VARSKIN 3: A Computer Code for Assessing Skin Dose From Skin Dose Contamination
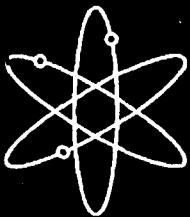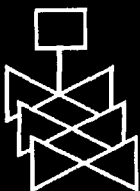
Center for Nuclear Waste Regulatory Analyses

VARSKIN 3: A Computer Code for Assessing Skin Dose From Skin Dose Contamination

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ABSTRACT

The computer code VARSKIN Mod 2, which calculates skin dose from radioactive skin contamination, has been significantly modified. The new code, Varskin 3, operates in a Windows® environment and is designed to be significantly easier to learn and use than VARSKIN Mod 2. Six different predefined source configurations are available: point, disk, cylinder, sphere, slab, and syringe. Improvements in Varskin 3 include a backscatter correction for three-dimensional sources, an upgraded photon dose model, air gap and cover material models. The default area for skin dose calculations has been changed to 10 cm^2 to conform to a recent regulatory requirement pursuant to 10 CFR 20.1201(c), but the area can be changed by the user. Data entry for the code has been 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 English and System Internationale units, and the source strength can be entered in units of activity or distributed in units of activity per area or activity per volume. The output page also has been simplified. In addition, adding radionuclides to the library has been greatly simplified. Previously, users added radionuclides to the library using SADDE Mod 2, the companion code to VARSKIN Mod 2. SADDE Mod 2 required the user to supply basic nuclear data so that radionuclides could be added to the VARSKIN Mod 2 library. In addition, SADDE Mod 2 did not include the contribution to dose from beta particles below a radionuclide-dependent cutoff energy, which affected the accuracy of the dose calculations at skin depths below 7 mg/cm^2 for high-energy-beta sources. In Varskin 3, the user merely needs to select the radionuclide name for the radionuclide to be added to the library. The library file also contains data on photons, internal conversion electrons, and Auger electrons. Varskin 3 also allows the user to build a customized library, eliminating radionuclides that are not of interest. Finally, an extensive, context-sensitive help file is available to provide guidance and to offer new users a tutorial in the use of Varskin 3. The help file contains all of the information in this document. This document describes the revised code, provides installation and operation instructions, provides detailed descriptions of the models used, and suggests methods for avoiding misuse of the code. The code is available from the Radiation Shielding Information and Computation Center (RSICC). Problems with the code should be reported to RSICC or the U.S. Nuclear Regulatory Commission Project Manager.

FOREWORD

The VARSKIN code is a tool for assessing doses from skin contamination, including hot particles. Although the original code was developed for use by the NRC staff to calculate skin dose for regulatory requirements, both the industry and academia have been interested in using the code.

VARSKIN 3, the third update to the VARSKIN series, operates in a Windows environment and is designed to be significantly easier to learn and use than its predecessor, VARSKIN Mod 2. In the following years after the release of VARSKIN Mod 2, users have identified several errors and suggested improvements. VARSKIN 3 addresses these errors and improves upon the users' needs and requirements.

This report describes the upgrades of VARSKIN 3 and includes a user's guide. Section 1 includes the introduction and describes the evolution of the VARSKIN series. Section 2 describes the contents of the VARSKIN 3 code package and includes instructions for installing and running the code on a personal computer. Section 3 discusses the technical basis for VARSKIN 3 and describes the models incorporated in the code. Section 4 contains the results of validation and verification testing for VARSKIN 3. Section 5 of this report describes the problems of and suggested improvements for VARSKIN Mod 2 that were included in VARSKIN 3 as well as new features of the code and its limitations. Section 6 explains the correct method for modeling "infinite" sources and how to calculate the maximum dose to 10 cm^2 from multiple contaminations. Appendix A contains the technical basis for the photon dose model. Finally, Appendix B provides three detailed solutions to practical examples using VARSKIN 3.

This report will support strategies that ensure the protection of public health and safety and the environment by utilizing regulatory programs and applied research effectively to anticipate and resolve safety issues.

Brian W. Sherod, Director
Office of Nuclear Regulatory Research

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ACKNOWLEDGMENTS

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data are contained in this report.

ANALYSES AND CODES: CNWRA computer analysis results are used in this report. VARSKIN Version 2.2 was acquired and is controlled under the Technical Operating Procedure (TOP)–18, Development and Control of Scientific and Engineering Software. The final version of Varskin 3 Version 3 will also be controlled under TOP–18.

1 INTRODUCTION

The original VARSKIN computer code (Traub, et al., 1987) was intended for calculation of skin dose from contamination directly on the skin. The contamination was assumed to be a point or infinitely thin disk source directly on the skin. Soon after the release of VARSKIN, a "new" type of skin contaminant was encountered in the industry. This contaminant consisted 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 exposures result from particles on the outside of protective clothing.

Using VARSKIN for calculating skin doses from hot particles or other contaminants on the skin or outside of a cover material such as protective clothing had three primary drawbacks. First, VARSKIN modeled the contaminant as having no thickness; thus, source self-shielding was not taken into account in the calculation. For example, hot particles containing weak beta-emitting radionuclides (such as Co-60), VARSKIN greatly overestimated calculated skin doses from particles that were thicker than about 1 μm. Second, VARSKIN did not model a cover material (e.g., protective clothing) that may exist between the source and skin, again leading to an overestimate of skin dose from skin contamination. Finally, it has been 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 mg/cm^2, the authors of VARSKIN correctly concluded that the photon dose would not be significant compared to the beta dose under these exposure conditions, and no photon dose model was included. Because of these and other shortcomings of the code, an upgrade of VARSKIN was needed in order to provide accurate skin dose calculations under a variety of exposure conditions.

The upgraded computer code VARSKIN Mod 2 (Durham, 1992) contained all of the features of the original VARSKIN with numerous significant additions. Additional features in VARSKIN Mod 2 included modeling of three-dimensional sources (cylinders, spheres, and slabs) that included self-shielding of the sources, modeling of materials placed between the source and skin (including air gaps) that attenuate the beta particles, and modeling of hot particle photon doses in certain cases. VARSKIN Mod 2 also used a correction for backscatter for one- and two-dimensional 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 dose model allowed the user to calculate the 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 as shown in Figure 1-1. This model can be used to calculate the dose averaged between two depths in tissue, which is useful when characterizing the dose measured by a finite-volume dosimeter such as 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 particular skin area from multiple hot particles not centered on that area.
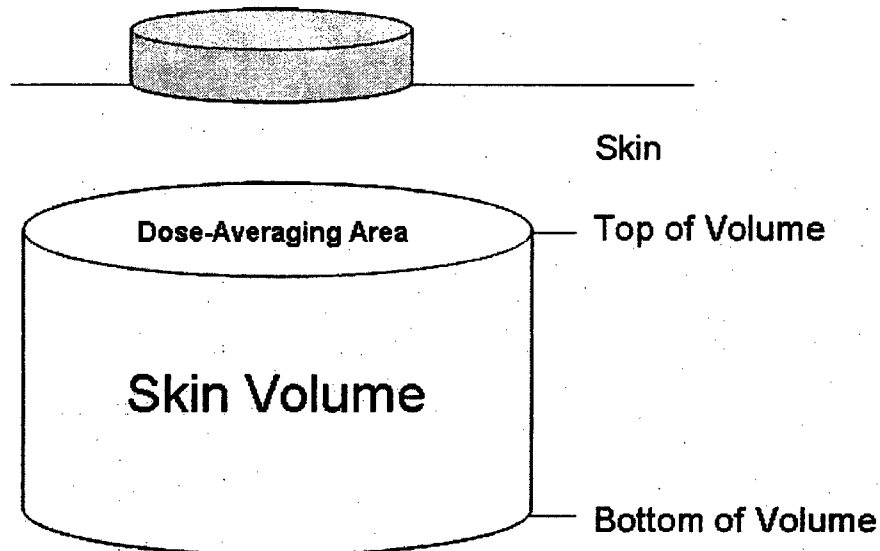
Figure 1-1. Schematic of the Volume-Averaged Dose Model

Finally, VARSKIN Mod 2 included the capability to use composite source terms that allowed a user to calculate the total dose from a mixture of beta-emitters instead of having to run the code separately for each radionuclide in the mix. This feature has been removed in Varskin 3. Instead, the number of radionuclides that can be included in a single calculation has been increased to 20. Note that one implication of removing the feature in Varskin 3 is that radioactive progeny of radionuclides must be added explicitly by the user.

Section 2 of this report describes the contents of the Varskin 3 code package, including instructions for installing and running the code on a personal computer. Section 3 discusses the technical basis for Varskin 3 and describes the models incorporated in the code. Section 4 contains the results of validation and verification testing for Varskin 3. Section 5 of this report describes the problems and suggestions for improvement of VARSKIN Mod 2 that were included in Varskin 3 as well as new features of the code and its limitations. Section 6 explains the correct method for modeling "infinite" sources and how to calculate the maximum dose to 10 cm^2 from multiple contaminations. Appendix A contains the technical basis for the photon dose model. Finally, three detailed solutions to practical examples using Varskin 3 are provided in Appendix B.

2 VARSKIN 3 USER'S MANUAL

This section serves as a user's guide for Varskin 3. It includes installation instructions, operating instructions, and a description of the features of Varskin 3.

2.1 Installing Varskin 3

The installation files for Varskin 3 are located on the disk provided from the Radiation Shielding Information and Computational Center (RSICC) at www.rsicc.oral.gov. To install Varskin 3, place the CD–ROM in the disk drive and execute the *setup.exe* file.

During installation, the user is asked to choose file locations for the program. The default file locations are recommended. However, any disk with a designated drive letter (e.g., *c:/*) is suitable to use for installation of the program.

Important Note: If a previously installed version of Varskin exists on your computer, then the older version must be uninstalled before the newer version is installed. Not uninstalling previous versions may result in more than one installation of Varskin appearing in the Start Menu, causing confusion for the user. Upgrades to Varskin 3 may be made available, as necessary. In the event the upgrades are available from a web site, then you must have previously installed Varskin 3 from RSICC or from NRC staff to use the upgrade. Upgrades to Varskin 3 will include only updated executable files. If Varskin 3 has not been installed from an installation disk, then the code will not be registered with Windows, the required data files will not exist, and the directory structure that is created when Varskin 3 is installed will not exist. Therefore, the user must install Varskin 3 from an installation disk before upgrades are installed. Simply download the upgraded executable file(s) into the subdirectory where Varskin 3 was installed. When asked if the existing files should be replaced, choose "Yes."

Note to Computer Administrators: Varskin 3 is designed to pass information between the Visual Basic Graphical User Interface (GUI) and the FORTRAN computation engines by writing files to the drive on which it is installed. Therefore, users of the computer on which it is installed must have permission to write to the directory in which Varskin 3 is installed. To enable this, an administrator must set the permissions on the Varskin 3 directory to "everyone." Varskin 3 is not designed for installation on a network. Attempts to install Varskin 3 on a network have been unsuccessful.

Hardware and Software Requirements: A personal computer with an 80386 processor or newer is required. The code requires 4 MB of disk space. Varskin 3 has been tested under Windows XP and 2000. It is anticipated that the code will also operate under Windows 9X and NT.

2.2 Running Varskin 3

To run Varskin 3 in Windows XP after installation, go to

Start > Programs > Varskin 3 > Varskin 3
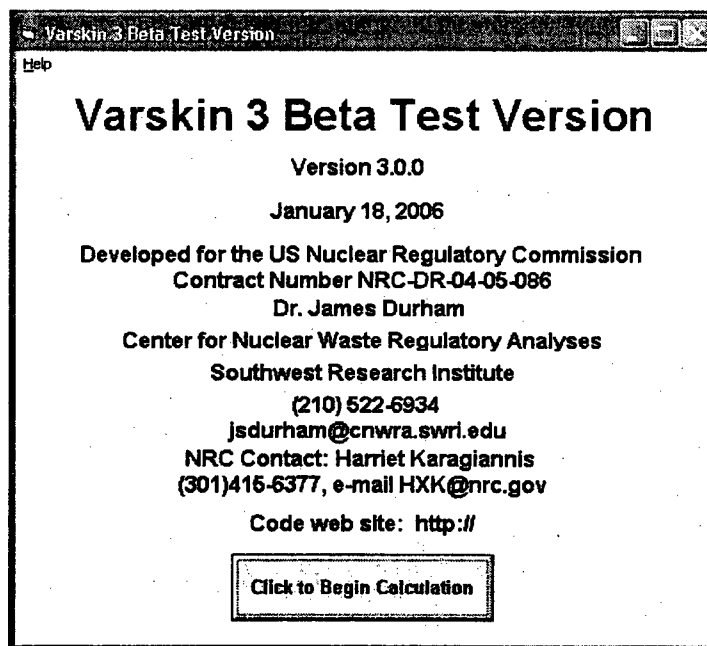
Figure 2-1. Opening Screen

Operations within Varskin 3 are designed to be intuitive. The opening screen provides the user with contact information and basic code information. The only options on this screen are to exit the program or to begin a calculation. The opening screen is shown in Figure 2-1.

2.2.1   Source Geometry

The Source Geometry Screen is shown in Figure 2-2. This screen contains all of the input information that is needed to perform a dose calculation. Although Varskin 3 allows the user to enter data in any order, the geometry package must be chosen first because changing the geometry package will reset all of the geometry parameters to their default values. Six geometry packages are available: point source, (infinitely thin) disk source, cylinder source (thick), spherical source, slab source (rectangular) , and syringe source. When the geometry package is changed, the required input parameters also change. In addition, if geometry-dependent units for the source strength have been chosen, a warning message will appear that informs the user that some of the selected radionuclides will be unselected. The source geometry option box is pictured in Figure 2-3.

The point source geometry is very simple to use, but should only be used for non-particulate contamination that is confined to a very small area of the skin or for a quick calculation to determine whether a regulatory limit has been potentially exceeded. The point source geometry does not account for self-shielding of the source 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. Varskin 3 models a point source as a cylinder source with a thickness of 1 μm, a radius of 1 μm, and a density of 0.001 g/cm^3. The point source geometry is shown schematically in Figure 2-4(A).
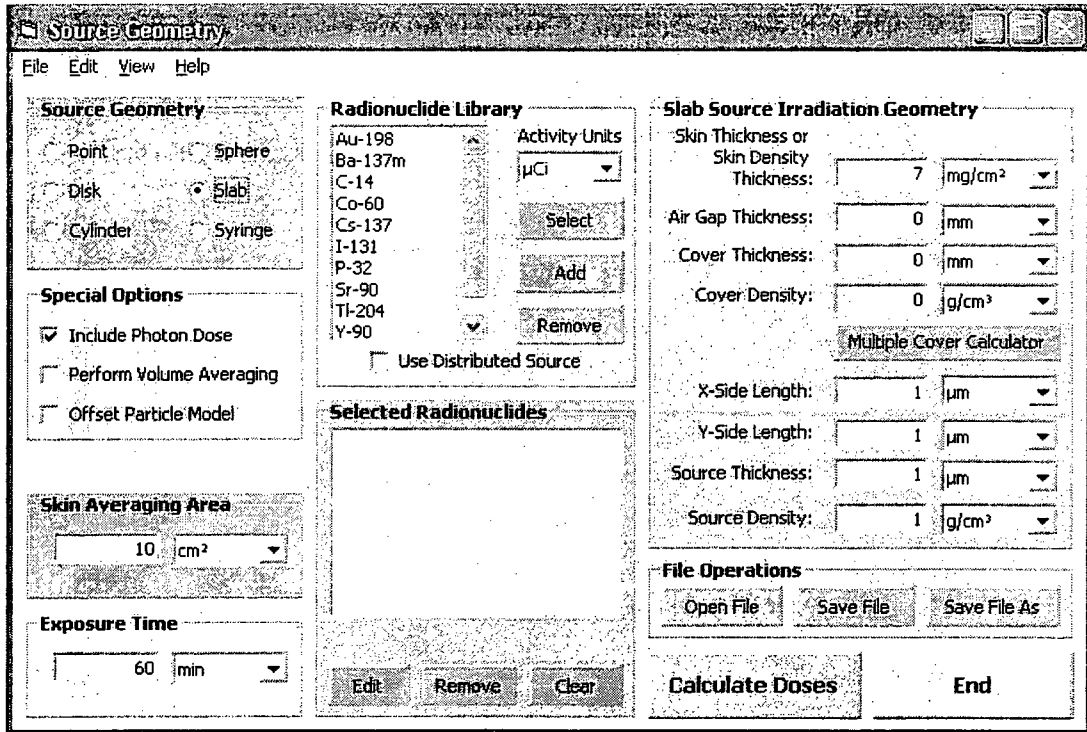
Figure 2-2. Source Geometry Screen (Slab Source Screen Shown)
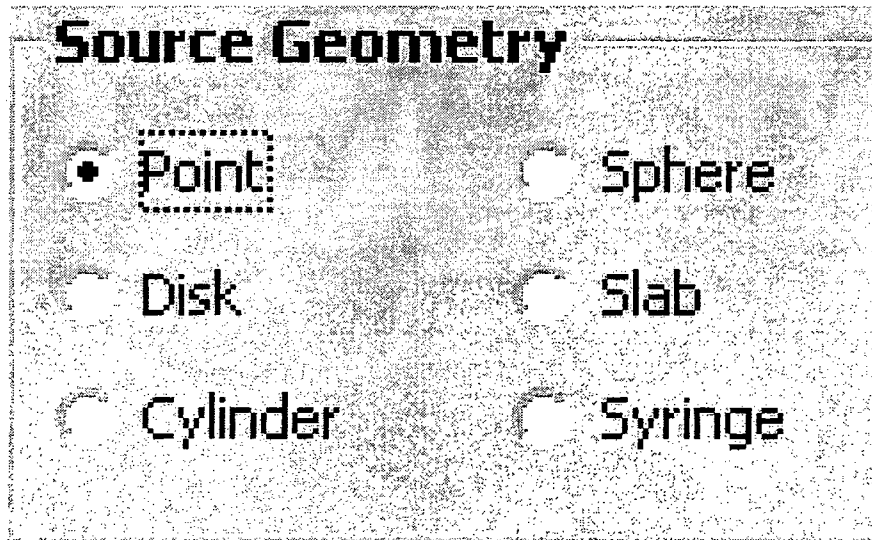
Figure 2-3. Source Geometry Option Box From the Source Geometry Screen
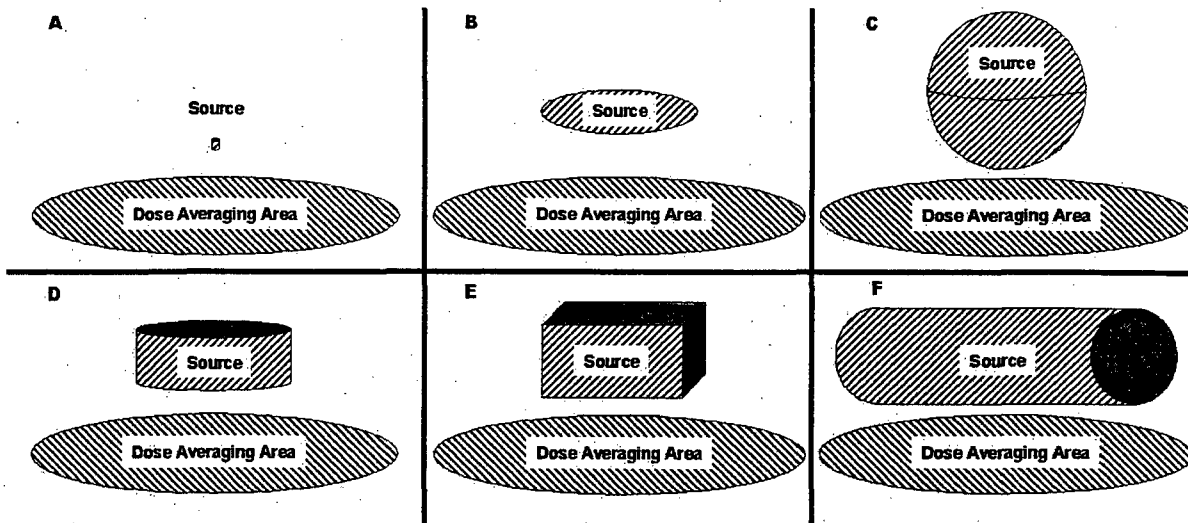
Figure 2-4. Schematic Representations of the Six Geometry Options

The disk source geometry model is simple and is recommended for modeling liquid skin contamination events. The disk source geometry requires the user to enter either the source diameter or the source area in the appropriate contamination 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 3 automatically calculates the area of the circle with that diameter. Similarly, when the user enters the area of the source, Varskin 3 automatically calculates the diameter of a circle with the same area. Varskin 3 models a disk source as a cylinder with a thickness of 1 μm and a density of 0.001 g/cm^3. The disk source geometry is shown schematically in Figure 2-4(B). If the area of contamination is not circular, entering the area of the actual contamination will generally result in a reasonable estimation of the dose.

The sphere source geometry is perhaps the simplest three-dimensional geometry to use for dose calculations because it requires knowledge of only one source dimension: the source diameter. The sphere source geometry assumes that the source is surrounded by air and touches the skin or cover material only at the bottom-most point on the sphere surface. Choosing the sphere source geometry will generally overestimate the dose compared to a similarly sized cylinder source with the same 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 and slab models), and a larger area of skin will be irradiated resulting in consistently higher doses. The sphere source geometry is shown schematically in Figure 2-4(C). The cylinder source geometry is recommended for sources that are not spherical.

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The cylinder model requires knowledge of two dimensions: the cylinder diameter and the cylinder thickness. The cylinder source geometry assumes that the source is surrounded by air but that the entire bottom of the cylinder is in contact with skin or cover material. This geometry requires the same amount of time to execute as the spherical model but generally offers a more accurate dose calculation. Of the two cylinder source dimensions, the calculated dose is much more sensitive to changes in the cylinder thickness than in the cylinder diameter. Because the cylinder source geometry allows the user to specify the thickness of the source (compared to the sphere source geometry), calculations using cylinder source geometry are more accurate than those using the sphere source geometry. The cylinder source geometry is shown schematically in Figure 2-4(D).

The slab source geometry requires knowledge of three physical dimensions: the x-side length, the y-side length, and the thickness. The slab source geometry requires two to five times more execution time than the cylinder and sphere geometries, and the accuracy of the calculation is significantly lower. As evidenced by the Varskin 3 Validation Test Plan and Report, results of calculations using the slab geometry differed by as much as 35 percent from the results obtained using the other five geometries when modeling the same source. This discrepancy is the result of a fundamental difference between the mathematical approach used for the slab geometry compared to the other geometry packages when modeling similar sources. These differences are described in more detail in Section 4. The slab geometry should only be used when skin dose from multiple, discrete particles is needed, as described in Section 6 (i.e., when the offset particle model is needed). The slab source geometry is shown schematically in Figure 2-4(E).

The syringe source geometry is a specialized geometry that calculates dose from a syringe or other cylindrical object for which the dose to the side of the cylinders is needed. The user needs to supply the syringe outer diameter, the syringe wall thickness, and the volume and density of the source. The syringe material density is assumed to be that of polyethylene (1.1 g/cm^3). Varskin 3 calculates the source length based on the input data, then models the syringe source as a cylinder with a thickness equal to the inner diameter of the source and a diameter such that the volume of the source is preserved. Because the dimensions of the syringe source geometry are larger than 1 mm, photon doses are not calculated for the syringe source geometry. The syringe source geometry is shown schematically in Figure 2-4(F).

The following general rules should govern the choice of geometry package, progressing from highest dose estimates to lower dose estimates:

- If nothing is known about the particle size and shape, use the point source geometry option. This option is also recommended for a quick screen against regulatory limits since the point geometry typically overestimates the 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 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 sphere source geometry option.

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

- If the particle is known to be rectangular, use the cylinder source geometry option. The thickness of the particle should be preserved, and the area of the contact surface should be selected such that the source volume is preserved. This option requires less time to run than the slab source geometry option and is more accurate.

- If the source is a syringe, use the syringe source geometry.

For all source geometries, doses are calculated to a circular area centered below the central axis of the source. When using the offset particle model, dose is calculated to circular area with the center located at the offset distance from the center of the source.

2.2.2 Adding Radionuclides to the Library

Varskin 3 employs two radionuclide libraries: a code library (supplied on the installation disk) that contains data for all radionuclides available to the user, and a user library that contains only those radionuclides that the user adds to it. When Varskin 3 is first installed, no radionuclides will appear in the user library. Varskin 3 is designed to allow the user to customize the radionuclide library so that only those radionuclides of interest to the user appear in the library. To add a radionuclide to the user library, the user clicks on the "Add" button (shown in Figure 2-5), and a new screen appears that displays every radionuclide for which data is available (a total of 838 radionuclides), as shown in Figure 2-6. Radionuclides are added to the library by highlighting the radionuclide and clicking on "Add Radionuclide" or simply double clicking on the name of the radionuclide. A scrolling status bar will appear indicating that calculations are being performed to compile the input file for the selected radionuclide. The status bar may scroll several times depending on the speed of the computer processor and the availability of computer resources. When the process of adding the radionuclide is completed,

Radionuclide Library

Au-198	Activity Units
Ba-137m	µCi
C-14	
Co-60	
Cs-137	Select
I-131	
P-32	Add
Sr-90	
Tl-204	
Y-90	Remove

Use Distributed Source
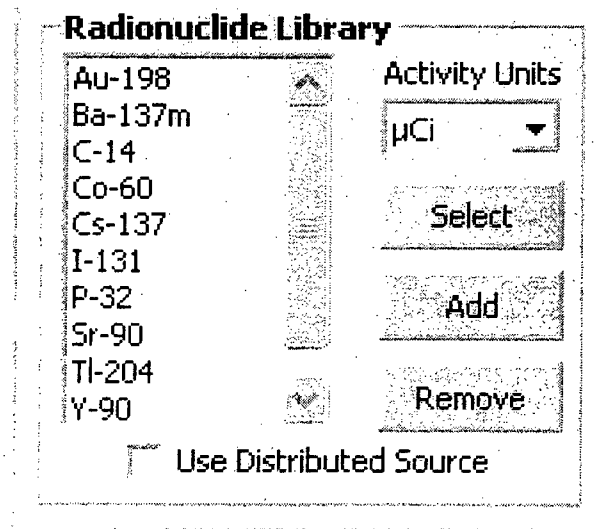
Figure 2-5. Radionuclide Library List Box

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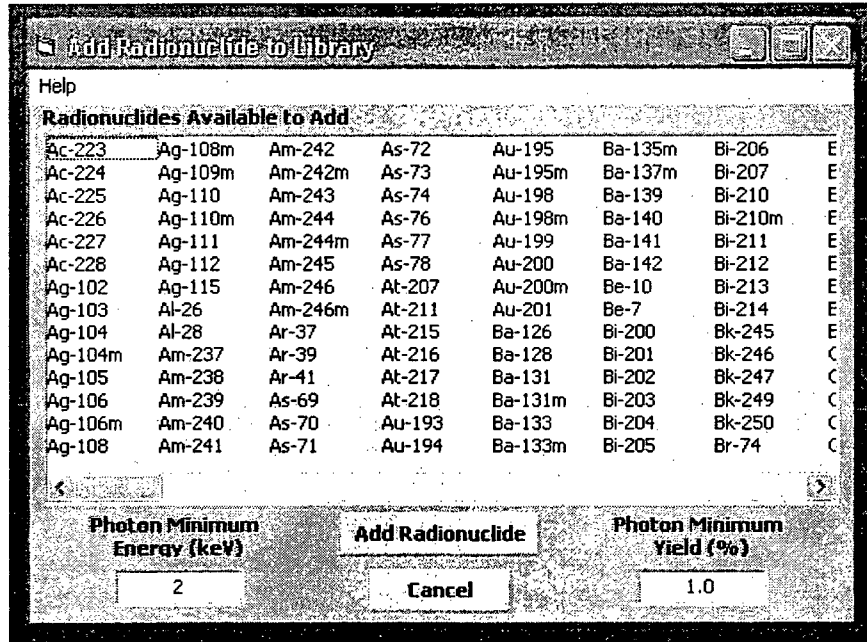
Figure 2-6. Add Radionuclide Screen

the Source Geometry screen will return, and the added radionuclide will be visible in the 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 on the Radionuclide Library frame.

When the "Add Radionuclide" button shown in Figure 2-5 is clicked, the following events occur in a separate executable file. First, data are extracted from the data files *ICRP38.dat*, *ICRP38.idx*, and *ICRP.bet*, 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 paths. If the radionuclide does not emit beta radiation, a tritium beta spectrum is generated with a yield of 0.001. Next, internal conversion and Auger electrons are added to the beta spectrum. Finally, photon energy and yield data are collected from the data files, and the average photon energy and total photon yield is calculated. 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 average photon energy, the specific gamma ray constant, and the photon yield 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.

The radionuclide library file will contain all known electrons and any photons with energies above the user-selected photon minimum energy and yield. The user may accept the default value of 2 keV for the Photon Minimum Energy (keV) text box or specify a different value by entering the cutoff energy in keV. The cutoff energy is the minimum energy for photons to be included in photon dose calculations. The user may also accept the default value of 1.0 percent for the Photon Minimum Yield (%) text box or specify a different value by entering the minimum yield in percent.

As discussed in Section 5.3, the choice of the minimum photon energy and yield can have significant effects on the accuracy of photon dose calculations. The limited photon dose model used in Varskin 3 calculates dose based on the specific photon dose constant, which includes a contribution from all photons included in its calculation. Thus, the photon dose model does not adjust the photon doses for absorption in the skin. When calculating skin dose at depths of 7 mg/cm^2, photons with energies as low as 2 keV contribute to skin dose. However, when the target is deeper tissue (for example, when calculating deep dose), only higher-energy photons (above 35 keV) will contribute to the dose. Because low-energy photons are not attenuated, the deep dose could be overestimated if a cutoff energy lower than 35 keV is chosen. Therefore, using a specific photon dose constant that includes low-energy photons to calculate deep dose will overestimate that dose. On the other hand, using a specific photon dose constant that does not include low-energy photons when calculating shallow dose will underestimate that dose. It is recommended that three files be created for radionuclides that emit low-energy photons: one for shallow dose (70 mg/cm^2), one for eye dose (300 mg/cm^2), and one for deep dose (1,000 mg/cm^2). Recommended values for the cutoff energies are 2 keV (shallow), 20 keV (eye), and 35 keV (deep). Multiple library files are created by giving each file a unique name (i.e., Cs-137, Cs-137e, and Cs-137d).

To create multiple library entries for a single radionuclide, choose "Add" radionuclide in the Radionuclide Library frame on the Source Geometry screen. When the Add Radionuclide to Library screen appears, select the radionuclide by clicking on the name once. For shallow dose, set the Photon Minimum Energy to 2 keV, then click on Add Radionuclide. A library file will be created in the \dat subdirectory using the name of the radionuclide. To create another library file with a different cutoff energy, choose Add in the Source Geometry screen and select the same radionuclide. For eye dose, set the photon minimum energy to 20 keV and double click on radionuclide name. After the scrollbar appears, the user will be informed that the library file already exists and the user is prompted if the user wants to cancel. Select "No," then enter a new name for the library file. For example, adding an "e" after the radionuclide name can indicate the particular file is to be used for the dose to the eye. This process can be repeated for deep dose by changing the photon minimum energy to 35 keV and appending a "d" to the library file name.

Radionuclides can be removed from the user library by highlighting the appropriate radionuclide and clicking on the "Remove" button. The "Add" button can also be used to replace radionuclides in the library by naming an added radionuclide with the same name as that of an existing library entry. Thus, a library file that calculates shallow dose and another library file that calculated deep dose from the same radionculide can exist in the user library.

In Varskin 3, radioactive progeny are not included in the user library file. The user must create a user library file for each radioactive progeny. Radioactive progeny are not included regardless of the half-life of the progeny.

2.2.3   Selecting Radionuclides From the User Library

Radionuclides can be selected for a calculation by double clicking on the name of the radionuclide or by highlighting the desired radionuclide and clicking the "Select" button (shown in Figure 2-5). The default unit of measure for activity is µCi. Users may change the activity unit by selecting a different unit from the Activity Units list box. The new unit must be chosen prior to 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. Up to 20 radionuclides may be selected for a given calculation.

For geometry packages other than the point source, the "Use Distributed Source" check box will appear as shown in Figure 2-5. The distributed source option allows the user to enter the source strength in activity/cm² for the disk source geometry or activity/cm³ for three-dimensional source geometries. The distributed source option only applies to radionuclides that are selected after the checkbox is checked. If the distributed source option is unchecked, subsequently selected radionuclides will have activities in terms of total inventory instead of distributed activity.

2.2.4   Geometry Parameters and Multiple Cover Calculator

The geometry parameters box (shown in Figure 2-7 for the slab geometry) changes depending on the particular geometry chosen for the calculation. Clicking on the arrow next to the units of the parameter and choosing from the drop-down list will choose the units for that particular parameter. It is also possible to intermix different units for the different parameters. Varskin 3 makes the necessary conversions internally. The default values for the various parameters are shown in Table 2-1.

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.

The results of a sensitivity analysis show that (i) the most sensitive source dimension for calculating dose is the source thickness and (ii) the dose will vary greatly for small variations in the value of this parameter. Similarly, the source density is an equally sensitive parameter. It is essential that these parameters are known accurately or that an underestimate of their values

Slab Source Irradiation Geometry		
Skin Thickness or Skin Density Thickness:	7	mg/cm² ▼
Air Gap Thickness:	0	mm ▼
Cover Thickness:	0	mm ▼
Cover Density:	0	g/cm³ ▼
Multiple Cover Calculator		
X-Side Length:	1	µm ▼
Y-Side Length:	1	µm ▼
Source Thickness:	1	µm ▼
Source Density:	1	g/cm³ ▼

Figure 2-7. Slab Source Geometry Parameters

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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
Cover Thickness	0 mm
Cover Density	0 g/cm^3
Source Area (Disk)	0.785 mm^2
Source Diameter (Disk)	1 mm
Source Diameter (Sphere)	1 µm
Source Thickness (Disk, Slab)	1 µm
Source X-Side Length (Slab)	1 µm
Source Y-Side Length (Slab)	1 µm
Source Volume (Syringe)	1 cm^3
Syringe Wall Thickness (Syringe)	1 µm
Source Density (Three-Dimensional Geometries)	1 g/cm^3
Source Diameter (Syringe)	1 cm

be made. Underestimating the source thickness or density will generally result in the calculation of larger doses. The following guidelines will help in choosing appropriate values for source dimensions and density:

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

(2)   Thickness (disk and slab) and sphere diameter: The dose calculation for all radionuclides is very sensitive to this dimension, especially for low-energy-beta-emitting radionuclides. Minimizing the value of this dimension will provide an overestimate of the dose.

(3)   Source Density (three-dimensional geometry models): 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.

Users can model the presence of a cover material and/or an air gap. A schematic drawing of the two models is shown in Figure 2-8, which depicts the cylinder geometry, although the two models are available for any of the source geometries. The required input for the cover material model is the thickness of the material and its corresponding density. Note that 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 in the material (material attenuation). For the air gap model, only the thickness of the air gap is required for input. Varskin 3 uses a default value of 0.001293 g/cm^3 for air density.

The physical characteristics of the air gap and cover material can significantly affect the calculated skin dose. While the air gap has little effect on material attenuation, its effect on geometric attenuation can be dramatic. Cover materials affect both the geometric and material attenuation. Some suggested thickness and density values are given in Table 2-2.

Varskin 3 allows multiple cover materials to be modeled as a composite cover by clicking on the "Multiple Cover Calculator" button. The multiple-cover calculator allows the user to add up to five covers together as shown in Figure 2-9 and is the only way for the user to enter multiple covers. The user must enter two of the following three parameters for each layer: Cover Thickness, Cover Density, and Cover Density Thickness. The user can choose the units for density and thickness, but the density thickness must be entered in g/cm^2. The calculator calculates the third parameter, adds the different layers together, and calculates the thickness and effective density of the composite cover. The composite cover density in mg/cm^3 and thickness in cm are then automatically entered in the appropriate boxes in the Source Geometry screen. If the user enters all three parameters, Varskin 3 will recalculate the density thickness from the density and thickness data prior to determining the characteristics of the composite cover. The printout from a dose calculation will include the data from each cover layer as well as the composite cover data.

Cover

Air Gap

Skin

Dose Area
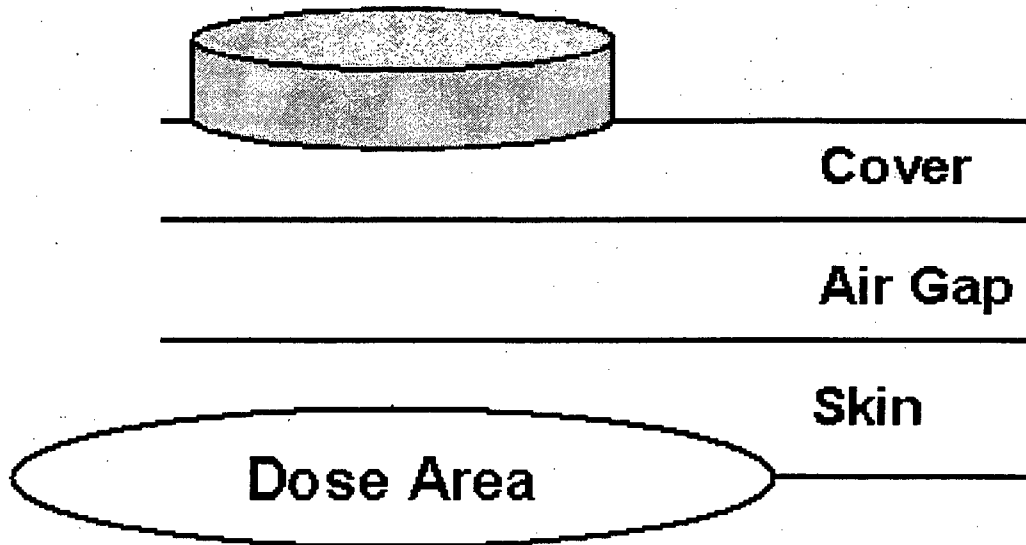
Figure 2-8. Schematic Showing the Cover Material and Air Gap Models

Table 2-2. Suggested Values for Cover Thickness and Density		
Material	Thickness (mm)	Density (g/cm³)
Lab Coat (Plastic)	0.1	0.036
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

Figure 2-9. Composite Cover Calculator Screen

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. However, 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.

2.2.5   Special Options

Depending on the geometry package selected, special options are available that affect the calculation, as shown in Figure 2-10. The first special option, which is available for all geometry packages except the syringe geometry package, 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 choose to uncheck the box so the photon dose will not be calculated. The photon dose calculation will not noticeably increase the overall calculation time. If the option to include the photon dose is chosen 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. Note that the syringe geometry package does not include a photon dose calculation.

The Varskin 3 photon dose model assumes that the source is small enough to be considered a point source and that any covering material is similar to tissue or water. Thus, the photon dose is only calculated for sources with dimensions smaller than 1 mm, and the photon dose is not calculated for the syringe source. The Varskin 3 photon dose model, which is described in detail in Section 2, is an extension of a model published by Lantz and Lambert (1990) that was the basis for the VARSKIN Mod 2 photon dose model. The Varskin 3 photon dose model is applied to irradiation areas up to 10 cm^2. For larger areas, the user will be informed that the photon dose will not be calculated even if the photon dose option is selected.
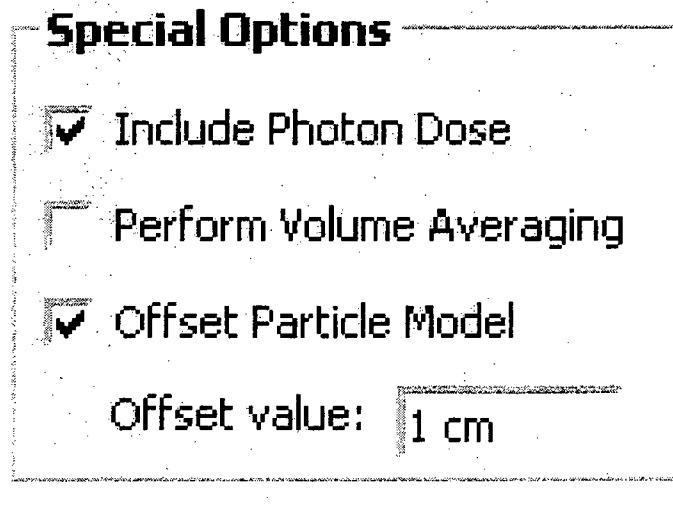
Figure 2-10. Special Options Subscreen

2-13

Photon doses are calculated as if the source was a point source, and the model includes effects due to the incomplete establishment of electronic equilibrium at shallow depths. Electronic equilibrium is established at different depths depending on the average energy of the photon (or photons) emitted by the source. At shallow depths, before electronic equilibrium is established, the photon dose is lower than the dose would be if electronic equilibrium is established.

In most cases, the calculated photon skin dose will be negligible compared to the beta skin dose, usually by several orders of magnitude. A significant exception to this concerns Co-60 and other low-energy beta emitters. A cover material can easily shield the relatively low-energy-beta particles from this radionuclide without significantly attenuating the photon dose. In this case, the photon dose will account for 100 percent of the calculated skin dose. Durham and Lantz (1991) published measurements verifying this phenomenon.

Despite upgrades to the photon dose model, Varskin 3 is primarily a beta dose calculation tool. The photon dose model is intended for use in estimating the photon dose from a particle. It is not intended for use with distributed contamination. Calculations of photon doses for distributed sources should be performed using a code designed to calculate photon dose.

The second special option (Figure 2-10) allows the dose to be averaged over a volume of tissue defined by two different skin depths and the area of irradiation instead of the dose at one given depth. An example of the use of the volume-averaged dose is evaluating the dose between 10 mg/cm^2 and 15 mg/cm^2 as recommended by the International Commission on Radiological Protection (1991) to evaluate the dermal effects of skin dose. Volume averaging greatly increases the calculation time to as long as several minutes for each selected radionuclide.

If volume averaging is chosen, the user is prompted to enter the skin density thicknesses associated with the top and bottom of the volume. The units of skin density thickness must be entered in mg/cm^2. The range of possible values for the top and bottom of the volume are also provided to the user and range from a skin density thickness of 0 mg/cm^2 to the maximum penetration depth of the beta particles. Entering a value for the bottom of the volume that is greater than the maximum penetration depth will result in an error message, and the user will be asked to enter a different value. Varskin 3 calculates the dose averaged over the dose averaging area at 50 depths between the top and bottom of the volume, as shown schematically in Figure 2-11. Thus, the volume-averaged dose model requires up to 50 times more execution time than that for a single depth. Calculation times in excess of 20 minutes on a pentium-class computer are possible.

When the slab 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 (Figure 2-10) over the dose area of interest, is useful for calculating dose from multiple hot particles. The default for this option is to not use the offset particle model. When the offset particle box is checked, the user is prompted to enter the offset distance. The offset distance is the horizontal distance between the center of the slab source and the center of the dose area, as shown in Figure 2-12. Note that the x-side length and the y-side length must be equal when using the offset particle model or an error message will be displayed. The value of the offset is the only additional input value that is required for the model, and the calculation is completed in roughly the same amount of time as a centered particle. The results screen (including the volume-averaged dose results screen) will display the offset value if this option is selected.
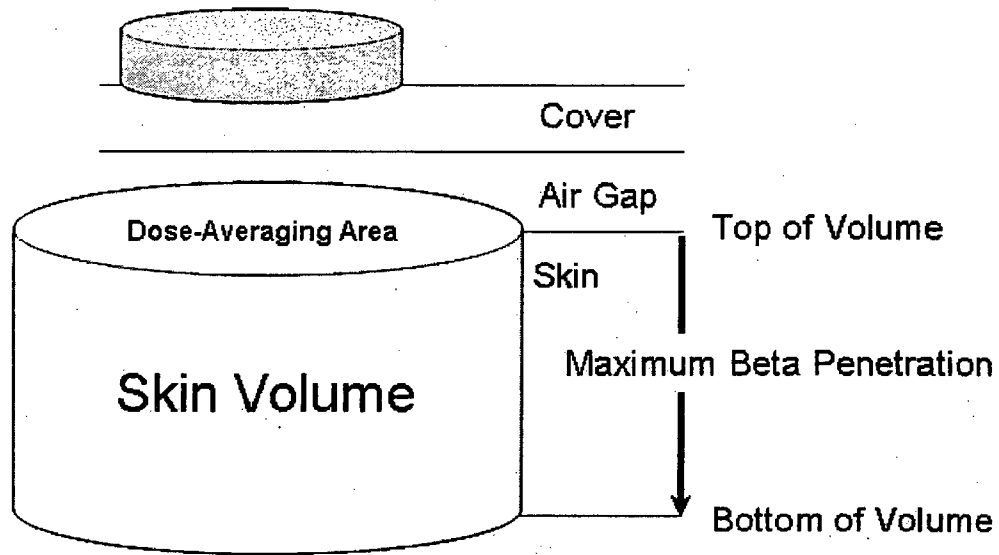
Figure 2-11. Schematic Diagram of the Volume-Averaged Dose Model Geometry
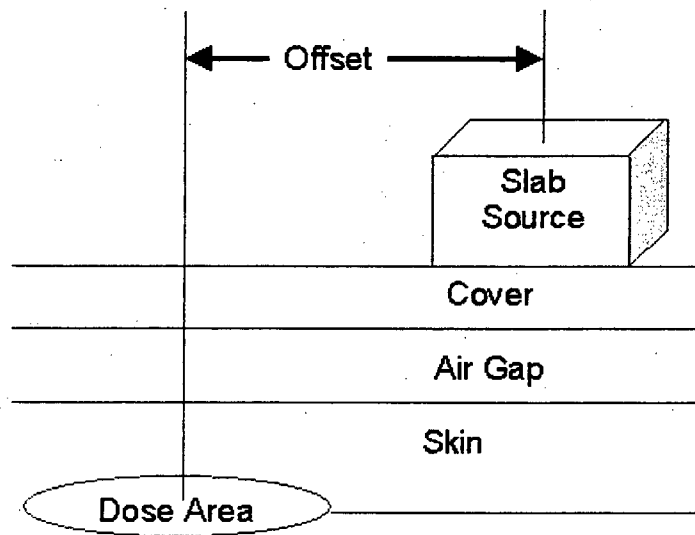
Figure 2-12. Schematic Diagram of the Offset Particle Model

The offset particle model can be used to calculate the dose from multiple hot particles. Use of the offset particle model is discussed in Section 6.2

2.2.6 Calculating Doses

When the desired geometrical parameters and options are selected, the calculation is initiated by clicking the "Calculate Doses" button (Figure 2-2). A progress bar will appear that will scroll at least once and possibly many times depending on the complexity of the calculations. The calculation time is greatly affected by the number of radionuclides used in the calculation and the various options that are selected. Volume-averaged doses require a particularly long time to complete.

Varskin 3 calculates doses using a compiled FORTRAN program entitled *Varcalc.exe*. The main program that collects the input data and displays the output data is written in Visual Basic. When the user clicks the "Calculate Doses" button, the Visual Basic program writes the input data in a file called *Output.dat*. Varcalc reads *Output.dat*, performs the calculations in the background, and then writes the results to a file entitled *Results.dat*. The Visual Basic code reads *Results.dat*, performs some additional calculations, and displays the results of the calculation. The logic flow diagram for Varskin 3 is depicted in Figure 2-13. Note that *output.dat* and *results.dat* are internal files and are not intended to be used or edited by the user.

2.2.7 Output Screen

The output screen for a nonvolume-averaged calculation is displayed immediately after a calculation is completed, as shown in Figure 2-14. The screen is separated into three distinct sections: results for individual radionuclides (upper left quadrant of the screen), combined results for all radionuclides (upper right quadrant of the screen), and source input data/code navigation (bottom half of the screen).

In the individual results section, only the results for the first radionuclide are shown initially. The results from other radionuclides are displayed by highlighting the radionuclide of interest from the list in the list box. Only the contribution to the dose from the selected radionuclide will be displayed on this screen.

The combined results section displays the combined results for all radionuclides added together. The data in this section cannot be edited and will not change unless a new calculation is initiated. This section of the output screen also contains a button that toggles the results between English and System Internationale (SI) units. The dose results on the output screen are displayed in either English or SI units depending on the choice of activity units for the last radionuclide entered. If the activity of the last radionuclide was entered in SI or metric units, the results will be displayed in SI units. Similarly, if the activity of the last radionuclide was entered in English units, the results will be displayed in English units. Clicking on the button labeled "SI Units" will switch the results from English units to SI units. Similarly, clicking on the button labeled "English Units" (when SI units are displayed) will switch the results from SI units to English units. The units will change for the calculated doses only; the input data will be displayed in the same units that were entered on the Source Geometry screen.

```
┌──────────────┐        ┌─────────────────────┐
│ Welcome Page │◄───────│ Initializes program, │
└──────┬───────┘        │  provides contact   │
       │                │ information and      │
       │                │ version information  │
       │                └─────────────────────┘
       │
┌──────▼───────┐        ┌─────────────────────┐
│Geometry Page │◄───────│ Collects all input   │
└──────┬───────┘        │  data, stores        │
       │                │ library information, │
       │                │ initiates dose       │
       │                │ calculation,         │
       │                │ writes Output.dat    │
       │                └─────────────────────┘
```

Add Radionuclide? —YES→ Add Radionuclide Page → Reads icrp38.idx, icrp38.dat, MassAttenCoeff.dat, Energy.dat; writes Sadout.dat; calls FORTRAN Module

NO

Add Radionuclide FORTRAN Module → Calculates Scaled Absorbed Dose Distribution function, reads Sadout.dat, writes SadInput.out, creates .rad library file, updates files.lst

Multiple Cover? —YES→ Multiple Cover Calculator Page → Calculates composite cover from density, thickness, and density thickness data

NO

Calculate Dose? —YES→ Dose Calculation FORTRAN Module → Calculates electron dose reads .rad files, reads Output.dat, writes Results.dat

NO

End

Results Page → Displays results, converts units, sends results to printer

Figure 2-13. Logic Flow Diagram for Varskin 3
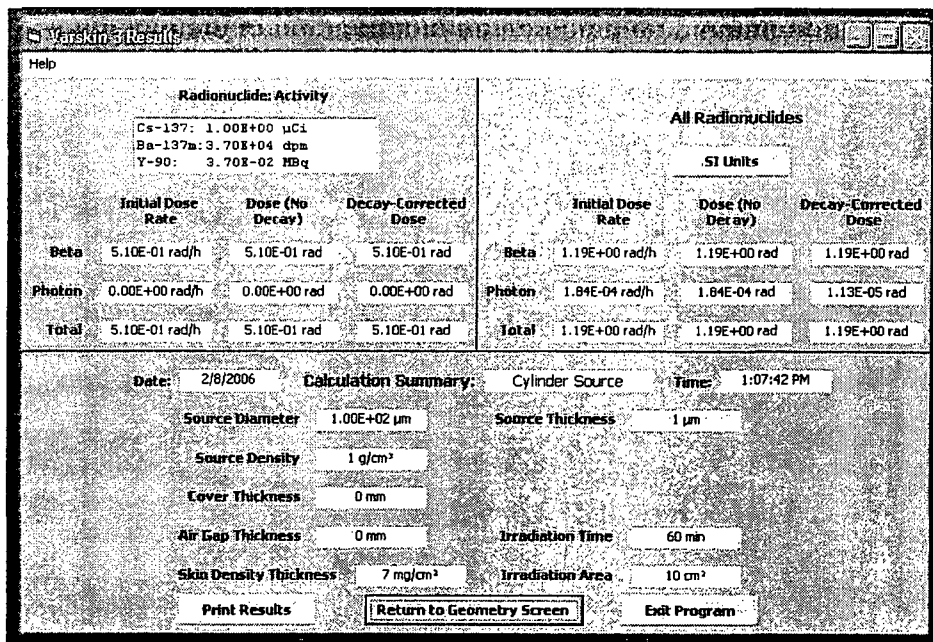
Figure 2-14. Results Screen for a Typical Calculation

The bottom half of the output screen contains a mirror of the input data that was 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 on the "Print Results" button will send a hard copy of all results to the default windows printer. Varskin 3 will not allow the user to change the default printer. In addition, the program will fail if a printer is not installed when the "Print Results" button is clicked. 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 3 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 clicking on 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 3.

A slightly different screen will appear for volume-averaged dose calculations. Because the dose can be averaged over different averaging volumes for different radionuclides, Varskin 3 does not provide a section for combined results of a volume-averaged dose calculation. Instead, only the results from the individual radionuclides are displayed, as shown in Figure 2-15. In this figure, the last unit entered was an SI unit, so the results are displayed in SI units. Only the results for the highlighted radionuclide are displayed. The upper left section of the volume-averaged results screen displays values of the top and bottom of the volume as well as the total volume over which the dose was averaged for the chosen radionuclide. Highlighting the name on the radionuclide list box allows other radionuclides to be chosen. The units may be toggled between English and SI by clicking on the "English Units" button when SI units are displayed or
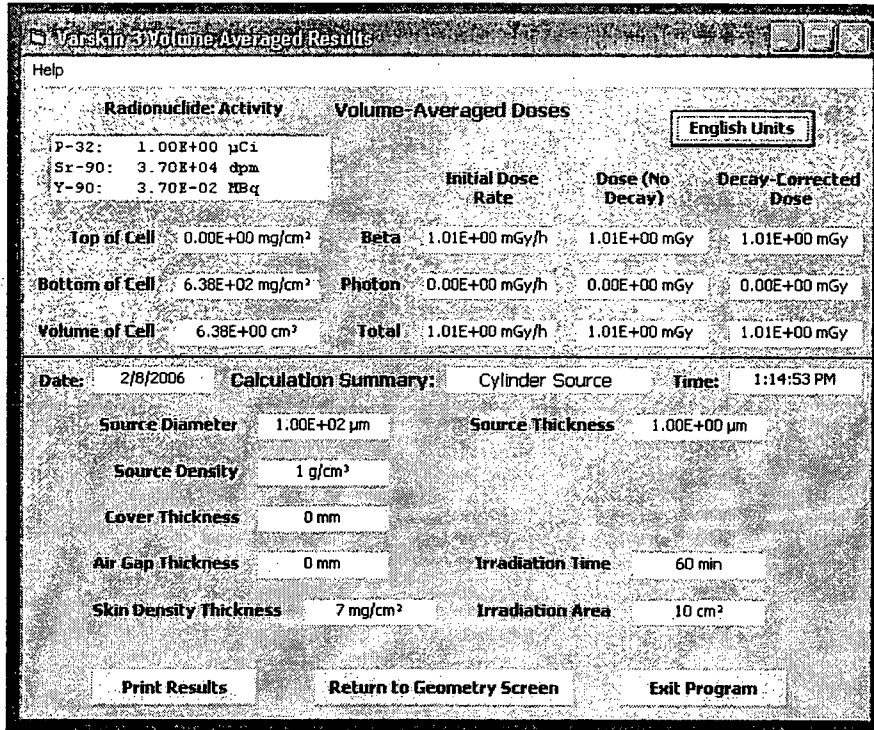
Figure 2-15. Results Screen for a Volume-Averaged Calculation

by clicking on the "SI Units" button when English units are displayed. A summary of the input parameters is displayed on the bottom half of the screen.

2.2.8 Exiting Varskin 3

There are several ways to exit Varskin 3. On the opening screen (Figure 2-1), clicking on the X box in the upper right corner of the screen will immediately cause the code to stop and exit. On the Source Geometry screen (Figure 2-2), clicking on either the X box in the upper right corner or the "End" button will result in a prompt to the user asking if the input data should be saved to a file, as shown in Figure 2-16. Similarly, the same outcome will result from the results screen by clicking on the X box in the upper right corner or the "Exit Program" button (Figures 2-14 and 2-15). The user is then asked if the file is to be saved. When the "Yes" button is clicked, the user is asked to create a file in which the input data will be saved so that the calculation can be recreated. Clicking on the "No" button will end the calculation and cause the program to end. Clicking on the "Cancel" button will return the user to the previous screen.

Data from a saved file are stored with a *.vs3* extension. When a saved file is opened, Varskin 3 reads the *.vs3* to obtain the data for the calculation. This file is an internal file and is not intended to be used or edited by the user.
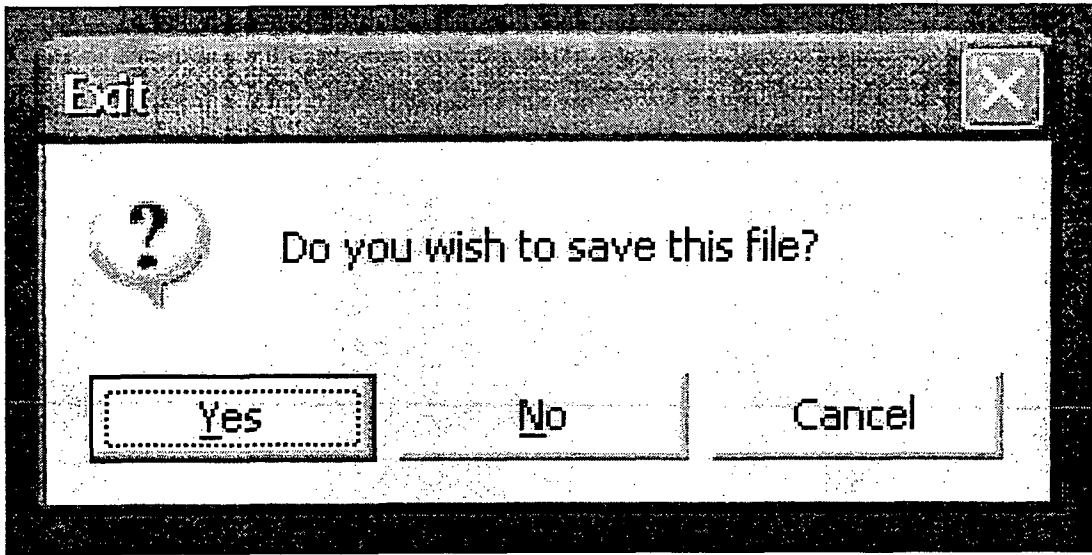
Figure 2-16. Exit Screen

3 DESCRIPTION OF CALCULATIONAL MODELS

Varskin 3 includes upgrades to several models that are described in detail in this chapter. In addition, improvements to models that were used in VARSKIN Mod 2 were incorporated into Varskin 3 and are also described here. First, the calculational methodology used in Varskin 3 is described.

3.1   Beta Dose Calculations

Varskin 3 calculates beta dose using essentially the same method used in VARSKIN Mod 2. In general, Varskin 3 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 3 calculates the beta dose rate by performing a numerical integration of the Berger point kernel (Berger, 1971). This kernel is mathematically written as

$$B(r) = \frac{k\ E_\beta\ Y\ F_\beta(r_1 / X_{99})}{(\pi \rho\ r^2 X_{99})} \tag{3-1a}$$

where

$B(r)$	=	the dose at the dose point from a source at a source point
r	=	the distance between a source point and the dose point
k	=	a unit conversion constant
E_β	=	the average beta energy for the radionuclide
Y	=	the beta yield per disintegration
$F_\beta(r_1/X_{99})$	=	the scaled absorbed dose distribution
r_1	=	the modified path length between a source point and the dose point
ρ	=	the density of the irradiated medium (assumed to be unity for tissue)

The following equation gives an example of the units that might be included in Eq. (3-1a)

$$B(r)\left[\frac{rad}{h \cdot dis}\right] = \frac{k\left[\frac{rad \cdot q}{MeV \cdot h}\right] * Y\left[\frac{1}{dis}\right] * F_\beta(r_1 / X_{99})[frac]}{\pi\ \rho\left[\frac{g}{cm^3}\right]r^2[cm^2]X_{99}[cm]} \tag{3-1b}$$

where dis stands for disintegration.

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 3, the range of the beta particles is chosen as the X_{99} distance, where X_{99} is equal to 1.8 times the X_{90} distance cited in the reference (Berger, 1971). Varskin 3 calculates $F_\beta(r_1/X_{99})$ for a selected radionuclide when the radionuclide is added to the library, as described later in this section.

For the purpose of illustrating a dose calculation for a symmetrical source, the following discussion describes a simplified dose calculation for the cylinder geometry shown in

Figure 3-1. Varskin 3 chooses a point located at the center of the irradiation area (dose point). The code then divides the sources into very small subvolumes (source points). The number of source points ranges from 512 to over 10^{81} depending on a number of factors. 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 dose/dis) is multiplied by the source strength (in dis) to get the dose 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. These dose points represent isodose curves within the irradiation area. Finally, the curves are average over the irradiation area to determine the total dose to the area.

A more detailed description is now presented. The integration is performed by choosing 60 dose points [points at which the dose rate is to be calculated, shown as (–) (Figure 3-1), beginning at the source centerline and proceeding radially outward from the centerline at the skin depth level. Since the source is symmetric, dose points represent concentric isodose circles that describe the radial dose rate profile at a given depth in skin. For each dose point, an integration is performed over the area of the disk-shaped source at a given height in the source represented by one of the eight elevation points (+) by choosing eight concentric circles located at radially equidistant positions on the source (denoted by *). One of these circles defined by a radial dose point (*) is chosen, subdivided into eight source points at equiangular locations (angular source points, x), and the dose rate at the dose point from each of these eight source points is calculated. The contribution to the dose from the first four points is then compared to the contribution to the last four points. If the relative difference between the two contributions is less than 0.0001, then convergence of the integral for the circle is considered to be achieved, and this 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 subdivided into eight source points, and the above procedure is repeated for each of the two sets. 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 kernel.
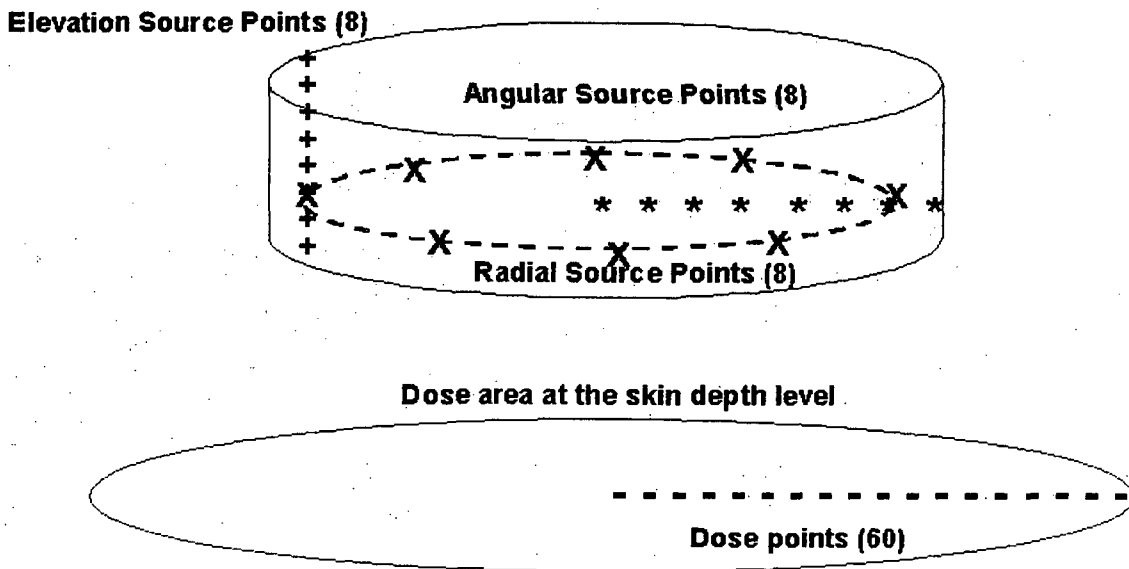
Figure 3-1. Schematic Representation of a Dose Calculation for a Symmetric Source

Varskin 3 calculates dose for each of the dose points (-) pictured in Figure 3-1. Once a dose rate value from each radial source point (*) is determined, the first four radial values are summed and compared to the sum of the last four radial values. These two groups of radial points are checked for convergence, and the above procedure is followed until convergence is reached for all radial points in the source.

The dose at a dose point is calculated using the quadrature integration routine according to the equation

$$\dot{D}(d) = \int_0^{2\pi} \int_0^R \int_0^{Thickness} S_v B(r',\theta,z) r' \, dz \, dr' \, d\theta \tag{3-2}$$

where S_v is the volumetric source strength and z is the depth in the cylinder. A similar equation can be written for spherical and slab geometries. These equations are

$$\dot{D}(d) = S_V \int_0^{\pi} \int_0^{2\pi} \int_0^R B(r',\theta,\phi) r' \sin\theta \, dr' \, d\theta \, d\phi \tag{3-3}$$

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

$$\dot{D}(d) = S_V \int_{-x_{max}}^{x_{max}} \int_{-y_{max}}^{y_{max}} \int_0^{Thickness} B(x,y,z) \, dz \, dy \, dx \tag{3-4}$$

in 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 rate profile defined by these 60 points as a function of target radius d' is denoted D(d'), then the dose rate averaged over an area in the skin is calculated using the equation

$$D_{Avg} = \frac{2\pi \int_0^R D(d') d' \, dd'}{\pi R^2} \tag{3-5}$$

The 60 dose points are not chosen linearly from the center of the irradiation area to its outer radius. Instead, the 60 dose points are chosen such that more points are chosen where the dose profile is changing the most. 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 Varskin 3 calculations. The distribution of dose points is chosen automatically within Varskin 3.

When modeling a three-dimensional source, two types of attenuation must be addressed: attenuation due to the presence of the source material and attenuation due to geometry (i.e., $1/r^2$ attenuation). The Varskin 3 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

3-3

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 density of the material to the density of water. The individual modified path lengths are then added to obtain the total modified path length, r_1, in Eq. (3-1).

3.2   Backscatter Model

In VARSKIN Mod 2, a backscatter model was introduced that has the effect of reducing the calculated dose from point and thin disk sources. The backscatter correction was needed because the Berger kernel (Berger, 1971) used in the dose calculation assumes that the source is located in an infinite medium. Thus, the dose includes the contribution from beta particles that were emitted away from the skin and subsequently scattered back toward the skin to contribute to skin dose. Thus, when the Berger point kernel is used to calculate skin dose from an infinitely thick (point or disk) source, the calculated dose will be an overestimate of the skin dose. Depending on the maximum energy of the beta spectrum, the overestimate can be as high as 40 percent (Cross, et al., 1992). VARSKIN Mod 2 applies an energy-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 finite source. An infinite source is one where the dimensions of the source are larger than the X_{99} distance of the beta-energy spectrum. A backscatter correction for three-dimensional sources was not included in VARSKIN Mod 2.

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 cm². The backscatter correction as a function of X_{99} distance is shown in Figure 3-2 (redrawn from Durham, 1992). The backscatter correction reduces the calculated dose by dividing the calculated dose by the correction factor. In Varskin 3, the backscatter model extended to areas of up to 10 cm² and includes a correction for three-dimensional sources that have dimensions that are less than the X_{99} distance in the source material. This section describes the model and the calculations that were performed to develop the model.
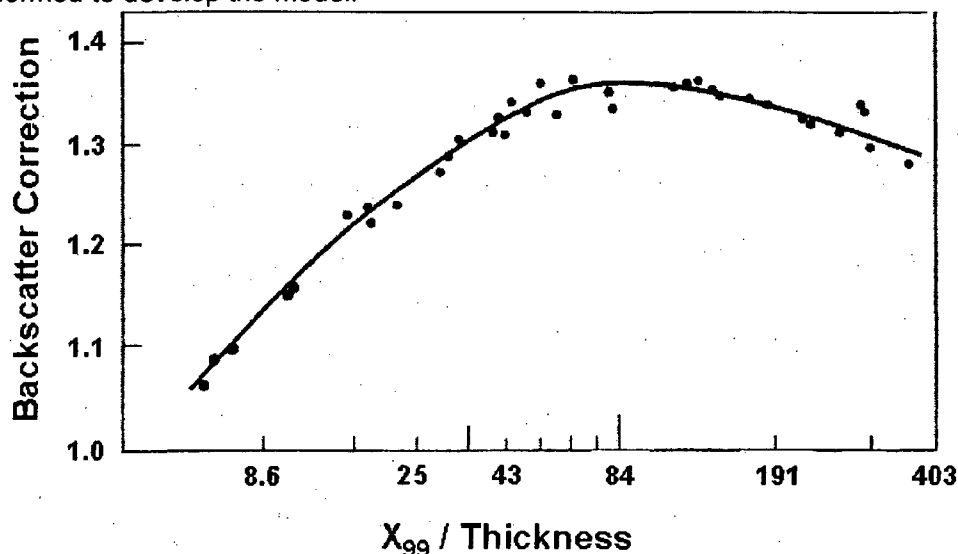
Figure 3-2. Backscatter Correction Factor for Infinitely Thin and Point Sources

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 range of a beta source is not a discrete value because of electron straggling effects. In Varskin 3, the range is equated to the X_{99} distance, which is 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 cylinder source with the thickness equal to the diameter. For the infinite-medium model, the source was surrounded by water (see Figure 3-3a). For the air-skin interface model, the region above the source was modeled as air (see Figure 3-3b). Note that the tissue in Figure 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. The source material was iron with a density of 7.86 g/cm^3, and the thickness of the disk was varied between 1 μm (the diameter of the point source in Varskin 3 calculations) and the X_{99} distance for the radionuclide.

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

For each data point, one million particles were generated in the source with a uniform emission angle for each simulated geometry. The simulations calculated energy flux through a circular

a   b
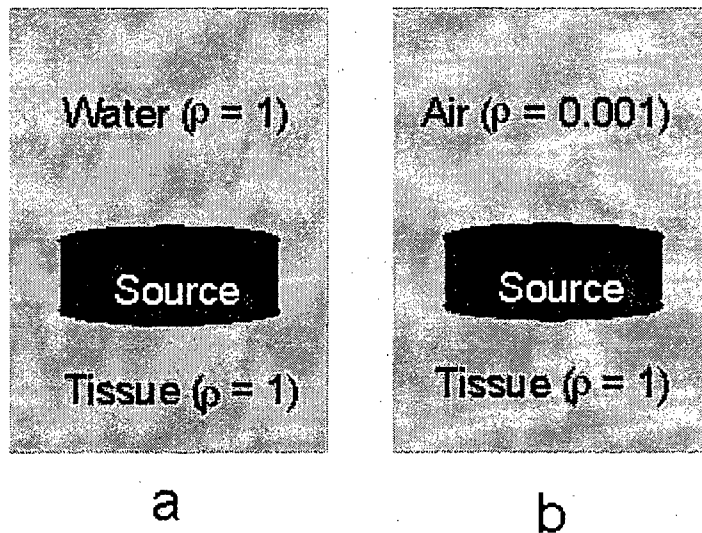
Figure 3-3. Geometry Used for MCNP Calculations for the Backscatter Model

Table 3-1. Radioactive Characteristics of the Sources Modeled for the Backscatter Correction			
Nuclide	Average Energy (keV)	Maximum Energy (keV)	Range in Iron (µm)
Pm-147	62	225	38
Sr-90	196	546	182
Tl-204	244	763	297
Y-90	935	2,280	1,190

disk located 70 µm below the bottom of the source sorted into 15 different energy bins. The dose was determined from the flux 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 (NIST) website (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 the (i) ratio of flux in the infinite medium to the flux in air and (ii) 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 Pm-147. 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. Figures 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 Sr-90, Tl-204, and Y-90, respectively. A common trait of all four figures is a steadily
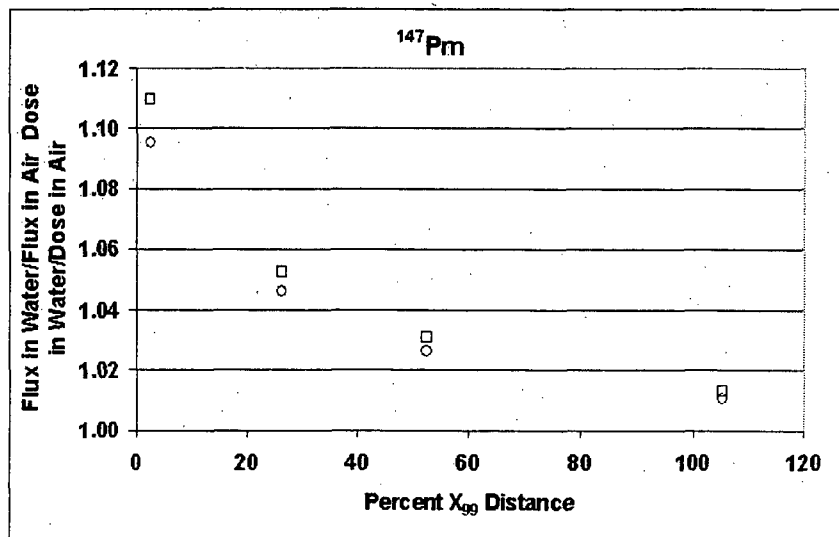
Figure 3-4. Ratio of Flux in Water to Flux in Air for Pm-147
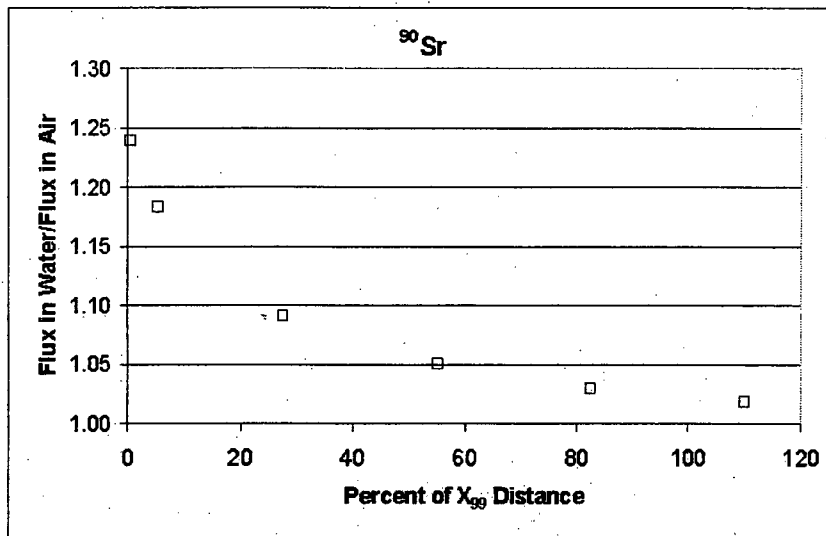
Figure 3-5. Ratio of Flux in Water to Flux in Air for Sr-90
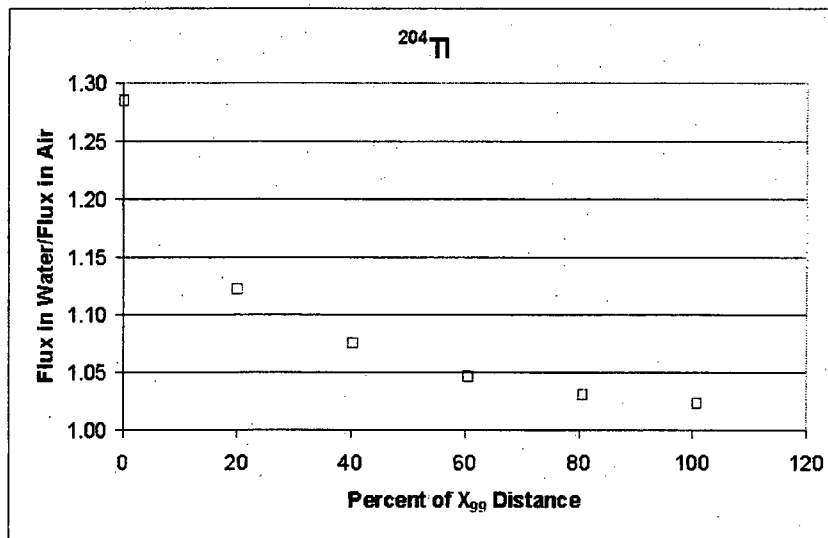
Figure 3-6. Ratio of Flux in Water to Flux in Air for Tl-204
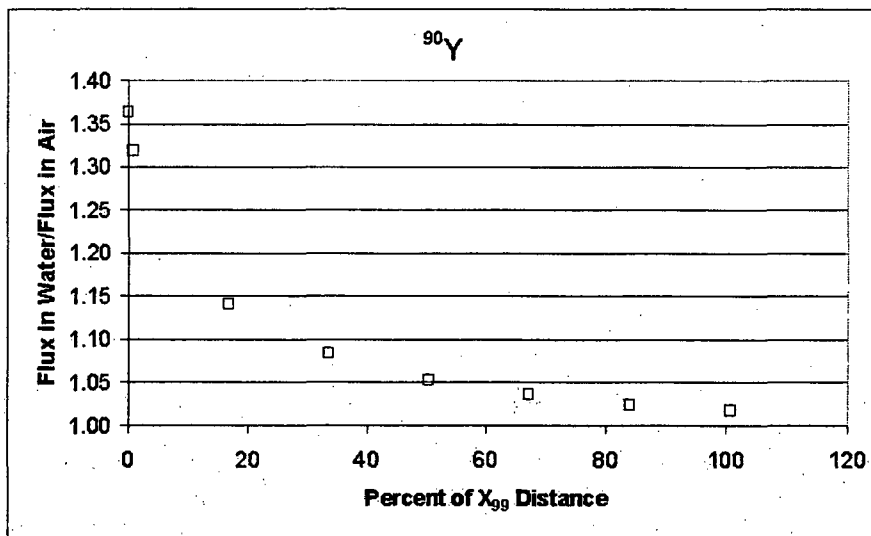
Figure 3-7. Ratio of Flux in Water to Flux in Air for Y-90

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 the backscatter correction applied to infinitely thin sources in VARSKIN Mod 2. Thus, the backscatter correction applied to sources with a thickness of less than 5 percent of the X_{99} distance is the same backscatter correction applied to point and disk sources. It should be noted that the point source backscatter correction model provides correction factors that are consistent with the current calculations.

The data in Figure 3-8 are obtained by taking the data from Figures 3-4 through 3-7 and consolidating them for all sources greater in size than 5 percent of the X_{99} distance. Several attempts were made to fit the data using curve-fitting techniques available in Microsoft Excel®. The curve-fitting technique that resulted in the highest R^2 value was the logarithmic fit with an R^2 value of 0.98. The trend line represents the Backscatter Correction Factor (BCF) as a function of the fraction of X_{99} distance. The equation for the backscatter correction factor is

$$BCF = 1.018 - 0.060\ln(\Delta t_{source} / X_{99}) \tag{3-6}$$

where Δt_{source} is the source thickness (or diameter for spheres).

In VARSKIN Mod 2 and Varskin 3, the backscatter correction factor is applied to the calculated dose for three-dimensional sources with a thickness 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 point backscatter correction factor is applied. For sources with a thickness that is 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.
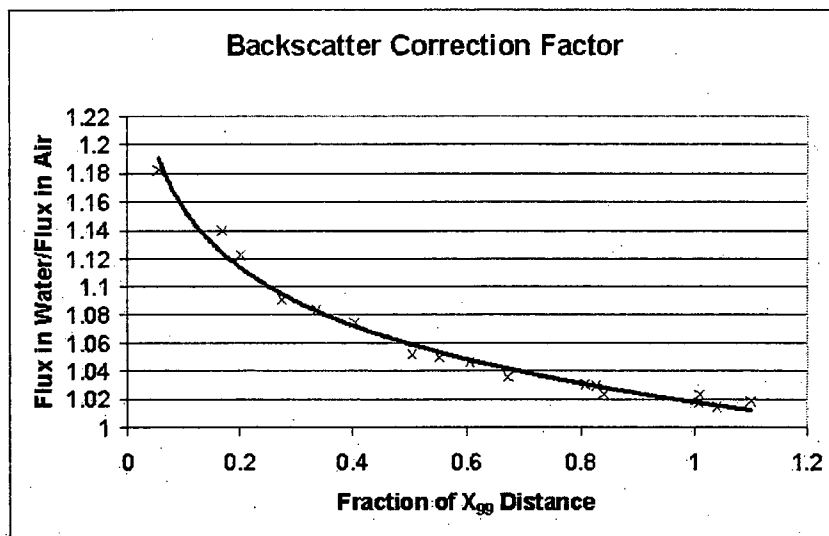
Figure 3-8. Combined Data for the Four Radionuclides

The VARSKIN Mod 2 backscatter correction model also accounted for material located between the source and the skin depth of interest. The current calculations support this model. The VARSKIN Mod 2 model for infinitely thin sources has been incorporated in Varskin 3, and for sources with a thickness of less than 5 percent of the X_{99} distance, the backscatter correction factor changes when the source is not in contact with the skin. The presence of covering material does not significantly affect the backscatter correction for three-dimensional sources because of the small magnitude of the correction. Therefore, the backscatter correction factor does not change with depth for sources with a thickness greater than 5 percent of the X_{99} distance in the source material.

A backscatter correction model has been developed for three-dimensional sources that can be used in the Varskin 3 skin dose code. For sources with a thickness of less than 5 percent of the X_{99} distance in the source material, the model uses a correction factor that is consistent with the backscatter model used in VARSKIN Mod 2. For sources with a thickness between 5 and 100 percent of the X_{99} distance, a new correction factor is applied as a function of the X_{99} distance that follows a logarithmic distribution. Sources that are thicker than the X_{99} distance are infinite sources, and no correction to the Berger kernel is required.

3.3   Cover Layer and Air Gap Models

Both cover materials and air gaps can be modeled using Varskin 3. The models use the concept of path length to determine the energy lost in either a cover material or air. 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. In order to prevent unintended applications of Varskin 3, the air gap is limited to a maximum of 5 cm.

The method used to determine path length within the source and within the cover material can be illustrated using Figure 3-9. 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

3-9
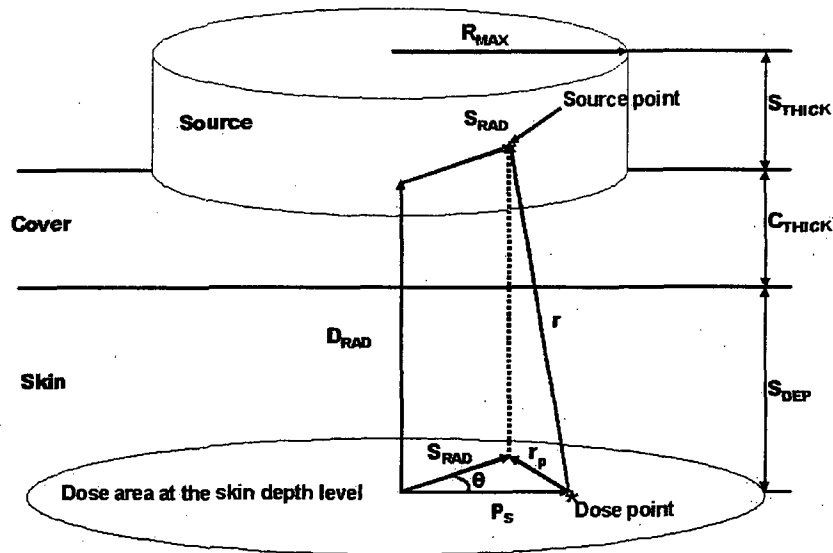
Figure 3-9. Schematic Drawing of a Generic Dose Calculation Performed by Varskin 3 for the Cylinder Geometry

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}). The quadrature routines 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:

$$r_p^2 = P_s^2 + S_{RAD}^2 - 2 \times P_s \times S_{RAD} \times \cos\theta \qquad (3\text{-}7)$$

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. The value of r can then be determined using the Pythagorean theorem

$$r = \sqrt{r_p^2 + D_{RAD}^2} \qquad (3\text{-}8)$$

This quantity is further analyzed to calculate the modified path length used to evaluate the scaled absorbed dose distribution as discussed next.

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

$$r_c = C_{THICK} \times r / D_{RAD} \qquad (3\text{-}9)$$

The distance traveled through the skin is given by

$$r_t = S_{DEP} \times r \, / \, D_{RAD} \qquad (3\text{-}10)$$

Finally, the distance traveled through the source is given by

$$r_s = (D_{RAD} - C_{THICK} - S_{DEP}) \times r \, / \, D_{RAD} \qquad (3\text{-}11)$$

The modified path length r_1 is then found from the equation

$$r_1 = (r_s \, \rho_s + r_c \, \rho_c + r_t \, \rho_t) \, / \, \rho_t \qquad (3\text{-}12)$$

where ρ_t is the density of tissue, assumed to be equal to the density 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. (3-12) must be further analyzed to determine the path length within the source and the path length outside the source, but above the cover-material level. 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 actual distance from source point to dose point is given by

$$r_p^2 = P_s^2 + S_{RAD}^2 \times \sin^2 \phi - 2 \times P_s \times S_{RAD} \times \sin \phi \times \cos \theta \qquad (3\text{-}13)$$

and in slab geometry the actual distance is given by the equation

$$r = \left[\left(x_{source} - x_{dose} \right)^2 + \left(y_{source} - y_{dose} \right)^2 + \left(z_{source} - z_{dose} \right)^2 \right]^{1/2} \qquad (3\text{-}14)$$

The remaining equations apply to both spherical and slab geometries.

3.4   Volume-Averaged Dose Model

The volume-averaged dose model (shown schematically in Figure 2-11) allows the calculation of doses averaged over volumes of skin. Any two planes of irradiated skin bound the volume (i.e., any two planes between zero skin depth and the skin depth that corresponds to the maximum penetration of beta particles emitted by the source). For sources in contact with the skin, the maximum penetration depth is equal to the X_{99} distance. Doses averaged over the dose-averaging area are calculated at 50 skin depths between these two limits, and a cubic spline (a third-order piecewise polynomial curve fit) is fit to this depth-dose distribution. When the user enters the skin depths corresponding to the volume of interest, Varskin 3 integrates the depth dose function over the region of interest to obtain the volume-averaged dose. The volume-averaged dose model requires roughly 50 times the execution time as a single depth

calculation to establish the depth dose function. Calculation times as long as 5 minutes are possible.

3.5　　Offset Particle Model

The offset particle model (shown schematically in Figure 2-12) allows calculation of skin dose averaged over areas that are not directly below the contaminant. This model was developed to calculate doses from multiple hot particles. The offset particle model is available only for the slab geometry.

The offset particle model requires only one input variable, the distance of the offset. When performing the calculations for the model, Varskin 3 requires that the offset is in the x direction. Since this requirement implies a symmetrical source, the x- and y-side lengths must be equal. If the user invokes the offset particle model with a source that does not have equal x- and y-side lengths, Varskin 3 will request that the user re-enter the x- and y-side lengths. Varskin 3 also provides the user with the x-side length that corresponds to a source of equivalent area should the user wish to maintain the area of the source.

For multiple particle irradiations, doses from each particle must be calculated separately, running Varskin 3 once for each particle. The offset particle model does not calculate the maximum dose to skin from several particles (the iterative process for determining the maximum dose to the dose-averaging area is outlined in Section 6.2).

3.6　　Photon Dose Model

Photon doses calculated by Varskin 3 use an expanded version of a simplified model developed by Lantz and Lambert (1990). Durham and Lantz (1991) verified the original photon dose model experimentally. The photon dose model assumes that the source is a point source and that any material between the source and skin is nearly tissue-equivalent. Therefore, the largest dimension of any source has been arbitrarily limited to a maximum of 1 mm. The photon dose is calculated (provided that the radionuclide emits photon radiation) for skin areas of up to 10 cm^2. The method used to develop the photon dose model is described in Appendix A.

It is important to note that the photon dose is calculated assuming that the source can be represented as a point source, regardless of the geometry package that is chosen by the user. If a three-dimensional source geometry is chosen, the photon source is assumed to be located at the bottom center of the source. Thus, if the radius of the source is changed, the photon dose will remain the same for the same amount of activity.

Two pieces of information are used to calculate the photon dose: the specific photon dose constant and the average photon energy. The specific photon dose constant is used to determine photon doses when electronic equilibrium is fully established. The average photon energy is used to determine the extent to which electronic equilibrium is established.

The specific photon dose constant, in units of rad-cm²/mCi/h is calculated for the radionuclides using the following equation modified from Attix (1986)

$$\Gamma\left[\frac{\text{rad} - \text{cm}^2}{\text{mCi} - \text{h}}\right] = 1938\left[\sum_{i=1}^{n} P_i E_i[\text{MeV}]\left(\frac{\mu_{en}}{\rho}\right)_{Ei,\text{tissue}}\left[\frac{m^2}{kg}\right]\right]$$ (3-15)

where P_i is the probability of the emission of a photon having an energy E_i and $(\mu_{en}/\rho)_{Ei,\text{tissue}}$ is the mass energy absorption coefficient in soft tissue for the photon. Data for $(\mu_{en}/\rho)_{Ei,\text{tissue}}$ were obtained from a NIST website (Hubbell and Seltzer, 2006) and based on ICRU–44 (International Commission on Radiation Units and Measurements, 1989). Data for E_i and P_i were obtained from the NUCDECAY data files (RSICC, 1995).

The average photon energy in keV is calculated using the equation

$$E_{avg}[\text{MeV}] = \frac{\sum_i P_i E_i[\text{MeV}]}{\sum_i P_i}$$ (3-16)

In Varskin 3, the specific photon dose constant and the average photon energy are included in the library file for the chosen radionuclide. The user can choose to eliminate low-energy photons by choosing a suitable cutoff energy when creating the radionuclide library file. The gamma dose model does not account for absorption in the skin. At skin depths of 7 mg/cm², photon energies as low as 2 keV contribute to the dose. However, at skin depths of 1,000 mg/cm², photons below 35 keV do not contribute to the dose. It is important that the user choose a cutoff energy that is appropriate for the depth at which the dose is being calculated. If a low cutoff energy is chosen for a deep skin depth, the dose may be overestimated. If a high cutoff energy is chosen for a shallow skin depth, the dose may be underestimated. Recommended cutoff energies for photons is 2 keV for shallow dose, 20 keV for eye dose, and 35 keV for deep dose equivalent.

3.7   Syringe Model

The syringe model in Varskin 3 employs a major approximation to an actual syringe and, in this respect, has several limitations. In the syringe model, Varskin 3 converts the syringe to a cylinder in which the diameter of the syringe is set equal to the thickness of the cylinder. The diameter of the cylinder is calculated by setting the volume of the cylinder equal to the volume of the syringe. The dose is then calculated at the bottom of the cylinder. This approximation has significant impacts for syringes that are long and narrow. Doses calculated for long, narrow syringes will probably be inaccurate. In addition, since the dimensions of the syringe are greater than 1 mm, photon doses will not be calculated. To calculate beta doses, the syringe model collects values from the user for the source volume, V; source density, ρ_s; the syringe wall thickness, w_T; and the outer diameter of the syringe, OD_{syr}. As with all geometry packages, the user has the option to include an air gap thickness and the thickness and density of a cover material, Δt_{cov} and ρ_{cov}, respectively. The syringe wall material is assumed to be polyethylene with a density of 0.92 g/cm³. Varskin 3 approximates the dose from a syringe source by using the cylinder geometry with input values modified to approximate the size of the syringe as described in the following discussion.

First, Varskin 3 calculates the diameter of the syringe source, d_s, using the following equation

$$d_s = OD_{syr} - 2w_T \qquad (3-17)$$

Varskin 3 constructs a cylinder with a thickness, Δt_{cyl}, equal to the diameter of the syringe source. While maintaining the volume of the source, the radius of the constructed cylinder, r_{cyl}, is determined using the equation

$$r_{cyl} = \sqrt{\frac{V}{\pi r \Delta t_{cyl}}} \qquad (3-18)$$

Finally, Varskin 3 calculates the total cover thickness and effective density that includes any cover material and the thickness of the syringe wall. The total cover thickness, Δt_{tot}, is calculated according to

$$\Delta t_{tot} = w_T \Delta t_{cov} \qquad (3-19)$$

and the effective density, ρ_{cov}, is found from the equation

$$\rho_e = \frac{\Delta t_{cov}\rho_{cov} + 0.92\,g/cm^3 \times w_T}{\Delta t_{tot}} \qquad (3-20)$$

3.8   Adding Radionuclides to the Varskin 3 Library

Adding radionuclides to the Varskin 3 library is accomplished using 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 in Varskin 3. 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, E_β; the beta yield, Y_β; the X_{99} distance (which is used to establish the range of the beta particles); and the scaled absorbed dose distribution, $F_\beta(r/X_{99})$. These data are calculated using the method described by Berger (1971), which is not repeated here. The X_{99} distance is used in this document 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 equation

$$X_{99} = 1.8\,X_{90} \qquad (3-21)$$

In Varskin 3, the beta spectrum is obtained from the data file *ICRP38.BET*, which is located in the \dat subdirectory of Varskin 3 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 file *ICRP.DAT* also includes photon data and the GUI in Varskin 3 calculates the specific photon dose constant and the average photon energy as described in Section 4.6. The GUI collects the beta spectrum for a selected radionuclide and writes a file

entitled *SadInput.dat* that 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 E_β, Y_β, the X_{99} distance, and $F_\beta(r/X_{99})$; 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.

The FORTRAN program *Sadcalc.exe* runs independently of the GUI, and no information is passed from *Sadcalc.exe* to the GUI when the executable is running. In order for the GUI to detect when the executable is finished running, *Sadcalc.exe* writes a small file entitled "*ping*" when it has finished writing *sadout.dat*. While the executable is running, the GUI executes a "do loop" that continuously checks for the presence of *ping* while updating a scroll bar at the same time. When the GUI detects *ping*, the do loop is exited, and the GUI continues with the subsequent calculations and operations.

A total of 838 radionuclides are available to add to the Varskin 3 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 that 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 library file. *Sadcalc.exe* then calculates $F_\beta(r/X_{99})$ 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 tritium spectrum. The presence of the tritium spectrum will calculate a small beta dose 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.

4 VALIDATION AND VERIFICATION OF VARSKIN 3

A validation plan and report was developed and implemented to demonstrate that Varskin 3 operates as expected and compares well with other methods. The validation plan and report is available on the Varskin 3 distribution disk. The portion of the validation plan and report that compares Varskin 3 results to other techniques is reproduced in this section.

4.1   Point Source on Skin

In this test, calculations were completed for the case of a point source directly on the skin (i.e., no material and no air gap between the source and skin). For a 1-µCi hot particle on the skin, the beta dose rate to 1 cm^2 at 7 mg/cm^2 was calculated using Varskin 3. For Co-60, a comparison of beta and gamma dose rates given by Chabot, et al. (1988) to those predicted by Varskin 3 was made. The results are shown in Table 4-1. There is reasonable agreement among the beta dose rates with those calculated using Varskin 3. The Varskin 3 results were slightly lower because of the backscatter correction that is discussed in Section 3.2. The difference in the photon dose calculation reflects the inclusion of charged particle equilibrium effects in Varskin 3.

4.2   Point Source on Cover Material

The model of Chabot, et al. (1988) was used in this test. The types of cover materials modeled were

*   One layer of cotton coveralls with a thickness of 0.37 mm and density of 0.7 g/cm^3

*   Two layers of cotton coveralls with a thickness double that of the above thickness

*   One layer of coveralls plus one layer of plastic suit material, the latter with a thickness of 0.4 mm and a density of 1.1 g/cm^3

The calculations were completed for the isotopes Co-60, Cs-137, Ba-137m, and Sr-90/Y-90, assuming a point source of 1 µCi each and no self-absorption. Air gaps of 0.2 and 1.0 cm were used for the first two clothing types, and 1.0 and 5.0 cm were used for the third. It was assumed that there was no air gap between the layers of protection clothing. Photon doses were calculated using the analytical expression in Chabot, et al. (1988), assuming no attenuation in clothing, no scatter, and a conversion from exposure to dose of 1 rem/R for photons.

Table 4-1. Comparison of Calculated Skin Dose Rates for a 1-µCi Hot Particle on the Skin						
	Beta Dose Rate (rad/h)			Photon Dose Rate (rad/h)		
Nuclide	Varskin 3	Chabot, et al.*	Difference (%)	Varskin 3	Chabot, et al.*	Difference (%)
Co-60	3.76	4.33	−15	0.329	0.364	−11
*Chabot, G.E., K.W. Skrable, and C.S. French. "When Hot Particles Are Not on the Skin." *Radiation Protection Management*. Vol. 5, No. 6. pp. 31–42. 1988.						

The results of these calculations and the same calculations completed with Varskin 3 are shown in Table 4-2. In general, there is reasonable agreement between the two calculations for both the beta and photon dose rate calculations. The largest differences occur for the case of Cs-137, Ba-137m on two layers of cotton coveralls.

4.3 Distributed Contamination on Skin

The third set of calculations was for the case of distributed contamination on the skin. A concentration of 1 mCi/cm^2 over a circular area of 100 cm^2 was assumed, and the beta dose rate to 1 cm^2 of skin centered under the contamination was calculated. The calculations were completed with Varskin 3, and the results were compared to values published by Rohloff and Heinzelmann (1986) and by Kocher and Eckerman (1987). The results from Varskin 3 and Rohloff and Heinzelmann (1986) (shown in Table 4-3) agree quite well because both methods account for the lack of backscatter from an infinitely thin source. Results using the Kocher and Eckerman (1987) method are somewhat higher because the method overestimates backscatter from air.

Table 4-2. Comparison of the Chabot Method and Varskin 3 for 1-μCi Hot Particle Point Source on Cover Material

Nuclide	Air Gap (cm)	Clothing	Beta Dose Rate (rem/h)			Photon Dose Rate (rem/h)		
			Chabot, et al.*	Varskin 3	Difference (%)	Chabot, et al.*	Varskin 3	Difference (%)
Co-60	0.2	1B†	0.203	0.196	−3	0.077	0.0721	−6
	1.0	1B	0.080	0.078	−1	0.011	0.010	−9
	0.2	2B	0.002	0	—	0.067	0.063	−6
	1.0	2B	0.004	0	—	0.010	0.0094	−6
	1.0	B+P ‡	0	0	—	0.010	0.0096	−4
	5.0	B+P	0	0	—	0.0005	0.0005	0
Cs-137/ Ba-137m	0.2	1B	1.33	1.40	+5	0.019	0.019	0
	1.0	1B	0.295	0.279	−5	0.0027	0.0027	0
	0.2	2B	0.357	0.475	+33	0.0167	0.0177	0
	1.0	2B	0.121	0.140	+16	0.0025	0.0025	0
	1.0	B+P	0.067	0.077	+15	0.0025	0.0025	0
	5.0	B+P	0.0035	0.0038	+9	0.0001	0.0001	0
Sr-90/ Y-90	0.2	1B	3.534	3.26	−8			
	1.0	1B	0.596	0.531	−11			
	0.2	2B	2.245	2.069	−8			
	1.0	2B	0.409	0.395	−3			
	1.0	B+P	0.337	0.326	−3			
	5.0	B+P	0.018	0.0167	−7			

*Chabot, G.E., K.W. Skrable, and C.S. French. "When Hot Particles Are Not on the Skin." *Radiation Protection Management.* Vol. 5, No. 6. pp. 31–42. 1988.
†B—Cover material = thickness of 0.37 mm, density of 0.7 g/cm^3.
‡P—Cover material = thickness of 0.4 mm, density of 1.1 g/cm^3.

Table 4-3. Comparison of Calculated Beta Skin Doses for Distributed Contamination of 1 µCi/cm² Averaged Over 100 cm² on the Skin			
		Beta Dose Rate (rad/h)	
Nuclide	Varskin 3	Rohloff and Heinzelmann*	Kocher and Eckerman†
Co-60	3.77	3.24	4.18
Cs-137	5.12	—	5.91
Sr-90	12.43	12.06	15.61

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

†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.

Next, results of Varskin 3 calculations were compared to the results of calculations using the following references:

- Delacroix (1986)
- Kocher and Eckerman (1987)
- Piechowski (1988)

These three papers give maximum dose rates from a source modeled as an infinitely thin, uniformly contaminated (1 µCi/cm²) plane surface. Doses were calculated at different depths in the skin. The Varskin 3 input data were

- Disk geometry
- 2-cm diameter
- 3.14-µCi activity

Tables 4-4 and 4-5 show that the results are in good agreement although the Varskin 3 results are lower because of the backscatter correction as discussed in Section 3.2.

Table 4-4. 70-µm Depth Dose Coefficients in rad-cm²/µCi/h					
Method	C-14	P-32	I-131	Sr-90	Y-90
Varskin 3	1.12	6.63	5.25	5.46	6.84
Delacroix*	1.07	9.15	6.42	6.99	9.18
Kocher and Eckermann†	1.22	8.87	6.34	6.76	8.87
Piechowski‡	1.2	7.0	6.0	5.9	7.5

*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.

†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.

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

Table 4-5. Dose Coefficients Versus Depth for Y-90 Averaged Over 0.01 cm^2 in rad-cm^2/µCi/h				
Method	**40 µm**	**70 µm**	**100 µm**	**400 µm**
Varskin 3	7.94	6.86	6.17	4.09
Delacroix*	10.46	9.18	8.37	5.24
Kocher and Eckerman†	10.14	8.87	—	5.07

*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.

†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.

5 CHANGES TO VARSKIN MOD 2 AND NEW FEATURES AND LIMITATIONS OF VARSKIN 3

This section describes the problems that were identified in VARSKIN Mod 2, fixes incorporated in Varskin 3, and the new features that are included in Varskin 3. It also provides information on the limitations of Varskin 3.

5.1   Corrections to Errors in VARSKIN Mod 2

In the years since the release of VARSKIN Mod 2, several errors have been identified and industry users have made many suggestions for improvement. VARSKIN Mod 2 calculated the dose averaged over 1 cm^2 of skin as the default value. The U.S. Nuclear Regulatory Commission (NRC) has proposed a new uniform skin dose limit that requires determining the dose averaged over an area of 10 cm^2 for comparison against the 50 rad limit for both point and distributed sources (NRC, 2002). Varskin 3 calculates the dose to 10 cm^2 as a default for comparison to the 50 rad limit. Varskin 3 also contains the capability of calculating the dose to areas other than 10 cm^2 to evaluate exposures to other areas.

VARSKIN Mod 2 was designed to operate efficiently on a personal computer containing an 80286 processor; this required several simplifications in the calculational methodology to be incorporated into the code to allow the dose calculations to be completed in a reasonable length of time. These simplifications did not significantly affect the accuracy of doses at a depth of 7 mg/cm^2 averaged over 1 cm^2 for which the code was designed. However, the accuracy of the code when applied to dose calculations averaged over significantly smaller or larger areas or when applied to irradiated volumes can be affected by the simplifications. In addition, the user interface in VARSKIN Mod 2 requires the user to enter radionuclide data sequentially even when the source and target geometry remained the same for each radionuclide. With the advent of powerful personal computers and the windowing capabilities of current operating systems, calculational simplifications are no longer necessary and sequential data entry can be avoided. Varskin 3 uses improved algorithms for calculating skin dose that take advantage of the increased power of modern personal computers and that improve the overall accuracy of the calculations.

Personnel at Ontario Power Generation, Inc., performed extensive testing of VARSKIN Mod 2. This testing covered many atypical applications of the code, and several errors were identified. A communication summarizing the errors and their impact on dose calculations was sent in 2004[1]. Errors associated with the following items have been identified, and the solution incorporated in Varskin 3 is identified. Errors were also identified in SADDE Mod 2. SADDE Mod 2 is a companion computer code to VARSKIN Mod 2 that allows radionuclides to be added to the VARSKIN Mod 2 radionuclide library. SADDE Mod 2 was developed shortly after VARSKIN Mod 2.

•   Source Density: The source density for point and two-dimensional calculations is defined by the last calculation using a three-dimensional geometry and is not reset to 0.001 g/cm^3 as intended. In VARSKIN Mod 2 and Varskin 3, point and

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[1]Chase, J. "pdf Version of Report." Email communication (September 15) to J. Durham, Colorado State University, Ft. Collins, Colorado. Toronto, Ontario, Canada: Ontario Power Generation, Inc. 2004.

two-dimensional disk sources are modeled as cylindrical sources with very small (~1 µm) dimensions, when appropriate, and a negligible density of 0.001 g/cm^3.

Solution: The source density is reset to 0.001 g/cm^3 when point and disk source geometries are used for calculations.

- Backscatter Correction: The backscatter correction is only included for point and two-dimensional geometries when the dose is averaged over 1 cm^2.

Solution: The backscatter correction model has been expanded to include three-dimensional sources and is applied regardless of the dose-averaging area.

- Low Results for Small Sources: The cylinder source geometry used for point, disk, and cylinder source geometries omits the dose contribution from a center cylinder with a 0.27-µm radius, where the cylinder height is the source height. This omission results in a relatively large dose contribution being ignored in calculations involving very small sources, significantly reducing the calculated dose. In VARSKIN Mod 2, the minimum distance between a source point and a target point was chosen to be 0.27 µm based on the average distance that an electron travels between interactions. In the sphere model, the dose contribution from a 0.27-µm radius sphere was also omitted.

Solution: Varskin 3 was revised so that the minimum distance between the source and target was reduced from 0.27 µm to a value of 0.01 µm.

- Incorrect Results for Very Shallow Skin Depths: Results of calculations at very shallow skin depths for sources directly on the skin were found to be unreliable.

Solution: Varskin 3 uses 60 radial-dose-calculation points on the target area instead of 26 points used in VARSKIN Mod 2. Once the 60-point distribution is calculated, the distribution is evaluated at 10,000 points to increase the reliability of the calculation.

- Incorrect Volume-Averaged Dose Results for Sources on Skin: The volume-averaging results were found to oscillate for sources directly on the skin. The recommended correction of placing a 1-µm layer of unit density cover between the source and skin only worked for radionuclides whose beta energy was less than or equal to that of Co-60 (318 keV).

Solution: Varskin 3 evaluates the dose at 50 depths for volume averaging instead of 20 depths. Once the 50-point depth-dose distribution is calculated, the distribution is evaluated over 10,000 points to increase the accuracy and eliminate oscillating results.

- Volume-Averaged Dose Backscatter Correction Factor: A single backscatter correction factor is used at all skin depths for volume-averaged doses in VARSKIN Mod 2. The backscatter correction factor is chosen when the skin depth is entered on the input screen.

Solution: Varskin 3 calculates the backscatter correction factor at each of the 50 depths in the volume-averaged dose distribution.

- Incorrect Charged Particle Equilibrium (CPE) Correction for Photon Dose Calculations: A programming error in the photon dose CPE correction was identified that allows unreliable calculations if clothing is present with a density much different than that of water and for large air gaps.

Solution: The programming error was corrected in Varskin 3.

- Mixtures of Radionuclides and Multiple Decay Paths: SADDE Mod 2 was found to incorrectly add mixtures of radionuclides and perform poorly with single radionuclides that have multiple decay paths with widely varying energies. This is caused in part by using a beta-screening model in SADDE Mod 2 that greatly affects low-energy beta particles when they are added to high-energy beta particles.

Solution: In Varskin 3, the capability of adding multiple radionuclides was eliminated, and a more accurate method of building library files was incorporated.

- Double Yield Problems in Doses With Single Radionuclides: SADDE Mod 2 was found to contain a programming error that resulted in the yield of a beta decay being applied twice. For yields that differ significantly from 1, the yield is either underestimated or overestimated.

Solution: The programming error was corrected in Varskin 3.

- Incorrect Dose Calculation for Small Target Areas, Low Energy Betas, and Large Sources: For large three-dimensional sources emitting low-energy betas, the calculated results were found to be incorrect. Specifically, the dose to a small target area at a very shallow skin depth from a S–35 cylinder source with a diameter of 34,000 μm and a thickness of 200 μm (the source density-thickness is comparable to the range of the beta particles) was found to be in error.

Action: The integration limits for these unique calculations were investigated, and the error was corrected for all geometry packages in Varskin 3.

- "Ringing" of Spline Function for Small Sources: For small sources on the skin or with a very thin cover or air gap, the dose rate decreases very rapidly with a small increase in radial distance, causing the spline interpolation function to oscillate or "ring." Ringing causes doses at the edge of the irradiation area.

Action: Ringing was found to be caused by using a linear fit of data that is changing very rapidly. Varskin 3 transforms the data to a log scale prior to applying the spline fit, thus eliminating this problem.

5.2 New Features in Varskin 3

In addition, the Chase communication[2] recommended investigation of several areas for improvement to the code. The action taken in Varskin 3 is provided for each of the suggestions.

1. Anomalies in Radial Dose Distributions: The radial dose distribution exhibited unexpectedly large dips and peaks.

   Action: The Relative Error has been changed from 0.001 in VARSKIN Mod 2 to 0.0001 in Varskin 3 to minimize the problem, and the user can no longer change this parameter. The relative error is the parameter that determines when the numerical integration routine has converged. This correction was possible because of the high speed of modern computers.

2. Improved Photon Dose Model: The photon dose model in VARSKIN Mod 2 was limited to a dose area of 1 cm^2. The photon dose model is inadequate for determining both shallow dose and deep dose at the newly recommended dose-averaging area of 10 cm^2.

   Action: An improved photon dose model that calculates the photon dose to any area smaller than 10 cm^2 was incorporated into Varskin 3. The new model is based on data provided by Lantz as shown in Appendix A.

3. More Accurate Beta Spectrum Information: The specific absorbed dose distributions used by VARSKIN Mod 2 were calculated from basic nuclear data.

   Action: In Varskin 3, beta spectra are obtained from abridged ICRP–38 (International Commission on Radiological Protection, 1983) data using NUCDECAY (RSICC, 1995) data files. This improves the reliability of the library files in Varskin 3 and results in more reliable dose calculations.

4. Poor Results From Internal Conversion and Auger Electrons at High Energies: Internal conversion and Auger electrons are treated correctly in SADDE Mod 2 only when they have energies much less than the maximum beta energy and have relatively small yields. This is caused by using a cubic spline to fit data that is rapidly changing, resulting in an oscillation or "ringing" of the fit. Ringing leads to inaccurate results.

   Action: Varskin 3 performs a log transformation prior to applying the cubic spline to fit the data, thus eliminating the ringing.

Users of VARSKIN Mod 2 in the nuclear power industry and in the field of medical isotopes have also suggested improvements to the code. The most common suggestion is to make a version that is Windows® compatible to allow the user to enter data more efficiently. The second most common suggestion is to make adding radionuclides to the library easier.

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[2]Chase, J. "pdf Version of Report." Email communication (September 15) to J. Durham, Colorado State University, Ft. Collins, Colorado. Toronto, Ontario, Canada: Ontario Power Generation, Inc. 2004.

With the release of the operating system Windows XP®, the Microsoft Corporation has significantly reduced its support of DOS. VARSKIN Mod 2 operates under the DOS operating system, and when DOS is eventually eliminated from Windows, operation of VARSKIN Mod 2 will no longer be possible. Therefore, Varskin 3 was written to operate under the Windows operating system.

The input data file for VARSKIN Mod 2, BETADATA.DAT, is no longer used in Varskin 3. Each user builds a library that contains only the radionuclides of interest to that user. The new data files contain physical data for the average energy, maximum energy, and yield based on data generated by the computer code NUCDECAY (RSICC, 1995), which uses data published in ICRP–38 (International Commission on Radiological Protection, 1983). Further information in the library files includes data for photon dose calculations and contributions from internal conversion and Auger electrons.

5.3   Limitations of Varskin 3

Varskin 3 is designed to calculate the dose to skin from skin contamination. Users may try to use Varskin 3 to perform calculations that are beyond the intended application of the code. This section discusses the known limitations of Varskin 3 and establishes the limits over which Varskin 3 has been tested.

The first item of note is not a limitation of Varskin 3, but a code design decision, and involves the treatment of radioactive progeny. In Varskin 3, radioactive progeny are not included with the parent radionuclide and must be entered explicitly.

Varskin 3 has been shown to be reliable for all particulate sources that have dimensions that are smaller than eight times the X_{99} distance of the radionuclide in tissue, depending on the area of irradiation, especially for relatively small irradiation area. The X_{99} distance, which is described in detail later, is essentially the range of the beta particles and appears on the printout. When a source becomes larger than this value, Varskin 3 may give results that are unreliable. It is suggested that a user who wishes to model sources larger than this limit begin with smaller sources and increase the source size gradually to ensure that spurious results are not being generated. However, modeling a source of this size is generally not necessary as most of the source does not contribute to skin dose. When modeling a gas cloud the size of the cloud should not be larger that eight times the X_{99} distance in the gas. Varskin 3 prompts the user with a warning if the potential for inaccurate results is modeled by choosing a source that is too large. The X_{99} distance is included on the printout of a calculation.

Varskin 3 has not been tested extensively for dose averaging areas greater than 10 cm². However, because of the nature of the calculations performed by Varskin 3, there is no reason to believe that doses to areas greater than 10 cm² will result in errors. It is suggested that the user begin with a calculation averaged over 10 cm² and gradually increase the dose-averaging area to ensure that spurious results are not obtained.

Beta doses involving air gaps greater than 5 cm have not been extensively tested. It is likely that erroneous results may be obtained for large air gaps because Varskin 3 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 3, and can lead to inaccurate results.

Varskin 3 will not perform calculations for air gaps greater than 5 cm and a warning message is displayed.

The photon dose model in Varskin 3 must be used with caution because it has limitations and may be improved in the future. The photon dose model in Varskin 3 treats the source as a point source, regardless of the actual geometry or size. The photon dose is only a function of the radionuclide, the materials between the source and skin, the skin depth, and the target area. Therefore, the photon dose from a Co-60 source to an area of 10 cm² at a skin depth of 7 mg/cm⁻² with no cover or air gap will be the same regardless of the source geometry or size. In addition, the photon dose model is inappropriate for air gaps larger than 5 cm. Although Varskin 3 will not calculate the photon dose for air gaps larger than 5 cm, the user can enter a larger cover thickness with the density of air that could lead to inappropriate results. Varskin will not calculate the photon dose from any source with a dimension greater than 1 mm. In addition, Varskin 3 will not calculate photon dose from a syringe source.

Another limitation of the photon dose model, as discussed in more detail in Section 3.6, is that the photon dose is based on the specific gamma ray exposure constant, Γ, that is calculated when a radionuclide is added to the Varskin 3 library. The value of Γ is strongly dependent on the energy of the photons that are included when it is calculated. Thus, the choice of the photon cutoff energy is a critical parameter when adding radionuclides to the library. In addition, the photon energy cutoff that is appropriate for calculating skin dose is generally not appropriate for calculating deep dose because the range of photons that contribute to skin dose may not be large enough to contribute to deep dose. For many radionuclides, it may be appropriate to create three different library files for a radionuclide: one for skin dose, one for eye dose, and one for deep dose as discussed in Section 3.6. The recommended photon cutoff energies are 2 keV, 20 keV, and 35 keV, for the shallow dose, eye dose, and deep dose, respectively.

Table 5-1 demonstrates the strong dependence of Γ on the cutoff energy using Co-57 as an example by comparing calculated values of Γ to the value published in the Radiological Health Handbook (U.S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service, 1970). These data show that the cutoff energy is a critical parameter when determining the photon dose.

Table 5-1. Specific Gamma Ray Constant Γ, As a Function of Cutoff Energy for Co-57	
Cut-Off Energy (keV)	$\Gamma(R\text{-}cm^2/mCi/h)$
2	14.98
10	1.00
20	0.556
100	0.556
Published Value*	0.9
*U.S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service. Radiological Health Handbook. Rockville, Maryland: U.S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service. 1970.	

6 SPECIAL TOPICS FOR ACCURATE USE OF VARSKIN 3

Varskin 3 is designed to be very flexible while maintaining a high level of accuracy. However, Varskin 3 can be misused, particularly when modeling infinitely large sources (sources with all dimensions greater than the X_{99} distance for these radionuclides). This section describes this possible misuse of Varskin 3 and how to avoid it. 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 3, the tendency is to choose very large dimensions for the source. This approach will result in the calculation of grossly inaccurate doses or zero doses 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 x- and y-side length are then determined using the equation

$$r_{max} = r_{dos} + (X_{99} / \rho_{min})\rho_w \qquad (6\text{-}1)$$

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 used, use the Varskin 3 default value for the density of air (0.001293 g/cm^3). If no cover material is used, use the density of tissue.

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

$$\Delta t_{max} = X_{99}\rho_w / \rho_s \qquad (6\text{-}2)$$

where ρ_s is the source density.

6.2 Maximum Dose to 10 cm^2 From Multiple Contaminations

Determining the maximum dose to the dose-averaging area for multiple contaminations requires multiple calculations and cannot be performed quickly. The calculations also require elements that are not available in Varskin 3 but that can be accomplished with some graph paper and a calculator or a spreadsheet program.

Before attempting to run the offset particle model (Section 2.5), determine the size of the irradiation area directly beneath each of the contaminated areas. Note that the size of sources do 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 there are no overlapping fields 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, choosing the value of the offset 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, a final calculation for each particle using the offset particle model can be performed. An accuracy of greater than 20 percent should not be anticipated.

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APPENDIX A

DATA FROM MICHAEL W. LANTZ FOR THE PHOTON DOSE MODEL

This appendix contains graphs of the data generated by Michael W. Lantz, Arizona Public Service Company, that was used for the photon dose model incorporated in Varskin 3. The methodology for generating the data is provided in Lantz and Lambert (1990) but modified as follows. The photon model was expanded to include a dose-averaging area of 10 cm^2 instead of 1 cm^2 used in the original publication. This area applies to both the calculated photon dose and the charged particle equilibrium (CPE) correction. The equation for the uncorrected photon dose rate averaged over 10 cm^2 in mrad/h per μCi as a function of depth, h, in cm is given by

$$I = \pi\Gamma\left[\ln\left(h^2 + 1.784^2\right) - \ln\left(h^2\right)\right] \tag{A–1}$$

where Γ is the specific photon dose constant, in units of rad-cm^2/μCi/h. The dose rate with the CPE correction included as a function of photon energy, E_p, and depth is given by

$$I_{CPE\ correction} = \sum_0^{1.784} \frac{\pi(R_1^2 - R_2^2)\Gamma}{h^2 + r^2}\left\{1 - \exp\left[139\exp\left(-0.00209E_p\right)\sqrt{h^2 + r^2}\right]\right\} \tag{A–2}$$

where R_2 and R_1 are radii of concentric circles within the circular dose averaging area on either side of r. The quantity (1–CPE fraction) as a function of photon energy was determined from these two equations by subtracting the ratio of Eq. (A–2) to Eq. (A–1) from 1 for a given depth and energy. Figure A–1 shows the family of curves generated for depths below 0.02 cm for photon energies ranging from 200 keV to 1400 keV. Figure A–2 shows the same data obtained for depths greater than 0.02 cm. Note that the trend line through each curve is of the form

$$y = a\exp(-bx) \tag{A–3}$$

The values of a and b for depths that are less than 0.02 cm as a function of energy are plotted in Figures (A–3) and (A–4), respectively. It is possible to fit the data to a function, which is shown on each figure. Figures (A–5) and (A–6) contain plots of a and b for depths that are greater than 0.02 cm, and similar functions are again obtained. It is now possible to write two sets of equations that describe the CPE correction for depths less than and greater than 0.02 cm that are a function of photon energy. These equations are

$$\text{Fraction}_{CPE} = 1 - a\exp(-bh) \tag{A–4}$$

where

$$a = 0.117 + 0.000272E_n, b = 170\exp\left(-0.001465E_n\right) \tag{A–5}$$

for d < 0.02 cm and

$$a = 0.0458 + 0.000267E_n, b = 147\exp\left(-0.00166E_n\right) \tag{A–6}$$

for d > 0.02 cm. As an example, the CPE fraction as a function of photon energy for a depth of 0.007 cm is shown in Figure (A–7).

Reference

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.

The equations shown in the plot are:

$y = 0.5061e{-}22.217x$
$y = 0.4753e{-}25.546x$
$y = 0.46e{-}27.407x$
$y = 0.4449e{-}29.38x$
$y = 0.4151e{-}33.786x$
$y = 0.3859e{-}38.887x$
$y = 0.3573e{-}44.832x$
$y = 0.3294e{-}51.768x$
$y = 0.3023e{-}59.923x$
$y = 0.276e{-}69.555x$
$y = 0.2508e{-}80.957x$
$y = 0.2266e{-}94.526x$
$y = 0.2036e{-}110.75x$
$y = 0.1818e{-}130.22x$

Legend: 200 keV, 300 keV, 400 keV, 500 keV, 600 keV, 700 keV, 800 keV, 900 keV, 1,000 keV, 1,100 keV, 1,200 keV, 1,250 keV, 1,300 keV, 1,400 keV

Axis: 1 - CPE Fraction vs Depth (cm)
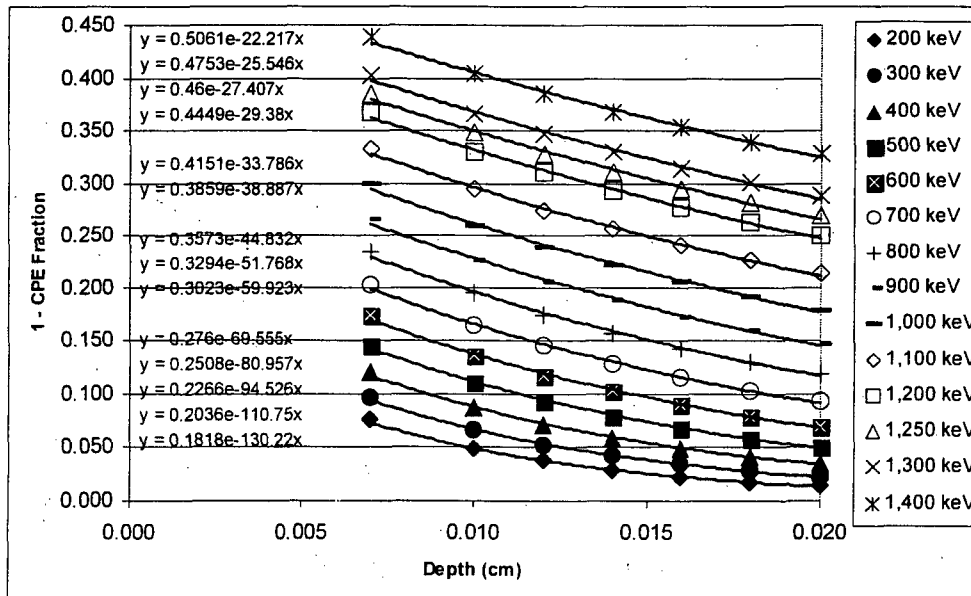
Figure A–1. 1–CPE Fraction as a Function of Depth for 14 Photon Energies. The Depth for These Data Range From 0.007 cm to 0.02 cm.
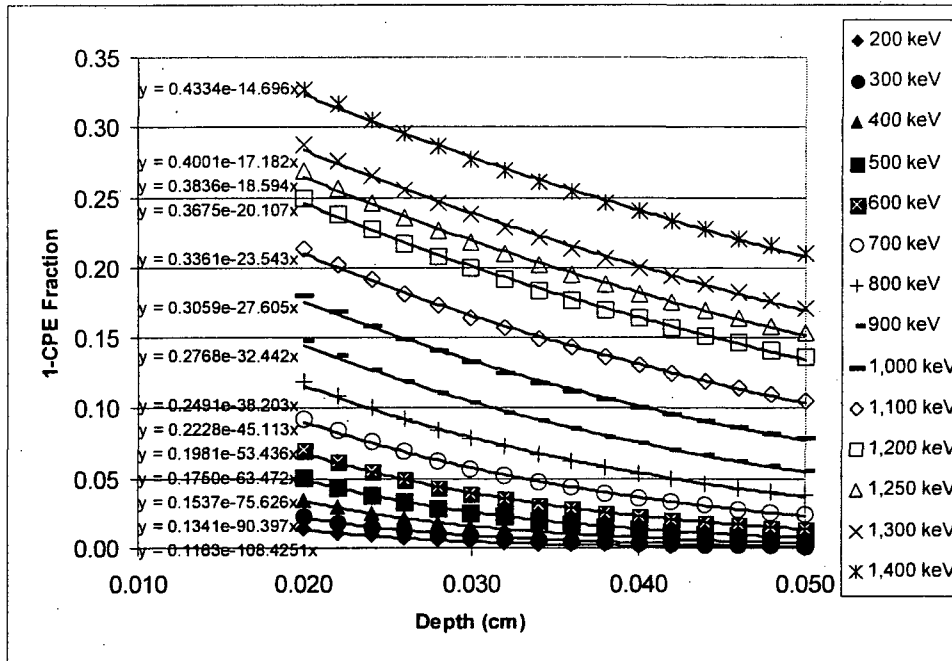
Figure A–2. 1– CPE Fraction as a Function of Depth for 14 Photon Energies. The Depth for These Data Range From 0.02 cm to 0.05 cm, Although the Actual Data Extend to Depths of 0.514 cm.

Figure A–3. The Parameter *a* as a Function of Energy for Depths Below 0.02 cm

A–3

Figure A–4. The Parameter *b* as a Function of Energy for Depths Below 0.02 cm

Figure A–5. The Parameter *a* as a Function of Energy for Depths Greater Than 0.02 cm

A–4

$$b = 147e^{-0.00166E}$$

Figure A–6. The Parameter *b* as a Function of Energy for Depths Greater Than 0.02 cm

Figure A–7. CPE Fraction as a Function of Energy for a Depth of 0.007 cm

A–5

APPENDIX B

EXAMPLES AND SOLUTIONS USING VARSKIN 3

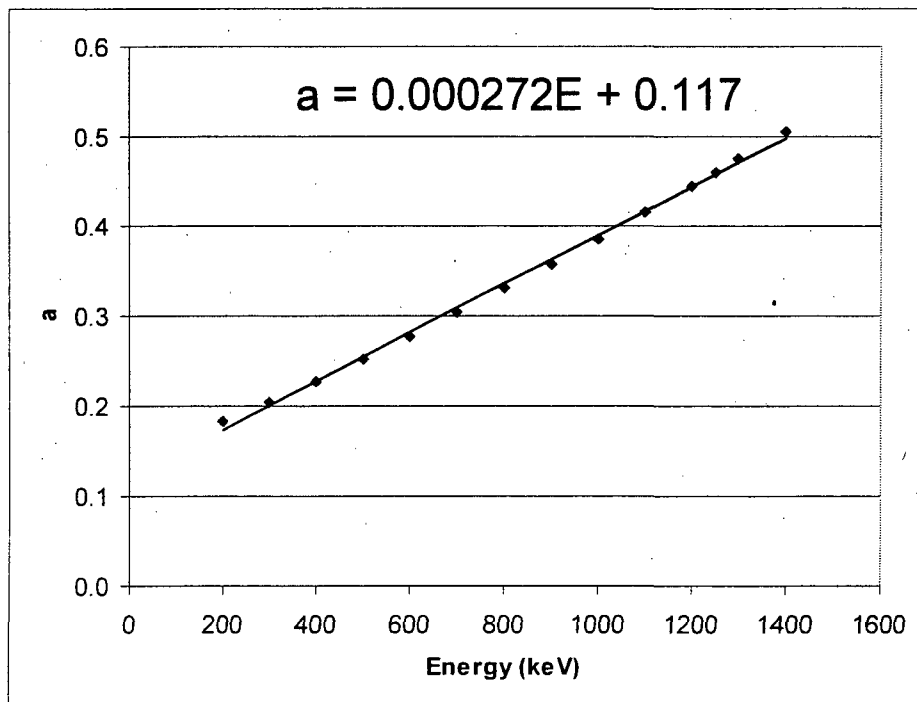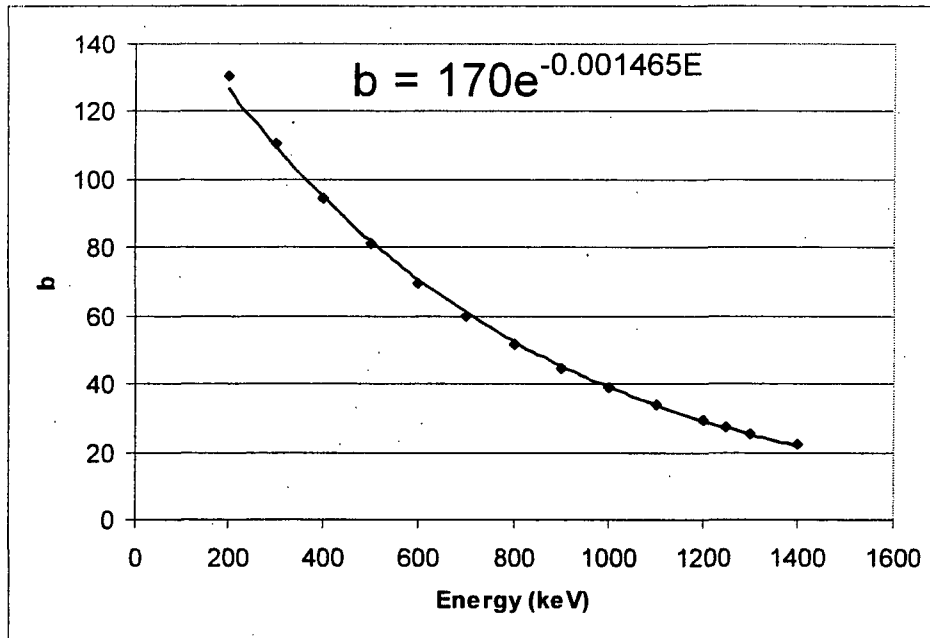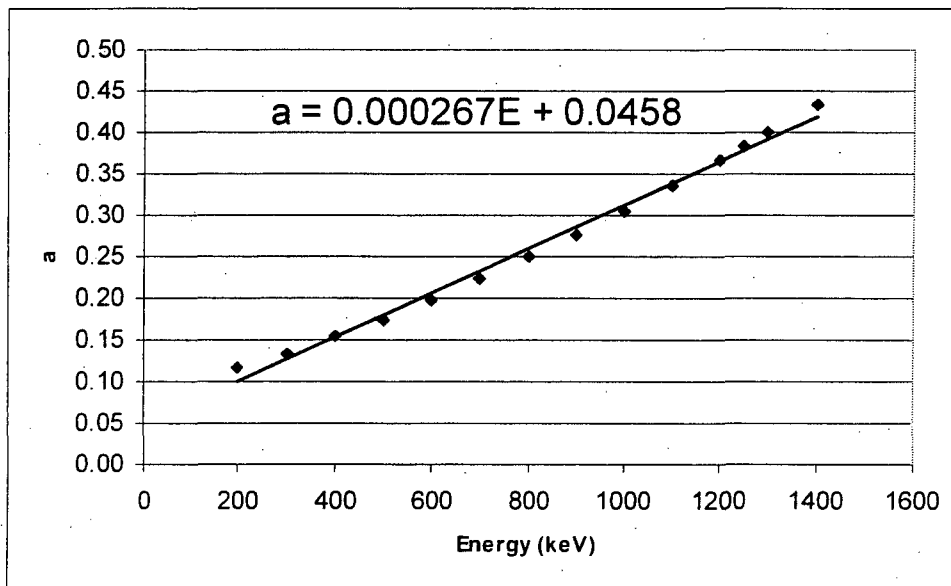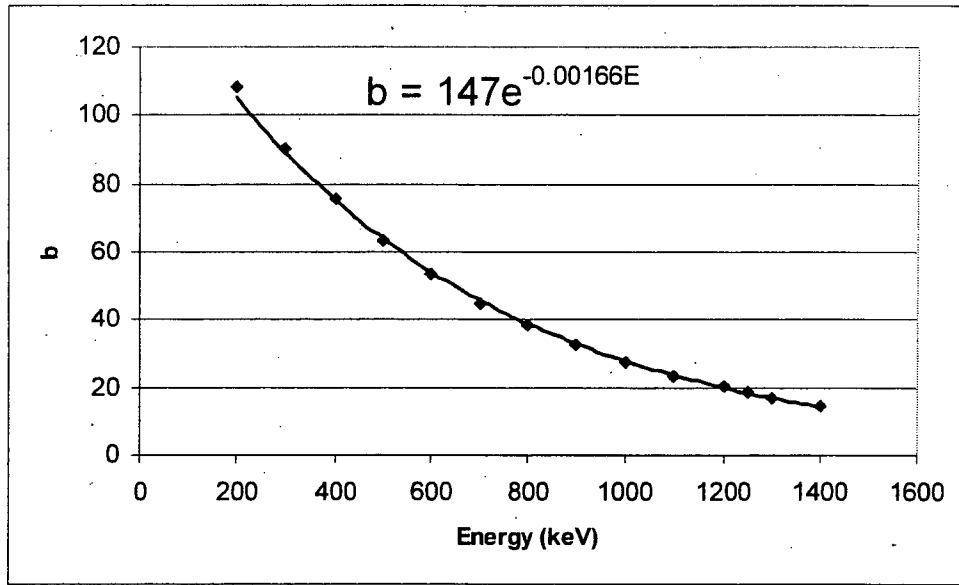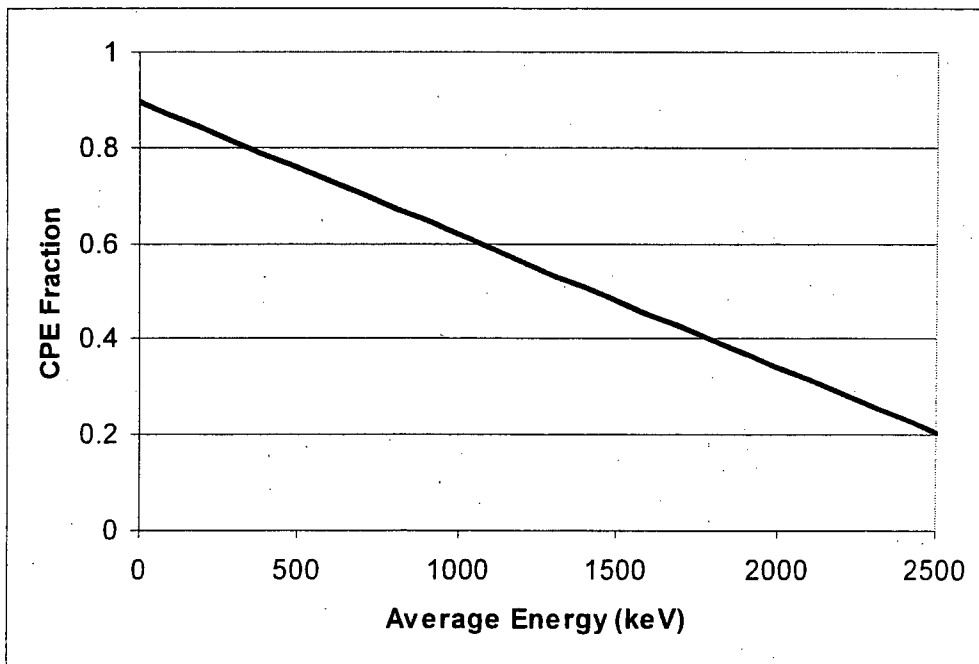This appendix describes three different practical applications of Varskin 3 using a example/solution format. Each example describes a situation followed by a solution that involves using Varskin 3 to calculate skin dose and deep dose equivalent. The purpose of these examples is to lead a new user of Varskin through several calculations that highlight many of the features of Varskin 3. Because Varskin 3 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 3 users will not need to perform all of the steps that are described in the solution in an actual situation. It is suggested that all three examples be completed in the order they are presented to develop familiarity with Varskin 3.

Example 1: Radiopharmaceutical Technician in Nuclear Medicine

At a research hospital, a doctor prescribed a 5 ml dose from a stock solution containing 10 µCi/ml of rhenium (Re)-186 for a clinical research study at 1:00 p.m. that day. Around 12:30 p.m., a lab technician was loading the dose under the hood, a fellow employee bumped into her, and the needle slipped out of the container. The entire 5 ml of the dose was spilled on the arm of her cloth lab coat in a uniform circular shape about 50 cm^2 in area. She was unaware of the accident and continued with her work until the end of the day around 5:00 p.m. Before she left work, a routine survey for contamination was performed and the contamination was discovered.

Solution 1: Radiopharmaceutical Technician in Nuclear Medicine

First, use the point source geometry to estimate the magnitude of the dose and to collect some other useful information. Start Varskin 3 and proceed to the Source Geometry screen. If Re-186 does not appear in the Radionuclide Library frame, Add Re-186 by selecting the "Add" button and double-clicking on Re-186 on the Add Radionuclide to Library screen. Enter the Exposure Time as 4.5 and change the unit to hours (hr) 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 dose (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 on the Re-186 library entry. When Varskin 3 asks for a source strength, enter 50. All other entries should retain their default values. Click on "Calculate Doses" and shortly the Varskin 3 Results screen will appear. Print the results of the calculation.

The Varskin 3 Results screen displays nine dose or dose rate 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 assumes that either the source has a very long half life or that the radionuclide is in secular equilibrium with its parent. The printout provides additional information about the source, including the half life of Re-186, the average photon energy, and the specific photon dose constant. 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 3 Results screen or the printout will show that the decay-corrected total dose is 136 rad, a value that exceeds regulatory limits. The results also indicate that there is a gamma component to the dose, so a deep dose calculation is warranted. Next, generate a library file for deep dose (see the discussion in section 2.2.2 for details) by returning to the Source

Geometry screen and selecting Add on the Radionuclide Library frame. Change the Photon Minimum Energy (keV) to 35 and double click on Re-186. When prompted to cancel, select "No" then choose the name Re-186d as the name of the library file. Add Re-186d to the list of selected radionuclides, set the activity to 50 μCi, and click on "Calculate Doses." From the results screen, print out the results. Compare the two values for the Specific Photon Dose Constants to see that the choice of cutoff energy does not affect its value because Re-186 does not emit any photons with energies below 35 keV that have a yield above 1 percent. Therefore, the entry for Re-186d can be removed from the Selected Radionuclides frame by highlighting the name and clicking on "Remove." Re-186d can also be permanently removed from the Radionuclide Library by clicking on "Remove."

Because the photon dose model in Varskin 3 treats photon sources as point sources, it is not possible to use the disk or cylinder models to calculate photon dose. The point source calculation is the only way to estimate the photon dose in this example. 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 mg/cm^2, and click on "Calculate Doses." The Varskin 3 Results screen displays a decay-corrected photon dose of 9.67 mrad.

The beta dose calculated using the point geometry was above regulatory limits. However, it should be obvious that the situation described in this example will be more accurately modeled using the disk or cylinder geometries. A more realistic 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. You must now re-enter the exposure time as 4.5 hr. Next, enter the Source Area as 50 cm^2. Note that the Source Diameter is automatically calculated to be 7.98 cm (this value will be needed for the next model). After clicking on "Calculate Doses," an error may appear that warns the user that the photon dose model only applies to sources with dimensions less than 1 mm and asks if the user wishes to proceed. If "Yes" is clicked, the calculation continues and the results screen shows a decay-corrected dose of 27.1 rad. 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 mm and a density of 0.9 g/cm^3. After returning to the Source Geometry screen, choose "Cylinder" in the Source Geometry frame. Previously-entered geometry data will return to the default values, so the Exposure Time must be re-entered as 4.5 hours. Enter the Source Diameter as 7.98 cm (from the disk calculation) and enter the Source Thickness as 0.4 mm (the thickness of the lab coat), and enter the Source Density as 0.9 g/cm^3 (the density of the lab coat). Click on "Calculate Doses" and after a short delay the Varskin 3 Results screen will display 16.6 rad as the decay-corrected beta dose.

It is interesting to look at 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 Source Geometry screen and change the geometry to the "Disk" source. Enter the Exposure Time as 4.5 hr, then enter the source area as 50 cm^2. Enter a Cover Thickness of 0.2 mm and a density of

0.36 g/cm^3. After clicking on "Calculate Doses" the Varskin 3 Results screen will display a total decay-corrected dose of 19.5 rad. It can be concluded that, based on the above calculations, using 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: cobalt (Co)-60
- Source strength: 2.5 mCi
- Particle thickness: 50 μm
- Particle size: 80 μm × 70 μm
- Glove thickness: 0.3 mm
- Glove density: 0.6 g/cm^3

The density of the particle is assumed to be 8.3 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 Varskin 3 and proceed to the Source Geometry screen. If Co-60 does not appear in the Radionuclide Library frame, add Co-60 by selecting the "Add" key and double-clicking on Co-60 on the Add Radionuclide to Library screen. Enter an Exposure Time of 15 minutes. Double-click on Co-60 in the Radionuclide Library and enter 2.5 mCi. Enter a Cover Thickness of 0.3 mm and a Cover Density of 0.6 g/cm^3. After clicking on "Calculate Doses," the Varskin 3 Results screen will display a photon dose of 18.9 rad and a total dose rate of 51.3 rad, which is above 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 taken into effect. As described in section 2.2, the cylinder model should be used for a particle that is known to be rectangular. Because the source does not have any dimensions larger than 1 mm, Varskin 3 will allow the cylinder model to calculate both shallow dose and deep dose. Return to the Source Geometry screen and choose the "Cylinder" source geometry. Enter 15 min as the Exposure Time, 50 μm as the Source Thickness, 0.3 mm as the Cover Thickness, and 0.6 g/cm^3 as the Cover Density. The diameter of a source with the same area as the rectangular source is found from Eq. (B–1)

$$d = 2 \cdot \sqrt{(x \cdot Y / \pi)} = 2 \cdot \sqrt{(80\mu m \cdot 70\mu m / \pi)} = 84\mu m \qquad \text{(B–1)}$$

Enter 84 μm for the Source Diameter and 8.3 g/cm^3 for the Source Density, then click on "Calculate Doses." The Varskin 3 Results screen will display a photon dose of 18.9 rad and a

total dose of 27.2 rad. Including the effects of self shielding greatly reduced the beta dose and resulted in a dose that is below regulatory limits. To calculate deep dose, simply return to the Source Geometry screen, change the Skin Thickness or Skin Density Thickness to 1,000 mg/cm², and click on "Calculate Doses." The Varskin 3 Results screen will display a deep dose of 3.38 rad.

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 an aluminum plate inside the hood that is contaminated. Upon further investigation it was 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 as low level radioactive waste and that the activity of C-14 on the plate must be determined. The plate is 6 in. by 6 in. and is uniformly contaminated over the entire surface. The RSO uses a calibrated circular Geiger-Muller "pancake" probe with an area of 50 cm² and a window thickness of 3 mg/cm² 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 3 for applications other than skin contamination events. In this situation the skin averaging area will be set to 50 cm² to correspond to the area of the probe, the skin density thickness will be set to 3 mg/cm² to correspond to the thickness of the probe window, and the Source Area will be set to 36 in² to correspond to the area of the contaminated plate. A source strength of 1 μCi/cm² 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 3.

For this solution, choose the Disk geometry. If the Radionuclide Library dose not contain C-14, add it by clicking on Add and double-clicking on 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 Source Geometry screen, click the "Use Distributed Source" checkbox. Notice that the default unit for activity is now μCi/cm². Double click on C-14 and set the source strength to 1 μCi/cm². Set the Skin Averaging Area to 50 cm², the Skin Thickness or Skin Density Thickness to 3 mg/cm², and the Source Area to 36 in². For this example the dose rate is of interest so the irradiation time can remain at the default value of 60 min. Click on "Calculate Doses" and shortly the Varskin 3 Results screen will appear displaying an initial dose rate of 4.68 rad/h [4,680 mrad/h]. The activity concentration on the plate can be found from the following equation

$$\frac{[A_{ACT}]}{[A_{CAL}]} = \frac{\dot{D}_{MEAS}}{\dot{D}_{CAL}} \qquad (B-2)$$

Therefore the activity concentration on the plate is given by Eq. (B–3)

$$\left(1\,\mu\text{Ci / cm}^2\right)*\left(190\,\text{mrad / h}\right) / 4680\,\text{mrad / h} = 0.04\,\mu\text{Ci / cm}^2 \qquad \text{(B–3)}$$

Multiplying the activity concentration by the area of the plate (6 in × 6 in = 232 cm²) results in a total activity of 9.3 µCi.

The measurement at a distance of 1 in. can be used to verify this result. Return to the Source Geometry screen and enter an Air Gap Thickness of 1 in. After clicking on "Calculating Doses" the Varskin 3 Results screen will display an initial dose rate of 1.43 rad/h. Comparing this dose rate to the measured dose rate gives an activity concentration of

$$\left(1\,\mu\text{Ci / cm}^2\right)*\left(60\,\text{mrad / h}\right) / 1430\,\text{mrad / h} = 0.04\,\mu\text{Ci / cm}^2 \qquad \text{(B–4)}$$

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.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

The computer code VARSKIN Mod 2, which calculates skin dose from radioactive skin contamination, has been significantly modified. The new code, Varskin 3, operates in a Windows environment and is significantly easier to learn and use than VARSKIN Mod 2. Six different predefined source configurations are available: point, disk, cylinder, sphere, slab, and syringe. Improvements in Varskin 3 include a backscatter correction for three-dimensional sources, an upgraded photon dose model, air gap and cover material models. The default area for skin dose calculations has been changed to 10 cm square to conform to a recent regulatory requirement pursuant to 10 CFR 20.1201(c), but the area can be changed by the user. Data entry for the code has been condensed to a single screen, and the user does not need to enter the data in any particular order. In addition, adding radionuclides to the library has been greatly simplified; the user merely needs to select the radionuclide name for the radionuclide to be added to the library. The library file also contains data on photons, internal conversion electrons, and Auger electrons. Finally, an extensive, context-sensitive help file is available to provide guidance in the use of Varskin 3.

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