U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

NUREG/CR-6918, Rev.1

VARSKIN 4: A COMPUTER CODE FOR SKIN CONTAMINATION DOSIMETRY

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at http://www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, in the Code of *Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402–0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: U.S. Nuclear Regulatory Commission
Office of Administration
Publications Branch
Washington, DC 20555-0001
E-mail: DISTRIBUTION.RESOURCE@NRC.GOV
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address http://www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-6918, Rev. 1

VARSKIN 4: A COMPUTER CODE FOR SKIN CONTAMINATION DOSIMETRY

Manuscript Completed: April 2011
Date Published: June 2011

Prepared by
D.M. Hamby, C.J. Lodwick, T.S. Palmer, S.R. Reese, and K.A. Higley

Department of Nuclear Engineering and Radiation Health Physics
Oregon State University
Corvallis, OR 97331-5902

M. Saba, NRC Project Manager

Prepared for
Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

ABSTRACT

The original VARSKIN computer code, an algorithm to calculate skin dose from radioactive skin contamination, has been modified on several occasions. Last version of this code, VARSKIN 3, enables users to calculate the skin dose (from both beta and gamma sources) attributable to radioactive contamination of skin or protective clothing. The code also offers the ability to compute the dose at any skin depth or skin volume, with point, disk, cylindrical, spherical, or slab (rectangular) sources, and even enables users to compute doses from multiple sources. The input data file was also modified for VARSKIN 3 to reflect current physical data, include the dose contribution from internal conversion and Auger electrons, and allow a correction for low-energy electrons.

The VARSKIN 4 code is designed to operate in both Windows® and MacIntosh® environments and is expected to be significantly easier to learn and use than its predecessors. PC and MAC users will download different executable files, but the functionality is identical. Five different predefined source configurations are available in VARSKIN 4 to allow simulations of point, disk, cylinder, sphere, and slab sources. Improvements to VARSKIN 4 include an enhanced photon dosimetry model, as well as models to account for air gap and cover materials for photon dosimetry. Although the user can choose any dose-averaging area, the default area for skin dose calculations in VARSKIN 4 is 10 square centimeters, to conform to regulatory requirements pursuant to Title 10 of the *Code of Federal Regulations*, Section 20.1201(c). Data entry is condensed to a single screen, and the user does not need to enter the data in any particular order. A variety of unit options are provided, including both British and International System (SI) units, and the source strength can be entered in units of total activity or distributed in units of activity per unit area or activity per unit volume. The output page and the user's ability to add radionuclides to the library are greatly simplified. A library file contains data on photons, internal conversion electrons, and Auger electrons. VARSKIN 4 allows the user to eliminate radionuclides that are not of interest and thus build a customized library. Finally, an extensive, context-sensitive help file is made available to provide guidance and to offer new users a tutorial in the use of VARSKIN.

VARSKIN 4 introduces an upgraded photon dosimetry model without changing any previous modeling schemes for beta dosimetry. The enhanced photon model accounts for photon attenuation, charged particle buildup, and electron scatter at all depths in skin. The model allows for volumetric sources and clothing/air gaps between source and skin. The syringe model (available in previous versions of VARSKIN) has been removed from use in VARSKIN 4 because it was not sufficiently detailed to yield accurate dose results and most of users of the code did not find it useful.

This document describes the VARSKIN 4 code, which is used by the NRC staff to perform confirmatory calculations of licensees' submittals regarding skin dose estimates. This report provides basic operating instructions, presents detailed descriptions of dosimetry models, and suggests methods for avoiding misuse of the code.

CONTENTS

FIGURES

TABLES

ACKNOWLEDGMENTS

This report was prepared to document work performed by Oregon State University (OSU) for the U.S Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES). RES first initiated the development of the VARSKIN code at the Pacific Northwest Laboratory in 1987. VARSKIN is used by the NRC to independently verify licensees' submittals pertaining to dose assessment. NRC subsequently funded development later versions at Colorado State University and the Center for Nuclear Waste Regulatory Analyses.

We are appreciative of the technical assistance received from J. Caffrey, S. Marshall, and M. Ryan in the production of this report and its findings. Our beta testers included J. Chase, J. Dubeau, K. Sejkora, M. Thornhill, R. Struckmeyer, and J. DeCicco. We are also grateful to S. Bush-Goddard, M. Saba, and S. Sherbini for their support during the development process of the enhanced photon dosimetry model. Authors of earlier versions of the VARSKIN code were indebted to L. Howard for technical review and D. Turner for programmatic review of reports. These authors also thanked L. Selvey for document preparation; E. Hanson for editorial review; and H. Karagiannis, S. Sherbini, A. Roecklein, S. Bush-Goddard, and E. Dickson of the NRC for their support, suggestions, and patience during the development of VARSKIN 3. The following people helped develop models for VARSKIN 3: J. Chase, B. Plain, M. Wierzbicki, M. Lantz, and K. Krobl. The following people provided comments after testing VARSKIN 3: G. Chabot, J. Dwyer, J. Lebda, E. Mercer, R. Nimitz, A. Salame-Alfie, M. Stabin, G. Sturchio, B. Tharakan, T. Vandermey, and M. Charles.

1 INTRODUCTION

The NRC funded the Pacific Northwest Laboratory (PNL) to develop the original VARSKIN computer code (Traub, et al., 1987) to allow the agency to perform independent confirmatory calculation of skin dose estimates submitted by NRC's licensees to verify their compliance with regulatory requirements specified in 10 CFR Part 20.1201(c). The code was intended as a tool for the calculation of tissue dose at various depths as the result of skin contamination. The contamination was assumed to be a point or an infinitely thin disk source located directly on the skin. Soon after the release of VARSKIN, a "new" type of skin contaminant was discovered. This contaminant consists of discrete microscopic radioactive particles, called "hot" particles. These particles differ radically from uniform skin contamination in that the particles have a thickness associated with them, and many of the skin exposures result from particles on the outside of protective clothing.

Originally, there were a few drawbacks to using VARSKIN to calculate skin doses from hot particles or other contaminants on the skin or outside of a cover material such as protective clothing. Formerly, VARSKIN modeled the contaminant as having no thickness; thus, the calculation did not account for source self-shielding. For example, for hot particles containing weak beta-emitting radionuclides (e.g., cobalt-60 (Co-60)), VARSKIN greatly overestimated calculated skin doses from particles that were thicker than about 1 micrometer ($\gamma\mu$m). Second, VARSKIN did not have the capability of modeling a cover material (e.g., protective clothing) that might exist between the source and skin, again leading to an overestimation of skin dose from skin contamination. Finally, it was shown that the gamma component of a mixed beta/gamma-emitting hot particle becomes increasingly important as the skin depth and the thickness of cover material increase (Durham and Lantz, 1991). Because VARSKIN did not model a cover material or allow skin depths other than 7 milligrams per square centimeter (mg/cm^2), the NRC staff concluded that the photon dose would not be significant compared to the beta dose under these exposure conditions, and thus the code did not include the photon dose model. Because of these and other shortcomings of the code, an upgrade of VARSKIN was needed to provide skin dose calculations under a variety of exposure conditions.

The NRC funded further development of the code and in 1992, VARSKIN Mod 2 was released. This version of the code contained all the features of the original VARSKIN, with many significant additions. Additional features in VARSKIN Mod 2 included the modeling of three-dimensional sources (cylinders, spheres, and slabs) that accounted for self-shielding, modeling of materials placed between the source and skin (including air gaps) that would attenuate beta particles, and, in specific cases, modeling hot particle photon doses. VARSKIN Mod 2 also used a correction for backscatter for one- and two-dimensional beta sources under limited conditions. Finally, the VARSKIN Mod 2 package incorporated a user interface that greatly simplified data entry for calculating skin dose, in addition to providing guidance in the form of help screens.

The upgraded code also contained a volume-averaged dose model and an offset particle model. The volume-averaged model allowed the user to calculate dose averaged over a volume of tissue defined by a cylinder with a diameter equal to that of the dose averaging area and bounded at the top and bottom by two selected skin depths (see Fig. 1-1). This model is useful

for calculations of dose that can then be compared to the dose measured by a finite-volume instrument (e.g., a thermoluminescent dosimeter). The offset particle model, which allows dose to be calculated for a particle that is not centered over the dose area of interest, is useful for calculating dose to a singular given skin area from multiple hot particles.

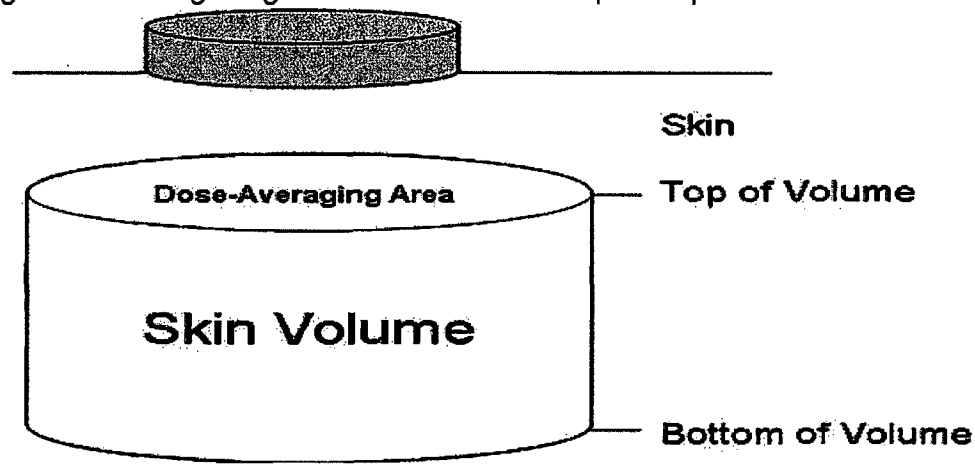

Fig. 1-1 Depiction of cylindrical dose averaging volume

Finally, VARSKIN Mod 2 gave the user the ability to select a composite source term, thus allowing the calculation of total dose from a mixture of beta-emitters instead of requiring the code to be run separately for each radionuclide in the mix. This feature was removed in VARSKIN 3 (Durham 2006), and instead, the maximum number of radionuclides included in a single calculation was increased to 20. One drawback of removing this feature in VARSKIN 3 is that the user must explicitly add radioactive progeny. The VARSKIN 3 photon dose model, which has been greatly improved in VARSKIN 4, was an extension of a model published by Lantz and Lambert (1990) that was the basis for the VARSKIN Mod 2 photon dose model. A syringe model was included in VARSKIN 3 but has been removed in VARSKIN 4; the model employed a major approximation to an actual syringe and, in that respect, had several limitations.

VARSKIN 4 development was initiated to improve the photon dosimetry model. This model includes charged particle buildup and subsequent transient equilibrium, along with photon attenuation, air and cover materials, and volumetric sources. In VARSKIN 3, only point photon sources could be modeled, charged particle equilibrium (CPE) and attenuation were not considered, and cover materials were not modeled.

Section 2 of this report describes the contents of the VARSKIN 4 code package, including instructions for code execution. Section 3 discusses the technical basis for VARSKIN 4 and describes the dosimetry models incorporated in the code, while Section 4 contains the results of validation and verification testing. Section 5 describes the problems and suggestions for improving VARSKIN Mod 2 and VARSKIN 3 that were included in VARSKIN 4, as well as new features of the code and its limitations. Section 6 explains the correct method for modeling "infinite" sources and how to hand-calculate the maximum dose to a single 10-square-centimeter (10-cm^2) area from multiple contamination sources. Additionally, Appendix A provides a graphical display of the results from Section 4, and Appendix B presents three detailed solutions to practical examples using VARSKIN 4.

2 VARSKIN 4 USER'S MANUAL

This section serves as a user's guide for VARSKIN 4. It includes operating instructions and a description of the features of VARSKIN 4.

2.1 Installing VARSKIN 4

The VARSKIN 4 files for the PC and the MAC are located in zipped folders that can be obtained via the Radiation Safety Information Computational Center (RSICC). No installation is necessary on the PC, but MAC users must install "mono", obtained at the site: (http://www.go-mono.com/mono-downloads/download.html). Users must download and unzip the VARSKIN 4 folder and double-click the V4 icon to execute the VARSKIN code. There is no need to uninstall previous versions of VARSKIN. Upgrades to VARSKIN 4 will be made available, as necessary. Obtaining upgrades is as simple as downloading the new zipped folder and beginning execution.

Hardware and Software Requirements: A personal computer with a Pentium II processor or newer is required. The code requires approximately 10 megabytes of disk space. VARSKIN 4 has been tested under a variety of Windows® or MacIntosh® operating systems.

2.2 Running VARSKIN 4

Operations within VARSKIN 4 are designed to be intuitive. After double-clicking the V4 icon, the user will see the Main Input screen (Fig. 2-1). If necessary, the "About VARSKIN 4.0" screen provides the user with contact information and basic code information (Fig. 2-2).

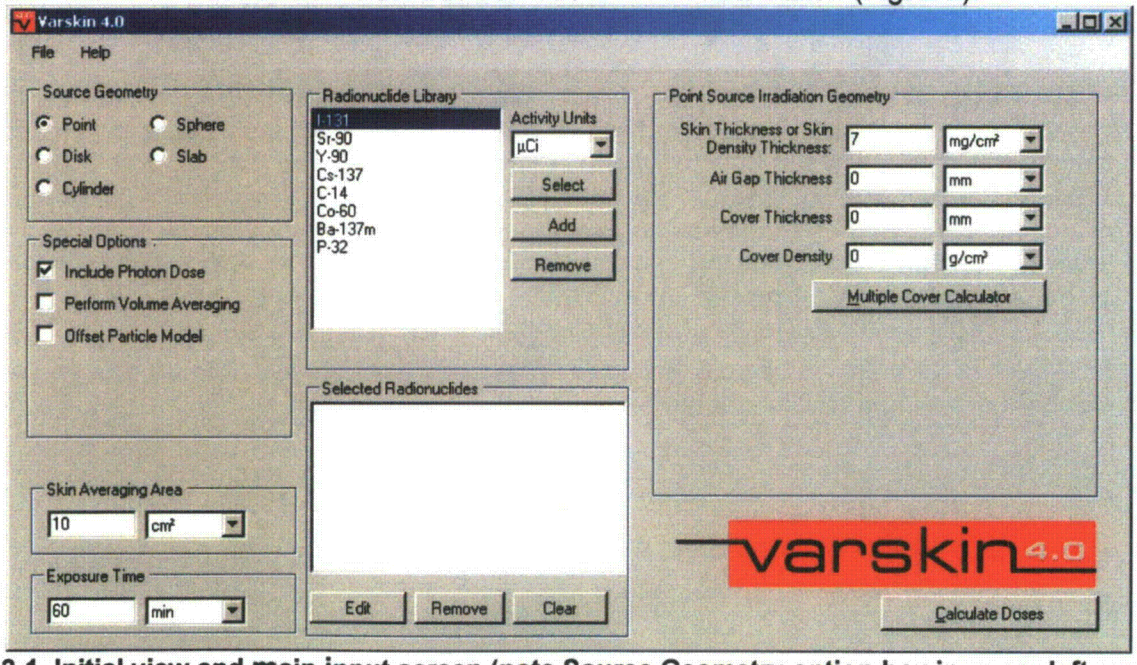

Fig. 2-1 Initial view and main input screen (note Source Geometry option box in upper left corner)

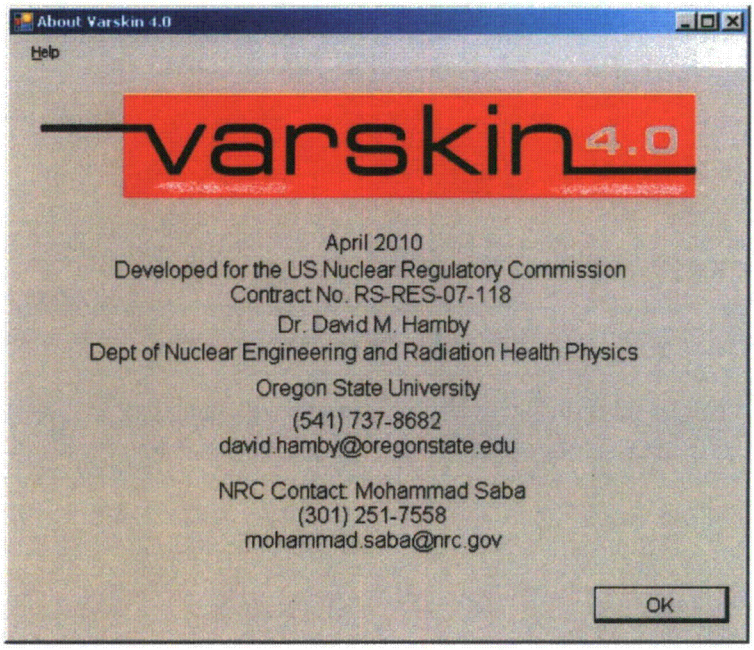

Fig. 2-2 "Form Welcome " screen

Source Geometry. The Source Geometry selection box is shown in the initial view "VARSKIN 4.0" screen in Fig. 2-1. This screen contains all of the input information that is needed to perform a dose calculation. Although VARSKIN 4 allows the user to enter data in any order, the **geometry package must be chosen first** because changing the geometry package will cause certain parameters to appear and others to be removed. Five geometry packages are available: point source, disk source (infinitely thin), cylinder source (thick), spherical source, and slab source (rectangular).

The point source geometry (Fig. 2-3(A)) is very simple to use and should be used as an initial screening tool for contamination that is confined to an extremely small area of the skin, or for a quick calculation to determine whether a regulatory limit is being approached or exceeded. The point source geometry does not account for beta self-shielding, so a three-dimensional source geometry should be used for particulate contamination. The point source model does not require any data for the physical description of the source and will generally yield the highest dose rate for a given activity of any of the available source geometries. For beta dosimetry, VARSKIN 4 models a point source as a cylindrical source with a thickness of 1 μm, a radius of 1 μm, and a density of 0.001 grams per cubic centimeter (g/cm^3). The offset particle model is available only when using the point source geometry.

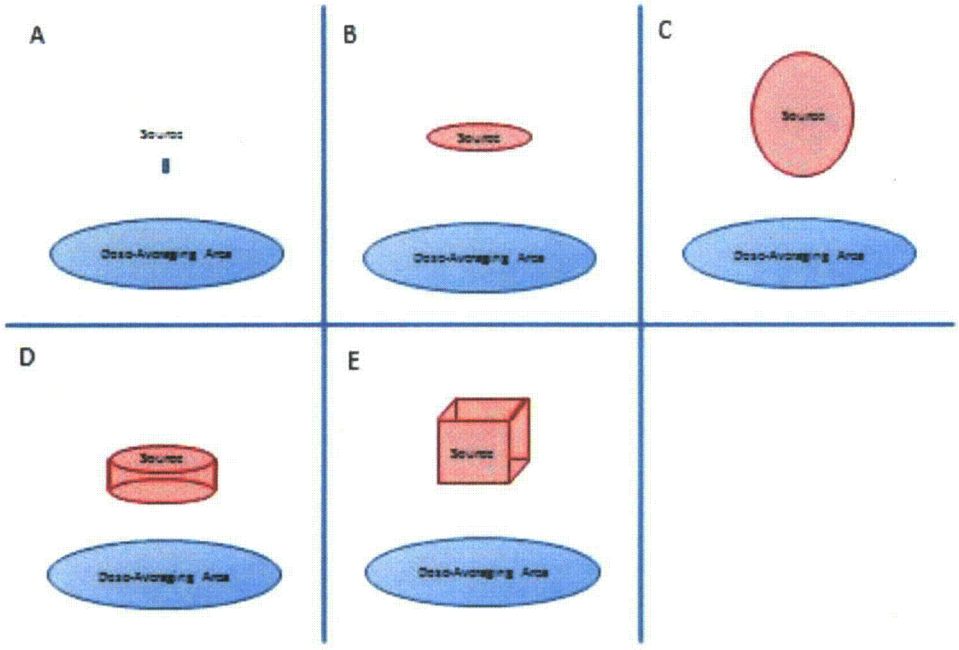

Fig. 2-3. Schematic representations of the five geometry options

The infinitely thin disk source geometry model (Fig. 2-3(B)) is simple and is recommended for modeling skin contamination events caused by liquid sources. The disk source geometry requires the user to enter either the source diameter or the source area at the bottom of the Disk Source Irradiation Geometry box. Entering the area of the contamination is useful for modeling sources when the area is known. Enter the area of the source in the text box labeled "Source Area." When the user enters the diameter of the source area, VARSKIN 4 calculates the area of the circle with that diameter. Similarly, when the user enters the area of the source, VARSKIN 4 calculates the diameter of a circle with the same area. Again, for beta dosimetry, VARSKIN 4 models a disk source as a cylinder with a thickness of 1 μm and a density of 0.001 g/cm^3; for photons, the disk is infinitely thin with no assumed density or thickness. If the area of contamination is not circular, entering the area of the actual contamination will generally result in a reasonable estimation of skin dose.

The spherical source geometry (Fig. 2-3(C)) is perhaps the simplest three-dimensional geometry to use for dose calculations because it requires knowledge of only one source dimension, its diameter. The spherical source geometry assumes that the source is surrounded by air and touches the skin or cover material only at the bottom point of the sphere. For photon dosimetry, it is assumed that the source material is equivalent to air for attenuation calculations. Choosing a spherical source will generally overestimate dose compared to a similarly sized cylindrical source (same radius and length) with the same total activity. The air surrounding the bottom hemisphere does not shield the source particles as efficiently as the source material

(which would be encountered by the particle in the cylinder or slab models), and a larger area of skin will be exposed, resulting in consistently higher doses.

The cylindrical source model (Fig. 2-3(D)) requires knowledge of two dimensions, the cylinder diameter and its height. The cylindrical source geometry assumes that the source is surrounded by air and that the entire bottom of the cylinder is in contact with skin or cover material. Of the two cylinder dimensions, the calculated dose is much more sensitive to changes in the cylinder height as opposed to the cylinder diameter.

The slab source geometry (Fig. 2-3(E)) requires knowledge of three physical dimensions: the first side length, the second side length, and the slab's thickness. As evidenced by the previous VARSKIN Validation Test Plan and Report, results of beta dose calculations using the slab geometry differ by as much as 35 percent from the results obtained using the other four geometries when modeling the same source. This discrepancy is the result of a fundamental difference between the mathematical approach used for the slab geometry and the other geometry packages when modeling similar sources. The slab geometry should be used only when skin dose from multiple, discrete particles is needed, as described in Section 6 (i.e., when the offset particle model is used).

The following general rules should govern the choice of geometry package, progressing from the most conservative to least conservative dose estimate:

- If nothing is known about the particle size and shape, use the point source geometry option. This option is also recommended for a quick comparison to regulatory limits since the point geometry typically overestimates actual skin dose.

- If the diameter is known, but the thickness cannot be estimated, or if a distributed source is being modeled (i.e., with a known source strength per unit area), use the two-dimensional disk source geometry option.

- If the particle is known to be spherical (few particles are truly spherical) and is not imbedded in another material, use the spherical source geometry option.

- If the thickness and the diameter of the source can be estimated, but the shape is unknown, use the cylindrical source geometry option because this geometry requires only two dimensions (height and radius) to describe the particle.

- If the particle is known to be rectangular, use the cylinder source geometry option. The height of the particle should be preserved, and the area of the contact surface should be selected such that the source volume is preserved.

For all source geometries, doses are calculated to an infinitely thin disk centered below the central axis of the source. When using the offset particle model, dose is calculated to the disk with its center located at the user-supplied offset distance from the center of the source.

Adding Radionuclides to the Library. VARSKIN 4 employs two radionuclide libraries, a master library (supplied with the code) that contains data for all radionuclides available to the

user, and a user library that contains only those radionuclides that are selected and added by the user (drawn from the master library). Beta energy emission spectra are obtained from an abridged ICRP–38 (International Commission on Radiological Protection, 1983) dataset using NUCDECAY (RSICC, 1995) data files.

When VARSKIN 4 is first executed, a few preselected radionuclides may appear in the user library. VARSKIN 4 is designed to allow the user to customize the radionuclide library so that only the nuclides of interest can be maintained for ready use. To add a radionuclide to the user library, the user clicks the "Add" button (shown in the upper center of Fig. 2-1), and a new screen appears (Fig. 2-4) that displays every radionuclide for which data are available (a total of 838 radionuclides). Radionuclides are added to the user library by highlighting the radionuclide and clicking the "Add Radionuclide" button, or simply double-clicking the name of the radionuclide. In building the user library, one can specify a minimum photon energy and minimum photon yield (photons per disintegration) to limit calculation times, if necessary. These defaults are set at 2 kiloelectronvolts (keV) and 1 percent, respectively. Computational speeds are generally not an issue; therefore, users are advised to use the default settings when building their library.

Once the "Add Radionuclide" button is selected (Fig. 2-4), calculations are performed internally to populate the user library for the selected radionuclide; this can take up to a few seconds depending on processing power. In these calculations, data are extracted from the data files *ICRP38.dat*, *ICRP38.idx*, and *ICRP.bet* (all of which are located in the *\dat* subdirectory of the application directory). If the radionuclide emits beta radiation, the beta spectrum is generated for one or more beta decay routes. If the radionuclide does not emit beta radiation, a tritium beta spectrum is generated with a yield of 0.001. The generation of this "dummy" spectrum is necessary since *Sadcalc.exe* expects a beta distribution in order to execute. By setting the yield to 1/10th of 1 percent, the contribution of the "dummy" beta spectrum is negligible. Internal conversion and Auger electrons are then added to the beta spectrum. Finally, photon energy and yield data are collected from the data files.

These data are processed by the FORTRAN executable file *Sadcalc.exe*, and an output file that contains the average beta spectrum energy, the electron and beta yield, the X_{99} distance, the scaled absorbed dose distribution, the photon energies, and the photon yields is generated with the extension ".dat." As discussed in Section 3.1, the X_{99} distance is used as the range of the beta particles.

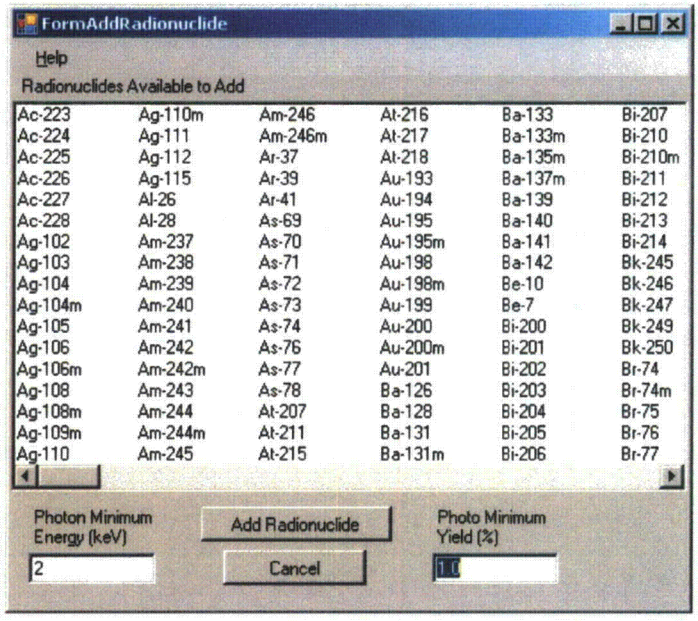

Fig. 2-4 Add Radionuclide screen

When the process of adding the radionuclide is completed, the Source Geometry screen will return, and the added radionuclide will be visible in the user list of available radionuclides. The added radionuclide will remain in the user library for subsequent calculations unless the user purposefully removes it using the "Remove" button (Fig. 2-1) on the Radionuclide Library frame; the nuclide data will always remain in the master library.

In VARSKIN 4, radioactive progeny do not follow their parent in the dose calculations. To have the code consider progeny, the user must create a user library file for each radioactive decay product. Radioactive decay products are not included, regardless of the half-life of the progeny. If evaluating dose from progeny alone, the user must be cautious and be aware of the half-lives of both parent and progeny and include the correct dose calculation (decay corrected or not) in the dose estimate. For example, in the case of ^{137m}Ba as a stand-alone product of ^{137}Cs decay, the user should report the "Dose (No Decay)" result for ^{137m}Ba dose. If the "Decay-Corrected Dose" is used, the very short decay time of ^{137m}Ba will cause the dose to be significantly underestimated, assuming that ^{137m}Ba is continuously supplied by the decay of ^{137}Cs.

Selecting Radionuclides from the User Library. Radionuclides can be selected for a dose calculation by double-clicking the radionuclide name or by highlighting the desired radionuclide and clicking the "Select" button (Fig. 2-1). The default unit of measure for activity is microcuries (μCi). Users may change the activity unit by selecting a different unit from the Activity Units list box. The new unit must be chosen before selecting the radionuclide. When a radionuclide is selected, a message box will appear asking the user to enter the value of the activity in the chosen units. Once the activity is entered, the radionuclide and its activity will be added to the Selected Radionuclide list box. A user may select up to 20 radionuclides for a given calculation.

For geometry packages other than the point source, the "Use Distributed Source" checkbox will appear (Fig. 2-1). The distributed source option allows the user to enter the source strength in

activity-per-unit-area for the disk sources or activity-per-unit-volume for volumetric sources. The distributed source option applies only to radionuclides that are chosen after the checkbox has been selected. If the distributed source option is unchecked, subsequently selected radionuclides will have activities expressed as total inventory instead of distributed activity.

Beta energy emission spectra are obtained from an abridged ICRP–38 (International Commission on Radiological Protection, 1983) dataset using NUCDECAY (RSICC, 1995) data files.

Geometry Parameters and Multiple Cover Calculator. The geometry parameters box (Fig. 2-5, shown on the right above the VARSKIN logo) changes depending on the particular geometry chosen for the calculation (slab geometry in this example). The user can choose the units of each parameter from the drop-down lists provided to the right of each input field. The units can be mixed for the different parameters; VARSKIN 4 makes the necessary conversions internally. Table 2-1 shows the default values for the various parameters.

Default State. VARSKIN 4 allows the user to save one default state for easy retrieval at a later time. If the user wishes to change the default settings of Table 2-1, the following actions should be taken. From the File drop-down menu, if the user selects "Save Default State," a file is written that contains all input parameters for the geometry described at that moment. At a later time, if that geometry is to be run again, the user can select "Load Default State," and all parameter values will return to their values at the time the default state was last saved.

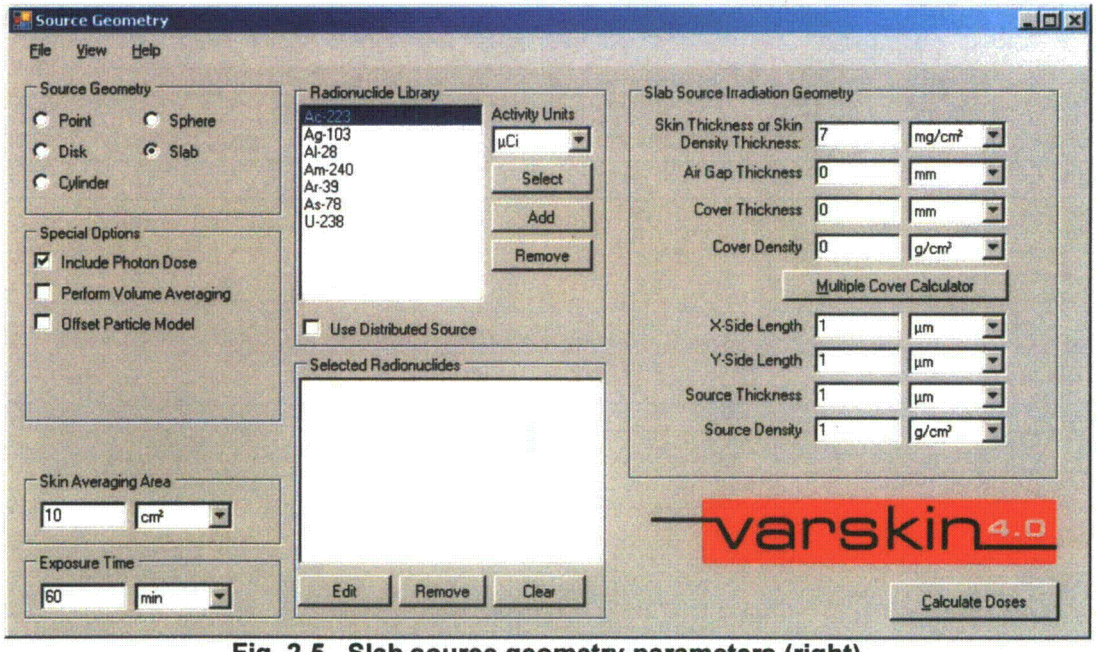

Fig. 2-5 Slab source geometry parameters (right)

In the disk geometry package, the user has the option of entering either the source radius or the source area. The units for the radius will be used when the area of the source is displayed. This feature simplifies data entry for two-dimensional sources where the area and the total activity are known.

Source thickness and source density are equally important for calculating skin dose, especially for beta dosimetry. It is essential that these parameters are known accurately; otherwise, their values should be underestimated so that conservative dose calculations will result. If source dimensions are unknown, the following guidelines will help in choosing appropriate values:

- Diameter (disk and cylinder) and side lengths (slab): The dose calculation for most radionuclides is relatively insensitive with respect to these dimensions for sizes below 2 millimeters (mm) with sources of the same activity. Overestimating source dimensions will generally result in an overestimation of dose, unless the source size is larger than the averaging area.

- Thickness (disk and slab) and sphere diameter: The beta dose calculation for all radionuclides is very sensitive to these dimensions, especially for low-energy beta emitters. Minimizing the value of this dimension will provide an overestimate of beta dose. For photons, these dimensions are not as critical for the dose calculation.

- Source density (three-dimensional geometry models): For beta dosimetry, users should choose a source density that is consistent with the material containing the source. For hot particle contaminations, a typical density for stellite (Co-60) is 8.3 g/cm^3, and a density of 14 g/cm^3 is typical for fuel. For photon dose estimates, the source is assumed to be air, with negligible consequence (see Table 3-3), except for large, dense sources and low-energy photons.

Table 2-1 Default Values and Units for Geometry Parameters

Parameter	Default Value
Skin Density Thickness	7 mg/cm^2
Air Gap Thickness	0 mm
Air Density (@ STP)	0.001293 g/cm^3
Cover Thickness	0 mm
Cover Density	0 g/cm^3
Source Area (Disk)	0.785 mm^2
Source Diameter (Disk)	1 mm
Source Diameter (Cylinder)	1 mm
Source Thickness (Cylinder)	1 μm
Source Diameter (Sphere)	1 mm
Source Thickness (Slab)	1 μm
Source X-Side Length (Slab)	1 μm
Source Y-Side Length (Slab)	1 μm
Source Density (Three-Dimensional Geometries)	1 g/cm^3

Users can model the presence of a cover material and/or an air gap. The schematic drawing below (Fig. 2-6) depicts the cylindrical source geometry to illustrate the cover/gap model. The required input to describe the cover is material thickness and its corresponding density. Both parameters are needed to account for the $1/r^2$ dependence of the Berger point kernel (geometric attenuation) and for the energy loss due to attenuation (material attenuation). For the air gap model, only the thickness of the air gap is required for input.

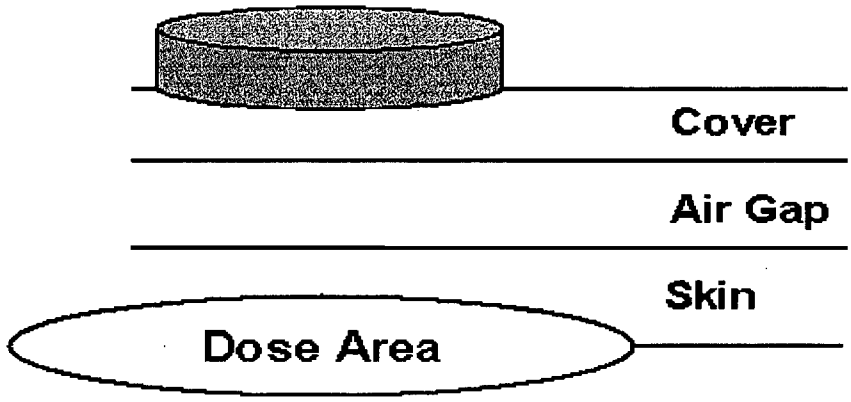

Fig. 2.6 Schematic showing the cover material and air gap models

The physical characteristics of the air gap and cover material can significantly affect the calculated skin dose. While the air gap has little consequence for material attenuation, its effect on geometric attenuation can be significant for beta dosimetry. The air gap in photon dosimetry has the effect of disrupting CPE and can appreciably influence dose at very shallow depths in tissue. Cover materials influence both the geometric and material attenuation. Table 2-2 gives some suggested thickness and density values.

VARSKIN 4 allows multiple cover materials to be modeled as a composite cover when the user clicks on the "Multiple Cover Calculator" button (Fig. 2-1). The multiple-cover calculator allows the user to combine up to five covers (Fig. 2-7). The user must enter a value for two of the following three parameters for each layer (while ensuring that the third parameter is blank): covert, cover density, and cover density thickness. The user can choose the units for density and thickness, but the density thickness must be entered in mg/cm^2. The calculator determines the third parameter, combines the different layers, and calculates an effective thickness and density of the composite cover. The appropriate input boxes in the Source Geometry screen are then populated with the composite cover density (mg/cm^3) and thickness (in cm). If the user enters all three parameters, VARSKIN 4 will indicate an error and ask the user to enter only two of the three parameters for a given layer. The printout from a dose calculation will include the data for each cover layer, as well as the composite cover data.

Table 2-2 Suggested Values for Cover Thickness and Density

Material	Thickness (mm)	Density (g/cm^3)
Lab Coat (Plastic)	0.2	0.36
Lab Coat (Cloth)	0.4	0.9
Cotton Glove Liner	0.3	0.3
Surgeon Glove	0.05	0.9
Outer Glove (Thick)	0.45	1.1
Ribbed Outer Glove	0.55	0.9
Plastic Bootie	0.2	0.6
Rubber Shoe Cover	1.2	1
Coveralls	0.7	0.4

To include more than five covers in the composite cover calculation, the user must calculate the composite cover thickness and density for the first five covers. The user must then run the calculator again and enter the first composite cover thickness and density as one of the layers. Accordingly, if a composite cover is entered as one of the covers, the layers composing the composite cover will not be individually displayed on the printout.

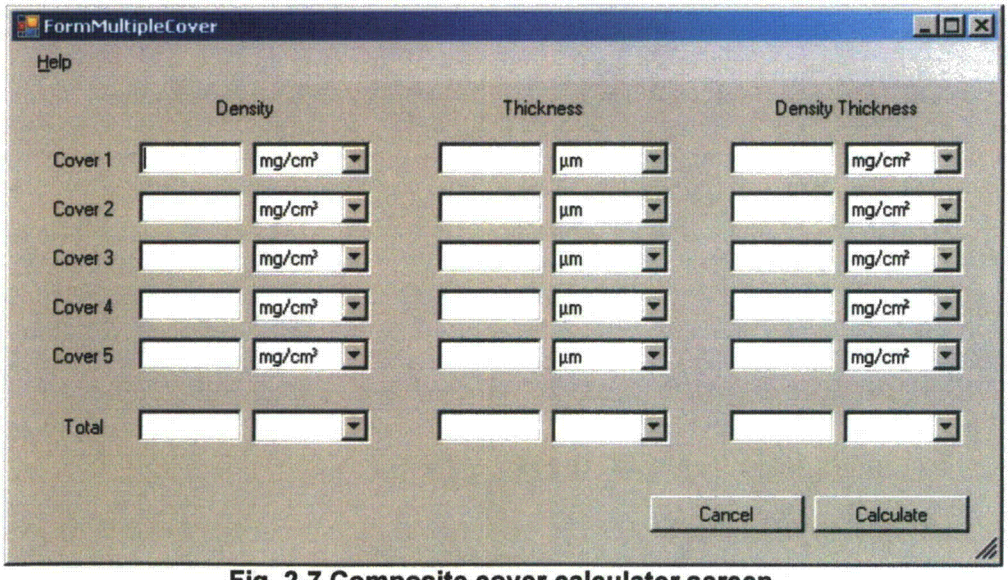

Fig. 2-7 Composite cover calculator screen

Special Options. Depending on the geometry package selected, special options are available that affect the calculation. The first special option, available for all packages, is to include the photon dose in the calculation. The default for this option is to calculate the photon dose, which includes x-rays and gamma rays; the user can, however, de-select this box so the photon dose will not be calculated. If the photon dose option is included when the "Calculate Doses" button is clicked, the photon dose will be calculated for all selected radionuclides. If the radionuclide does not emit photons, a dose of zero will be displayed.
In most cases, the calculated photon skin dose will be negligible relative to the beta skin dose. A noteworthy exception to this is evident when modeling Co-60 or other low-energy beta emitters with significant photons. A cover material can easily shield low-energy beta particles without appreciably affecting photon dose. In this case, the photon dose will account for the majority of the calculated skin dose.

The second special option allows the calculation of dose to be averaged over a volume of tissue defined by a cylinder of specific diameter and thickness. The use of the volume-averaged dose calculation can be important, for example, in evaluating the dose between 10 mg/cm^2 and 15 mg/cm^2, as recommended by the International Commission on Radiological Protection (1991), for evaluating the dermal effects of skin dose.

If volume averaging is chosen, the user is prompted (after selecting the "Calculate Doses" button) to enter the skin density thicknesses associated with the boundaries (shallow and deeper tissue depths defining the cylindrical averaging volume). Skin density thickness must be entered in units of mg/cm^2. A range of suggested values for the shallow and deep tissue depths is provided based on the physical range of beta particles associated with the selected radionuclide(s). Suggested values are from a skin density thickness of 0 mg/cm^2 to the maximum penetration depth of the beta particle(s) being modeled; however, any nonnegative value of density thickness can be entered. The user is cautioned, therefore, to be certain of the depths requested; some depths may result in negative values for beta dose. The VARSKIN 4 model calculates the average dose over the averaging area at 10 discrete depths between the shallow and deep tissue depths (Fig. 2-8). Thus, the volume-averaged dose model requires 10 times more execution time than that for a single depth.

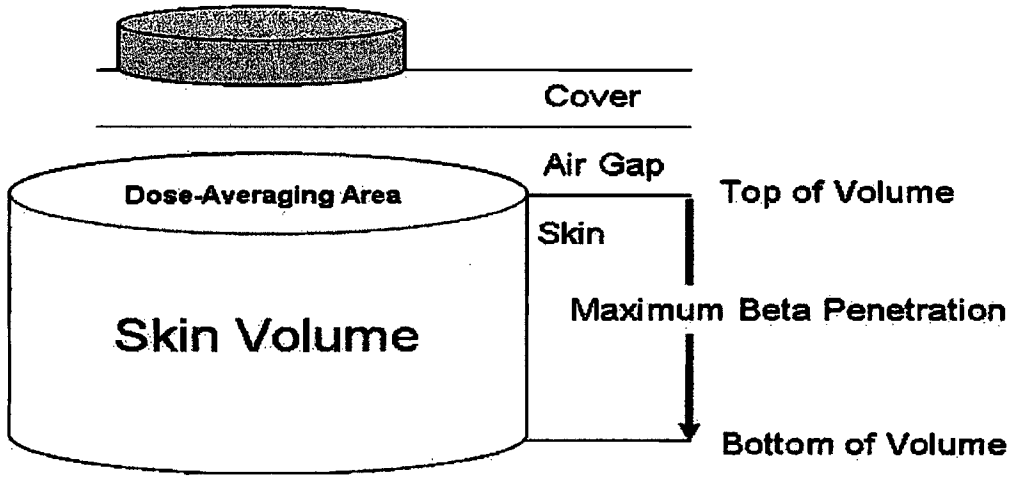

Fig. 2-8 Schematic diagram of the volume-averaged dose model geometry

When the point source geometry is selected, the "Offset Particle Model" checkbox appears in the Special Options frame. The offset particle model, which allows dose to be calculated for a particle that is not centered over the dose area of interest, is useful for calculating dose from multiple hot particles. The offset particle model is normally not accessed unless selected by the user. When the "Offset Particle Model" box is checked, the user is prompted to enter the offset distance. The offset distance is the lateral distance between the point source and the center of the dose area. The value of the offset is the only additional input value that is required for the model. The results screen (including the volume-averaged dose results screen) will display the offset value, if this option has been selected. Section 6.2 describes in more detail the use of the offset particle model.

Calculating Doses. Once the desired geometrical parameters and options have been selected, the user initiates the calculation by clicking the "Calculate Doses" button (Fig. 2-1). A progress bar will appear below the VARSKIN logo, which will scroll repeatedly depending on the complexity of the calculations. The number of radionuclides to be analyzed and the various options that have been selected will impact the calculation time.

VARSKIN 4 calculates dose using compiled FORTRAN programs entitled *VarCalc.exe* and *GamCalc.exe*. When the user clicks the "Calculate Doses" button, the GUI writes the input data in a file called *output.dat*. *Varcalc.exe* and *GamCalc.exe* read *output.dat*, perform the calculations, and then write results to a file entitled *results.dat*. The GUI reads *results.dat* and displays the results of the calculation. Fig. 2-9 depicts the logic flow diagram. Note that *output.dat* and *results.dat* are internal files and are not intended to be accessed or edited by the user.

Output Screen. The Results screen for a nonvolume-averaged calculation (Fig. 2-10) is displayed immediately after the dose calculation is completed. The screen is separated into three distinct sections: results for individual radionuclides (upper left quadrant), combined results for all radionuclides (upper right quadrant), and source input data (lower half).

In the individual results section of the initial display, only the results for the first radionuclide are shown. The results from other radionuclides are displayed by highlighting the radionuclide of interest in the list box (upper left). This screen will display only the contribution to the dose from the selected radionuclide. The combined results section displays the total dose for all radionuclides. The data in this section cannot be edited and will not change unless a new calculation is made. This section of the output screen also contains unit selection bubbles, which allow the user to select dose results in English or International (SI) units.

The lower half of the results screen contains a mirror of the input data entered in the Source Geometry screen. The format of this section will change depending on the geometry chosen for the calculation. This section of the output screen also contains buttons that allow the user to perform certain functions. Clicking the "Print Results" button will send a hard copy of all results to the default Windows printer. VARSKIN 4 will not allow the user to change the default printer. Additionally, the program will fail if a printer is not installed when the "Print Results" button is selected. The user will be asked to supply a title for the printed output, and then the output file will be sent to the printer. VARSKIN 4 does not allow the user to save the output as a computer file; the only record of the calculation is the printout. However, the user may save the input data to the calculation by selecting the "Return to Geometry Screen" button and using the file

operations buttons as described above. This button can also be used to change a parameter in the current calculation or to start a new calculation. Finally, the "Exit Program" button allows the user to end VARSKIN 4.

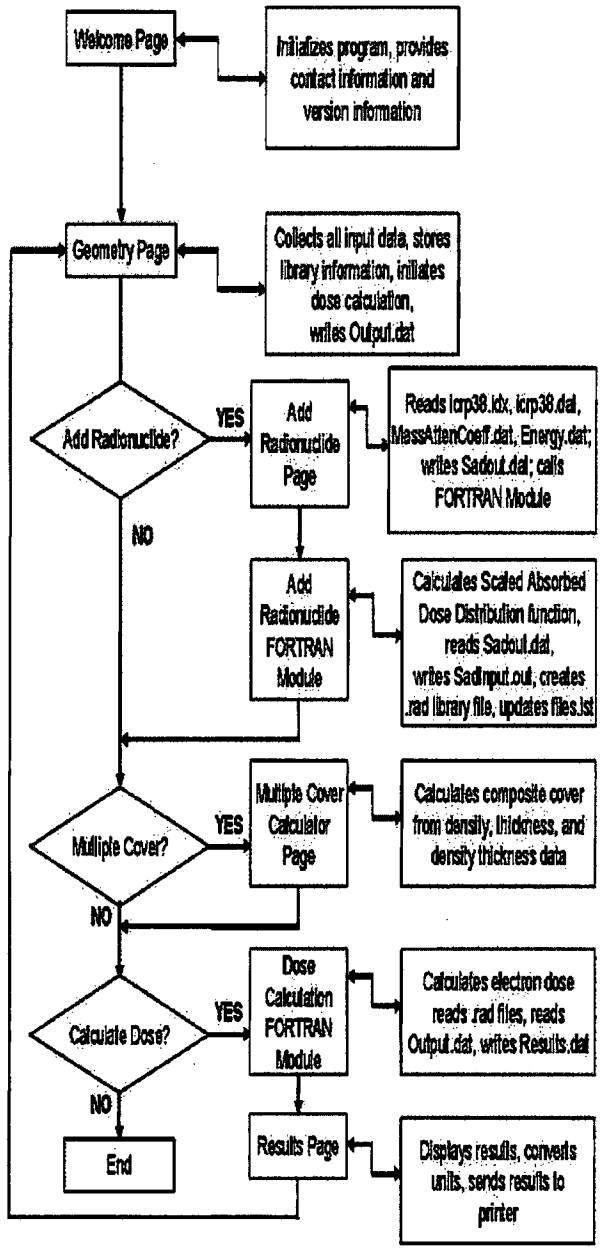

Fig. 2-9 Logic flow diagram

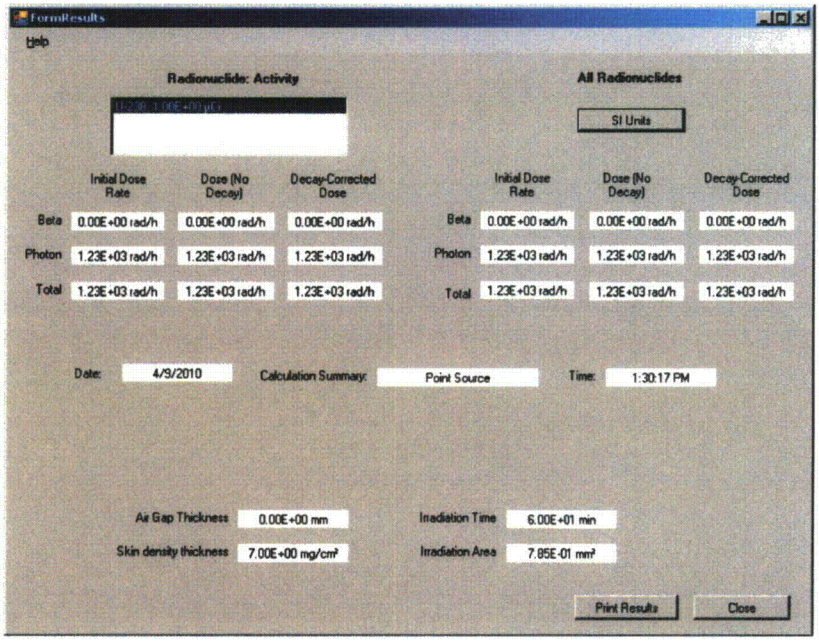

Fig. 2-10 Results screen for a typical calculation

A slightly different screen will appear for volume-averaged dose calculations (Fig. 2-11). Because the dose can be averaged over different averaging volumes for different radionuclides, VARSKIN 4 does not provide a section for combined results of a volume-averaged dose calculation. Instead, only the results from the highlighted radionuclide are displayed. The upper left section of the volume-averaged results screen displays values of the shallow and deep skin depths, as well as the total volume over which the dose was averaged for the chosen radionuclide. Other radionuclides can be chosen individually by highlighting them in the radionuclide list box. As with the other results screen, this output screen contains unit-selection bubbles allowing the user to select volume-averaged dose results in English or SI units. Again, a summary of the input parameters is displayed on the lower half of the screen.

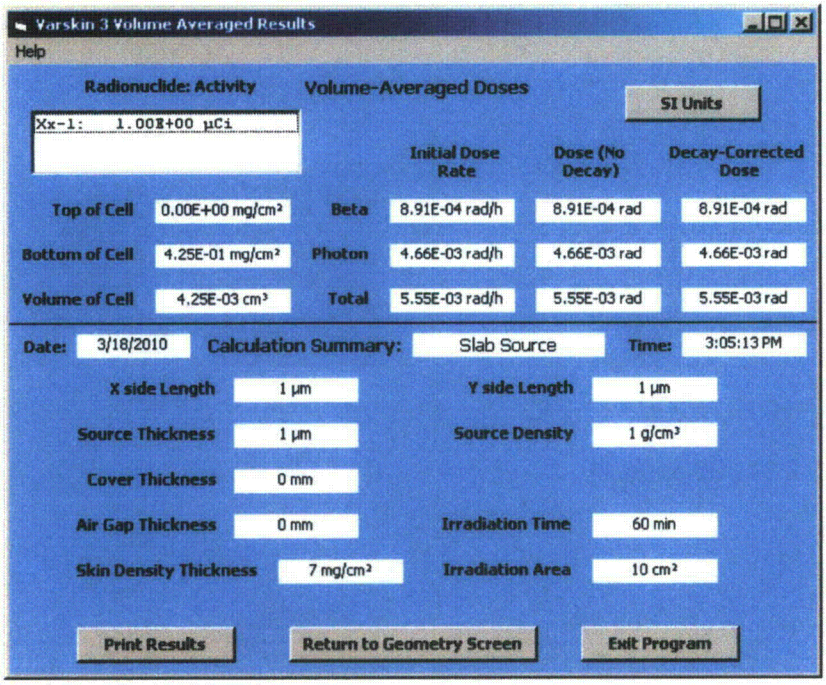

Fig. 2-11 Results screen for a volume-averaged calculation

Exiting VARSKIN 4 The VARSKIN 4 code is exited from the main screen (Fig. 2-1), either by clicking the "X" in the upper right corner or by selecting "Exit" from the File drop-down menu. Before exiting, the user is asked if the current input file is to be saved. When the "Yes" button is clicked, the user is asked to create a file name in which the input data will be saved so that the calculation can be recreated. Clicking the "No" button will cause the program to end without saving the current data. Clicking the "Cancel" button will return the user to the main screen.

Data from a saved file are stored with a *.vs3* extension. When a saved file is recalled (by selecting "Open" from the File drop-down menu), VARSKIN 4 reads the *.vs3* to obtain the data for the calculation. These are internal files, not intended to be used or edited by the user.

3 DESCRIPTION OF DOSIMETRY MODELS

VARSKIN 4 includes enhancements to the photon skin dosimetry model which this chapter describes in detail. In addition, improvements to models that were used in VARSKIN Mod 2 and VARSKIN 3 are incorporated in VARSKIN 4 and are also described here. The beta dosimetry model was not altered during the transition from VARSKIN 3 to VARSKIN 4.

3.1 Beta Dosimetry

VARSKIN 4 calculates beta dose using the same method as in VARSKIN Mod 2 and VARSKIN 3. In general, VARSKIN 4 performs a five-dimensional integration of the source volume and the target area. With the exception of the slab model, the integration is simplified significantly because the dose is symmetric for a circular target area centered under the source.

VARSKIN 4 calculates the beta dose rate by performing a numerical integration of the Berger point kernel (Berger, 1971). This dose kernel per nuclear transition (nt) is written as:

$$B(r) = \frac{k \cdot \bar{E}_\beta \cdot Y \cdot F_\beta\left(r_1/X_{99}\right)}{\pi \cdot \rho \cdot r^2 \cdot X_{99}} \qquad [3\text{-}1]$$

where,

$B(r)$ = the dose rate to a point at a distance r from the source (rad hr^{-1} nt^{-1});
r = the distance between source point and dose point (cm);
k = a unit conversion constant (rad g MeV^{-1} hr^{-1});
$\bar{E}_\beta$ = the average beta emission energy for the radionuclide (MeV nt^{-1});
Y = the beta yield per disintegration (nt^{-1});
$F_\beta\left(r_1/X_{99}\right)$ = the Berger scaled absorbed dose distribution (unitless);
ρ = the density of the irradiated medium (g cm^{-3}; assumed to be unity for tissue);
r_1 = the modified path length between source point and dose point (cm); and
X_{99} = the distance within which 99 percent of beta energy is deposited (cm).

The X_{99} distance is defined as the radius of a sphere of water surrounding a point source of beta radiation in which 99 percent of the beta energy is deposited. In VARSKIN 4, the beta-particle range is chosen as the X_{99} distance, where X_{99} is equal to 1.8 times the X_{90} distance cited in Berger (1971). VARSKIN 4 calculates $F_\beta\left(r_1/X_{99}\right)$ for the selected radionuclide when that nuclide is added to the user library (described later in this section).

For the purpose of illustrating a dose calculation for a symmetrical source, the following discussion focuses on the cylindrical source geometry (Fig. 3-1). VARSKIN 4 chooses a point located near the center of the irradiation area (dose point). The code then divides the source into very small subvolumes (source points). The contribution from each source point to the

dose point is evaluated using Eq. [3-1] and the contributions are summed. The total contribution (in units of rad hr^{-1} nt^{-1}) is multiplied by the source strength (in units of nt) to determine the dose rate to the dose point. This procedure is repeated for each of 60 dose points beginning at the center of the irradiation area and extending to its edge. The dose points are then averaged over the irradiation area to determine dose rate to that area.

Presented in more detail, the integration is performed by choosing 60 dose points (i.e., points at which the dose rate is to be calculated, shown as "–" in the lower portion of Fig. 3-1), along a radius of the dose-averaging disk at a specified dose depth. Since the source geometry is symmetric about the dose-averaging area, dose points represent concentric isodose circles that describe the radial dose profile at a given depth in skin. For each of the 60 dose points, a numerical integration is performed over the area of the cylindrical source at a given height in the source represented by 8 elevations, 8 radii, and 8 angular locations.

The integration starts by choosing one of the eight elevation points ("+") in the source. At one of these elevations, one of eight concentric circles ("*") is chosen. One of these circles is then subdivided into eight source points at 45-degree angles from each other (angular source points "X"). Finally, the dose rate is calculated at each dose point from each of these eight source points at a given elevation and radius. The contribution to the dose from the first four points is compared to the contribution of the last four points in a given circle. If the relative difference between the two contributions is less than 0.01 percent, then convergence of the integral for the circle is considered to be achieved, and the procedure is repeated at the next radial position ("*"). If the relative difference between the two contributions is greater than the relative error, each of the two contributions is further subdivided into eight additional source points, and the above procedure is repeated for each of the two sets of eight points. This process, known as the Newton-Cotes eight-panel quadrature routine, provides a fast and accurate method of numerically integrating complex functions such as the Berger point kernel.

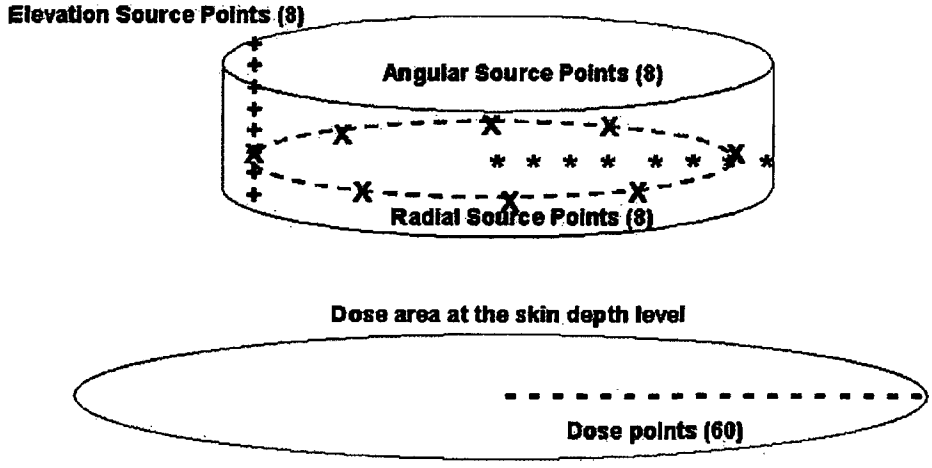

Fig. 3-1 Schematic representation of a dose calculation for a symmetric source

dose rate at a dose point ("-") is calculated using the quadrature integration routine according to the equation:

$$D(d) = S_V \int_0^{2\pi} \int_0^R \int_0^Z \acute{r} \cdot B(z, \acute{r}, \theta)\, dz\, d\acute{r}\, d\theta \qquad [3\text{-}2]$$

where S_V is the volumetric source strength and z is the depth ("+") in the source cylinder. A similar equation can be written for spherical and slab geometries. These equations are:

$$D(d) = S_V \int_0^{\pi} \int_0^{2\pi} \int_0^{R} \acute{r} \cdot sin\theta \cdot B(\acute{r}, \theta, \phi)\, d\acute{r}\, d\theta\, d\phi \qquad [3\text{-}3]$$

in the spherical geometry, where θ and ϕ are the azimuthal and polar angles, respectively, and:

$$D(d) = S_V \int_{-x_{max}}^{x_{max}} \int_{-y_{max}}^{y_{max}} \int_0^{Z} B(\acute{r}, \theta, \phi)\, dz\, dy\, dx \qquad [3\text{-}4]$$

in the slab geometry.

The dose rate at the next dose point is then calculated until values are obtained at all 60 dose points. If the dose profile defined by these 60 points as a function of target radius $\acute{d}$ is denoted $D(\acute{d})$, then the dose rate averaged over an area at depth in the skin is calculated using,

$$\overline{D} = \frac{2\pi \int_0^{R} D(\acute{d}) \cdot \acute{d}\, d\acute{d}}{\pi R^2} \qquad [3\text{-}5]$$

The 60 dose points are not chosen linearly from the center of the irradiation area to its outer radius. Instead, the dose points are selected such that more points are chosen where the dose profile has the largest gradient. Typically, this occurs at the edge of the source. Increasing the number of dose points in the area where the dose is changing the most increases the accuracy of the average dose calculation.

When modeling a three-dimensional source, attenuation caused by the presence of the source material and attenuation attributable to geometry (i.e., $1/r^2$ attenuation) must be addressed. The VARSKIN 4 code determines the attenuation within the source material by calculating the path lengths within the source, outside the source but above the skin, in the cover material (if any), and in the skin. Each of the path lengths is then modified by multiplying the path length by the ratio of the material density to tissue density. The individual modified path lengths are then summed to obtain the total modified path length, r_1, for Eq. [3-1].

3.2 Backscatter Model

VARSKIN Mod 2 introduced a backscatter model that has the effect of reducing the calculated dose from point and thin disk sources. The backscatter correction was needed because the Berger point kernel (Berger, 1971) dose model assumes that the source is located in an infinite, homogeneous medium. Thus, the calculation of dose includes the contribution from beta particles that are emitted away from the skin and subsequently scattered back toward the skin to contribute to skin dose. Therefore, when the Berger point kernel is used to calculate skin dose from an infinitely thick (point or disk) source, the calculation will overestimate the actual skin dose. Depending on the maximum energy of the beta energy spectrum, the overestimate can be as high as 40 percent (Cross, et al., 1992). VARSKIN Mod 2 applies an energy- and depth-dependent backscatter correction to doses calculated for point and disk sources. The

backscatter factor is the ratio of the dose from a source in an infinite medium to that from a source in a finite medium (e.g., with the source backed by air). An infinite medium would be defined as one in which its dimensions are larger than the X_{99} distance of the beta-energy spectrum.

The backscatter correction in VARSKIN Mod 2 was based on data calculated by Cross, et al. (1992) for point and disk sources and dose calculations averaged over 1 cm^2. Fig. 3-2 shows the backscatter correction as a function of X_{99} distance. In VARSKIN 3 and VARSKIN 4, the backscatter model extends to areas of up to 10 cm^2 and includes a correction for three-dimensional sources that have dimensions less than the X_{99} distance in the source material.

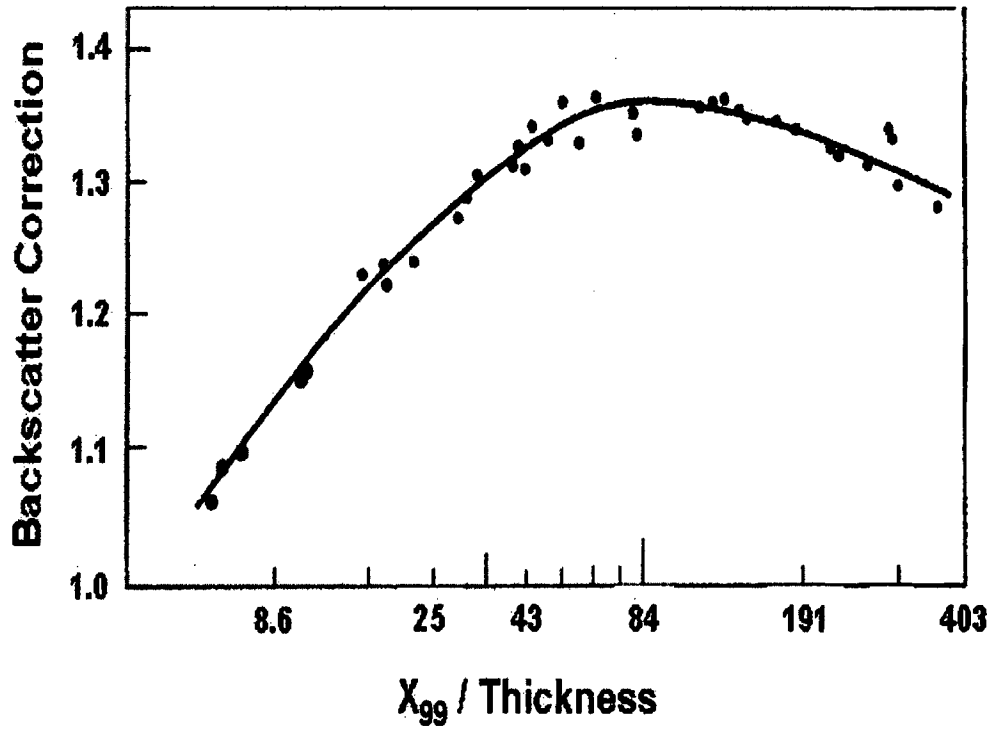

Fig. 3-2 Backscatter correction factor for infinitely thin and point sources (redrawn from Durham, 1992)

A backscatter correction is needed for three-dimensional sources that have dimensions that are smaller than the range of the beta particles emitted by the source. The particle range for a given beta emitter is not a discrete value because of electron straggling. In VARSKIN 4, the range is assumed to be equal to the X_{99} distance (i.e., the radius of a sphere of water surrounding a point source of beta radiation in which 99 percent of the beta energy is deposited).

Calculations for the backscatter model were performed using the Monte Carlo Transport Code MCNP4c2 (RSICC, 2001). The source was modeled as a uniformly distributed cylindrical source with a height equal to its diameter. For the infinite-medium model, the source was

assumed to be surrounded by water (Fig. 3-3a). For the air-skin interface model, the region above the source was modeled as air (Fig. 3-3b). Note that the tissue in Fig. 3-3 extends to the top of the source for both cases. The source was modeled in this fashion because only the effect of backscatter on the ratio of the doses was of interest. If the sides of the source were not covered in the air-skin interface model, the beta particles emanating from the sides of the source would affect the dose ratios for reasons other than backscatter because a larger area would be irradiated. Iron (ρ = 7.86 g/cm^3) was assumed as the source material, and the height of the cylinder was varied between 1 μm (the diameter of point source in VARSKIN 3) and the nuclide-specific X_{99} distance.

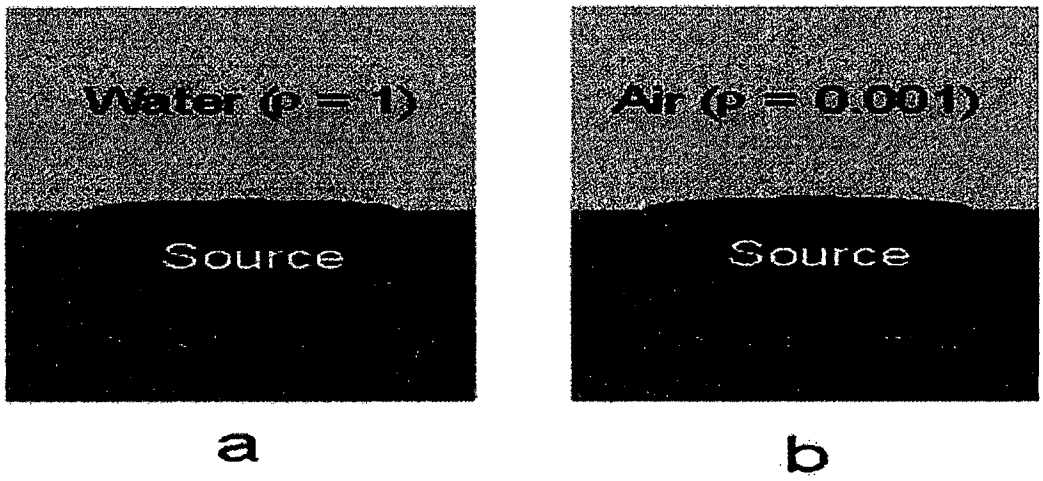

Fig. 3-3 Geometry used for MCNP calculations for the backscatter model

Four different radionuclides were used as sources that emitted very low-, low-, intermediate-, and high-energy beta particles. Table 3-1 presents the radioactive attributes of each of the four sources. Beta energy emission spectra for the four radionuclides were obtained from the computer code NUCDECAY (RSICC, 1995).

For each data point, 1 million particles were generated in the source with a uniform emission angle for each simulated geometry. The simulations were used to calculate the energy flux, sorted into 15 different energy bins, of beta particles passing through a circular disk located 70 μm below the bottom of the source. The dose was determined by multiplying the flux in each bin by the average stopping power for that energy bin and summing the results. Values for mass stopping power were obtained from the National Institute of Standards and Technology (Berger, et al., 2006). The calculated quantity of interest was the ratio of the flux in the infinite-medium model to the flux in the air-interface model.

Figure 3-4 displays (1) the ratio of flux in the infinite medium (water) to the flux in air and (2) the ratio of dose in the infinite medium to dose in the finite medium as a function of the source size expressed as a percent of the X_{99} distance for ^{147}Pm. With the exception of very shallow depths, the ratio of fluxes and ratio of doses are essentially the same. This trend was observed for all four radionuclides. Since the VARSKIN Mod 2 model is sufficient for small particles, the remaining figures show only the ratio of fluxes as a function of the X_{99} distance. Figs. 3-5 through 3-7 contain the ratio of fluxes as a function of the size of the particle-expressed fraction

of the X_{99} distance for strontium (Sr)-90, thallium (Tl)-204, and yttrium (Y)-90, respectively.

Table 3-1 Radioactive Characteristics of the Sources Modeled for the Backscatter Correction

Nuclide	Average Energy (keV)	Maximum Energy (keV)	Range in Iron (ϒm)
Pm-147	62	225	38
Sr-90	196	546	182
Tl-204	244	763	297
Y-90	935	2,280	1,190

A common trait of all four figures is a steadily diminishing correction factor with depth in the source. The correction approaches unity as the size of the source approaches the range of the beta particles (the X_{99} distance). When the source size is expressed as the fraction of the X_{99} distance, all four figures are similar, with the exception of sources with sizes less than 5 percent of the X_{99} distance. The backscatter correction associated with these extremely small sources is similar to that applied to infinitely thin sources in VARSKIN Mod 2. Thus, the backscatter correction applied to sources with a height of less than 5 percent of the X_{99} distance is the same backscatter correction applied to point and disk sources.

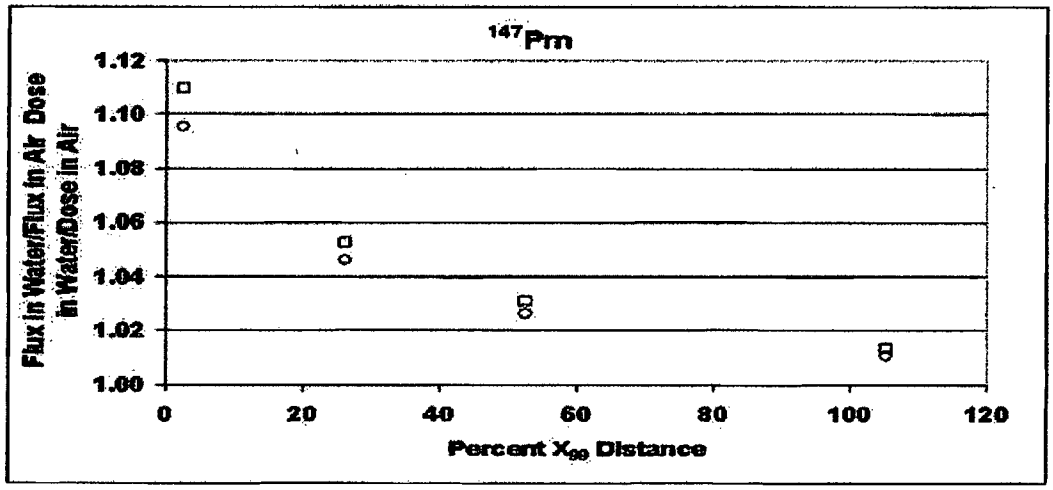

Fig. 3-4 Figure showing the ratio of flux in water to flux in air (squares), and a similar ratio of doses as a function of source size normalized to the X_{99} distance (circles), for Pm-147.

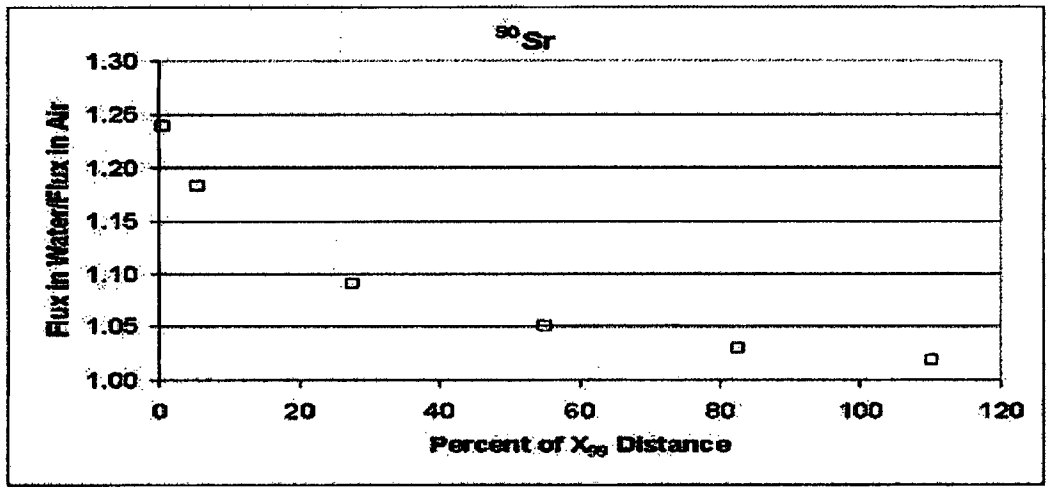

Fig 3-5 Ratio of flux in water to flux in air for Sr-90

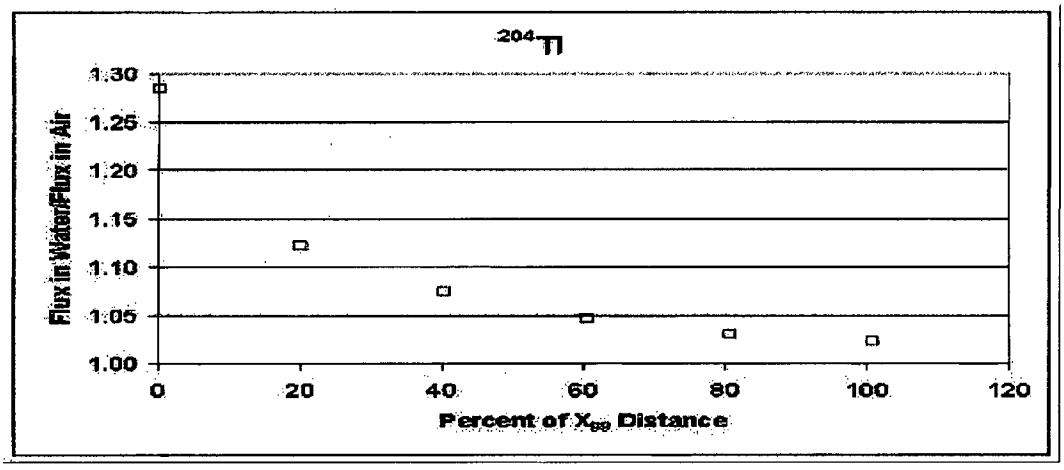

Fig. 3-6 Ratio of flux in water to flux in air for Tl-204

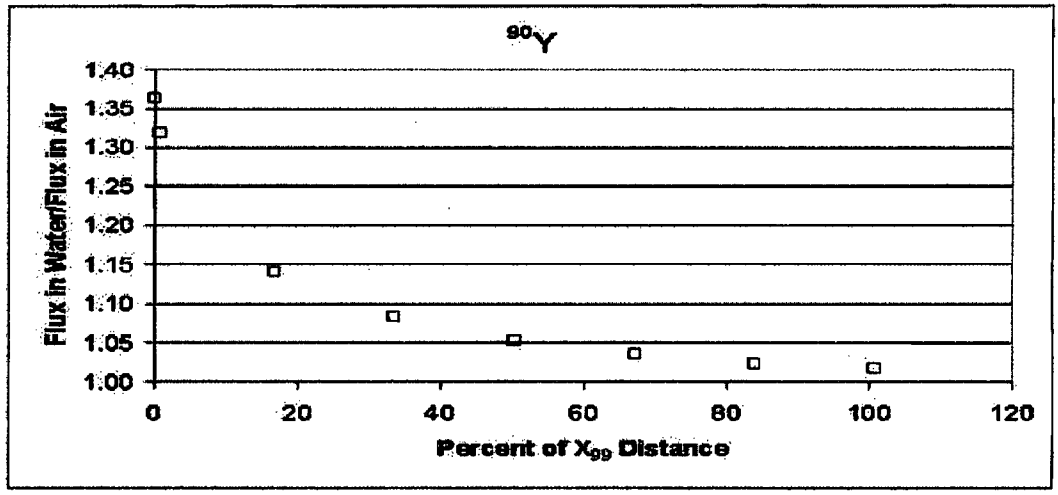

Fig. 3-7 Ratio of flux in water to flux in air for Y-90

The data in Fig. 3-8 are obtained by taking the data from Figs. 3-4 through 3-7 and consolidating them for all sources greater in size than 5 percent of the X_{99} distance. The empirically determined trend line (R^2 = 0.98) represents the backscatter correction factor (BCF) as a function of the fraction of X_{99} distance and is given by,

$$BCF = 1.018 - 0.060\ ln\left({}^{\Delta t}/_{X_{99}}\right) \qquad [3\text{-}6]$$

where Δt is the source thickness (or diameter for spheres).

In VARSKIN 4, the BCF is applied to the calculated dose for three-dimensional sources with a thickness, Δt, that is less than the X_{99} distance in the source material. If the source thickness is less than 5 percent of the X_{99} distance in the source material, then the BCF for a point source is applied. For sources with a thickness greater than the X_{99} distance, no backscatter correction is applied because the source is "infinitely thick" and the Berger kernel is accurate for these sources.

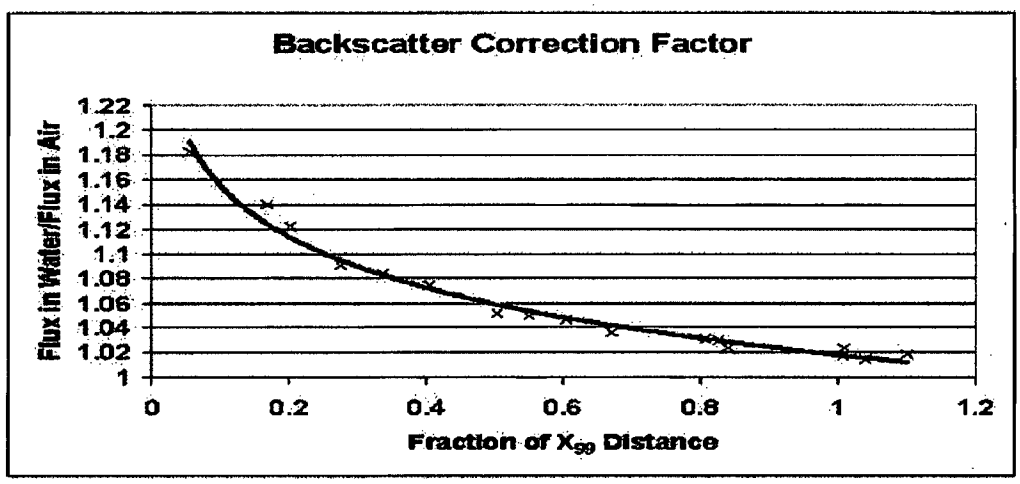

Fig. 3-8 Combined data for the four radionuclides

The VARSKIN 4 backscatter correction model also accounts for material located between the source and the skin depth of interest. For sources with a thickness of less than 5 percent of the X_{99} distance, the BCF changes when the source is not in contact with the skin. The BCF does not change with depth for sources with a thickness greater than 5 percent of the X_{99} distance in the source material.

3.3 Cover Layer and Air Gap Models

Cover materials and air gaps can be modeled using VARSKIN 4. The models use the concept of effective path length to determine the beta energy lost in either a cover material or air before it enters the skin. The path length is not the true path traversed by the beta particle; it is merely a mathematical convenience introduced to provide a measure of the energy lost in each layer. To prevent unintended applications of VARSKIN 4, the air gap is limited to a maximum of 5 cm.

Fig. 3-9 illustrates the method used to determine path length within the source and within the cover material. For the pictured cylindrical source, the known values in the figure are the source radius (R_{max}), the horizontal distance from the centerline to the source point (S_{RAD}), the source thickness (S_{THICK}), the cover thickness (C_{THICK}), the skin depth (S_{DEP}), the source and cover densities (ρ_s and ρ_c, respectively), the angular distance from the center of the dose area to the dose point (P_s), and the distance from the skin to the plane of the source point (D_{RAD}).

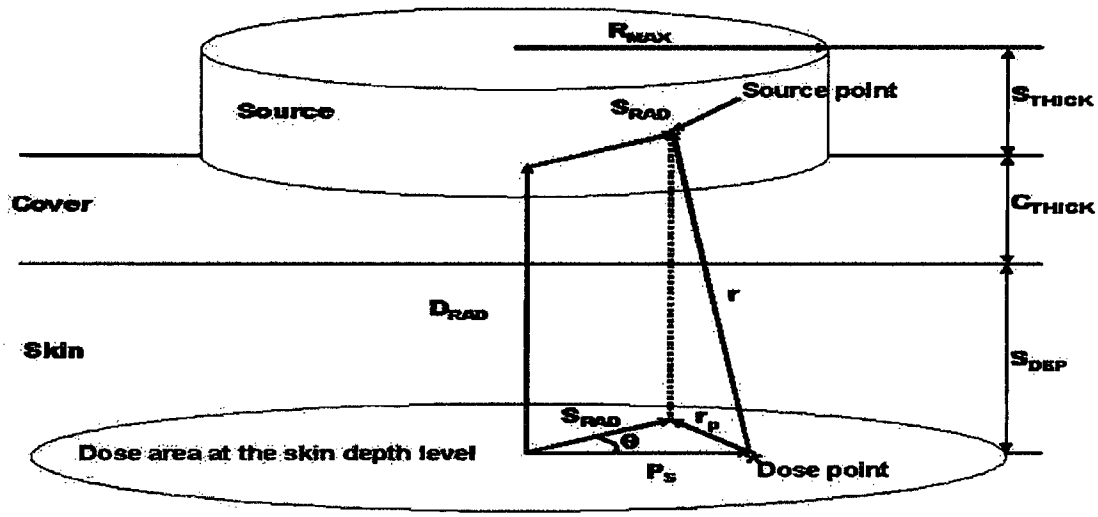

Fig. 3-9 Schematic drawing of a generic dose calculation performed by VARSKIN 4 for the cylinder geometry

The quadrature routines are coded to choose values for S_{RAD}; the distance from the centerline to the P_s source point; θ, the angle between S_{RAD} and P_s; and D_{RAD}, the height of the dose point. The first quantity to be calculated is r, the physical distance from a source point to a dose point. To do this, the square of the projected distance, r_p^2, is calculated using the law of cosines:

$$r_p^2 = P_s^2 + S_{rad}^2 - 2P_s S_{rad} cos\theta \qquad [3\text{-}7]$$

The quantity r is used in the denominator of the expression in Eq. [3-1] and represents the geometric attenuation between the dose point and the source point. This quantity is further analyzed to calculate the modified path length used to evaluate the scaled absorbed dose distribution.

By the law of similar triangles, the ratio to r of each of the actual distances along r through the source, the cover material, and the tissue is the same as the ratios of the thickness of the cover material to D_{RAD}, the thickness of tissue layer to D_{RAD}, and the remaining distance along r to D_{RAD} respectively, provided that the line connecting the dose point and the source point exits through the part of the source that is in contact with the cover material. Thus, the distance traveled through the cover material is written as the following:

$$r_c = C_{thick} \cdot \left({}^{r}/_{D_{rad}}\right). \qquad [3\text{-}8]$$

The distance traveled through the skin is given by:

$$r_t = S_{dep} \cdot \left({}^{r}/_{D_{rad}}\right). \qquad [3\text{-}9]$$

Finally, the distance traveled through the source is given by:

$$r_s = \left(D_{rad} - C_{thick} - S_{dep}\right) \cdot \left({}^{r}/_{D_{rad}}\right). \quad [3\text{-}10]$$

For beta dosimetry, the modified path length r_1 is then found using the following equation:

$$r_1 = \frac{(r_s\rho_s + r_c\rho_c + r_t\rho_t)}{\rho_t} \quad [3\text{-}11]$$

where ρ_t is the density of tissue, assumed to be equal to that of water (1 g cm^{-3}).

For small-diameter sources, the path between the dose point and the source point may pass through the side of the source (e.g., the path may exit the sources and pass through air before passing into skin). Thus, the quantity in Eq. [3-11] must be further analyzed to determine the path length within the source and the path length outside the source but above the level of the cover material. The actual path length within the source is multiplied by the source density, and the path length outside the source and above the cover material is multiplied by the density of the material outside the source, assumed to be air.

In spherical geometry, the physical distance from source point to dose point is given by:

$$r_p^2 = P_s^2 + S_{rad}^2 sin^2\phi - 2P_s S_{rad} sin\phi cos\theta. \quad [3\text{-}12]$$

In slab geometry, the physical distance is given by:

$$r = \sqrt{[(X_{source} - X_{dose})^2 + (Y_{source} - Y_{dose})^2 + (Z_{source} - Z_{dose})^2]}. \quad [3\text{-}13]$$

3.4 Volume-Averaged Dose Model

The volume-averaged dose model (shown schematically in Fig. 2-8) allows the calculation of dose averaged over a given tissue volume. Any two planes of irradiated skin can be assigned to bound the skin volume. For sources in contact with the skin, the maximum penetration depth for beta particles is equal to the X_{99} distance. Doses averaged over the dose-averaging area are calculated at 10 skin depths between two limits set by the user, and a cubic spline (a third-order piecewise polynomial curve fit) is fit to this depth-dose distribution. When the user specifies the skin depths corresponding to the volume of interest, VARSKIN 4 integrates the depth dose function over the region of interest to obtain the volume-averaged dose.

3.5 Offset Particle Model

The offset particle model allows calculation of skin dose averaged over areas that are not directly beneath the contaminant. This model was developed to determine dose to a single averaging area resulting from multiple hot particles. The offset particle model is available only for the point geometry. It requires only one input variable, the distance of the offset. For multiple particle irradiations, the dose from each particle must be calculated separately, with the user running VARSKIN 4 once for each particle. The offset particle model does not calculate

the maximum dose to skin from several particles (Section 6.2 outlines the iterative process for determining the maximum dose to the dose-averaging area); rather, the user must manually add doses from each of the sources to a common dose-averaging disk at depth.

3.6 Adding Radionuclides to the VARSKIN 4 Library

Radionuclides are added to the VARSKIN 4 user library through the use of a FORTRAN executable file entitled *Sadcalc.exe*. The purpose of the program, which is an adaptation of a stand-alone program formerly called SADDE Mod 2 (Reece, et al., 1989), is to produce a data file that contains the information needed to calculate both beta and photon doses. For beta doses, the data file includes four of the variables that are shown in Eq. [3-1] for a chosen radionuclide. These variables include the average beta energy, $\bar{E}_\beta$; the beta yield, Y; the X_{99} distance (which is used to establish the range of the beta particles); and the scaled absorbed dose distribution, $F_\beta\left({}^{r_1}/_{X_{99}}\right)$. These data are calculated using the method described by Berger (1971). The X_{99} distance is used in VARSKIN and has been adapted from the X_{90} concept introduced by Berger (1971) in order to simplify the concepts. The relation between X_{90} and X_{99} is given by the following:

$$X_{99} = 1.8X_{90}. \qquad [3\text{-}14]$$

In VARSKIN 4, beta spectra are obtained from the data file *ICRP38.BET*, which is located in the *\dat* subdirectory of the VARSKIN 4 folder and contains the maximum energy and the yield information for each of a number of energy bins defined in the file *ENERGY.DAT* (also located in the *\dat* subdirectory). The beta yield for the radionuclide is determined by summing each of the values in *ICRP.DAT*. A file that is associated with the beta spectra is *ICRP.IDX*, an index file (also located in the *\dat* subdirectory) used to quickly locate data in the large *ICRP.DAT* file. Also included in *ICRP.DAT* is information on any internal conversion or Auger electrons emitted by the radionuclide. The GUI collects the beta spectrum for a selected radionuclide and writes a file entitled *SadInput.dat* which contains the radionuclide name, the yield, the half-life, the maximum beta energy, the beta spectrum, and the energy and yield of any electrons. *Sadcalc.exe* reads this file; adds any electrons to the beta spectrum to form a new spectrum that includes internal conversion and Auger electrons; calculates $\bar{E}_\beta$, Y, the X_{99} distance, and $F_\beta\left({}^{r_1}/_{X_{99}}\right)$; and then writes these data to the file *sadout.dat*. The GUI reads *sadout.dat*, adds the photon data, and writes the library file with the extension *.rad*. The user enters the name of the file when prompted by the GUI. Note that *sadout.dat* and *sadinput.dat* are internal files and are not intended to be used or modified by the user.

A total of 838 radionuclides are available in the master library, each of which could be added to the VARSKIN 4 user library. Once a radionuclide is added to the library, it is available to be used in all subsequent calculations until the user purposefully removes the radionuclide from the library. Note that not all of the 838 radionuclides emit beta particles, electrons, or photons; some of the radionuclides emit only alpha particles, which do not contribute to skin dose. In that case, the user will be notified that the radionuclide does not emit these types of radiation, and no library file will be produced. If the radionuclide emits photons and/or electrons but no beta particles, then the following occurs. First, a tritium spectrum is generated with a yield of 0.001. Any electrons are added to the tritium spectrum, and the photon parameters are calculated for the user library file. *Sadcalc.exe* then executes a calculation of $F_\beta\left({}^{\tau_1}/_{X_{99}}\right)$ for the tritium spectrum and any electrons. This procedure is necessary because *Sadcalc.exe* requires that a beta spectrum be present to calculate the scaled absorbed dose distribution. Tritium was chosen because of its extremely low energy, and the low yield was chosen to minimize the impact of dose from the imaginary tritium spectrum. The presence of the tritium spectrum will result in the calculation of a very small beta dose contribution in the rare case of dose calculations at extremely shallow depths (i.e., depths less than 2 mg/cm^2) for radionuclides that do not emit beta particles.

3.7 Photon Dosimetry

The photon dose model implemented by VARSKIN 4 is new and is an improvement to the basic photon model used in VARSKIN 3. The photon model uses a point kernel method that considers the buildup of CPE, transient CPE, photon attenuation, and off-axis scatter. The photon dose model has many of the basic assumptions carried in the beta dosimetry model, namely that the source can be a point, disk, cylinder, sphere, or slab and that dose is calculated to an averaging disk immediately beneath the surface of skin at a depth specified by the user. Photon dose is calculated for a specific skin averaging area, also specified by the user.

A major problem associated with deterministic photon dosimetry is that of determining the amount of charged particle buildup and electron scatter within shallow depths. Federal law (Title 10 of the *Code of Federal Regulations* (10 CFR) Section 20.1201(b)) states that a dose averaging area of 10 cm^2 is appropriate for skin dosimetry (specifically at the shallow-dose equivalent depth of 0.007 cm in tissue (i.e., 7 mg/cm^2 in unit density material)). Penetrating radiation dosimetry also involves the calculation or determination of the lens-dose equivalent (at a depth of 0.3 cm) and the deep-dose equivalent (at a depth of 1 cm) in tissue. Throughout this section, the word "depth" is meant to indicate the distance from the skin surface to some point directly beneath a point source, normal to the skin surface.

To begin the explanation of the dose model, we assume the simple instance of a volume of tissue exposed to a uniform fluence, Φ_0, of uncollided photons of energy, E, from a point source in a homogeneous medium. When we ignore attenuation and assume that CPE is established, the dose to any and every point in that volume of tissue is,

$$D(E) = \Phi_0 \cdot E \cdot \left(\frac{\mu_{en}}{\rho}\right)_{tissue} \qquad [3\text{-}15]$$

where $\left(\frac{\mu_{en}}{\rho}\right)_{tissue}$ is the energy-dependent mass energy absorption coefficient for tissue. With this calculation of dose, we essentially assume that the volume is infinitely thin and that interactions occur in two dimensions, normal to a beam of incident photons. The uncollided fluence originating from a point source can be determined by,

$$\Phi_0 = \frac{S}{4\pi d^2}, \qquad [3\text{-}16]$$

where S has units of photons emitted per nuclear transition (i.e., yield), and d is the distance between the source and dose locations, in an infinitely large homogeneous volume. Thus, a point kernel tissue dose per transition at distance, d, from a point source can be calculated for radionuclides emitting i photons of energy E and yield y, given that,

$$Dose\left[\frac{\text{Gy}}{\text{nt}}\right] = \frac{k\left[\frac{\text{J·g}}{\text{MeV·kg}}\right]}{4\pi d^2[\text{cm}^2]} \cdot \Sigma_i \left[y_i \left[\frac{\text{photon}}{\text{nt}}\right] \cdot E_i \left[\frac{\text{MeV}}{\text{photon}}\right] \cdot \left(\frac{\mu_{en}}{\rho}\right)_{i,tissue} \left[\frac{\text{cm}^2}{\text{g}}\right] \right], \qquad [3\text{-}17]$$

where $k = 1.602x10^{-10}\left[\frac{\text{J·g}}{\text{MeV·kg}}\right]$.

If the point source is assumed to rest on the skin surface (with a density interface), and a profile of dose with depth in tissue is of interest, Eq. [3-17] must be modified to account for the attenuation of photons in tissue, the electronic buildup, and electron scatter at shallow depths leading to CPE. First, given that attenuation is occurring as photons travel through tissue, photon fluence is decreasing by the factor $e^{-\mu d}$ where μ is the energy-dependent linear attenuation coefficient for tissue (coefficients are taken from International Commission on Radiation Units and Measurements (ICRU) Report 44, 1989). Since tissue typically is assumed to be of unit density (1 g/cm^3), the numerical value of μ (in units of cm^{-1}) is identical to the numerical value of μ/ρ (in units of cm^2/g).

To simplify software coding, analytical expressions were developed for VARSKIN 4 (as opposed to using "look-up tables") for a number of dosimetry parameters. An empirical relationship to estimate μ/ρ for tissue as a function of incident photon energy (in megaelectronvolts (MeV)) was developed and is given below. For energies less than or equal to 20 keV,

$$\frac{\mu}{\rho}(E) = \frac{1}{0.0000145 + 3810E^{2.5} + 134400E^3}, \qquad [3\text{-}18]$$

and for energies from 20 keV to 3 MeV,

$$\frac{\mu}{\rho}(E) = e^{\left[-3.22 - 0.11(lnE)^2 + 0.5566\sqrt{E} - 0.7713lnE + \left(0.000721/E^2\right)\right]}. \qquad [3\text{-}19]$$

Figure 3-10 shows a comparison between the ICRU 44 (1989) values of μ/ρ for soft tissue and the functions of Eqs. [3-18] and [3-19].

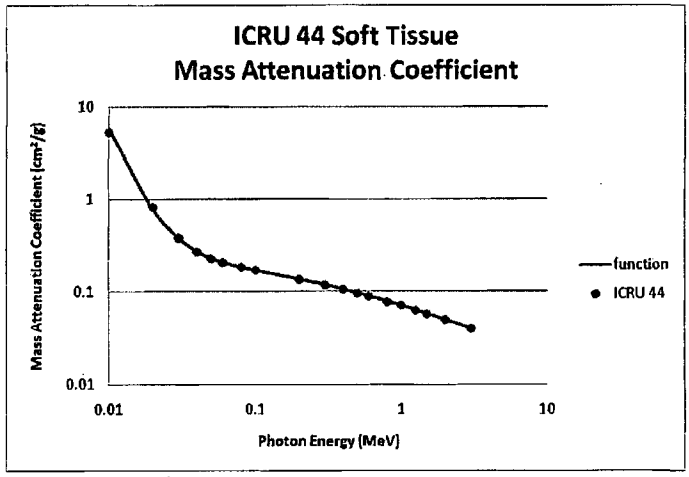

Fig. 3-10 ICRU 44 soft tissue mass attenuation coefficients compared to the empirical functions

The function of Eq. [3-20] was also developed as part of the VARSKIN 4 enhancements to approximate the energy-dependent value of μ_{en}/ρ for tissue. That function,

$$\frac{\mu_{en}}{\rho}(E) = \frac{a+clnE+e(lnE)^2+g(lnE)^3+i(lnE)^4}{1+blnE+d(lnE)^2+f(lnE)^3+h(lnE)^4+j(lnE)^5}, \qquad [3\text{-}20]$$

has a different set of coefficients for energies less than or equal to 30 keV and energies from 30 keV to 3 MeV. Table 3-2 provides the coefficients.

Table 3-2. Coefficients for Eq. [3-20]

Coefficient	E ≤ 30 keV	E > 30 keV
a	0.02971	0.03072
b	0.7453	0.4972
c	0.01519	0.009879
d	0.2236	0.1825
e	0.0009557	-0.0002386
f	0.03370	0.07303
g	-0.0001513	0.0006930
h	0.002545	0.01520
i	0.00006018	0.0003239
j	0.00007744	0.001084

Fig. 3-11 gives the fit of Eq. [3-20] to the ICRU 44 (1989) data.

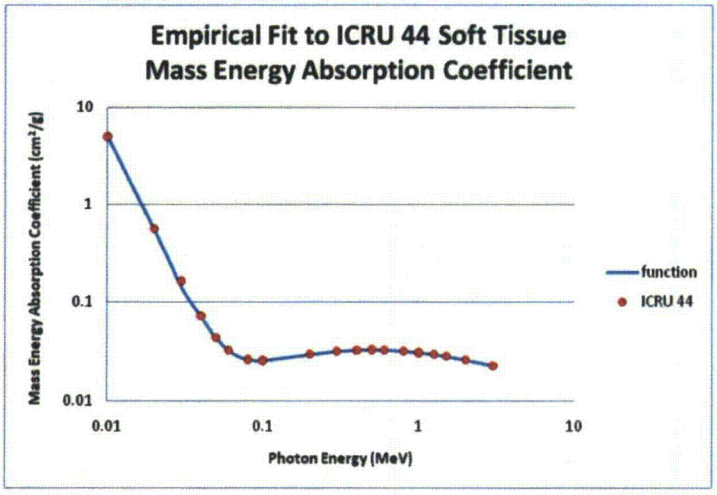

Fig. 3-11 ICRU 44 soft tissue mass energy absorption coefficients compared to the functions of Eqs. [3-18] and [3-19]

In consideration of CPE, Attix (1986) states that the condition exists if, in an infinitely small volume, "...each charged particle of a given type and energy leaving [the volume] is replaced by an identical particle of the same energy entering." For dose at shallow depths to be accurate, the CPE as a function of depth must be determined. The VARSKIN 4 determination of CPE is based on Monte Carlo simulations and the difference between energy released (KERMA) and energy absorbed (dose).

Since energy transfer (KERMA) from photons and energy absorption (dose) from the resulting charged particles does not occur in the same location (Johns and Cunningham, 1983), there is a "buildup region" in which dose is zero at the skin surface and then increases until a depth is reached at which dose and KERMA are equal. The depth at which equilibrium occurs is approximately equal to the range of the most energetic electron created by the incident photons (Johns and Cunningham, 1983). We determined an energy-dependent factor accounting for CPE buildup (f_{cpe}) by Monte Carlo simulation (Monte Carlo N-Particle, Version 5, referred to as MCNP5); this factor is the ratio of dose, D, to KERMA, K, for a particular incident photon energy at a given tissue depth such that,

$$f_{cpe}(E,d) = {}^{D}/_{K}. \qquad [3\text{-}21]$$

When considering CPE and attenuation, a relationship is achieved with depth in a medium in which dose is proportional to KERMA (Attix, 1986); this relationship is referred to as transient charged particle equilibrium (TCPE). Dose reaches a maximum "at the depth where the rising slope due to buildup of charged particles is balanced by the descending slope due to attenuation" (Attix, 1986), and then dose continues to decrease with depth because of subsequent attenuation of photons. At the point where TCPE occurs, dose is essentially equal to KERMA for low-energy photons and the value of f_{cpe} is equal to unity (1). As photon energy increases over about 1 MeV, this assumption of dose and KERMA equality begins to fail, but not so significantly that it affects deep-dose estimations appreciably. Based on experience with the

Monte Carlo simulation of shallow and deep depths, the model used in VARSKIN 4 limits the value of f_{cpe} to 1.05 (i.e., it allows dose to exceed KERMA by a maximum of 5 percent at depth).

A function for f_{cpe} that is dependent on initial photon energy is given as,

$$f_{cpe}(x) = \frac{1}{a+bln(x)+{}^{c}/_{\sqrt{x}}}, \quad [3\text{-}22]$$

where x (in cm) is a function of energy and is equal to the point kernel distance between source point and dose point, and the coefficients a, b, and c are functions of energy (in keV) as described below:

$$a = 19.78 + 0.1492\,ElnE - 0.008390\,E^{1.5} + 0.00003624\,E^2 + 3.343\sqrt{E}lnE - {}^{10.72\,E}/_{lnE} \quad [3\text{-}23]$$

$$b = 1.217x10^{-12}E^4 - 5.673x10^{-9}E^3 + 7.942x10^{-6}E^2 - 0.002028E + 0.3296 \quad [3\text{-}24]$$

$$c = 9.694x10^{-13}E^4 - 4.861x10^{-9}E^3 + 7.765x10^{-6}E^2 - 0.001856E + 0.1467 \quad [3\text{-}25]$$

The f_{cpe} factor is used for all materials; any buildup in air or thin covers is expected to be insignificant as compared to tissue.

Estimates of f_{cpe} were determined assuming that the line created between the source and dose points was normal to the surface. For a given distance, however, the fractional CPE for point kernel calculations, in which the dose point is located off axis and near the edge of the averaging disk, will vary because of the escape of energetic particles near the air-tissue interface. This loss of energy occurs for more energetic particles, generally from photons of energy greater than a few hundred keV. We have accounted for this off-axis scatter of energy out of tissue, slowing the buildup of equilibrium, by including an off-axis scatter factor, F_{oa}. The factor, taking on values between 0 and 1, is necessary only for point kernel calculations in which the angle between the central axis at the surface and the dose point is greater than 70 degrees from normal, and for photon energies greater than 300 keV; otherwise, F_{oa} is set equal to unity (1). The off-axis scatter factor is calculated from empirical data obtained through Monte Carlo simulation. The factor is represented by,

$$F_{oa} = (-1.57 + 0.000334\,\theta^{2.5} - 0.0000325\,\theta^3)(0.93 + 0.1R), \quad [3\text{-}26]$$

where R is the radius of the dose-averaging disk and θ is the off-axis scatter angle (in degrees). Fig. 3-12 gives a plot of off-axis correction as a function of scatter angle and the area of the dose-averaging disk. The considerable dip in the function for a 0.1-cm^2 averaging area is an artifact of Eq. [3-26] and is not phenomenologically significant.

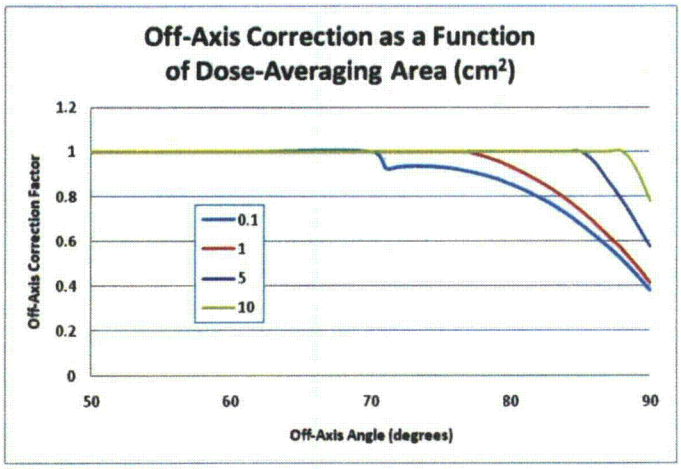

Fig. 3-12 Off-axis correction factor as a function of off-axis angle and dose-averaging area. Averaging disks of 0.1, 1, 5, and 10 cm^2 are shown.

Fully accounting for charged particle buildup and attenuation, Eq. [3-17] now becomes:

$$Dose\left[\frac{Gy}{nt}\right] = \frac{k}{4\pi d^2} \cdot \Sigma_i \left[y_i \cdot E_i \cdot \left(\frac{\mu_{en}}{\rho}\right)_{i,tissue} \cdot \left(f_{cpe}\right)_i \cdot (F_{oa})_i \cdot e^{-\mu_i d} \right]. \qquad [3\text{-}27]$$

As stated above, Federal law requires the determination of average dose to skin over an averaging area (e.g., 10 cm^2) at some depth in tissue (e.g., 7 mg/cm^2). To determine average dose at depth from a source at the surface, we must integrate Eq. [3-27] over the averaging area. Integrating the exponential, however, results in a solution with imaginary components. Therefore, a stepwise numerical integration of Eq. [3-27] is necessary, essentially providing an average of the point kernel dose over combinations of photon emission locations within the volume of the radioactive source and dose point locations within an infinitely thin disk of tissue at depth, *h*, from the surface.

The authors conducted convergence studies to determine which numerical integration method achieved convergence most rapidly for photon dosimetry (i.e., dividing the dose-averaging disk into the fewest number of segments). The studies investigated three segmenting methods (see Fig. 3-13): (1) segments determined by equal radii of the dose-averaging disk, (2) segments determined by equal off-axis angles, and (3) segments determined by equal annular area.

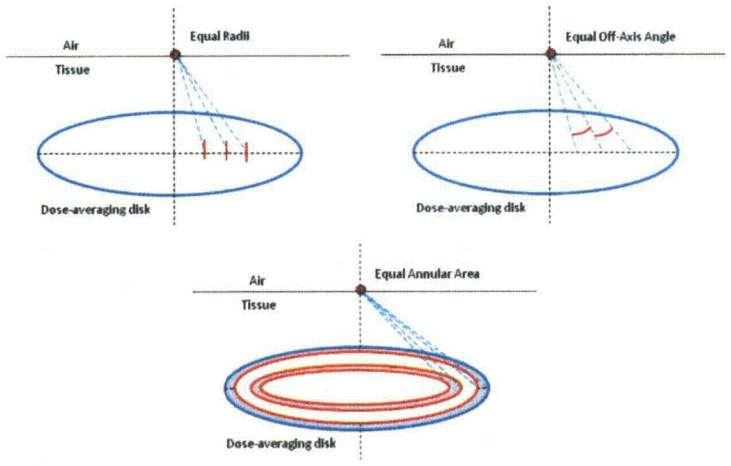

Fig. 3-13 Depiction of methods for determining integration segments of the dose-averaging disk

These studies indicated that segments divided according to equal lengths (radii) along the radius of the averaging disk converged with the fewest number of iterations, with segments divided by equal annular area requiring the most iteration. Fig. 3-14 shows that convergence was achieved within about 300 iterations for equal lengths along the radius of a 10-cm^2 averaging disk; the VARSKIN 4 numerical integration, therefore, utilizes 300 segments along the radius/diameter. Convergence was achieved with fewer segments when analyzing a smaller averaging disk.

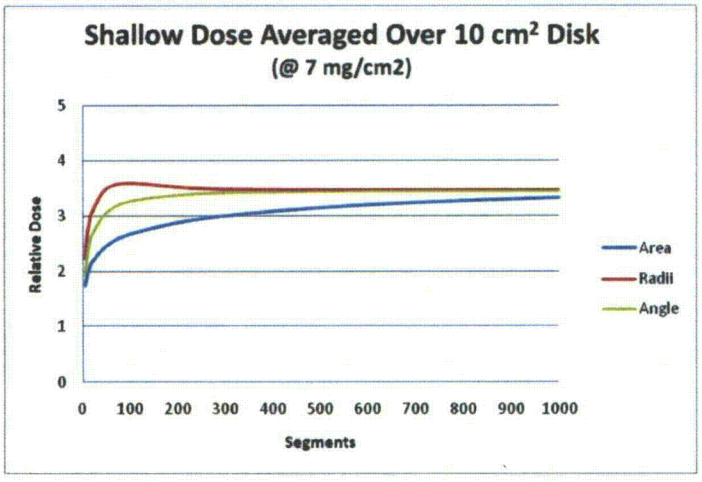

Fig. 3-14 Relative dose as a function of the number of segments in a numerical integration (iterations), by method

Therefore, given a point source on the skin, the first task in the integration process is to divide the dose-averaging disk into N small segments (annuli), j, of uniform incremental radii. If an averaging area, A, of radius, R, is at some depth, h, beneath the surface of skin, a method

based on the convergence study is used in which values of radii, R_j, of the averaging disk are selected such that a radial increment, Δr, is defined,

$$\Delta r = \frac{R}{N} \quad [3\text{-}28]$$

and

$$R_j = \sum_{j=0}^{N}(j \cdot \Delta r). \quad [3\text{-}29]$$

If point kernel dose calculations are conducted where dose is estimated to the midpoint of the annulus, each dose must be weighted by w_j, the ratio of the area of the annulus created by R_j, and R_{j+1}, to the total area of the disk. Given that R_0 = 0 and R_N = R, the values of w_j are determined by,

$$w_j = \frac{R_j^2 - R_{j-1}^2}{R^2}, \quad [3\text{-}30]$$

where j takes on values from 1 to N. We also define r_j, which represents the average of the two radii describing the annulus in each calculation, such that,

$$r_j = \frac{R_j - R_{j-1}}{2}. \quad [3\text{-}31]$$

Once all values of r_j are determined, then the dose per nuclear transition for a given point source radionuclide with i emissions, averaged over an infinitely thin disk of radius R, at normal depth in tissue h and radius r_j, is calculated by,

$$\dot{D}(h,R)\left[\frac{\text{Gy}}{\text{nt}}\right] = \frac{k}{4\pi} \cdot \sum_{j=1}^{N} \frac{w_j}{d_j^2}\left[\sum_i \left[y_i \cdot E_i \cdot \left(\frac{\mu_{en}}{\rho}\right)_i \cdot (f_{cpe})_{i,j} \cdot (F_{oa})_{i,j} \cdot e^{-\mu_i d_j}\right]\right], \quad [3\text{-}32]$$

where $d_j = \sqrt{(h^2 + r_j^2)}$.

3.8 Attenuation Coefficients for Cover Materials

For photon dose calculations, the cover materials (and associated attenuation coefficients) are "forced" to be either latex or cotton. This determination is made by the density entry, i.e., if the density is less than 1.25 g/cm^3, then latex is assumed, if greater, cotton is assumed. These are the two most likely materials used for cover. It is noted that the cover attenuation is minor and this decision should be insignificant for the dose calculation.

An empirical function of energy was used for attenuation coefficients for cotton and latex, namely:

$$\mu_{cotton/latex} = e^{(a+b\sqrt{E}\cdot \ln(E)+c\sqrt{E})} \quad [3\text{-}33]$$

where a = -1.0132, b = 0.31505, and c = -1.6086 for cotton, and a = -1.0286, b = 0.32189, and c = -1.6217 for latex. Coefficients for air were determined from,

$$\mu_{air} = \left(\left(a + \frac{b}{\sqrt{E}}\right) + \left(c \cdot \frac{\ln(E)}{E}\right) + \left(\frac{d}{E}\right) + \left(\frac{e}{E^{1.5}}\right) + \left(f \cdot \frac{\ln(E)}{E^2}\right) + \left(\frac{g}{E^2}\right)\right) * 0.001168 \qquad [3\text{-}34]$$

where a = 0.027413, b = -0.12826, c = 0.11227, d = 0.060526, e = 0.12508, f = -0.0030978, and g = -0.021571. Both of these functions track very well with data from ICRP 44.

3.9 Off-Axis Calculation of Dose

The model described thus far is constructed under the assumption that the source of photons is a point, located directly above and on axis with the averaging disk, and that there is symmetry in dose calculations along a radius of the dose-averaging disk (Fig. 3-15).

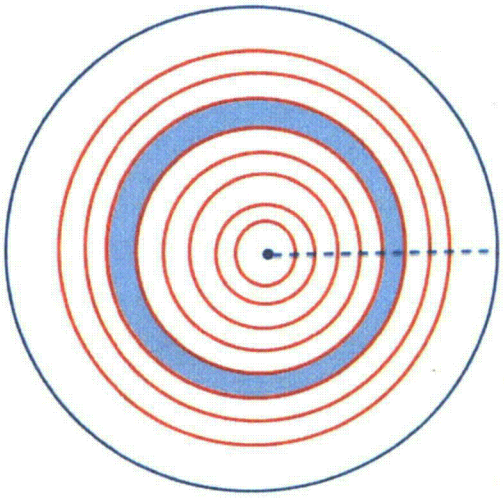

Fig. 3-15 Dose-averaging disk with the source point located on axis

To extend the model to handle point kernel calculations for volumetric sources, or for multiple point sources, we must consider the case where the point source is off axis yet still over the dose-averaging disk (Figs. 3-16 and 3-17) and the case where the point source is completely removed from the dose-averaging disk (Figs. 3-18 and 3-19). The implication is simply a geometric determination of the distance between source and dose points in each point kernel calculation and an area-weighted factor for the symmetric dose location on the averaging disk.

In the first case, where the point source is off axis yet still over the dose area, there is symmetry along a diameter of the dose-averaging disk. The average of the point kernel doses will be

determined by a weighting of doses calculated along the diameter. The calculation begins by projecting the dose point to the averaging disk, normal to the skin surface (see Fig. 3-16).

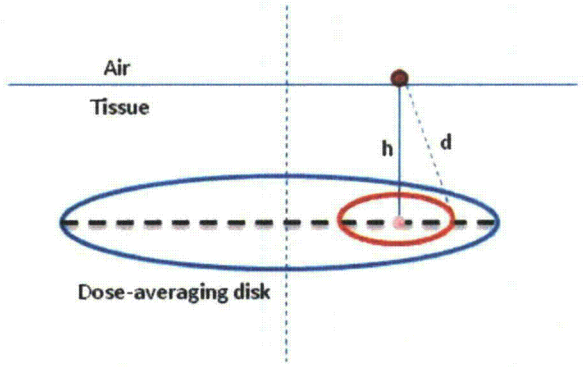

Fig. 3-16 Dose-averaging disk located at depth h beneath an offset point source

The averaging disk then is divided, as described above, into a series of concentric annuli, about the projected dose point, until the radius of the annuli reaches the nearest edge of the averaging disk (Fig. 3-17). At this point, the weighting model transitions to a series of arcs passing through the averaging disk; these arcs are created by differential radii of two intersecting circles (Fig. 3-18). The model creates a total of 300 annuli and arcs. Point kernel dose is calculated along the diameter in each of the 300 segments defined by the differential annuli and arcs and then weighted based on the fractional area of each segment.

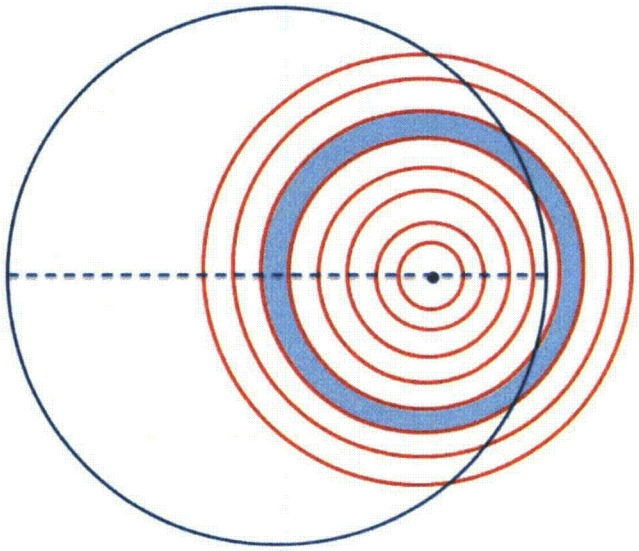

Fig. 3-17 Dose-averaging disk with the source point located off axis, yet still over the averaging disk

The weight (fractional area) of each annulus to the total is straightforward, in that,

———— ———. [3-35]

The weight of each arc is determined by a method considering intersecting circles. In the case of Fig. 3-18, the area of the "lens" created by the two intersecting circles is given by:

———— ————

– ———————————————————. [3-36]

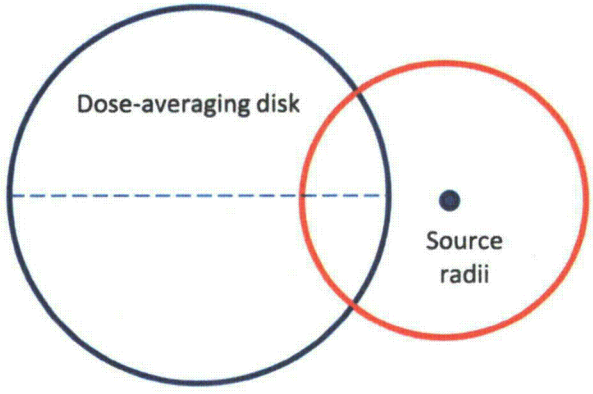

Fig. 3-18 Relationship between the source-averaging disk and one of the radii for dose calculation. A "lens" is created by the intersection of the two circles.

The area of the arc formed (Fig. 3-18) by two concentric circles (two radii from the point source) that overlap another circle (the averaging disk) is the difference in the area calculations of Eq. [3-35]. The arc weight is then the ratio of the arc area to the total area of the averaging disk. In the case where the source projection does not fall on the dose-averaging disk (Fig. 3-19), the weighting scheme is based solely on arcs.

The numerical integration is conducted from the point source to each of 300 locations along the diameter of the averaging disk (or along the radius if the source point is directly on axis with the disk). Then, for volumetric sources, point source locations are chosen in equal symmetric increments at 15 point locations in each of the three dimensions within the source volume, relative to the averaging-disk diameter. For each volumetric source dose estimate, 1,000 calculations of dose from each of 15 x 15 x 15 source point locations are executed (1 million dose calculations).

The new VARSKIN 4 photon dosimetry model accounts for attenuation in cover materials and air. As with the beta dosimetry model, up to five layers above the skin are allowed, with the air layer only acceptable just above the skin surface. For photon calculations, the other material

layers are restricted to cotton and/or latex, and the source material is assumed to have the same characteristics as air. This latter assumption is not significant for very small volumetric sources and for photon energies above about 50 keV. For example, if we examine the ratio of air attenuation to lead, tin, copper, aluminum, and water attenuation, the greatest difference is obviously at low photon energies with higher-Z materials (i.e., instances of higher interaction probability).

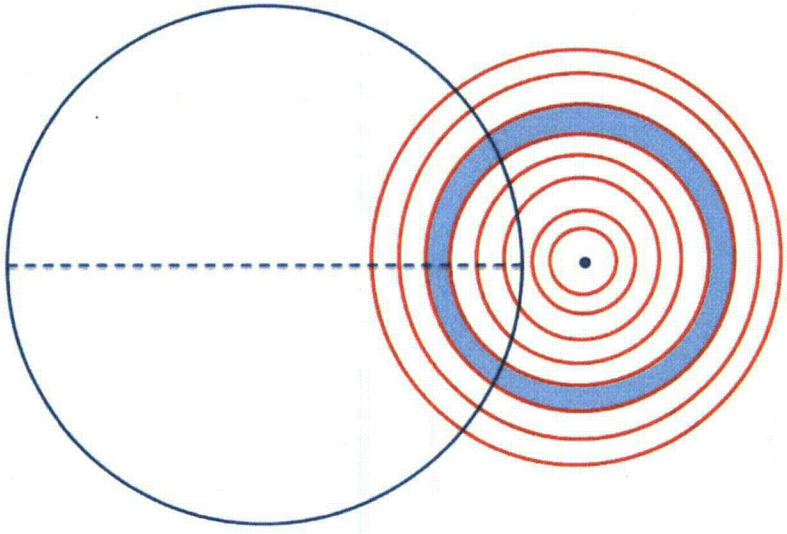

Fig. 3-19 Dose-averaging disk from above with the source point located off axis, far enough removed to be off the averaging disk

The data indicate that, for volumetric sources with a maximum linear dimension less than about 100 microns, the assumption that the source material is similar to air is of no consequence whatsoever for photon energies between 10 keV and 3 MeV. As the source particle dimensions increase in size, an assumption of air for the source material can be quite significant for very low photon energies (e.g., energies less than about 40 keV). The significance, however, is one of conservatism in that more low-energy photons than actual will be modeled as striking the skin surface when source dimensions are large. The analysis of attenuation also shows that the assumption of air and water (tissue) being similar, in terms of attenuation, over very short distances (i.e., less than 5 mm) is a good assumption.

4 VALIDATION AND VERIFICATION OF VARSKIN 4

To validate the new photon dosimetry model incorporated into VARSKIN 4, results were compared to the general purpose radiation transport code MCNP5. The MCNP5 software package is a Monte Carlo transport code, which simulates movement and interaction of particles in material (Los Alamos National Laboratory, 2003).

4.1 Comparison with MCNP

For the MCNP5 simulation, five different sources were modeled close to the skin: a point; a 1-mm diameter disc; a 1-mm diameter cylinder with a height of 1 mm; a 1-mm x 1-mm slab with a height of 1 mm; and a 1-mm diameter sphere. The fundamental geometry, illustrated in Fig. 4-1, involves an infinite volume of air located above an infinite volume of tissue. Composition of these materials was taken from National Institute of Standards and Technology standards for each material. Each of the sources was situated 1 μm above the skin and above the perpendicular bisect of the volume of tissue over which the dose is calculated.

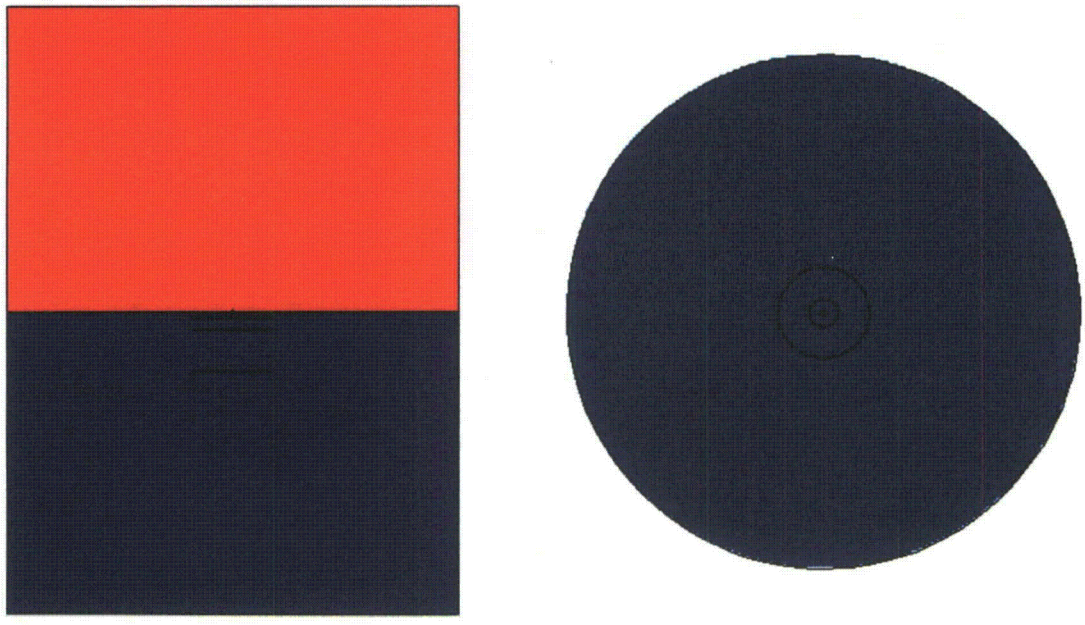

Fig. 4-1 Horizontal (left) and vertical (right) cross-sectional views of the MCNP5 input deck geometry

As illustrated in Fig. 4-2, the dose per photon was calculated for each of the sources at tissue depths of 7, 100, 300, and 1,000 mg/cm^2. The density thicknesses of 7, 300, and 1,000 mg/cm^2 correspond to the depth required by 10 CFR Part 20, "Standards for Protection against Radiation," for calculation of doses to the skin, lens of the eye, and the deep dose, respectively. Although the value of 100 mg/cm^2 does not correspond to a regulatory-significant density

thickness, results at that depth are provided as an indication of accuracy at an intermediate, yet shallow, depth.

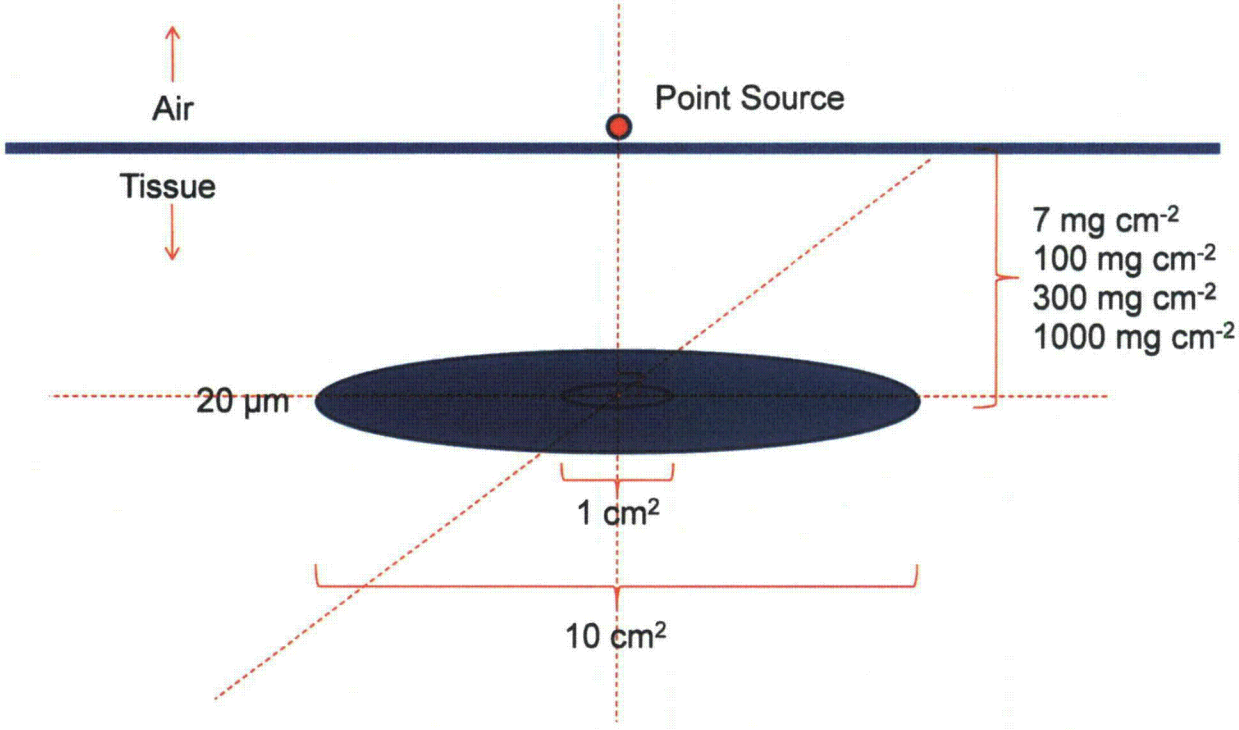

Fig. 4-2 Illustration of the point source geometry of the tissue volumes of interest at various density thicknesses in tissue

At each density thickness, the dose to two volumes of tissue, $2x10^{-3}$ cm^3 and $2x10^{-2}$ cm^3, was calculated. These volumes correspond to cylindrical volumes within tissue, each having a thickness of 20 µm and a cross-sectional area of 1 cm^2 and 10 cm^2, respectively. The value of 20 µm was selected for use in MCNP to create a volume large enough that uncertainties resulting from low numbers of particles interacting in the volume would not be an issue. Sherbini et al. (2008) showed that at thicknesses greater than 10 µm, any effects of dose averaging over increasingly smaller volumes are avoided.

The "*F8" tally was used, with coupled photon/electron transport, to calculate energy deposited in the volume of interest. This tally determines the average energy deposited by a photon interaction per photon generated from one of the initial sources. The number of particle histories executed was sufficiently high to maintain statistical errors below 6 percent, with the majority producing an error of approximately 3 percent. Dose rate was calculated by multiplying the results of the *F8 tally by a simulated source strength of 1 µCi, with a photon yield of 100 percent at a given energy ranging from 25 keV to 3 MeV. While this is not specific to any particular nuclide, it demonstrates the energy dependence of each methodology and also shows which current models are accurate predictors (as compared to MCNP5) and which are not. Work continues to improve those models that appear to have deficiencies.

Point Source Geometry. VARSKIN 3.1 and VARSKIN 4 model the photons indicated above, as well as all x-rays and charged particles produced from the decay of each nuclide specified. To better compare the two versions of VARSKIN, "dummy" nuclides were created that emit only photons with a yield of 100 percent at a single specific energy. Figs. A-1 to A-4 in Appendix A provide the results of the point source geometry comparisons. The VARSKIN 4 results fit the Monte Carlo calculations extremely well for the point source geometry.

Disk Source Geometry. Comparisons at various skin depths were made between MCNP and VARSKIN 4 where the source was modeled as a 1-mm diameter disk positioned directly on the surface of the skin. Results of this comparison appear in Figs. A-5 to A-8. These results indicate excellent agreement between the two methodologies.

Cylinder Source Geometry. Comparisons were made between MCNP5 and VARSKIN 4 where the source was modeled as a cylinder with a diameter of 1 mm and a height of 1 mm positioned directly on the surface of the skin. This geometry was modeled such that no attenuation occurs in the source itself. Figs. A-9 to A-12 give the results of this comparison for cylindrical geometries. As compared to MCNP5, VARSKIN 4 consistently overpredicts the dose in the cylindrical geometry at energies above 200 keV.

Slab Source Geometry. Comparisons were made between MCNP5 and VARSKIN 4 where the source was modeled as a slab with a length and width of 1 mm and a height of 1 mm positioned directly on the surface of the skin. This geometry was modeled such that no attenuation occurs in the source itself. Figs. A-13 to A-16 present the results of this comparison. Again, VARSKIN 4 consistently overpredicts skin dose for the slab geometry at energies greater than about 200 keV.

Sphere Source Geometry. Comparisons were made between MCNP5 and VARSKIN 4 where the source was modeled as a sphere with a diameter of 1 mm positioned directly on the surface of the skin. This geometry was modeled such that no attenuation occurs in the source itself. Figs. A-17 to A-20 present the results of this comparison for spherical geometries. As with cylinders and slabs, VARSKIN 4 overpredicts Monte Carlo simulated doses for the sphere geometry.

4.2 Effect of Cover Material

The effect of cover material between the source and skin was evaluated by performing a number of comparisons between VARSKIN 3.1, VARSKIN 4, and MCNP5. The photon dose to $2x10^{-3}$ cm^3 and $2x10^{-2}$ cm^3 tissue cell volumes was calculated for the point source geometry as a function of energy at depth in the skin equivalent to density thicknesses of 7, 100, 300, and 1,000 mg/cm^2. The cover material modeled was a single layer of cotton coveralls with a thickness of 0.37 mm and a density of 0.7 g/cm^3. The results shown in Figs A-21 to A-24, are very similar to those observed for the point source.

4.3 Shallow Dose Comparisons

No changes were made to the beta dosimetry model between VARSKIN 3.1 and VARSKIN 4. To verify that the beta dose estimate is still consistent with VARSKIN 3.1, a series of

calculations was performed to compare the two. All the calculations presented in the previous version of this NUREG (see Appendix B) were conducted using VARSKIN 4 with similar results. The results confirm that the beta dosimetry calculations did not change, and they present new estimates of shallow skin dose for photon exposure.

Point Source on the Skin. In this test, calculations were completed for the case of a Co-60 point source placed directly on the skin (i.e., no material and no air gap between the source and skin). For a 1-μCi hot particle and a 1-hour exposure time, the beta and photon dose averaged over 1 cm^2 at a depth of 7 mg/cm^2 was calculated with VARSKIN 3.1 and VARSKIN 4. Table 4-1 shows the results of this calculation. No difference was observed between the two beta dose estimates; however, because of the inclusion of charged particle buildup and photon attenuation, the photon dose decreases dramatically between VARSKIN 3.1 and VARSKIN 4 at shallow depths.

Table 4-1 Comparison between Beta and Photon Shallow Dose Calculations from VARSKIN 3.1 and VARSKIN 4 for a 1-μCi Point Source of Co-60 Exposing the Skin for 1 Hr

Nuclide	VARSKIN 3.1 Beta Dose (mGy)	VARSKIN 4 Beta Dose (mGy)	VARSKIN 3.1 Photon Dose (mGy)	VARSKIN 4 Photon Dose (mGy)
Co-60	37.6	37.6	3.29	0.79

Point Source on Cover Material. Dose calculations at 7 mg/cm^2 were also performed in VARSKIN 3.1 and VARSKIN 4 for Co-60, Cs-137/Ba-137m, and Sr/Y-90 with three different cover material configurations. In each case, a 1-μCi point source and an exposure time of 1 hour were assumed with no air gap between the layers of cover material. Doses were calculated for a 1-cm^2 averaging disk. Table 4-2 shows the results of this calculation. As expected, there was no observed difference in beta dosimetry between the two versions. Depending on photon energy, changes to the photon dose estimate occur between the two versions of VARSKIN.

Distributed Beta Contamination on Skin. Calculations were performed for the same three nuclides using VARSKIN 3.1 and VARSKIN 4 to compare the beta dose estimate for a distributed disk source on the skin over an exposure period of 1 hour. The beta dose at a depth of 7 mg/cm^2 was calculated for a simulated contamination scenario with a concentration of 1 $\mu Ci/cm^2$ distributed over a circular area of 100 cm^2. Beta dose calculations were completed with VARSKIN 3.1 and VARSKIN 4 with a dose-averaging area of 1 cm^2, and the results were compared to values published by Rohloff and Heinzelmann (1986) and by Kocher and Eckerman (1987). The results from VARSKIN and Rohloff and Heinzelmann (1986) agree quite well because both methods account for the lack of backscatter from an infinitely thin source. Results obtained using the Kocher and Eckerman (1987) method are somewhat higher, however, because the method overestimates backscatter from air. Table 4-3 presents the results of this calculation.

Table 4-2 Comparison between VARSKIN 3.1 and VARSKIN 4 of the Shallow Dose for Various Cover Material Configurations

Nuclide	Air Gap (cm)	Cover Material	VARSKIN 3.1 Beta Dose (mGy)	VARSKIN 4 Beta Dose (mGy)	VARSKIN 3.1 Photon Dose (mGy)	VARSKIN 4 Photon Dose (mGy)
Co-60	0.2	M_1	1.96	1.96	0.571	0.292
Cs-137/ Ba-137m	0.2	M_1	14.0	14.0	0.199	0.0969
Sr/Y-90	0.2	M_1	32.6	32.6	0	0
Co-60	0.2	$M_1 + M_1$	0	0	0.558	0.257
Cs-137/ Ba-137m	0.2	$M_1 + M_1$	4.75	4.75	0.181	0.0836
Sr/Y-90	0.2	$M_1 + M_1$	20.7	20.7	0	0
Co-60	1.0	M_1	0.813	0.813	0.0797	0.0429
Cs-137/ Ba-137m	1.0	M_1	2.79	2.79	0.0277	0.0129
Sr/Y-90	1.0	M_1	5.37	5.37	0	0
Co-60	1.0	$M_1 + M_1$	0	0	0.0836	0.0402
Cs-137/ Ba-137m	1.0	$M_1 + M_1$	1.40	1.40	0.0270	0.0121
Sr/Y-90	1.0	$M_1 + M_1$	3.95	3.95	0	0
Co-60	1.0	$M_1 + M_2$	0	0	0.0876	0.0400
Cs-137/ Ba-137m	1.0	$M_1 + M_2$	0.770	0.770	0.0271	0.0120
Sr/Y-90	1.0	$M_1 + M_2$	3.26	3.26	0	0
Co-60	5.0	$M_1 + M_2$	0	0	0.00453	0.00205
Cs-137/ Ba-137m	5.0	$M_1 + M_2$	0.0384	0.0384	0.00138	0.00061
Sr/Y-90	5.0	$M_1 + M_2$	0.167	0.167	0	0

M_1—Cover material = thickness of 0.37 mm, density of 0.70 g/cm^3.
M_2—Cover material = thickness of 0.40 mm, density of 1.1 g/cm^3.

Table 4-3 Comparison between VARSKIN 3.1 and VARSKIN 4 of the Beta Dose (mGy) for a 1-hr Exposure to Distributed Contamination on the Skin

Nuclide	VARSKIN 3.1	VARSKIN 4	Rohloff et al. (1986)	Kocher et al. (1987)
Co-60	37.7	37.7	32.4	41.8
Cs-137	51.2	51.2	-	59.1
Sr/Y-90	123.4	123.4	121	156

Additional comparisons were made for shallow beta dosimetry assuming a 1-hour exposure from a source modeled as an infinitely thin, uniformly contaminated (1 μCi/cm^2) two-dimensional disk with a diameter of 2 cm. Doses were calculated at different depths in the skin and

compared to similar values in the literature. Tables 4-4 and 4-5 show that the results are in good agreement, although the VARSKIN 4 results are lower than the published values because of the backscatter correction, as discussed in Section 3.2.

Table 4-4 Dose (mGy) vs. Depth for Various 1 μCi/cm^2 Distributed Disk Sources and a 1-hr Exposure Time (dose calculated at a depth of 7 mg/cm^2 and averaged over 1 cm^2)

Method	C-14	P-32	I-131	Sr-90	Y-90
VARSKIN 3.1	11.2	66.3	52.5	54.7	68.2
VARSKIN 4	11.2	66.3	52.5	54.7	68.2
Delacroix (1986)	10.7	91.5	64.2	69.9	91.8
Kocher and Eckerman (1987)	12.2	88.7	63.4	67.6	88.7
Piechowski (1988)	12	70	60	59	75

Table 4-5 Dose (mGy) vs. Depth for a 1 μCi/cm^2 Distributed Disk Source of Y-90 and a 1-hr Exposure Time (dose averaged over 1 cm^2)

Method	4 mg/cm^2	7 mg/cm^2	10 mg/cm^2	40 mg/cm^2
VARSKIN 3.1	79.0	68.2	61.4	40.7
VARSKIN 4	79.0	68.2	61.4	40.7
Delacroix (1986)	104.6	91.8	83.7	52.4
Kocher and Eckerman (1987)	101.4	88.7	—	50.7

5 VARSKIN LIMITATIONS

VARSKIN calculates skin dose to an infinitely thin disk at depth in tissue for comparison to the NRC limit of 0.5 gray (Gy) for both point and distributed sources (NRC, 2006). VARSKIN can calculate the dose to averaging areas from a minimum of 0.01 cm^2 to a maximum of 100 cm^2. Users are cautioned that VARSKIN is designed to calculate the dose to skin from skin contamination. Using VARSKIN to perform calculations that are beyond the intended application of the code may result in erroneous dose estimates. This section discusses the known limitations of VARSKIN and establishes the limits over which the code has been tested.

The first item of note is not a limitation, but a code design decision, and involves the treatment of radioactive progeny. In VARSKIN, radioactive progeny are not included with the parent radionuclide and must be entered explicitly, i.e., selecting ^{137}Cs gives you only that nuclide, ^{137m}Ba is not included unless it is specifically called. The user is additionally cautioned to consider the half-life of the progeny when selecting the appropriate dose contribution (decay-corrected or not) from daughter products. As an example, for the case of ^{144}Ce and its daughter, ^{144}Pr (with a short half-life), the dose result from the daughter product must be taken from the non-decay corrected calculation. If the user takes the decay-corrected dose in this case, the dose would be significantly underestimated. The limitation that must be recognized by the user in this case is that VARSKIN uses the decay characteristics of each nuclide, whether that nuclide is in secular equilibrium with a parent, or not.

VARSKIN has been shown to be reliable for particulate sources that have dimensions smaller than eight times the X_{99} distance of the radionuclide in tissue. The X_{99} distance is essentially 99 percent of the range of beta particles in tissue emitted by nuclides in the source term. When the physical size of the source approaches this value, VARSKIN may give unreliable results. If the source dimensions selected are too large, VARSKIN 4 prompts the user with a warning of the potential for inaccurate results. The X_{99} distance is included on the printout of a calculation to assist the user in determining the appropriateness of input source dimensions. A user who wants to model sources larger than this limit may wish to begin with smaller sources and increase the source size gradually to ensure that spurious results are not being generated. Modeling a source of this size is generally not necessary, however, as most of the source does not contribute to beta skin dose because of self-shielding.

VARSKIN has not been tested extensively for dose-averaging areas other than 1 and 10 cm^2. However, because of the nature of the calculations performed by VARSKIN, there is no reason to believe that doses to areas less than or greater than 10 cm^2 will result in errors. A quick and limited study of dose results as a function of averaging disk area shows that the code appears to be stable and linear in this regard from 0.01 to 100 cm^2.

Dose calculations involving air gaps greater than 5 cm have not been tested and are, therefore, not allowed. It is likely that erroneous results may be obtained for large air gaps because the code does not account for multiple scattering events in air. These events may result in the dose being delivered to an area greater than that determined using VARSKIN and can lead to inaccurate results. VARSKIN is limited such that calculations for air gaps greater than 5 cm are not possible and a warning message is displayed.

The photon dosimetry model assumes that all volume sources are made of air. This assumption results in greater accuracy when modeling larger, less dense sources (a gas cloud, for example). However, when modeling volumetric sources of greater density, VARSKIN 4 is optimized for small dimensions (less than about a millimeter). This optimization is the result of a tradeoff between attenuation and charge particle buildup within the source itself. Care should be exercised when modeling large-volume sources.

6 SPECIAL TOPICS FOR ACCURATE USE OF VARSKIN

VARSKIN is designed to be very flexible while maintaining a high level of accuracy. However, the code can be misused, particularly when modeling infinitely large sources (i.e., sources with physical dimensions greater than eight times the X_{99} distance for the source radionuclides). This section describes this possible misuse of VARSKIN and how it can be avoided. This section also describes a method to determine the maximum dose to an area from multiple hot particles.

6.1 Infinite Sources

When modeling infinite or semi-infinite sources (e.g., an enveloping cloud) with VARSKIN, the tendency is to choose very large dimensions for the source. This approach will result in the calculation of a grossly inaccurate dose or a zero dose because the integration routine becomes unstable. The correct method is to determine the maximum penetration distance (i.e., the X_{99} distance) and set the source dimensions accordingly.

The X_{99} distance can be found by running a simple calculation for the radionuclide of interest and looking at the printout for the value. The maximum source radius (r_{max}) and the side lengths are then determined using the equation,

$$r_{max} = r_{dos} + \left({}^{X_{99}}/_{\rho_{min}}\right)\rho_w, \qquad [6\text{-}1]$$

where r_{dos} is the radius of the dose-averaging area (in cm), ρ_w is the density of water, and ρ_{min} is the smallest density of the covering material, source, air (if an air gap is included), or tissue. Using the density of the least dense material will ensure that the dose-averaging area includes contributions from the entire source. If an air gap is included, using the VARSKIN default value for the density of air (0.001293 g/cm^3) is appropriate. If no cover material is specified, using tissue density is the best choice.

When modeling infinite sources, the use of the cylinder source geometry is recommended. When using the cylinder source geometry, the source thickness, Δt_{max}, should be determined using the equation,

$$\Delta t_{max} = \frac{X_{99}\rho_w}{\rho_s}, \qquad [6\text{-}2]$$

where ρ_s is the source density.

6.2 Maximum Dose from Multiple Contamination Sources

Determining the maximum dose to the dose-averaging area for multiple contaminations requires multiple calculations. These calculations require elements that are not available in VARSKIN but can be accomplished manually, as described below.

Before attempting to run the offset particle model, the user should determine the size of the

irradiation area directly beneath each of the contaminated areas. Note that the size of sources does not need to be the same for each particle. By comparing these areas for each source, it may be possible to eliminate one or more of the contaminated areas because no overlapping fields are associated with them. For contaminated areas with overlapping fields, the doses and their relative positions should then be plotted on a sheet of graph paper, leaving plenty of room between the sources for results from additional calculations.

Next, calculations using the offset particle model should be performed for locations midway between any two contaminated areas. For more than two sources that are not in a straight line, a central location should be chosen, and the dose at this point should be calculated using the offset particle model. Thus, for three contaminated areas in a triangular formation, a total of four calculations should be performed. The value of the offset should be chosen to be one-half of the distance between any two sources, with one additional dose calculation performed in the center of the triangle.

After these calculations have been performed, it is left to the user's discretion to determine the most probable area of highest dose based on the distribution of dose on the graph paper. After determining this area, the user can perform a final calculation for each particle by using the offset particle model. An accuracy of greater than 20 percent should not be anticipated.

7 REFERENCES

Attix, F.H. Introduction to Radiological Physics and Radiation Dosimetry. New York, NY: John Wiley & Sons. 1986.

Berger, M.J. "Distribution of Absorbed Dose Around Point Sources of Electrons and Beta Particles in Water and Other Media." Medical Internal Radiation Dose Committee, Pamphlet No. 7. *Journal of Nuclear Medicine*. Vol. 12, Supplement No. 5. pp. 5–22. 1971.

Berger, M.J., J.S. Coursey, M.A. Zucker, and J. Change. "Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions." ESTAR, PSTAR, and ASTAR databases. Washington, DC: National Institute of Standards and Technology. <http://physics.nist.gov/PhysRefData/Star/Text/contents.html> (February 14, 2006).

Cross, W.G., N.O. Freedman, and P.Y. Wong. "Tables of Beta-Ray Dose Distributions in Water." AECL 10521, CA9200298. Chalk River, Ontario, Canada: Chalk River Laboratories, Dosimetric Research Branch. 1992.

Delacroix, D. "Beta Particle and Electron Absorbed Dose Calculations for Skin Surface Contaminations" (in French). DCES/SPR/SRI/86–656. Paris, France: Commissariat à l'Energie Atomique. 1986.

Durham, J.S. "VARSKIN 3: A Computer Code for Assessing Skin Dose from Skin Contamination." NUREG/CR-6918. Washington, DC: U.S. Nuclear Regulatory Commission. 2006.

Durham, J.S. "VARSKIN Mod 2 and SADDE Mod 2: Computer Codes for Assessing Skin Dose from Skin Contamination." NUREG/CR-5873, PNL-7913. Washington, DC: NRC. 1992.

Durham, J.S., and M.W. Lantz. "Determination of Gamma Dose Rates and Charged Particle Equilibrium from Hot Particles." *Radiation Protection Management*. Vol. 8, No. 3. pp. 35–41. 1991.

International Commission on Radiation Units and Measurements. "Tissue Substitutes in Radiation Dosimetry and Measurement." ICRU Report 44. Bethesda, MD: International Commission on Radiation Units and Measurements. 1989.

International Commission on Radiological Protection. "The Biological Basis for Dose Limitation in the Skin." Publication 59. Oxford, England: Pergamon Press. 1991.

International Commission on Radiological Protection. "Radionuclide Transformations." Publication 38. Oxford, England: Pergamon Press. 1983.

Johns, H.E., and J.R. Cunningham. The Physics of Radiology. 4th Edition. Springfield, IL: Charles C. Thomas. 1983.

Kocher, D.C., and K.F. Eckerman. "Electron Dose-Rate Conversion Factors for External Exposure of the Skin from Uniformly Deposited Activity on the Body Surface." *Health Physics.* Vol. 53. pp.135–141. 1987.

Lantz, M.W., and M.W. Lambert. "Charged Particle Equilibrium Corrections for the Gamma Component of Hot Particle Skin Doses." *Radiation Protection Management.* Vol. 7, No. 5. pp. 38–48. 1990.

Los Alamos National Laboratory, X-5 Monte Carlo Team. "MCNP—A General Monte Carlo N-Particle Transport Code, Version 5. LA-CP-03-0245. Los Alamos, NM: LANL. 2003.

Piechowski, J. "Dosimetry and Therapy of Skin Contaminations" (in French). CEA–R–5441. Paris, France: Commissariat à l'Energie Atomique. 1988.

Radiation Safety Information Computational Center. "MCNP4c2, Coupled Neutron, Electron Gamma 3-D Time-Dependent Monte Carlo Transport Calculations." CCC–701. Oak Ridge, TN: RSICC. 2001.

Radiation Safety Information Computational Center. "NUCDECAY: Nuclear Decay Data for Radiation Dosimetry Calculations for ICRP and MIRD." CCC–701. Oak Ridge, TN: RSICC. 1995.

Reece, W.D., S.D. Miller, and J.S. Durham. "SADDE (Scaled Absorbed Dose Distribution Evaluator), A Code to Generate Input for VARSKIN." NUREG/CR–5276. Washington, DC: NRC. 1989.

Rohloff, F. and M. Heinzelmann. "Calculation of Dose Rates for Skin Contamination by Beta Radiation." *Radiation Protection Dosimetry.* Vol. 14. pp. 279–287. 1986.

Sherbini, S., J. DeCicco, A.T. Gray, and R. Struckmeyer. "Verification of the Varskin Beta Skin Dose Calculation Computer Code," *Health Physics.* Vol. 94. pp. 527–538. 2008.

Traub, R.J., W.D. Reece, R.I. Scherpelz, and L.A. Sigalla. "Dose Calculation for Contamination of the Skin Using the Computer Code VARSKIN." NUREG/CR–4418. Washington, DC: NRC. 1987.

U.S. Nuclear Regulatory Commission. News Release No. 02-039. http://www.nrc.gov/reading-rm/doc-collections/news/2002/02-039.html. April 2, 2002. Last Accessed March 2006.

APPENDIX A

Supporting Figures from Section 4

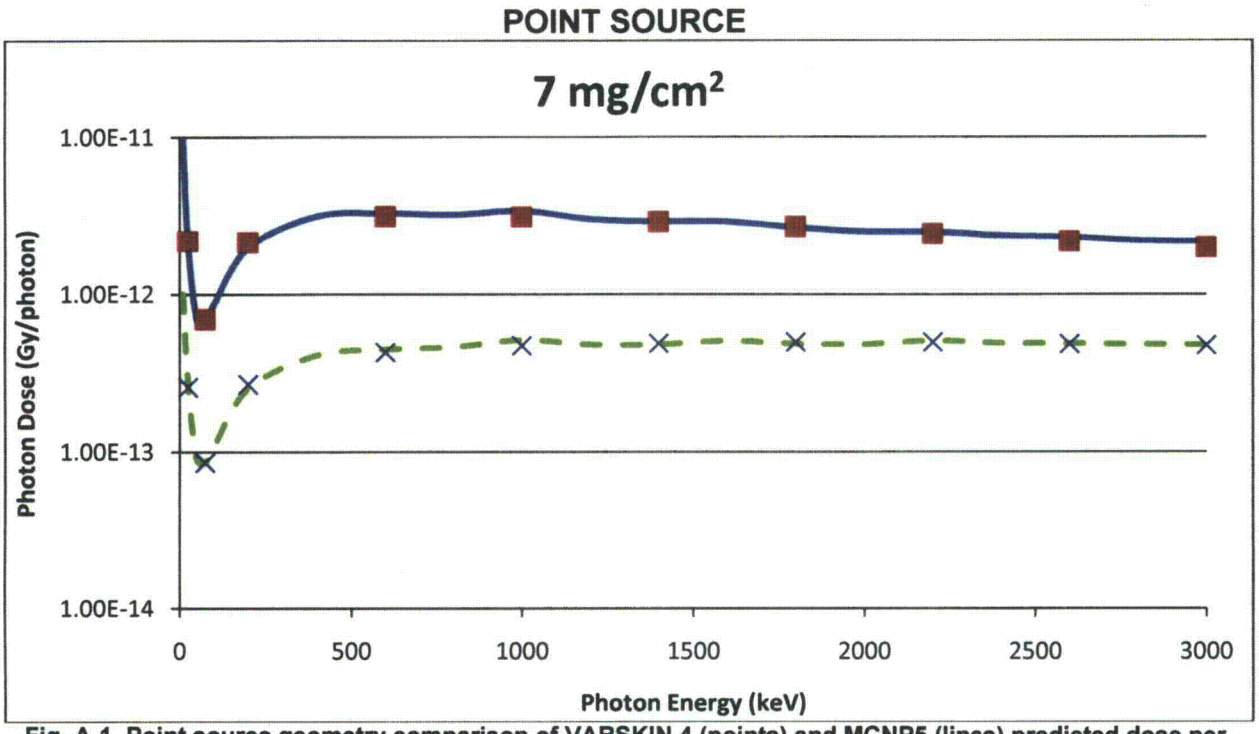

Fig. A-1 Point source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

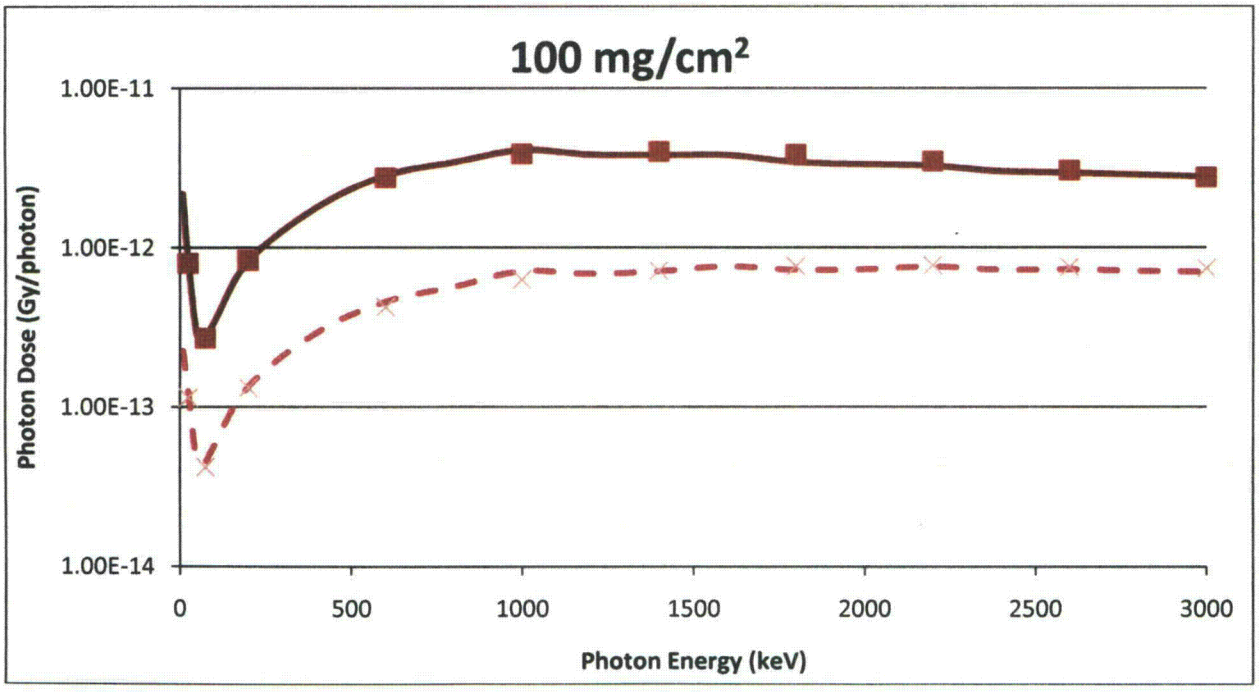

Fig. A-2 Point source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

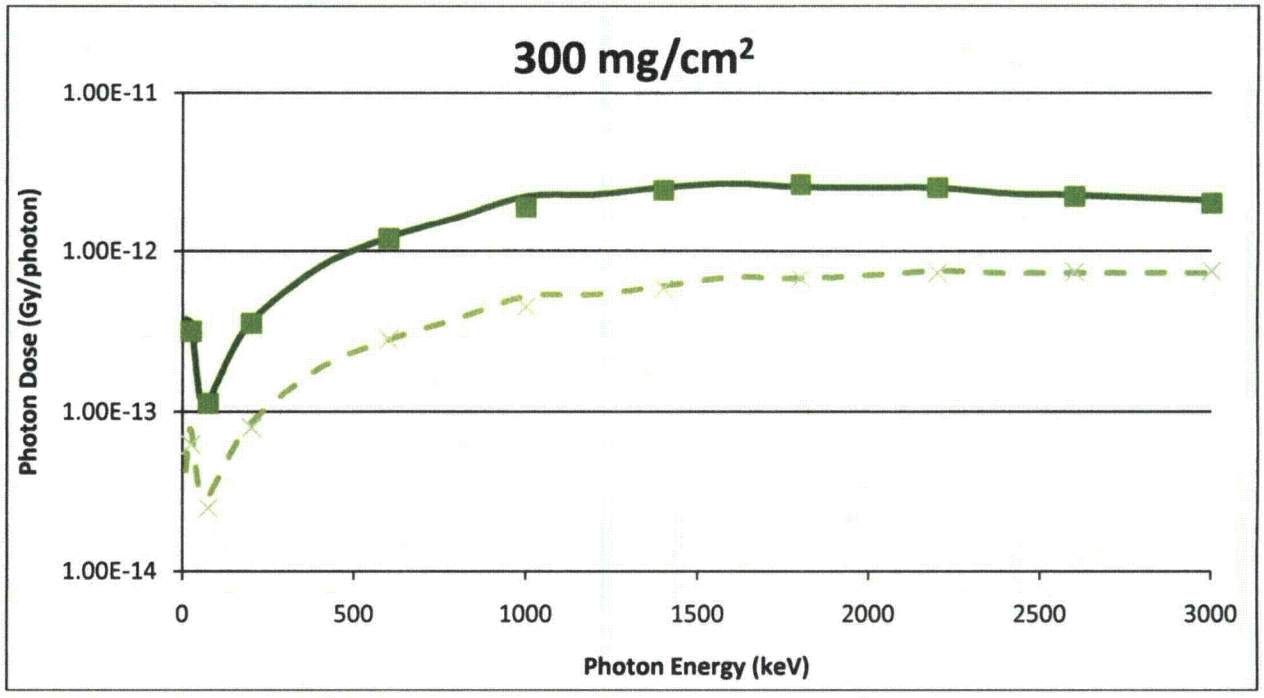

Fig. A-3 Point source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

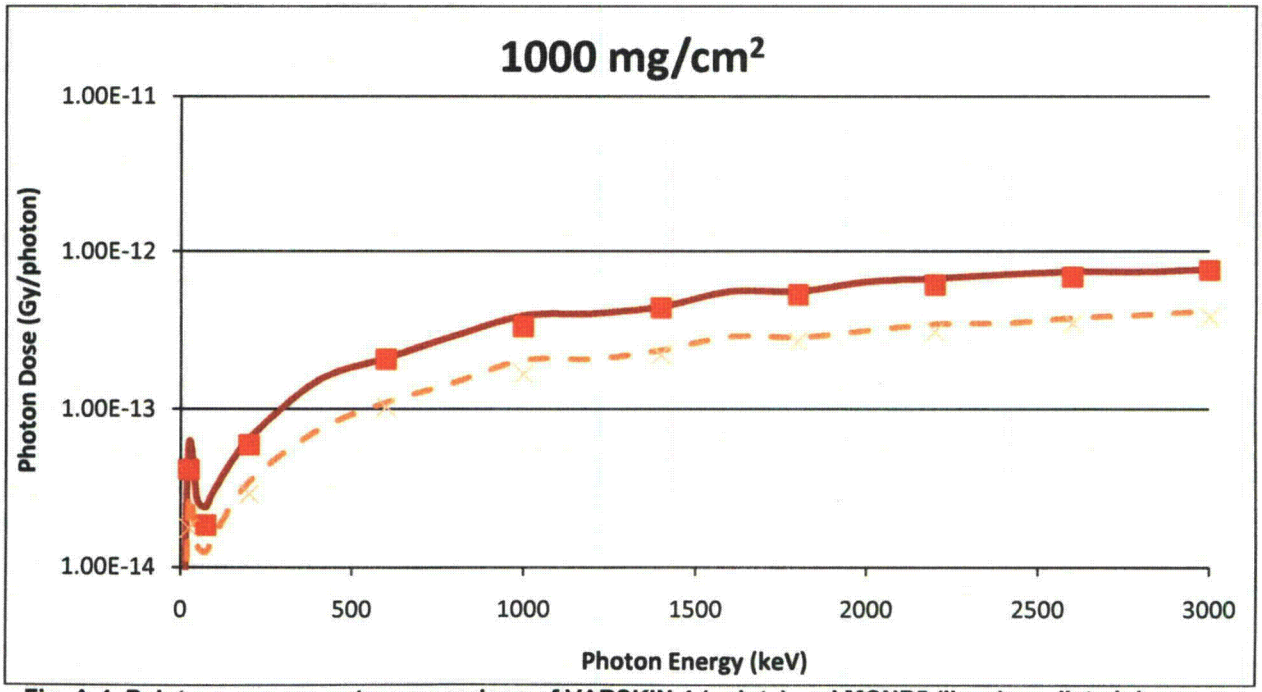

Fig. A-4 Point source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

DISK SOURCE

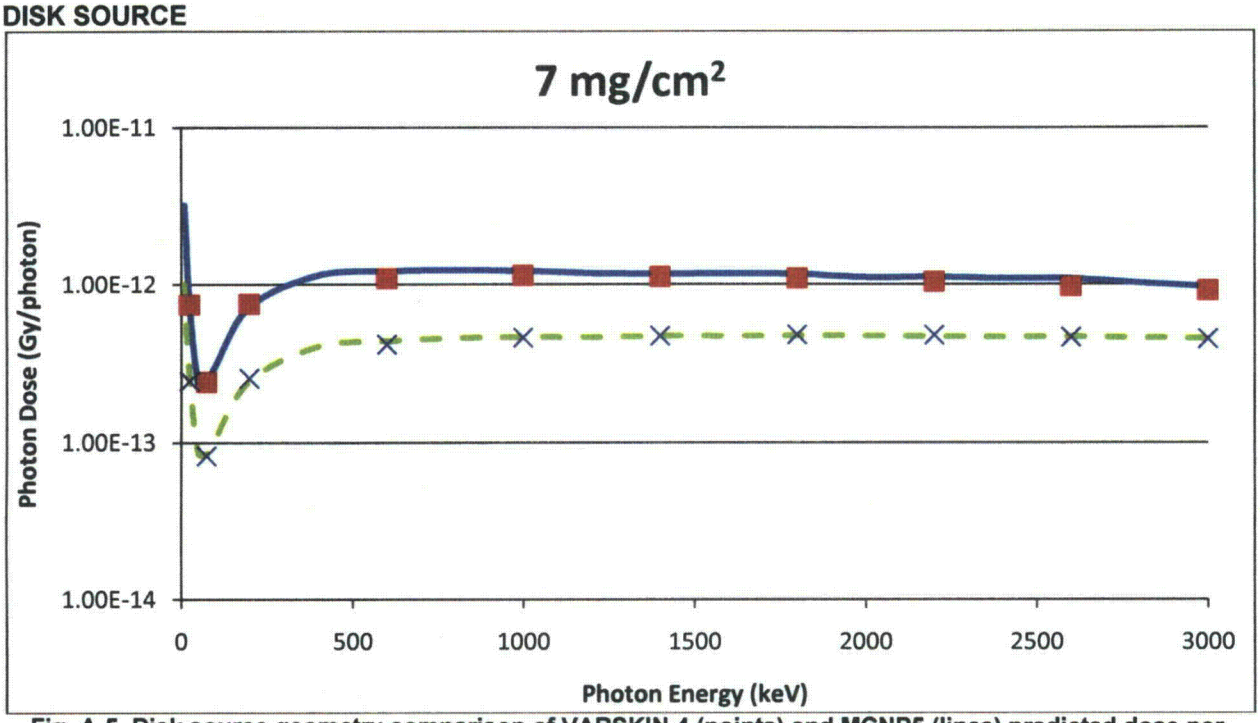

Fig. A-5 Disk source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

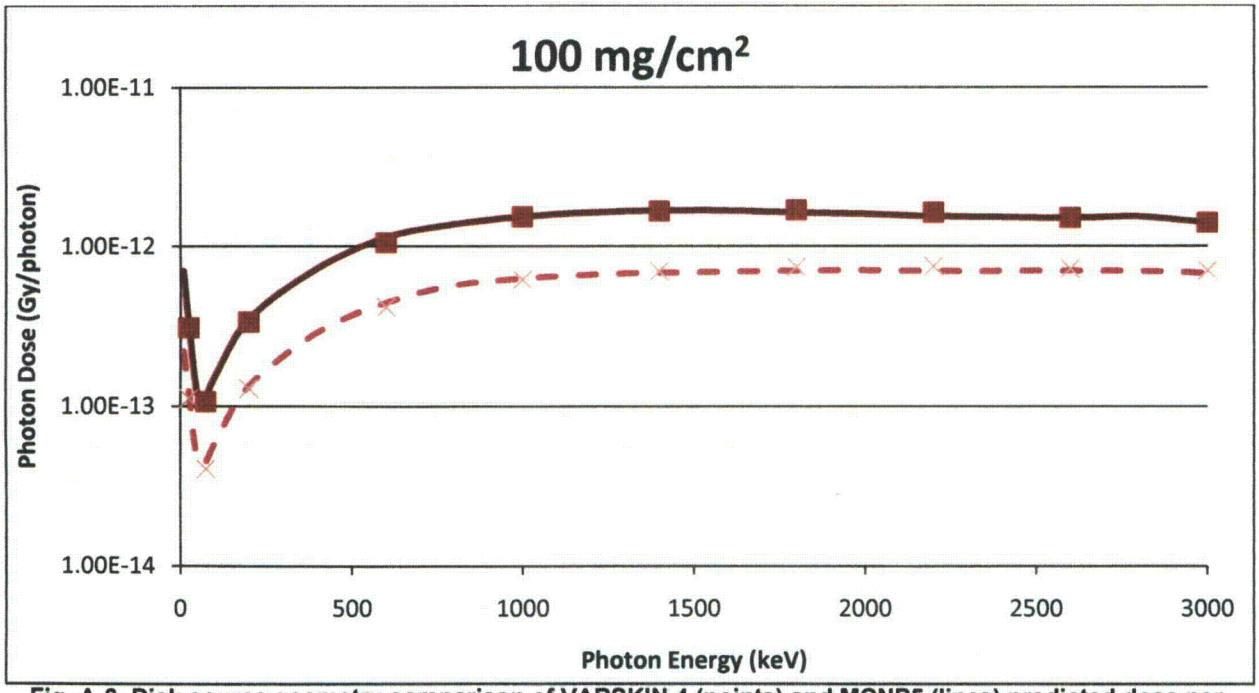

Fig. A-6 Disk source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

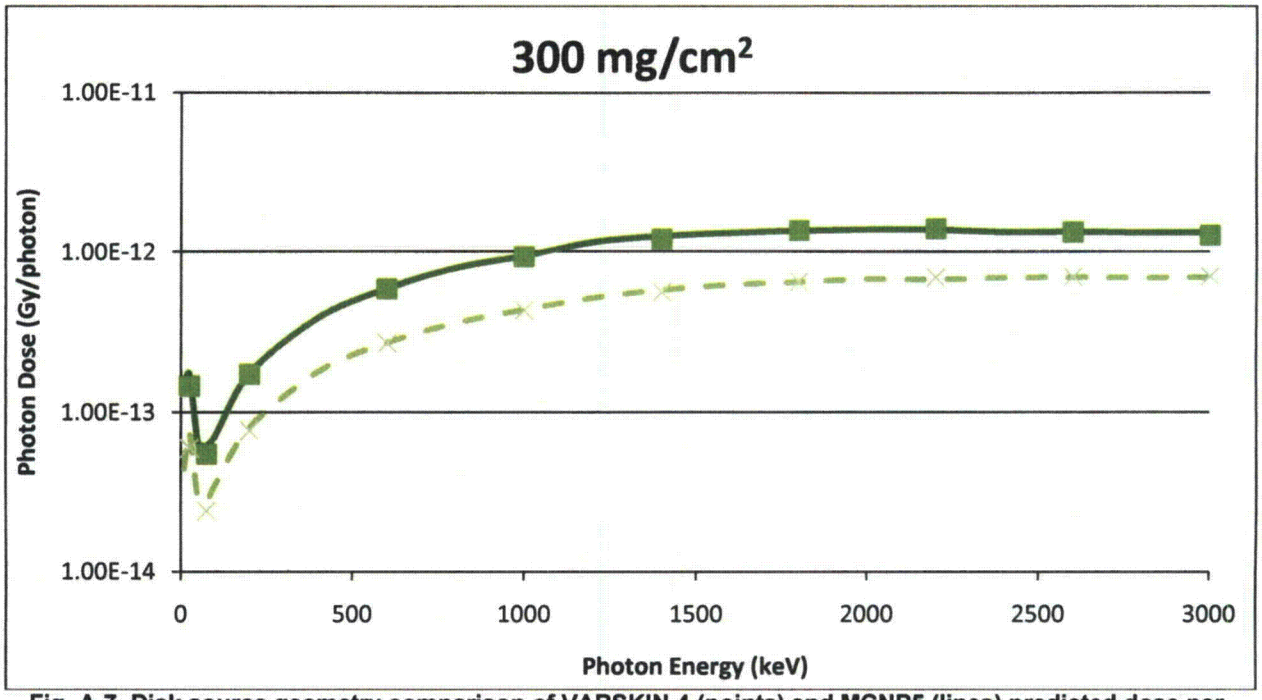

Fig. A-7 Disk source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

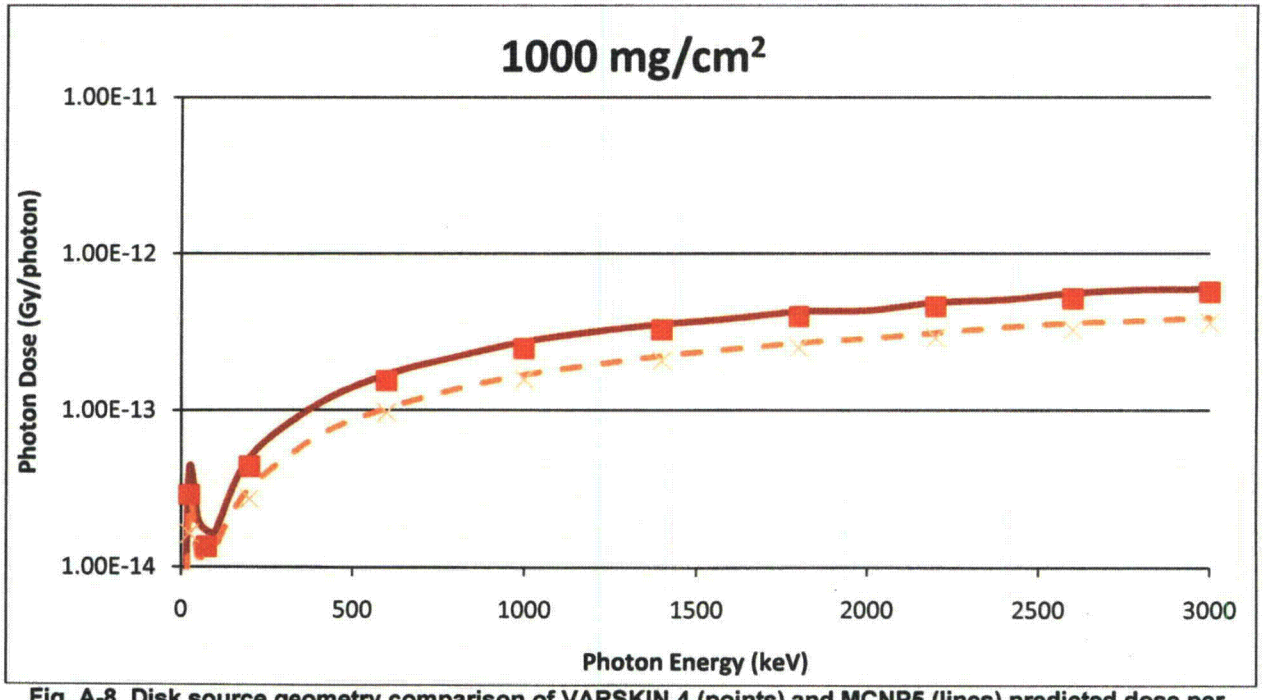

Fig. A-8 Disk source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

CYLINDRICAL SOURCE

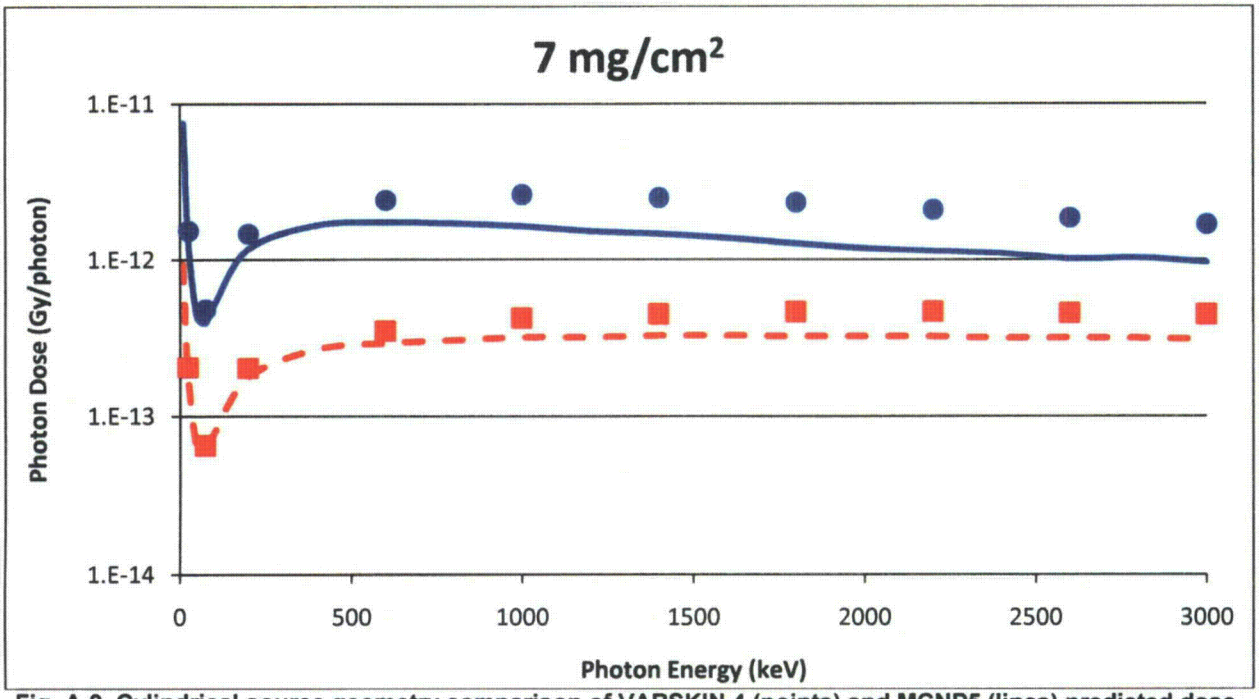

Fig. A-9 Cylindrical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

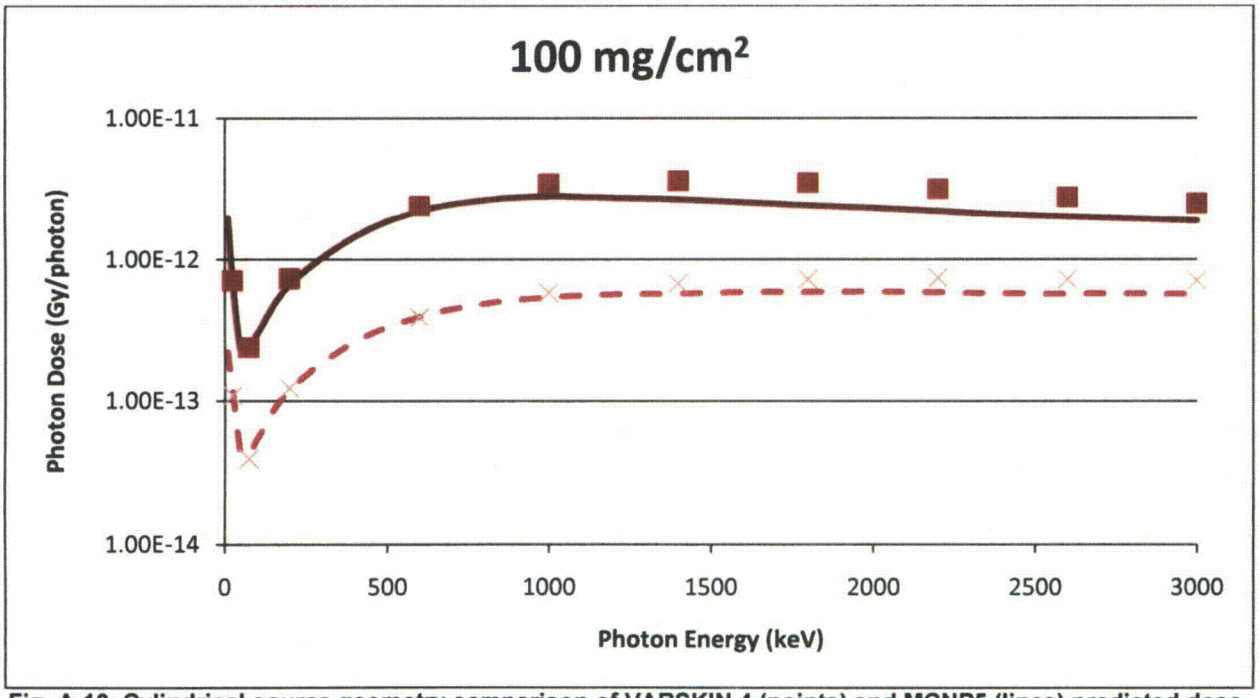

Fig. A-10 Cylindrical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

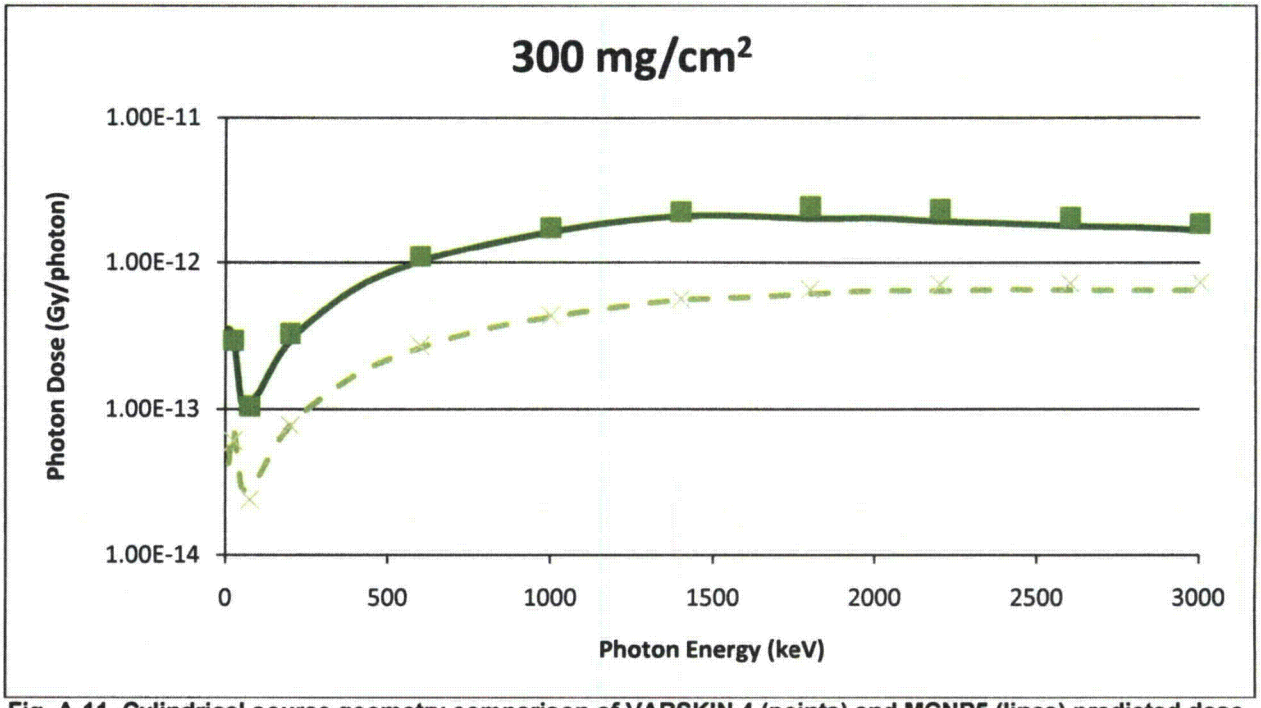

Fig. A-11 Cylindrical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

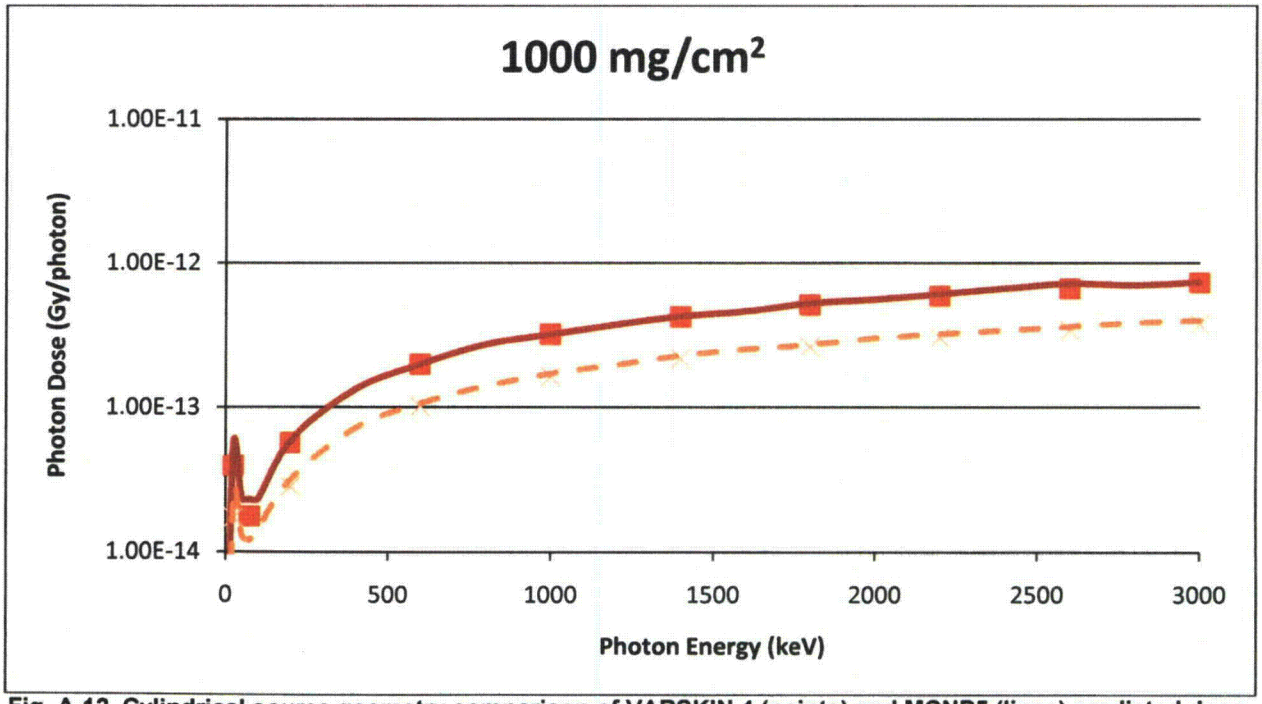

Fig. A-12 Cylindrical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

SLAB SOURCE

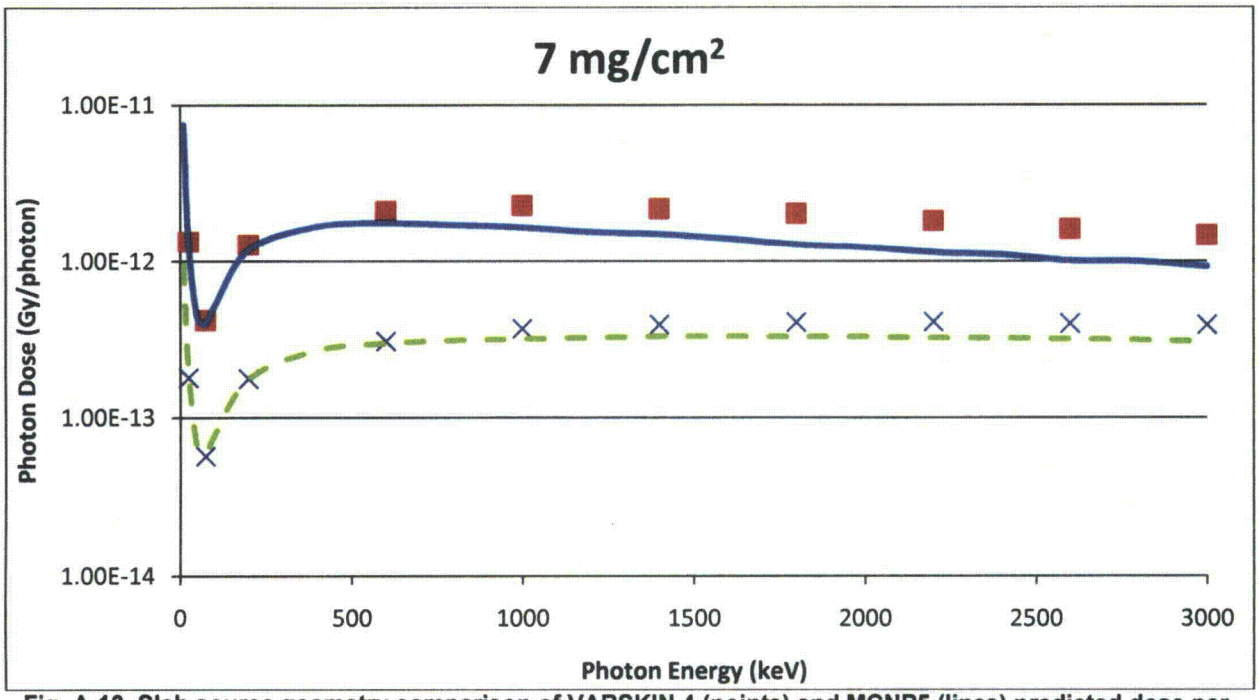

Fig. A-13 Slab source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

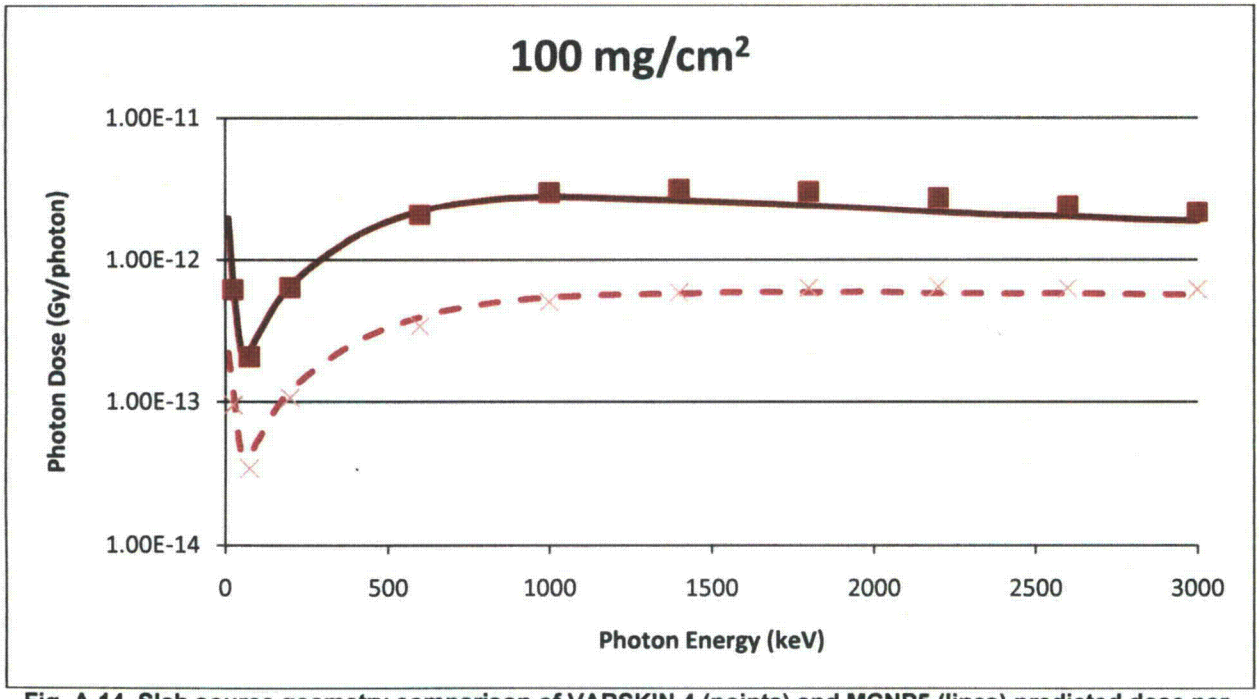

Fig. A-14 Slab source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

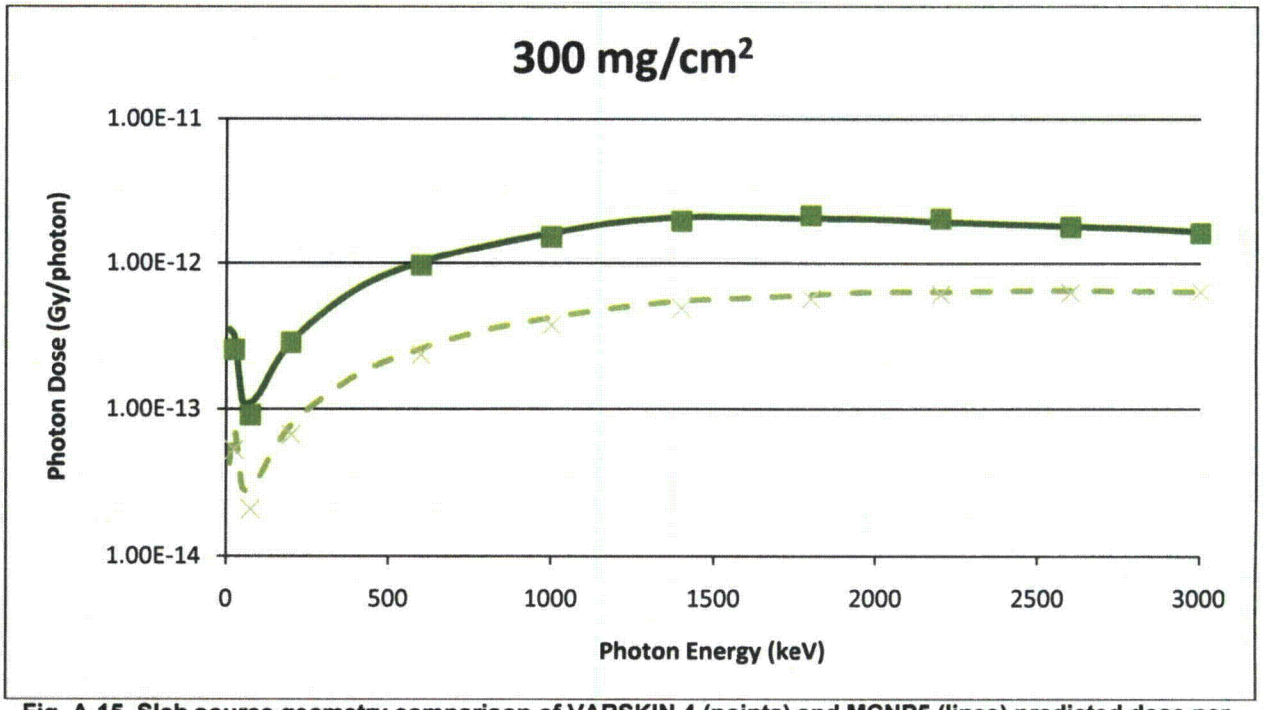

Fig. A-15 Slab source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

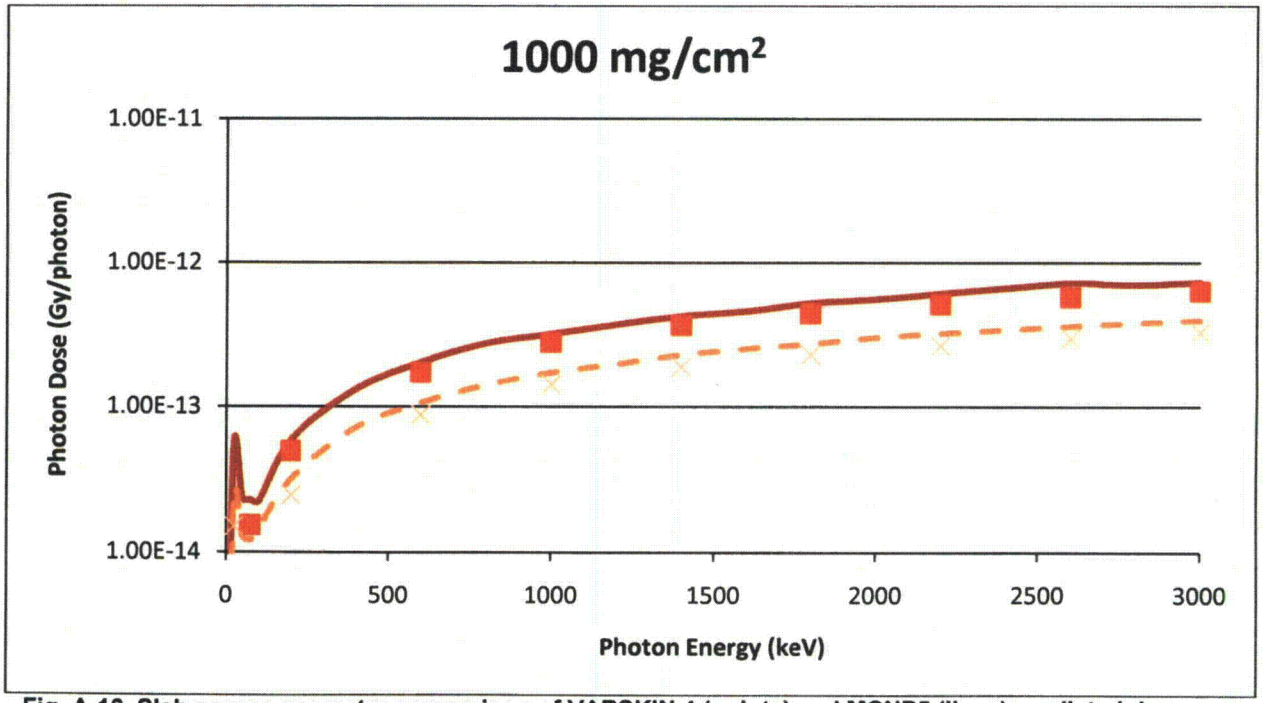

Fig. A-16 Slab source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

SPHERICAL SOURCE

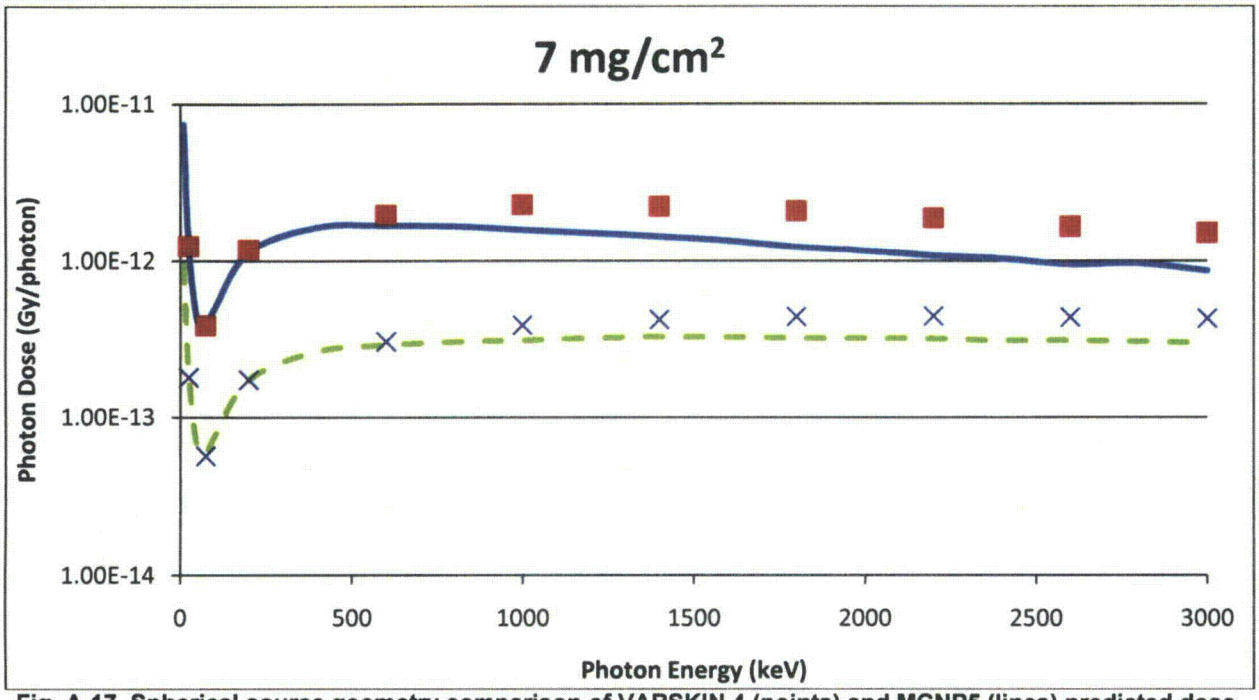

Fig. A-17 Spherical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

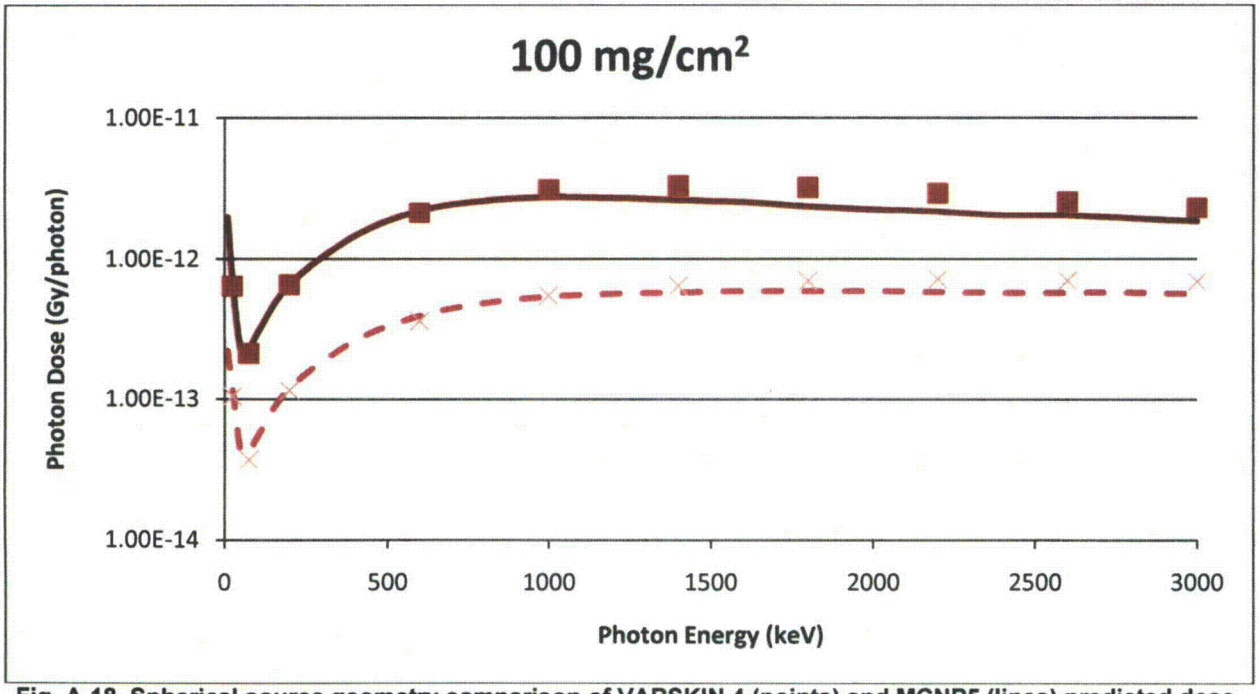

Fig. A-18 Spherical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

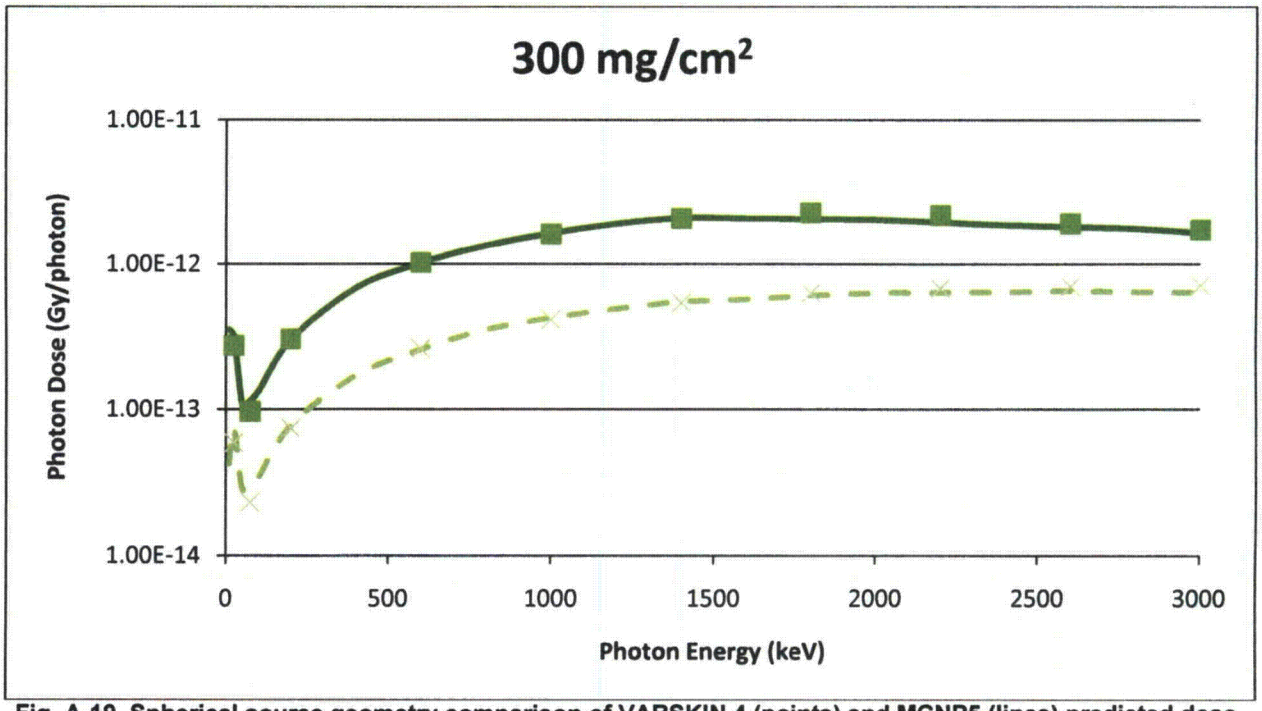

Fig. A-19 Spherical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

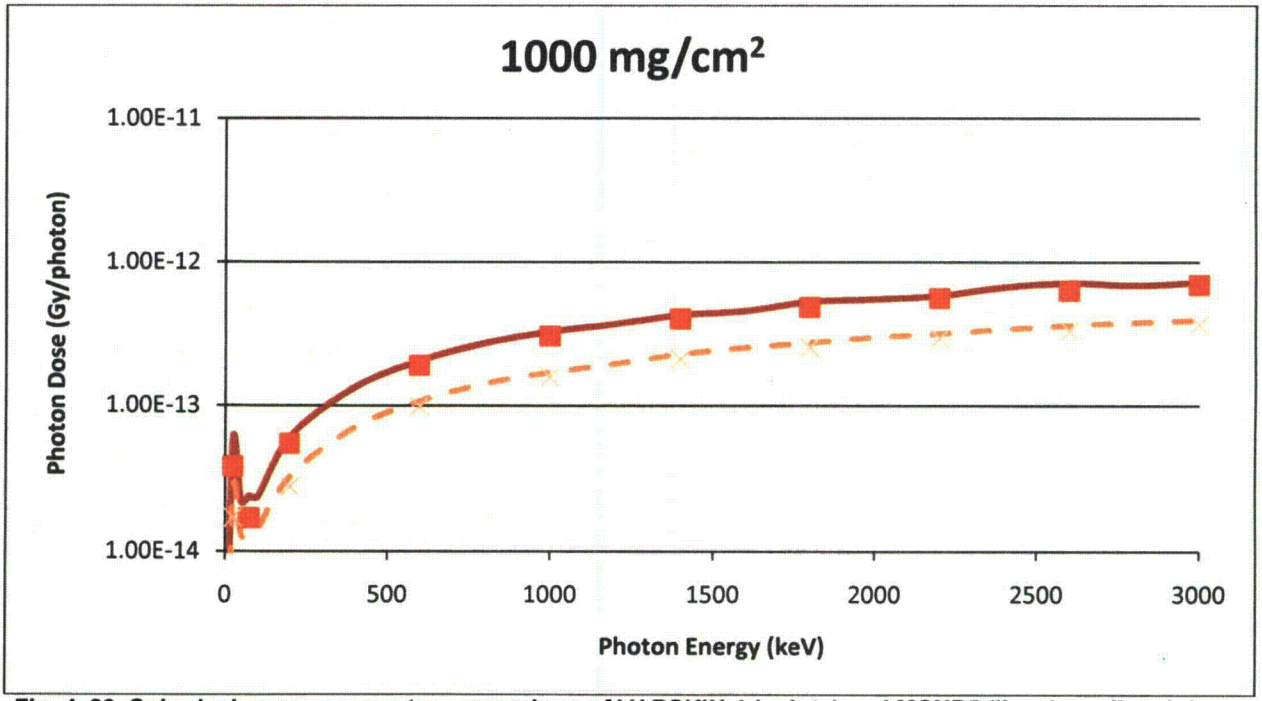

Fig. A-20 Spherical source geometry comparison of VARSKIN 4 (points) and MCNP5 (lines) predicted dose per initial photon as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

POINT SOURCE WITH AIR GAP AND COTTON COVER

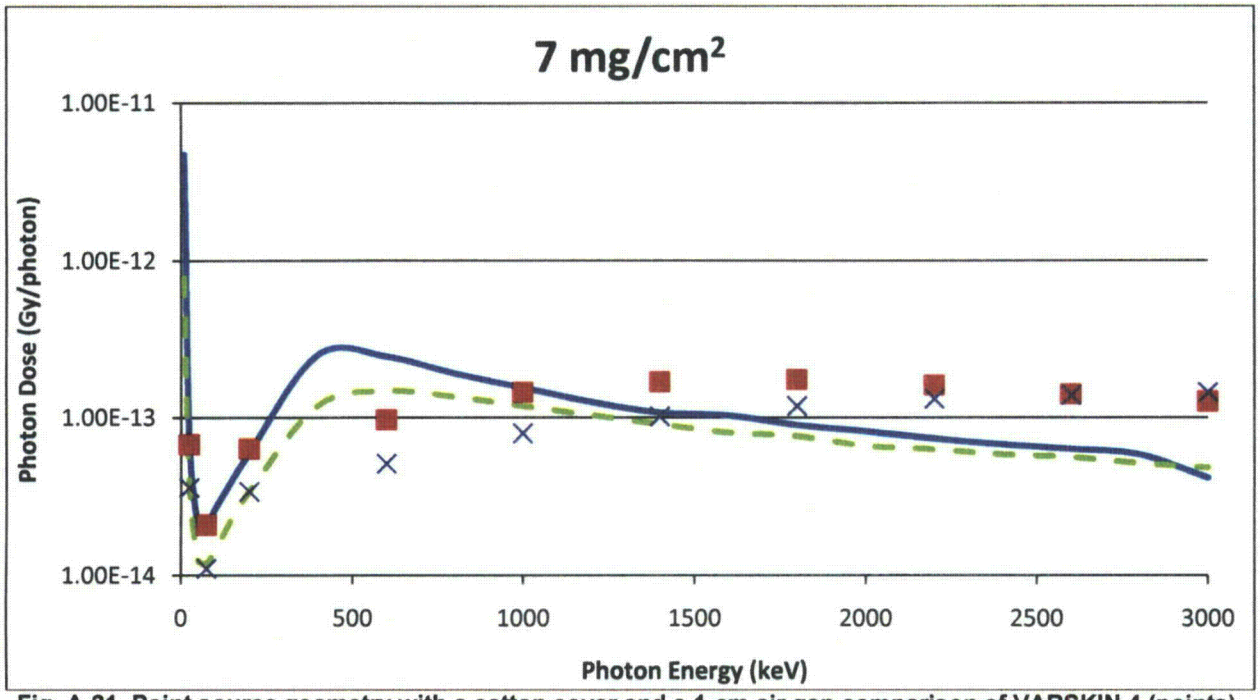

Fig. A-21 Point source geometry with a cotton cover and a 1-cm air gap comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

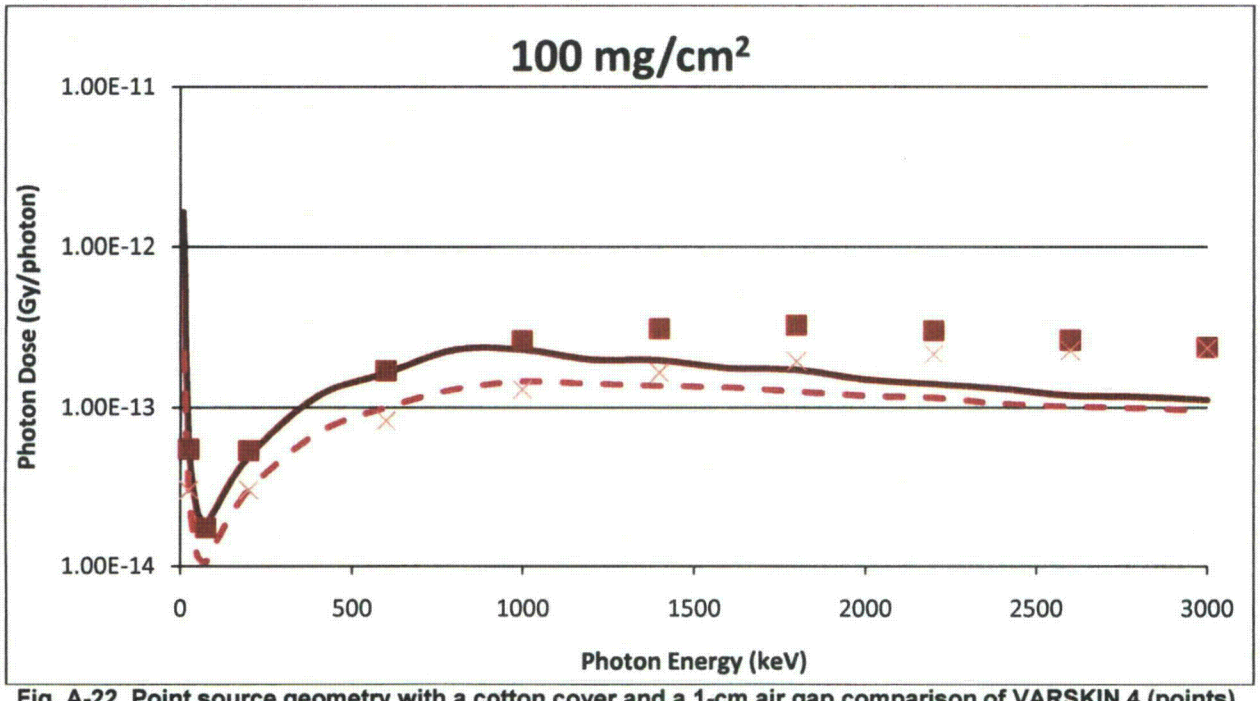

Fig. A-22 Point source geometry with a cotton cover and a 1-cm air gap comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

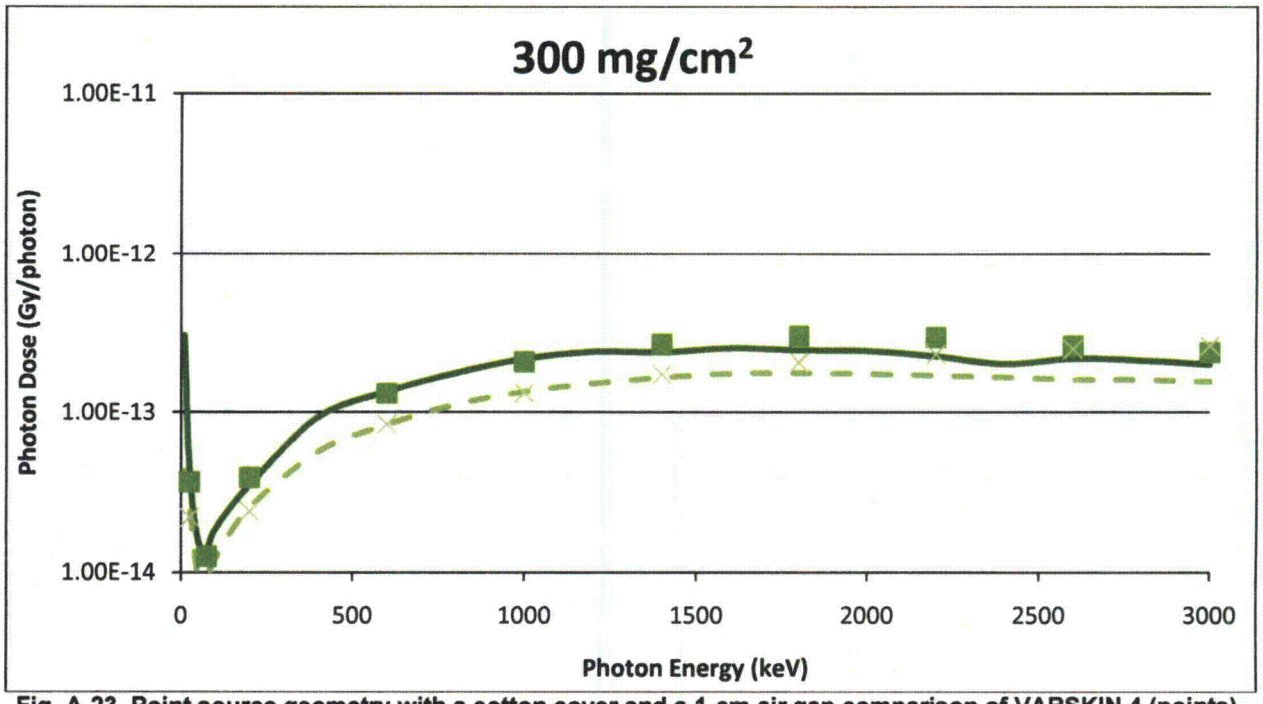

Fig. A-23 Point source geometry with a cotton cover and a 1-cm air gap comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

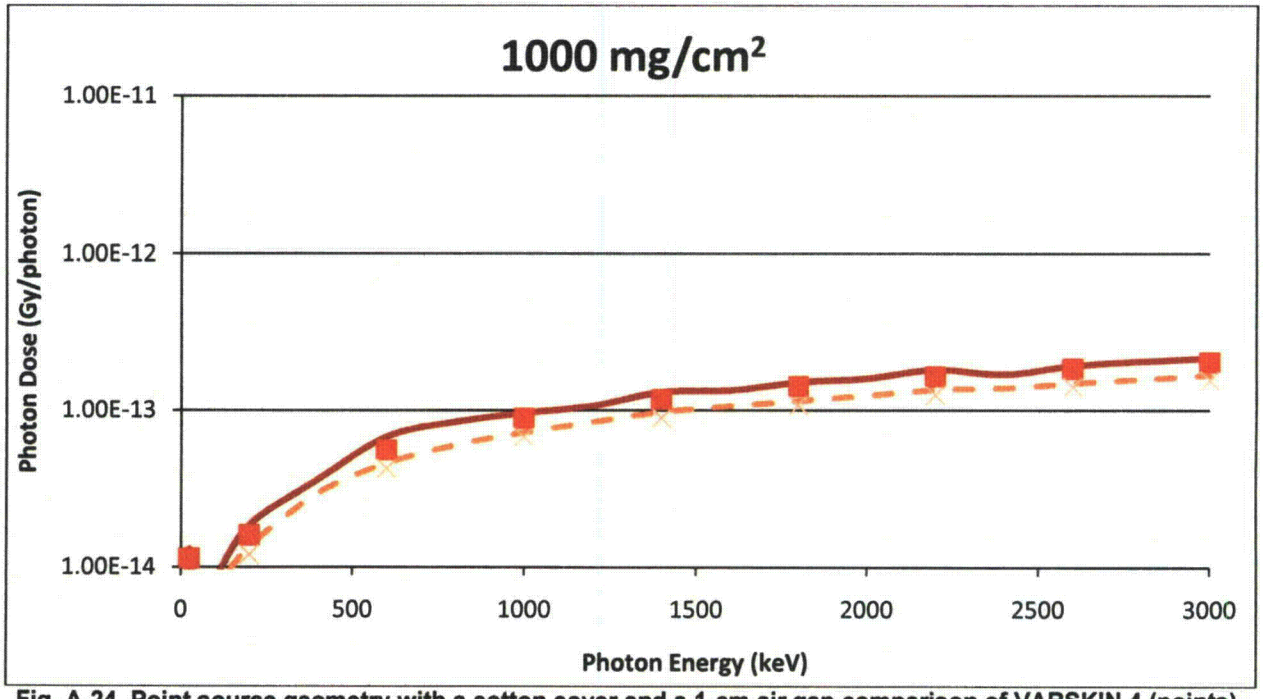

Fig. A-24 Point source geometry with a cotton cover and a 1-cm air gap comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

POINT SOURCE 1 CM OFF AXIS

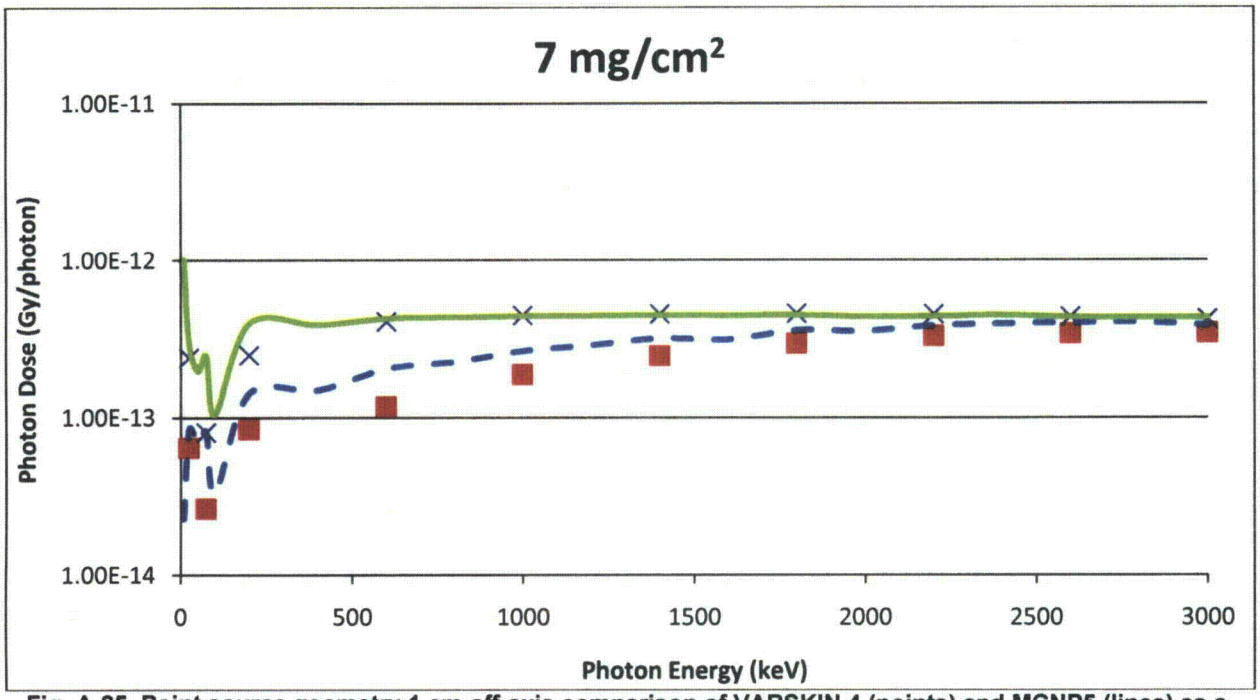

Fig. A-25 Point source geometry 1 cm off-axis comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 7 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

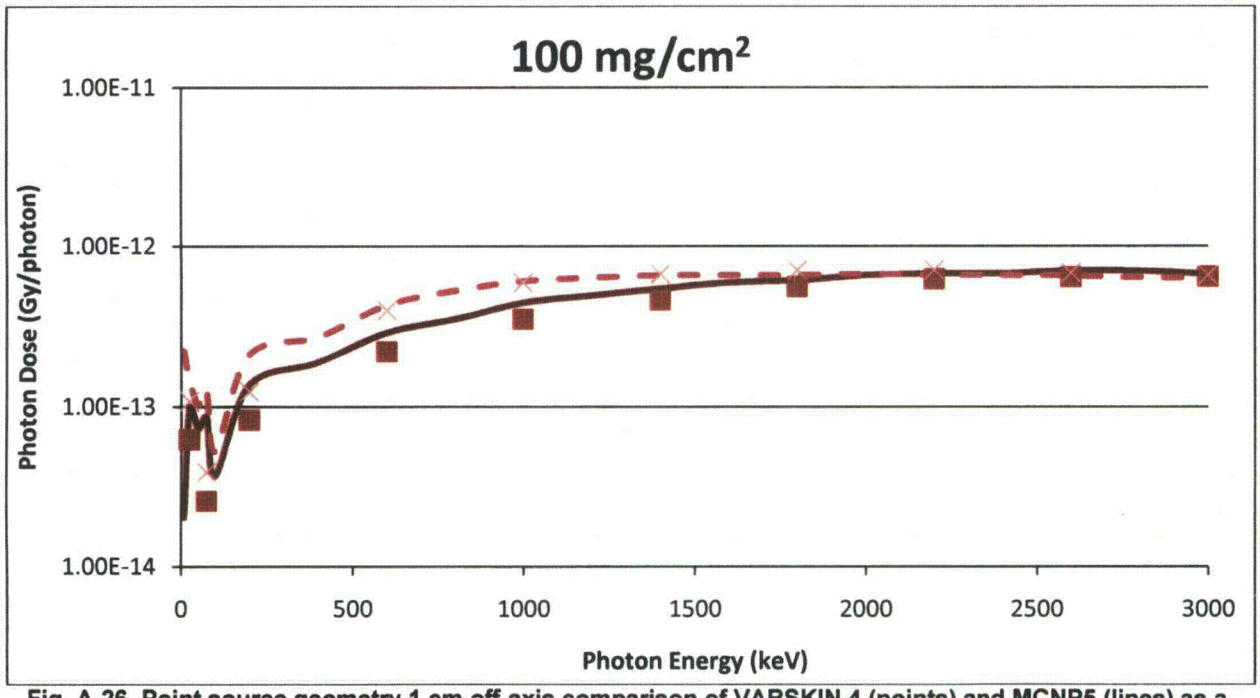

Fig. A-26 Point source geometry 1 cm off-axis comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 100 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

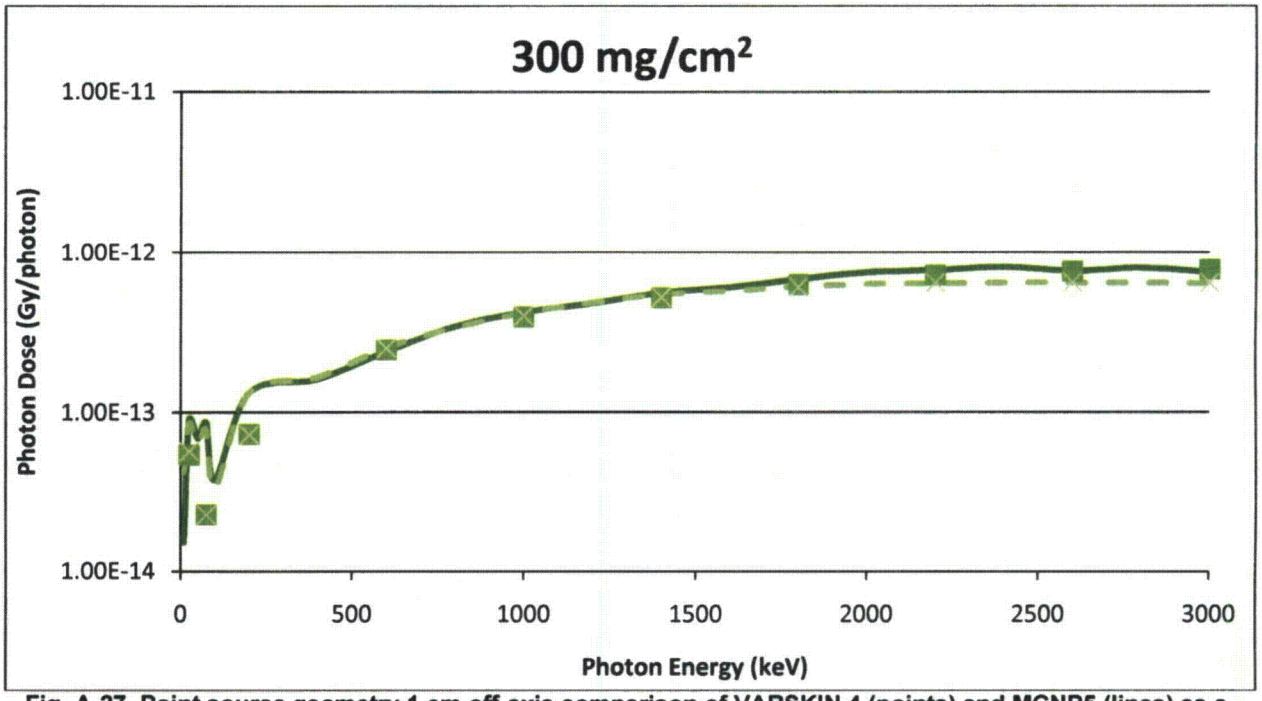

Fig. A-27 Point source geometry 1 cm off-axis comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 300 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

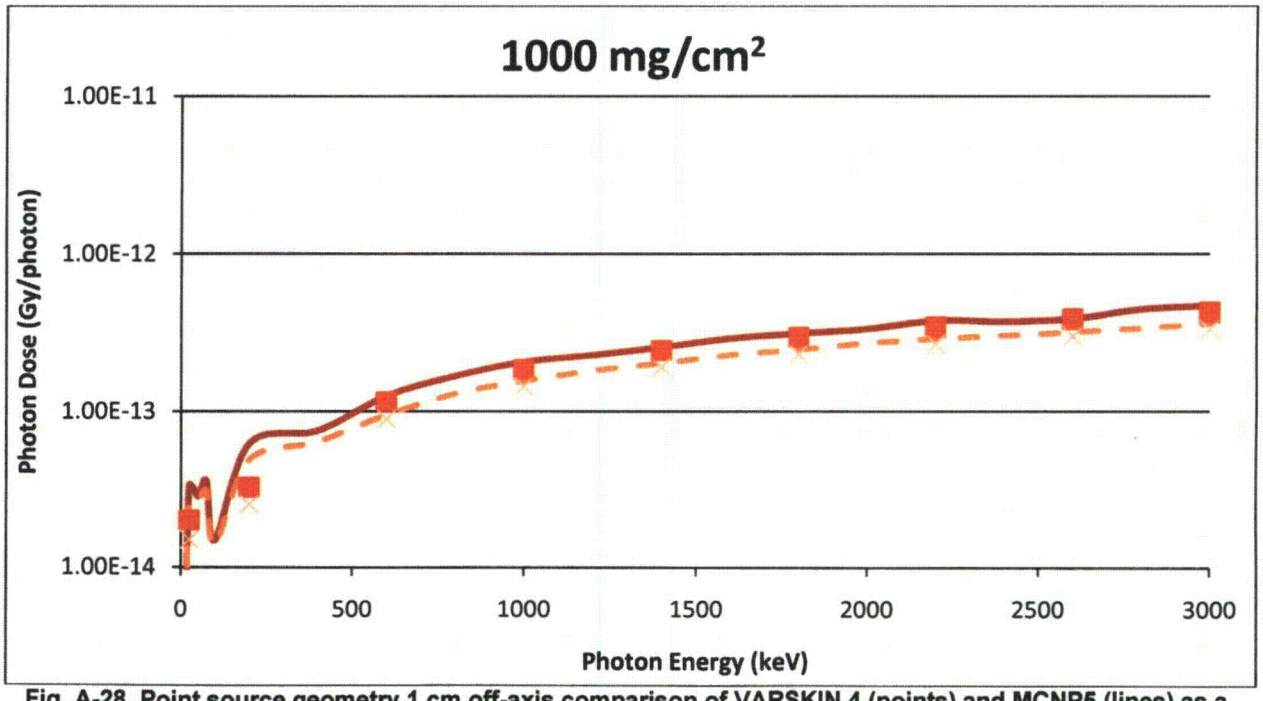

Fig. A-28 Point source geometry 1 cm off-axis comparison of VARSKIN 4 (points) and MCNP5 (lines) as a function of photon energy in tissue at a density thickness of 1,000 mg/cm^2 and a tissue volume cylinder of area 1 cm^2 (solid line) and 10 cm^2 (dashed line), with a thickness of 20 μm

APPENDIX B

Examples and Solutions Using VARSKIN 4

EXAMPLES AND SOLUTIONS USING VARSKIN 4

This appendix describes three different practical applications of VARSKIN 4 using an example/solution format. Each example describes a situation followed by a solution that involves the use of VARSKIN 4 to estimate skin dose and deep-dose equivalent. The purpose of these examples is to lead a new user of VARSKIN through several calculations that highlight many of its features. Because VARSKIN 4 is a flexible tool, there are always several ways to calculate the dose for a given example. The solutions presented here reflect the recommendations that are provided throughout the user's manual. With some experience, most VARSKIN 4 users will not need to perform all of the steps described in the solution in an actual situation. It is suggested that the user complete all three examples in the order in which they are presented to develop familiarity with VARSKIN 4.

Example 1: Radiopharmaceutical Technician in Nuclear Medicine

At a research hospital, a doctor prescribes a 5-milliliter (mL) administration from a stock solution containing 10 microcuries per milliliter (μCi/ml) of rhenium (Re)-186 for a clinical research study at 1 p.m. that day. Around 12:30 p.m., a lab technician loads the dose under the hood. Subsequently, a fellow employee bumps into her, and the needle slips out of its container. The entire 5 mL of the solution is spilled on the arm of her cloth lab coat in a circular shape with an area of approximately 50 square centimeters (cm^2). She is unaware of the accident and continues with her work until the end of the day. Around 5 p.m., a routine survey for contamination is performed, and the contamination is discovered.

Solution 1: Radiopharmaceutical Technician in Nuclear Medicine

The point source geometry is suggested as a starting point to estimate the magnitude of the dose and to collect some other useful information. Run VARSKIN 4 and check the user "Radionuclide Library." If Re-186 does not appear in the "Radionuclide Library" window, add Re-186 by selecting the "Add" button and double-clicking Re-186 in the Add Radionuclide to Library screen. Enter the Exposure Time as 4.5 and change the time unit to hours using the drop-down menu or the down-arrow key. Because the point source geometry is being used, it is necessary to calculate the source strength by multiplying the concentration of the stock solution (10 μCi/ml) by the size of the administration (5 ml) to get a total source strength of 50 μCi. Be sure that the source strength units are set to μCi, then double-click the Re-186 library entry. When VARSKIN 4 asks for the source strength, enter 50. The other defaults will establish a dose calculation at 7 mg/cm^2 and a dose-averaging disk of 10 cm^2. All other entries should retain their default values. Click "Calculate Doses." After the calculation is performed, the VARSKIN 4 Results screen will appear.

The VARSKIN 4 Results screen displays two groups of nine dose or dose-rate values (the group to the left is for nuclide-specific doses and the group to the right is total (over all nuclides) dose). Since only one nuclide has been selected, the two groups will display the same dose values. For each of beta, photon, and total, the initial dose rate, the dose with no decay, and the decay-corrected dose are displayed. The dose with no decay is provided so that the user can assume that either the source has a very long half-life or that the radionuclide is in secular

equilibrium with its parent. Note that Re-186 has a relatively short half-life; therefore, the decay-corrected dose is the appropriate dose for the current calculation. Looking at either the VARSKIN 4 Results screen or the results printout (by clicking the "Print Results" button) will show that the decay-corrected total dose is **136 radiation absorbed dose (rad) (136 rad** from beta and **48.6 millirad (mrad)** from photons), a value that exceeds regulatory limits. To calculate the deep dose, return to the Source Geometry screen, change the value of the Skin Thickness or Skin Density Thickness to 1,000 milligrams per square centimeter (mg/cm^2), and click "Calculate Doses." The VARSKIN 4 Results screen displays a decay-corrected beta dose of **0** (zero) and a photon dose of **7.01 mrad**.

The total shallow dose calculated using the point geometry was above regulatory limits. However, the situation described in this example will obviously be more accurately modeled using the disk or cylinder geometries. A more realistic, yet conservative approach would be to use the disk geometry and calculate the dose as if all of the contamination were directly on the skin. Return to the Source Geometry screen and choose "Disk" in the Source Geometry frame. Confirm the Exposure Time of 4.5 hours. Next, enter the Source Area as 50 cm^2 (don't forget to change the units from the default setting). Note that the Source Diameter is automatically calculated to be 7.98 cm (this value will be needed for the next model). Change the Skin Thickness or Skin Density Thickness back to the shallow depth of 7 mg/cm^2 and click "Calculate Doses." The Results screen shows a decay-corrected beta dose of **27.1 rad** and a photon dose of **9.94 mrad**. While the dose is still quite high, it is now below regulatory limits.

Even more realism can be introduced by using the cylinder model to simulate contamination that is uniformly distributed throughout the thickness of the lab coat. In this case, the lab coat is assumed to soak up the contamination instead of acting as a protective cover material. The data in Table 2-2 for a cloth lab coat give a thickness of 0.4 millimeters (mm) and a density of 0.9 g/cm^3. After returning to the input screen, choose "Cylinder" in the Source Geometry frame. Confirm the exposure time of 4.5 hours. Paying close attention to each unit's entry, confirm the Source Diameter as 7.98 cm (from the disk calculation), and establish a Source Thickness of 0.4 mm (the thickness of the lab coat) and a Source Density of 0.9 g/cm^3 (the density of the lab coat). Click "Calculate Doses"; the VARSKIN 4 Results screen then will display **16.6 rad** and **9.94 mrad** as the decay-corrected beta and photon doses, respectively.

It is interesting to see what the beta dose would be if the lab coat was impervious to the liquid contamination, and the contamination resided as an infinitely thin layer of contamination on the plastic. In this case, the plastic lab coat acts as a cover material instead of defining the size and density of the source. To perform this calculation, return to the input screen and change the geometry to a "Disk" source. Confirm the Exposure Time of 4.5 hours and the source area of 50 cm^2. Enter a Cover Thickness of 0.2 mm with a density of 0.36 g/cm^3. After the user clicks "Calculate Doses," the VARSKIN 4 Results screen will display decay-corrected doses of **19.5 rad** for beta and **9.67 mrad** for photons. It can be concluded that, based on the above calculations, a thicker, absorbent lab coat will give more protection than a thin, impervious material.

Example 2: Radiation Worker in Reactor Containment

A worker damages his outer glove while working inside containment during an outage at a nuclear reactor. His outer glove is removed, leaving only a surgeon's glove. The worker proceeds to the step-off pad, which takes about 15 minutes. During the exit survey, contamination is detected on the surgeon's glove, and the glove is removed and taken to the laboratory for analysis. The laboratory report concludes that the contamination is a stellite hot particle with the following characteristics:

- Radioactive contaminant: Co-60
- Source strength: 2.5 mCi
- Particle thickness and density: 50 μm; 8.3 g/cm^3
- Particle size: 80 μm x 70 μm
- Glove thickness: 0.3 mm
- Glove density: 0.6 g/cm^3

Solution 2: Radiation Worker in Reactor Containment

First, use the point source geometry to estimate the magnitude of the dose and to collect some other useful information. Start or "Reset" (from the File drop-down menu) VARSKIN 4. If Co-60 does not appear in the Radionuclide Library frame, add Co-60 by selecting the "Add" key and double-clicking "Co-60" in the Add Radionuclide to Library window. Enter an Exposure Time of 15 minutes. Double-click "Co-60" in the Radionuclide Library, and enter 2.5 millicuries (mCi). Enter a Cover Thickness of 0.3 mm and a Cover Density of 0.6 g/cm^3. After you click "Calculate Doses," the VARSKIN 4 Results screen will display a beta dose of **32.5 rad**, a photon dose of **10.5 rad,** and a total dose of **43.0 rad**, a value approaching the regulatory limit. Thus, a more realistic calculation is desirable. In addition, there is a gamma component to the dose, so a deep-dose calculation is needed.

Using the cylinder model will result in a more realistic calculation because the effects of self-shielding of the beta particles will be considered. As described in Section 2.2, the cylinder model should be used for a particle that is known to be rectangular. Return to the input screen, and choose the "Cylinder" source geometry. Confirm 15 minutes as the Exposure Time, 0.3 mm as the Cover Thickness, and 0.6 g/cm^3 as the Cover Density. Enter 50 μm as the Source Thickness. The diameter of a disk source with the same area as the rectangular source is found by:

$$d = 2\sqrt{X \cdot Y/\pi} = 2\sqrt{80\ \mu m \cdot 70\ \mu m/\pi} = 84\ \mu m.$$

Enter 84 μm for the Source Diameter and 8.3 g/cm^3 for the Source Density, and then click "Calculate Doses." The VARSKIN 4 Results screen will display a beta dose of **8.36 rad**, a photon dose of **10.5 rad**, and a total dose of **18.9 rad**. Including the effects of self-shielding greatly reduced the beta dose and resulted in a dose that is now below regulatory limits. To calculate deep dose, simply return to the input screen, change the Skin Thickness or Skin Density Thickness to 1,000 mg/cm^2, and click "Calculate Doses." The VARSKIN 4 Results screen will display a deep dose of **3.25 rad**, all from photons.

Example 3: Contaminated Metal in a University Laboratory Hood

During a radiation survey of a fume hood, a new Radiation Safety Officer (RSO) at a university discovers a contaminated aluminum plate inside the hood. Upon further investigation, it is found that the plate was used to hold beakers of solution containing carbon (C)-14 for use in radiobiology experiments. The RSO decides that the plate should be disposed of as low-level radioactive waste and that the activity of C-14 on the plate must be determined. The plate is 6 inches (in.) by 6 in. and is uniformly contaminated over the entire surface. The RSO uses a calibrated circular detector with an area of 50 cm^2 and a window thickness of 3 mg/cm^2 to measure a dose rate of 190 mrad/h on contact and 60 mrad/h at a distance of 1 in.

Solution 3: Contaminated Metal in a University Laboratory Hood

The solution to this example demonstrates a method of using VARSKIN 4 for applications other than skin contamination events. In this situation, the Skin Averaging Area will be set to 50 cm^2 to correspond to the area of the probe, the Skin Density Thickness will be set to 3 mg/cm^2 to correspond to the thickness of the probe window, and the Source Area will be set to 36 in^2 to correspond to the area of the contaminated plate. A source strength of 1 $\mu Ci/cm^2$ will be used for the calculation, and the results of the calculation will be scaled to the measurements obtained by the RSO. Both of the measurements can be modeled because the air gap in Example 3 is smaller than 5 cm, the limit for air gaps in VARSKIN 4.

For this solution, first "Reset" VARSKIN 4 and choose the Disk geometry. If the Radionuclide Library does not contain C-14, add it by clicking "Add" and double-clicking "C-14" in the Add Radionuclide to Library screen. C-14 does not emit photons so it is not necessary to change the photon minimum energy. From the input screen, click the "Use Distributed Source" checkbox. Notice that the default unit for activity has changed. Double-click "C-14" and set the source strength to 1 $\mu Ci/cm^2$. Set the Skin Averaging Area to 50 cm^2, the Skin Thickness or Skin Density Thickness to 3 mg/cm^2, and the Source Area to 36 in^2. For this example, the dose rate is of interest so the irradiation time can remain at the default value of 60 minutes. Click "Calculate Doses"; the VARSKIN 4 Results screen will appear, displaying an initial beta dose rate of **4.68 rad/h**, with no photon dose. The activity concentration on the plate then can be found using,

$$\frac{[A_{act}]}{[A_{cal}]} = \frac{\dot{D}_{meas}}{\dot{D}_{cal}}.$$

Therefore, the activity concentration on the plate is given by:

$$\frac{\left(1^{\mu Ci}/_{cm^2}\right)\left(190^{mrad}/_{hr}\right)}{4680^{\,mrad}/_{hr}} = 0.04\ ^{\mu Ci}/_{cm^2}.$$

Multiplying the activity concentration by the area of the plate (6 in. x 6 in. = 232 cm^2) results in a total activity of 9.3 μCi.

The measurement at a distance of 1 in. can be used to verify this result. Close the Results screen, return to the Input screen, and enter an Air Gap Thickness of 1 in. After you click "Calculating Doses," the VARSKIN 4 Results screen will display an initial beta dose rate of

1.43 rad/h. Comparing this dose rate to the measured dose rate gives an activity concentration of:

$$\frac{\left(1\,{}^{\mu Ci}/_{cm^2}\right)\left(60\,{}^{mrad}/_{hr}\right)}{1430\,{}^{mrad}/_{hr}} = 0.04\,{}^{\mu Ci}/_{cm^2}.$$

From this value, the total activity of the plate is calculated to be 9.3 μCi. Thus, the two measurements result in a consistent determination of the activity on the plate.

NRC FORM 335
(12-2010)
NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-6918, Rev.1

2. TITLE AND SUBTITLE

NUREG/CR-6918 Rev.1, "VARSKIN 4: A Computer Code Contamination Dosimetry"

3. DATE REPORT PUBLISHED

MONTH	YEAR
June	2011

4. FIN OR GRANT NUMBER

RES-08-137

5. AUTHOR(S)

D.M. Hamby, C.J. Lodwick, T.S. Palmer, S.R. Reese, and K.A. Higley

6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Department of Nuclear Engineering and Radiation Health Physics
Oregon State University
Corvallis, OR 97331-5902

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington DC, 20555-0001

10. SUPPLEMENTARY NOTES

Mohammad S. Saba, Project Manager and Sami Sherbini, Technical Monitor

11. ABSTRACT *(200 words or less)*

Improvements to VARSKIN 4 include an enhanced photon dosimetry model, as well as models to account for air gap and cover materials for photon dosimetry. Although the user can choose any dose-averaging area, the default area for skin dose calculations in VARSKIN 4 is 10 square centimeters, to conform to regulatory requirement pursuant to Title10 of the Code of Federal Regulations, Section20.1201(c). Data entry is condensed to a single screen, and the user does not need to enter the data in any particular order. A variety of unit options are provided, including both British and International System (SI) units, and the source strength can be entered in units of total activity or distributed in units of activity per unit area or activity per unit volume. The output page and the user's ability to add radionuclides to the library are greatly simplified. A library file contains data on photons, internal conversion electrons, and Auger electrons. VARSKIN 4 allows the user to eliminate radionuclides that are not of interest and thus build a customized library. Finally, an extensive, context-sensitive help file is made available to provide guidance and to offer new users a tutorial in the use of VARSKIN.

This document describes the VARSKIN 4 code, provides basic operating instructions, presents detailed descriptions of dosimetry models, and suggests methods for avoiding misuse of the code.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

NUREG/CR-6918
skin dose
skin dosimetry
VARSKIN 4
photon dose
beta dose
skin contamination

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)
unclassified

(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS