpg      nps =    74119093     coll =    189174836     ctm =      60.01   nrn =       2589093389

1problem summary

      run terminated when    90000000  particle histories were done.
+                                                                  04/18/07 13:41:55
      c     Created on: Monday, March 06, 2006 at 14:51                         probid =  04/18/07 12:26:17
0
 photon creation     tracks      weight        energy           photon loss        tracks      weight        energy
                             (per source particle)                                         (per source particle)

 source           90000000    3.2967E+10    1.4050E-01          escape                 91    3.3333E+04    1.2690E-07
                                          energy cutoff           0    0.            3.0301E-05
```

```
                                        time cutoff            0    0.          0.
weight window          0    0.          0.              weight window          0    0.          0.
cell importance        0    0.          0.              cell importance        0    0.          0.
weight cutoff          0    0.          0.              weight cutoff          0    0.          0.
e or t importance      0    0.          0.              e or t importance      0    0.          0.
dxtran                 0    0.          0.              dxtran                 0    0.          0.
forced collisions      0    0.          0.              forced collisions      0    0.          0.
exp. transform         0    0.          0.              exp. transform         0    0.          0.
from neutrons          0    0.          0.              compton scatter        0    0.          3.8181E-03
bremsstrahlung   9078468    3.3254E+09  1.1407E-03      capture        199278417    7.2996E+10  1.8699E-01
p-annihilation         0    0.          0.              pair production        0    0.          0.
photonuclear           0    0.          0.              photonuclear abs       0    0.          0.
electron x-rays        0    0.          0.
1st fluorescence 86123100   3.1547E+10  4.7818E-02
2nd fluorescence 14076940   5.1564E+09  1.3783E-03
  total        199278508    7.2996E+10  1.9084E-01        total        199278508    7.2996E+10  1.9084E-01

  number of photons banked              23155408      average time of (shakes)          cutoffs
  photon tracks per source particle     2.2142E+00       escape          1.3303E-01        tco   1.0000E+33
  photon collisions per source particle 2.5523E+00       capture         3.1425E-03        eco   1.0000E-03
  total photon collisions              229708454      capture or escape 3.1425E-03        wc1  -5.0000E-01
                                                      any termination   3.1425E-03        wc2  -2.5000E-01

computer time so far in this run    73.80 minutes          maximum number ever in bank        4
computer time in mcrun              73.76 minutes          bank overflows to backup file      0
source particles per minute         1.2202E+06
random numbers generated            3143875873             most random numbers used was       189 in history
47715372

range of sampled source weights = 3.2967E+10 to 3.2967E+10
1photon   activity in each cell                                              print table 126
```

cell		tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	95935042	109545913	212829146	7.7959E+10	1.1500E-01	1.1500E-01	3.2967E+10	2.5431E-02
2	2	759511	926294	1656468	6.0676E+08	1.1279E-01	1.1279E-01	3.2967E+10	2.5051E-02
3	3	666070	782069	1280558	4.6907E+08	1.1331E-01	1.1331E-01	3.2967E+10	2.5161E-02
4	4	1333691	1518617	2657697	9.7351E+08	1.1233E-01	1.1233E-01	3.2967E+10	2.4988E-02
5	5	390976	443247	742712	2.7206E+08	1.1131E-01	1.1131E-01	3.2967E+10	2.4806E-02
6	6	586275	617284	1102456	4.0383E+08	1.1092E-01	1.1092E-01	3.2967E+10	2.4734E-02
7	7	183082	224954	406850	1.4903E+08	1.1386E-01	1.1386E-01	3.2967E+10	2.5243E-02
8	8	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
9	9	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
10	10	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
11	11	93708242	90052253	9014145	3.3019E+09	1.3362E-01	1.3362E-01	3.2967E+10	6.3859E+00
12	12	103409410	90065858	18420	6.7472E+06	1.2527E-01	1.2527E-01	3.2967E+10	5.5729E+03
13	13	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
14	14	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
15	15	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
16	16	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
17	17	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
18	18	3	3	0	0.0000E+00	7.6768E-02	7.6768E-02	3.2967E+10	5.1166E+00
19	19	1	1	0	0.0000E+00	1.4050E-01	1.4050E-01	3.2967E+10	7.0782E+00
20	20	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
21	21	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
22	22	13	13	0	0.0000E+00	1.0240E-01	1.0240E-01	3.2967E+10	5.1594E+03
23	23	27	27	0	0.0000E+00	1.1027E-01	1.1027E-01	3.2967E+10	5.1106E+03
24	24	96	92	2	7.3260E+02	1.2812E-01	1.2812E-01	3.2967E+10	5.6115E+03
total		296972439	294176625	229708454	8.4142E+10				

```
1tally   4       nps =    90000000
           tally type 4    track length estimate of particle flux.      units   1/cm**2
```

```
        tally for  photons

        volumes
              cell:      13         14         15         16         17         18         19
                   1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00  1.57080E+00
              cell:      20         21
                   1.57080E+00  1.57080E+00

 cell  13
           0.00000E+00 0.0000

 cell  14
           0.00000E+00 0.0000

 cell  15
           0.00000E+00 0.0000

 cell  16
           0.00000E+00 0.0000

 cell  17
           0.00000E+00 0.0000

 cell  18
           5.87936E+02 0.5903

 cell  19
           2.38616E+02 1.0000

 cell  20
           0.00000E+00 0.0000

 cell  21
           0.00000E+00 0.0000

 there are no nonzero tallies in the tally fluctuation chart bin for tally   4

1status of the statistical checks used to form confidence intervals for the mean for each tally bin


 tally   result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all
bins

    4   no nonzero tallies were made in the tally fluctuation chart bin
        missed all bin error check:     9 tally bins had     7 bins with zeros and     2 bins with relative errors exceeding
0.10


 the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.

 the tally bins with zeros may or may not be correct: compare the source, cutoffs, multipliers, et cetera with the tally
bins.

 warning.     1 of the   1 tally fluctuation chart bins did not pass all 10 statistical checks.
 warning.     1 of the   1 tallies had bins with relative errors greater than recommended.
1tally fluctuation charts

                  tally    4
      nps      mean     error   vov  slope    fom
    8192000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   16384000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   24576000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   32768000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   40960000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   49152000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   57344000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   65536000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
```

```
   73728000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   81920000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00
   90000000   0.0000E+00 0.0000 0.0000  0.0 0.0E+00

************************************************************************************************************************
dump no.    3 on file runtpg       nps =    90000000     coll =      229708454     ctm =       73.76   nrn =       3143875873

       4 warning messages so far.

run terminated when    90000000  particle histories were done.

computer time =   73.80 minutes

mcnp     version 5     06212004                  04/18/07 13:41:55                  probid =  04/18/07 12:26:17
```