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MEDICAL PHYSICS CALCULATIONS WITH MCNPTM: A PRIMER

ABSTRACT

The rising desire for individualized medical physics models has sparked a transition from the use of tangible phantoms toward the employment of computational software for medical physics applications. One such computational software for radiation transport modeling is the Monte Carlo N-Particle (MCNP) radiation transport code. However, no comprehensive document has been written to introduce the use of the MCNP code for simulating medical physics applications. This document, a primer, addresses this need by leading the medical physics user through the basic use of MCNP and its particular application to the medical physics field.

This primer is designed to teach by example, with the aim that each example will illustrate a practical use of particular features in MCNP that are useful in medical physics applications. These examples along with the instructions for reproducing them are the results of this thesis research. These results include simulations of: dose from Tc-99m diagnostic therapy, calculation of Medical Internal Radiation Dose (MIRD) specific absorbed fraction (SAF) values using the ORNL MIRD phantom, x-ray phototherapy effectiveness, prostate brachytherapy lifetime dose calculations, and a radiograph of the head using the Zubal head phantom. Also included are a set of appendices that include useful reference data, code syntax, and a database of input decks including the examples in the primer. The sections in conjunction with the appendices should provide a foundation of knowledge regarding the MCNP commands and their

uses as well as enable users to utilize the MCNP manual effectively for situations not specifically addressed by the primer.

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1. INTRODUCTION

1.1 Overview

The rising desire for individualized medical physics models has sparked a transition from the use of tangible phantoms toward the employment of computational software for medical physics applications. The result of this desire is that many research groups have developed their own highly detailed CT-based voxel geometries for MCNPTM [1]. The increasing number of medical physics users has encouraged the MCNP development team to produce a primer to lead the medical physics user through the basic use of MCNP and its particular application to the medical physics field. The current published research includes MCNP modeling of medical physics applications such as neutron capture therapy for brain tumors [2], IMRT treatment [3], patient-specific dose distributions for radioimmunotherapy [4], and dose calculations from simulated CT x-ray sources [5]. However, no comprehensive document has been published to instruct the medical physics user on the use of MCNP and its specific applications.

In the footsteps of its predecessor, *Criticality Calculations with MCNPTM: A Primer*, this primer is designed to teach by example, with the aim that each example illustrates a practical use of particular features in MCNP that are useful in medical physics applications. Also included are a set of appendices that detail useful reference data, code syntax, and a database of input decks for the examples in the primer, many that utilize reference phantoms developed by other researchers. The sections in

conjunction with the appendices should provide a foundation of knowledge regarding the MCNP commands and their uses as well as enable users to utilize the MCNP manual effectively for situations not specifically addressed by the primer.

1.2 Methods

Medical Physics Calculations with MCNPTM: A Primer is designed to enable a user with medical physics interests to understand and use the MCNP Monte Carlo code for radiation transport simulations. The document assumes that the user has education and/or experience equivalent to a college degree in a technical field but assumes no prior familiarity with any Monte Carlo code. The primer begins with a Quick Start section to introduce basic concepts for using the MCNP code. The following sections expand on the ideas presented in the Quick Start section by presenting practical example problems varying in scope and complexity. The sections in the body of this project include specific examples on the subjects of: organ-to-organ dose calculations, x-ray phototherapy, sealed source brachytherapy, radiography tallies, meshed/voxelized geometries and using tallies to calculate doses throughout a region of interest in a patient-specific geometry.

This document has been written to stand alone, allowing the user to understand the basic methods for completing a problem from start to finish. However, it is recommended that the primer be used in conjunction with the MCNP manual for further

research into concepts that may be briefly described or only referenced by the primer. Some topics may be omitted entirely from the primer.

Upon completion of this primer, a medical physicist or student in training should feel confident in his or her skills to use MCNP to model situations typically encountered in the medical physics field. The user is free to modify any of the input files that may be provided in this document in order to accommodate a particular problem. While this primer aims to provide the necessary information to create and run problems with MCNP, it makes no attempt to teach the theory of radiation interaction with matter. The MCNP code performs checks to ensure that problem geometries, materials, and sources are self-consistent throughout the input file, but the code cannot distinguish whether the information in the input file is an accurate representation of the physical properties of a particular problem. Correct problem specification is a duty that resides with the user, but this primer uses many example problems to give the user an idea of how to correctly specify a wide variety of problems that he or she is likely to encounter.

1.3 Results

The intended result of this project is a step-by-step guide to be distributed with MCNP so the medical physics user can make the most of his or her time while learning to use the code for this specific application. The Quick Start guide, Section 2 of this work, serves as an orientation for using the MCNP code. This section describes the necessary “cards” for creating an MCNP input deck and provides simple examples to

reiterate the concepts that have been taught throughout the section. Section 3 steps through the calculation of MIRD organ-to-organ dose coefficients using an ORNL MIRD phantom. Section 4 describes x-ray phototherapy on a tumor loaded with gadolinium using basic macrobody geometries. The example problem of Section 5 calculates prostate dose from brachytherapy sealed sources modeled as point sources using an ORNL MIRD phantom. Section 6 describes an external beam therapy problem in which a dose profile of the brain is created using a voxelized Snyder head phantom and radiography tallies.

The example problems in this document will be distributed with a database of MCNP input decks created by other researchers including: a lattice-based tissue cube, the ORNL MIRD phantom, voxel and analytical Snyder head phantoms, a revised MCAT phantom, and the Zubal head phantom. In addition to the primer content, the appendices included with the primer provide an abundance of useful information for using MCNP in medical physics applications. These sections include: specifications and mass densities of selected materials, constants used to calculate dose, and complete, uninterrupted, example problem input decks to use for practice runs. Through the introductory Quick Start section, extensive example problems, and helpful data to use in medical physics applications, this primer serves as a useful educational tool to introduce medical physics users to the MCNP code.

1.4 Summary

With the advent of detailed voxelized and analytical phantoms and the significant increases in microprocessor speed and memory, the use of computational modeling software for medical physics applications has gained momentum. The purpose of this primer is to help medical physicists and medical physics students to understand and use the Los Alamos National Laboratory Monte Carlo N-Particle (MCNP) code for medical physics applications. This document makes no assumption of familiarity with any Monte Carlo code. It includes many examples to illustrate the features of MCNP that are most useful for medical physics applications. The second section, the Quick Start guide, is intended to introduce basic use of the MCNP program and can be skipped if the user is already familiar with MCNP.

2. MCNP QUICKSTART

2.1 What You Will Be Able to Do

- 1) Interpret an MCNP input file.
- 2) Setup a simple medical physics problem with MCNP.

2.2 MCNP input file format

The MCNP input file is used to describe the geometry of the problem, specific materials and radiation sources, and format and types of results needed from the calculation. Specific problem geometries are developed by defining cells that are bounded by one or more surfaces. Cells can be filled with a specific material or defined as a void. For the purposes of this tutorial, MCNP syntax in the text will be placed in quotations for easy identification. In figures, pieces of input files will be written in bold Courier New font as shown in Figure 2-1.

MCNP input files are structured into three major sections: cell cards, surface cards, and data cards. The cell card section is preceded by a one-line title card. In this document and throughout the MCNP manual, the word “card” describes a single line of input that can consist of up to 80 characters. A “section” consists of one or more cards. The input file structure is shown in Figure 2-1 below.

Title Card
Cell Cards
Blank Line Delimiter
Data Cards
Blank Line Terminator (optional)

Figure 2-1. MCNP input file structure

2.2.1 Title Card

The title card is the first card in an MCNP input file. As mentioned above, it can consist of up to 80 characters. It is wise to utilize the title card to describe the problem being modeled for future reference. In this way, the title card serves as a quick reference for the information contained in the input file as well as a label for distinguishing between multiple input files. Also for future reference, the title will be echoed multiple times throughout the MCNP output file.

2.2.2 General Card Format

Within each section, cards can be placed in any order. There is no specification of format with regard to alphabetic characters, i.e. upper, lower, or mixed case can be used as desired. MCNP calls for a blank line delimiter to denote separation between the three key sections.

The general format is the same for the cell, surface, and data cards. The cell or surface number or data card name must be placed within the first five columns.

Different entries on a card must be separated by one or more blanks. Input lines cannot exceed 80 columns. The character “c” can be used in the first column of a line to denote a comment line in an input file after the title card. The character “\$” can be used after input data on a line to denote that anything following is a comment. The character “&” can be used to indicate that data on the next line is a continuation. This character can be used in columns 1-80. Also, blanks in the first five columns can be used to indicate continuation of a previously named card.

2.2.3 Cell Cards

After the title card, the first section is for the cell cards and has no blank line delimiter at the front of it. However, comment cards, describing the input deck for example, may be placed between the title card and the cell cards. Cells are used to define the shape and material content of the physical space of the problem. The specific format for a cell card is shown in Figure 2-2.

```
j      m      d      geom      params
```

Figure 2-2. Cell card format

The cell number, denoted above as “j”, should be an integer from 1 to 99999. The material number, “m”, specifies the material present in a particular cell and is also an integer from 1 to 99999. The data card section of the input file is used to define the

composition of each specific material used in a particular problem. If two or more cells consist of the same material, each cell will have a different cell number but the same material number. When defining the cell material density, “d”, a positive entry indicates an atomic density in *atoms per barn-centimeter*. A negative entry indicates a mass density in *grams per cubic centimeter*. The geometry specification, “geom.”, uses Boolean operators in conjunction with signed surface numbers to describe how the surfaces bound regions of space to create cells. In MCNP, the surfaces are geometric shapes and are used to form the boundaries of the problem being modeled. The optional “params” feature can be used to specify cell parameters on the cell card line instead of in the data card section. For example, the importance card “imp:n” specifies the relative cell importance for neutrons, one entry for each cell of the problem. The “imp:n” card can go in the data card section, or it can be placed on the cell card line at the end of the list of surfaces. The “imp:n” card will be discussed more thoroughly in the following sections. {Chapter 3 of the MCNP manual provides a full explanation of the “params” option.}

Figure 2-3 is an example of a cell card. The optional comment card has a c in column 1, followed by a blank and the comment itself. The second line shows the cell number (3) followed by the material number (2) and the material density (1.234e-3). Because 1.234e-3 is positive, the density of material 2 is in units of *atoms per barn-cm*. The “-2” indicates that cell 3 is bounded only by surface 2. Surface 2 is defined in the surface card section. The negative sign preceding the surface number means that cell 3 is the region of space that has a negative sense with respect to surface 2.

```

C      Cell Card
3 2 1.234e-3 -2  imp:n=1

```

Figure 2-3. Cell card example.

2.2.4 Surface Cards

The specific format for a surface card is shown in Figure 2-4.

```

j      a      list

```

Figure 2-4 Surface card format.

The character “j” represents the surface number (1-99999) and must start in columns 1-5. The surface type, represented here by the character “a”, is the next parameter in the surface definition. The “list” feature on the surface card is a space for the user to list (in format specified in the MCNP manual) numbers that describe the surface, such as dimensions and radius in cm. Figure 2-5 is an example of a surface card. The number of this surface is 1. The mnemonic “cz” defines an infinite cylinder centered on the z-axis, with a radius of 20.0 cm. The \$ terminates data entry and everything that follows, “infinite z cylinder”, is interpreted as a comment, providing the user with more detail.

```
1  cz  20.0  $ infinite z cylinder
```

Figure 2-5. Surface card example.

2.2.5 Data Cards

The format of the data card section is the same as the cell and surface card sections. The data card name must begin in columns 1-5. At least one blank must separate the data card name and the data entries. The most important data cards for medical physics applications include: problem type, source specification, tally specification, and material and cross section specification. These are only a few examples of the many available MCNP data cards. {See chapter 3 of the MCNP manual.} No data card can be used more than once with the same number or particle type designations. For example, “M1” and “M2” are acceptable as are “CUT:N” and “CUT:P”, but two “M1” cards or two “CUT:N” cards are not allowed.

2.2.5a Problem Type

The “MODE” code card specifies what particles might be created and tracked in the problem. Every problem that involves transport of particles other than neutrons should contain a problem type, “MODE” card. The format for the “MODE” card is shown below in Figure 2-6.

```

MODE x1... xi
xi = N for neutron transport
      P for photon transport
      E for electron or positron transport

```

Figure 2-6. “MODE” card format.

If the “MODE” card is omitted, “MODE N” is assumed. The entries on the “MODE” card are space delineated.

2.2.5b Source Definition

For medical physics purposes, the general source “SDEF” specification will usually suffice. Within this source definition, the user can specify source distribution functions specified on “SIn”, “SPn”, “SBn”, and “DSn” cards. The “MODE” card, discussed above, also serves as part of the source specification in some cases by implying the type of particle to be started from the source. The general source card, “SDEF,” is specified by the form given in Figure 2-7.

```
SDEF source variable=specification...
```

Figure 2-7. General source card format.

For medical physics purposes, the specification of a source variable is usually either an explicit value or a distribution number prefixed by a “D”. However, it can also be specified as a function of another variable. Additional information about the “SDEF” card can be found starting on page 3-51 of the MCNP manual. The most common source variables used for “SDEF” specification are listed below in Table 2-1.

Table 2-1
Most common variables used for general source (“SDEF”) specification

<u>Variable</u>	<u>Meaning</u>	<u>Default</u>
CEL	Cell	Determined from XXX, YYY, ZZZ and possibly UUU, VVV,
WWW		
SUR	Surface	Zero (means cell source)
ERG	Energy (MeV)	14 MeV
NRM	Sign of the surface normal	+1
POS	Reference point for position sampling	0,0,0
RAD	Radial distance of the position from POS or AXS	0
EXT	Cell case: distance from POS along AXS	0
	Surface case: cosine of angle from AXS	0
AXS	Reference vector for EXT and RAD	No direction
X	x-coordinate of position	No X
Y	y-coordinate of position	No Y
Z	z-coordinate of position	No Z
PAR	Particle type source will emit	1,n=neutron if MODE N, NP, or PE 2,p=photon if MODE P or PE 3,e=electron if MODE E 4,f=positron if MODE E
WGT	Particle weight	1

The specification of “WGT” and “PAR” must be only an explicit value. These are only some of the source variables available in MCNP. {See MCNP manual page 3-53 for other variables.} The allowed value for “PAR” is 1 for neutrons, 2 for photons, 3 for electrons, or 4 for positrons. The default is the lowest of these three that corresponds to an actual or default entry on the “MODE” card. Only one kind of particle is allowed in a “SDEF” source.

Most of the source variables mentioned above are scalar values. “POS” and “AXS” are vector values. Where a value of a source variable is required, as on “SDEF,” “SI,” or “DS,” cards, usually a single number is appropriate, but with “POS” and “AXS,” the value must actually be a triplet of numbers, the x , y , and z components of the vector.

The source variables “SUR,” “POS,” “RAD,” “EXT,” “AXS,” “X,” “Y,” and “Z” are used in various combinations to determine the coordinates (X,Y,Z) of the starting positions of the source particles. With them you can specify three different kinds of volume distributions and three different kinds of distributions on the surfaces. More elaborate distributions can be approximated by combining several simple distributions, using the “S” option of the “SIn” and “DSn” cards.

The three volume distributions are Cartesian, spherical, and cylindrical. The value of the variable “SUR” is zero for a volume distribution. A volume distribution can be used in combination with the “CEL” variable to sample uniformly throughout the interior of a cell. A Cartesian, spherical, or cylindrical region that completely contains a cell is specified and is sampled uniformly in volume. If the sampled point is found to be

inside the cell, it is accepted. Otherwise it is rejected and another point is sampled. If you use this technique, you must make sure that the sampling region actually contains every part of the cell because MCNP has no way of checking for this.

Never position any kind of degenerate volume distribution in such a way that it lies on one of the defined surfaces of the problem geometry. Even a bounding surface that extends into the interior of a cell can cause trouble. If possible, use one of the surface distributions instead. Otherwise, move to a position just a little off of the surface. It will not make any detectable difference in the answers, and it will prevent particles from getting lost.

Three other cards are often used with the “SDEF” card. These are the Source Information, “SI,” card, the Source Probability, “SP,” card, and the Source Bias, “SB,” card. The forms used for these cards are listed in Figure 2-8 through Figure 2-10 below.

```

      SIn  option  I1...Ik
Default:  SIn  H   I1...Ik

```

Figure 2-8. Source Information card format.

The Source Information, “SI,” card format is shown in Figure 2-8 above. The “n” following the “SI” parameter represents the distribution number (1-999) and should be consistent with the “SDEF” card. The “option” parameter indicates how the following “I_i” values are to be interpreted. For this parameter, an “H” indicates that the

following values are bin boundaries for a histogram distribution, for scalar variables only. This parameter is the default. An “L” indicates that discrete source variable values follow. An “A” indicates that the following values are points where a probability density distribution is defined, and “S” indicates that more distribution numbers follow. The values “I₁...I_k” are the source variable values or distribution numbers; their type indicated by the character in the “option” parameter space.

```

SPn  option      P1 ... Pk or
      SPn  f      a b
Default: SPn  D  P1 ... Pk

```

Figure 2-9. Source Probability card format.

The Source Probability, “SP,” card format is shown in Figure 2-9 above. The “n” parameter on the “SP” card represents the distribution number (1-999) and should be consistent with the “SDEF” card and the “SI” card that corresponds to this probability definition. The “option” parameter indicates how the following “P_i” values are to be interpreted. For this parameter, a “D” indicates that the following values are bin probabilities for an “H” or “L” distribution on the corresponding “SI” card. This is the default value. A “C” as the “option” parameter indicates that the following values are cumulative bin probabilities for an “H” or “L” distribution specified on the corresponding “SI” card. A “V” as the “option” parameter is for cell distributions only and indicates that the probability is proportional to cell volume (times P_i if the P_i are

present). The values “ $P_1 \dots P_k$ ” are the source variable probabilities of the type indicated by the “option” parameter. The second format style shown in Figure 2-9 is an alternative way to format the “SP” card. In this format, the “f” parameter is a negative number designator for a built-in function. The “a,b” values for this format are parameters for the built-in function indicated by the “f” parameter (see MCNP Manual page 3-64).

```

SBn  option  B1 ... Bk or
          SBn  f  a b
Default:  SBn  D  B1 ... Bk

```

Figure 2-10. Source Bias card format.

The Source Bias, “SB,” card format is shown in Figure 2-10 above. For this card, the “n,” “option,” “f,” “a,” and “b” parameters are the same as described for the “SPn” card. However, the only values allowed for “f” are “-21” and “-31,” which represent the power law and exponential distributions, respectively. The “ $B_1 \dots B_k$ ” values on this card represent the source variable biased probabilities.

The first form of the “SP” card, where the first entry is positive or nonnumeric, indicates that it and its “SI” card define a probability distribution function. The entries on the “SI” card can be values of the source variable or, when the “S” option is used, distribution numbers. The entries on the “SP” card are probabilities that correspond to the entries on the “SI” card. The “SB” card is used to provide a probability distribution for sampling that is different from the true probability distribution on the “SP” card. Its

purpose is to bias the sampling of its source variable to improve the convergence rate of the problem. The “DS” card is used instead of the “SI” card for a variable that depends on another source variable, as indicated on the “SDEF” card. No “SP” or “SB” card is used. The form for the “DS” card is shown below in Figure 2-11 below.

```

DSn  option J1...Jk
Default: DSn H J1...Jk

```

Figure 2-11. “DS” card format.

The “n” parameter on this card indicates the distribution number (1-999). The “option” parameter indicates how the “J_i” values are to be interpreted. For this parameter, an “H” indicates that the following values are source variable values in a continuous distribution and is used for scalar values only. “H” is the default for this parameter. An “L” indicates that discrete source variable values follow. An “S” indicates that more distribution numbers follow. The values “J₁...J_k” are the source variable values or distribution numbers as indicated by the “option” parameter.

Below, Figures 2-12 through 2-16 show examples of the “SDEF” card to illustrate some practical applications of the options described above.

```
SDEF ERG=D1 POS=0 0 0 PAR=P
SI1  L 1.173 1.332
SP1  D 1 1
```

Figure 2-12. Point isotropic source of Co-60 placed at the origin.

Figure 2-12 above shows the “SDEF” card format to describe a point isotropic source of Co-60 placed at the origin.

```
SDEF SUR=3 ERG=2 PAR=1 POS=5 0 -1 RAD=D1
SI1 H 0 5
SP1 -21 1
```

Figure 2-13. Source of 2-MeV neutrons placed on surface 3.

The “SDEF” card featured in Figure 2-13 is used to define a disc source sitting on surface 3 and centered at (5, 0, -1) with radius ranging from 0 to 5 cm. The “SP1” card distributes the source evenly across the disc using the power law “-21” built-in function.

```
SDEF SUR=2 NRM=-1 ERG=D1 PAR=2
SI1  H 0.01 0.05 0.25 1 2 5
SP1  5 4 3 2 1 0.5
SI2  0 3
SP2  -21 2
```

Figure 2-14. Inward-directed surface source.

The inward-directed source in Figure 2-14 is designated by “NRM=-1” and lies on surface 2, a sphere in this case. The source energy is a histogram distribution between 0.001 and 5 MeV, since 1 keV is the lowest energy at which MCNP transports photons and electrons. The “SP1” card indicates that the energy distribution is biased toward lower-energy photons.

```
SDEF CEL=5 POS=9 0 0 ERG=0.662 RAD=D1 EXT=D2 AXS=1 0 0
      PAR=2
SI1  0 0.25
SP1  -21 1
SI2  0.75
SP2  -21 0
```

Figure 2-15. Source distributed throughout a volume.

The source in Figure 2-15 is distributed uniformly in volume throughout cell 5, which presumably approximates a cylinder. The cell is enclosed by a sampling volume centered at (9,0,0). The axis of the sampling volume is the line through (9,0,0) in the direction of (1,0,0). The inner and outer radii of the sampling volume are 0 cm and 0.25 cm, and it extends along (1,0,0) for a distance ± 0.75 from (20,0,0). The user has to make sure that the sampling volume totally encloses cell 5. The source particles are 0.662 MeV photons from a cesium-137 seed or pellet. The direction of the source particles is isotropic.


```

SDEF      POS=D1      ERG=FPOS=D2
SI1      L 5 3.3 6      75 3.3 6
SP1      0.3 0.7
DS2      S 3 4
SI3      H 2 10 14
SP3      D 0 1 2
SI4      H 0.1 0.5 2
SP4      D 0 1 1

```

Figure 2-16. Point isotropic source in two locations.

The source definition in Figure 2-16 is a point isotropic source in two locations, shown by two sets of coordinates on the “SI1” card. The code will determine the starting cell. The first location will be picked with probability 0.3, and the second location will be chosen with probability 0.7. Each location has a different energy spectrum, pointed to by the “DS2” card, which lists the numbers of following distributions since the S option is present. Since the energy is a function of position, MCNP assumes that the energy distributions will be in the same order as the position distributions. When MCNP selects the first location, the first entry on the corresponding “DS” card is chosen, distribution 3 in this case. When MCNP selects the second location, the second entry on the “DS” card is chosen, distribution 4 in this case. Therefore, distribution 3 corresponds to the first position, and distribution 4 corresponds to the second location. The “SI3” card indicates that the first point source has a distribution of energies indicated by a histogram. The “SP3” card indicates that the relative probabilities for the energy bins are 0, 1, and 2 for the regions 0-2 MeV, 2-10 MeV, and 10-14 MeV, respectively. The “SI4” and “SP4” cards give the energy bin

distribution for the second point source. From these cards you can see that there are two equally probably energy bins, 0.1-0.5 MeV and 0.5-2 MeV.

2.2.5c Tally Specification

The tally cards are used to specify what type of information the user wants to gain from the Monte Carlo calculation; that is, current across a surface, flux at a point, energy deposition averaged over a cell, etc.

Tally types 1, 2, 4, 6, and 7 are used for tallying over a surface or cell. The form for surface and cell tallies is given below in Figure 2-17.

```

Fn:pl S1 (S2...S3) S6S7
n = tally number
pl = N or P or N,P or E
Si = problem number of surface or cell for tallying or T

```

Figure 2-17. Surface and cell tally format.

Only surfaces bounding cells and listed in the cell card description can be used on “F1” and “F2” tallies. Tally 6 does not allow E. Tally 7 allows N only. Entries within parentheses indicate that the tally is for the union of the items within the parentheses. For unnormalized tallies (tally type 1), the union of tallies is a sum, but for normalized tallies (types 2, 4, 6, and 7), the union results in an average. T indicates that

a tally is desired which represents the average of the flux across all indicated surfaces or cells. A list of useful tallies and their corresponding units is shown in Table 2-2 below.

In this case, “E” stands for electrons and positrons.

Table 2-2
MCNP tally commands and their corresponding units

<u>Mnemonic</u>	<u>Tally Description</u>	<u>Fn units</u>	<u>*Fn units</u>
F1:N or F1:P or F1:E	Current integrated over a surface	particles	MeV
F2:N or F2:P or F2:E	Flux averaged over a surface	particles/cm ²	MeV/cm ²
F4:N or F4:P or F4:E	Flux averaged over a cell	particles/cm ²	MeV/cm ²
F5a:N or F5a:P	Flux at a point or ring detector	particles/cm ²	MeV/cm ²
F6:N or F6:N,P or F6:P	Energy deposition averaged over a cell	MeV/g	jerks/g
F8:P or F8:E or F8:P,E	Energy distribution of pulses in a detector	pulses	MeV

The form for the detector tally (type 5) is shown below in Figure 2-18.

```

                                Fn:pl X Y Z ±R0
n = tally number
pl = N for neutrons or P for photons
X Y Z = location of the detector point
±R0 = radius of the sphere of exclusion:
        in centimeters, if R0 is entered as positive
        in mean free paths, if entered as negative

```

Figure 2-18. “F5” tally card format.

The MCNP5 manual describes the point detector tally as a “next-event estimator.” It is a tally of the flux at a point as if the “next event” were a particle trajectory directly to the detector point without further collision. Exponential attenuation through all materials between the collision point and the detector is included in this tally. For this estimate, a contribution to the point detector is made at every source or collision event. Between the present event and the detector point, MCNP accounts for attenuation and the solid angle effect. The expected $1/(4\pi R^2)$ relation in the solid angle term approaches zero when a source or collision event occurs near the detector point, causing the flux to approach infinity. When many scattering events are expected to occur, near the detector, a cell or surface tally should be used instead of the point detector tally. However, if cell and surface tallies are impossible because so few scattering events occur near the detector, a point detector can be used in conjunction with a specified average flux region close to the detector. This region, R_0 , should be about 1/8 to 1/2 mean free paths for particles of average energy at the sphere and zero in a void. Supplying R_0 in terms of mean free path will increase the variance and is not recommended unless you have no idea how to specify it in centimeters.

The last tally to be discussed in this Quick Start guide is the pulse height (type 8) tally. The “F8” tally provides the energy distribution of pulses created in an experimental detector by radiation. The “F8” card is used to list the cell bins. The union of tallies produces a tally sum, not an average. Both photons and electrons will be tallied if present, even if only “E” or only “P” is on the “F8” card. An asterisk on the

“F8” card converts the tally from a pulse height tally to an energy deposition tally. The form for the “F8” tally is shown below in Figure 2-19.

Fn:pl S₁(S₂...S₃)(S₄...S₅)S₆S₇

n = tally number
pl = P, E, or P,E
S_i = problem number of cell for tallying

Figure 2-19. “F8” tally card format.

The pulse height tally card is often used in conjunction with the Tally Energy Card, “E_n”. The “E_n” card is used to enter the desired energy bins used for the tally. If the “E_n” card is absent, there will be one bin over all energies. An “E0” card can be used to set up a default energy bin structure for all tallies. A specific “E_n” card will override the default structure when applied to tally n. The format for the tally energy card is shown below in Figure 2-20.

En E₁...E_k

n = tally number
E_i = upper bound (MeV) of the ith energy bin for tally n

Figure 2-20. Tally energy card format.

Special-use tallies such as the radiography and mesh tallies will be discussed in detail later in the primer through example problems. Converting tally quantities to dose quantities is also explained later in the discussion of the Tally Multiplier (“FMn”), Dose Energy (“DE”), and Dose Function (“DF”) cards. Figures 2-21 through 2-24 show a few examples of tally cards in order to emphasize the information provided above.

F2:N 1 3 6 T

Figure 2-21. Neutron surface flux tally.

The card in Figure 2-21 specifies four neutron surface flux tallies, one across each of the surfaces 1, 3, and 6 and one which is the average of the flux across all three of the surfaces.

F1:P (1 2) (3 4 5) 6

Figure 2-22. Photon current tally.

The card shown in Figure 2-22 specifies three photon current tallies, one for the sum over surfaces 1 and 2; one for the sum over surfaces 3, 4, and 5; and one for surface 6 alone.

F1:N (1 2 3) (1 4) T

Figure 2-23. Neutron current tally.

The card shown in Figure 2-23 provides three neutron current tallies, one for the sum over surfaces 1, 2, and 3; one for the sum over surfaces 1 and 4; and one for the sum over surfaces 1, 2, 3, and 4. This example illustrates that the T bin is not confused by the repetition of surface 1.

F8:P 5

E8 0 1E-5 1E-3 1E-1 1 2 5

Figure 2-24. Pulse height tally and energy cards.

The card shown in Figure 2-24 provides a pulse height tally for photon pulses in cell 5. The “E8” card stipulates the energy-binning scheme for the output pulse height distribution. Care must be taken when selecting energy bins for a pulse height tally. It is recommended that a zero bin and an epsilon bin be included. The zero bin will catch non-analog knock-on electron negative scores. The epsilon (1E-5) bin will catch scores from particles that travel through the cell without depositing any energy.

At this point, it is important to mention that it would be to the user’s advantage to review the MCNP photon physics treatment options when designing a problem that

includes photon tallies. A description of the MCNP photon interaction models begins on page 2-57 of the MCNP5 manual. Pay particular attention to the “*Caution for detectors and coherent scattering*” section on page 2-64. In short, when using point or ring detectors, it is wise to either use simple photon physics treatment or turn off coherent scattering when using detailed photon physics treatment. Turning off coherent scattering in either of these ways can improve the figure of merit for you calculation by more than a factor of 10 for tallies with small relative error because coherent scattering is highly peaked in the forward direction.

2.2.5d Material and Cross-Section Specification

The next topic of discussion is the material card. The format of the material, or m card, is shown below in Figure 2-25.

```

mn zaid1 fraction1 zaid2 fraction2 ...

mn = Material card name (m) followed immediately by the material number (n) on
    the card. The mn cards starts in columns 1-5.

zaid = Atomic number followed by the atomic mass of the isotope. Preferably
    (optionally) followed by the data library extension, in the form of .##L
    (period, two digits, one letter).

fraction = Nuclide fraction
    (+) Atom density (atoms/b-cm)
    (-) Weight fraction

```

Figure 2-25. Material card format.

An example of a material card where two isotopes of chlorine are used is shown in Figure 2-26. The material number n is an integer from 1 to 99999. Each material can be composed of many isotopes. Default cross-sections are used when no extension is given. Chapter 3 and Appendix G of the MCNP manual describes how to choose cross sections from different libraries.

```
m1      17035.66c -0.7577
        17037.66c -0.2423
```

Figure 2-26. Data card of default ZAIDs with material format in weight fractions.

The first ZAID is “17035.66c” followed by the weight fraction. The atomic number is 17 for chlorine. The atomic mass is 35 corresponding to the 35 isotope of chlorine. The “.66c” is the extension used to specify the ENDF66 (continuous energy) library. A second isotope in the material begins immediately after the first using the same format and so on until all material components have been described. Notice that the material data is continued on a second line. If a continuation line is desired or required, make sure the data begins after the fifth column of the next line, or end the previous line with an ampersand, “&”. Because the fractions are entered as negative numbers, weight fractions are described by this material card. If the atom or weight fractions do not add to unity, MCNP will automatically renormalize them. It is important to note here that neutron cross-sections in the data libraries are generally

isotopic, while photon cross-sections are generally elemental. There are a few exceptions to this rule such as the mendf5 neutron cross-sections (.50c) which exist for elemental carbon (6000) and carbon-12 (6012). When the “000” cross-section is not available for a particular element, the majority of important isotopes are typically present. It is up to the user to define the isotopes present and their corresponding concentrations.

For medical physics problems, it is also important to consider the relevance of free gas thermal treatment when considering a problem specification. This treatment takes into account how a collision between a neutron and an atom is affected by the thermal motion of the atom and the presence of other atoms nearby. In MCNP, thermal motion is accounted for based on the free gas approximation. The code also has an explicit $S(\alpha,\beta)$ capability to account for the effects of chemical binding and crystal structure for incident energies below about 4 eV. Information about $S(\alpha,\beta)$ data is contained in Appendix G of the MCNP manual. In medical physics problems, two different $S(\alpha,\beta)$ treatments could be appropriate for neutrons in tissue. These include hydrogen in light water (ltwr.60t) and hydrogen in polyethylene (poly.60t). To see which of these treatments is most appropriate, we will plot these cross sections coincident with a tissue material cross section and observe the results.

To plot cross sections you must use “ixz” for the options parameter on the execution line. After running the execution line, you will see a “mcplot>” prompt. After this prompt, you can plot $S(\alpha,\beta)$ cross sections coincident with material cross sections by using a command line similar to the following:

```
xs m1001 mt 1 coplot xs poly.60t mt 1 coplot xs lwtr.60t mt 4
```

The “xs” portion of the command line stipulates that you desire a cross section plot. For the given command line, MCNP is instructed to plot the cross section for material m100 (hydrogen, in this case) coincident with the $S(\alpha,\beta)$ cross sections for hydrogen in polyethylene (poly.60t) and hydrogen in light water (lwtr.60t). Material m1001 in this example corresponds to ICRU tissue. A listing of the available $S(\alpha,\beta)$ cross section libraries is given in Table G.1 of the MCNP5 manual. The numbers following each “mt” entry on the command line stipulate which reaction numbers to plot for each corresponding cross section. The “mt 1” entries correspond to the total cross sections for materials m1001 and poly.60t. The “mt 4” entry corresponds to the total neutron cross section for lwtr.60t, since “mt 1” is not available for this cross section. A plot using these commands is shown in Figure 2-27. Based on this cross section plot, thermal scattering treatment has little effect above energies of approximately 0.001 eV. Below this energy, the light water thermal treatment conforms more to the hydrogen total cross section than the polycarbonate thermal treatment. Above 0.001 eV, either treatment can be used, but it is evident that one of the two treatments should be used.

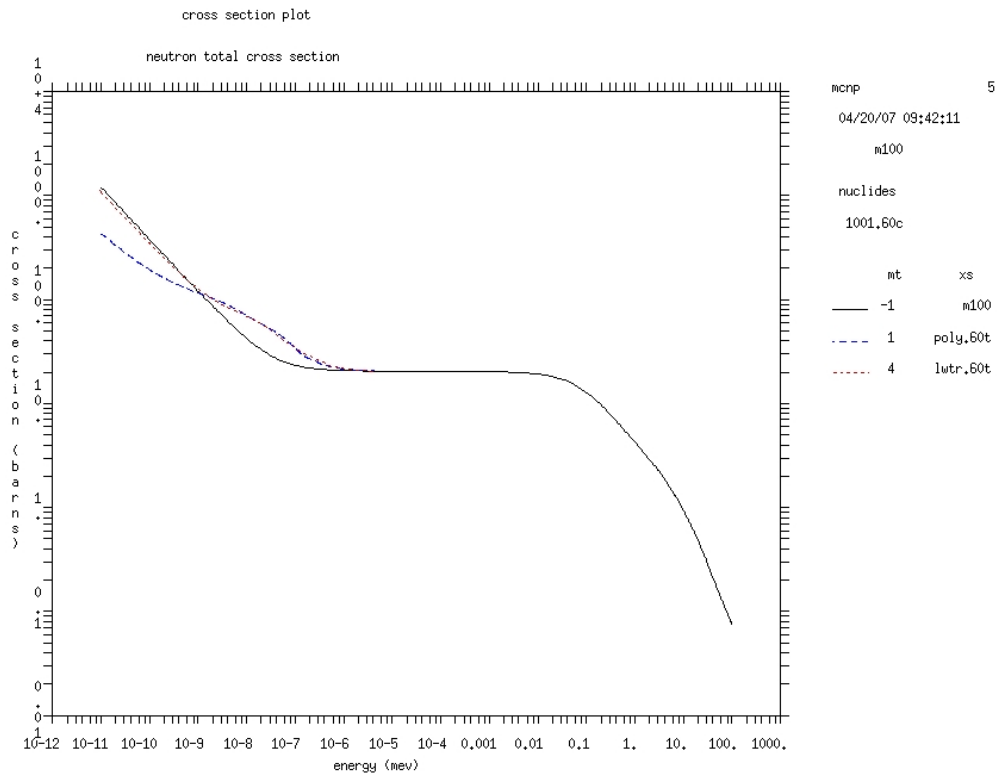


Figure 2-27. Neutron total cross section plot for hydrogen and $S(\alpha,\beta)$ cross sections for hydrogen in polyethylene (poly.60t) light water (lwtr.60t).

2.3 Building a Complete Input File

As a simple first example, we will build one complete input file to finish out this Quick Start section. For this example, we will calculate the number of photons incident on a point detector from a homogenous disc surface source of 1-MeV photons with no shielding. Figure 2-28 shows a pictorial representation of the problem geometry.

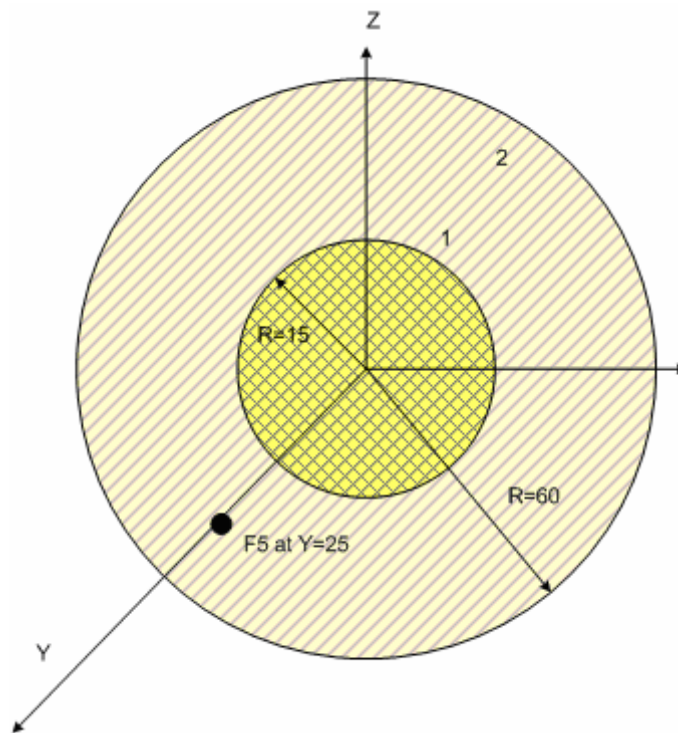


Figure 2-28. Section 2 problem geometry.

The first step for developing any input file is to give it a title card. Figure 2-29 shows a suitable title card for this problem. Remember that cards cannot exceed 80 characters in length.

Disc surface source incident on point detector

Figure 2-29. Title card for Section 2.

Although cell cards follow the title card in the input file format, it is easiest to write the surface cards next since the problem surfaces must be used to define the cell cards. A suggested format for input file numbering is to number surfaces beginning with 1000, cells beginning with 100, and materials beginning with 1. This numbering convention will be used while building this input file for illustrative purposes. For this problem, we will be defining a surface source on the “SDEF” card. Therefore, we need a plane for the surface to sit on and a sphere which will define the scope of transport for the problem. Particles will be killed if they leave this sphere. We will define this sphere as centered at the origin with a radius of 60 cm, and the plane as normal to the x axis at the origin. These surface card definitions are shown in Figure 2-30. The “\$” indicates that the following text is a comment and not part of the surface definition.

```
1000 so 60 $Sphere centered at origin with R=60 cm  
1001 px 0
```

Figure 2-30. Surface card for Section 2.

We will next define the material cards for this example so that we will have already assigned numbers to the materials for placement on the cell cards. The material cards are placed in the data section of the input deck after the surface cards with a blank line delimiter placed between the surface cards and the data cards. The data cards themselves can be placed in order. We will use air to transport our particles and a void

to define the area outside of our transport region. We will, therefore, only need to define one material, air. This material definition is shown in Figure 2-31. The negative values indicate weight fractions. If weight fractions on a material card do not sum to unity, MCNP will normalize them.

```
m1 6000 -0.00012 7014 -0.75527 8016 -0.23178 20000 -0.01283 $Air
```

Figure 2-31. Material card for air.

Next we will define the cell cards for this example. We will need two cell cards, one to define the region in which we will transport problems and another to define the area outside of the transport region. These cell cards are shown in Figure 2-32. The negative value located after the material number on cell 100 indicates the material density in grams per cubic centimeter. When a cell contains a void, no density value is needed. Remember that the cell cards are placed immediately after the title card and that a blank line delimiter must be placed between the cell cards and the surface cards in the output file.

```
100 1 -1.293e-3 -1000 $Inside transport sphere
101 0 1000 $Outside transport sphere
```

Figure 2-32. Cell cards for Section 2.

The next card that should be defined for this example is the “SDEF” card. The “SDEF” card needed for this example is shown in Figure 2-33. We define that the source particles are 1 MeV photons by specifying “par=2” and “erg=1.0.” We must also specify the surface on which the source is placed (“sur=1001”) and the position of the center of the disc (“pos=0 0 0”). The radius of the source must be defined as a distribution (“rad=d1”) between 0 and 15 cm distributed evenly across the disc. The “H” on the “SI1” card indicates that the radial distribution is a histogram, and the “-21 1” entry on the “SP1” card indicates that the source particles will be distributed along the radius of the disc with a power law to the first power, the desired distribution for particles within a circular surface source. The “SDEF” card for this example defines an isotropic disc source.

```
SDEF par=2 erg=1.0 sur=1001 pos=0 0 0 rad=d1
SI1 H 0 15
SP1 -21 1
```

Figure 2-33. “SDEF” card for Section 2.

In order to tally the number of photons striking the point detector, we will define an “F5” tally for photons. The first three entries on the “F5” tally give the coordinates of the point source, and the last entry specifies the sphere of exclusion desired for the tally. This feature is used to prevent large contributions from particles that scatter in close proximity to the point detector. Since we are transporting photons with a small

interaction probability in air, the value for this entry is a small, non-zero sphere of exclusion. We will add a tally multiplier card to convert the tally result from $\#/cm^2$ per source particle to number of photons per source particle by multiplying by the source area (πr^2). The tally and multiplier cards are shown in Figure 2-34.

```
F5:p  25 0 0  0.5
Fm5  706.858
```

Figure 2-34. Tally and tally multiplier cards for Section 2.

Three more data cards must be added in order to run this input file. We must specify the mode of the problem (“mode”), the cell importances (“imp”), and the number of particle histories to run (“nps”). For this problem, we will only be transporting photons (“mode p”). We would like to transport photons inside cell 1 and kill them once they reach cell 2. Since the entries on the “imp” card correspond to the order of the cells on the input card, the values for the “imp” card are 1 and 0, in that order. For this example, we will run $5e4$ particles (“nps $5e4$ ”). These additional data cards are shown in Figure 2-35. One blank line must be placed after the last data card to signal the end of the input file.

```
mode      p
imp:p     1 0
nps       5e4
```

Figure 2-35. Additional data cards for Section 2.

The input file from this input file is now complete. The command line for running this input file is shown below.

```
mcnp5 i=ex2 o=ex2out1
```

On the command line, the “i=ex2” entry indicates the name that the input file is given inside the MCNP directory. The “o=ex2out1” entry tells MCNP what to name the output file once it is created. By default, this output file is placed in the same directory as the input file. Any input and output names that you desire can be used as long as the entire command line does not exceed 256 characters in length (in versions MCNP5 1.50 or later).

The complete input file created in this section is shown below in Figure 2-36.

```

Disc surface source incident on point detector

100 1 -1.293e-3 -1000 $Inside transport sphere
101 0          1000 $Outside transport sphere

1000 so 60  $$Sphere centered at origin with R=60 cm
1001 px 0

m1 7014 -0.7808 8016 -0.2095 18000 -0.0093 $Air
SDEF par=2 erg=1.0 sur=1001 pos=0 0 0 rad=d1
SI1 H 0 15
SP1 -21 1
F5:p 25 0 0 0
Fm5 706.858
mode p
imp:p 1 0
nps 5e4

```

Figure 2-36. Complete input file for Section 2.

The result calculated from this run was 0.285 photons per source particle. Another interpretation of this result is that 28.5% of the source photons strike the point detector in this problem.

2.4 Summary

This Quick Start section has addressed key features of the MCNP and their appropriate use for modeling radiation transport in matter. The section has hopefully served valuable in establishing a knowledge base of the MCNP code. The following sections will elaborate on the features discussed in this section and will present medical physics example problems to reinforce the basic instruction found here.

3. TUMORS IN TISSUE

3.1 What You Will Be Able to Do

- 1) Practice using macrobody surfaces.
- 2) Use the Boolean intersection geometry operator.
- 3) Define a multi-cell problem.
- 4) Create a source distribution card using independent and dependent distributions.
- 5) Use the cell fluence (F4) tally to calculate dose to tumors via the heating number method.

3.2 Problem Description

Technetium-99m is one of the most widely used radioactive isotopes for diagnostic studies in nuclear medicine. Different chemical forms are used for brain, bone, liver, spleen and kidney imaging and also for blood flow studies. This example problem includes a rectangular parallelepiped of tissue containing three spherical tumors with a desired tissue to tumor Tc-99m concentration ratio. The tumors and the surrounding media are all emitting Tc-99m gamma rays isotropically. The geometry is defined using macrobody notation. The rectangular parallelepiped has dimensions of 10 cm in all directions. Each tumor sphere has a radius of 1 cm and have centers located at (0, -2, 0), (0, 2, 0), and (2, 0, 0).

3.3 Geometry

3.3.1 Surfaces

The setup for this problem will be done in a different order than found in an MCNP input file to aid in user understanding. Recall that the cell cards precede the surface cards, but it is often easier to begin by defining the surfaces first. We will then combine these surfaces to form the cells. We will define the surfaces in terms of macrobodies. The surface cards needed to define the rectangular parallelepiped in this problem are shown below in Figure 3-1.

```

1 rpp    -5  5   -5  5   -5  5
2 s      0 -2  0    1
3 s      0  2  0    1
4 s      2  0  0    1
5 so     10

```

Figure 3-1. Section 3 surface cards.

3.3.2 Cells

Now that the surface cards are defined, the geometric cells can be defined. Cells are defined by identifying individual surfaces and combining these surfaces using the Boolean *intersection*, *union*, and *complement* operators. Remember that the first card of the input file is the problem *title* card.

Cell 1 is a rectangular parallelepiped of tissue, excluding three tumor cells that exist inside the tissue volume. Cell 1 is assigned material 1, which is tissue for this

problem definition. The gram density follows the material number. Recall from the first section that a gram density is entered as a negative number. The cell cards for this example are shown below in Figure 3-2.

Tissue Containing Tumor Spheres					
C	Cell	Cards			
1	2	-1.04	-1	2	3 4
2	2	-1.04	-2		
3	2	-1.04	-3		
4	2	-1.04	-4		
5	0		1	-5	
6	0		5		

Figure 3-2. Section 3 cell cards.

Continuing with cell 1, the tissue is contained inside the rectangular parallelepiped; therefore, the sense of surface 1 with respect to (wrt) cell 1 is negative. Cell 1 now needs to be restricted to the region that does not contain any of the tumor spheres. The description for this cell is written using the Boolean *intersection* operator. This is illustrated on line 3 of Figure 3-2. The senses of surfaces 2, 3, and 4 are all positive wrt cell 1. This indicates that cell 1 consists of the area inside (negative sense) surface 1 and outside (positive sense) surfaces 2, 3, and 4. Cells 2, 3, and 4 are defined using the negative sense (denoting that the cell is *inside* the specified surface) of surfaces 2, 3, and 4, respectively. Cell 5 denotes the space between the tumor and tissue geometry and a sphere defining a boundary between the geometry of interest and the outside world. Cell 5 is defined as a void but could easily be defined as air or any other desired medium by creating a material card for the desired composition. MCNP requires that you define

all space, so the only remaining geometry to be defined for this example is the outside world, cell 6. This cell is also defined as a void, i.e. the material number is zero.

Remember, a void has no material density entry. It is wise to space over to the area under the other surface relationships to remind yourself what each number stands for in your input file. Since the outside world consists of everything *outside* surface 5, this surface has a positive sense for the definition of cell 6.

If you do not desire to transport any particles outside of the defined tissue rectangular parallelepiped, as would most likely be the case for this example, the outside world can be defined wrt surface 1 as illustrated below in Figure 3-3.

6 0 1

Figure 3-3. Revised definition for cell 6.

A screen capture from the MCNP interactive geometry plotter is given below in Figure 3-4.

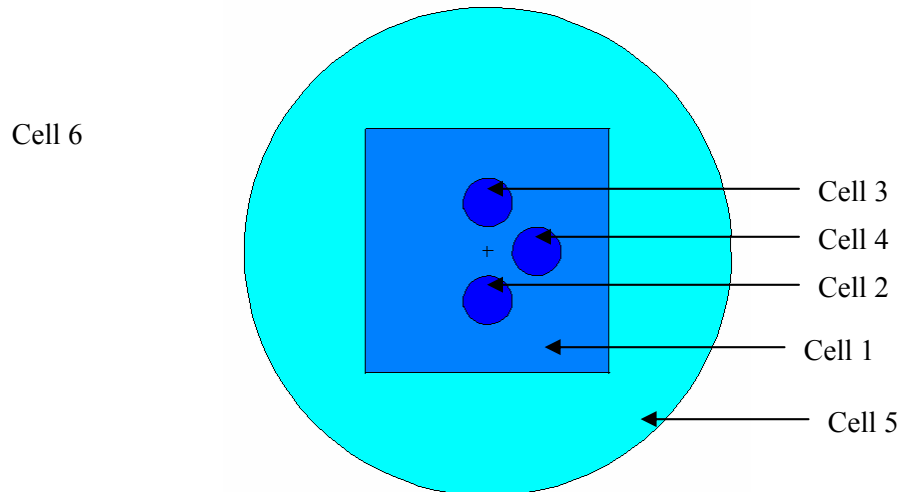


Figure 3-4. XY slice the origin of the tissue and tumor configuration.

The cells in Figure 3-4 are clearly labeled. Different colors on the plot represent the different materials used in this problem. The royal blue coloring cells 2, 3, and 4 represents tumor tissue. The lighter blue of cell 1 represents normal tissue. These colors have been used in this figure for illustrative purposes. The input deck for this problem does not actually specify different materials for the tumors versus the healthy tissue. However, a different material specification can be made for the tumor tissue if desired by adding an additional material card and specifying that material on the cell card definitions for the spheres composing the tumors. The aqua color of cell 5 represents air for this problem. Cell 6 has no color because this material was defined as a void for the outside world.

3.4 Materials

Now that the geometry for this problem is defined, we need to identify the material. This example only requires tissue and air, which can both be defined using weight fraction compositions including several elements. The composition for soft tissue was taken from the input deck for the ORNL MIRD phantom. The two material cards used in this problem are shown in Figure 3-5.

```

c      Material card for soft tissue
m1     1000      -0.10454
        6000      -0.22663
        7000      -0.0249
        8000      -0.63525
        11000     -0.00112
        12000     -0.00013
        14000     -0.0003
        15000     -0.00134
        16000     -0.00204
        17000     -0.00133
        19000     -0.00208
        20000     -0.00024
        26000     -0.00005
        30000     -0.00003
        37000     -0.00001
        40000     -0.00001
C      Material card for dry air
m2     7000 -0.755 8000 -0.232 18000 -0.013

```

Figure 3-5. Section 3 material specifications.

Since no cross section extension is specified, MCNP will use the most recent cross sections for each of the specified ZAIDs. For photon source problems such as this example, it is acceptable to use the elemental ZAIDs as shown above.

3.5 Source Definition

The next part of the input file needed for this section is the source definition. For this example, we need for particles to be distributed throughout the tumor spheres (cells 2, 3, and 4) and throughout the surrounding tissue medium (cell 1) with a ratio of 6:6:6:1 for cells 2, 3, 4, and 1, respectively. We will use the general source card (“SDEF”) to define this source. The format for the “SDEF” card is shown below in Figure 3-6.

```
SDEF par=2 erg=d1 cel=d2 rad=fcel=d3 pos=fcel=d8
SI1 L 0.1426 0.1405
SP1 D 0.014 0.986
SI2 L 1 2 3 4
SP2 D 1 6 6 6
DS3 s 4 5 6 7
SI4 0 7.5
SP4 -21 2
SI5 0 1
SP5 -21 2
SI6 0 1
SP6 -21 2
SI7 0 1
SP7 -21 2
DS8 L 0 0 0 0 0 -2 0 0 2 0 2 0 0
```

Figure 3-6. Section 3 general source definition.

For this “SDEF” source, “par=2” indicates that the source particles will be created as photons. The energy of the particles is represented by distribution “d1.” The “SI1” card indicates that the photons have discrete energies (indicated by “L”) of 0.1426 MeV and 0.1405 MeV. The “SP1” shows that these energies occur with a probability of 0.014 (1.4%) and 0.986 (98.6%), respectively. Since this problem has source particles starting in four different cells, the “cel” parameter is also a distribution, represented above by

“d2.” The “SI2” card shows that source particles will begin in cells 1, 2, 3, and 4. The “SP2” card stipulates that particles will start with the ratio of 1:6:6:6 for cells 1, 2, 3, and 4, respectively. The third distribution specified in this source definition applies to the radii used to define the volumes that MCNP will incorporate into the rejection technique used for placing source particles inside specific cells. In this case, “D3” is a dependent distribution with regard to the cell distribution. The “DS3” card, using the “s” parameter, defines subsequent distributions that will describe the radii needed for this problem. Since we have already specified on the first line of the source definition that the radii definition is a function of the cell definition, MCNP assumes that these distributions will be defined in an order corresponding to the order in which the cells were defined. For example, the four distributions mentioned on the “DS3” card will correspond to cells 1, 2, 3, and 4, in that order. Therefore, distributions 4, 5, 6, and 7 show that the radii of the spheres used to place particles into cells 1, 2, 3, and 4, are each of radius 7.5 cm, 1 cm, 1 cm, and 1 cm, respectively. The “SP” cards for these distributions illustrate that these source particles will be distributed along each of these radii using a power law of the second power (indicated by “-21 2”). This is the probability distribution used to evenly distribute particles in a spherical volume. The last distribution in this source distribution is used to indicate position and is dependent on the cell distribution. The “DS8” distribution indicates the position (center) of each of the source spheres based on cell number. Again, these positions (discrete values as indicated by the “L” parameter) are in the same order as the cell distribution. Therefore, these positions correspond to cells 1, 2, 3, and 4, in that order.

For this problem, spheres the same size as each of the tumors (radius=1 cm) are defined to place particles inside those tumor spheres. Another sphere (radius=7.5cm) is defined with dimensions that will encompass the rectangular parallelepiped. MCNP then uses a rejection technique to start particles inside the rectangular parallelepiped, excluding the region of the parallelepiped that includes the actual tumors since we have defined the source term on the basis of cells. Any particle inside this encompassing sphere that does not fall inside cell 1 is rejected; particles that fall inside cell 1 are kept.

3.6 Tallies and Miscellaneous Data Cards

Now that the source has been defined for this problem, we can now focus on establishing the tallied quantities. We will use the “F4” (cell fluence) tally for this problem. The “F4” tally gives a quantity in units of particles/cm² per source particle. In order to convert these units to units of dose, we will use the “Fm” (tally multiplier) card. Two basic approaches are useful for converting from fluence quantities to units of dose. One option is to fold in one or more fluence to dose conversion function. The other option is to use a heating number method. Both approaches are valid for photon dose, but the use of conversion functions is recommended for neutron dose equivalent, ambient dose equivalent, and effective dose. This example will illustrate the heating number method.

In the heating number method, MCNP calculates absorbed dose on the basis of the KERMA approximation, which assumes that kinetic energy transferred to charged

particles is locally deposited. This KERMA approximation is valid as long as the following conditions are satisfied:

- Charged particle equilibrium (CPE) or at least transient CPE exists such that the range of primary radiation is much greater than the secondary particle range.
- Radiative losses in the medium are negligible.

The conditions for CPE or transient CPE are often not fulfilled in the following situations:

- at the interface between two different material compositions or densities;
- near the edge of a beam or in regions very close to a radioactive source;
- when the photon spectrum changes drastically with depth of penetration through a particular medium; and
- when a high-energy photon beam is incident on a high-Z target, i.e. radiative losses are no longer negligible [6].

Using the KERMA approximation, dose can be represented using the following equation:

$$D\left(\frac{\text{Gy}}{\text{source particle}}\right) = \frac{C}{N} \sum_{j=1}^N \sum_{i=1}^T \phi \sigma_T(E) H(E), \quad \text{Equation 3.1}$$

$$\text{where } C = \left(1.602 \times 10^{-10} \frac{\text{Gy}}{\text{Mev/g}}\right) \left(1 \times 10^{-24} \frac{\text{cm}^2}{\text{barn}}\right) \left(\frac{N_a \eta}{M}\right). \quad \text{Equation 3.2}$$

N_a = Avagadro's constant = $6.022 \times 10^{23} \text{ mol}^{-1}$;

η = number of atoms per molecule;

M = molar mass of material in grams;

ϕ = fluence score in particles/cm²;

σ_T = total atomic cross section at energy of scoring track in barns;

H = heating number in MeV per collision at energy of scoring track;

N = number of source particles; and

T = number of scoring source particle tracks.

The summation in Equation 3.1 indicates a sum over all scoring particle tracks (T) and over all source particles (N). A list of C values for various materials is given in Appendix C. A database of heating numbers is internal to MCNP and is provided with the data libraries.

Figure 3-7 shows the format to follow for writing a tally multiplier card to perform the operations above for the heating number method.

```
fmn I m -5 -6
```

Figure 3-7. Tally multiplier card format for the heating number method.

For this card, “I” represents a constant based on the material and the number of source particles of interest for a particular problem. This value incorporates the C value described above and any conversion factors needed to calculate the desired tally quantity. An example of the calculation needed for this constant will be illustrated later in this section. The next entry on the multiplier card should be the material in which the dose is to be calculated. This should be indicated using a material card number that you defined in the data section of the input deck. The “-5” entry on this card indicates that each score should be multiplied by the total microscopic cross section, $\sigma_T(E)$, at the energy of the

scoring track. The “-6” entry indicates that each score should be multiplied by H(E) at the energy of the scoring track. The tally and multiplier cards used for this problem are shown below in Figure 3-8.

```

F4:p    1
fm4    0.011682 2 -5 -6
f14:p   2
fm14   0.011682 2 -5 -6
F24:p   3
fm24   0.011682 2 -5 -6
f34:p   4
fm34   0.011682 2 -5 -6

```

Figure 3-8. Section 3 tally and multiplier cards.

These multiplier cards follow the format shown in Figure 3-8. The “I” value given on each fm card was derived using the following equation:

$$20 \times 10^{-3} \text{ Ci} \times \frac{3.7 \times 10^{10} \frac{\text{decays}}{\text{s}}}{\text{Ci}} \times \frac{1 \text{ photon}}{\text{decay}} \times \frac{1.5787 \times 10^{-11} \text{ Gy}}{\text{source photon}} = 0.011682 \frac{\text{Gy}}{\text{s}} \quad \text{Equation 3.3}$$

Therefore, each tally result will be in units of Gy/s.

In addition to the tally and multiplier cards, a few other key data cards must be included before MCNP will have sufficient information to run this problem. The additional cards needed for this input deck are shown below in Figure 3-9.

```
mode p e  
imp:p 1 1 1 1 1 0  
nps 100000
```

Figure 3-9. Section 3 additional data cards.

The “mode” card indicates which types of particles MCNP is to track and tally. Even though MCNP can only start one type of source particle, the program can track secondary particles for tally purposes. By tracking secondary electrons, MCNP can subsequently track any Bremsstrahlung radiation and the resulting dose, energy fluence, or other quantity of interest related to this radiation. The “imp” card gives the importance values for all cells defined in the problem geometry. In this case, we would like to track particles that may move within the tumor spheres or the surrounding medium, but we can save computational time by killing particles that leave the boundary of the tissue volume. Since particles which pass into this outer volume are killed, the user should set up his or her geometry so that particles in the outer regions have none or very little impact on the tallies. Therefore, we assign an importance of 1 to cells 1, 2, 3, and 4, and an importance of 0 to the area outside of the rectangular parallelepiped surface. The “nps” card indicates how many particle histories you would like to run. The input file in its entirety is contained in Appendix A.

3.7 Running and Output

To run this problem, you should use the following command line:


```
mcnp5 i=ex3 o=ex3out1 r=ex3r1
```

You may use any input and output file names that you desire. It is wise to name your runtpe file (indicated by “r=ex3r1”) so that it can be easily located for any particular run. You will need this file if you plan to plot tallies within MCNP or continue an existing run.

Once the calculation is complete, check the output file to see your results. The run time of this problem should be on the order of 1.5 minutes, but will vary according to processor speed. At the end of the output file, you will see the “tally fluctuation charts.” Just above these charts, MCNP will indicate whether your tallies pass all ten of the built-in statistical checks. As a rule, your run should pass these checks. After running 2.5E5 particles, this problem passed all ten of the built-in statistical checks. By examining the tally fluctuation chart for each tally, you should notice features listed for various numbers of particle histories. Your values should converge within reason by the end of your total particle histories. A relative error value of less than 5% usually results in reasonable convergence. The errors from this run are all less than 1% for 2.5E5 particle histories, which lends great confidence in the statistical error of the results. Table 3-1 summarizes the tally results for this example problem.

Table 3-1
Tally results for Section 3

Cell	Dose Rate (Gy/s)	Relative Error
1	2.4226E-06	0.0008
2	2.9142E-05	0.0036
3	2.8992E-05	0.0036
4	2.9989E-05	0.0035

As expected, the dose rate within the surrounding tissue volume (cell 1) is much less than the dose rate inside the tumor spheres. It is also interesting to note that the dose rate in cell 4 is noticeably greater than the dose rates in cells 2 and 3. If you recall, cell 4 is located in between cells 2 and 3 and is receiving a more significant dose from particles starting in the other two tumor cells. Since the mean free path for 140 keV photons is only approximately 6 cm in tissue, the dose in the tissue volume is much less than that in the tumors.

3.8 Summary

This section presented you with an example to calculate the dose rate within four different cells, including three tumor spheres and the surrounding tissue volume. The geometry was defined using macrobody surface definitions. You saw how to define a rather complicated “SDEF” source with eight different distributions, including the independent and dependent types. This problem also described how to use the “F4” (cell fluence) tally and the heating number method to calculate dose rate for the four cells of interest.

4. MIRD SPECIFIC ABSORBED FRACTIONS

4.1 What You Will Be Able to Do

- 1) Use a ready-made geometry input deck to tally SAF values for particular source and target organs.
- 2) Define a volume source for irregularly-shaped cells.
- 3) Isolate and repair geometry errors.

4.2 Problem Description

This problem will illustrate how to calculate SAF values for two different source organs and six different target organs which are defined in the ORNL MIRD phantom created by researchers at Hanyang University in Korea. For the source organs, we will use the spleen and the pancreas. The target organs for this problem include: kidneys, liver, ovaries, pancreas, spleen, and thyroid. SAF values are source energy dependent, and are expressed in units of MeV^{-1} . For ease of calculation, we will use 1 MeV source photons. Therefore, no tally multiplier card will be needed.

4.3 Geometry

Since we are using a ready-made input deck for the geometry specification, we will not be writing any cell or surface cards for this example; these cards have already

been written for us by persons at Hanyang University. (See disclaimer at start of the Section 4 input deck in Appendix A.) You should take a few minutes to familiarize yourself with the cell and surface definitions from this input deck. You will notice that the composers of this input deck used comments to indicate which parts of the body they were defining at any given time. These comments will be very useful as you define the scope of any problem in which you use the ORNL MIRD phantom. Plots of the ORNL MIRD phantom taken from the MCNP geometry plotter are shown below in Figure 4-1.

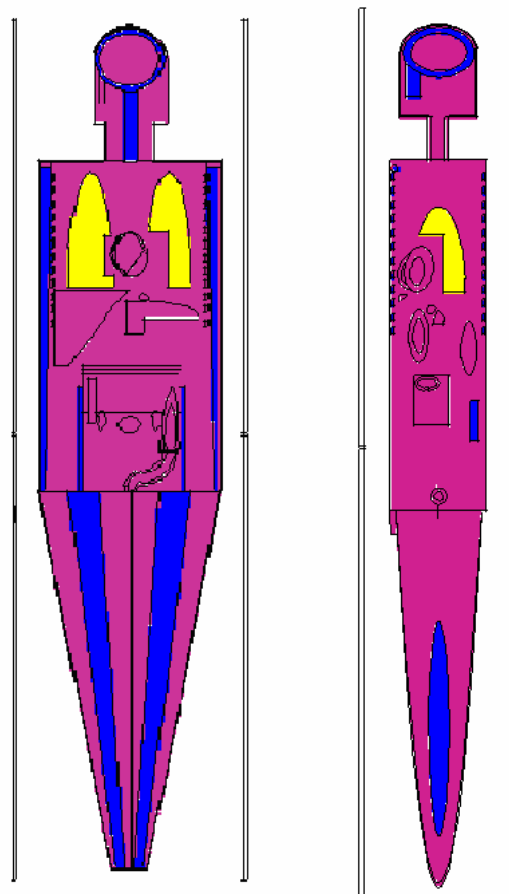


Figure 4-1. Coronal (left) and sagittal (right) slices of the ORNL MIRD phantom from the MCNP geometry plotter.

4.4 Materials

The materials for this problem are also defined in the ORNL MIRD input deck. The anatomical features modeled by the ORNL MIRD phantom are constructed of soft tissue, bone, or lung material. Since cells clearly correspond to different organs, it would be easy to add more detailed material compositions if the user desires. Each of these materials is defined on the “mn” cards in the input deck using weight fractions (indicated by negative values on each material card).

4.5 Source Definition

The source definition is one part of the input file that we actually have to create ourselves for this example problem. We will create independent source distributions for the spleen and for the pancreas. Since MCNP will only allow the definition of one “SDEF” card per input file, we will create two separate input files to run independently for this problem. An “SDEF” card could easily be created to distribute source particles over multiple source organs, but the two separate input files in this case will allow us to tally the dose from each organ source independently.

The best way to define the source for this problem is to utilize MCNP’s rejection technique for placing source particles in a particular cell, as illustrated in Section 3. Therefore, we must look at the geometry input deck and locate the cell numbers that correspond to the organs that we are interested in identifying as source organs. We will work on defining the “SDEF” card for the spleen as the source organ first. From the ORNL MIRD input deck, we can see that the spleen corresponds to cell 2600. Now we

need to define a volume that encompasses cell 2600. Since this cell is defined wrt surface 2600 (an ellipsoid), it is easiest to use a sphere surrounding this ellipsoid for the rejection technique. In order to define the volume for the “SDEF” card, it is a good idea to use the geometry plotter to be sure that you are defining a volume that completely encompasses the cell that you intend to use for the volume source. Therefore, you can cut and paste the cell and surface definitions from the ORNL MIRD input file to create a separate “test” file in order to view your surrounding geometry. You can then use a trial and error method to adjust the volume parameters. An example of such a “test” file is shown below in Figure 4-2.

```
Spleen geometry test
C Spleen cell definition
2600    0 -2600    imp:p=1 vol=176
2701    0 2600 -2800    imp:p=0
2800    0 2800    imp:p=0

C Spleen surface definition
2600    sq 0.081633 0.25 0.027778 0 0 0 -1 11 3 37
2800    s 11 3 37 6.2

nps 1000
```

Figure 4-2. Test input file for defining spleen volume source.

For this test file, surface 2600 and cell 2600 were copied directly from the ORNL MIRD input file. Surface 2800 was created to mimic the cell that would surround the spleen cell. Cell 2701 defines the area that is inside the encompassing sphere but outside of the spleen. Cell 2800 defines the outside world. The “nps” statement gives an arbitrary number of particles so that MCNP can recognize the end of the input file. It is fine to define all materials as a void since we are simply using this file to view our source

geometry and will not be running any particles or making any tallies. Since this test file is only used to refine the source definition, particles are terminated in the region outside of the source cell. In reality, particles need to be transported outside of the source cell in order to contribute dose in target organs.

The starting position for the sphere defined by surface 2800 was taken from the definition of the ellipsoid (surface 2600) defining the spleen. The last three entries on the sq and gq cards are the coordinates of the specified shape's center. A listing of other surface cards and where the entries for their centers are placed is on page 3-13 of the MCNP manual. You can also use a trial and error method to pick an appropriate center point; it is not imperative that this point be the direct center of the cell that you are trying to approximate. This value just needs to be close to the center so that you may optimize the radius of the sphere to leave as little unused space as possible. To plot this geometry using the MCNP geometry plotter included with your software package, you should use the following command line. Geometry plotting commands are explained comprehensively in Appendix B of the MCNP manual.

```
mcnp5 i=(your input filename) ip
```

For this command line, the “i” instructs MCNP to process the indicated input file, and the “p” tells MCNP to plot the geometry. Figures 4-3, 4-4, and 4-5 show the geometry plotter output from running the input file from Figure 4-2. Enter the center coordinates with the command “or 11 3 27” and zoom in.

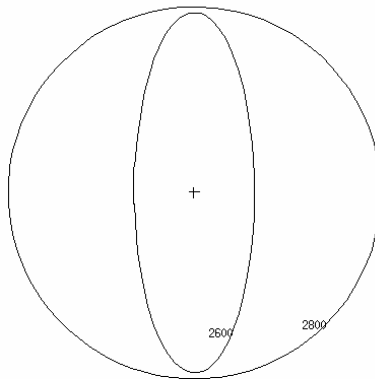


Figure 4-3. YZ view of spleen (2600) and source (2800) cells.

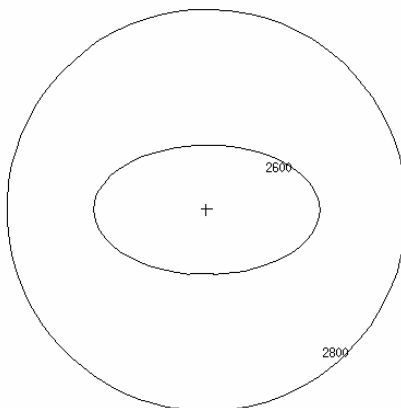


Figure 4-4. XY view of spleen (2600) and source(2800) cells.

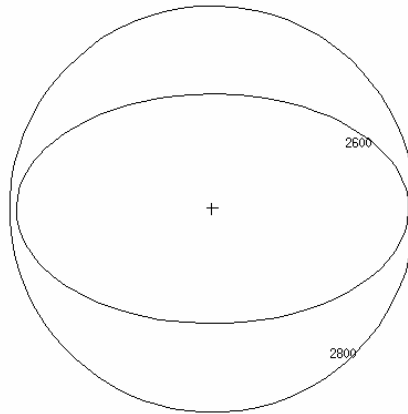


Figure 4-5. ZX view of spleen (2600) and source (2800) cells.

Once you have checked a slice from all three planes through the origin (the slice should be of the largest dimension for an ellipsoid), you can be confident that you have chosen a source volume that fully encompasses your source cell. MCNP does not know, nor will it tell you, if some of the acceptance cell (spleen in this case) is outside the possible sampled positions that have been defined explicitly or through a distribution on the “SDEF” card. This outside portion of the cell may be intended to be part of the source, but MCNP would not create source particles in that region. The next step is to define the “SDEF” card according to this chosen volume and the photon energies of interest. Since SAF values are defined in units of MeV/g of deposited energy per MeV of emitted energy, we will use 1 MeV source particles in order to simplify the tallying process. The “SDEF” card for this problem is shown in Figure 4-6.

```
C Distributed volume source in the spleen
C 1.0 MeV gamma
SDEF cel=2600 pos=11 3 37 erg=1.0 rad=D1
SI1 H 0 6.2
SP1 -21 2
```

Figure 4-6. “SDEF” card for Section 4.

The “cel” parameter indicates that sampled source locations outside cell 2600 will be rejected. The “pos” parameter indicates the center of the sphere that we are using for the rejection technique to place particles in cell 2600. The “erg” parameter indicates that the energy of the source particles is 1.0 MeV. In the absence of an “axs” card, the “rad” keyword specifies a sphere when defining a volume source. The next entry (“rad=D1”) indicates that the radius of the sphere will be designated by distribution 1. The “H” entry on the “SI1” card indicates that the following values are bin boundaries. The values on the “SI1” card indicate that the radius varies from 0 to 6.2 cm. The “SP1” card instructs MCNP to distribute source particles along the radius of the sphere with a power law to the second power, the desired distribution for particles homogeneously distributed within a spherical volume. You may question whether particles will be evenly distributed in the spleen, an ellipsoid, with this set of “SI” and “SP” cards that are based on a sphere. However, since the ellipsoid is fully contained within the sphere, you should be able to convince yourself that, as long as particles are evenly distributed within the encompassing sphere, any piece of that sphere should also have an even distribution of particles. This condition is satisfied for any shape combination that you use to define a

volume source as long as the cell in question is fully encompassed by the shape that you choose to define for the “SDEF” card.

4.6 Tallies and Miscellaneous Data Cards

After defining the source, we must now define the tallied quantities desired for this problem. Since we are interested in the SAF value of MeV/g deposited per MeV emitted for a 1-MeV source, it is most logical to use the “F6” (energy deposition) tally, which gives values in units of MeV/g. We do not need a tally multiplier card in this case since we have used 1-MeV source particles. If you desire SAF values for another gamma energy, then you would need a multiplier card with 1/E (in MeV) as the multiplier. You would also need to change the source energy on the “SDEF” card.

For this problem, we will tally the energy deposition to six different target organs. Table 4-1 shows the cell number (taken from the ORNL MIRD input deck) for the organs of interest for this example.

Table 4-1
Target organs and corresponding MCNP cell numbers

Organ	Cell Number
kidneys	2100
liver	2200
ovaries	2400
pancreas	2500
spleen	2600
thyroid	2900

Using these cell numbers, the tally cards should be formatted as shown below in Figure 4-7.

```

fc6 kidney<--spleen Specific Absorbed Fraction (1/g)
F6:p 2100
fc16 liver<--spleen Specific Absorbed Fraction (1/g)
f16:p 2200
fc26 ovaries<--spleen Specific Absorbed Fraction (1/g)
F26:p 2400
fc36 pancreas<--spleen Specific Absorbed Fraction (1/g)
f36:p 2500
fc46 spleen<--spleen Specific Absorbed Fraction (1/g)
F46:p 2600
fc56 thyroid<--spleen Specific Absorbed Fraction (1/g)
F56:p 2900

```

Figure 4-7. Tally cards for Section 4.

The “fcn” cards featured above in Figure 4-7 represent tally comment cards. Since this problem includes six different tallies, it is wise to include these comment cards for your own benefit when reviewing the output file.

In addition to the tally cards, this example problem requires two additional data cards. These cards are shown below in Figure 4-8. Notice that no importance card is required as in Section 3. This is because the ORNL MIRD phantom input deck places the necessary importance values on the cell definition lines.

```

mode p e
nps 1.2e6

```

Figure 4-8. Section 4 additional data cards.

4.7 Running and Output

To run this problem, you should use the following command line.

```
mcnp5 i=ex4 o=ex4out1 r=ex4r1
```

You may use any input and output file names that you desire as long as the entire command line does not exceed 256 characters in length. It is wise to name your runtime file (indicated by “r=ex4r1”) so that it can be easily located for any particular run. You will need this file if you plan to plot tallies within MCNP or continue an existing run.

Once the calculation is complete, check the output file to see your results. You may need to perform several iterations of this run, increasing the number of particle histories, to achieve the desired relative error values of <5% for each tally. The tallies most likely to have high relative errors are the tallies for the ovaries and thyroid. When organs are very small and/or far from the source organ, particles are less likely to enter these volumes, introducing larger statistical error than for organs that are larger and/or closer to the source organ. If you make a run and decide to run more particles with everything else in the input file left the same, you may perform a continue run. Alternatively, the error can often be reduced without running more particles by employing variance reduction techniques as described beginning on page 2-130 of the MCNP manual. In order to make a continue run to increase the number of particles, you need to create a new input file containing the following two lines.

```
continue  
nps n
```

The parameter “n” should be the new total number of particle histories you would like to run. For example, if you ran 5E5 particle histories and would like to run 2.5E5 more, then “n” for the continue run should be 7.5E5.

After running 9E5 particle histories, MCNP calculated the results displayed in Table 4-2. In this table, the MIRD values are also given for comparison as well as the percent difference of the MCNP values with respect to the MIRD values.

Table 4-2
MCNP SAF results (g^{-1}) for Section 4 compared with MIRD values [7].

Target Organ	MCNP	Relative Error	MIRD	% Difference
kidneys	2.70E-05	0.0026	2.59E-05	4.247
liver	3.51E-06	0.0038	3.53E-06	0.567
ovaries	1.88E-06	0.0377	1.70E-06	10.588
pancreas	5.15E-05	0.0027	5.80E-05	11.207
spleen	4.10E-04	0.0005	4.10E-04	0.005
thyroid	6.26E-07	0.0482	5.68E-07	10.211

4.8 Defining Another Volume Source

This section has already explained the process to use when defining a volume source. However, we will provide one more example to make sure that the methodology for using irregularly-shaped cells as volume sources is clear. For this example, we will describe the “SDEF” definition for using the pancreas as a source organ. Again, we will create a test file to examine the dimensions of the source cell and decide which shape will best approximate the cell for use with MCNP’s rejection technique. The input for a test file of the pancreas geometry is shown below in Figure 4-9.

```

Test file for defining pancreas volume source
C CELL CARDS
C Pancreas
2500 2 -1.04 (-2500 2501 -1905):(-2500 2502 1905) imp:p=1
    vol=90.7
C Sphere for volume source
9000 0 -9001 #2500
C Outside world
9001 0 9001

C SURFACE CARDS
1905    px 3
C Pancreas          (2500)
2500    sq 0.003906 0.694444 0.091827 0 0 0 -1 -1 0 37
2501    px -1
2502    pz 37
C Cylinder for volume source
9001 RCC -3 0 37 18.5 0 0 10

nps 1000

```

Figure 4-9. Test input file for defining pancreas volume source.

After examining the cell shape for the pancreas, a cylinder seems to be the best shape to approximate this irregularly-shaped cell. Through trial and error, an extent of 10 cm and a radius of 18.5 cm were chosen to fully encompass this cell. Figure 4-10 shows a few slices of this geometry from the MCNP geometry plotter. The trial and error plotting method described in this section and in section 3.5 is useful for determining the shape and dimensions for defining any volume source.

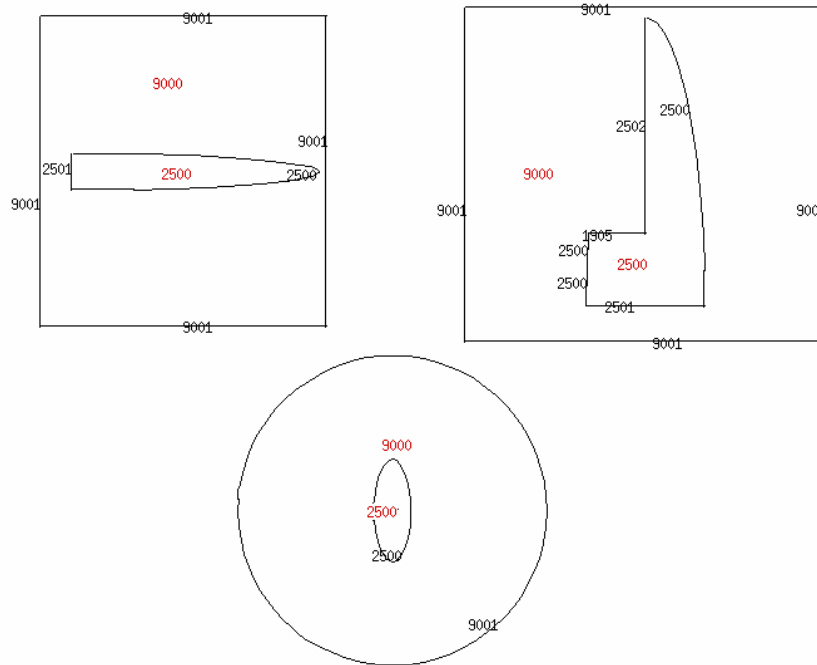


Figure 4-10. Slices through the XY (top left), ZX (top right), and YZ (bottom) planes for the pancreas source test geometry.

4.9 Finding and Correcting Geometry Errors

When using a ready-made geometry input deck or your own, you may often overlook errors in the geometry specification. When this occurs, MCNP may lose particles at the points in the geometry that are incorrectly defined. It is a good idea to test the geometry you are using by running particles distributed throughout the geometry with all materials voided. This minimizes run time since particles will not interact with any material, increasing the chance that a particle will attempt to travel through an area that contains a geometry error. In order to do this, you need to add a void card to your input file by simply typing “void” at the end of the file. Run a large number of particles by typing “1e6” or “1e7” as the “n” value for your “nps” card. Do this using the ORNL

MIRD phantom geometry, and search the output file for “lost particles”. For this example, you will see that MCNP loses 3 particles out of 1e6. MCNP creates an event log in the output file for each lost particle. By looking at the event log for the first lost particle, you will see that this photon reached cell 3500 before MCNP lost track of the photon. The event log also gives the x, y, and z coordinates of the photon’s last location. For this example, the coordinates are:

x:	0.406
y:	3.054
z:	42.002

Since the particle was lost by MCNP at this point, you should be able to locate an error at this point in the geometry. To see this error, you should first plot the geometry and change the origin to the x,y,z coordinates stated above. Next, change the basis so that the particles trajectory is coincident with the horizontal axis of the plotter. In the data window of the plotter you should type “basis -0.43 0.56 0.71 0 0 1” to change the axis for this problem. The first three entries of the basis command represent the u,v,w direction cosines given in the lost particle history of the output file. These entries set the horizontal basis. The last three entries set the vertical basis and are arbitrary for this problem. You may have to zoom in on this location if the error is a small overlap in cells or surfaces. Zoom in on the plotter screen until you can clearly see the error, retyping the origin coordinates as necessary. When this location is plotted in the MCNP geometry plotter, an error is found as shown in Figure 4-11. The “+” symbol in the figure indicates the point in space where the first particle was lost (0.406, 3.054, 42.002). The horizontal axis of the plot shows the direction that the particle was traveling at the time it was lost.

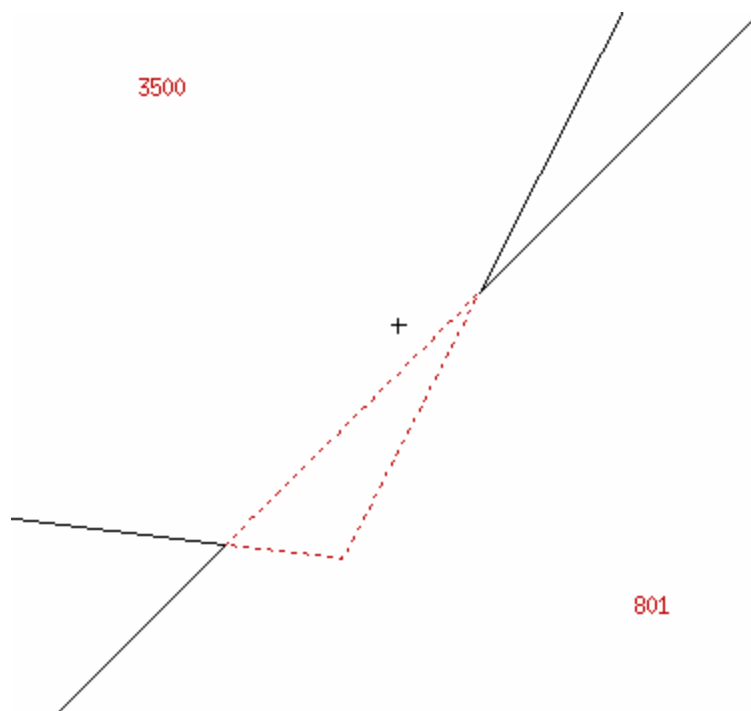


Figure 4-11. MCNP geometry plotter view of ORNL MIRD geometry error.

If you look through the ORNL MIRD input file, you can deduce that the error involves an overlap of the esophagus (cell 3500) with the mid part of the spine (cell 801). This error can be repaired by adding surface 802 as a bounding plane for cell 3500. In the input file, surface 802 is defined as an ellipsoid. Surface 802 should be added to the cell 3500 cell definition as shown below in Figure 4-12.

```
3500 2 -1.04 (-3500 3501 2202 -102):(-3503 3504 -3505 802)
```

Figure 4-12. New cell definition for cell 3500.

When surface 802 is added to the cell 3500 definition, effectively removing the overlap of cell 801 with cell 3500, the geometry error is fixed as shown in Figure 4-13.

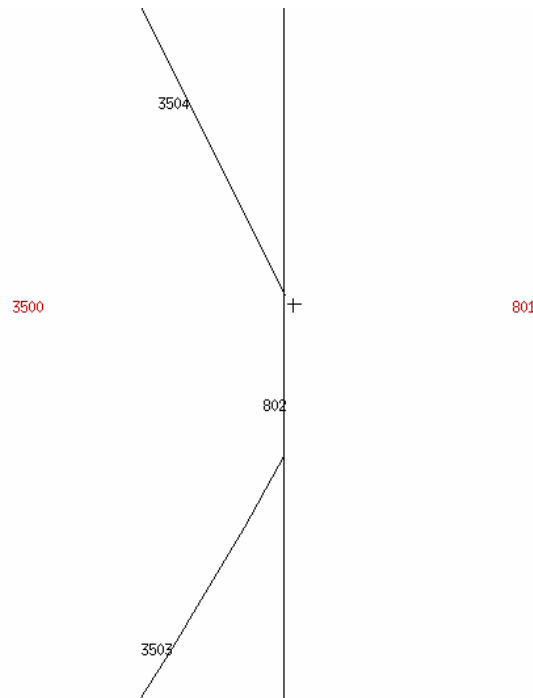


Figure 4-13. Repaired ORNL MIRD geometry error.

4.10 Summary

This section described how to use the ORNL MIRD phantom input deck to calculate SAF values for six target organs with two independent source organs. These two example problems utilized the F6 energy deposition tally for each of the six tally cells. The source definition section of this section illustrated how to define volume sources for

irregularly-shaped cells. Finally, a geometry error was introduced into the problem, and instructions were given on how to isolate and correct this problem.

5. X-RAY PHOTOTHERAPY

5.1 Overview

This example utilizes an analytical Snyder head phantom to analyze the effectiveness of x-ray phototherapy for delivering dose to a brain tumor. X-ray phototherapy describes the technique of loading a tumor with material of high atomic number and irradiating it with kilovoltage x-rays. Conventional iodine and gadolinium contrast agents are ideal candidates for this process [8]. The large photoelectric cross section of this high-Z material will produce secondary radiations such as photoelectrons, Auger cascades, and characteristic x-rays that are high in linear energy transfer (LET). These radiations enhance the localized dose distribution and minimize the dose to healthy tissue.

5.2 What You Will Be Able to Do

- 1) Use the analytical Snyder head phantom with an explicit tumor for calculating tumor energy fluence from an external x-ray beam.
- 2) Define a degenerate cylindrical source to model a beam.
- 3) Use the F8 (pulse height) tally to evaluate photon energy deposition spectra within the tumor.

5.3 Problem Description

This problem will illustrate a method for analyzing the effectiveness of x-ray phototherapy for maximizing the dose delivered to a brain tumor. For this example, we will add gadolinium to the tumor as a contrast agent. Using the “F8” (pulse height) tally, you will be able to analyze the photon energy spectra that result from differing concentrations of gadolinium in the tumor.

5.4 Geometry

This example will utilize the analytical Snyder head phantom input deck included available through the MCNP website. This phantom is composed of three ellipsoids and a sphere comprising the tumor at the center of the concentric ellipsoids. The equations used to create the surface cards for these ellipsoids are shown below.

$$\text{Brain: } \left(\frac{x}{6}\right)^2 + \left(\frac{y}{9}\right)^2 + \left(\frac{z-1}{6.5}\right)^2 = 1 \quad \text{Equation 4.1}$$

$$\text{Skull: } \left(\frac{x}{6.8}\right)^2 + \left(\frac{y}{9.8}\right)^2 + \left(\frac{z}{8.3}\right)^2 = 1 \quad \text{Equation 4.2}$$

$$\text{Skin: } \left(\frac{x}{7.3}\right)^2 + \left(\frac{y}{10.3}\right)^2 + \left(\frac{z}{8.8}\right)^2 = 1 \quad \text{Equation 4.3}$$

The tumor at the center of the head is described by a sphere at the origin with a radius of 2.54 cm. The explicit inclusion of the tumor in the model allows the brain and tumor to have different materials and, therefore, different concentrations of Gd contrast agent.

5.5 Materials

The materials that compose the Snyder head phantom in this problem are the ICRU Publication 46 materials for adult whole brain, adult whole cranium, and adult skin [9]. The ZAID values for the different materials and their corresponding weight fractions (indicated by negative values on each material card) are given in the Table 5-1 below.

Table 5-1
ICRU 46 material specifications [8]

Adult Whole Brain		Whole Cranium		Adult Skin	
ZAID	Weight Fraction	ZAID	Weight Fraction	ZAID	Weight Fraction
1001	0.107	1001	0.050	1001	0.100
6000	0.145	6000	0.212	6000	0.204
7014	0.022	7014	0.040	7014	0.043
8016	0.712	8016	0.435	8016	0.645
11023	0.002	11023	0.001	11023	0.002
15031	0.004	12000	0.002	15031	0.001
16000	0.002	15031	0.081	16000	0.002
17000	0.003	16000	0.003	17000	0.003
19000	0.003	20000	0.176	19000	0.001

This problem utilizes gadolinium as the contrast material for the x-ray phototherapy process. For illustrative purposes, four runs were performed with this input file, one with no gadolinium in the tumor mass and three with varying weight fractions of gadolinium in the tumor tissue.

5.6 Source Definition

In x-ray phototherapy, a tumor doped with a contrast agent is irradiated by a beam of kilovoltage x-rays. One way to define a beam with MCNP is using a degenerate cylindrical source, represented by a cylinder with no extent. The beam for this problem was placed along the z-axis at $z=15$. For this example, a beam of x-rays from a palladium-100 source was chosen. Table 5-2 shows the x-ray energies and relative intensities for the palladium-100 x-rays.

Table 5-2
Palladium-100 x-ray energies and relative intensities

Energy (keV)	Relative Intensity
32.66	4.90
42.08	13.50
53.52	0.08
61.60	0.51
72.52	0.15
74.78	92.00
84.00	100.00
86.37	0.05
119.18	0.13
126.15	15.00
139.92	0.35
151.88	0.61
154.00	0.06
158.87	3.20

The source definition for this degenerate cylinder creating a beam of palladium-100 x-rays with discrete energies and intensities is shown below in Figure 5-1.


```

SDEF pos=0 0 15 vec=0 0 -1 axs=0 0 -1 ext=0 dir=1
      ara=78.53982 rad=d1 erg=d2
SI1  0 5
SP1  -21 1
SI2  L 0.03266
      0.04208
      0.05352
      0.06160
      0.07252
      0.07478
      0.08400
      0.08637
      0.11918
      0.12615
      0.13992
      0.15188
      0.15400
      0.15887
SP2  4.90
      13.50
      0.08
      0.51
      0.15
      92.00
      100.00
      0.05
      0.13
      15.00
      0.35
      0.61
      0.06
      3.20

```

Figure 5-1. “SDEF” card for Section 5 input file.

As described earlier, the center of the beam has been placed at “0 0 15,” as indicated by the “pos” values on the “SDEF” card. The “vec” and “axs” commands describe the direction of the beam relative to the z-axis. As mentioned above, the “ext” for a degenerate cylinder is 0. The area variable, “ara,” is required only for direct contributions to a point detector from a planar surface source. As described in previous sections, the “rad” variable specifies the radius of the surface or volume source. In this case, the radius of the degenerate cylinder varies from 0 to 5. The “SP1” card indicates

that source particles will be distributed along the radius of the disc with a power law to the first power, the desired distribution for particles within a circular surface source. While MCNP is able to calculate the bremsstrahlung photon production in the x-ray tube target, this process would require a lengthy calculation. For this case, we will explicitly model the photon source on the “SDEF” card. For this beam source, the discrete gamma energies emitted are indicated by the “erg” variable and are shown in distribution 2. The “L” on the “SI2” card indicates that the following values are discrete and occur with the respective probabilities given on the “SP2” card.

5.7 Tallies and Miscellaneous Data Cards

In order to analyze the energy deposition spectra for this example, we will use the “*F8” pulse height tally. The tally card for the “*F8” tally used in this problem is shown in Figure 5-2 along with the energy distribution card.

```
*F8:p,e 101  
e8 1e-10 100i 0.2
```

Figure 5-2. Pulse height tally and energy distribution cards for Section 5.

The “e8” card shown in Figure 5-2 specifies 101 energy bins ranging from 1e-10 MeV to 0.2 MeV. Although the lower limit of electron and photon transport in MCNP is 1 keV, the code can calculate energy deposition in far smaller increments.

In addition to the tally and energy distribution cards, this example problem requires a “mode” and an “nps” card. We will also use a “phys” card to turn off Doppler energy broadening for this MCNP run. This problem also requires photon and electron importances, specified by the “imp” card. All of these data cards are shown in Figure 5-3.

```

mode p e
phys:p 1j 0 0 1j 1
imp:p 1 1 1 1 1 0
imp:e 1 1 1 1 1 0

```

Figure 5-3. Additional data cards for Section 5.

5.8 Running and Output

To run this problem, use the following command line:

```
mcnp5 i=ex5 o=ex5out1 r=ex5r1
```

Any input and output names that you desire can be used as long as the entire command line is no more than 256 characters long. It is wise to name your runtpe file (indicated by “r=ex4r1”) so that it can be easily located for a particular run. Please follow the guidelines described in previous examples for locating and checking the statistical validity of the tally results.

The data from the output files for this example have been pasted into Excel for conversion into graphical form. A plot made from this data is shown in Figure 5-4. This figure illustrates that the 101-bin energy resolution was sufficient for showing the major

characteristics of the palladium-100 x-ray energy spectrum used for the tumor irradiation in this problem. The major features of this spectrum have been denoted on the plot. The shift in the energy spectrum is apparent as the gadolinium concentration in the tumor was increased. As expected, an increase in gadolinium content shifted the energy deposition spectrum of the x-rays toward higher energies.

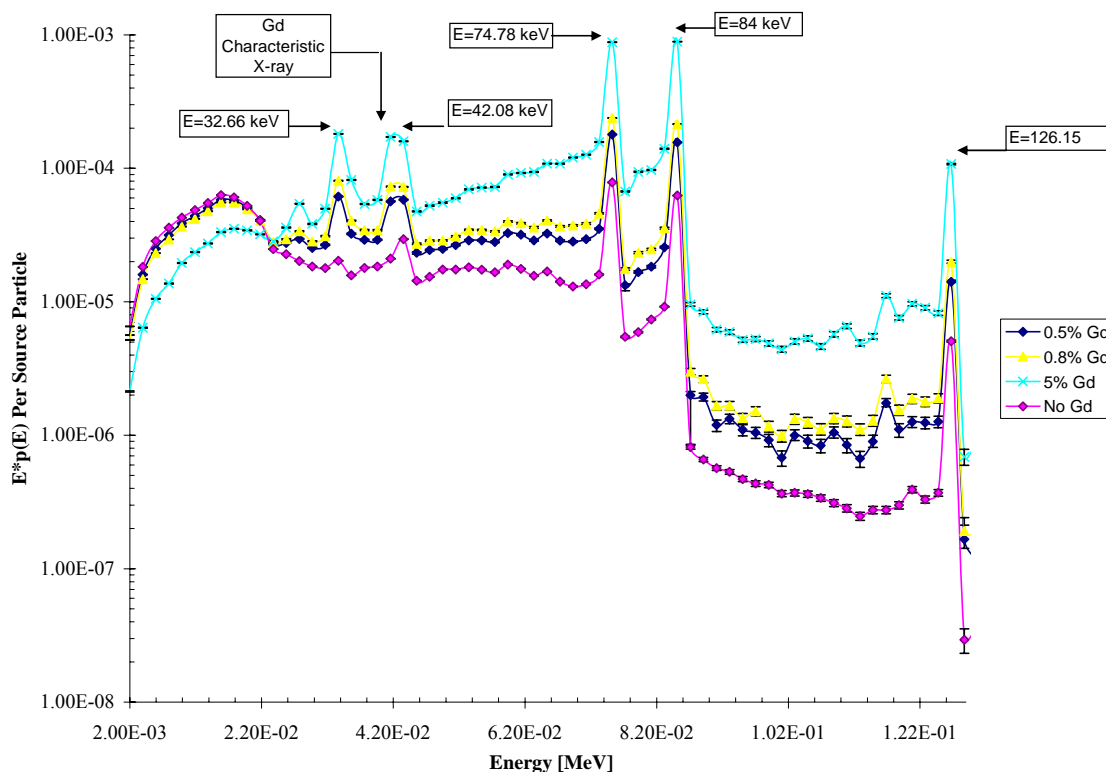


Figure 5-4. Energy deposition spectra in the tumor with with varying Gd concentrations.

5.9 Summary

This section described a method for using MCNP to create energy deposition spectra for x-ray phototherapy of a brain tumor using palladium-100 x-rays and

gadolinium contrast material. The Snyder head phantom was used with an added tumor to calculate the above results. As expected, the energy deposition spectra were shifted toward higher energies as the concentration of gadolinium in the tumor was increased.

6. PROSTATE BRACHYTHERAPY

6.1 What You Will Be Able to Do

- 1) Add an organ to the ORNL MIRD phantom.
- 2) Define multiple point sources to model ^{125}I brachytherapy seeds.
- 3) Void a portion of the problem geometry to remove the scattering contribution from a particular region.
- 4) Calculate the absorbed dose per particle transformation in key organs.

6.2 Problem Description

Brachytherapy has been an effective procedure for killing cancer cells in the process and for preventing recurring tumors. In prostate brachytherapy, radioactive seeds are permanently placed in the prostate gland. The nuclei in these seeds decay by electron capture and, as a result, emit photons. For this example, we will be using 98 iodine-125 brachytherapy seeds, each with an activity of 0.6 mCi. Iodine-125 has a half life of 59.4 days and emits a gamma ray with an energy of 35.49 keV. A common question for evaluating the dose effectiveness of this type of procedure is whether it is necessary to include any scatter component that may contribute to the doses in key organs. Therefore, for this example, we will calculate organ doses with and without a scattering component from the legs of the phantom. The critical organs considered for this problem are the: small intestine, descending colon wall, descending colon contents, sigmoid colon wall,

sigmoid colon contents, testes, urinary bladder wall, urinary bladder contents, and prostate.

6.3 Geometry

As mentioned above, the ORNL MIRD phantom will be used as the geometry basis for this example. However, this phantom does not include the prostate that we need to use as the source organ for this problem. Therefore, we will need to add an analytical prostate to this phantom. For this example, the prostate was modeled as a sphere of radius 2.2 cm set just under the urinary bladder and centered at (0, -6.0025, 2.505). A lateral view of the pelvis of the phantom cut at $x=1$ is shown in Figure 6-1 and illustrates the relative position of the prostate with respect to the urinary bladder and male genitalia.

The aim of this problem is to illustrate whether the scattering contribution from the legs of the phantom appreciably affects the dose to key organs. Therefore, the ORNL MIRD phantom has to be modified in order to remove any possibility of scatter from the legs. This method simulates the use of a torso and pelvic CT scan rather than a whole-body scan. In order to remove the contribution from the legs, the material number and density indicated on the cell cards that comprise the legs were removed and replaced with zeros. This voids the leg material so that MCNP will transport particles as if the legs do not exist on the phantom. This voiding process was performed on the cell cards for the legs, leg bones, and leg skin. Alternatively, the leg regions could have been voided using the "VOID" card. Anterior and side cross sections of the ORNL MIRD phantom illustrating this new feature are shown in Figure 6-2.

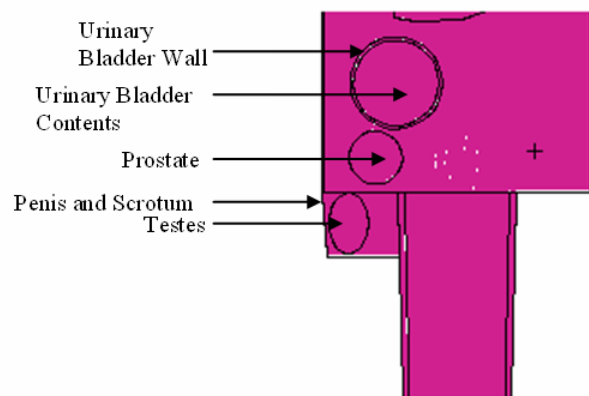


Figure 6-1. Lateral view of the ORNL MIRD pelvis with added prostate organ.

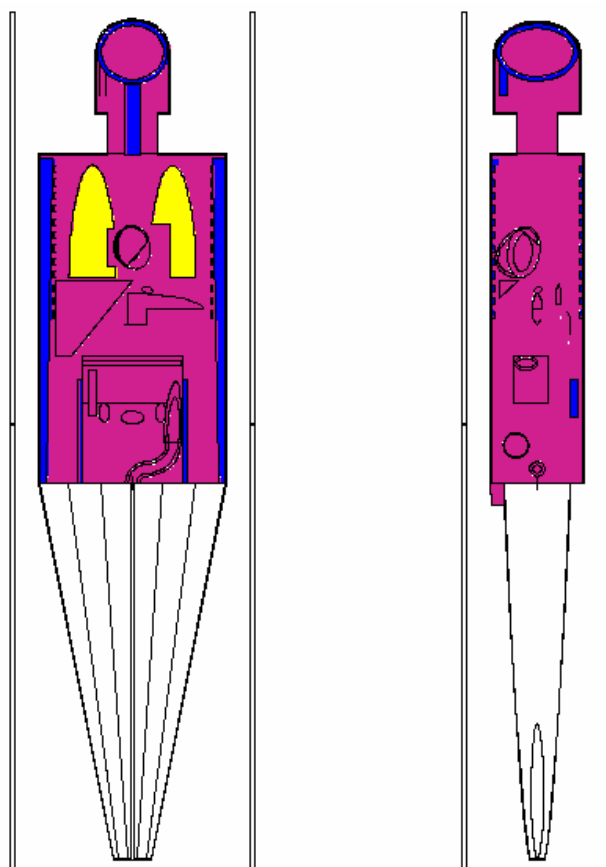


Figure 6-2. Anterior and side cross sections of the ORNL MIRD phantom with voided legs, leg bones, and leg skin.

6.4 Materials

As in Section 4, the materials for this phantom are defined in the ORNL MIRD input deck. The various tissues that make up the phantom include soft tissue, bone, and lung material. When adding the prostate to this phantom, it was assigned a soft tissue material card.

6.5 Source Definition

As mentioned in the Problem Description, the source for this example consists of 99 ^{125}I brachytherapy seeds, which emit gamma rays with energy 35.49 keV. These 98 seeds were defined as point sources and placed at various locations in the prostate, avoiding the central region of the prostate gland so that they are external to the prostatic urethra that goes through the center of the gland. Alternatively, a model of the small stainless steel seeds could be added to the geometry, even if they are fractions of a millimeter in radius and length. The exact locations of the ^{125}I seeds can be viewed in the input file for Example 5 in Appendix A. A portion of the “SDEF” card for this problem is shown in Figure 6-3.

```

sdef erg=.03549 par= 2 pos=d1

SI1 L  0 -5.5025 4.305
      0 -5.0025 4.305
      -.5 -6.0025 4.305
      -.5 -5.5025 4.305
      -.5 -5.0025 4.305
      .5 -5.0025 4.305
      .5 -5.0025 4.305
      .5 -5.0025 4.305
      . . . . .
      .5 -6.0025 1.805
      .5 -5.5025 1.805
      .5 -5.0025 1.805
      1.5 -6.0025 1.805
      1.5 -5.5025 1.805
SP1 D  1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1

```

Figure 6-3. A portion of the “SDEF” card for Section 6, showing 13 of the 98 position definitions and the complete “SP1” card.

6.6 Tallies and Miscellaneous Data Cards

The “*F8” tally was used to calculate the energy deposited in each organ of interest due to both photon and electron interactions. An example of the “*F8” tally and a corresponding tally comment card are shown in Figure 6-4.

```
*f18:p,e 1700
fc18 Energy deposition (MeV/trans) for small intestine
```

Figure 6-4. Section 6 tally and comment cards for energy deposition in the small intestine.

In addition to tally and comment cards for each critical organ, other data cards were used in this input file as shown in Figure 6-5.

```
mode p e
phys:p,e 1j 0 0 1j 1
nps 1000000
```

Figure 6-5. Additional data cards used in the Section 6 input file.

The “mode” card dictates which types of particles will be transported in this problem, photons and electrons in this case. The “phys” card is used in this example to turn off Doppler energy broadening for this MCNP run. Doppler broadening was turned off to avoid an infinite loop in MCNP5_RSICC_1.30. Previous and future versions have had this bug corrected and do not need this workaround. Further information about the “phys” card can be found in the MCNP Manual on page 3-125. As mentioned previously, the “nps” card specifies the number of particle histories to run.

6.7 Running and Output

The following command line can be used to run this problem.

```
mcnp5 i=ex6 o=ex6out1 r=ex6r1
```

As always, you may use any input and output file names that you choose, as long as the entire command line does not exceed 256 characters in length. Naming the runtime file (indicated by “r=ex6r1”) is useful so that it can be easily located for a particular run if continuation of that run is desired at a later time. You may also need this file if you plan to plot tallies with MCNP.

Once the run is complete, check the output file to find the results of the run. It may be necessary to continue this run to more particle histories in order to achieve the desired relative error values of <5% for each run. The process for continuing a run is described in Section 3 of this primer. It is also wise to make sure that your tallies pass all ten statistical checks implemented into MCNP. After running 1E6 particles for each input file, one including the leg scattered component and one with the leg region voided, both runs yielded tally values with less than 5% relative error for all organs of interest. All tallies passed the ten statistical checks except for the check on mean behavior for the tallies on the descending colon contents. For each of these tallies, the mean behavior is increasing rather than the desired random behavior. Since the relative errors are 4.35% and 4.39% for the runs with and without leg scattering, respectively, it would be wise to

run more particle histories to lower the relative error and to obtain a random mean value over the course of the run.

6.8 Results

The tallied quantities in this problem give results for the absorbed energy per transformation for each critical organ at the time when the brachytherapy seed were implanted. However, these nuclides will continue to decay until they are no longer radioactive. Therefore, you must calculate the total number of transformations that will occur in the brachytherapy seeds over the mean lifetime of the radionuclide. This mean lifetime (τ) is represented by the reciprocal of the decay constant (λ) as represented in Equation 6.1.

$$\tau = \frac{1}{\lambda} \quad \text{Equation 6.1}$$

The total number of transformations (U_s) can be determined using Equation 6.2 below.

$$U_s = A_0 \tau = \frac{A_0}{\lambda} \quad \text{Equation 6.2}$$

where A_0 = initial activity in Bq.

Once the total number of transformations has been determined, the total dose to the organs can be calculated by multiplying the tally results in Mev/trans by the total number of transformations and dividing by the mass of the organ. Since the ORNL MIRD phantom input deck includes organ volumes and tissue densities, the mass of each

organ can be easily determined. As mentioned in the Problem Description, each brachytherapy seed has an activity of 0.35 mCi, yielding a total activity of 34.65 mCi (1.2821E9 Bq). The results for energy deposition per particle transformation and lifetime dose to each organ are shown in Tables 6-1 and 6-2.

Table 6-1
Calculated results for input file accounting for leg scatter

Organ	Density (g/cc)	Volume (cc)	Absorbed Energy per Transformation (Mev/trans)	Absorbed Dose per Transformation (Gy/trans)	Total Number of Transformations	Lifetime Dose (Gy)	Relative Error
Small Intestine	1.04	1060	2.89E-05	4.20E-18	1.63E+15	6.84E-03	0.033
Descending Colon Wall	1.04	89.9	1.34E-05	2.30E-17	1.63E+15	3.74E-02	0.047
Descending Colon Contents	1.04	102	1.60E-05	2.42E-17	1.63E+15	3.94E-02	0.044
Sigmoid Colon Wall	1.04	70.4	3.03E-04	6.62E-16	1.63E+15	1.08	0.010
Sigmoid Colon Contents	1.04	35.6	1.47E-04	6.38E-16	1.63E+15	1.04	0.014
Testes	1.04	37.6	3.55E-04	1.45E-15	1.63E+15	2.37	0.009
Urinary Bladder Wall	1.04	45.7	2.49E-04	8.40E-16	1.63E+15	1.37	0.011
Urinary Bladder Contents	1.04	203	1.00E-03	7.59E-16	1.63E+15	1.24	0.006
Prostate	1.04	15.2	6.43E-03	6.52E-14	1.63E+15	106.04	0.002

Table 6-2
Calculated results for input file with legs voided

Organ	Density (g/cc)	Volume (cc)	Absorbed Energy per Transformation (Mev/trans)	Absorbed Dose per Transformation (Gy/trans)	Total Number of Transformations	Lifetime Dose (Gy)	Relative Error
Small Intestine	1.04	1060	2.85E-05	4.14E-18	1.63E+15	6.73E-03	0.033
Descending Colon Wall	1.04	89.9	1.32E-05	2.27E-17	1.63E+15	3.69E-02	0.047
Descending Colon Contents	1.04	102	1.58E-05	2.38E-17	1.63E+15	3.87E-02	0.044
Sigmoid Colon Wall	1.04	70.4	2.80E-04	6.12E-16	1.63E+15	1.00	0.010
Sigmoid Colon Contents	1.04	35.6	1.37E-04	5.93E-16	1.63E+15	0.96	0.015
Testes	1.04	37.6	3.28E-04	1.34E-15	1.63E+15	2.19	0.010
Urinary Bladder Wall	1.04	45.7	2.46E-04	8.28E-16	1.63E+15	1.35	0.011
Urinary Bladder Contents	1.04	203	9.86E-04	7.48E-16	1.63E+15	1.22	0.006
Prostate	1.04	15.2	6.40E-03	6.48E-14	1.63E+15	105.50	0.002

Tables 6-1 and 6-2 indicated lifetime doses to the prostate in excess of 100 Gy. Doses to the prostate in this range are expected from a brachytherapy procedure of this nature. The percent difference between the two values of lifetime dose calculated for this problem are shown in Table 6-3.

Table 6-3

Values given by organ for the percent difference between the lifetime dose when tallying with the legs intact and with the legs voided

Organ	Percent Difference
Small Intestine	1.49
Descending Colon Wall	1.42
Descending Colon Contents	1.61
Sigmoid Colon Wall	7.64
Sigmoid Colon Contents	7.09
Testes	7.62
Urinary Bladder Wall	1.53
Urinary Bladder Contents	1.42
Prostate	0.51

These results show that there can be a significant difference between the dose quantities calculated for both cases discussed in the example, as evidenced by several percent differences that greatly exceed the margin of error of the calculation. This difference was especially significant for the sigmoid colon wall, sigmoid colon contents, and testes, three organs that are close in proximity to the leg region. As expected, little difference occurred between the two results for the prostate itself as well as the urinary bladder wall and contents. These results show that particles directed toward the legs that fail to interact in these organs are unlikely to scatter in the legs and make it back to

interact in this region. A negligible difference also occurs for the small intestine, an organ reasonably far from the leg region. Any particles scattering from the legs that are directed toward the small intestine are unlikely to traverse enough medium to deposit significant energy in this organ.

6.9 Summary

This section described a method for determining whether the scattering contribution for the legs can appreciably affect dose calculations for organs in the pelvic region. However, the small intestine, prostate, urinary bladder wall, and urinary bladder contents are virtually unaffected by leg scatter. The problem discussed here utilized the ORNL MIRD phantom with an added prostate gland to calculate the above results. It was determined that this scattering contribution can alter the dose calculations in significant excess of the relative error for the sigmoid colon wall, sigmoid colon contents, and testes tally calculations.

7. ZUBAL HEAD RADIOGRAPH

7.1 What You Will Be Able to Do

- 1) Use a source card to create a left lateral photon beam irradiation of the Zubal head phantom.
- 2) Create a radiography (“FIR”) tally.
- 3) Use the MCNP tally plotter (“MC PLOT”) to create a radiograph image based on flux tallies.
- 4) Understand how the MCNP lattice feature can be used to represent patient-specific geometries.

7.2 Problem Description

This example problem utilizes the Zubal head phantom to illustrate the methodology for creating a radiograph using the MCNP radiography tallies. The Zubal head phantom is a voxelized phantom of a human head generated from a CT scan created by Jeff Evans from the Department of Mechanical Engineering at The Ohio State University [10]. The neck and jaw of the phantom are modeled analytically. Sagittal and transverse slices of the Zubal head phantom as generated by the MCNP plotter are shown in Figure 7-1. This example will describe how to use the radiography (“FIR”) tally in MCNP to image an input geometry.

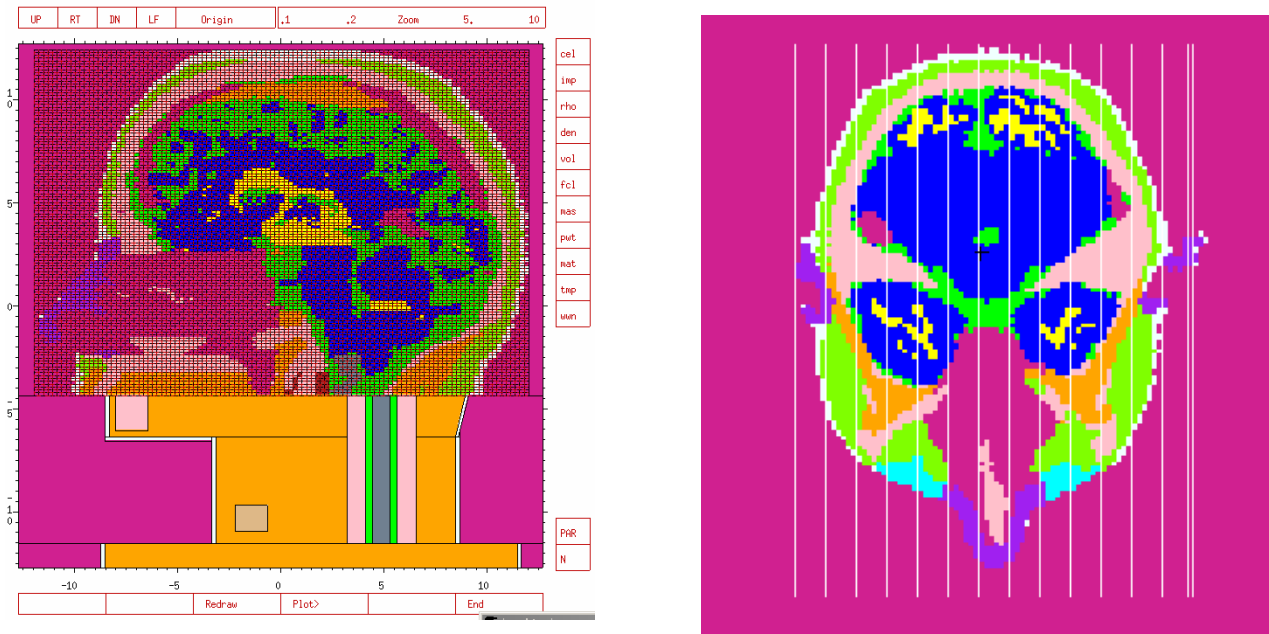


Figure 7-1. Sagittal/YZ (left) and transverse/XY (right) slices of the Zubal head phantom. Each color represents a different tissue type.

7.3 Geometry

As mentioned above, the Zubal head phantom will be used as the geometry basis for this example. As with use of the ORNL MIRD phantom, this problem utilizes a ready-made input deck for the geometry specification; therefore, we do not need to write any cell or surface cards for this example. See the warnings for using ready made public input decks in Section 4. The Zubal head phantom is composed of $85 \times 109 \times 120$ voxels, each of dimensions $2.2 \times 2.2 \times 1.4$ mm. The most negative corner element of the lattice for all directions is placed at $(-8.91, -13.42, 77.2)$ in the MCNP geometry. The phantom consists of 15 materials and is segmented to facilitate running up to 29 critical head structure tallies. The data card input deck for this phantom geometry is given in

Appendix A. The full input deck is available in the Zupal_Phantom sub-directory in the Medical Physics directory of the Sample Problems distributed with the MCNP5 executable from RSICC. It is also available at <http://mcnp.lanl.gov>.

7.4 Introduction to Lattice Geometries

Lattice geometries are quite useful for medical physics applications. Creation of a lattice in an MCNP input deck establishes a regular grid within the problem geometry. Each grid location is referred to as an individual “voxel” and is typically (in medical physics applications) a single homogenized material. Specifying “LAT=1” on the cell card means that the lattice is made of hexahedra, or solids with six faces. This is the case with the Zupal head phantom. “LAT=2” specifies a lattice composed of hexagonal prisms, solids with 8 faces. After designing the lattice, you must decide which element is the (0,0,0) element and in which directions the three lattice indices will increase. Constraints for these choices are explained on page 3-29 of the MCNP manual. The bounding surfaces of the (0,0,0) element should then be entered on the cell card with the “LAT” keyword in the right order. For a hexahedral lattice cell, such as in the Zupal head phantom input deck, the surfaces should be listed such that the (1,0,0) element is beyond the first surface listed, the (-1,0,0) element is beyond the second surface listed, then the (0,1,0), (0,-1,0), (0,0,1), and (0,0,-1) lattice elements in that order, for a total of six surfaces. The listing of these surfaces fully defines the lattice arrangement to MCNP so that the code will understand the placement of particular elements when specified. Surface specifications for hexagonal prism lattices are listed on page 3-29 of the MCNP

manual. If a universe, “U,” card is used on the cell description, the lattice must be the only thing in its universe. See page 3-27 of the MCNP manual for more on universes.

The “FILL” card is perhaps the most useful portion of the lattice specification for medical physics purposes. Non-zero entries on the “FILL” card indicate the numbers of the universes that fill the corresponding cell. When the filled cell is a lattice, the “FILL” specification can be a single entry or an array. The Zubal head phantom input deck uses an array specification. With an array specification, the portion of the lattice covered by the “FILL” array is explicitly defined, and the rest of the lattice does not exist. For the single entry case on the “FILL” card, every element in the lattice is filled by the same universe. The array specification will be most common for use with medical physics problems because it allows easy access to definitions of multiple organs and/or material types. The fill card should first be defined by dimension declarators defining the ranges of the three lattice indices. For example, “FILL=0:1 1:2 0:1” defines a 2x2x2 lattice with 8 possible elements to fill. After this fill definition, the array elements must be defined. The value of each array element (voxel) is the number of the universe that is to fill the corresponding lattice element. A “0” indicates that the corresponding element does not exist. Giving the array value the same universe number that the lattice cell has gives that voxel the material and density specified on the cell card for the lattice cell. An entry of “#r” indicates that the previous entry should be repeated “#” times and is a convenient shorthand for making large lattices that have little variation. More options for filling array elements can be found on page 3-30 of the MCNP manual.

Once the lattice has been created and all voxels in the problem have been categorized according to universe, tallying over particular materials and/or parts of the

body becomes a straightforward process. Likewise, a user who understands the lattice and array element placement conventions described above can easily interpret lattice geometries created by other researchers.

7.5 Materials

The materials for this example are also defined in the Zubal head phantom input deck. The anatomical features modeled by this phantom are constructed of grey brain matter [11], white brain matter [11], cerebrospinal fluid [11], eyes [11], eye lens [11], skeletal muscle [9], cranium [9], cartilage [9], spongiosa [9], spinal chord [9], adult skin [9], adult thyroid [9], and adult #2 adipose tissue [9]. Each of these materials is defined on the “mn” cards in the input deck using weight fractions (indicated by negative values on each material card). Each material in the input deck corresponds to particular cells and universes in the lattice, allowing for straightforward construction of tallies over individual tissues.

7.6 Source Definition

In order to create a radiograph of the Zubal head model, we will specify a beam of 30-MeV photons approximately 15 cm from the left surface of the head. As mentioned in the x-ray phototherapy example of Section 5, a beam can be defined in MCNP using a degenerate cylindrical source, represented by a cylinder with no extent. The photon beam for this problem was placed at the X,Y,Z coordinates “24 0 84” and directed toward the left lateral side (-x direction) of the Zubal head. For this example, a beam of 30-MeV photons was chosen. The source definition for this degenerate cylinder creating a beam of 30-MeV photons is shown below in Figure 7-2.

```

c   Left lateral irradiation w/ source plane located 5 cm from skin
c   surface
sdef erg=30 dir=d3 vec=-1 0 0 pos=24 0 84 rad=d2 ara=1134.115 ext=0
    axs=-1 0 0
si2 h 0 19          $ radial extent over disk source, in cm
sp2 -21 1          $ disk source equiprobable over area
si3 h 0.99999 1.0 $ angular distribution required with notran card
sp3 0              1.0 $ one angular bin, uniform distribution in that bin

```

Figure 7-2. “SDEF” card for Section 7 input file.

As described earlier, the center of the beam has been placed at “24 0 84,” as indicated by the “pos” values on the “SDEF” card. The “vec” command indicates that the source particles are directed in the negative x direction. The “axs” command is required for cylindrical sources and indicates that the axis of the cylindrical source lies in the negative x direction. The “dir” command defines μ , the cosine of the angle between the reference vector (“VEC”) and the direction of flight for the source particles (see page

3-53 of the MCNP manual for more information). A distribution (“SI3”) is indicated for this parameter, as required for use of the “notrn” card that will be discussed later in this section. For this case, the angular distribution is forward-directed with all of the particles directed between $0.99999 < \mu < 1.0$. This range of μ was calculated such that any source particle would have about one radiograph spatial bin’s width as its maximum deflection at the tally grid. The “ext” for a degenerate cylinder is “0.” The area variable, “ara,” is required only for direct contributions to a point detector from a planar surface source. As described in Section 3, the “rad” variable specifies the radius in centimeters of the surface or volume source. In this case, the radius of the degenerate cylinder varies from 0 to 19 cm. The “-21 1” entry on the “SP1” card indicates that source particles will be distributed along the radius of the disc with a power law to the first power, the desired distribution for particles uniform in area within a homogenous circular surface source. The “erg” variable indicates the energy of the photons in the beam, 30 MeV in this case.

7.7 Tallies and Miscellaneous Data Cards

The “FIR” tally was used for this problem to establish a flux image on a rectangular radiograph grid. This tally uses an array of point detectors to measure flux at various points on a grid. When this grid is placed on the opposite side of the problem geometry from the source, variances in the measured flux paired with a color spectrum can create an image similar to the common x-ray radiograph. The radiograph tally in conjunction with the MCNP plotting features discussed later in this section create such an

image and can be quite useful in medical physics problems. The cards necessary for this tally are shown in Figure 7-3.

```
FIR5:p -80 0 84 0 25 0 84 0 0 0 $ radiograph tally
FS5 -20 200i 20 $ radiograph vertical resolution
C5 -20 200i 20 $ radiograph horizontal resolution
```

Figure 7-3. Radiography tally cards for Section 7.

The “5” on the “FIR5:p” command line indicates the tally number. All radiography (“FIR”, “FIC,” “FIP”) tallies are type 5; therefore, the tally number must end with a 5. However, multiple tally cards can be created with varying tally numbers such as 5, 15, 25, etc. The “p” on this command indicates that this problem will tally photon flux in units of particles/cm². The next three terms on the “FIR” card indicate the coordinates (X₁, Y₁, Z₁) for the center of the flux image grid. The next term is for the R₀ value but is not used for this type of tally specification. Zero should be entered as a placeholder. The following three values are coordinates (X₂, Y₂, Z₂) used to establish the grid reference direction as being from (X₁, Y₁, Z₁) to (X₂, Y₂, Z₂). The first “0” entry after the (X₂, Y₂, Z₂) entries is the “F₁” parameter and indicates that the source and scattered contributions to the tally will be scored. A value <1 for the F₁ parameter indicates that only the scattered contributions will be scored. Alternatively, the “notrn” card can be used to obtain a direct image when F₁=1. The next entry is the “F₂” parameter defines any radial restriction for which “0” indicates none for this problem. The last entry on the “FIR” card is the “F₃” parameter, which specifies where in the image bin to direct flux

contributions from the tally. The “0” entry indicates that all flux contributions are directed to the center of each image grid bin.

The “FSn” and “Cn” cards that follow the “FIR” card determine the width and binning of the two-dimensional tally grid. The “n” entry on these cards should match the flux image tally number, “5” in this case. The first entry on these cards sets the lower limit in cm of the first image bin, and the subsequent entries set the upper limit of each bin. For this card, an “#i” entry can be used if equally-spaced bins are desired between two limits. The “FSn” card applies to the s-axis, and the “Cn” card applies to the t-axis as shown in Figure 2-11 on page 2-93 of the MCNP manual. In Figure 7-3 of this section, the “FSn” and “Cn” cards create 201 equally-spaced bins from -20 cm to 20 cm on the s-axis and 201 equally-spaced bins from -20 cm to 20 cm on the t-axis. With these cards, each element of the tally grid is approximately 2 mm by 2 mm.

Five miscellaneous data cards can also be included with the input deck for this example and are shown in Figure 7-4. The “prdmp” card controls the print and dump cycles of the run. The current card configuration skips the first two entries, indicated by “2j,” instructs MCNP to write a “MCTAL” file to store the tally results, and directs MCNP to store only the last data dump in the “RUNTPE” file. Storing only one dump will keep the “RUNTPE” file small; for complicated geometries and/or long runs, large “RUNTPE” files can become an issue. More information about the “prdmp” card can be found on page 3-139 of the MCNP manual. These parameters can be adjusted to suit a user’s individual needs. The “-85” and “-128” entries on the “print” card instruct MCNP to print the full output except for the electron range and scattering tables and the universe map, respectively. The universe map for lattice problems is quite large and will slow the

run down considerably in addition to taking up large amounts of memory, resulting in a large output file. The “phys” card specifies cutoffs for energy physics in the problem. In this specific configuration, MCNP will track bremsstrahlung photons and coherent scattering and Doppler energy broadening will occur. More information about the “phys” card can be found on page 3-127 of the MCNP manual. The “notrn” card in the input file prevents transport of the neutral source particles in the problem. Therefore, only the direct neutral particle source contributions to all the “FIR” point detector tallies are made. This card is especially useful in this case for making a significantly faster calculation to generate the direct tally. This does not emulate reality, however, and should only be used if scatter does not contribute largely to the tally. The “nps” card directs MCNP to run 50e6 particle histories.

```

prdmp 2j 1 1 j      $ create a mctal file at the end of run
print -85 -128     $ no output over lattice, reduce memory usage
phys:p 1j 0 0 1j 0
notrn              $ no transport of particles (transmission only)
nps      50e6

```

Figure 7-4. Section 7 miscellaneous data cards.

7.8 Running and Output

The following command line can be used to run this problem.

```
mcnp5 i=ex6 o=ex7out1 r=ex7r1 mctal=ex7m1
```

As mentioned for previous examples, any input and output file names can be used as long as the entire command line does not exceed 256 characters in length. Naming the “RUNTPE” file (indicated by “r=ex7r1”) is useful so that it can be easily located for a particular run if continuation of that run is desired later. Naming the “MCTAL” file (indicated by “mctal=ex7m1”) is useful for easy retrieval of this file when plotting the tally.

The output of chief concern for this example is the radiograph tally result and the corresponding plot that can be generated from the tally. This tally plot can be generated using the built-in MCNP plotter at any time during the run (by entering Ctrl-c) or after the run is complete. For this example, we will use the “WASH” command to generate a lateral radiograph of the Zubal head phantom. In the command window, the following command line can be used to initiate the MCNP tally plotter after the run is complete.

```
mcnp5 i=ex7 z
```

The “z” command opens communication with the tally plotter. After entering the above execution line (or after entering “m” after the Ctrl-c interrupt), you should see a “mcplot” prompt in the command window. Next, if continuing after the run is complete, you will need to read in the “MCTAL” file using the command “rmctal=ex7m1.” The “FREE” command is used to designate the independent variables for the plot, “s” and “c” in this case to indicate segmentation and cosine bins, respectively, which are used in the “FIR” tally to store the spatial bins. Lastly, turn on the wash plot function using the command

“WASH ON.” Figure 7-5 below shows a wash plot of the radiography tallies using the plot commands given in this section.

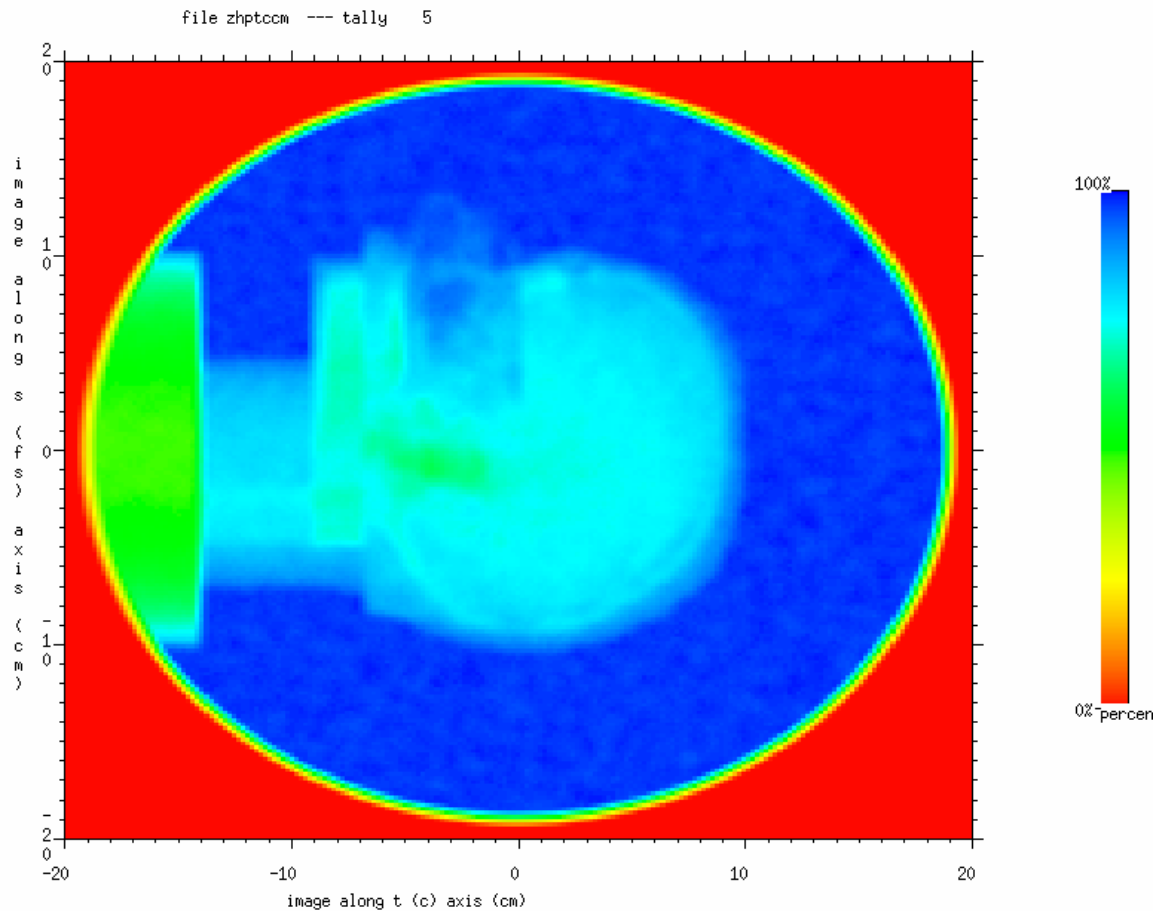


Figure 7-5. Radiograph image of the Zubal head phantom.

7.9 Results

The tally results for this problem can be found in the specified output and mctal files. The central result of this example is, as previously mentioned, the tally plot generated by the MCNP tally plotter. Examination of Figure 7-5 reveals an image of the

Zubal head phantom with highest flux transport through the scalp, neck, and sinus cavity. Significantly less particle flux was transported through the jaw line, skull, and torso, as expected given the varying material composition and increased densities. The disc-shaped boundary shown on the plot represents the dimensions of the source beam. The boundary fades to red because, due to the source definition, no particles exist outside of this boundary.

7.10 Summary

This section has described a method for obtaining a radiograph image from a voxelized MCNP input file. Using the built-in MCNP tally plotter, a wash plot can be generated to create the desired radiograph image. The high resolution of the Zubal head phantom provided an instructive geometry template for illustrating the usefulness of MCNP for creating radiograph images.

8. SUMMARY

This document was designed to help medical physics users understand and use the MCNP Monte Carlo code. It began with the Quick Start section which served as an introduction to the basics of using MCNP. The Quick Start section concluded with the assimilation of one complete input file, an isotropic disk source incident on a point detector. The following sections expanded on the ideas presented in the Quick Start section by presenting a varying range of problems from dose analysis in spherical tumors surrounded by a rectangular parallelepiped of tissue to creating a radiograph image of the Zubal head phantom. This primer was written to stand alone, but it is recommended that the user consult the MCNP5 manual when questions or situations arise that were not specifically addressed by the primer.

This document provides the necessary information to create and run a variety of medical physics problems. However, please remember that a single tally calculation and its associated confidence interval is meaningless without an understanding of the context of the problem and the integrity of the solution with regard to material specifications, cross section data, and correct problem definition.

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APPENDIX A

EXAMPLE PROBLEM INPUT DECKS

Section 2: Quick Start

```

Disc surface source incident on point detector
100 1 -1.293e-3 -1000 $Inside transport sphere
101 0          1000 $Outside transport sphere

1000 so 60  $Sphere centered at origin with R=60 cm
1001 px 0

m1 7014 -0.7808 8016 -0.2095 18000 -0.0093 $Air
SDEF par=2 erg=1.0 sur=1001 pos=0 0 0 rad=d1
SI1 H 0 15
SP1 -21 1
F5:p 25 0 0 0
Fm5 706.858
mode p
imp:p 1 0
nps 5e4

```

Section 3: Tumors in Tissue

```

Section 3: Tumors in Tissue
C *****
C          CELL CARDS
C *****
1 1 -1.04   -1 2 3 4 vol=987.434
2 1 -1.04   -2          vol=4.18879
3 1 -1.04   -3          vol=4.18879
4 1 -1.04   -4          vol=4.18879
5 2 -1.29e-3 1 -5      vol=3188.79
6 0          5

C *****
C          SURFACE CARDS
C *****
1 rpp -5 5 -5 5 -5 5
2 s 0 -2 0 1
3 s 0 2 0 1
4 s 2 0 0 1
5 so 10

C *****
C          DATA CARDS
C *****

```



```

mode p e
phys:p 3 0 0 1j 1
imp:p 1 1 1 1 1 0
SDEF par=2 erg=d1 cell=d2 rad=fcel=d3 pos=fcel=d8
SI1 L 0.1426 0.1405
SP1 D 0.014 0.986
SI2 L 1 2 3 4
SP2 D 1 6 6 6
DS3 s 4 5 6 7
SI4 0 7.5
SP4 -21 2
SI5 0 1
SP5 -21 2
SI6 0 1
SP6 -21 2
SI7 0 1
SP7 -21 2
DS8 L 0 0 0 0 -2 0 0 2 0 2 0 0
c MATERIAL CARD soft tissue
ml 1000 -0.10454
6000 -0.22663
7000 -0.0249
8000 -0.63525
11000 -0.00112
12000 -0.00013
14000 -0.0003
15000 -0.00134
16000 -0.00204
17000 -0.00133
19000 -0.00208
20000 -0.00024
26000 -0.00005
30000 -0.00003
37000 -0.00001
40000 -0.00001
c MATERIAL CARD dry air
m2 7000 -0.755 8000 -0.232 18000 -0.013
F4:p 1
fm4 0.011682 1 -5 -6
f14:p 2
fm14 0.011682 1 -5 -6
F24:p 3
fm24 0.011682 1 -5 -6
f34:p 4
fm34 0.011682 1 -5 -6
nps 250000
print

```

Section 4: MIRD Specific Absorbed Fractions

Section 4: MIRD Specific Absorbed Fractions

```

c -----
c ORNL phantom (1996 version) was coded by the authors
c in department of nuclear engineering, Hanyang University, Korea.

```

c If you want to use this model, the author would appreciate
 c your notice and mentioning the origin of this file in your article.
 c Please keep in mind the following conditions:
 c (1) The input shall be used only for the purpose of non-profit research.
 c (2) The author shall be free of any liability with regard to defects.
 c If you need additional information, please contact us.
 c Sanghyun Park, doctoral candidate
 c Phone : +82-2-2220-0571
 c E-mail : shpark@rrl.hanyang.ac.kr

```

c -----
c   cell card
c   trunk
100   2 -1.04 ((-100 101 -102):(102 -3301 -3202 803)) #600 #700 #800 #801
        #1000 #1100 #1200 #1300 #1500 #1501 #1600 #1601 #1700 #1800
        #1801 #1802 #1803 #1900 #1901 #1902 #1903 #2000 #2001 #2002
        #2003 #2004 #2005 #2006 #2007 #2100 #2200 #2300 #2301 #2400
        #2500 #2600 #2800 #3000 #3001 #3100 #3500 #3501
        imp:p=1 vol=43090
c   head (including neck)
200   2 -1.04 ((3301 -200 -201 803) #2900 ):           $ neck
        (-3202 201 -202 803):                         $ head 1
        ((202 -203 -204 901) #802 #901 #902):         $ head 2
        ((204 -205 901) #901 #902)                   $ head 3
        imp:p=1 vol=5250
c   legs
300   2 -1.04 ((-101 302 -300):(-101 302 -301)) #500
        imp:p=1 vol=20800
c   genitalia
400   2 -1.04 ((400 -101) (401 -402) (-403 404) (3400 3401)) 2700 2701
        imp:p=1 vol=196
c   leg bones
500   3 -1.40 (-500 -101 302):(-501 -101 302)
        imp:p=1 vol=2800
c   arm bones
600   3 -1.40 (-600 -602 101):(-601 -602 101)
        imp:p=1 vol=956
c   pelvis
700   3 -1.40 ((-704 705 700 -702 101 -703):(-704 705 700 703 -701))
        imp:p=1 vol=606
c   spine
800   3 -1.40 701 -800 -802
        imp:p=1 vol=205.053 $ spine, lower part
801   3 -1.40 800 -102 -802
        imp:p=1 vol=543.154 $ spine, mid part
802   3 -1.40 102 -801 -803
        imp:p=1 vol=234.793 $ spine, upper part
c   skull (cranium&facial skeleton&brain)
c   cranium
900   3 -1.40 900 -901
        imp:p=1 vol=618
c   facial skeleton
901   3 -1.40 -902 903 -403 904 -905 901
        imp:p=1 vol=305
c   brain
902   2 -1.04 -900
        imp:p=1 vol=1370
c   rib cage
1000  3 -1.40 (-1000 1001 800 -1003):(-1000 1001 1004 -1005):
        (-1000 1001 1006 -1007):(-1000 1001 1008 -1009):
        (-1000 1001 1010 -1011):(-1000 1001 1012 -1013):
        (-1000 1001 1014 -1015):(-1000 1001 1016 -1017):
        (-1000 1001 1018 -1019):(-1000 1001 1020 -1021):
        (-1000 1001 1022 -1023):(-1000 1001 1024 -1025)

```

```

                                imp:p=1 vol=694
c    clavicles
1100  3 -1.40 (-1100 -1101 1103 -403):(-1100 -1102 -1104 -403)
                                imp:p=1 vol=54.7
c    scapulae
1200  3 -1.40 (-1200 1000 1201 -1025 403 -1203 1205):
                                (-1200 1000 1201 -1025 403 1204 -1206)
                                imp:p=1 vol=202
c    adrenals
1300  2 -1.04 (-1300 1301):(-1302 1301)
                                imp:p=1 vol=15.7
c    breasts
1400  2 -1.04 (-1400 100):(-1401 100)
                                imp:p=1 vol=337
c    gall bladder
1500  2 -1.04 (-1504 1505 -1502):(-1500 1501 1502 -1503)
                                imp:p=1 vol=10.1 $ wall
1501  2 -1.04 (-1505 -1502):(-1501 1502 -1503)
                                imp:p=1 vol=53.6 $ contents
c    stomach
1600  2 -1.04 -1600 1601
                                imp:p=1 vol=152 $ wall
1601  2 -1.04 -1601
                                imp:p=1 vol=250 $ contents
c    small intestine
1700  2 -1.04 (((-705 1700 -1701 1803 -1703) #1802 #1803):
                                (-705 1800 1700 -1701 1702 -1803)) #1900 #1901
                                imp:p=1 vol=1060
c    upper large intestine
c    ascending colon
1800  2 -1.04 -1800 1801 1802 -1803
                                imp:p=1 vol=91.2 $ wall
1801  2 -1.04 -1801 1802 -1803
                                imp:p=1 vol=96.3 $ contents
c    transverse colon
1802  2 -1.04 -1804 1805 1806 -1807
                                imp:p=1 vol=121 $ wall
1803  2 -1.04 -1805 1806 -1807
                                imp:p=1 vol=127 $ contents
c    lower large intestine
c    descending colon
1900  2 -1.04 -1900 1901 1902 -1803
                                imp:p=1 vol=89.9 $ wall
1901  2 -1.04 -1901 1902 -1803
                                imp:p=1 vol=102 $ contents
c    sigmoid colon
1902  2 -1.04 (-1903 1904 1905 -1902):(-1906 1907 -1905 101)
                                imp:p=1 vol=70.4 $ wall
1903  2 -1.04 (-1904 1905 -1902):(-1907 -1905 101)
                                imp:p=1 vol=35.6 $ contents
c    heart & contents
c    left ventricle
2000  2 -1.04 -2000 2001 2002
                                imp:p=1 vol=177 $ wall
2001  2 -1.04 -2001 2002
                                imp:p=1 vol=102 $ contents
c    right ventricle
2002  2 -1.04 -2003 2004 2002 -2005 2000
                                imp:p=1 vol=67.2 $ wall
2003  2 -1.04 -2004 2002 -2005 2000
                                imp:p=1 vol=108 $ contents
c    left atrium
2004  2 -1.04 (-2006 2007 -2002 2005):(-2008 2009 -2002 -2005)

```

```

                imp:p=1 vol=31.6 $ wall
2005    2 -1.04 (-2007 -2002 2005):(-2009 -2002 -2005)
                imp:p=1 vol=115 $ contents
c      right atrium
2006    2 -1.04 -2010 2011 -2002 -2005 2008
                imp:p=1 vol=27.4 $ wall
2007    2 -1.04 -2011 -2002 -2005 2008
                imp:p=1 vol=111 $ contents
c      kidney
2100    2 -1.04 (-2100 1905):(-2101 -2103)
                imp:p=1 vol=288
c      liver
2200    2 -1.04 -2200 -2201 1703 -2202
                imp:p=1 vol=1830
c      lung
c      right lung
2300    4 -0.296 (-2300 1008 -2303):(-2300 2303 -2304 -2305 -2306)
                :(-2300 2303 -2304 2305):(-2300 2304)
                imp:p=1 vol=1810
c      left lung
2301    4 -0.296 (-2301 1008 -2307 -2308 2309):(-2301 1008 -2307 2308)
                :(2307 -2301)
                imp:p=1 vol=1560
c      ovaries
2400    2 -1.04 -2400:-2401
                imp:p=1 vol=8.38
c      pancreas
2500    2 -1.04 (-2500 2501 -1905):(-2500 2502 1905)
                imp:p=1 vol=90.7
c      spleen
2600    2 -1.04 -2600
                imp:p=1 vol=176
c      testes
2700    2 -1.04 -2700:-2701
                imp:p=1 vol=37.6
c      thymus
2800    2 -1.04 -2800
                imp:p=1 vol=20.1
c      thyroid
2900    2 -1.04 (-2901 2902 3301 -2900 2903 -2904):
                (-2901 2902 3301 -2900 2903 2905)
                imp:p=1 vol=19.9
c      urinary bladder&contents
3000    2 -1.04 -3000 3001
                imp:p=1 vol=45.7 $ wall
3001    2 -1.04 -3001
                imp:p=1 vol=203 $ contents
c      uterus
3100    2 -1.04 -3100 3101
                imp:p=1 vol=76
c      skin (3200, 3300, 3400, 3401)
c      head & neck skin
3200    2 -1.04 (200 -3202 3301 -201):                $ neck
                (201 -202 3202 -3200):                $ head 1
                (-3200 203 202 -204):                $ head 2
                (204 205 -3201)                        $ head 3
                imp:p=1 vol=318
c      trunk skin
3300    2 -1.04 (-3300 3202 102 -3301):                $ top of trunk
                (-3300 100 101 -102 3302 3303):        $ side of trunk
                (100 1400 -3302):(100 1401 -3303)      $ breasts skin
                imp:p=1 vol=1440
c      leg skin

```

```

3400    2 -1.04 (-101 302 -3400 300):(-101 302 -3401 301):
          (3402 -302 -3400):(3402 -302 -3401)
          imp:p=1 vol=1210          $ leg skin
c      esophagus (thoracic + abdominal)
3500    2 -1.04 (-3500 3501 2202 -102):(-3503 3504 -3505)
          imp:p=1 vol=44.7
c      void in esophagus
3501    0      -3501 2202 -102
          imp:p=1
c      shielding
8000    0 8000 -8001 8002 -8004 imp:p=0
8001    0 8000 -8001 8005 -8003 imp:p=0
c      outsides of phantom
5000    0      (((204 3201):(-204 3200 201)):
          (-201 3202 3301):          $ outside of head
          (-3301 3300 3302 3303 101): $ outside of neck
          (-101 3402 3400 3401):-3402) $ outside of trunk
          -5000 #400 #2700 #8000 #8001 $ outside of legs
          imp:p=1                    $ except genitalia region
c      outside of sphere
5010    0      5000
          imp:p=0

c      surface card
c      trunk(100)
100     sq 0.00255 0.010412 0 0 0 0 -1 0 0 0
101     pz 0
102     pz 69.8
c      head & neck(200) (neck, head1, head2, head3)
200     cz 5.2 $neck
201     pz 78.4 $neck, head1
202     pz 78.6 $head1, head2
203     sq 0.016437 0.010412 0 0 0 0 -1 0 0 0          $head2
204     pz 91.45 $head2, head3
205     sq 0.016437 0.010412 0.020703 0 0 0 -1 0 0 91.45 $head3
c      legs(300)
300     gq 1 1 0 0 0 -0.2 -20 0 0.04 3.96 $left leg
301     gq 1 1 0 0 0 0.2 20 0 0.04 3.96 $right leg
302     pz -79.8
c      genitalia(400)
400     pz -4.8 $z1
401     p 1 0 0.1 -10 $xz plane
402     p 1 0 -0.1 10 $xz plane
403     py 0 $y plane
404     p 0 1 0.1 -10 $yz plane
c      leg bones(500)
500     gq 1 1 0.00907 0 0 -0.200501 -20 0 1.785714 87.75 $left leg bone
501     gq 1 1 0.00907 0 0 0.200501 20 0 1.785714 87.75 $right leg bone
c      arm bones(600)
600     gq 0.513868 0.1371742 0 0 0 0.0103891 -19.6271888 0
          -0.2056517 187.1651186
          $left arm bone
601     gq 0.513868 0.1371742 0 0 0 -0.0103891 19.6271888 0
          -0.2056517 187.1651186
          $right arm bone
602     pz 69
c      pelvis (700)
700     py -3
701     pz 22
702     py 5
703     pz 14
704     sq 0.00694 0.00694 0 0 0 0 -1 0 -3 0
705     sq 0.00783 0.00783 0 0 0 0 -1 0 -3.8 0

```

```

c spine (800)
800 pz 35.1 $ 701 and 800 lower, 800 and 102 middle
801 pz 84.8 $ 102 and 801 upper
802 sq 0.25 0.16 0 0 0 0 -1 0 5.50 0 $ mid, lower
803 sq 0.25 0.16 0 0 0 0 -1 0 1.45 0 $ upper
c skull
c cranium (900)
900 sq 0.022957 0.013521 0.030246 0 0 0 -1 0 0 91.45
901 sq 0.017778 0.01108 0.022613 0 0 0 -1 0 0 91.45
c facial skeleton (901)
902 sq 0.020408 0.012346 0 0 0 0 -1 0 0 0
903 sq 0.031888 0.017313 0 0 0 0 -1 0 0 0
904 pz 82.4
905 pz 93.13
c rib cage(1000)
1000 sq 0.0034602 0.0104123 0 0 0 0 -1 0 0 0
1001 sq 0.00367 0.01156 0 0 0 0 -1 0 0 0
1003 pz 36.5
1004 pz 37.9
1005 pz 39.3
1006 pz 40.7
1007 pz 42.1
1008 pz 43.5
1009 pz 44.9
1010 pz 46.3
1011 pz 47.7
1012 pz 49.1
1013 pz 50.5
1014 pz 51.9
1015 pz 53.3
1016 pz 54.7
1017 pz 56.1
1018 pz 57.5
1019 pz 58.9
1020 pz 60.3
1021 pz 61.7
1022 pz 63.1
1023 pz 64.5
1024 pz 65.9
1025 pz 67.3
c clavicles(1100)
1100 tz 0 11.1 68.25 20 0.7883 0.7883
1101 p 0.89415 1 0 11.1
1102 p -0.89415 1 0 11.1
1103 p 7.0342 1 0 11.1
1104 p 7.0342 -1 0 -11.1
c scapulae(1200)
1200 sq 0.00277 0.010412 0 0 0 0 -1 0 0 0
1201 pz 50.9
1203 p 0.25 -1 0 0 $left
1204 p 0.25 1 0 0 $right
1205 p 0.8 -1 0 0 $left
1206 p 0.8 1 0 0 $right
c adrenals(1300)
1300 1 sq 0.444444 4 0.04 0 0 0 -1 0 0 0 $left
1301 1 pz 0 $left
1302 2 sq 0.444444 4 0.04 0 0 0 -1 0 0 0 $right
c breasts(1400)
1400 sq 0.044321 0.058064 0.064092 0 0 0 -1 10 -8.660254 52
$left breast
1401 sq 0.044321 0.058064 0.064092 0 0 0 -1 -10 -8.660254 52
$right breast
c gall bladder (wall : 1500, contents : 1501)

```

```

1500    3 kz 9.318681 0.051756
1501    3 kz 8.791209 0.051756
1502    3 pz 0
1503    3 pz 8
1504    3 so 2.12
1505    3 so 2
c      stomach      (wall : 1600, contents : 1601)
1600    sq 0.0625   0.111111 0.015625 0 0 0 -1 8 -4 35
1601    sq 0.087171 0.175507 0.018326 0 0 0 -1 8 -4 35
c      small intestine, SI(1700)
1700    py -4.86
1701    py 2.2
1702    pz 17
1703    pz 27
c      upper large intestine, ULI(1800, 1801, 1802, 1803)
c      ascending colon (wall : 1800, contents : 1801)
1800    sq 0.16     0.16     0 0 0 0 -1 -8.5 -2.36 0
1801    sq 0.311578 0.311578 0 0 0 0 -1 -8.5 -2.36 0
1802    pz 14.45
1803    pz 23.99
c      transverse colon (wall : 1802, contents : 1803)
1804    sq 0 0.16     0.444444 0 0 0 -1 0 -2.36 25.5
1805    sq 0 0.256889 1.056268 0 0 0 -1 0 -2.36 25.5
1806    px -10.5
1807    px 10.5
c      lower large intestine, LLI(1900, 1901, 1902, 1903)
c      descending colon (wall : 1900, contents : 1901)
1900    gq 0.282933 0.220415 0.006638 0 0.072125 -0.028886
        -4.541008 -0.628932 0.128904 17.669146
1901    gq 0.556917 0.395554 0.01204 0 0.129435 -0.056858
        -8.938371 -1.128675 0.271613 35.669768
1902    pz 8.72
c      sigmoid colon (wall : 1902, contents 1903)
1903    ty 3 0 8.72 5.72 1.57 1.57 $ upper
1904    ty 3 0 8.72 5.72 0.91 0.91 $ upper
1905    px 3
1906    ty 3 0 0 3 1.57 1.57 $ lower
1907    ty 3 0 0 3 0.91 0.91 $ lower
c      heart & contents(2000)
c      left ventricle (wall : 2000, contents : 2001)
2000    4 sq 0.013521 0.04 0.104058 0 0 0 -1 0 0 0
2001    4 sq 0.018765 0.073046 0.308642 0 0 0 -1 0 0 0
2002    4 px 0
c      right ventricle (wall : 2002, contents : 2003)
2003    4 sq 0.013521 0.04 0.020408 0 0 0 -1 0 0 0
2004    4 sq 0.015625 0.051653 0.024414 0 0 0 -1 0 0 0
2005    4 pz 0
c      left atrium (wall : 2004, contents : 2005)
2006    4 sq 0.034294 0.04 0.104058 0 0 0 -1 0 0 0
2007    4 sq 0.038447 0.045269 0.127551 0 0 0 -1 0 0 0
2008    4 sq 0.034294 0.04 0.226757 0 0 0 -1 0 0 0
2009    4 sq 0.038447 0.045269 0.308642 0 0 0 -1 0 0 0
c      right atrium (wall : 2006, contents : 2007)
2010    4 sq 0.034294 0.04 0.020408 0 0 0 -1 0 0 0
2011    4 sq 0.038447 0.045269 0.022277 0 0 0 -1 0 0 0
c      kidney (2100)
2100    sq 0.049383 0.444444 0.033058 0 0 0 -1 6 6 32.5 $left
2101    sq 0.049383 0.444444 0.033058 0 0 0 -1 -6 6 32.5 $right
2103    px -3
c      liver (2200)
2200    sq 0.0036731 0.015625 0 0 0 0 -1 0 0 0
2201    p 0.0285714 0.022222 -0.0232558 -1
2202    pz 43

```

```

c      lung                (right : 2300, left : 2301)
2300   sq 0.04 0.017778 0.001736 0 0 0 -1 -8.5 0 43.5 $right
2301   sq 0.04 0.017778 0.001736 0 0 0 -1 8.5 0 43.5 $left
2303   pz 46 $right
2304   pz 54 $right
2305   py 1.5 $right
2306   px -5.4 $right
2307   pz 55 $left
2308   py 1 $left
2309   px 8 $left
c      ovaries             (2400)
2400   sq 1 4 0.25 0 0 0 -1 6 0 15 $left
2401   sq 1 4 0.25 0 0 0 -1 -6 0 15 $right
c      pancreas           (2500)
2500   sq 0.003906 0.694444 0.091827 0 0 0 -1 -1 0 37
2501   px -1
2502   pz 37
c      spleen             (2600)
2600   sq 0.081633 0.25 0.027778 0 0 0 -1 11 3 37
c      testes             (2700)
2700   sq 0.591716 0.444444 0.189036 0 0 0 -1 1.3 -8 -2.3 $left
2701   sq 0.591716 0.444444 0.189036 0 0 0 -1 -1.3 -8 -2.3 $right
c      thymus            (2800)
2800   sq 0.444444 1.5625 0.0625 0 0 0 -1 0 -7.3 57
c      thyroid           (2900)
2900   pz 75
2901   c/z 0 -4 2.2
2902   c/z 0 -4 1
2903   py -4
2904   px -0.8
2905   px 0.8
c      urinary bladder & contents (wall : 3000, contents : 3001)
3000   sq 0.040681 0.083628 0.083628 0 0 0 -1 0 -4.5 8
3001   sq 0.045154 0.097291 0.097291 0 0 0 -1 0 -4.5 8
c      uterus            (3100)
3100   sq 0.145679 0.036699 0.405696 0 0 0 -1 0 -2 14
3101   py -4.62
c      skin (3200)
c      head & neck skin
3200   sq 0.015625 0.01 0 0 0 0 -1 0 0 0 $head
3201   sq 0.015625 0.01 0.019561 0 0 0 -1 0 0 91.45 $head
3202   cz 5.4 $neck
c      trunk skin (3300)
3300   sq 0.0025 0.01 0 0 0 0 -1 0 0 0
3301   pz 70
c      breast skin
3302   sq 0.040812 0.052847 0.058064 0 0 0 -1 10 -8.660254 52
      $left breast
3303   sq 0.040812 0.052847 0.058064 0 0 0 -1 -10 -8.660254 52
      $right breast
c      leg & genitalia skin(leg skin : 3400, genitalia skin :3401)
3400   gq 1 1 0 0 0 -0.2 -20 0 0 0 $ left leg skin
3401   gq 1 1 0 0 0 0.2 20 0 0 0 $ right leg skin
3402   pz -80
c      esophagus (3500, thoracic portion + abdominal portion)
3500   sq 0.730514 5.668934 0 0 0 0 -1 0 2.575 0
3501   sq 1.321178 69.444444 0 0 0 0 -1 0 2.575 0
3503   5 cx 0.7
3504   5 px 0.1
3505   5 px 7.8
c      outside(5000)
5000   so 1000
c      shielding

```



```

8000    sq 0.0016 0.004444 0 0 0 0 -1 0 0 0
8001    sq 0.001479 0.003906 0 0 0 0 -1 0 0 0
8002    pz -82
8003    pz 100
8004    pz 12.179
8005    pz 12.821

c physics cards
mode p e
phys:p 3 0 0 1j 1
c *****
c transformations
tr1    3.5 5 38 0.615661 0.788011 0 -0.788011 0.615661 0 0 0 1
tr2    -3.5 5 38 0.615661 -0.788011 0 0.788011 0.615661 0 0 0 1
tr3    -4.5 -3.2 30 0.9615 0 -0.2748 -0.0574 0.9779 -0.2008
        0.2687 0.2090 0.9403
tr4    1 -1.8 50 0.6751 -0.4727 -0.5664 -0.464 0.3249 -0.8241 0.5736 0.8191 0
tr5    0 2.575 42.3 0.736084 -0.604969 -0.303634 0.634945 0.772557 0
        0.234575 -0.192791 0.952789
c *****
c SOURCE DEFINITION
c *****
c Distributed volume source in the spleen
c 1.0 MeV gamma
SDEF cel=2600 POS=11 3 37 RAD=D1 ERG=1.0
SI1 0 6.2
SP1 -21 2
c *****
c TALLIES
c F6 tally used for energy deposition (MeV/g)
c *****
fc6 kidney<---spleen Specific Absorbed Fraction (g^-1)
F6:p 2100
fc16 liver<---spleen Specific Absorbed Fraction (g^-1)
f16:p 2200
fc26 ovaries<---spleen Specific Absorbed Fraction (g^-1)
F26:p 2400
fc36 pancreas<---spleen Specific Absorbed Fraction (g^-1)
f36:p 2500
fc46 spleen<---spleen Specific Absorbed Fraction (g^-1)
F46:p 2600
fc56 thyroid<---spleen Specific Absorbed Fraction (g^-1)
F56:p 2900
fc66 bladder wall<---spleen Specific Absorbed Fraction (g^-1)
F66:p 3000
c
*****
c MATERIAL CARDS
c
*****
c material card $m2=soft tissue m3=bone m4=lung
m2      1000      -0.10454
        6000      -0.22663
        7000      -0.0249
        8000      -0.63525
        11000     -0.00112
        12000     -0.00013
        14000     -0.0003
        15000     -0.00134
        16000     -0.00204
        17000     -0.00133
        19000     -0.00208
        20000     -0.00024

```

	26000	-0.00005
	30000	-0.00003
	37000	-0.00001
	40000	-0.00001
m3	1000	-0.07337
	6000	-0.25475
	7000	-0.03057
	8000	-0.47893
	9000	-0.00025
	11000	-0.00326
	12000	-0.00112
	14000	-0.00002
	15000	-0.05095
	16000	-0.00173
	17000	-0.00143
	19000	-0.00153
	20000	-0.10190
	26000	-0.00008
	30000	-0.00005
	37000	-0.00002
	38000	-0.00003
	82000	-0.00001
m4	1000	-0.10134
	6000	-0.10238
	7000	-0.02866
	8000	-0.75752
	11000	-0.00184
	12000	-0.00007
	14000	-0.00006
	15000	-0.00008
	16000	-0.00225
	17000	-0.00266
	19000	-0.00194
	20000	-0.00009
	26000	-0.00037
	30000	-0.00001
	37000	-0.00001
nps	100000	
prdmp	10000 5000	

Section 5: X-ray Phototherapy

Section 5: X-ray Phototherapy with Gadolinium

C*****

C CELL CARDS

C*****

c Surrounding Ellipsoids

100 100 -1.04 -10 42

101 101 -1.04 -42

200 200 -1.61 10 -20

300 300 -1.09 20 -30

400 400 -1.293E-03 30 -40

500 0 40

C*****

C SURFACE CARDS

C*****

10 sq 0.0277778 0.0123456 0.0236686 0 0 0 -1 0.0 0.0 1.0

```

20 sq 0.0216263 0.0104123 0.0145159 0 0 0 -1 0.0 0.0 0.0
30 sq 0.0187652 0.0094260 0.0129133 0 0 0 -1 0.0 0.0 0.0
c Snyder phantom: Surfaces, Center is 0,0,0
c (x/6)**2 + (y/9)**2 + ([z-1]/6.5)**2 = 1 (brain)
c (x/6.8)**2 + (y/9.8)**2 + (z/8.3)**2 = 1 (skull)
c (x/7.3)**2 + (y/10.3)**2 + (z/8.8)**2 = 1 (skin)
c
40 so 50
42 so 2.54
c boundary with external universe
c
C*****
C      DATA CARDS
C*****
c BRAIN (ICRU 46 Adult Whole Brain dens=1.040)
m100  1001 -0.107
      6000 -0.145
      7014 -0.022
      8016 -0.712
      11023 -0.002
      15031 -0.004
      16000 -0.002
      17000 -0.003
      19000 -0.003
c BRAIN (ICRU 46 Adult Whole Brain dens=1.040) w/ Gd!
m101  1001 -0.10699679
      6000 -0.14499565
      7014 -0.02199934
      8016 -0.71197864
      11023 -0.00199994
      15031 -0.00399988
      16000 -0.00199994
      17000 -0.00299991
      19000 -0.00299991
      64000 -0.050000
c SKULL (ICRU 46 Skeleton, Whole Cranium dens=1.610 g/cm3)
m200  1001 -0.050
      6000 -0.212
      7014 -0.040
      8016 -0.435
      11023 -0.001
      12000 -0.002
      15031 -0.081
      16000 -0.003
      20000 -0.176
c SCALP (ICRU 46 Adult Skin dens=1.090 g/cm3)
m300  1001 -0.100
      6000 -0.204
      7014 -0.042
      8016 -0.645
      11023 -0.002
      15031 -0.001
      16000 -0.002
      17000 -0.003
      19000 -0.001
c AIR (Medical Physics Air dens=0.0013 g/cm3)
m400  6000 -0.00012
      7014 -0.75527
      8016 -0.23178
      20000 -0.01283
mode p e
phys:p 1j 0 0 1j 1

```

```

imp:p 1 1 1 1 0
imp:e 1 1 1 1 0
SDEF pos=0 0 15 vec=0 0 -1 axs=0 0 -1 ext=0 dir=1 ara=78.53982 rad=d1 erg=d2
SI1 0 5
SP1 -21 1
SI2 L 0.03266
      0.04208
      0.05352
      0.06160
      0.07252
      0.07478
      0.08400
      0.08637
      0.11918
      0.12615
      0.13992
      0.15188
      0.15400
      0.15887
SP2 4.90
     13.50
     0.08
     0.51
     0.15
     92.00
    100.00
     0.05
     0.13
     15.00
     0.35
     0.61
     0.06
     3.20
*F8:p,e 101
e8      1e-10 100i 0.2
nps 10000000

```

Section 6: Prostate Brachytherapy

```

ORNL/TM-8381 - ORNL MIRD phantom (1996 version)
c      cell card
c      trunk
100    2 -1.04 ((-100 101 -102):(102 -3301 -3202 803)) #600 #700 #800 #801
          #1000 #1100 #1200 #1300 #1500 #1501 #1600 #1601 #1700 #1800
          #1801 #1802 #1803 #1900 #1901 #1902 #1903 #2000 #2001 #2002
          #2003 #2004 #2005 #2006 #2007 #2100 #2200 #2300 #2301 #2400
          #2500 #2600 #2800 #3000 #3001 #3100 #3500 #3501 #6000
          imp:p,e=1 vol=43090
c      head (including neck)
200    2 -1.04 ((3301 -200 -201 803) #2900 ):          $ neck
          (-3202 201 -202 803):          $ head 1
          ((202 -203 -204 901) #802 #901 #902):      $ head 2
          ((204 -205 901) #901 #902)          $ head 3
          imp:p,e=1 vol=5250
c      legs
300    2 ((-101 302 -300):(-101 302 -301)) #500
          imp:p,e=1 vol=20800
c      genitalia

```

```

400      2 -1.04 ((400 -101) (401 -402) (-403 404) (3400 3401)) 2700 2701
           imp:p,e=1 vol=196
c      leg bones
500      3 (-500 -101 302):(-501 -101 302)
           imp:p,e=1 vol=2800
c      arm bones
600      3 -1.40 (-600 -602 101):(-601 -602 101)
           imp:p,e=1 vol=956
c      pelvis
700      3 -1.40 ((-704 705 700 -702 101 -703):(-704 705 700 703 -701))
           imp:p,e=1 vol=606
c      spine
800      3 -1.40 701 -800 -802
           imp:p,e=1 vol=205.053 $ spine, lower part
801      3 -1.40 800 -102 -802
           imp:p,e=1 vol=543.154 $ spine, mid part
802      3 -1.40 102 -801 -803
           imp:p,e=1 vol=234.793 $ spine, upper part
c      skull (cranium&facial skeleton&brain)
c      cranium
900      3 -1.40 900 -901
           imp:p,e=1 vol=618
c      facial skeleton
901      3 -1.40 -902 903 -403 904 -905 901
           imp:p,e=1 vol=305
c      brain
902      2 -1.04 -900
           imp:p,e=1 vol=1370
c      rib cage
1000     3 -1.40 (-1000 1001 800 -1003):(-1000 1001 1004 -1005):
           (-1000 1001 1006 -1007):(-1000 1001 1008 -1009):
           (-1000 1001 1010 -1011):(-1000 1001 1012 -1013):
           (-1000 1001 1014 -1015):(-1000 1001 1016 -1017):
           (-1000 1001 1018 -1019):(-1000 1001 1020 -1021):
           (-1000 1001 1022 -1023):(-1000 1001 1024 -1025)
           imp:p,e=1 vol=694
c      clavicles
1100     3 -1.40 (-1100 -1101 1103 -403):(-1100 -1102 -1104 -403)
           imp:p,e=1 vol=54.7
c      scapulae
1200     3 -1.40 (-1200 1000 1201 -1025 403 -1203 1205):
           (-1200 1000 1201 -1025 403 1204 -1206)
           imp:p,e=1 vol=202
c      adrenals
1300     2 -1.04 (-1300 1301):(-1302 1301)
           imp:p,e=1 vol=15.7
c      breasts
1400     2 -1.04 (-1400 100):(-1401 100)
           imp:p,e=1 vol=337
c      gall bladder
1500     2 -1.04 (-1504 1505 -1502):(-1500 1501 1502 -1503)
           imp:p,e=1 vol=10.1 $ wall
1501     2 -1.04 (-1505 -1502):(-1501 1502 -1503)
           imp:p,e=1 vol=53.6 $ contents
c      stomach
1600     2 -1.04 -1600 1601
           imp:p,e=1 vol=152 $ wall
1601     2 -1.04 -1601
           imp:p,e=1 vol=250 $ contents
c      small intestine
1700     2 -1.04 (((-705 1700 -1701 1803 -1703) #1802 #1803):
           (-705 1800 1700 -1701 1702 -1803)) #1900 #1901
           imp:p,e=1 vol=1060

```

```

c    upper large intestine
c    ascending colon
1800    2 -1.04 -1800 1801 1802 -1803
        imp:p,e=1 vol=91.2 $ wall
1801    2 -1.04 -1801 1802 -1803
        imp:p,e=1 vol=96.3 $ contents
c    transverse colon
1802    2 -1.04 -1804 1805 1806 -1807
        imp:p,e=1 vol=121 $ wall
1803    2 -1.04 -1805 1806 -1807
        imp:p,e=1 vol=127 $ contents
c    lower large intestine
c    descending colon
1900    2 -1.04 -1900 1901 1902 -1803
        imp:p,e=1 vol=89.9 $ wall
1901    2 -1.04 -1901 1902 -1803
        imp:p,e=1 vol=102 $ contents
c    sigmoid colon
1902    2 -1.04 (-1903 1904 1905 -1902):(-1906 1907 -1905 101)
        imp:p,e=1 vol=70.4 $ wall
1903    2 -1.04 (-1904 1905 -1902):(-1907 -1905 101)
        imp:p,e=1 vol=35.6 $ contents
c    heart & contents
c    left ventricle
2000    2 -1.04 -2000 2001 2002
        imp:p,e=1 vol=177 $ wall
2001    2 -1.04 -2001 2002
        imp:p,e=1 vol=102 $ contents
c    right ventricle
2002    2 -1.04 -2003 2004 2002 -2005 2000
        imp:p,e=1 vol=67.2 $ wall
2003    2 -1.04 -2004 2002 -2005 2000
        imp:p,e=1 vol=108 $ contents
c    left atrium
2004    2 -1.04 (-2006 2007 -2002 2005):(-2008 2009 -2002 -2005)
        imp:p,e=1 vol=31.6 $ wall
2005    2 -1.04 (-2007 -2002 2005):(-2009 -2002 -2005)
        imp:p,e=1 vol=115 $ contents
c    right atrium
2006    2 -1.04 -2010 2011 -2002 -2005 2008
        imp:p,e=1 vol=27.4 $ wall
2007    2 -1.04 -2011 -2002 -2005 2008
        imp:p,e=1 vol=111 $ contents
c    kidney
2100    2 -1.04 (-2100 1905):(-2101 -2103)
        imp:p,e=1 vol=288
c    liver
2200    2 -1.04 -2200 -2201 1703 -2202
        imp:p,e=1 vol=1830
c    lung
c    right lung
2300    4 -0.296 (-2300 1008 -2303):(-2300 2303 -2304 -2305 -2306)
        :(-2300 2303 -2304 2305):(-2300 2304)
        imp:p,e=1 vol=1810
c    left lung
2301    4 -0.296 (-2301 1008 -2307 -2308 2309):(-2301 1008 -2307 2308)
        :(2307 -2301)
        imp:p,e=1 vol=1560
c    ovaries
2400    2 -1.04 -2400:-2401
        imp:p,e=1 vol=8.38
c    pancreas
2500    2 -1.04 (-2500 2501 -1905):(-2500 2502 1905)

```

```

                imp:p,e=1 vol=90.7
c   spleen
2600  2 -1.04 -2600
                imp:p,e=1 vol=176
c   testes
2700  2 -1.04 -2700:-2701
                imp:p,e=1 vol=37.6
c   thymus
2800  2 -1.04 -2800
                imp:p,e=1 vol=20.1
c   thyroid
2900  2 -1.04 (-2901 2902 3301 -2900 2903 -2904):
                (-2901 2902 3301 -2900 2903 2905)
                imp:p,e=1 vol=19.9
c   urinary bladder&contents
3000  2 -1.04 -3000 3001
                imp:p,e=1 vol=45.7 $ wall
3001  2 -1.04 -3001
                imp:p,e=1 vol=203 $ contents
c   uterus
3100  2 -1.04 -3100 3101
                imp:p,e=1 vol=76
c   skin (3200, 3300, 3400, 3401)
c   head & neck skin
3200  2 -1.04 (200 -3202 3301 -201):           $ neck
                (201 -202 3202 -3200):         $ head 1
                (-3200 203 202 -204):         $ head 2
                (204 205 -3201)                $ head 3
                imp:p,e=1 vol=318
c   trunk skin
3300  2 -1.04 (-3300 3202 102 -3301):           $ top of trunk
                (-3300 100 101 -102 3302 3303): $ side of trunk
                (100 1400 -3302):(100 1401 -3303) $ breasts skin
                imp:p,e=1 vol=1440
c   leg skin
3400  2 -1.04 (-101 302 -3400 300):(-101 302 -3401 301):
                (3402 -302 -3400):(3402 -302 -3401)
                imp:p,e=1 vol=1210           $ leg skin
c   esophagus (thoracic + abdominal)
3500  2 -1.04 (-3500 3501 2202 -102):(-3503 3504 -3505)
                imp:p,e=1 vol=44.7
c   void in esophagus
3501  0      -3501 2202 -102
                imp:p,e=1
c   shielding
8000  0 8000 -8001 8002 -8004 imp:p,e=0
8001  0 8000 -8001 8005 -8003 imp:p,e=0
c   outsides of phantom
5000  0      (((204 3201):(-204 3200 201)):
                (-201 3202 3301):           $ outside of head
                (-3301 3300 3302 3303 101): $ outside of neck
                (-101 3402 3400 3401):-3402) $ outside of trunk
                -5000 #400 #2700 #8000 #8001 $ outside of legs
                imp:p,e=1                   $ except genitalia region
c   outside of sphere
5010  0      5000
                imp:p,e=0
c   prostate
6000  2 -1.04 -9000 vol=16.3625
                imp:p,e=1
C -----
c   surface card

```

```

c      trunk(100)
100    sq 0.00255 0.010412 0 0 0 0 -1 0 0 0
101    pz 0
102    pz 69.8
c      head & neck(200) (neck, head1, head2, head3)
200    cz 5.2  $neck
201    pz 78.4  $neck, head1
202    pz 78.6  $head1, head2
203    sq 0.016437 0.010412 0 0 0 0 -1 0 0 0          $head2
204    pz 91.45 $head2, head3
205    sq 0.016437 0.010412 0.020703 0 0 0 -1 0 0 91.45 $head3
c      legs(300)
300    gq 1 1 0 0 0 -0.2 -20 0 0.04 3.96 $left leg
301    gq 1 1 0 0 0 0.2 20 0 0.04 3.96  $right leg
302    pz -79.8
c      genitalia(400)
400    pz -4.8  $z1
401    p 1 0 0.1 -10  $xz plane
402    p 1 0 -0.1 10  $xz plane
403    py 0          $y  plane
404    p 0 1 0.1 -10  $yz plane
c      leg bones(500)
500    gq 1 1 0.00907 0 0 -0.200501 -20 0 1.785714 87.75 $left leg bone
501    gq 1 1 0.00907 0 0 0.200501 20 0 1.785714 87.75 $right leg bone
c      arm bones(600)
600    gq 0.513868 0.1371742 0 0 0 0.0103891 -19.6271888 0
        -0.2056517 187.1651186
        $left arm bone
601    gq 0.513868 0.1371742 0 0 0 -0.0103891 19.6271888 0
        -0.2056517 187.1651186
        $right arm bone
602    pz 69
c      pelvis (700)
700    py -3
701    pz 22
702    py 5
703    pz 14
704    sq 0.00694 0.00694 0 0 0 0 -1 0 -3 0
705    sq 0.00783 0.00783 0 0 0 0 -1 0 -3.8 0
c      spine (800)
800    pz 35.1  $ 701 and 800 lower, 800 and 102 middle
801    pz 84.8  $ 102 and 801 upper
802    sq 0.25 0.16 0 0 0 0 -1 0 5.50 0  $ mid, lower
803    sq 0.25 0.16 0 0 0 0 -1 0 1.45 0  $ upper
c      skull
c      cranium (900)
900    sq 0.022957 0.013521 0.030246 0 0 0 -1 0 0 91.45
901    sq 0.017778 0.01108 0.022613 0 0 0 -1 0 0 91.45
c      facial skeleton (901)
902    sq 0.020408 0.012346 0 0 0 0 -1 0 0 0
903    sq 0.031888 0.017313 0 0 0 0 -1 0 0 0
904    pz 82.4
905    pz 93.13
c      rib cage(1000)
1000   sq 0.0034602 0.0104123 0 0 0 0 -1 0 0 0
1001   sq 0.00367 0.01156 0 0 0 0 -1 0 0 0
1003   pz 36.5
1004   pz 37.9
1005   pz 39.3
1006   pz 40.7
1007   pz 42.1
1008   pz 43.5
1009   pz 44.9

```



```

1010 pz 46.3
1011 pz 47.7
1012 pz 49.1
1013 pz 50.5
1014 pz 51.9
1015 pz 53.3
1016 pz 54.7
1017 pz 56.1
1018 pz 57.5
1019 pz 58.9
1020 pz 60.3
1021 pz 61.7
1022 pz 63.1
1023 pz 64.5
1024 pz 65.9
1025 pz 67.3
c clavicles(1100)
1100 tz 0 11.1 68.25 20 0.7883 0.7883
1101 p 0.89415 1 0 11.1
1102 p -0.89415 1 0 11.1
1103 p 7.0342 1 0 11.1
1104 p 7.0342 -1 0 -11.1
c scapulae(1200)
1200 sq 0.00277 0.010412 0 0 0 0 -1 0 0 0
1201 pz 50.9
1203 p 0.25 -1 0 0 $left
1204 p 0.25 1 0 0 $right
1205 p 0.8 -1 0 0 $left
1206 p 0.8 1 0 0 $right
c adrenals(1300)
1300 1 sq 0.444444 4 0.04 0 0 0 -1 0 0 0 $left
1301 1 pz 0 $left
1302 2 sq 0.444444 4 0.04 0 0 0 -1 0 0 0 $right
c breasts(1400)
1400 sq 0.044321 0.058064 0.064092 0 0 0 -1 10 -8.660254 52
$left breast
1401 sq 0.044321 0.058064 0.064092 0 0 0 -1 -10 -8.660254 52
$right breast
c gall bladder (wall : 1500, contents : 1501)
1500 3 kz 9.318681 0.051756
1501 3 kz 8.791209 0.051756
1502 3 pz 0
1503 3 pz 8
1504 3 so 2.12
1505 3 so 2
c stomach (wall : 1600, contents : 1601)
1600 sq 0.0625 0.111111 0.015625 0 0 0 -1 8 -4 35
1601 sq 0.087171 0.175507 0.018326 0 0 0 -1 8 -4 35
c small intestine, SI(1700)
1700 py -4.86
1701 py 2.2
1702 pz 17
1703 pz 27
c upper large intestine, ULI(1800, 1801, 1802, 1803)
c ascending colon (wall : 1800, contents : 1801)
1800 sq 0.16 0.16 0 0 0 0 -1 -8.5 -2.36 0
1801 sq 0.311578 0.311578 0 0 0 0 -1 -8.5 -2.36 0
1802 pz 14.45
1803 pz 23.99
c transverse colon (wall : 1802, contents : 1803)
1804 sq 0 0.16 0.444444 0 0 0 -1 0 -2.36 25.5
1805 sq 0 0.256889 1.056268 0 0 0 -1 0 -2.36 25.5
1806 px -10.5

```

```

1807   px 10.5
c     lower large intestine, LLI(1900, 1901, 1902, 1903)
c     descending colon (wall : 1900, contents : 1901)
1900   gq 0.282933 0.220415 0.006638 0 0.072125 -0.028886
      -4.541008 -0.628932 0.128904 17.669146
1901   gq 0.556917 0.395554 0.01204 0 0.129435 -0.056858
      -8.938371 -1.128675 0.271613 35.669768
1902   pz 8.72
c     sigmoid colon (wall : 1902, contents 1903)
1903   ty 3 0 8.72 5.72 1.57 1.57 $ upper
1904   ty 3 0 8.72 5.72 0.91 0.91 $ upper
1905   px 3
1906   ty 3 0 0 3 1.57 1.57 $ lower
1907   ty 3 0 0 3 0.91 0.91 $ lower
c     heart & contents(2000)
c     left ventricle (wall : 2000, contents : 2001)
2000   4 sq 0.013521 0.04 0.104058 0 0 0 -1 0 0 0
2001   4 sq 0.018765 0.073046 0.308642 0 0 0 -1 0 0 0
2002   4 px 0
c     right ventricle (wall : 2002, contents : 2003)
2003   4 sq 0.013521 0.04 0.020408 0 0 0 -1 0 0 0
2004   4 sq 0.015625 0.051653 0.024414 0 0 0 -1 0 0 0
2005   4 pz 0
c     left atrium (wall : 2004, contents : 2005)
2006   4 sq 0.034294 0.04 0.104058 0 0 0 -1 0 0 0
2007   4 sq 0.038447 0.045269 0.127551 0 0 0 -1 0 0 0
2008   4 sq 0.034294 0.04 0.226757 0 0 0 -1 0 0 0
2009   4 sq 0.038447 0.045269 0.308642 0 0 0 -1 0 0 0
c     right atrium (wall : 2006, contents : 2007)
2010   4 sq 0.034294 0.04 0.020408 0 0 0 -1 0 0 0
2011   4 sq 0.038447 0.045269 0.022277 0 0 0 -1 0 0 0
c     kidney (2100)
2100   sq 0.049383 0.444444 0.033058 0 0 0 -1 6 6 32.5 $left
2101   sq 0.049383 0.444444 0.033058 0 0 0 -1 -6 6 32.5 $right
2103   px -3
c     liver (2200)
2200   sq 0.0036731 0.015625 0 0 0 0 -1 0 0 0
2201   p 0.0285714 0.022222 -0.0232558 -1
2202   pz 43
c     lung (right : 2300, left : 2301)
2300   sq 0.04 0.017778 0.001736 0 0 0 -1 -8.5 0 43.5 $right
2301   sq 0.04 0.017778 0.001736 0 0 0 -1 8.5 0 43.5 $left
2303   pz 46 $right
2304   pz 54 $right
2305   py 1.5 $right
2306   px -5.4 $right
2307   pz 55 $left
2308   py 1 $left
2309   px 8 $left
c     ovaries (2400)
2400   sq 1 4 0.25 0 0 0 -1 6 0 15 $left
2401   sq 1 4 0.25 0 0 0 -1 -6 0 15 $right
c     pancreas (2500)
2500   sq 0.003906 0.694444 0.091827 0 0 0 -1 -1 0 37
2501   px -1
2502   pz 37
c     spleen (2600)
2600   sq 0.081633 0.25 0.027778 0 0 0 -1 11 3 37
c     testes (2700)
2700   sq 0.591716 0.444444 0.189036 0 0 0 -1 1.3 -8 -2.3 $left
2701   sq 0.591716 0.444444 0.189036 0 0 0 -1 -1.3 -8 -2.3 $right
c     thymus (2800)
2800   sq 0.444444 1.5625 0.0625 0 0 0 -1 0 -7.3 57

```

```

c      thyroid          (2900)
2900   pz  75
2901   c/z 0 -4 2.2
2902   c/z 0 -4 1
2903   py  -4
2904   px  -0.8
2905   px  0.8
c      urinary bladder & contents      (wall : 3000, contents : 3001)
3000   sq 0.040681 0.083628 0.083628 0 0 0 -1 0 -4.5 8
3001   sq 0.045154 0.097291 0.097291 0 0 0 -1 0 -4.5 8
c      uterus          (3100)
3100   sq 0.145679 0.036699 0.405696 0 0 0 -1 0 -2 14
3101   py -4.62
c      skin (3200)
c      head & neck skin
3200   sq 0.015625 0.01 0 0 0 0 -1 0 0 0          $head
3201   sq 0.015625 0.01 0.019561 0 0 0 -1 0 0 91.45 $head
3202   cz 5.4          $neck
c      trunk skin (3300)
3300   sq 0.0025 0.01 0 0 0 0 -1 0 0 0
3301   pz 70
c      breast skin
3302   sq 0.040812 0.052847 0.058064 0 0 0 -1 10 -8.660254 52
      $left breast
3303   sq 0.040812 0.052847 0.058064 0 0 0 -1 -10 -8.660254 52
      $right breast
c      leg & genitalia skin(leg skin : 3400, genitalia skin :3401)
3400   gq 1 1 0 0 0 -0.2 -20 0 0 0 $ left leg skin
3401   gq 1 1 0 0 0 0.2 20 0 0 0 $ right leg skin
3402   pz -80
c      esophagus (3500, thoracic portion + abdominal portion)
3500   sq 0.730514 5.668934 0 0 0 0 -1 0 2.575 0
3501   sq 1.321178 69.444444 0 0 0 0 -1 0 2.575 0
3503   5 cx 0.7
3504   5 px 0.1
3505   5 px 7.8
c      outside(5000)
5000   so 1000
c      shielding
8000   sq 0.0016 0.004444 0 0 0 0 -1 0 0 0
8001   sq 0.001479 0.003906 0 0 0 0 -1 0 0 0
8002   pz -82
8003   pz 100
8004   pz 12.179
8005   pz 12.821
C      prostate
9000 s 0 -6.0025 2.505 2.2

c physics cards
mode p e
phys:p,e 3 0 0 1j 1
c *****
c transformations
tr1  3.5 5 38 0.615661 0.788011 0 -0.788011 0.615661 0 0 0 1
tr2  -3.5 5 38 0.615661 -0.788011 0 0.788011 0.615661 0 0 0 1
tr3  -4.5 -3.2 30 0.9615 0 -0.2748 -0.0574 0.9779 -0.2008
      0.2687 0.2090 0.9403
tr4  1 -1.8 50 0.6751 -0.4727 -0.5664 -0.464 0.3249 -0.8241 0.5736 0.8191 0
tr5  0 2.575 42.3 0.736084 -0.604969 -0.303634 0.634945 0.772557 0
      0.234575 -0.192791 0.952789
C *****
C SOURCE DEFINITION
C *****

```

```
C 99 I-125 Brachytherapy seeds
C 0.03549 MeV gamma
sdef erg=.03549 par= 2 pos=d1
SI1 L 0 -5.5025 4.305
      0 -5.0025 4.305
      -.5 -6.0025 4.305
      -.5 -5.5025 4.305
      -.5 -5.0025 4.305
      .5 -5.0025 4.305
      .5 -5.0025 4.305
      .5 -5.0025 4.305
      -1 -6.0025 4.055
      -1 -5.5025 4.055
      -1 -5.0025 4.055
      -.5 -6.0025 4.055
      -.5 -5.5025 4.055
      .5 -6.0025 4.055
      1 -6.0025 4.055
      1 -5.5025 4.055
      1 -5.0025 4.055
      -1 -6.0025 3.805
      -1 -5.5025 3.805
      -1 -5.0025 3.805
      -.5 -6.0025 3.805
      -.5 -5.5025 3.805
      .5 -6.0025 3.805
      1 -6.0025 3.805
      1 -5.5025 3.805
      1 -5.0025 3.805
      -1 -6.0025 3.555
      -1 -5.5025 3.555
      -1 -5.0025 3.555
      -.5 -6.0025 3.555
      -.5 -5.5025 3.555
      .5 -6.0025 3.555
      1 -6.0025 3.555
      1 -5.5025 3.555
      1 -5.0025 3.555
      -1.5 -6.0025 3.305
      -1.5 -5.5025 3.305
      -1.5 -5.0025 3.305
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      1 -5.5025 3.305
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      1.5 -5.0025 3.305
      -1.5 -6.0025 3.055
      -1.5 -5.5025 3.055
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      1 -5.5025 3.055
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      1.5 -5.0025 3.055
      -2 -5.0025 2.805
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      -1.5 -5.0025 2.805
      2 -6.0025 2.805
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2 -5.5025 2.805
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-1.5 -5.5025 1.805
-1.5 -5.0025 1.805
-.5 -6.0025 1.805
-.5 -5.0025 1.805
.5 -6.0025 1.805
.5 -5.5025 1.805
.5 -5.0025 1.805
1.5 -6.0025 1.805
1.5 -5.5025 1.805
SP1 D 1 1 1 1 1 1 1 1 1 1
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1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
C *****
C TALLIES
C *F8 tally used for energy deposition per transformation (Mev/trans)
C *****
*f18:p,e 1700
fc18 Energy deposition (MeV/trans) for small intestine
*f68:p,e 1900
fc68 Energy deposition (MeV/trans) for descending colon wall
*f78:p,e 1901
fc78 Energy deposition (MeV/trans) for descending colon contents
*f88:p,e 1902
fc88 Energy deposition (MeV/trans) for sigmoid colon wall
*f98:p,e 1903
fc98 Energy deposition (MeV/trans) for sigmoid colon contents
*f108:p,e 2700
fc108 Energy deposition (MeV/trans) for testes

```

```

*f118:p,e 3000
fc118 Energy deposition (MeV/trans) for urinary bladder wall
*f128:p,e 3001
fc128 Energy deposition (MeV/trans) for urinary bladder contents
*f138:p,e 6000
fc138 Energy deposition (MeV/trans) for prostate
c
*****
c MATERIAL CARDS
c
*****
c      material card m2=soft tissue m3=bone m4=lung
m2      1000      -0.10454
        6000      -0.22663
        7000      -0.0249
        8000      -0.63525
        11000     -0.00112
        12000     -0.00013
        14000     -0.0003
        15000     -0.00134
        16000     -0.00204
        17000     -0.00133
        19000     -0.00208
        20000     -0.00024
        26000     -0.00005
        30000     -0.00003
        37000     -0.00001
        40000     -0.00001
m3      1000      -0.07337
        6000      -0.25475
        7000      -0.03057
        8000      -0.47893
        9000      -0.00025
        11000     -0.00326
        12000     -0.00112
        14000     -0.00002
        15000     -0.05095
        16000     -0.00173
        17000     -0.00143
        19000     -0.00153
        20000     -0.10190
        26000     -0.00008
        30000     -0.00005
        37000     -0.00002
        38000     -0.00003
        82000     -0.00001
m4      1000      -0.10134
        6000      -0.10238
        7000      -0.02866
        8000      -0.75752
        11000     -0.00184
        12000     -0.00007
        14000     -0.00006
        15000     -0.0008
        16000     -0.00225
        17000     -0.00266
        19000     -0.00194
        20000     -0.00009
        26000     -0.00037
        30000     -0.00001
        37000     -0.00001
nps 1000000
prdmp 2j -1 2j

```

print -130 -140

Section 7: Zubal Head Radiograph

```

mode p
imp:p 1 84r 0
c Left lateral irradiation w/ source plane located 5 cm from skin
surface
sdef erg=30 dir=d3 vec=-1 0 0 pos=24 0 84 rad=d2 ara=1134.115 ext=0
    axs=-1 0 0
si2 h 0 19
sp2 -21 1
si3 H 0.99999 1.0
sp3 0 1.0
c Air [Metzger et al., 1993]
    m1 7014 -.752 7015 -.003 8016 -.232 18000 -.013
c Brain, grey matter [Duck FA, 1990]
    m2 1001 -.107 6000 -.095 7014 -.018 8016 -.767
        11023 -.002 15031 -.003 16000 -.002 17000 -.003
        19000 -.003
c Brain, white matter [Duck FA, 1990]
    m3 1001 -.106 6000 -.194 7014 -.025 8016 -.661
        11023 -.002 15031 -.004 16000 -.002 17000 -.003
        19000 -.003
c Cerebrospinal fluid [Duck FA, 1990]
    m4 1001 -.111 8016 -.880 11023 -.005 17000 -.004
c Eyes [Duck FA, 1990]
    m5 1001 -.107 6000 -.069 7014 -.017 8016 -.803
        15031 -.001 16000 -.001 19000 -.002
c Eye lens, Adult [ICRU Report 46, 1992]
    m6 1001 -.096 6000 -.195 7014 -.057 8016 -.646
        11023 -.001 15031 -.001 16000 -.003 17000 -.001
c Muscle (skeletal), Adult [ICRU Report 46, 1992]
    m7 1001 -.102 6000 -.143 7014 -.034 8016 -.710
        11023 -.001 15031 -.002 16000 -.003 17000 -.001
        19000 -.004
c Skeleton-cranium (whole), Adult [ICRU Report 46, 1992]
    m8 1001 -.050 6000 -.212 7014 -.040 8016 -.435
        11023 -.001 12000 -.002 15031 -.081 16000 -.003
        20000 -.176
c Skeleton-cartilage, Adult [ICRU Report 46, 1992]
    m9 1001 -.096 6000 -.099 7014 -.022 8016 -.744
        11023 -.005 15031 -.022 16000 -.009 17000 -.003
c Skeleton-spongiosa, Adult [ICRU Report 46, 1992]
    m10 1001 -.085 6000 -.404 7014 -.028 8016 -.367
        11023 -.001 12000 -.001 15031 -.034 16000 -.002
        17000 -.002 19000 -.001 20000 -.074 26056 -.001
c Spinal chord [Duck FA, 1990]
    m11 1001 -.107 6000 -.145 7014 -.022 8016 -.712
        11023 -.002 15031 -.004 16000 -.002 17000 -.003
        19000 -.003
c Skin, Adult [ICRU Report 46, 1992]
    m12 1001 -.100 6000 -.204 7014 -.042 8016 -.645
        11023 -.002 15031 -.001 16000 -.002 17000 -.003
        19000 -.001

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c Thyroid, Adult [ICRU Report 46, 1992]
  m13 1001 -.104 6000 -.119 7014 -.024 8016 -.745
      11023 -.002 15031 -.001 16000 -.001 17000 -.002
      19000 -.001 53127 -.001
c Adipose tissue, Adult #2 [ICRU Report 46, 1992]
  m14 1001 -.114 6000 -.598 7014 -.007 8016 -.278
      11023 -.001 16000 -.001 17000 -.001
nps 50000000
rand seed=12343
prdump 2j 1 1 j $create a mctal file at the end of the run
print -85 -128 $no output over lattice, reduce memory usage
FIR5:p -80 0 84 0 25 0 84 0 0 0 $radiograph tally
FS5 -20 200i 20 $radiograph vertical resolution
C5 -20 200i 20 $radiography horizontal resolution
phys:p 1j 0 0 1j 0
notrn $no transport of particles (transmission only)
```


APPENDIX B

COMMON MATERIAL SPECIFICATIONS

Air

m1 7014 -0.7808 8016 -0.2095 18000 -0.0093 \$Air

ICRU 46 Adult Whole Brain (Density=1.040 g/cc)

m100 1001 -0.107
 6000 -0.145
 7014 -0.022
 8016 -0.712
 11023 -0.002
 15031 -0.004
 16000 -0.002
 17000 -0.003
 19000 -0.003

ICRU 46 Skeleton, Whole Cranium (Density=1.610 g/cc)

m200 1001 -0.050
 6000 -0.212
 7014 -0.040
 8016 -0.435
 11023 -0.001
 12000 -0.002
 15031 -0.081
 16000 -0.003
 20000 -0.176

ICRU Adult Skin (Density=1.090 g/cc)

m300 1001 -0.100
 6000 -0.204
 7014 -0.042
 8016 -0.645
 11023 -0.002
 15031 -0.001
 16000 -0.002
 17000 -0.003
 19000 -0.001

Medical Physics Air (Density=0.0013 g/cc)

m400 6000 -0.00012
 7014 -0.75527
 8016 -0.23178
 20000 -0.01283

Soft Tissue (Density=1.04 g/cc)

m2 1000 -0.10454
 6000 -0.22663
 7000 -0.0249
 8000 -0.63525
 11000 -0.00112
 12000 -0.00013
 14000 -0.0003
 15000 -0.00134
 16000 -0.00204
 17000 -0.00133

19000	-0.00208
20000	-0.00024
26000	-0.00005
30000	-0.00003
37000	-0.00001
40000	-0.00001

Bone (Density=1.40 g/cc)

m3	1000	-0.07337
	6000	-0.25475
	7000	-0.03057
	8000	-0.47893
	9000	-0.00025
	11000	-0.00326
	12000	-0.00112
	14000	-0.00002
	15000	-0.05095
	16000	-0.00173
	17000	-0.00143
	19000	-0.00153
	20000	-0.10190
	26000	-0.00008
	30000	-0.00005
	37000	-0.00002
	38000	-0.00003
	82000	-0.00001

Lung (Density=0.296 g/cc)

m4	1000	-0.10134
	6000	-0.10238
	7000	-0.02866
	8000	-0.75752
	11000	-0.00184
	12000	-0.00007
	14000	-0.00006
	15000	-0.00008
	16000	-0.00225
	17000	-0.00266
	19000	-0.00194
	20000	-0.00009
	26000	-0.00037
	30000	-0.00001
	37000	-0.00001

APPENDIX C

DOSE CONVERSION CONSTANTS

Recall from Section 3 that the C value used in Equation 3.1 to calculate dose per source particle includes material-specific quantities such as the molar mass of the material and the number of atoms per molecule in the material. The dose conversion (C) constants for air, water, Lucite, and tissue are shown below.

Air – 6.6222×10^{-12} Gy/source photon

Water – 1.6045×10^{-11} Gy/source photon

Lucite – 1.4436×10^{-11} Gy/source photon

Tissue – 1.5787×10^{-11} Gy/source photon

Additional dose conversion constants can be calculated using the Equation 3.1 as needed.