

# Varskin 3: A Computer Code for Assessing Skin Dose from Skin Contamination

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**{PRIVATE }ABSTRACT{tc \l 1 "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<sup>®</sup> environment and is designed to be significantly easier to learn and use than VARSKIN Mod 2. Six different geometry packages are available: point, thin disk, thick disk, sphere, slab, and syringe, a model that was not available in VARSKIN Mod 2. Varskin 3 includes upgraded backscatter correction and gamma dose models, air gap and cover material models, and the default area for skin dose calculations has been changed to 10 cm<sup>2</sup> to conform to recent regulatory guidance. Data entry for the code has been condensed to a single page 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 SI 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 has also been simplified. All of the features that were available with VARSKIN Mod 2 are available in Varskin 3. 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. In addition, SADDE Mod 2 did not include the contribution to dose from beta particles below 50 keV, which affected the accuracy of the dose calculations at skin depths below 7 mg/cm<sup>2</sup>. In Varskin 3, the user merely needs to select the radionuclide name and the radionuclide is 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 customize the 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 new code, Varskin 3, including installation and operation instructions, provides detailed descriptions of the models used, and suggests methods for avoiding misuse of the code.

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## CONTENTS

	<i>Page</i>
Abstract .....	ii
Acknowledgements .....	iii
1 Introduction .....	1
1.1 Background .....	1
1.2 Corrections to Errors in VARSKIN Mod 2 .....	2
1.3 New Features in Varskin 3 .....	3
2 Varskin 3 User's Manual .....	5
2.1 Installing Varskin 3 .....	5
2.2 Running Varskin 3 .....	5
2.2.1 Adding Radionuclides to the Library .....	6
2.2.2 Selecting Radionuclides from the Library .....	7
2.2.3 Geometry Options and Multiple Cover Calculator .....	8
2.2.4 Special Options .....	10
2.2.5 Calculating Doses .....	11
2.2.6 Output Screen .....	11
2.2.7 Exiting Varskin 3 .....	13
3 Validations and Verification of Varskin 3 .....	14
4 Description of Calculational Models .....	17
4.1 Beta Dose Calculations .....	17
4.2 Backscatter Model .....	18
4.3 Cover Layer and Air Gap Models .....	21
4.4 Volume-Averaged Dose Model .....	22
4.5 Offset Particle Model .....	22
4.6 Photon Dose Model .....	22
4.7 Building Radionuclide Library Files .....	23
5 Special Topics for Accurate Use of Varskin 3 .....	26
5.1 Infinite Sources .....	26
5.2 Maximum Dose to 1 cm <sup>2</sup> from Multiple Contaminations .....	26
6 References .....	27

## FIGURES

2.1 Opening Screen .....	5
2.2 Geometry Screen (Slab Source Screen Shown) .....	5
2.3 Geometry Option Box from the Geometry Screen .....	6
2.4 Radionuclide Library List Box .....	7
2.5 Add Radionuclide Screen .....	7
2.6 Slab Source Geometry Parameters .....	8
2.7 Schematic Showing the Cover Material and Air Gap Models .....	9
2.8 Composite Cover Calculator Screen .....	10
2.9 Special Options Subscreen .....	10
2.10 Schematic Diagram of the Volume-Averaged Dose Model Geometry .....	11
2.11 Schematic Diagram of the Offset Particle Model .....	11
2.12 Results Screen for Non-Volume Averaged Calculation .....	12
2.13 Results Screen for Volume Averaged Calculation .....	12
2.14 Exit screen .....	13
4.1 Schematic Representation of a Dose Calculation for a Symmetric Source .....	18
4.2 Backscatter Correction Factor for Infinitely-Thin and Point Sources .....	19

4.3	Geometry Used for MCNP Calculations for the Backscatter Model .....	19
4.4	Ratio of Flux in Water to Flux in Air for <sup>147</sup> Pm .....	20
4.5	Ratio of Flux in Water to Flux in Air for <sup>90</sup> Sr .....	20
4.6	Ratio of Flux in Water to Flux in Air for <sup>204</sup> Tl .....	20
4.7	Ratio of Flux in Water to Flux in Air for <sup>90</sup> Y .....	20
4.8	Combined Data for the Four Radionuclides .....	20
4.9	Schematic Drawing of a Generic Dose Calculation Performed by Varskin 3 for the Three-Dimensional Disk Geometry .....	21

## TABLES

2.1	Default Values and Units for Geometry Parameters .....	9
2.2	Suggested Values for Cover Thickness and Density .....	9
3.1	Comparison of Chabot's Method and VARSKIN Mod 2 for 1-μCi Hot Particle Point Source on Cover Material .....	15
3.2	Comparison of Calculated Skin Dose Rates for a 1-μCi Hot Particle on the Skin .....	15
3.3	Comparison of Calculated Beta Skin Doses for Distributed Contamination of 1 μCi cm <sup>-2</sup> Averaged over 100 cm <sup>2</sup> on the Skin .....	15
3.4	70 μm Depth Dose Coefficients in rad-cm <sup>2</sup> -μCi <sup>-1</sup> -h <sup>-1</sup> .....	16
3.5	Dose Coefficients Versus Depth for <sup>90</sup> Y Averaged Over 0.01 cm <sup>2</sup> in rad-cm <sup>2</sup> -μCi <sup>-1</sup> -h <sup>-1</sup> .....	16
4.1	Radioactive Characteristics of the Sources Modeled for the Backscatter Correction .....	19

# 1 INTRODUCTION

This section describes the problems that were identified in Varskin Mod 2 and the new features that are included in Varskin 3.

## 1.1 Background

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 an infinitely thin layer of radioactive material distributed over an area or at a single point on the skin. Soon after the release of VARSKIN, a "new" type of skin contaminant was encountered in the industry. This contaminant consists of discrete microscopic radioactive particles, called "hot" particles. These particles differ radically from uniform skin contamination in that the particles have a thickness associated with them and many of the exposures result from particles on the outside of protective clothing. Since no other option for calculating skin dose from hot particles was readily available, skin dose calculations from hot particles were performed using VARSKIN.

Calculating skin doses from hot particles using VARSKIN had three primary drawbacks. First, VARSKIN modeled the contaminant as having no thickness; thus, source self-shielding is not taken into account in the calculation. For many hot particles consisting of the weak beta-emitting radionuclide  $^{60}\text{Co}$ , VARSKIN greatly overestimates calculated skin doses, including particles that are thicker than about 1  $\mu\text{m}$ . Second, VARSKIN does not model a cover material such as protective clothing that is sometimes between the source and skin, again leading to an overestimate of skin dose from beta-emitting fuel particles. 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, most importantly, the thickness of cover material increase. Since VARSKIN does not model cover material, the gamma dose is not generally

significant and no gamma dose model was included. Thus, an upgrade of VARSKIN was needed to provide accurate skin dose calculations.

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 (thick disks, spheres, and slabs), modeling of materials placed between the source and skin (including air gaps), modeling of hot particle gamma doses in certain cases, and methods to model multiple hot particles and volume-averaged doses. VARSKIN Mod 2 also used a correction for backscatter for one- and two-dimensional sources in certain cases. In addition, the VARSKIN Mod 2 package incorporated a user interface that greatly simplifies data entry for calculating skin dose in addition to providing guidance in the form of help screens.

VARSKIN Mod 2 included models for particle self-shielding and attenuation by cover material and air gaps. Also included in the upgraded code were volume averaging and offset particle models. The volume-averaging model allows the user to calculate the dose averaged over a volume defined by two different skin depths instead of the dose at one given depth. The offset particle model, which allows dose to be calculated for a particle that is not centered over the dose area of interest, is useful for calculating dose from multiple hot particles. Finally, the operation of VARSKIN Mod 2 was facilitated by a user interface with on-line help and the capability to use composite source terms that allow a user to calculate the total dose from a mixture of beta-emitters in the same amount of time required for one radionuclide. However, the inclusion of multiple sources in a single library entry added unexpected confusion as to whether progeny radionuclides were included with the parent radionuclide.

## 1.2 Corrections to Errors in VARSKIN Mod 2

In the 12 years since the release of VARSKIN Mod 2, several changes and errors have been identified and industry users have made many suggestions for improvement. VARSKIN Mod 2 calculated the dose averaged over 1 cm<sup>2</sup> of skin as the default value. The NRC has proposed a new uniform skin dose limit that requires determining the dose averaged over an area of 10 cm<sup>2</sup> for comparison against the 50 rad limit for both point and distributed sources. Varskin 3 calculates the dose to 10 cm<sup>2</sup> as a default for comparison to the 50 rad limit. Varskin 3 also contains the capability of calculating the dose to 1 cm<sup>2</sup> to evaluate an exposure against the eye dose limit.

VARSKIN Mod 2 was designed to operate efficiently on a personal computer containing an 80286 processor; consequently, several approximations and limitations in the calculational methodology were incorporated into the code to allow the dose calculations to be completed in a reasonable length of time. These approximations and shortcuts did not significantly affect the accuracy of doses at a depth of 7 mg/cm<sup>2</sup> averaged over 1 cm<sup>2</sup> 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 approximations. In addition, the user interface in VARSKIN Mod 2 requires the user to enter radionuclide data repeatedly even when the source and target geometry remained the same for each radionuclide. With the advent of powerful personal computers and windowing capabilities of current operating systems, calculational approximations 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 non-typical applications of the code and several errors were identified. A presentation summarizing the errors and their impact on dose calculations was made at the 2000 Annual Meeting of the Health Physics Society (Chase et al., 2000). 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.

**Source Density:** The source density for point and 2-D calculations is defined by the last calculation using a 3-D geometry and is not reset to 0.001 g/cm<sup>3</sup> as intended. **Solution:** The source density is reset to 0.001 g/cm<sup>3</sup> when point and 2-D models are used for calculations.

**Backscatter Correction:** The backscatter correction is only included for point and 2-D geometries when the dose is averaged over 1 cm<sup>3</sup>. **Solution:** The backscatter correction model has been expanded to include 3-D sources and is applied regardless of the dose-averaging area.

**Low Results for Small Sources:** Point source calculations were found to be 7% lower in comparison to a 20 µm diameter 2-D disk and results for small 3-D sources were found to be up to 29% lower. **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 Averaging 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  $\mu\text{m}$  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  $^{60}\text{Co}$  (318 keV). Solution: Varskin 3 evaluates the dose at 50 depths for volume averaging instead of 20 points. Once the 50 point distribution is calculated, the distribution is evaluated over 10,000 points to increase the accuracy and eliminate oscillating results.

**Volume Averaging Backscatter Correction Factor:** A single backscatter correction factor is used at all skin depths for volume averaging in VARSKIN Mod 2. The backscatter correction factor is the one for the skin depth 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 Gamma Dose Calculations:** A programming error in the gamma 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 creating 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.

### 1.3 New Features in Varskin 3

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

**Anomalies in Radial Dose Distributions:** The radial dose distribution exhibited unexpectedly large dips and peaks (e.g., a 13010- $\mu\text{m}$  diameter  $^{210}\text{Bi}$  2-D disk source gives results that are approximately 50% low when the dose calculation radius is 1.0271 cm]. 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.

**Incorrect Dose Calculation for Small Target Areas, Low Energy Betas & Large Sources:** For large 3-D sources with 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  $^{35}\text{S}$  3-D disk source with a diameter of 34,000  $\mu\text{m}$  and a thickness of 200  $\mu\text{m}$  thick and a source density-thickness 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 large distances to become negative. 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.

**Improved Gamma Dose Model:** The gamma dose model in VARSKIN mod 2 was limited to a dose area of 1 cm<sup>2</sup>. The gamma dose model is inadequate for determining either shallow dose or deep dose equivalent (DDE) at the newly recommended dose-averaging area of 10 cm<sup>2</sup>. **Action:** An improved gamma dose model was incorporated into Varskin 3 that calculates the gamma dose to any area smaller than 10 cm<sup>2</sup>. The new model is based on data provided by Mike Lantz (Durham and Lantz, 2004).

**More Accurate Beta Spectrum Information:** The Specific Absorbed Dose Distributions used by VARSKIN Mod 2 were calculated from basic nuclear data. In Varskin 3, beta spectra are obtained directly from ICRP-38 data using Radecay data files. This improves the reliability of the library files in Varskin 3 and results in more reliable dose calculations. This also corrects a problem with modeling positron sources that existed in VARSKIN Mod 2.

**Poor Results from Internal Conversion (IC) and Auger Electrons at High Energies:** IC 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 the use of a cubic spline to fit data that is rapidly changing, resulting in an oscillation or “ringing” of the fit. Ringing leads to inaccurate results. **Solution:** Varskin 3 performs a log-transformation prior to applying the cubic spline to fit the data.

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<sup>®</sup> compatible to allow the user to enter data more efficiently. The second most common suggestion is to make adding radionuclides to the library easier. Postings to

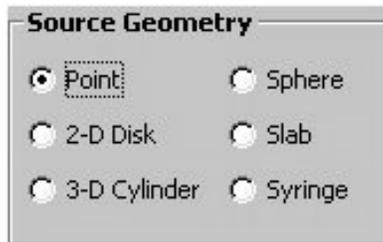
the Internet bulletin board service RADSAFE, which serves as a forum for health physics professionals to discuss pertinent topics and to share information, indicate a need for calculating the deep dose equivalent from skin contaminations. ICRP 60 and NUREG/CR-6204 require calculation of the deep dose equivalent. Varskin 3 includes the capability to calculate the deep dose equivalent from gamma-emitting radionuclides in accordance with recommendations and regulations.

With the release of the operating system Windows XP<sup>®</sup>, the Microsoft Corporation has eliminated its support of DOS. VARSKIN Mod 2 operates under the DOS operating system, and when DOS is eliminated from Windows<sup>®</sup>, operation of VARSKIN Mod 2 will no longer be possible. Varskin 3 was, therefore, written to operate under the Windows<sup>®</sup> 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 (Oak Ridge National Laboratory 1995), which uses data published in ICRP 38 (1983). Further information in the library files includes data for gamma dose calculations and contributions from internal conversion and Auger electrons.

Section 2 of this report describes the contents of the Varskin 3 code packages, including instructions for installing each package on a personal computer and for running the package. Section 3 will eventually contain the validation and verification for Varskin 3. Section 4 discusses the technical basis for Varskin 3 and describes the new models incorporated in the code. Finally, Section 5 explains the correct method for modeling “infinite” sources and how to calculate the maximum dose to 1 cm<sup>2</sup> from multiple contaminations.





**Figure 2.3 Geometry Option Box from the Geometry Screen**

The spherical geometry model is perhaps the simplest three-dimensional geometry to use because it requires knowledge of only one source dimension: the sphere diameter. The sphere model 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. The air surrounding the sphere does not shield the source particles as efficiently as in the disk and slab models, and the average path length within a spherical source is at a minimum; therefore, doses calculated using the spherical model will be consistently higher than those calculated using the other models. Because radioactive particles seldom resemble spheres, this model is of more limited utility than the other two models.

The three-dimensional disk model requires knowledge of two dimensions: the disk diameter and the disk thickness. The disk model assumes that the source is surrounded by air but that the entire bottom of the disk is in contact with skin or cover material. This model requires the same amount of time to execute as the spherical model but offers a more practical application. Of the two disk source dimensions, the calculated dose is much more sensitive to changes in the disk thickness than in the disk diameter.

The three-dimensional slab geometry model requires knowledge of three physical dimensions: the x-side length, the y-side length, and the thickness. The slab model requires 2 to 5 times more execution time than the three-dimensional disk and sphere models, and the accuracy of the calculation is significantly lower. The 3-D slab geometry model should only be used when skin dose from multiple, discrete particles is needed.

The syringe model is a specialized model that calculates dose from a syringe or other cylindrical object for which the dose to the side of the source is needed.

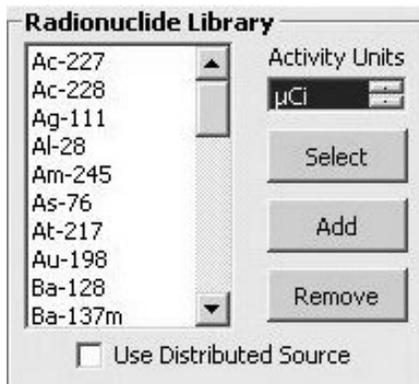
The following general rules should govern the choice of geometry package, progressing from most conservative to least conservative:

- if nothing is known about the particle size and shape, use the point source option
- 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 2-D disk source option
- if the thickness and the diameter can be estimated but the shape is not known, use the 3-D disk source option because this geometry requires only two dimensions (thickness and radius) to describe the particle
- if the particle is known to be spherical and is not imbedded in another material, use the sphere source option
- if the particle is known to be rectangular, use the 3-D disk source geometry. The thickness of the particle should be maintained and the area of the contact surface should be equivalent. This option requires less time to run than the slab source model and is more accurate

### 2.2.1 Adding Radionuclides to the Library

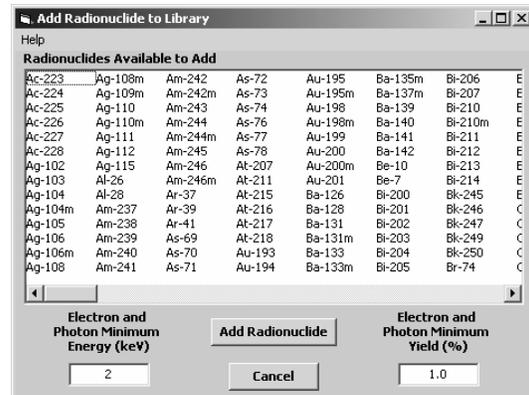
When Varskin 3 is first installed, no radionuclides will appear in the library. Varskin 3 is designed to allow the user to customize the radionuclide library so that only those radionuclides of interest are included. To add a radionuclide to the library, the user clicks on the "Add" button (shown in Figure 2.4) and a new screen appears that displays every radionuclide for which data is available (a total of 838 radionuclides) as shown in Figure 2.5.

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 5 or more times depending on the speed of the computer processor and the availability of computer resources. When the process of adding the radionuclide is completed, the Source Geometry screen will return and the added radionuclide will be visible in the list of available radionuclides.



**Figure 2.4 Radionuclide Library List Box**

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. The user may accept the default value of 35 keV for the “Beta and 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 electrons to be included in the radionuclide library file. The user may also accept the default value of 1.0% for the “Beta and Photon Minimum Yield (%)” text box or specify a different value by entering the minimum yield in %. Finally, photon energy and yield data are collected from the data files and the average photon energy and total photon yield is calculated. Finally, these data are processed by the executable file “Sadcalc.exe” and an output file is generated with the extension “.dat” that contains basic nuclide data, the scaled absorbed dose distribution, the average photon energy, the specific gamma ray constant, and the photon yield.



**Figure 2.5 Add Radionuclide Screen**

Choosing the electron and photon minimum energy will affect the accuracy of beta dose calculations if the cutoff value eliminates electrons that would normally contribute to skin dose. Beta dose calculations are not affected if low energy electrons are included in the data file. However, choosing a photon cutoff energy that is too low or too high can have a significant effect on the photon dose. The limited photon dose model used in Varskin 3 calculates dose based on the specific gamma ray constant that reflects a contribution from all photons included in its calculation. When calculating skin dose, 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 equivalent) only photons with energies greater than 20 keV contribute and the deep dose will be overestimated if a cutoff energy lower than 20 keV is chosen. If low-energy photons that do not contribute to skin dose are included in the specific gamma ray constant, the photon dose will be overestimated. If photons that would contribute to skin dose are omitted, then the photon dose will be underestimated.

Radionuclides can be removed from the 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 an existing library entry.

## 2.2.2 Selecting Radionuclides from the 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 2.4). The default unit of

measure for activity is  $\mu\text{Ci}$  (Bq for the international version). Users may change the activity unit by selecting a different unit from the Activity Units list box. When using the arrows to scroll through the unit options, it is necessary to click on the unit in order to select it. The selected unit will have a blue background. The new unit must be selected 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.

For geometry packages other than the point source, the "Use Distributed Source" check box will appear as shown in Figure 2.4. The distributed source option allows the user to enter the source strength in activity/cm<sup>2</sup> for the two-dimensional disk source or activity/cm<sup>3</sup> for three-dimensional sources. The distributed source option only applies to radionuclides that are selected after the checkbox is checked.

### 2.2.3 Geometry Options and Multiple Cover Calculator

The geometry options box, shown in Figure 2.6 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 all source parameters. The selected units will appear with a blue background; users should take care that the proper units are highlighted in blue or unexpected results may be obtained. It is possible to intermix different units for the different parameters. The default values for the various parameters are shown in Table 2.1. The default values are the same for both the standard and the international versions.

In two-dimensional 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 the most sensitive source dimension for calculating dose is the source thickness, and that 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 be made. The following guidelines will help in choosing appropriate values for source dimensions and density:

1. Diameter (2-D and 3-D disks); X-side and Y-side lengths (3-D Slab): The dose calculation for most radionuclides is relatively insensitive with respect to these dimensions for sizes below 1-2 mm. Choosing a larger rather than a smaller value for this dimension will provide a conservative dose estimate.
2. Thickness (3-D disk, 3-D 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 a conservative dose estimate.
3. Source Density (3-D geometries): Choose a source density that is consistent with the radionuclide within the source. For hot particle contaminations, a typical density for stellite (<sup>60</sup>Co) is 8.3 g/cm<sup>3</sup> and for fuel is 14 g/cm<sup>3</sup>.

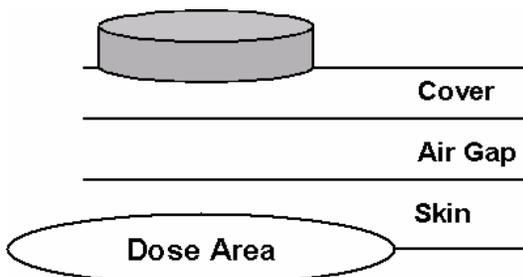
The image shows a software dialog box titled "Slab Source Irradiation Geometry". It contains several input fields with numerical values and unit dropdown menus. The units for "Skin Density Thickness", "Clothing or Cover Density", "X-Side Length", "Y-Side Length", "Source Thickness", and "Source Density" are highlighted in blue. A button labeled "Multiple Cover Calculator" is located below the density field.

Parameter	Value	Unit
Skin Thickness or Skin Density Thickness	7	mg/cm <sup>2</sup>
Air Gap Thickness	0	mm
Clothing or Cover Thickness	0	mm
Clothing or Cover Density	0	g/cm <sup>3</sup>
X-Side Length	1	µm
Y-Side Length	1	µm
Source Thickness	1	µm
Source Density	1	g/cm <sup>3</sup>

Figure 2.6. Slab Source Geometry Parameters

Parameter	Default Value
Skin Density Thickness	7 mg/cm <sup>2</sup>
Air Gap Thickness	0 mm
Cover Thickness	0 mm
Cover Density	0 g/cm <sup>3</sup>
Source Area (disk)	0.785 μm <sup>2</sup>
Source Diameter (disk, sphere, syringe)	1 mm
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 <sup>3</sup>
Syringe Wall Thickness (syringe)	1 μm
Source Density (3-D geometries)	1 g/cm <sup>3</sup>

Users can opt to model the presence of a cover material and/or an air gap. A schematic drawing of the two models is shown in Figure 2.7, which depicts the three-dimensional disk 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 clothing 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 value of 0.001293 g/cm<sup>3</sup> for air density.



**Figure 2.7 Schematic Showing the Cover Material and Air Gap Models**

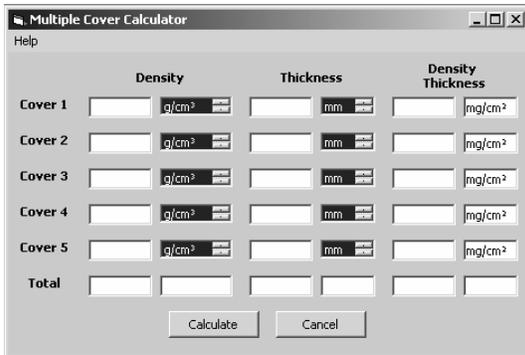
The physical characteristics of the air gap and cover material can significantly affect the calculated skin dose. While the air gap has little effect on material attenuation, its effect on geometric attenuation can be dramatic.

Protective clothing affects both the geometric and material attenuation. Some suggested thickness and density values are given in Table 2.2.

{PRIVATE } Material	Thickness (mm)	Density (g/cm <sup>3</sup> )
Lab Coat (plastic)	0.1	0.036
Cotton Glove Liner	0.3	0.3
Surgeon's Glove	0.5	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	1.0
Coveralls	0.7	0.4

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 2.8. 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 mg/cm<sup>2</sup>. 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<sup>3</sup> and thickness in cm are then automatically entered in the appropriate boxes in the geometry screen.

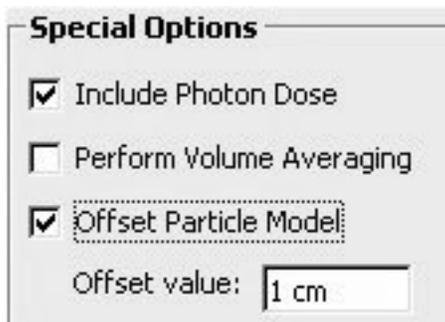
To include more than five covers in the composite cover calculation, the user must calculate the composite cover thickness and density for the first five covers. The user must then run the calculator again and enter the first composite cover thickness and density as one of the layers.



**Figure 2.8 Composite Cover Calculator Screen**

## 2.2.4 Special Options

Depending on the geometry package selected, special options are available that affect the calculation as shown in Figure 2.9. The first option, which is available for all geometry packages, is to include the photon dose in the calculation. The default for this option is to calculate the photon dose, which includes both x- and gamma rays; the user can choose to uncheck the box and 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 0 will be displayed.



**Figure 2.9 Special Options Subscreen**

The Varskin 3 gamma 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. The Varskin 3 gamma dose model, which is described in detail in Section 4, is an extension of a model published by Lantz and Lambert (1990) that was the basis for the VARSKIN Mod 2 gamma dose model. The Varskin 3 gamma dose model is applied to irradiation areas up to 10 cm<sup>2</sup>.

Gamma doses are calculated as if the source was a point source, and the model includes effects due to the incomplete establishment of electronic equilibrium. Electronic equilibrium is established at different depths, depending on the average energy of the gamma photon (or photons) emitted by the particle. At shallow depths (before electronic equilibrium is established), the gamma dose is lower than the dose would be if electronic equilibrium had been fully established. The gamma dose calculation does not significantly increase the calculation time.

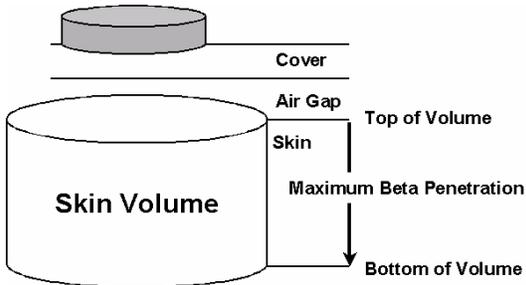
In most cases, the calculated gamma skin dose will be negligible compared to the beta skin dose, usually by several orders of magnitude. A significant exception to this concerns <sup>60</sup>Co. A cover material can easily shield the relatively low energy beta particles from this radionuclide without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

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

The second option allows the dose to be averaged over a volume of tissue defined by two different skin depths instead of the dose at one given depth. An example of the use of volume averaging is evaluating the dose between 10 mg/cm<sup>2</sup> and 15 mg/cm<sup>2</sup> as recommended by the International Commission on Radiological Protection to evaluate dermal effects of skin dose. Volume averaging will greatly increase the calculation time to as much as several minutes for each selected radionuclide.

If volume averaging is chosen, Varskin 3 calculates the dose at 50 depths between a skin depth of zero and the maximum penetration depth of the beta particles, as shown schematically in Figure 2.10. Thus, the volume-averaging model requires up to 50 times more execution time than that for a single depth.

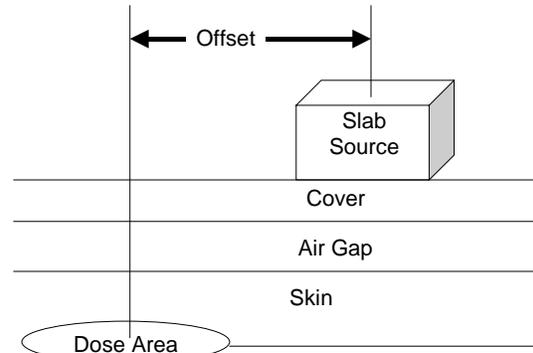
Calculation times in excess of 20 minutes are possible. Prior to performing the calculations, the user is prompted to enter the skin depths corresponding to the top and bottom of the volume. The units of skin depth must be entered in  $\text{mg}/\text{cm}^2$ .



**Figure 2.10 Schematic Diagram of the Volume-Averaged Dose Model Geometry**

When the slab source geometry is selected, the Offset Particle Model checkbox appears in the special options subscreen. The offset particle model, which allows dose to be calculated for a particle that is not centered over the dose area of interest, is useful for calculating dose from multiple hot particles. The 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 particle and the center of the dose area as shown in Figure 2.11. 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 offset particle model can be used to calculate the dose from multiple hot particles. One of the particles is chosen to be the centered particle, and the dose to the dose-averaging area is calculated. The offset for each of the remaining particles is then determined, and the dose to the dose-averaging area is calculated for each particle. The user can then add the contributions from each particle to obtain the total skin dose to the dose-averaging area.



**Figure 2.11 Schematic Diagram of the Offset Particle Model**

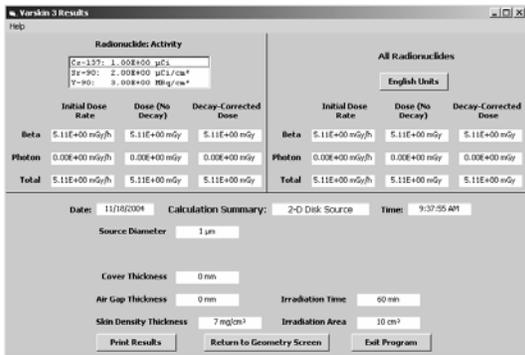
## 2.2.5 Calculating Doses

When the desired geometrical parameters and options are selected, the calculation is initiated by clicking on “Calculate Doses.” 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. 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 background, 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.

## 2.2.6 Output Screen

The output screen is displayed immediately after a calculation is completed as shown in Figure 2.12 for a non-volume averaged calculation. The screen is separated into three distinct sections: results for individual radionuclides (upper left quadrant of screen), combined results for all radionuclides (upper right quadrant of screen), and source input data / code navigation (bottom half of screen).



**Figure 2.12 Results Screen for Non-Volume Averaged Calculation**

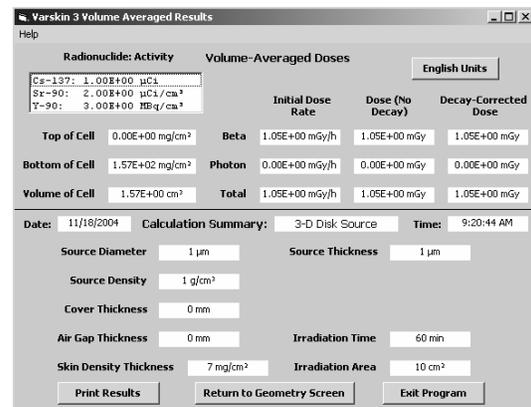
In the individual results section, only the results for the first radionuclide are shown initially. The results from other radionuclides are displayed by highlighting the radionuclide of interest from the list in the list box. Only the contribution to the dose from the selected radionuclide will be displayed 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 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 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 from English units to SI units. Similarly, clicking on the button labeled “English Units” (when SI units are displayed) will switch from SI units to English units. The units will change only for the calculated doses only; the input data will be displayed in the same units that were entered on the geometry screen.

The bottom half of the output screen contains a mirror of the input data that was entered in the 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 allows 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. 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.

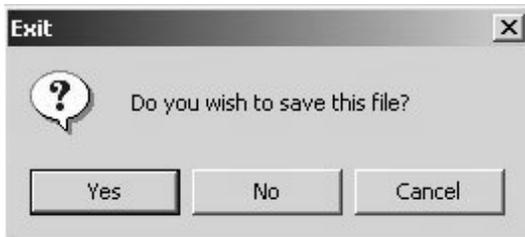
A slightly different screen will appear for volume-averaged dose calculations. Because the dose can be averaged over different averaging areas for different radionuclides, Varskin 3 does not provide a section for combined results of a volume-averaged dose calculation. Instead, only the results from the individual radionuclides are displayed as shown in Figure 2.13. 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 the top and bottom limits of the volume-averaging area 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 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.



**Figure 2.13 Results Screen for Volume Averaged Calculation**

### 2.2.7 Exiting Varskin 3

There are several ways to exit Varskin 3. On the opening screen, clicking on the X box in the upper right corner of the screen will immediately cause the code to stop and exit. On the geometry screen, 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 2.14. 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. When the Yes button is clicked, the user is asked to create a file in which the input data is saved so that the calculation can be recreated. Clicking on the No button will end the calculation and cause the program to exit. Clicking on the Cancel button will return the user to the previous screen.



**Figure 2.14** Exit screen

### 3 VALIDATION AND VERIFICATION OF VARSKIN 3

Several independent users who agreed to test the program in a draft form and compare Varskin 3 results to results obtained using other calculational methods performed verification of Varskin 3. Several users compared the results obtained using Varskin 3 to results obtained using independent methods, and those results are provided in this chapter.

#### 3.1 Point Source on Cover Material

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

- one layer of brown cotton coveralls, of thickness 0.37 mm and density  $0.7 \text{ g cm}^{-3}$  (1B)
- two layers of brown cotton coveralls, double the above thickness (2B)
- one layer of brown coveralls plus one layer of plastic suit material, the latter of thickness 0.4 mm and density  $1.1 \text{ g cm}^{-3}$  (B+P)

The calculations were done for the isotopes  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$ , and  $^{90}\text{Sr/Y}$ , assuming a point source of  $1 \mu\text{Ci}$  of 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 for the third. It was assumed that there was no air gap between layers of protection clothing. Gamma-ray doses were calculated using the analytical expression in Chabot et al. (1988), assuming no attenuation in clothing, no scatter, and  $1 \text{ rem R}^{-1}$ .

The results of these calculations and the same calculations done with Varskin 3 are shown in Table 3.1. In general, there is reasonable agreement between the two calculations for both the beta and gamma dose rate calculations. The largest differences occur for the case of  $^{137}\text{Cs}$  on two layers of cotton coveralls.

#### 3.2 Point Source on Skin

In this test, calculations were done 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  $1 \mu\text{Ci}$  hot particle on the skin, the beta dose rate to  $1 \text{ cm}^2$  at  $7 \text{ mg cm}^{-2}$  was calculated using Varskin 3. For  $^{60}\text{Co}$ , 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 3.2. There is again reasonable agreement among the beta dose rates. The difference in the gamma dose calculation reflects the inclusion of charged particle equilibrium effects in Varskin 3.

#### 3.3 Distributed Contamination on Skin

The final set of calculations was for the case of distributed contamination on the skin. A concentration of  $1 \text{ mCi cm}^{-2}$  over a circular area of  $100 \text{ cm}^2$  was assumed, and the beta dose rate to  $1 \text{ cm}^2$  of skin centered under the contamination was calculated. The calculations were done with Varskin 3 and the results compared with values published by Rohloff and Heinzlmann (1986) and by Kocher and Eckerman (1987). The results from Varskin 3 and Kocher and Eckerman (1987), shown in Table 3.3, agree quite well, while those from Rohloff and Heinzlmann (1986) are somewhat lower because they neglected backscatter from air.

D. Delacroix and J. P. Bourion of Centre D'Études Nucléaires de Saclay compared the results of calculations using Varskin (V) and the work of the following:

- (D): Delacroix 1986
- (K): Kocher and Eckerman 1987
- (P): Piechowski et al. 1988.

These three papers give maximum dose rates (# e) from a source modeled as an "infinitely thick," uniformly contaminated ( $1 \mu\text{Ci/cm}^2$ ) plane surface. Doses were calculated at different depths in the skin. The Varskin 3 input data were

- 2-D disk geometry
- 2 cm diameter
- $3.14 \mu\text{Ci}$  activity

Tables 3.4 and 3.5 show that the results are in good agreement.

Nuclide	Air Gap (cm)	Clothing	Beta Dose Rate (rem h <sup>-1</sup> )			Gamma Dose Rate (rem h <sup>-1</sup> )		
			Chabot et al.	Varskin 3	Diff. (%)	Chabot et al.	Varskin 3	Diff. (%)
<sup>60</sup> Co	0.2	1B	0.203	0.194	-4	0.077	0.0725	-6
	1.0	1B	0.080	0.078	-2	0.011	0.0102	-7
	0.2	2B	0.002	0	-	0.067	0.064	-5
	1.0	2B	0.004	0	-	0.010	0.0096	-4
	1.0	B+P	0	0	-	0.010	0.0095	-5
	5.0	B+P	0	0	-	0.0005	0.0005	0
<sup>137</sup> Cs	0.2	1B	1.33	1.39	+4	0.019	0.020	+5
	1.0	1B	0.295	0.275	-7	0.0027	0.0028	+4
	0.2	2B	0.357	0.474	+32	0.0167	0.0175	+5
	1.0	2B	0.121	0.140	+16	0.0025	0.0026	+4
	1.0	B+P	0.067	0.075	+12	0.0025	0.0026	+4
	5.0	B+P	0.0035	0.0037	+6	0.0001	0.0001	0
<sup>90</sup> Sr/Y	0.2	1B	3.534	3.68	+4			
	1.0	1B	0.596	0.587	-2			
	0.2	2B	2.245	2.38	+6			
	1.0	2B	0.409	0.438	+7			
	1.0	B+P	0.337	0.365	+8			
	5.0	B+P	0.018	0.0185	+3			

Nuclide	Beta Dose Rate (rad h <sup>-1</sup> )		Gamma Dose Rate (rad h <sup>-1</sup> )	
	Varskin 3	Chabot	Varskin 3	Chabot
<sup>60</sup> Co	4.12	4.33	0.185	0.364
<sup>137</sup> Cs	6.36	-	0.075	-
<sup>90</sup> Sr/Y	15.8	-	-	-

Nuclide	Beta Dose Rate (rad h <sup>-1</sup> )		
	Varskin 3	Rohloff and Heinzlmann (1986)	Kocher and Eckerman (1987)
<sup>60</sup> Co	4.07	3.24	4.18
<sup>137</sup> Cs	6.3	-	5.91
<sup>90</sup> Sr/Y	15.7	12.06	15.61

Method	Area	$^{14}\text{C}$	$^{32}\text{P}$	$^{131}\text{I}$	$^{90}\text{Sr}$	$^{90}\text{Y}$
V	1 $\text{cm}^2$	1.08	8.94	6.22	6.67	9.04
	0.1 $\text{cm}^2$	1.08	9.07	6.21	6.60	8.17
	0.01 $\text{cm}^2$	1.08	9.09	6.24	6.65	9.21
	0.001 $\text{cm}^2$	1.07	9.09	6.23	6.73	9.21
	0.0001 $\text{cm}^2$	1.06	9.09	6.23	6.72	9.21
D		1.07	9.15	6.42	6.99	9.18
K		1.22	8.87	6.34	6.76	8.87
P		1.2	7.0	6.0	5.9	7.5

Method	40 $\mu\text{m}$	70 $\mu\text{m}$	100 $\mu\text{m}$	400 $\mu\text{m}$
V	10.6	9.21	8.38	5.18
D	10.46	9.18	8.37	5.24
K	10.14	8.87	-	5.07

## 4 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 that are also described here. First, though, the calculational methodology used in Varskin 3 is described.

### 4.1 Beta Dose Calculations

Varskin 3 calculates beta dose using essentially the same method used in Varskin Mod 2. In general, Varskin 3 performs a 5-dimensional integration of the source volume and the target area. With the exception of the slab and syringe models, 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

$$B(r) = k E_{\beta} Y F_{\beta}(r_1/X_{90}) / (4 \pi \rho r^2 X_{90})$$

where

$r$  = the distance between a source point and a dose point

$k$  = a unit conversion constant

$E_{\beta}$  = the average beta energy for the radionuclide

$Y$  = the beta yield per disintegration

$F_{\beta}(r_1/X_{90})$  = the scaled absorbed dose distribution

$r_1$  = the modified path length between the source point and dose point

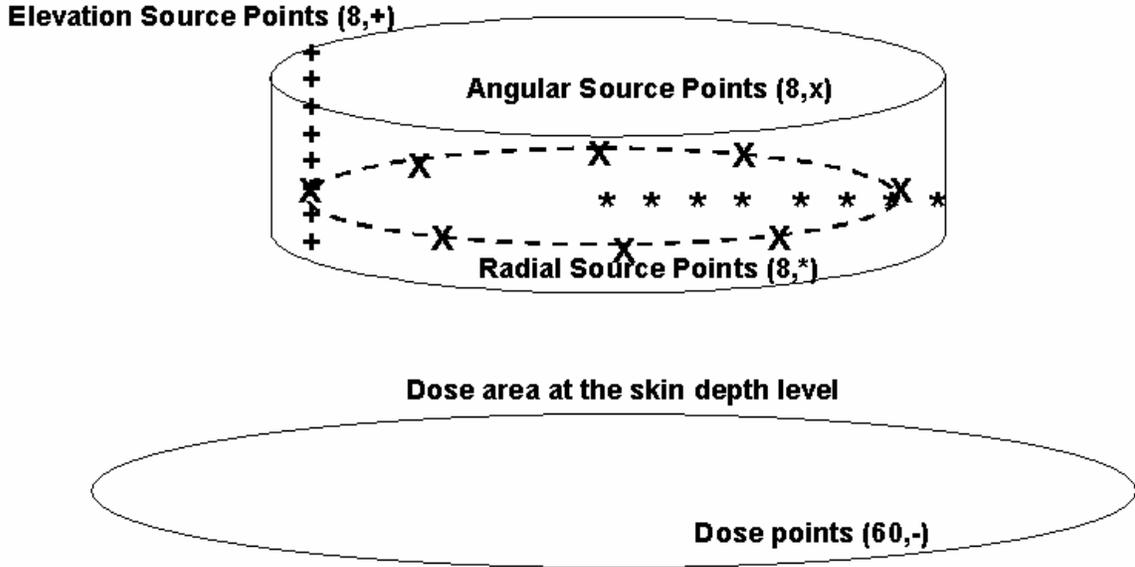
$\rho$  = the density of the irradiated medium (assumed to be unity for tissue).

The  $X_{90}$  distance is defined as the radius of a sphere in which 90% of the beta energy is deposited from a point source in an infinite medium. Varskin 3 calculates  $F_{\beta}(r_1/X_{90})$  for a selected radionuclides 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 dose calculation for the

three-dimensional disk geometry shown in Figure 4.1. The integration is performed by choosing 60 dose points (points at which the dose rate is to be calculated, shown as a (-) in Figure 4.1), 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. One of these circles defined by a radial dose point is chosen, subdivided into eight source points at equiangular locations (angular source points, +), 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 again 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.

Varskin 3 calculates dose for each of the dose points (-) pictured in Figure 4.1. Once a dose rate value from each radial dose 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.



**Figure 4.1 Schematic Representation of a Dose Calculation for a Symmetric Source**

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

$$\dot{D}(d') = \int_0^{2\pi} \int_0^R \int_0^T S_v B(r', d, \theta, z) r' dz dr d\theta$$

where  $S_v$  is the volumetric source strength. A similar equation can be written for spherical and slab geometries. Those equations are

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

in spherical geometry, and

$$\dot{D}(d) = S_v \int_{-x_{max}}^{x_{max}} \int_{-y_{max}}^{y_{max}} \int_0^{thickness} B(d', x, y, z) dz dy dx$$

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

$$D_{avg} = \frac{2 \pi \int_0^R D(d') d' dd'}{\pi R^2}$$

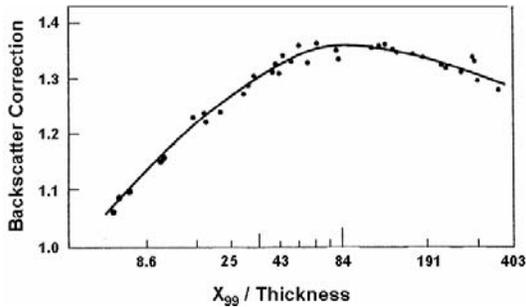
The 60 dose points are chosen such that more points are chosen where the dose profile is changing the most. In general, this occurs at the edge of the source. The distribution of dose points is chosen automatically within VARSKIN

3 based on where the dose is changing most rapidly.

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 Mod 2 code determines the attenuation within the source material by calculating the path lengths within the source, outside the source but above the skin, in the cover material (if any), and in the skin. Each of the path lengths is then modified by multiplying the path length by the ratio of the density of the material to the density of water.

## 4.2 Backscatter Model

In VARSKIN Mod 2, the dose to  $1 \text{ cm}^2$  from a point or area source includes a correction for the lack of backscatter associated with infinitely thin sources. The correction was based on data calculated by Cross et al. (1990) for point and disk sources and dose calculations averaged over  $1 \text{ cm}^2$ . The backscatter correction as a function of  $X_{99}$  distance is shown in Figure 4.2. In Varskin 3, the backscatter model is applied to areas of up to  $10 \text{ cm}^2$  and includes a correction for three-dimensional sources that have dimensions that are less than the range of electrons in the source material. This section describes the model and the calculations that were performed to develop the model.



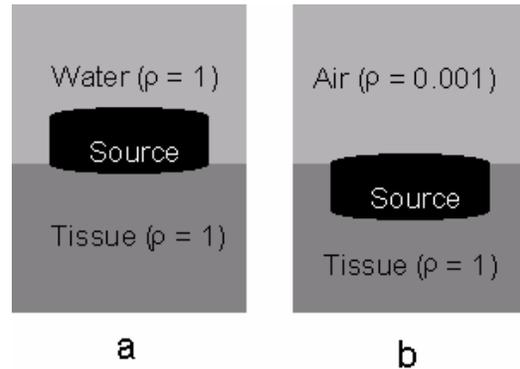
**Figure 4.2 Backscatter Correction Factor for Infinitely-Thin and Point Sources**

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 in which 99% of the energy from a point source of beta radiation deposits its energy.

In Varskin 3, the point source geometry is actually modeled as a three-dimensional disk source with a thickness of  $1 \mu\text{m}$ , a diameter of  $1 \mu\text{m}$ , and a density of  $0.001 \text{ g/cm}^3$ . Similarly, the infinitely thin disk source is modeled with a thickness of  $1 \mu\text{m}$ , and a density of  $0.001 \text{ g/cm}^3$ . The choice of the source size (thickness and diameter) for minute sources is arbitrary. Results of the calculations presented below indicate that a source size less than 5% of the  $X_{99}$  distance can be considered to be infinitely thin.

Calculations for the backscatter model were performed using the Monte Carlo Transport Code MCNP4c2 (2001). The source was modeled as a uniformly distributed disk source with the thickness equal to the diameter. For the infinite-medium model, the source was surrounded by water as shown in Figure 4.3a. For the air-skin interface model, the region above the source was modeled as air as shown in Figure 4.3b. Note that the water in Figure 4.3b extends to the top of the source. 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. The source material was iron with a density of  $7.86 \text{ g/cm}^3$ , and the thickness of the disk was varied between  $1 \mu\text{m}$  (the diameter

of the point source in Varskin 3 calculations) and the  $X_{99}$  distance for the radionuclide.



**Figure 4.3 Geometry Used for MCNP Calculations for the Backscatter Model**

Four different radionuclides were modeled that emitted very low-, low-, intermediate-, and high-energy beta particles. The radioactive attributes of each of the four sources are provided in Table 4.1. Spectra for the four radionuclides were obtained from the computer code NucDecay (1995).

<b>Table 4.1. Radioactive Characteristics of the Sources Modeled for the Backscatter Correction</b>			
Nuclide	Average Energy (keV)	Maximum Energy (keV)	Range in Iron ( $\mu\text{m}$ )
$^{147}\text{Pm}$	62	225	38
$^{90}\text{Sr}$	196	546	182
$^{204}\text{Tl}$	244	763	297
$^{90}\text{Y}$	935	2280	1190

One million particles were generated in the source with a uniform emission angle for each simulated geometry. The simulations calculated flux through a circular disk located 70 m below the bottom of the source in 15 different energy bins. The dose was determined from the flux by multiplying the flux in each bin by the stopping power for that energy bin and summing the results. Values for mass stopping power were obtained from the NIST web site (Berger et al.). The calculated quantity of interest was the ratio of the flux in the infinite medium model to the flux in the air-interface model.

Figures 4.4 through 4.7 contain the ratio of fluxes and doses as a function of the size of the particle expressed fraction of the  $X_{99}$  distance for

$^{147}\text{Pm}$ ,  $^{90}\text{Sr}$ ,  $^{204}\text{Tl}$ , and  $^{90}\text{Y}$ , respectively. A common trait of all four figures is a steadily diminishing correction factor with depth in the source and that the correction approaches unity as the size of the source approaches the range of the beta particles. When the source size is expressed as the fraction of the  $X_{99}$  distance, all four figures are remarkably similar with the exception of sources with sizes less than 5% 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 3. Thus, the backscatter correction applied to sources with a thickness of less than 5% of the  $X_{99}$  distance is same backscatter correction applied to point and two-dimensional sources. It should be noted that the point source backscatter correction model provides correction factors that are consistent with the current calculations.

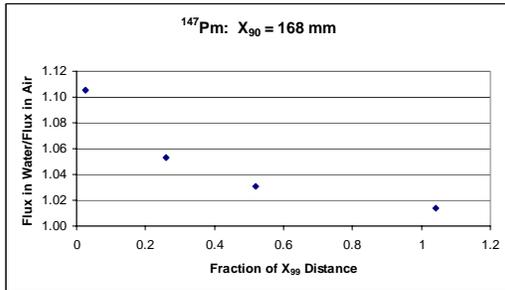


Figure 4.4 Ratio of Flux in Water to Flux in Air for  $^{147}\text{Pm}$ .

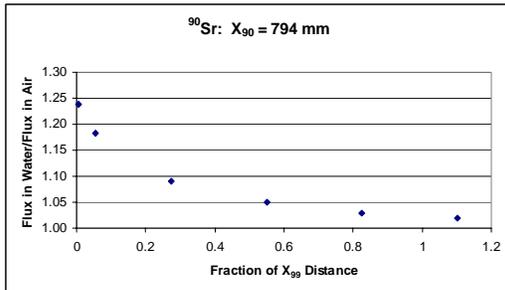


Figure 4.5 Ratio of Flux in Water to Flux in Air for  $^{90}\text{Sr}$ .

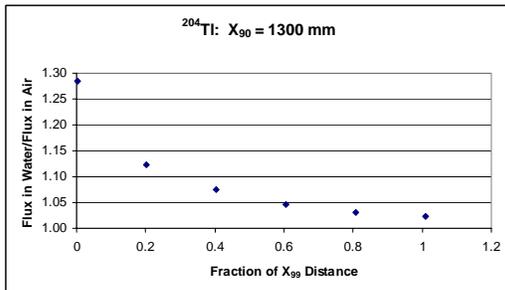


Figure 4.6 Ratio of Flux in Water to Flux in Air for  $^{204}\text{Tl}$ .

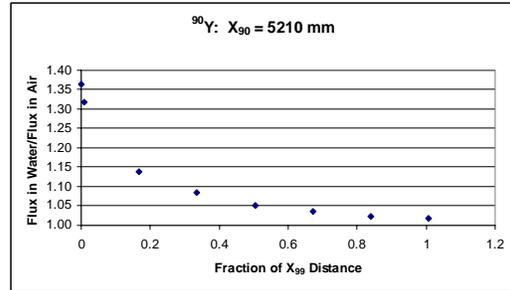


Figure 4.7 Ratio of Flux in Water to Flux in Air for  $^{90}\text{Y}$ .

If the data from Figures 4.4 through 4.7 are consolidated for all sources greater in size than 5% of the  $X_{99}$  distance, the data in Figure 4.8 are obtained. Several attempts were made to fit the data using curve-fitting techniques available in 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

$$\text{BCF} = 1.018 - 0.060 \ln(\text{sourcesize} / X_{99}).$$

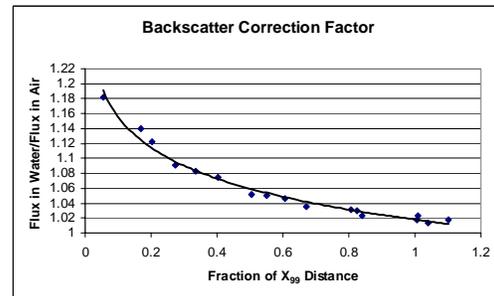


Figure 4.8 Combined Data for the Four Radionuclides.

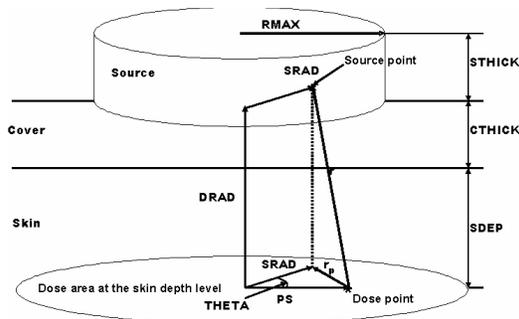
The backscatter correction factor is applied to the calculated dose for a three-dimensional source with a thickness that is less than the  $X_{99}$  distance in the source material. If the source thickness is less than 5% of the  $X_{99}$  distance in the source material, then the point backscatter correction factor is applied. For a source with a thickness greater than the  $X_{99}$  distance, no backscatter correction is applied because the source is “infinitely thick” and the Berger kernel is accurate for these sources.

### 4.3 Cover Layer and Air Gap Models

Both protective clothing and air gaps can be modeled using Varskin 3. The models use the concept of path length to determine the energy lost in either clothing 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.

The method used to determine path length within the source and within the cover material can be illustrated using Figure 4.8. For the pictured cylindrical or three-dimensional disk source, the known values in the figure are the source radius (RMAX), the horizontal distance from the centerline to the source point (SRAD), the source thickness (STHICK), the cover thickness (CTHICK), the skin depth (SDEP), the source and cover densities ( $\rho_s$  and  $\rho_c$ , respectively), the distance from the centerline to the dose point (PS), and the distance from the skin to the plane of the source point (DRAD). The quadrature routines choose values for the distance from the centerline to the source point (SRAD), the angle between SRAD and PS (THETA), and the height of the dose point (DRAD). 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:

$$r_p^2 = PS^2 + SRAD^2 - 2 \cdot PS \cdot SRAD \cdot \cos(\text{THETA})$$



**Figure 4.9 Schematic Drawing of a Generic Dose Calculation Performed by Varskin 3 for the Three-Dimensional Disk Geometry**

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

$$r = \sqrt{r_p^2 + \text{DRAD}^2}$$

The quantity  $r$  is used in the denominator of the expression in Equation (4.1) and represents the geometric attenuation between the dose point and the source point. This quantity is further analyzed to calculate the modified path length used to evaluate the scaled absorbed dose distribution as discussed below.

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 ratio to DRAD of the thickness of the cover material, the tissue, and the remaining distance along DRAD, respectively, providing that the line connecting the dose point and the source point exits through that part of the source that is in contact with the cover material. Thus, the distance traveled through the cover material is written

$$r_c = \text{CTHICK} \cdot r / \text{DRAD}$$

The distance traveled through the skin is given by

$$r_t = \text{SDEP} \cdot r / \text{DRAD}$$

Finally, the distance traveled through the source is given by

$$r_s = (\text{DRAD} - \text{CTHICK} - \text{SDEP}) \cdot r / \text{DRAD}$$

The modified path length  $r_1$  is then found from the equation

$$r_1 = (r_s \rho_s + r_c \rho_c + r_t \rho_t) / \rho_t$$

where  $\rho_t$  is the density of tissue (water).

For small-diameter sources, the path between the dose point and the source point may pass through the side of the source, that is, the path may exit the sources and pass through air before passing

into skin. Thus, the quantity in Equation (4.7) 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

$$r_p^2 = PS^2 + SRAD^2 \sin^2 \phi - 2 \cdot PS \cdot SRAD \sin \phi \cdot \cos(\text{THETA})$$

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

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

The remaining equations then apply to both spherical and slab geometries.

#### 4.4 Volume-Averaged Dose Model

The volume-averaged dose model, shown schematically in Figure 2.10, 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  $1.8 \times X_{90}$ . Doses averaged over  $1 \text{ cm}^2$  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. Note that the doses calculated at the various skin depths are averaged over  $1 \text{ cm}^2$  when Varskin 3 is first invoked. The user can choose to calculate volume-averaged doses for different areas only after calculating volume-

averaged doses for areas of  $1 \text{ cm}^2$ . The volume-averaged dose model requires roughly 50 times the execution time as a single depth calculation to establish the depth dose function.

#### 4.5 Offset Particle Model

The offset particle model, shown schematically in Figure 2.11, 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. In the interests of reasonable execution time and code complexity, the offset particle model is available only for the three-dimensional 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 assumes 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 a 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 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  $1 \text{ cm}^2$  is outlined in Section 5.2.

#### 4.6 Photon Dose Model

Photon doses calculated by Varskin 3 use an expanded version of a simplified model developed by Lantz and Lambert (1990). 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. Also, the size of any air gap is limited to 5 cm. The photon dose is calculated (provided that the radionuclide emits photon radiation) for skin areas of up to 10 cm<sup>2</sup>. Durham and Lantz (1991) verified the original photon dose model experimentally.

Two pieces of information are required to calculate the photon dose: the specific gamma-ray exposure constant and the average photon energy. The specific gamma-ray exposure 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 gamma-ray exposure constant, in units of R-cm<sup>2</sup>-mCi<sup>-1</sup>-h<sup>-1</sup> is calculated for the radionuclides using the following equation (Attix 1986):

$$\Gamma = 1938 \left[ \sum_{i=1}^n P_i E_i \left( \frac{\mu_{en}}{\rho} \right)_{E_i, \text{air}} \right]$$

where P<sub>i</sub> is the probability of emission of a photon having an energy E<sub>i</sub> in MeV and (μ<sub>en</sub>/ρ)<sub>E<sub>i</sub>,air</sub> is the mass energy absorption coefficient in air in units of m<sup>2</sup>/kg for the photon. Data for (μ<sub>en</sub>/ρ)<sub>E<sub>i</sub>,air</sub> were obtained from the NIST web site and data for E<sub>i</sub> and P<sub>i</sub> were obtained from the RADECAY data files.

The average photon energy in keV was calculated using the equation

$$E_{\text{avg}} = \frac{\sum_i P_i E_i}{\sum_i P_i}$$

The specific gamma-ray exposure 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. It is important that the user choose a cutoff energy that is appropriate for the depth at which the dose is being calculated. Since the specific gamma-ray exposure constant is used to calculate the photon dose directly, any contribution to the specific gamma-ray exposure constant from photons that do not contribute to the dose because their range is too short will result in an overestimation of the photon dose. Recommended cutoff energies for photons is 2 keV for shallow dose and 35 keV for deep dose equivalent.

#### 4.7 Building Radionuclide Library Files

This section presents the technical approach used when radionuclide library files are built. The new method of building radionuclide library files is based on the method used in SADDE MOD 2 but is much simpler for the user.

From the basic definitions of specific absorbed fraction for monoenergetic electrons given by Berger (1971), the absorbed dose rate is defined as follows:

$$R(x, E_0) = A n k E_0 \phi(x, E_0)$$

where

R(x, E<sub>0</sub>) = the absorbed dose rate

x = the distance from the point source

A = the source activity

n = the number of electrons emitted at energy E<sub>0</sub> per unit of source activity

k = a unit conversion factor

E<sub>0</sub> = the initial energy of the electron

Φ(x, E<sub>0</sub>) = the specific absorbed fraction of the energy.

For a spectrum of energies such as would be emitted from a source undergoing beta decay, the absorbed dose rate R<sub>β</sub>(x) would be:

$$R_{\beta}(x) = A Y_{\beta} k \int_0^{E_{\text{max}}} E S(E) \phi(x, E) dE$$

where  $E_{\max}$  is the endpoint energy of the beta spectrum,  $Y_{\beta}$  is the number of beta particles emitted per disintegration (the yield), and  $S(E)$  is the energy spectrum of the beta particles in particles/MeV.

For convenience, Equation (4.2) can be cast into the same form as Equation (4.1):

$$R_{\beta}(x) = A Y_{\beta} k E_{\text{av}} \phi_{\beta}(x)$$

where  $E_{\text{av}}$ , the mean energy of the spectrum, is defined as

$$E_{\text{av}} = \frac{\int_0^{E_{\max}} E S(E) dE}{\int_0^{E_{\max}} S(E) dE}$$

and

$$\phi_{\beta}(x) = \int_0^{E_{\max}} (E/E_{\text{av}}) S(E) \phi(x, E) dE$$

Data for the beta spectrum are obtained from the Nudacay data files, which are based on data from ICRP-38. The spectrum is interpolated to 1500 values using a spline interpolation routine.

These interpolated values are stored in an array called SPEC1 (see Appendix E for a listing of the FORTRAN programs). The average energy of the composite spectrum is calculated using the following algorithm:

$$EAV = \int_0^{E_{\max}} \text{COMP}(E) E dE$$

where  $E_{\max}$  is the maximum endpoint energy for the composite spectrum.

The subroutine SADD uses the average energy and SPEC1 to calculate the scaled absorbed dose function,  $\Phi_{\beta}(x)$ . The SADD routine determines the maximum beta range and sets the range step size to 1/150 of this maximum range. The scaled absorbed dose function for the beta spectrum is calculated for each distance step by integrating

through energy in steps of 1/150th of the maximum energy using the following equation:

$$\phi_{\beta} = \frac{1}{E_{\text{av}}} \int_0^{E_{\max}} E n(E) \Phi(x, E) dE$$

where  $\Phi(x, E)$  is the scaled absorbed dose function for monoenergetic electrons.

The function  $\Phi(x, E)$  is determined within the SADD routine by a routine named SPENS, an algorithm for interpolating Spencer's data (1959) for scaled absorbed dose distribution as a function of distance and electron energy through energy and distance. When SADD picks an energy ( $E$ ) and a distance ( $x$ ),  $\Phi(x, E)$  is calculated by the following algorithm:

$$\Phi(x, E) = F(\xi, E) / 4 \pi \rho x^2 X_{90}(E)$$

where  $\xi$  is  $x/X_{90}(E)$  and  $\rho$  is the density of the absorbing medium.

$F(\xi, E)$  is a tabulated function of  $\xi$  and  $E$  that is interpolated to calculate the function value.

Output of the routine SADD is the function  $\Phi_{\beta}(x)$ , the array PHI in the FORTRAN program, which has 150 values.

The  $X_{90}$  distance is calculated using the array PHI and EAV. The values of  $dE/dx$  are summed over distance to arrive at the total energy in the beta spectrum:

$$\frac{dE}{dx} = 4 \pi \rho x^2 E_{\text{av}} \Phi_{\beta}(x)$$

Therefore,

$$E_{\text{Tot}} = \sum_i \Delta x_i 4 \pi \rho x^2 E_{\text{av}} \Phi_{\beta}(x)$$

Once the total energy in the spectrum is found, a second sum is computed as follows:

$$\text{FRAC} = \sum_i \Delta x_i 4 \pi \rho x^2 E_{\text{av}} \Phi_{\beta}(x) / E_{\text{Tot}}$$

FRAC is evaluated for successively larger values of x until FRAC is 0.9, then the current x value becomes the X<sub>90</sub> value and is stored as the FORTRAN variable X90.

The routine FBETA calculates the function F<sub>β</sub>(ξ). The routine uses X90 and PHI to perform the following calculation:

$$F_{\beta}(\xi) = 4 \pi \rho x^2 X_{90} \Phi_{\beta}(x)$$

The values of x are divided by X<sub>90</sub> and then F<sub>β</sub>(x) is tabulated against the x values. The resulting values of F<sub>β</sub>(ρ) are stored in the array F. The

final routine FIT uses linear interpolation to extract the 30 specific values of F<sub>β</sub>(ρ) needed by VARSKIN and writes these values to the output file.

The library file for a radionuclide includes the contribution from Auger and internal conversion electrons to the scaled absorbed dose distribution function, F<sub>β</sub>. Low-energy electrons can be eliminated when adding radionuclides by choosing a cutoff energy on the Add Radionuclide screen. However, including low-energy electrons will not affect the accuracy of the beta dose calculation.

## 5 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 a dose area from multiple hot particles.

### 5.1 Infinite Sources

When modeling "infinite" or "semi-infinite" sources such as 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 inaccurate. The correct method is to determine the maximum penetration distance (i.e.,  $1.8 \times X_{90}$  distance, or  $X_{99}$  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,  $r_{\max}$ , for x- and y-side lengths is then determined using the equation:

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

where  $r_{\text{dos}}$  is the radius of the dose-averaging area (in cm),  $\rho_w$  is the density of water, and  $\rho_{\min}$  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 area over which the dose is averaged includes contributions from the entire source. If an air gap is used, use the density of air ( $0.001293 \text{ g/cm}^3$ ). If no cover material is used, use the density of tissue.

When modeling infinite sources, the use of three-dimensional slab geometry is recommended. When using slab geometry, the source thickness,  $\Delta t_{\max}$ , should be determined using the equation:

$$\Delta t_{\max} = X_{99} \rho_w / \rho_s$$

where  $\rho_s$  is the source density.

### 5.2 Maximum Dose to $1 \text{ cm}^2$ from Multiple Contaminations

Determining the maximum dose to  $1 \text{ cm}^2$  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.

Before attempting to run the offset particle model (Section 4.5), determine the dose directly beneath each of the contaminated areas. If not, entering a larger area will eventually provide the radius of the irradiated area. 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% should not be sought since the error associated with determining the relative positions of the contaminated areas on skin or protective clothing will usually exceed 20%.

## 6 REFERENCES

- Attix, F. H. Introduction to Radiological Physics and Radiation Dosimetry, John Wiley and Sons, New York (1986).
- Berger, M. J. Distribution of Absorbed Dose Around Point Sources of Electrons and Beta Particles in Water and Other Media. Medical Internal Radiation Dose Committee, Pamphlet No. 7, Journal of Nuclear Medicine 12(5):5 (1971).
- Berger, M. J. Improved Point Kernels for Electron and Beta-Ray Dosimetry, NSBIR 73-107 (1973).
- Chabot, G. E., K. W. Krable, and C. S. French. When Hot Particles are Not on the Skin. Radiation Protection Management 5(6):31-42 (1988).
- Cross, W. G., Wong, P. Y., and Freedman, N. O. Beta-Ray Depth Dose Distributions from Incident Beams and Skin Contamination. Presented at the Health Physics Society Annual Meeting in Anaheim, CA, June 24-28 (1990).
- Delacroix, D. Beta Particle and Electron Absorbed Dose Calculations for Skin Surface Contaminations (in French). DCES/SPR/SRI/86-656, Commissariat à l'Energie Atomique, Paris (1986).
- Durham, J. S. VARSKIN Mod 2 and SADDE Mod 2: Computer Codes for Assessing Skin Dose From Skin Contamination, NUREG/CR-5873, PNL-7913 (1992).
- Durham, J. S., Reece, W. D., and Merwin, S. E. Modelling Three-Dimensional Beta Sources for Skin Dose Calculations Using VARSKIN Mod 2, Radiation Protection Dosimetry 37(2):89-94 (1991).
- Durham, J. S., and Lantz, M. W. Determination of Gamma Dose Rates and Charged Particle Equilibrium from Hot Particles. Radiation Protection Management 8(3):35-41 (1991). International Commission on Radiological Protection (ICRP). 1991.
- International Commission on Radiological Protection. Radionuclide Transformations. Publication 38, Pergamon Press, Oxford (1983).
- International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. Publication 60, Pergamon Press, Oxford (1991).
- Kocher, D. C. Radionuclide Decay Data Tables. DOE/TIC-11026, U.S. Department of Energy, Washington, D.C. (1981).
- 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 53:135-141 (1987).
- Lantz, M. W., and Lambert, M. W. Charged Particle Equilibrium Corrections for the Gamma Component of Hot Particle Skin Doses. Radiation Protection Management 7(5):38-48 (1990).
- MCNP4c2, Coupled Neutron, Electron Gamma 3-D Time-Dependent Monte Carlo Transport Calculations. Radiation Shielding Information Computational Center Data Library CCC-701, PO Box 2008, Oak Ridge, TN 37831-6362 (2001).
- NUCDECAY: Nuclear Decay Data for Radiation Dosimetry Calculations for ICRP and MIRD. Radiation Shielding Information Computational Center Data Library CCC-701, PO Box 2008, Oak Ridge, TN 37831-6362 (1995).

Piechowski et al. Dosimetry and Therapy of Skin Contaminations (in French). CEA-R-5441, Commissariat à l'Energie Atomique, Paris (1988).

Reece, W. D., Miller, S. D., and Durham, J. S. SADDE (Scaled Absorbed Dose Distribution Evaluator), A Code to Generate Input for VARSKIN. NUREG/CR-5276, U.S. Nuclear Regulatory Commission, Washington, D.C. (1989).

Rohloff, F., and M. Heinzelmann. Calculation of Dose Rates for Skin Contamination by Beta Radiation. Radiation Protection Dosimetry 14:279-287 (1986).

Spencer, L. V. Energy Dissipation by Fast Electrons. Monograph No. 1, National Bureau of Standards, Washington, D.C. (1959).

Traub, R. J., Reece, W. D., Scherpelz, R. I., and Sigalla, L. A. Dose Calculation for Contamination of the Skin Using the Computer Code VARSKIN. NUREG/CR-4418, U.S. Nuclear Regulatory Commission (1987).