VARSKIN+ 2 USER MANUAL

February 2025

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ABSTRACT

VARSKIN+ is a U.S. Nuclear Regulatory Commission (NRC) computer code used by staff members and NRC licensees to calculate occupational dose to the skin resulting from exposure to radiation emitted from hot particles or other contamination on or near the skin. These assessments are required by Title 10 of the *Code of Federal Regulations* (10 CFR) 20.1201(c), which states that the assigned shallow dose equivalent is to the part of the body receiving the highest exposure over a contiguous 10 cm^2 of skin at a tissue depth of 0.007 centimeters (7 mg/cm^2). Additionally, NRC staff evaluate radioactive intakes through wounds pursuant to 10 CFR 20.1202(d). VARSKIN+ can be used to perform wound dose assessments if the metabolic modeling and dosimetry methods are consistent with NRC regulations (e.g., use of 10 cm^2 averaging area for skin dose assessments and tissue or organ weighting factors as defined in 10 CFR 20.1003). VARSKIN+ also allows estimates of dose from neutron exposure, dose to the lens of the eye, and dose from extravasation events involving radiopharmaceuticals.

The VARSKIN+ computer code, an algorithm to calculate skin dose from radioactive skin contamination, has been modified on several occasions. As in previous versions, predefined source configurations are available in VARSKIN+ to allow simulations of point, disk, cylinder, sphere, slab, and syringe sources. Improvements to earlier versions included enhanced photon, electron, and alpha dosimetry models, as well as models to account for airgap and cover materials. VARSKIN+ gives the user the option to have the code automatically include all decay products in dosimetry calculations or to allow the user to manually add progeny. Both ICRP 38, “Radionuclide Transformations – Energy and Intensity of Emissions” (1983), and ICRP 107, “Nuclear Decay Data for Dosimetry Calculations” (2008a), nuclide libraries are available at the user’s option and contain data on gamma rays, X rays, beta particles, alpha particles, internal conversion electrons, and Auger electrons. Although the user can choose any dose-averaging area, the default area for skin dose calculations is 10 square centimeters, to conform to the requirements in 10 CFR 20.1201(c). A variety of unit options are provided (including both British and International System (SI) units), and the source strength can be entered in units of total activity or distributed in units of activity per unit volume. The photon model accounts for photon attenuation, charged particle buildup, and electron scatter at all depths in skin. The model allows for volumetric sources and clothing or airgaps between source and skin. The electron dosimetry model has a robust accounting for electron energy loss and particle scatter. Dose point kernels are Monte-Carlo based and results agree very well with Electron Gamma Shower (EGS) and Monte Carlo N Particle (MCNP) probabilistic simulations.

With the release of VARSKIN+ 1.0 three new physics modules were introduced: (1) wound dosimetry; (2) neutron dosimetry; and (3) eye dosimetry. Skin and wound dosimetry implement a new alpha dosimetry model for shallow skin assessments. The new VARSKIN+ user interface is written in Java with all scientific coding updated to Fortran 2018. Extravasation dosimetry is new in VARSKIN+ 2.0. A chronology of VARSKIN development since its inception in 1987 is provided below.

Chronological Development of VARSKIN (1987 to present)

VARSKIN (1987)

original code for calculating radiation dose around a point source in water from beta emitters; point and disk sources

SADDE (1989)

new calculation of scaled absorbed dose distributions for electrons emitted by nuclides that are not listed in the MIRD No. 7 publication

VARSKIN Mod 2 (1992)

uses new routine to calculate scaled absorbed dose distributions for more nuclides and mixtures thereof; includes volumetric sources, layers of protective clothing, and a basic gamma dose estimator; backscatter correction applied; conversion and Auger electrons now considered along with beta emissions

VARSKIN 3 (2006)

new Windows operating environment; syringe model added; new backscatter correction model; upgraded photon model; considers airgap and cover materials for electrons; inputs simplified; user can enter distributed activity; help file available

VARSKIN 4 (2011)

syringe model removed; enhanced photon dosimetry model is enhanced to account for attenuation, charged particle buildup, and electron scatter; airgap and cover materials now considered for photons

VARSKIN 5 (2014)

electron dosimetry model is enhanced and based on EGS Monte Carlo simulations rather than Berger's point kernels; takes better account of electron scatter and energy loss in tissue, air, and volumetric sources; new backscatter correction model

VARSKIN 6 (2018)

user can choose to include emissions from daughter products; the ICRP 107 nuclide decay database is made available

VARSKIN+ 1.0 (2021)

implements a new first-principles alpha skin dosimetry model, a fundamental neutron dosimetry model, a Monte Carlo based eye dosimetry model, and the NCRP 156 wound

dosimetry model; the user interface is written in JAVA with all scientific coding updated to Fortran 2018; execution speed is enhanced

VARSKIN+ 2.0 (2025)

Introduces the new Extravasation Dosimetry module, incorporates the Rad Toolbox v3.0 software, and addresses various bug fixes

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ACKNOWLEDGMENTS

This report documents the work performed by Renaissance Code Development, LLC (RCD) for the U.S Nuclear Regulatory Commission (NRC) under Contract No31310022C0011. Staff at the Pacific Northwest National Laboratory authored initial versions of VARSKIN (US NRC 1987), with later versions amended at Colorado State University (US NRC 1992), the Center for Nuclear Waste Regulatory Analyses (US NRC 2006), and Oregon State University (US NRC 2011; US NRC 2014; US NRC 2018). RCD performed the activities described herein on behalf of the NRC Office of Nuclear Regulatory Research, Division of Systems Analysis. This report is a product of RCD and does not necessarily reflect the views or regulatory position of the NRC.

The authors are indebted to S. Bush-Goddard, B. Allen, R. Flora, V. Shaffer, J. Tomon, M. Saba, and S. Sherbini for their support during development and maintenance of many of the dosimetry models now appearing in VARSKIN+.

1 INTRODUCTION

The original VARSKIN computer code (US NRC 1987) was intended as a tool for the calculation of tissue dose at user-defined depths as the result of skin contamination. The contamination was assumed to be a point, or an infinitely thin disk source located directly on the skin. Soon after the release of VARSKIN, the industry encountered a “new” type of skin contaminant consisting of discrete microscopic radioactive fragments, called “hot particles”. These particles differ radically from uniform skin contamination in that they have a volume associated with them and many of the skin exposures result from particles on the outside of protective clothing. These assessments are required by Title 10 of the Code of Federal Regulations (10 CFR) 20.1201(c), which states that the assigned shallow dose equivalent (SDE) is to the part of the body receiving the highest exposure over a contiguous 10 cm2 of skin at a tissue depth of 0.007 centimeters (7 mg/cm2).

VARSKIN MOD2 (US NRC 1992) contained all the features of the original VARSKIN, with many significant additions. Features in MOD2 included the modeling of three-dimensional (3D) sources (cylinders, spheres, and slabs) that accounted for self-shielding, and modeling of materials placed between the source and skin (i.e., airgaps and covers) that could absorb electron energy and attenuate photons. VARSKIN MOD2 also used a correction for backscatter for one-dimensional and two-dimensional (2D) electron sources under limited conditions. Finally, the VARSKIN MOD2 package incorporated a user interface that greatly simplified data entry for calculating skin dose.

Additionally, VARSKIN MOD2 gave the user the ability to select a composite source term, thus allowing the calculation of total dose from a mixture of radionuclides instead of requiring the code to be executed separately for each constituent. This feature was upgraded in VARSKIN 3 (US NRC 2006), allowing the user to select up to twenty radionuclides in a single calculation. One drawback of removing this feature in VARSKIN 3 was that the user was forced to explicitly add radioactive progeny. Subsequent VARSKIN versions incorporate radioactivity progeny at the user’s discretion.

Enhancements to VARSKIN 4 (US NRC 2011) focused on the photon dosimetry model. The photon model includes charged-particle buildup and subsequent transient equilibrium, along with photon attenuation, air and cover attenuation, and the option to model volumetric sources. The VARSKIN 5 (US NRC 2014) package updated electron dosimetry model to better account for charged-particle energy loss as the particle moves through the source, cover material, air, and tissue. VARSKIN 6 (US NRC 2018) further enhanced the physics models and the user interface. SkinDose, introduced in VARSKIN+, employs a new user interface written in Java and updated Fortran for physics calculations based on Fortran 2018 fundamentals. Speed increases of 25x have been realized in various data-handling routines of the updated Fortran.

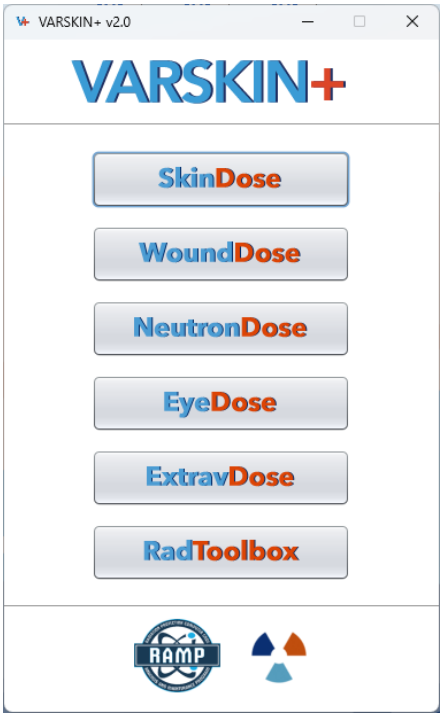
Chapter 2 of this report comprises the VARSKIN+ User’s Manual. It is subdivided into four segments and mimics the layout of the GUI. The segments are SkinDose, WoundDose, NeutronDose, EyeDose, and Extravasation Dose. Chapter 3 discusses the technical basis for the SkinDose (classic VARSKIN) module, while Chapters 4, 5, 6, and

8 describe the physics models employed for wound, neutron, eye, and extravasation dosimetry. Chapter 7 describes details of the Radiological Toolbox. Chapter 8 examines the new Extravasation Dosimetry module added in 2025. Verification and validation results for each of the five dosimetry modules are contained in the specific chapter describing the module. Appendix A provides a few sample problems for each dose module and the user is encouraged to become familiar with dosimetry functions by exercising each sample problem.

As contracted, RCD is actively working to comply with Section 508 of the Rehabilitation Act of 1973 (as amended by 29 USC 794d) by conforming to the Act and supporting the requirements of the Standards for Section 508 (36 CFR 1194.1). This conformance is ongoing, and the User will see edits throughout the lifecycle of VARSKIN+ (and other RAMP software) to demonstrate compliance.

2 VARSKIN+ USER'S MANUAL

This section serves as the user's guide for VARSKIN+ (V+). It includes operating instructions and a description of its features. Chapters 3 through 8 describe the computational dosimetry models for each of the dosimetry modules. VARSKIN was originally designed as a versatile calculational tool intended for use as an estimator of skin dosimetry from radioactive contamination and hot particles. In the 35 years since its introduction, the tool has grown into what is known as VARSKIN+, which includes the classic VARSKIN dosimetry module (SkinDose), a wound dosimetry module (WoundDose), a neutron dosimetry module (NeutronDose), and an eye dosimetry module (EyeDose). The initial user interface shown to the side is the first to appear; this interface acts as the central control panel and allows the user to select any of the four dosimetry modules (described below).



SkinDose calculates dose equivalent from photon, electron, and alpha radiation from more than 1,200 radionuclides that may be encountered in a variety of skin-contamination applications from laboratory use to medical and therapeutic applications. SkinDose can calculate the dose to averaging areas from a minimum of 0.01 cm^2 to a maximum of 100 cm^2, and airgaps between source and skin of up to 20 cm. SkinDose calculates shallow dose to an infinitely thin disk at a depth of 0.007 mg/cm^2 in tissue for comparison to the NRC shallow dose limit of 0.5 gray (Gy) for both point and distributed sources. Other user-specified depths from zero to 2 cm are allowable. Users are cautioned that SkinDose is designed to calculate the dose to skin from skin contamination or sources close to the skin surface (within 20 cm). Using SkinDose to perform calculations that are beyond its intended application may result in erroneous dose estimates. SkinDose offers the option of dose calculations based on the decay data of International Commission on Radiological Protection (ICRP) 38, "Radionuclide Transformations – Energy and Intensity of Emission" (ICRP 1983), or ICRP 107, "Nuclear Decay Data for Dosimetric Calculations" (ICRP 2008a).

WoundDose is based on National Council on Radiological Protection and Measurement (NCRP) Report 156, "Development of a Biokinetic Model for Radionuclide-Contaminated Wounds and Procedures for Their Assessment, Dosimetry and Treatment" (NCRP 2007) and calculates shallow dose equivalent (SDE), local dose equivalent, and committed effective (and organ) dose equivalent from industrial or medical events resulting in the subdermal introduction of radioactivity following skin injury. The user will notice that many of the features of WoundDose are derived from the SkinDose module and their utilization is similar. Point-source and line-source geometries are allowable.

NeutronDose estimates shallow tissue dose at a user-specified depth following exposure to a source of neutrons with energies ranging several orders of magnitude from thermal to fast. The user can select monoenergetic neutrons or can choose from a list of ICRP 107 (2008a) nuclides and reaction compounds resulting in various neutron spectra. Neutrons are assumed to be orthogonally incident on the body.

EyeDose allows for the evaluation of photon and electron dose to the lens of the human eye for radionuclides in the ICRP 38 or ICRP 107 database or for monoenergetic beams. The source of photons and electrons is assumed to be on-axis with the eyeball (i.e., the exposed individual is staring at the source). Lens dose is calculated for unshielded and shielded eyes. Shielding is provided by standard safety glasses containing 2 mm leaded glass.

To download VARSKIN+, locate the executable file (.exe) and place it on your desktop. Other than to clean up files and save memory, there is no need to uninstall previous versions of V+. New versions are installed in the same manner and multiple versions can be run simultaneously. The V+ app requires approximately 215 megabytes of disk space. If any of the V+ interface windows are not fully visible on the display screen, the user should adjust resolution and magnification as appropriate. Double-click the executable file to install V+. Once the installation is complete, you will see a shortcut for V+ on your desktop. To run V+, double-click the V+ icon.

In V+ 2.0, a license key is required to run the Extravasation Dose (ExtravDose) module. After downloading and running the executable, V+ will install as it normally does. The license key will be required only if the user wishes to execute ExtravDose. On the first execution, entry of the license key will be requested (Figure 2-1). A single entry of a valid key will remain with the code and will not be required at each module run unless the key expires. Click the Accept button and, if the key is valid, ExtravDose will be available to the user and will load. All other modules can run without the license key.

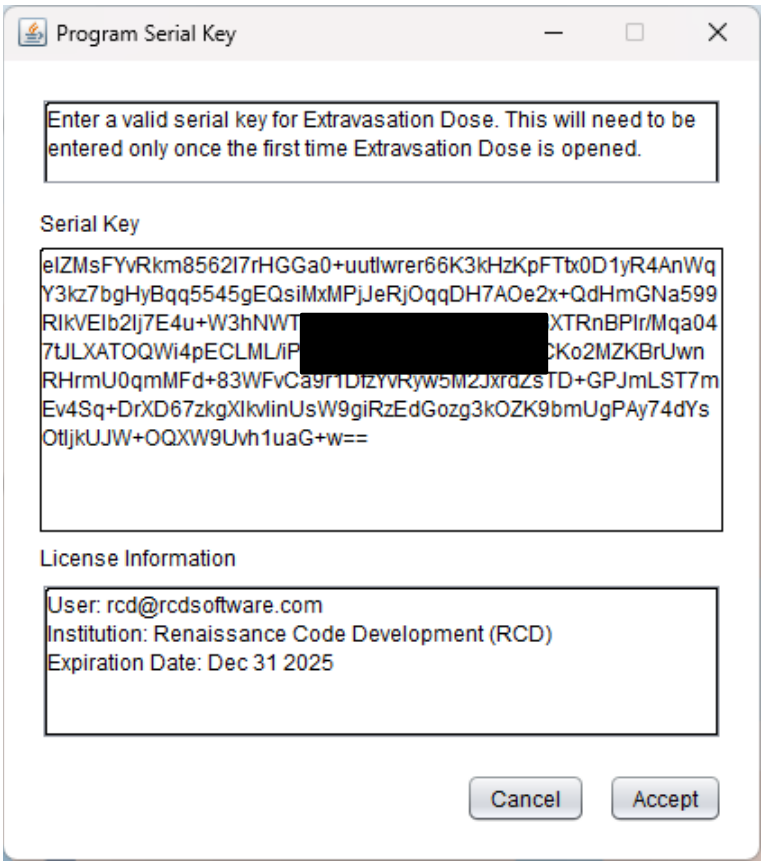


Figure 2-1 License Key Entry Window.

VARSKIN+ defaults to using the English language in all modules. The code contains a library of six additional languages, including Spanish, French, Ukrainian, German, Korean, and Akan. Language is changed by selecting the Language dropdown and choosing the appropriate language from the list. Alternative language is not yet available in the extravasation dosimetry module.

For the general user, access to V+ files is not required (and not recommended). If such access is paramount, the V+ folder location can be found in the “Shortcut” tab of the Properties window (right click on the V+ shortcut icon and select “Properties”). The “Target” field contains the location on the user’s local machine where all files are stored.

The user exits individual modules by clicking the “X” in the upper right corner of each of the windows. The user can exit the entire V+ code by clicking the “X” in the upper right corner on the V+ interface. Note that the entire code shuts down if the V+ interface is closed.

2.1 Running SkinDose

To run SkinDose (classic VARSKIN), the user selects the SkinDose module from the initial V+ window. After selecting the SkinDose button, the user will see the interface window below (Figure 2-2). The user defines the exposure scenario by selecting and providing data entry fields in the input window. The inputs for SkinDose are defined in this section.

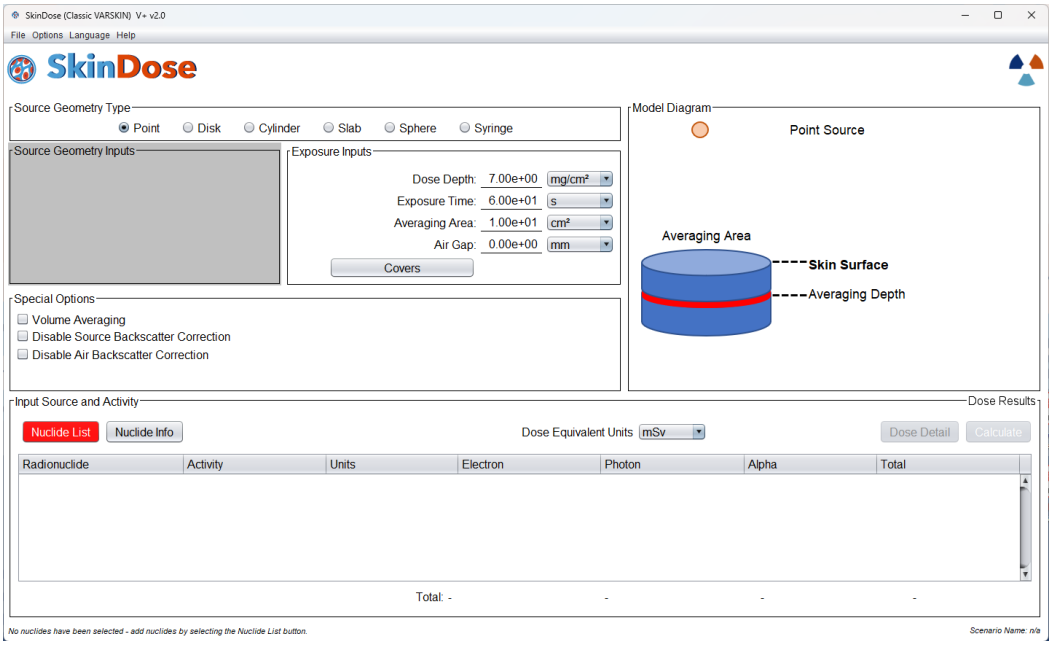


Figure 2-2 SkinDose User Interface.

2.1.1 Source Geometry

Although SkinDose allows the user to enter data in any order, it is best practice to input the source geometry first, because changing the geometry option will cause certain parameters to appear and others to be removed. Six geometry packages are available: point source, disk source (infinitely thin), cylinder source (thick), spherical source, slab source (rectangular), and syringe source. Source activity is assumed to be evenly distributed throughout the area or volume for all source geometries.

The point source geometry (Figure 2-3 (A)) is often used as an initial screening tool for contamination that is confined to an extremely small area of the skin, or for a conservative calculation to determine whether a regulatory limit is being approached or exceeded. The point source geometry does allow for self-shielding, so a 3D source geometry is best for particulate contamination. The point source model does not require any data describing the physical dimensions of the source and will generally yield the highest dose rate for a given activity of any of the available source geometries. For electron dosimetry, a point source is automatically modeled (due to historical code constraints) as a cylindrical source with a thickness of 1 micron, a radius of 1 micron, and a density of 0.001 grams per cubic centimeter (g/cm^3).

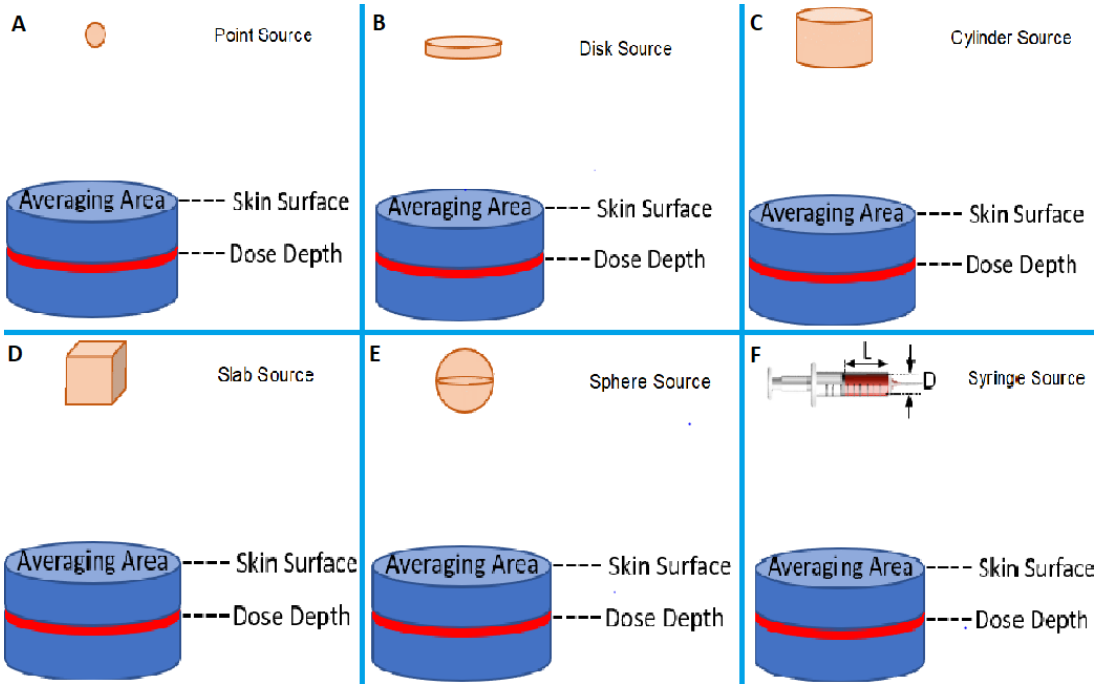


Figure 2-3 Schematic Representations of the Six Geometry Options

The infinitely thin disk source geometry model (Figure 2-3 (B)) is simple and is recommended for modeling skin contamination events caused by liquid sources. The disk source geometry requires the user to enter either the source diameter or the source area at the bottom of the Disk Source Irradiation Geometry box. Entering the area of the contamination is useful for modeling sources when the area is known. Enter the area of the source in the textbox labeled "Source Area." When the user enters the diameter of the source area, SkinDose calculates the area of the 2D disk with that diameter. Similarly, when the user enters the area of the source, SkinDose calculates the diameter of the disk with the same area. If the area of contamination is not circular, entering the area of the actual contamination will generally result in a reasonable estimation of skin dose.

The cylindrical source model (Figure 2-3 (C)) requires knowledge of density and two dimensions, the cylinder diameter and its height (thickness). The cylindrical source geometry assumes that the source is surrounded by air and that the entire bottom of the cylinder is in contact with skin or cover material. Of the two dimensions describing a cylinder, the calculated dose is much more sensitive to changes in the cylinder height as opposed to the cylinder diameter (US NRC 1992).

The slab source geometry (Figure 2-3 (D)) requires knowledge of density and three physical dimensions: the first side length, the second side length, and the slab's thickness. Generally, as in the cylindrical model, slab thickness will have more influence on tissue dose than will lateral dimensions.

The spherical source geometry (Figure 2-3(E)) is perhaps the simplest 3D geometry to use for dose calculations because it requires knowledge of source density and only one

source dimension, its diameter. The spherical source geometry assumes that the source is surrounded by air and touches the skin or cover material only at the bottom point of the sphere. For photon dosimetry, it is assumed that the source material is equivalent to air for attenuation calculations. Choosing a spherical source will generally overestimate dose compared to a similarly sized cylindrical source (same radius and length) with the same total activity. The air surrounding the bottom hemisphere does not shield the source particles as efficiently as the source material (which would be encountered by the particle in the cylinder or slab models), and a larger area of skin will be exposed, resulting in consistently higher doses.

The syringe geometry (Figure 2-3(F)) allows the user to enter the length and diameter of the radioactivity fluid; the dimensions are those of the fluid and not the physical syringe. The syringe model essentially behaves like the cylinder model except that the cylinder would be standing on the skin surface while the syringe is assumed to be lying on the skin surface.

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

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

- If the diameter is known, but the thickness cannot be estimated, or if a distributed source is being modeled (i.e., with a known source strength per unit area), use the two-dimensional disk source geometry option. If an infinite plane source is desired, a source area of at least 15 cm^2 is generally sufficient.

- If the particle is known to be spherical (few particles are truly spherical), use the spherical source geometry option.

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

- If the particle is known to be rectangular, use the slab or cylinder source geometry options. The height of the particle should be preserved, and the area of the contact surface should be selected such that the source volume is preserved. Executing both slab and cylinder will aid in providing bounding doses.

It is not intended that SkinDose models be used to simulate large volumetric sources and the user is cautioned against using dimensions greater than a few centimeters. For all source geometries, dose is averaged over an infinitely thin disk centered below the central axis of the source.

2.1.2 Adding Radionuclides to the Exposure Scenario

SkinDose employs two main decay libraries and a user library that contains only those radionuclides that have been selected and added by the user. Nuclide decay information is obtained from abridged datasets published by the ICRP, namely the ICRP 38 (1983) or ICRP 107 (2008a) databases; SkinDose defaults to the ICRP 38 database. The user selects the nuclear database from which to extract decay data when radionuclides are selected from the main library to be added to the user library. Additionally, the user will choose between the automatic inclusion of decay progeny (designated by "D"), or manual (or none) progeny selection.

In addition to selecting the master library (either ICRP 38 or ICRP 107, with or without progeny), and the nuclide from that library, the user must specify an effective atomic number (Z_{eff}) to characterize the source material in which the radioactivity is incorporated. The default value for Z_{eff} is 7.42 (the effective atomic number of water), meaning the radioactivity itself is assumed to be dissolved or suspended in water.

Radioactive progeny in calculations involving decay-enabled ("D") databases for SkinDose account for in-growth and decay of daughters up to and through the exposure period. This model is currently only available for SkinDose. When first adding a parent nuclide, additional inputs are requested that define the time since purity (i.e., time elapsed since only the parent was present). To allow for backwards compatibility with previous versions of VARSKIN+ the user can select the secular equilibrium box for nuclides that can establish secular equilibrium. In this case the time since purity defaults to a value equal to ten times the progeny half-life.

The yield tables and spectrum plots for a parent and associated daughters include the effects of in-growth periods and branching ratios. These are available by selecting Nuclide Info on the main screen for the selected nuclide. Here the time since purity may also be modified.

If evaluating dose from progeny alone, the user must note its half-life and include the correct dose calculation (decay corrected or not) in the dose estimate. For example, in the case of barium (Ba)-137m as a stand-alone product of cesium (Cs)-137 decay, the user should report the "Dose (No Decay)" result for barium (Ba)-137m dose; this would force the assumption that barium (Ba)-137m is continuously supplied by the decay of cesium (Cs)-137 (in this example, the branching ratio from cesium (Cs)-137 to barium (Ba)-137m is 94.6%). However, if the "Decay-Corrected Dose" is used, the very short decay time of barium (Ba)-137m will cause the dose to be significantly underestimated.

When SkinDose is first executed, a few preselected radionuclides may appear in the user library. SkinDose is designed to allow the user to customize the user library so that only the nuclides of interest can be maintained for ready use. To add a radionuclide to the user library, the user clicks the "Nuclide List" button, after which a new window appears to obtain the user's choice of nuclide decay database, whether decay products are to be included, and the source effective atomic number (Figure 2-4). The user then highlights

the radionuclide and clicks the “Add Selected” button, or simply double-clicks the name of the radionuclide.

More than a thousand radionuclides are available in the main library, each of which could be added to the SkinDose user library, each from a different decay database, and each with its own effective atomic number (i.e., multiple selections of the same nuclide can be made, but with different values of Z_{eff}). The final ‘nuclide’ in the list is denoted “XX-MeV”. This entry allows the user to select specific particle (photon, electron, alpha) energies along with a nuclide half-life. The half-life default in this case is one-million years, i.e., something very long so that source activity is not changing during the dose calculation. The user can change this half-life if the scenario warrants.

Once the “Add Selected” button is pressed (Figure 2-4), the code will automatically populate the user library for the selected radionuclide; this can take up to a minute or so, depending on the processing power of your computer. The tricolored trefoil (lower right) will spin while the calculations are taking place. If the radionuclide emits electrons, an electron energy spectrum is generated for all emissions with yield greater than 0.1 percent. Photons with energy greater than 2 keV and decay yield greater than 1 percent, and alphas with a yield greater than 1 percent are collected from these data files.

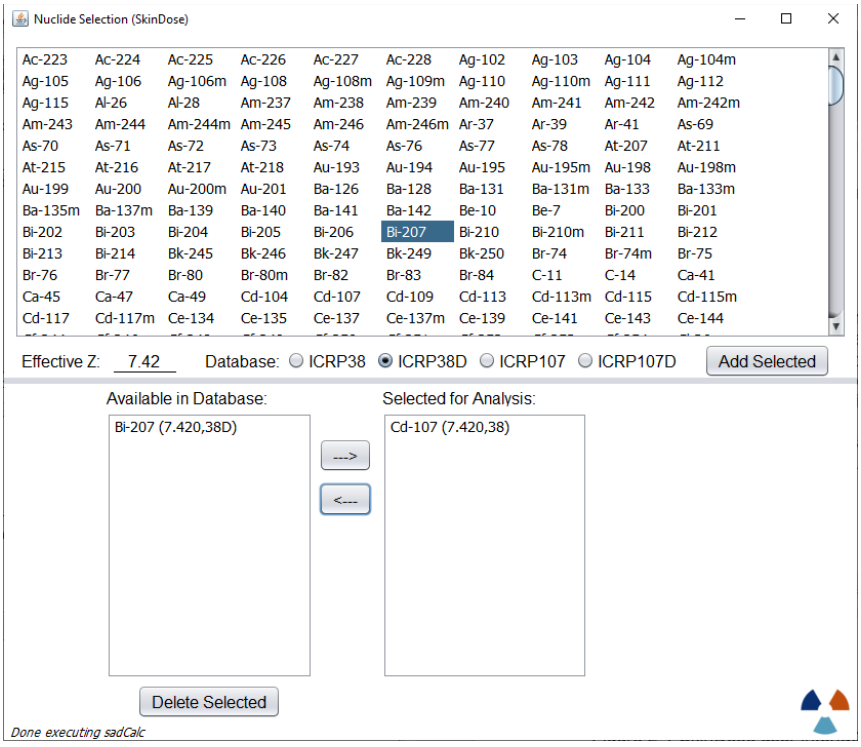


Figure 2-4 Nuclide Selection Window

When the process of adding the radionuclide is completed, the trefoil will stop spinning and the user will see the added nuclides in the “Selected for Analysis” window. The nuclide name will indicate the database from which the data were drawn, the effective

atomic number of the source material, and whether decay progeny are included, e.g., “Sr-90 (7.42,38D)”.

Once a radionuclide is added to the user library (“Available in Database”) it is available to be used in all subsequent calculations. The added radionuclide will remain unless the user purposefully removes it using the “Delete Selected” button beneath the “Available in Database” frame or uploads a new version of VARSKIN+. The nuclide data will always remain in the ICRP 38 and 107 main libraries.

In the main SkinDose (and WoundDose) window, the user has the option to view the radiological emission data by selecting (single clicking) the nuclide for which the information is requested and pressing the “Nuclide Info” button. After selecting the nuclide, the user is presented with the Nuclide Information window (Figure 2-5). Tabular information on all emission types, yield, and energy is provided along plots of emission spectra (i.e., emission yield as a function of energy), including beta, electron, alpha, gamma, and X-ray emissions, if emitted by the selected nuclide (Figure 2-6).

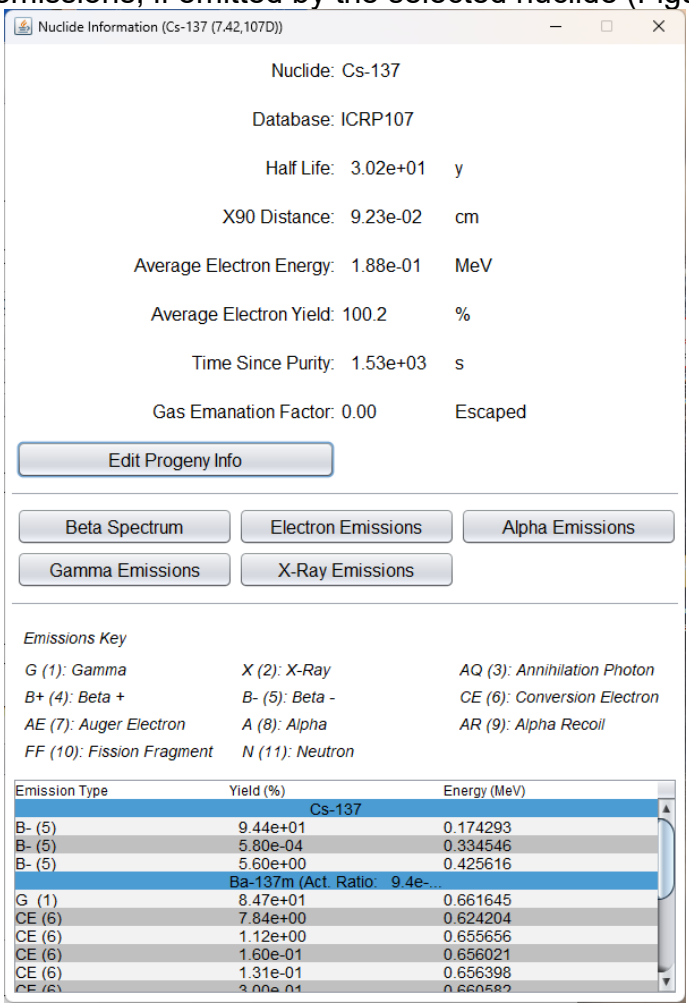


Figure 2-5 Nuclide Information Window

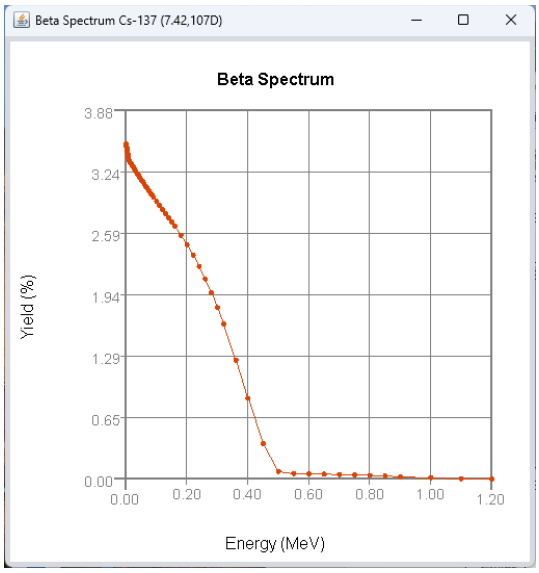


Figure 2-6 Example of an energy emission spectra

2.1.3 Detail of Decay Progeny Selection

Beginning in V+ v1.2, the Bateman equation has been implemented to parse the decay mechanisms of progeny-enabled nuclides and calculate their activities following a user-provided “time since purity” entry. If the decay chain includes a noble gas, the fraction of gas that escapes an open system can also be provided (with a default of zero escape). These activities are integrated over the user-provided exposure time to produce a decay factor by which to account for total dose due to the ingrowth and decay of radioactive progeny.

The user is asked for a time since purity, so that appropriate decay factors can be calculated by numerically integrating the Bateman equation from this “start” time to the “end” time -- the time since purity plus the irradiation time. Dose rates are calculated for each decay progeny individually, then adjusted by the proper decay factors to produce a decay-corrected dose for the whole chain.

Instead of compiling one composite nuclide, all progeny nuclides are retrieved individually with dose rates calculated for each. Progeny emissions are listed in the Nuclide Information dialog, separated by which parent nuclide produced them. The user-specified time since purity and gas emanation factor are also listed (and can be modified) there. The gas emanation factor describes what fraction of inert gas products (i.e., argon, krypton, xenon, and radon) have escaped. Time since purity entries longer than ten parent half-lives are not supported, and secular equilibrium is disabled for cases where the first progeny's half-life is longer than the parent's half-life.

Importantly, these updates to the progeny activity calculations apply only to the SkinDose module. While the shallow dose option of the WoundDose module uses essentially the same calculational method as SkinDose, the effective dose option uses tabulated values that do not account for progeny. Inclusion of progeny in the effective dose option would

thus require re-calculation of all the tabulated values. For this reason, progeny are excluded from the entirety of WoundDose until such time as progeny can be accounted for in all three dose options.

The nuclide addition window is unchanged, and users still select progeny-enabled nuclides by selecting “ICRP38D” or “ICRP107D” as the target database. If a nuclide has one or more radioactive progeny, a dialog box asking for Decay Information will be displayed (Figure 2-7) to collect time since purity and gas emanation information from the user.

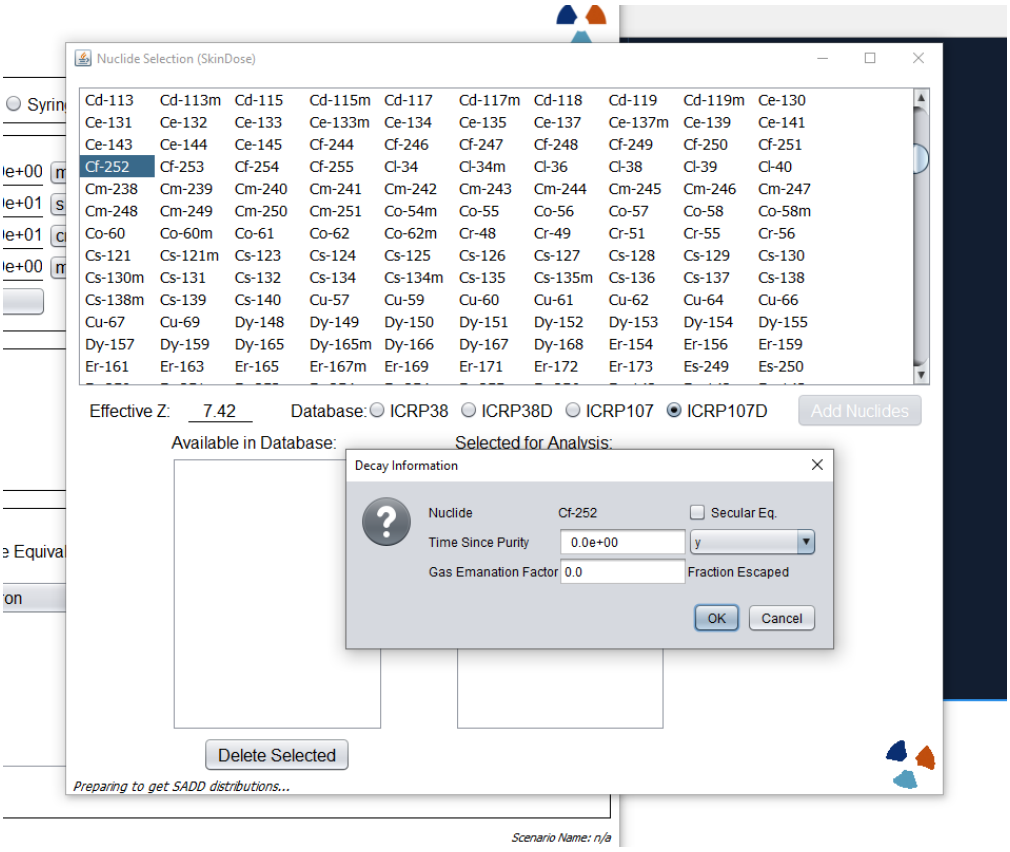


Figure 2-7 Decay information dialog

The time since purity and gas emanation factors are initialized to zero, to ensure that any user entry (and therefore progeny correction) is intentional. Units for time since purity default to the units of the parent nuclide’s half-life; the gas emanation factor is unitless and must take on a value between zero and one (1). If the selected parent has no progeny that would be affected by the gas emanation factor, that text entry box is disabled (grayed out).

Checking the box for secular equilibrium (Figure 2-8) grays out the time since purity entry box, while leaving intact any entry the user has made (in case the user changes their mind). This indicates that the time since purity entry, if any, has been overridden; the value to be used for secular equilibrium is set to ten times the half-life of the *first progeny*. This will ensure that an equilibrium (if one exists) with that progeny has been established.

However, it *does not guarantee* that equilibrium has been established with any later progeny.

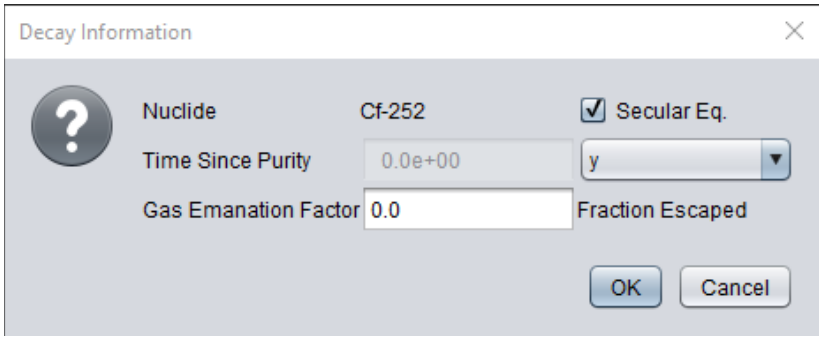


Figure 2-8 Decay Information dialog box with secular equilibrium selected

If the first progeny's half-life is greater than the parent's half-life, then no equilibrium of any type (secular or otherwise) will ever be established, and so the secular equilibrium check box is disabled. Similarly, if the entered time since purity exceeds ten times the parent's half-life, then very little parent activity will remain at the time of calculation. This results in an error while calculating the initial number of parent atoms N_0, which generally ends up being so large as to be effectively infinite. The message below (Figure 2-9) is displayed in this case.

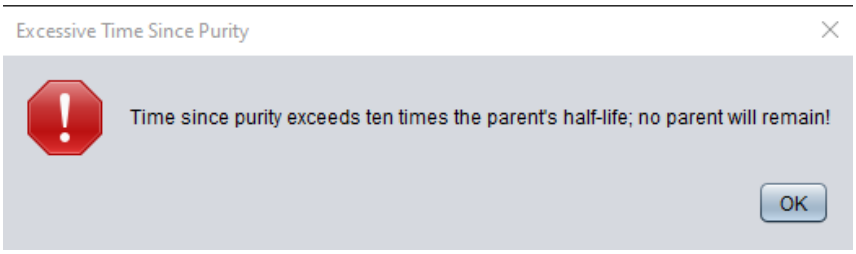


Figure 2-9 Error dialog for excessive time since purity

Clicking "OK" in the Decay Information window causes V+ to run SADCALC for the parent and all located progeny nuclides; this can take a minute or two depending on your computer speed. The status bar at the bottom of the Nuclide Selection dialog will indicate the proper number of progeny nuclides being calculated (not just the single parent nuclide). The parent nuclide then appears in the "Selected for Analysis" list.

The progeny nuclides (and emissions) included in a progeny-enabled dose calculation can be viewed in the Nuclide Information window (Figure 2-10). The table of emissions has been modified to list all combined emissions, with "separators" consisting of the responsible progeny's name. These separators also contain the activity ratio of the listed progeny, accounting for branching ratio and ingrowth time (i.e., the listed yield is the relative activity of the progeny at the beginning of irradiation). The "Edit Progeny Info" button below the gas emanation factor will bring up the same Decay Information dialog (see Figure 2-7), to allow the user to change those values.

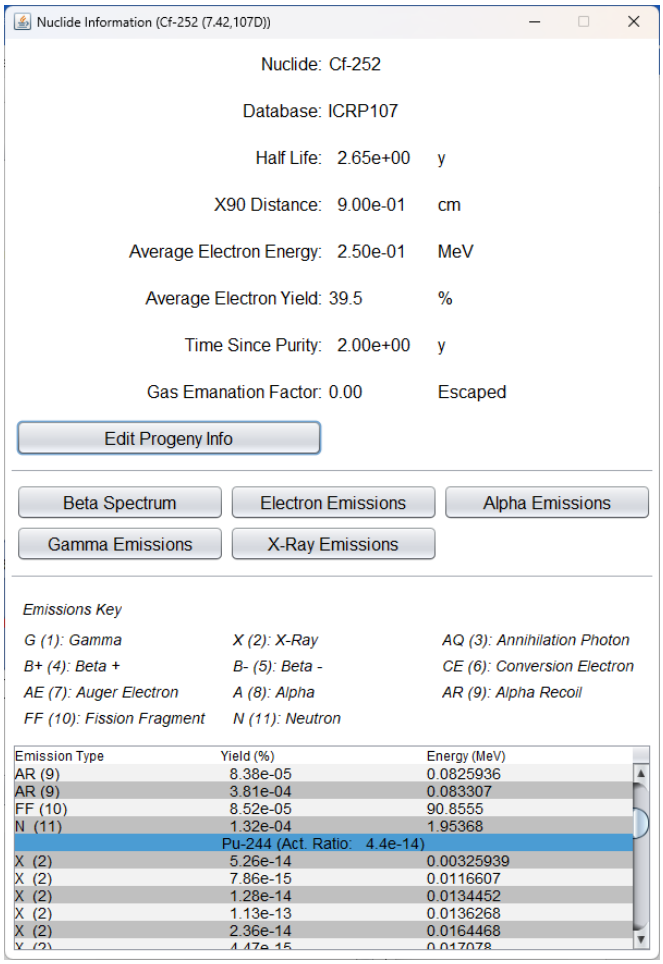


Figure 2-10 Nuclide Information dialog

2.1.4 Geometry Parameters

The default unit of measure for activity is the Becquerel (Bq). Users may change the activity unit by selecting a different unit from the dropdown list. The new unit must be chosen after selecting radionuclides; units can be mixed. Activity is entered to the right of the nuclide by selecting the numeric entry field; a default value of 1.0 is displayed. A user may select up to 100 radionuclides for a given scenario; nuclides with progeny are counted as only one (i.e., the parent) nuclide. If the "D" database is used for a given parent nuclide, all decay progeny, regardless of time, are assumed to be in equilibrium with the parent. If the user knows this not to be true, the progeny should be selected manually (non-starred decay database) so that independent dose values will be calculated for each decay product.

For the 3D geometry types, a "Distributed Source" checkbox will appear to the right of the "Nuclide Info" button. This option allows the user to enter the source strength in activity per unit volume for 3D sources. The distributed source option applies to all radionuclides in the scenario list. If the distributed source option is unchecked, selected radionuclides

will have activities expressed as total inventory instead of distributed activity. The user is cautioned to be certain of the activity units in each dosimetry calculation.

The geometry parameter in the Source Geometry Inputs frame (Figure 2-11, upper left beneath the SkinDose logo) changes contingent on the geometry chosen for the calculation. The user can choose the units of each parameter from the dropdown lists provided to the right of each input field. The units can be mixed for the different parameters; SkinDose makes the necessary conversions internally. Source thickness and source density are equally important for calculating skin dose, especially for electron dosimetry (alpha emissions will likely be absorbed for most volumetric sources). It is essential that these parameters are known accurately; otherwise, if necessary, their values should be underestimated so that conservative dose calculations will result. Modeling a lower source density and thickness decreases the effects of self-shielding, which in turn will generally increase shallow skin dose. If source dimensions are unknown, the following guidelines will help in choosing appropriate values. Table 2-1 shows the default values for the various parameters.

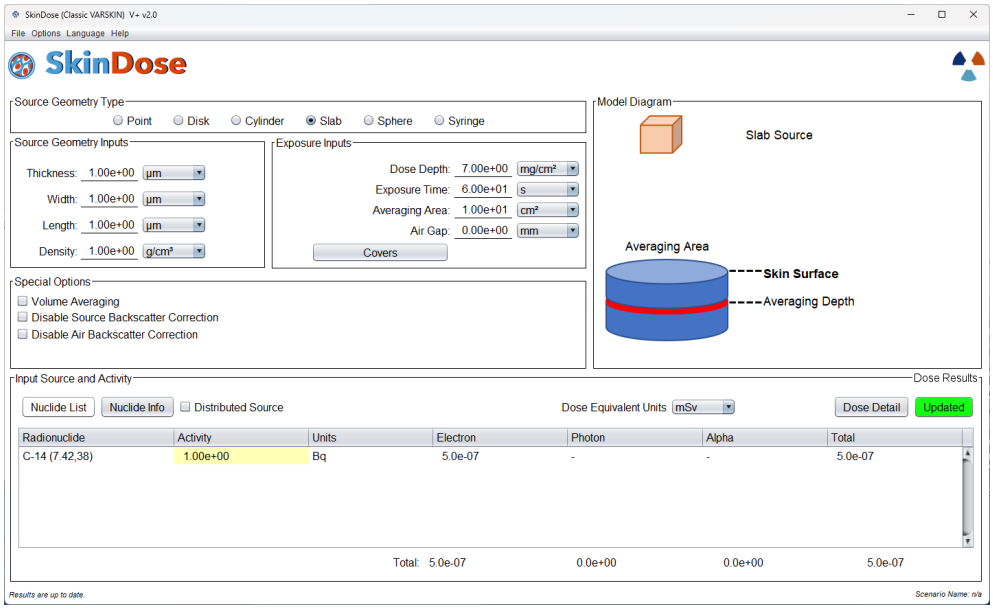


Figure 2-11 Slab Source Geometry Parameters (upper left)

2.1.5 Default State

SkinDose allows the user to save one default state for easy retrieval later. If the user wishes to change the default settings of Table 2-1, the following actions should be taken. From the File dropdown menu, selecting “Save As…” creates a file that contains all input parameters for the geometry described at that moment. If that geometry is to be run again later, the user can select “Open …” and enter the file name, thus recalling parameter values.

Source thickness and source density are equally important for calculating skin dose, especially for electron dosimetry (alpha emissions will likely be absorbed for most

volumetric sources). It is essential that these parameters are known accurately; otherwise, if necessary, their values should be underestimated so that conservative dose calculations will result. Modeling a lower source density and thickness decreases the effects of self-shielding, which in turn will generally increase shallow skin dose. If source dimensions are unknown, the following guidelines will help in choosing appropriate values:

Table 2-1 Parameter Limits and Default Values for Geometry Inputs

Parameter (x)	Limits	Default Value
Skin Density Thickness		7.0 mg/cm^2
Source Strength	None	1 Bq
Number of Sources	None	0
Dose Depth	0.0 <= Y <= 2.0 cm	7.0 mg/cm^2
Exposure Time	Y >= 0.864 s	60 s
Skin Averaging Area	0.01 <= Y <= 100.0 cm^2	10 cm^2
Airgap Thickness	0.0 <= Y <= 20.0 cm	0.0 cm
Cover Thickness	0.0 <= Y <= 5.0 cm	0.0 cm
Cover Density	0.0 <= Y <= 25.0 g/cm^3	0.0 g/cm^3
Source Diameter	1E-4 <= Y <= 35.7 cm	1.0 cm
Source Thickness (cylinder/slab)	1E-4 <= Y <= 10.0 cm	1.0 µm
Source Density	1E-3 <= Y <= 25.0 g/cm^3	1.0 g/cm^3
Source Width	1E-4 <= Y <= 20.0 cm	1 µm
Source Length	1E-4 <= Y <= 20.0 cm	1 µm
Source Diameter (syringe)	1E-4 <= Y <= 20.0 cm	1.0 cm
Source Length (syringe)	1E-4 <= Y <= 20.0 cm	10.0 cm
Source Density (syringe)	1E-3 <= Y <= 25.0 g/cm^3	1.0 g/cm^3
Volume Averaging Shallow Depth	0.0 <= Y <= 2.0 cm	1.0 mg/cm^2
Volume Averaging Deep Depth	0.0 <= Y <= 2.0 cm	10.0 mg/cm^2
Injury Depth (WoundDose)	0.0 <= Y <= 1.0 cm	0.1 mm
Abrasion Thickness (WoundDose)	0.0 <= Y <= 0.5 cm	0.0 mm
Biological Half-Life (WoundDose)	0.0 <= Y <= 200,000 d	0.4 d

Diameter (disk, cylinder) and length/width (slab): For sources of the same activity, the dose calculation for most radionuclides is relatively insensitive to these lengths for dimensions less than about 2 mm. Overestimating source dimensions will generally result in an overestimation of dose, unless the source size is larger than the averaging area, in which case the source may “appear” infinite.

- Thickness (disk, slab) and diameter (sphere): The electron dose calculation is very sensitive to these dimensions, especially at low energies. Minimizing the value of this dimension overestimate electron dose. For photons, these dimensions are not as critical for the dose calculation.

- Source density (volumetric geometries): For electron dosimetry, users should choose a source density that is consistent with the material containing the source. For hot particle contaminations, a typical density of stellite (cobalt/chromium alloy)

is 8.3 g/cm^3, and a density of 14 g/cm^3 and Z_{eff} of 25.8 are typical for fuel. For photon dose estimates, the source is assumed to be air, with negligible consequence, except for large, dense sources and very low-energy photons.

2.1.6 Covers and Airgap

Users can model the presence of a cover material, an airgap, or both. Figure 2-12 depicts the cylindrical source geometry to illustrate the cover/airgap model. The required input to describe the cover is material thickness and its corresponding density. Both parameters are needed to account for the $1/r^2$ dependency of the point kernel (geometric attenuation) and for the energy loss due to attenuation or residual energy absorption (material attenuation). For the airgap model, only the thickness of the airgap is required for input.

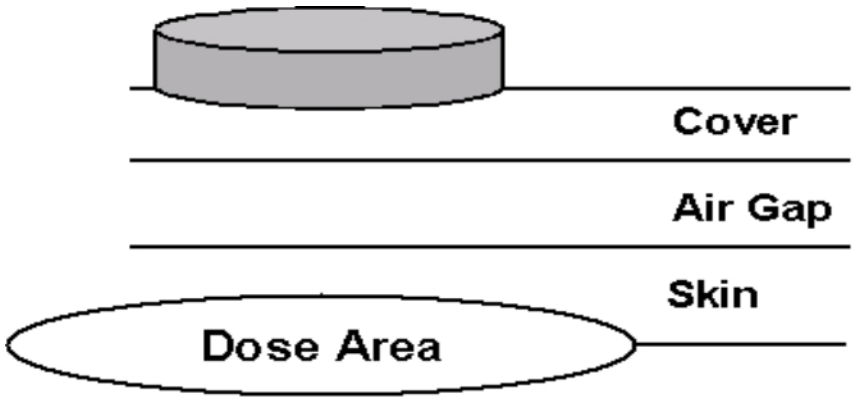


Figure 2-12 Schematic Showing the Cover Material and Airgap Models

The physical characteristics of the airgap and cover material can significantly affect the calculated skin dose. While the airgap has little consequence for material attenuation, its effect on geometric attenuation can be significant for electron dosimetry. SkinDose allows airgaps up to 20 cm. The airgap in photon dosimetry has the effect of disrupting charged particle equilibrium (CPE) and can appreciably influence dose at very shallow depths in tissue. Cover materials influence both the geometric and material attenuation. Table 2-2 gives some suggested thickness and density values.

SkinDose allows multiple cover materials to be modeled as a composite cover when the user selects the “Covers” button (Figure 2-2). The multiple-cover calculator allows the user to combine up to five covers (Figure 2-13). The user must enter a value for cover thickness and cover density; the cover density-thickness is then calculated. The calculator combines the different layers and calculates an effective thickness and density of the composite cover. The Model Diagram frame provides a visual indication that covers are being considered in the dose calculation. The printout from a given dose calculation will include the data for each cover layer, as well as the composite cover data.

To include more than five covers in the composite cover calculation, the user should calculate the composite cover thickness and density for the first five covers and then run the calculator again entering the first composite cover thickness and density as one of the

layers. Accordingly, if a composite cover is entered as one of the covers, the printout will not display the individual layers making up the composite cover.

Table 2-2 Suggested Values for Cover Thickness and Density

Material	**Thickness (cm)**	**Density (g/cm^3)**
Lab Coat (Plastic)	0.02	0.36
Lab Coat (Cloth)	0.04	0.9
Cotton Glove Liner	0.03	0.3
Nonsterile Nitrile Glove	0.005	0.9
Surgeon's Glove	0.02	0.9
Outer Glove (Thick)	0.045	1.1
Ribbed Outer Glove	0.055	0.9
Plastic Bootie	0.02	0.6
Rubber Shoe Cover	0.12	1
Coveralls	0.07	0.4

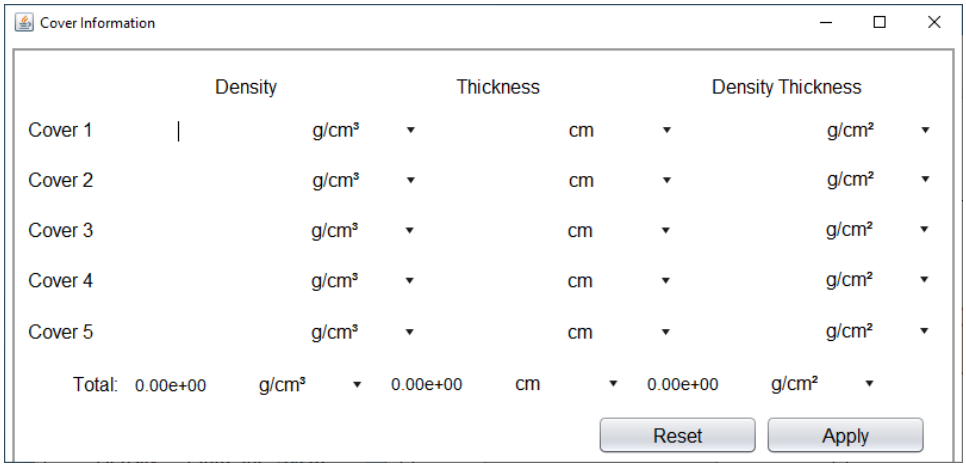


Figure 2-13 Multiple Cover Calculator Window

2.1.7 Special Options

SkinDose offers the user with two useful options that broaden the utility of the dose calculation to various portions of the skin. The choices of volume averaging and turning off backscatter correction (for electrons) are provided. These options should not be selected when the code is used to demonstrate regulatory compliance.

SkinDose allows the calculation of dose to be averaged over a user-defined volume of tissue described by a cylinder of specific diameter and thickness. The use of the volume-averaging dose calculation can be important, for example, in predicting the tissue dose averaged between 100 and 150 microns, as recommended by the ICRP (1991), for evaluating the dermal effects of skin dose. To perform a dose assessment to a volume of tissue beneath the surface, the user will select the Volume Averaging box in the center-left of the SkinDose window. The user is then prompted to enter the depths of which to

bound the dose calculation. The SkinDose model calculates the dose over the averaging area at 50 discrete layers between the bounds of tissue depths Figure 2-14. Thus, the volume-averaged dose model requires 50-fold more execution time than that for a single depth.

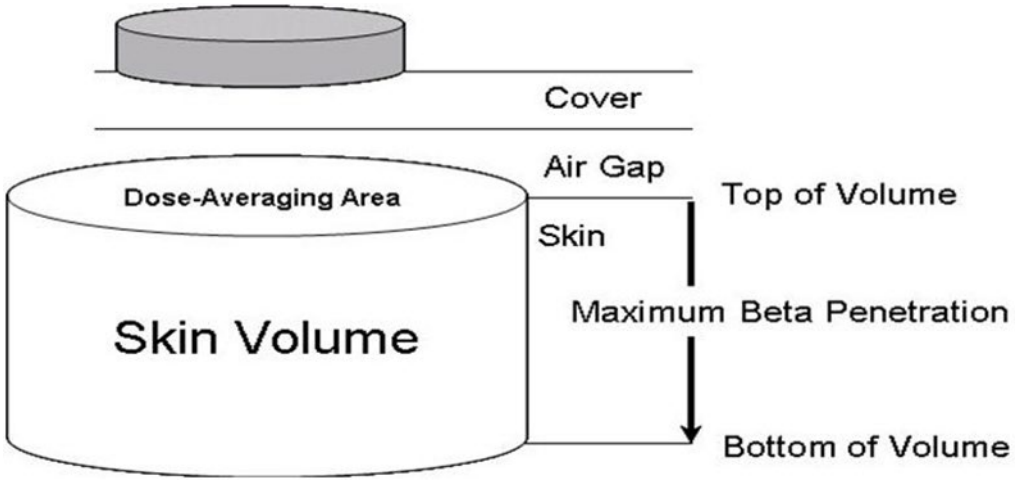


Figure 2-14 Schematic Diagram of the Volume-Averaged Dose Model Geometry

SkinDose is essentially based on Monte Carlo simulation of electron energy loss in water and various source materials. The fundamental model assumes that electron emissions occur in a homogeneous sphere of water. The model is then enhanced for the skin dose calculation by applying backscatter correction factors (see Section 2.1.7) to account for the presence of air above the skin. Several advanced users have wanted the flexibility to turn off this correction so that skin dose can be calculated for sources beneath the skin surface. The special options of turning off source backscatter correction and air backscatter correction are provided for these specialized cases. With the backscatter correction is ON, the source is modeled in SkinDose as sitting on the surface of the skin with air above. With the backscatter correction turned OFF, the source is modeled as being fully within a water sphere with electron scatter occurring equally in all directions.

Again, the typical user will not select any of the special options for regulatory compliance demonstration.

2.1.8 Calculating Dose

After selecting the desired geometric parameters, source nuclides and activities, the user initiates the calculation by clicking the red “Calculate” button. A progress bar will appear at the bottom of the SkinDose window, and the trefoil will be seen spinning for extended calculations. The number of radionuclides to be analyzed will affect the calculation time. Once complete, the red “Calculate” button turns to a green “Update” button indicating that the calculated doses in the output table are specific to the entry data visible in the SkinDose window.

2.1.9 Dosimetric Output

The dose results are displayed in the bottom third of the SkinDose window when the dose calculation is complete (see Figure 2-2). Dose equivalent units in British and International Systems can be displayed by selection in the dropdown menu. Dose equivalent for electrons, photons, and alpha particles are displayed along with totals for each emission type, for each nuclide, and for the overall scenario. Additional information can be obtained for each radionuclide by selecting (single clicking) that nuclide from the list and clicking "Nuclide Info". The information includes emission types, yield, energy, and other data (see Figure 2-5).

Additional dosimetry information can be obtained by selecting the nuclide of interest and clicking the "Dose Detail" button. The information provided in the Detailed Results window (Figure 2-15) includes the initial (i.e., instantaneous at time zero) dose rate in units of mSv/h by nuclide and by emission type (electron, photon, and alpha). The user is cautioned that a nuclide with a short half-life may not maintain that initial dose rate for the duration of the time unit.

The window also provides electron, photon, and alpha integrated dose with no decay correction. The purpose of these values is to provide the user with a dose estimate that allows for manual calculation of progeny contributions. For example, the user may wish to see the Ba-137m dose contribution from the Cs-137 parent, and since the half-life of Ba-137m is very short, the nuclide would quickly decay away. To account for continuous replenishing of Ba-137m, as is the case when it is in secular equilibrium with its parent, the user would view the No Decay Correction dose. In the WoundDose module, note the No Decay Correction doses do not have physical decay applied, but they do consider biological removal from the wound site.

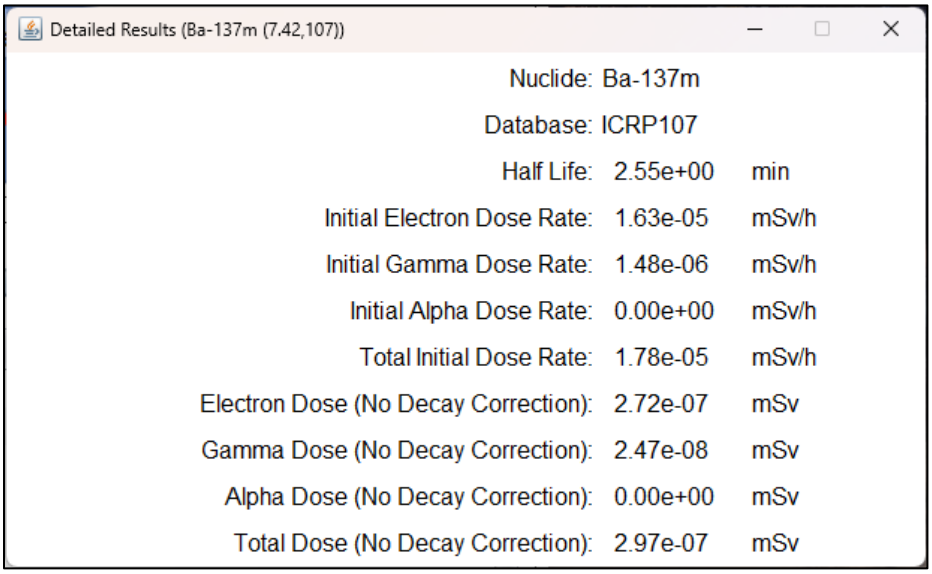


Figure 2-15 Detailed Results Provided by the Dose Detail Selection

2.1.10 Printed Dose Report and Code Documentation

A detailed dose report can be obtained by selecting the File dropdown menu and choosing “Save Report” (Figure 2-16).

Information contained in the report includes execution information, code name and version, input parameter values, nuclide information, dose results, and progeny dose contributions if included. This report is meant to provide documentation of a particular execution of SkinDose to support an employee dosimetry record.

If a quick view of the User Manual is necessary while running V+, the user may select the Help dropdown and choose User’s Manual to display a PDF of this NUREG.

```
********************************************************************************
SkinDose Report
********************************************************************************

--------------------------------------------------------------------------------
Execution Information
--------------------------------------------------------------------------------
Date: 2024-07-05
Time: 07:08:35.958614200
User Name: <username>
Host Name: RCD-ADM10
OS Name: Windows 11
OS Version: 10.0
OS Architecture: amd64

--------------------------------------------------------------------------------
Code and Version Information
--------------------------------------------------------------------------------
Main Code:                              VARSKIN+
Version:                                v2.0
Sub-code:                               SkinDose

********************************************************************************
Inputs
********************************************************************************

--------------------------------------------------------------------------------
Source Geometry Information
--------------------------------------------------------------------------------
Source Geometry Type:                   point

--------------------------------------------------------------------------------
Exposure Information
--------------------------------------------------------------------------------
              Dose Depth:        7.000     mg/cm²
           Exposure Time:       60.000         s
      Dose Averaging Area:       10.000       cm²
        Air Gap Thickness:        0.000        mm
```

Figure 2-16 SkinDose Report

2.2 Running WoundDose

The technical basis for the WoundDose module can be found in Chapter 4. To run WoundDose, the user selects the module name from the V+ window. On selection, the WoundDose user interface appears (Figure 2-17).

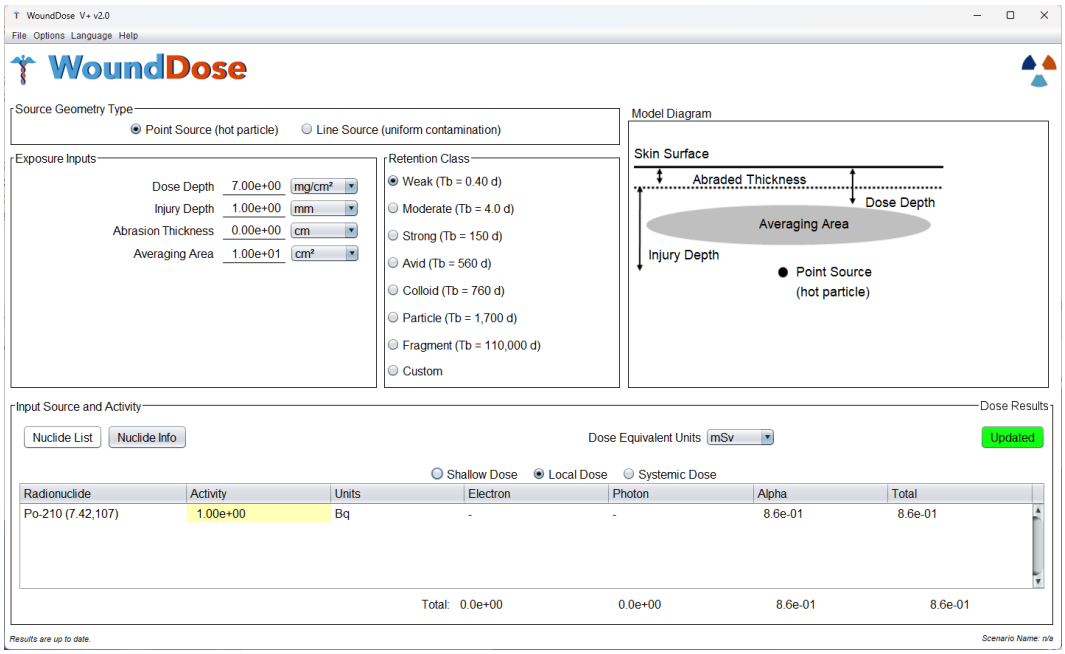


Figure 2-17 The WoundDose User Interface

2.2.1 User Inputs

The WoundDose module requires several inputs from the user. Each input will be discussed as well as the scenarios for which the inputs are most suited. Inputs should be entered without the use of the thousandth's separator.

Dose Depth. This is the depth at which the dose equivalent will be assessed. The regulatory standard for shallow dose is 70 microns (0.007 cm or 7 mg/cm^2). By default, WoundDose is set to this value. The user may choose to change the value, however, for most calculations the default is appropriate. Dose depth should not be changed out of concern about interaction with other input fields. The value at which dose is assessed is fixed to this singular input and is not affected by the other three fields.

Injury Depth. This depth is specified when a more severe trauma has forced radiation under the skin. Examples of such injuries would include severe burns, lacerations, or penetrating puncture wounds. The user will determine the depth of the injury and enter that value without any manipulation. If required, abrasion thickness can be used to model missing skin layers in the dose scenario. As illustrated in the Model Diagram (Figure 2-17 upper right), WoundDose first "removes" the abraded thickness and then applies the injury depth. If the user adjusts injury depth to include abrasion thickness and populates

that field, as WoundDose will combine the two, resulting in an errant injury depth for the dose scenario.

Abrasion Thickness (Point Source Only). This input is used to model missing skin layers for the dose scenario. When skin is removed by a trauma, it changes the thickness of tissue through which radiation must traverse to deposit energy in the basal cell layer. Electron exposure is especially sensitive to this field; a change of a few microns can heavily influence electron dose. Abrasion thickness can be used on its own or in conjunction with "injury depth". Most commonly, this field is applicable when the skin remains intact but has sustained some surface damage. Abrasions and light burns are examples of such scenarios. Again, the user should not adjust dose depth because of inputs for this field, as WoundDose internally handles all calculations and adjustments.

Dose-averaging Area. Much like dose depth, averaging area is set to the regulatory standard by default for assessing shallow dose (10 cm^2). For regulatory applications, the user will want to leave this value as such. WoundDose, however, offers experienced users the ability to customize this field. Inputs are accepted in microns, millimeters, centimeters, and inches from 0.01 cm^2 to 100 cm^2.

Retention Class. The final data entry needed for the WoundDose module is retention class. When radiation sources penetrate the body because a surface wound, they remain at the wound site for a certain time based on their physical properties, location of the wound, and biological clearance from the wound site. For WoundDose, these are divided into four main uptake categories: (1) soluble radionuclides; (2) particulates, aggregates, and bound states (PABS); (3) colloid stages; and (4) fragments (NCRP 2007). This field is used to describe the approximate biological half-life of the contamination. Used in conjunction with the nuclear half-life, the removal rate is calculated by WoundDose, and an integrated exposure time determined. The exposure time, or residence time (τ) of material remaining at the wound site, is determined by Eq. [2.1]:

$$\tau = 1.44\, T_e = 1.44 \left(\frac{T_r\, T_b}{T_r + T_b} \right), \qquad [2.1]$$

If the user has data on the biological half-life of the contaminant, the user may select "custom" and input the value directly. WoundDose allows the user to input a custom value with units of seconds, minutes, hours, days, or years.

2.2.2 Scenario Definition

WoundDose offers two distinct source geometries: point (hot particle) or line (uniform distribution). Point geometry should be chosen when the user wants to simulate a hot particle that has penetrated the skin. The particle can be placed at any depth beneath the skin surface up to 5 mm. The line geometry should be chosen when the user wants to simulate uniform contamination along the entire injury route. Line geometry should be used when the skin is punctured by a contaminated object (e.g., a contaminated screwdriver). For these calculations, all wound punctures are assumed to be normal to the skin surface.

Depending on the source type, WoundDose will present the user with three or four inputs, all of which are covered above. It is not mandatory to fill out each input (e.g., if there is no abrasion or deeper wound the fields can be set to zero). If abrasion depth and wound depth are both zero, however, the user should use the SkinDose module. Most nuclides can be classified into the various offered retention times. If users wish to input their own retention time for greater accuracy, they may. It is important to pay attention to the physical state of the contamination; chemical forms in different phases have vastly different retention times despite containing the same primary nuclide.

Nuclide selection is very similar to that in SkinDose. In the WoundDose module, the user once again has access to the full library of nuclides, but not the automatic progeny calculation function. Depending on their needs, users can opt to select nuclides from either ICRP 38 or ICRP 107. To add a nuclide to the dose scenario the user first clicks “Nuclide List”. The user then clicks the desired radionuclide and then “Add Selected”; the trefoil in the lower right corner will begin spinning as WoundDose generates decay tables. The trefoil will stop spinning and the nuclide will appear in the “Selected for Analysis” table. At this point the user may add another nuclide or close the nuclide library window to return to the dose scenario. To remove a nuclide, the user can select the nuclide in the “Selected for Analysis” table and click the arrow button facing away from the nuclide will move it into the “Available in Database” table. The nuclide will no longer be shown in the dose scenario, but WoundDose will retain the generated energy loss tables. To remove the nuclide from the user library entirely, the user should select it then click “Delete Selected”. The user can re-add the nuclide from the main library later, if needed.

2.2.3 Executing Dose Calculations

Once the user sets up the dose scenario, the calculation is initiated with the red “Calculate” button. If the button is greyed out, then a source has not been properly added to the scenario. The user should ensure that there is a nuclide displayed in the input/output table; when there is, the button will again turn red. After the user clicks the “Calculate” button, the trefoil in the upper right corner will begin spinning to indicate that WoundDose is processing. When the trefoil finishes spinning, the “Calculate” button will turn green and read “Updated”. At this point, WoundDose has finished calculations and the user may choose to record data. If any parameters for the dose scenario are changed the button will once again display “Calculate”. With the dose scenario updated, the user can opt to view either shallow, local, or systemic dose. These options are available as part of the input/output table customization options.

2.3 Running NeutronDose

The technical basis for NeutronDose can be found in Chapter 4. To run NeutronDose, the user selects the NeutronDose module from the V+ panel. On selection, the module's window appears (Figure 2-18).

2.3.1 Source Selection

When NeutronDose is initiated, a total of six different source types are selectable from a drop-down box at the top of the window: Spontaneous Fission, Neutron-Induced Fission, two types of Reaction source (alpha and gamma), Monoenergetic, and Custom. The first four source types (i.e., those except Monoenergetic and Custom) provide a list of pre-defined sources. The selection of Monoenergetic allows the user to enter a specific neutron energy, and Custom allows the user to upload a neutron energy spectrum. The "Spectrum" button (available for all Source Types except monoenergetic) is available to display the energy distribution of a given source.

NeutronDose contains an internal library comprised of 28 nuclides (from ICRP 107) which decay through spontaneous fission. The nuclides included in the library are isotopes of Cf, Cm, Es, Fm, U, and Pu. Neutron-induced fission spectra are provided for 5 nuclides, and reaction sources are provided for 6 (α,n) and 14 (γ,n) combinations, respectively. More technical detail is provided in Section 5.

A custom neutron spectrum can be uploaded using the following format: a comma-delimited file with neutron energies (in MeV) in the first column and yields in the second column (shown below). Emission yields are normalized, if necessary. If the file provided is not a valid file (i.e., does not yield any usable data), an error dialog box will appear. An error will also be generated if an exception is generated while attempting to read the file (most likely caused by Java not having permission to read the file).

```
* Neutron Energy (MeV), Yield (decimal fraction)
1.0,0.057692308
1.25,0.038461538
1.5,0.346153846
1.75,0.576923077
2.0,0.769230769
2.25,0.884615385
2.5,1.0
2.75,0.961538462
```

For other applications, NeutronDose allows the user to define a monoenergetic neutron source. The user simply needs to enter the energy value and select the appropriate units from the corresponding dropdown list.

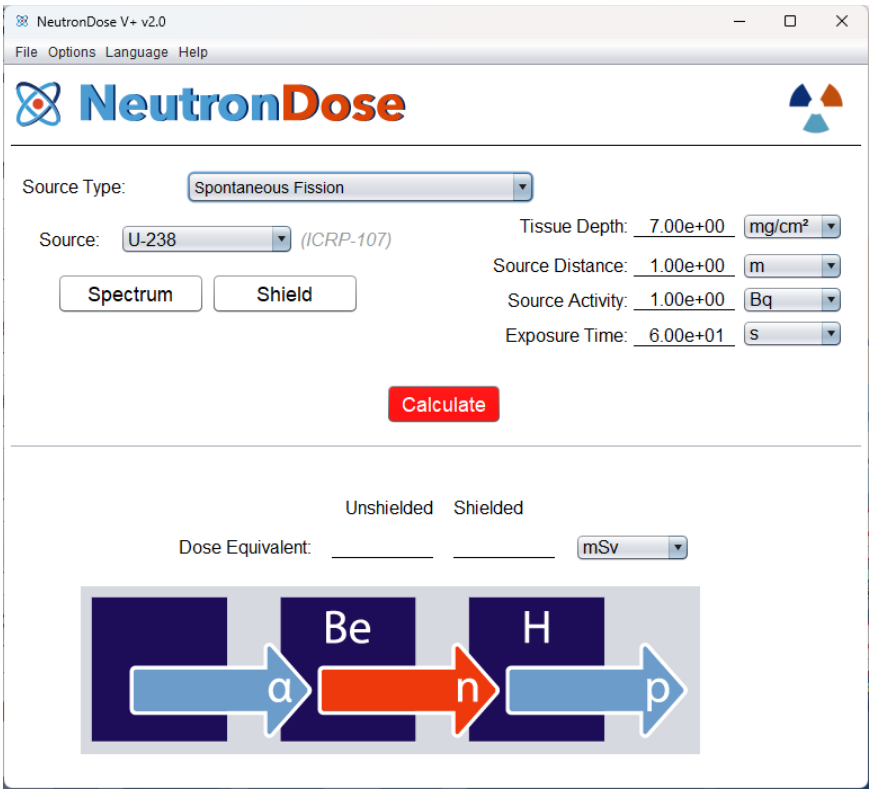


Figure 2-18 The NeutronDose User Interface

2.3.2 Defining the Dose Scenario

NeutronDose will display the window in Figure 2-18 and the source type dropdown bar shows “monoenergetic” by default when the user first opens the module (Figure 2-18). When used in this format, NeutronDose requires the user to input tissue dose depth and neutron fluence; fluence must be in units of neutrons per square centimeter.

Options in the Source Type dropdown (see Figure 2-19) include spontaneous fission, neutron-induced fission reactions, alpha reactions (α, n), photoneutron reactions (γ, n), monoenergetic, and custom. After selecting the appropriate nuclide, the user will input the tissue depth and the required source characteristics of source distance from target, source activity, and exposure time. NeutronDose will then calculate the neutron fluence used in the dose scenario. As a cautionary note, multiple units are available for each of the inputs; the user should verify that the units are correct before each calculation.

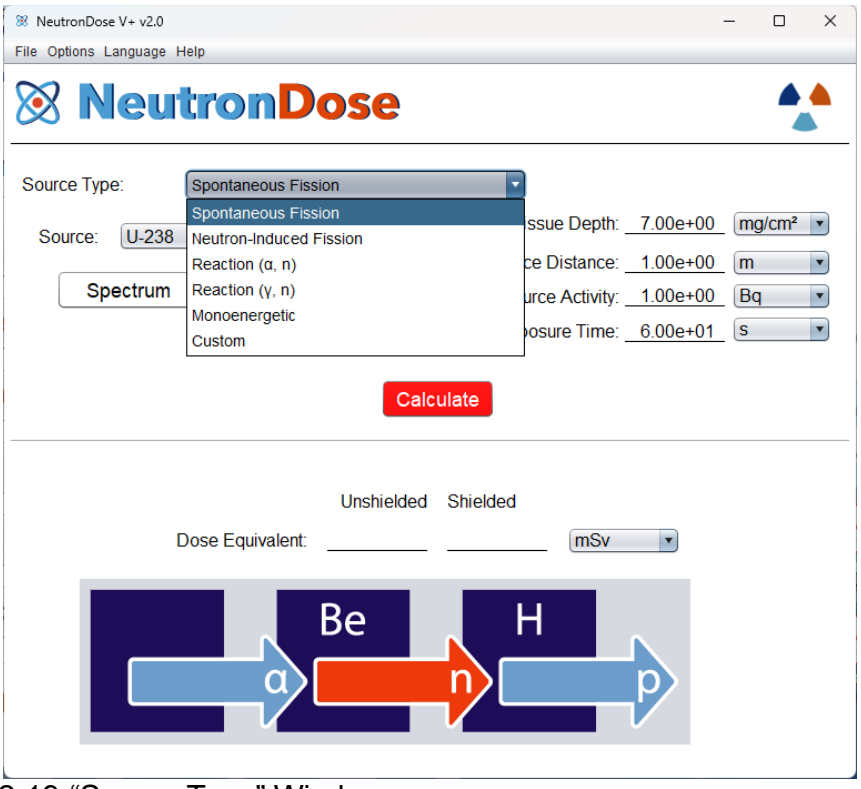


Figure 2-19 “Source Type” Window

2.3.3 Calculating Dose

Once the required fields are populated, the user initializes the calculation by clicking the red “Calculate” button. The calculations within NeutronDose are quick and the “Calculate” button will transform into a green “Updated” button to indicate completion. The user can change any parameters after the calculation; however, the “Updated” button will transform back into the “Calculate” button. This indicates that the calculated dose equivalent is not accurate for the currently displayed inputs. The user simply clicks the “Calculate” button again and NeutronDose will calculate the new dose equivalent. NeutronDose returns the dose equivalent in units of Sievert or rem. For convenience, each unit can be internally converted to the unit prefix of pico, nano, micro, or milli.

2.4 Running EyeDose

The technical basis for EyeDose appears in Section 5. To run EyeDose, the user selects the EyeDose module from the V+ window. On selection, the module's window appears (Figure 2-20).

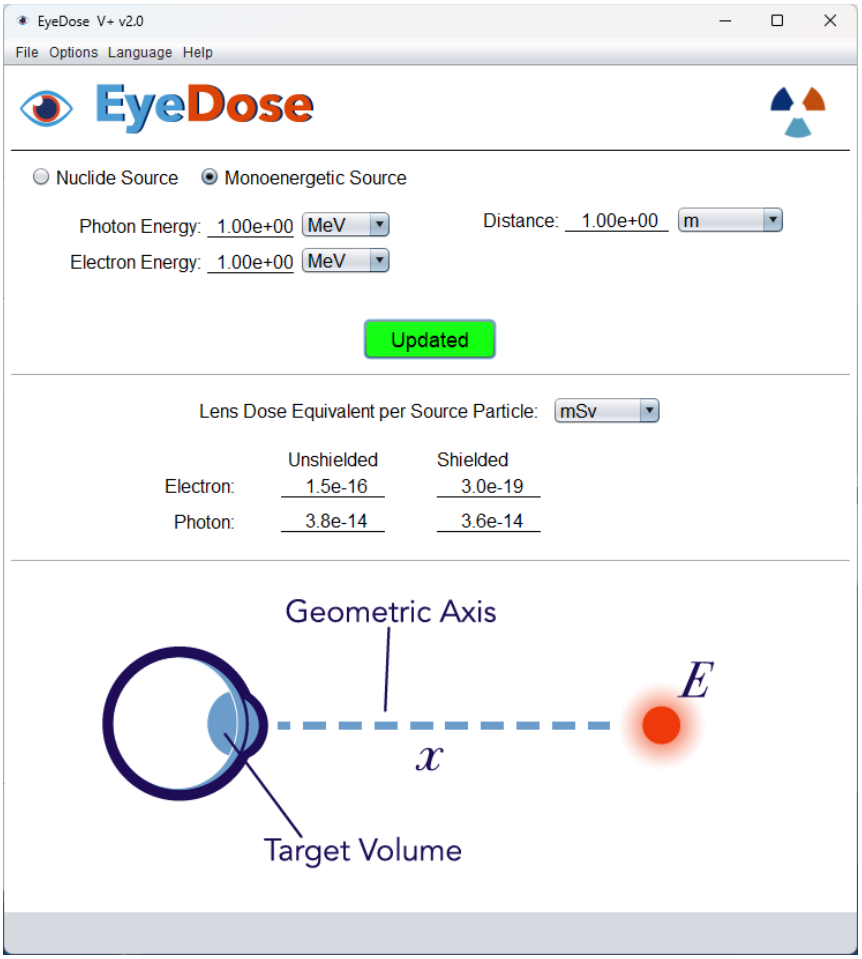


Figure 2-20 The EyeDose User Interface

2.4.1 Dose Scenario

The user begins by selecting either the "Nuclide Source" or "Monoenergetic Source" option. Each source option has its own distinct inputs with different required fields. Figure 2-20 shows the "Monoenergetic Source" option and Figure 2-21 depicts the "Nuclide Source" option. EyeDose contains an extensive internal library of photon and beta emitting nuclides which is accessed via this option. This library features full emission spectra for relevant nuclides which provides a high degree of accuracy in the calculations. When selecting a nuclide, the user may opt to use either the ICRP 38 or ICRP 107 nuclide database. The user is cautioned that the selected nuclide does not include any progeny emissions.

With “Nuclide Source” selected, EyeDose introduces several new user-populated fields (Figure 2-21). To begin, the user should select either ICRP 38 or 107, and the source nuclide from the adjacent dropdown list. With the appropriate nuclide database selected, the user then enters source distance, source activity, and exposure time. As with other V+ modules, the user can choose from multiple units. When entering data for the dose scenario, the user should ensure that the units are correct.

For monoenergetic sources, the user only needs to input particle energy and distance from the eye. No exposure time is required because EyeDose returns these calculations as dose equivalent per source particle emitted.

2.4.2 Running Calculations in EyeDose

The user initiates calculations within EyeDose with the red “Calculate” button. Processing power may influence calculation time in some cases; however, calculations should be nearly instantaneous for most users. To indicate that the calculation is complete, the “Calculate” button transforms into a green button that reads “Updated”.

2.4.3 Results

Because EyeDose presents dose in several different formats, it is imperative that the user understands what is being displayed. First, the user will notice that there are two columns: shielded and unshielded. Unshielded dose assumes a direct path from the source to the surface of the eyeball. Shielded dose refers to dose equivalent to the lens of the eye after incoming radiation has been attenuated by a standard pair of safety glasses (2 mm leaded glass). The glass is assumed to be centered around the eye while still resting on the nose. For specifics on the composition of the lens, the user can mouse over the word “shielded”. The safety glass begins at a fixed value of 1.05 cm from the surface of the eye. Therefore, EyeDose will report “N/A” for shielded doses if the distance between source and eyeball is less than or equal to 1.25 cm. The user should remember that when dealing with higher energy photons, it is possible that the shielded dose equivalent is higher than the unshielded due to attenuation, buildup, and redirection.

The other unique EyeDose result is from the “Monoenergetic Source” selection. Because of the customizability of incident beams, it is not feasible to return a dose from exposure time. EyeDose instead returns the dose equivalent per source particle. The user must then determine the number of source particles the dose scenario involved, and manually calculate total dose. Dose equivalent can be displayed in the units of Sievert and rem, with a variety of unit prefixes.

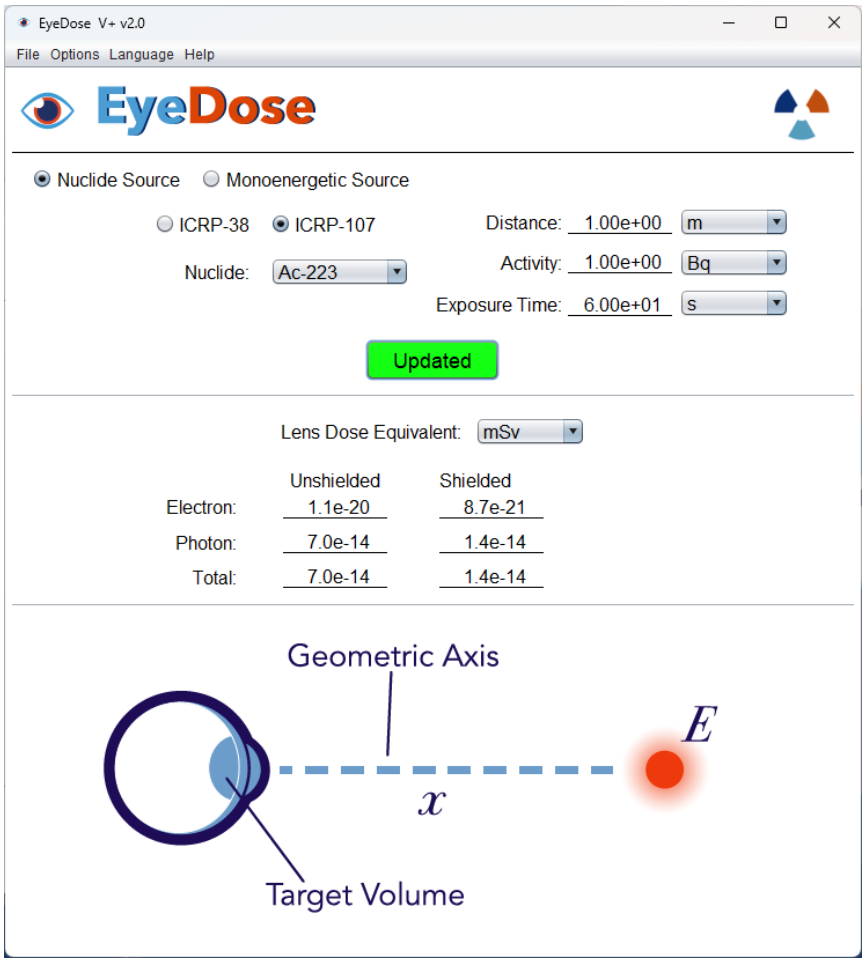


Figure 2-21 EyeDose “Nuclide Source” Window with User Input Fields

2.5 Running Extravasation Dose

Extravasation Dose (ExtravDose) is a new module in VARSKIN+ 2.0 for calculating local tissue dose from radiopharmaceutical extravasation during medical administration. The developed extravasation dosimetry model is a time-dependent, multi-dimensional, and multi-physics simulation that breaks the region into mesh/voxel volumes for analysis. It simulates the injection of a fluid with a defined activity concentration that is then transported throughout a region while accounting for mixing (i.e., concentration changes). With the transport of the concentrated fluid, a subsequent calculation of the spatial dependent dose rates and accumulated doses to tissue resulting from the fluid transport is determined. Models have been developed with the goal of focusing on ease of use for the end user in terms of the minimal number of required inputs while ensuring a reliable solution is obtained to help inform the decision-making process.

Users can perform quick approximations based on a minimal number of basic inputs (Basic mode) or in-depth assessments utilizing advanced modeling features with an expanded set of input parameters (Advanced mode).

To run the Extravasation Dose module, the user selects the module name from the V+ main window. On selection, ed. opens in basic mode and runs with minimal inputs required of the user. Input parameters for a basic calculation are available on a single screen display (Figure 2-22). Users can select an advanced calculation with the Mode dropdown tab at the top of the input screen. The input window for an advanced calculation is shown in Figure 2-23.

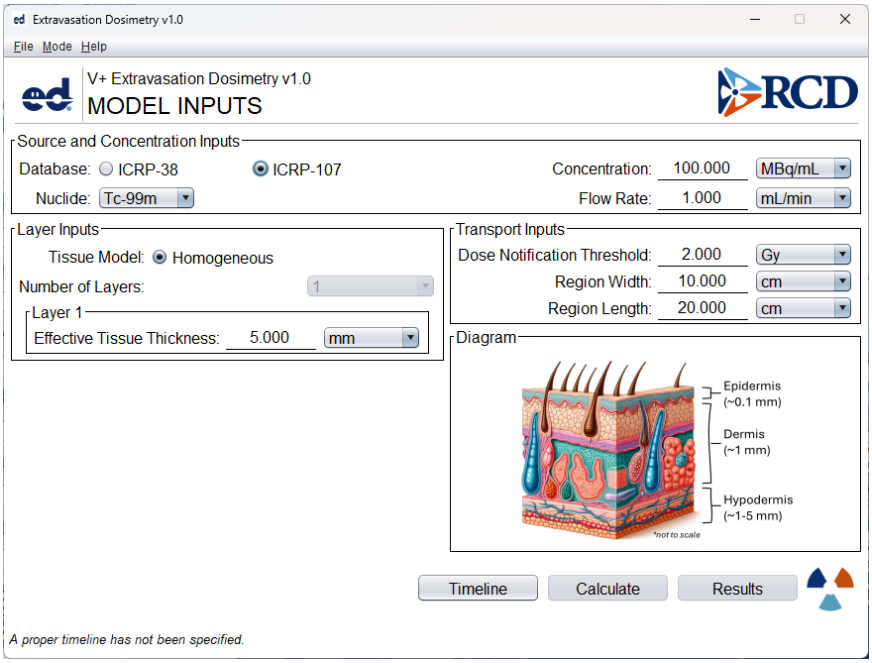


Figure 2-22 User Interface for a Basic calculation.

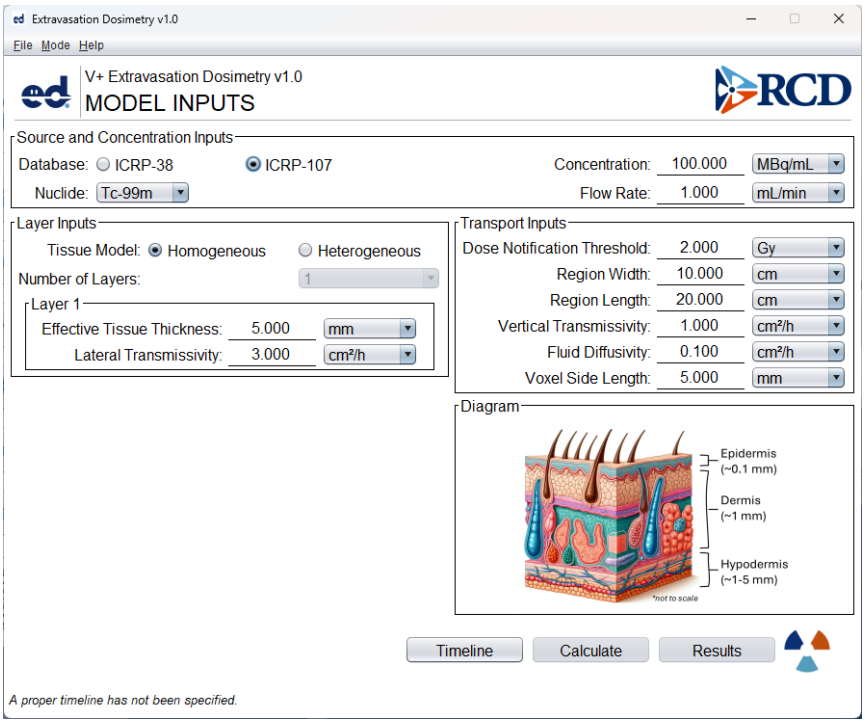


Figure 2-23 Main User Interface for an Advanced calculation.

The window for timeline inputs, needed for both modes, is displayed in Figure 2-24.

Table 2-3 lists the input parameters and features available for Basic and Advanced calculations. The extravasation module contains default values for many input parameters. However, default values are not recommended values. Users should select values that best represent individual extravasations. Inputs for ed. fall into four categories:

- Parameter is known at the time of administration.
- Parameter is readily deduced from clinical information.
- Parameter is inferred from clinical information during extravasation assessment.
- Modeling feature selection is made for the calculation.

The input category, default value, and brief rationale are discussed for the individual inputs of basic and advanced calculations, respectively.

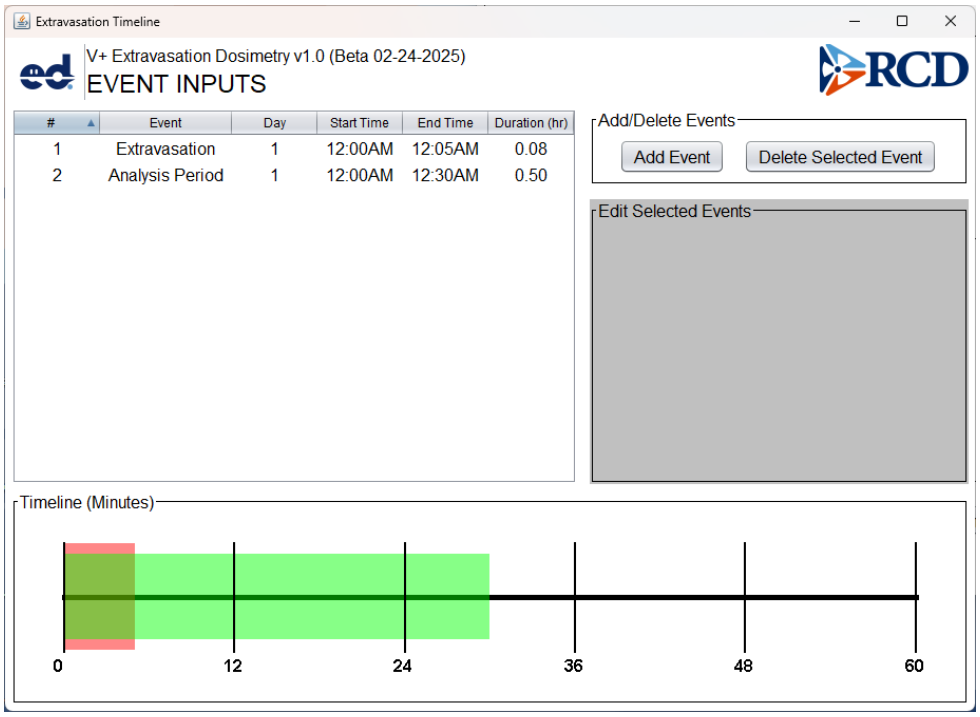


Figure 2-24 User Interface for Timeline Inputs.

Table 2-3 Parameters Available for Input in Basic & Advanced Calculations

Parameter or Feature	Basic Calculation	Advanced Calculation
Decay Database	✓	✓
Nuclide	✓	✓
Concentration	✓	✓
Flow Rate	✓	✓
Region Width	✓	✓
Region Length	✓	✓
Dose Notification Threshold	✓	✓
Tissue Model	homogeneous	heterogeneous
Number of Layers	1	✓ (up to 4)
Tissue Thickness	single value	one value per layer
Lateral Transmissivity	single value	one value per layer
Vertical Transmissivity	-	✓
Fluid Diffusivity	-	✓
Cubic Voxel Side Length	set to tissue thickness	✓
Timeline Inputs	✓	✓

2.5.1 User Inputs for Basic Calculation

Basic calculations are allowed for homogenous tissue properties with the following input parameters and modeling features. When inputs limits are provided, they are soft limits such that if values outside the recommended window are specified a warning will be provided to the user. In some cases, hard limits are provided to ensure program functionality, these are noted below where they apply. Figure 2-25 provides a high-level diagram depicting the hierarchy of setting geometry. As shown, it is best to first define the minimum thickness of tissue to resolve, followed by the voxel size desired to resolve the problem, and then finally the length and width of the region of interest. After completion of any entry point in Figure 2-25 a final call to "Set Voxel Size" is made for a last sweep to ensure consistency.

Database. Select radioactive decay and emission data from ICRP Publication 38 or ICRP Publication 107.
Default value: ICRP 107 decay data.
Rationale: ICRP 107 decay data are more recent and provide an expanded set of radionuclides, compared to ICRP 38 decay data.
Category: This input is a modeling feature.

Nuclide. Enter radionuclide in the radiopharmaceutical.
Default value: Tc-99m
Rationale: User must select nuclide from a drop-down list.
Category: This parameter should be known at the time of administration.

Tip: The criteria for particle emission selection (energy and probability) is the same as that applied in the SkinDose module. If the user wishes to see the list of emissions for a given nuclide, go to the SkinDose module, call that nuclide into the simulation, and then select the "Nuclide Info" button.

Concentration. Activity concentration for administered radiopharmaceutical.
Default value: 100 MBq/mL
Input Limits: 0.000001 – 1,000,000 MBq/ml
Rationale: Order-of-magnitude placeholder value for therapeutic administrations
Category: This parameter should be known at the time of administration.

Flow Rate. Radiopharmaceutical flow rate into patient during administration.
Default value: 1 mL/min
Input Limits: 0.1 – 1,000 ml/min
Rationale: Order-of-magnitude placeholder value. Upper range may only be appropriate for injections of less than 1 minute.
Category: This parameter should be known at the time of administration.

Tissue Model. Homogeneous tissue model is selected. Homogeneous tissue is supported in a Basic calculation and assigns one effective lateral transmissivity to tissue infiltrated by extravasated fluid. Vertical transmissivity representing flow across tissue layers is unaffected by lateral transmissivity.
Default value: Homogeneous in Basic mode.
Rationale: Basic tissue modeling in this mode.
Category: This input is a modeling feature.

Effective Tissue Thickness. Specify the thickness of tissue infiltrated by radioactive fluid during the extravasation. Smaller values for effective thickness tend to constrain radioactivity in thinner tissue layers, which can result in higher local tissue doses. When extravasated fluid infiltrates deeper into tissue, a more representative value should be entered. Refer to Effective Lateral Transmissivity for additional discussion on selecting a representative value.
Default value: 5 mm
Input Limits: 1 – 100 mm
Rationale: Generic value for tissue surrounding a vein is a few millimeters (i.e., larger than vein diameter). Patient anatomy can influence this parameter. The effective tissue thickness should be consistent with tissue experiencing extravasated fluid flow.
Category: The parameter can be inferred from clinical information after the extravasation is discovered.

Dose Notification Threshold. Parameter highlights certain outputs so that the user can assess potential severity.
Default value: 2 Gy
Input Limits: 0.001 – 50 Gy
Rationale: A generic lower level of interest is suggested for small volumes of tissue. No regulatory requirements are implied by this default value.
Category: This input is a modeling feature that does not influence the calculation.

Region Width. The region of interest is three-dimensional and defined by a width, a length, and a depth. This parameter sets the maximum tissue width available for radioactive fluid infiltration from extravasation. Equivalent, for example, to the physical width of patient's arm where the extravasation occurs.
Default value: 10 cm
Input Limits: 1 – 50 cm; These input limits are hard limits to prevent unrealistically large problems from being generated. If a value is specified outside of this window the window value is set.
Rationale: Order-of-magnitude placeholder value. User should enter an appropriate value for the patient. Model assumes the radiopharmaceutical is administered at the center of the region of interest.
Category: This parameter can be readily deduced from clinical information.

Region Length. This parameter sets the maximum tissue length available for radioactive fluid infiltration from extravasation and is equivalent, for example, to the physical length of tissue of interest where extravasation occurs.

Default value: 20 cm
Input Limits: 1 – 50 cm; These input limits are hard limits to prevent unrealistically large problems from being generated. If a value is specified outside of this window the window value is set.
Rationale: Order-of-magnitude placeholder value. User should enter an appropriate value for the patient. Model assumes the radiopharmaceutical is administered at the center of the region of interest.
Category: This parameter can be readily deduced from clinical information.

Timeline Inputs. Timeline inputs are a modeling feature with a separate user interface (Figure 2-24). The interface includes fields for *Extravasation* timing, optional *Warm Compress* timing, optional *Limb Elevation* timing (with angle of lift), and *Analysis Period* timing. Elevation orientation is aligned with the longitudinal direction of the limb (i.e., polar angle equals zero degrees and is not specified by the user). This simplification accommodates elevation of the entire limb (e.g., lifting an arm at the shoulder with a straight elbow or lifting a leg at the hip with a straight knee). The *Warm Compress* event increases the vascular-lymphatic removal rate from 0.15 h^{-1} to 0.25 h^{-1}.

When adjustments to lateral transmissivity are necessary to produce general trends in the spatial distribution of radioactivity in local tissue, and its retention over time for an individual patient, users are encouraged to perform an advanced calculation.

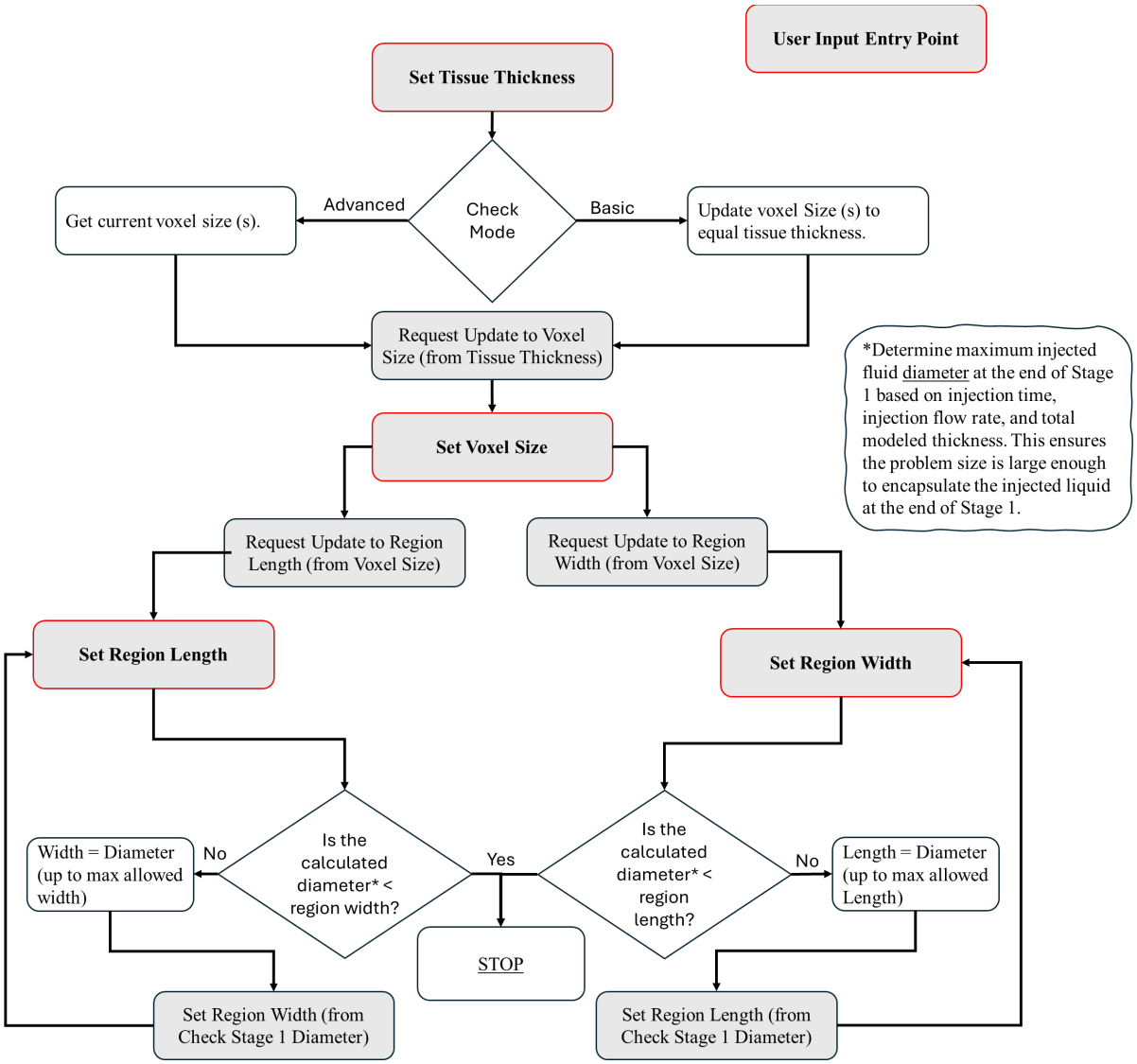


Figure 2-25. Logic for ensuring consistent region geometry is defined.

2.5.2 Inputs for the Advanced Calculation

Users can invoke an advanced calculation with the Mode dropdown tab at the top of the input screen. Advanced calculations allow different tissue layers and parameter values for those layers. During an advanced calculation, lateral transmissivity is automatically modified according to the amount of extravasated fluid present. Mitigative actions that change the tissue conditions can be added in the timeline inputs window (e.g., tissue elevation to promote fluid flow away from the area or a warm compress to increase vascular-lymphatic removal). A warm compress increases the vascular-lymphatic removal rate from 0.15 h^{-1} to 0.25 h^{-1}. There are at least 10 input parameters and 5 modeling features as well as timeline inputs for an advanced calculation. For advanced calculations with multiple tissue layers, each tissue layer adds two parameters. Compared to a basic calculation, more input parameter values are inferred from the

extravasation assessment in an advanced calculation. In addition to the basic inputs that are not repeated, the following advanced inputs are available.

Tissue Model. The user selections either Homogeneous or Heterogeneous. In heterogeneous model, up to four layers are allowed to characterize the tissue. The effective thickness and lateral transmissivity can be adjusted in each layer to provide faster or slower lateral movement of extravasated material depending on tissue depth.

Number of Layers. [No. X notation refers to Layer X]
User enters the number of tissue layers to obtain the desired modeling fidelity as supported by user-obtained clinical information regarding the patient and extravasation. Multiple tissue layers would require a more detailed assessment of the extravasation.
Default value: 1
Input Limits: 1 – 4 layers
Rationale: Default establishes the first (or only) layer in Advanced mode. When the user has information to select different lateral transmissivities for multiple layers, a value greater than 1 would be entered to establish multiple layers.
Category: This input is a modeling feature that activates other input parameters.

No. X Tissue Thickness. [No. X notation refers to Layer X]
Tissue thickness for Layer X. When multiple tissue layers are specified, the user is permitted to enter different thicknesses for each layer. The total thickness of tissue receiving radioactive fluid equals the sum of thicknesses of all layers.
Default value: 1 mm
Input Limits: 1 – 50 mm
Rationale: Generic value for tissue surrounding a vein is a few millimeters (i.e., larger than vein diameter). Patient anatomy can influence this parameter. Default thickness of 1 mm is an approximation for dermal thickness with Number of Layers equal to 1 (default). Additional layers can be added for the hypodermis when those layers are infiltrated by extravasated fluid flow. The total thickness of all layers should be consistent with tissue experiencing extravasated fluid flow.
Category: The parameter can be inferred from clinical information after the extravasation is discovered.

No. X Lateral Transmissivity. [No. X notation refers to Layer X]
Nominal lateral transmissivity for Layer X. Lateral transmissivity affects fluid movement according to a pressure gradient. Limited data are available for this parameter. When multiple tissue layers are specified, the user is permitted to enter a different lateral transmissivity for each layer.
Default value: 3 cm^2/h
Input Limits: 0.01 – 100 cm^2/h
Rationale: Intended to accommodate the largest extravasated fluid volumes with thicker tissue thicknesses, the default value is slightly greater than the geometric median for the very large range of this parameter. Smaller lateral transmissivities are recommended for extravasated fluid volumes less than 20 ml. Flow modeling in thin tissue layers warrants smaller lateral transmissivities for each layer. The flow model adjusts lateral transmissivity

based on the amount extravasated fluid present. For these reasons, users should be prepared to reduce lateral transmissivity values so that the lateral spreading in tissue over time corresponds to clinical observations or expectations.
Category: This parameter can be inferred from clinical information during the extravasation assessment.

Vertical Transmissivity. Vertical transmissivity affects fluid movement between layers according to a pressure gradient. Limited data are available for this parameter. Vertical flow across tissue layers is expected to be more restrictive compared to lateral flow within a tissue layer.
Default value: 1 cm^2/h
Input Limits: 0.0001 – 10 cm^2/h
Rationale: Default value is one third of the default lateral transmissivity.
Category: This parameter can be potentially inferred from clinical information during the extravasation assessment.

Fluid Diffusivity. Diffusivity affects radioactivity transport according to a concentration gradient. The influence of this parameter on local tissue dose for extravasation time frames is not well understood.
Default value: 0.1 cm^2/h
Input Limits: 0.00001 – 1 cm^2/h
Rationale: Order of magnitude estimate for diffusive flow driven by the extravasated fluid concentration gradient between adjacent computational cells (voxels). Value is a factor of ten smaller than the vertical transmissivity. Smaller values may be appropriate.
Category: The parameter can be potentially inferred from clinical information after the extravasation is discovered.

Cubic Voxel Side Length. Voxel side lengths that are a mathematical factor of the thinnest layer thickness are recommended because one or more computational cells will stack to completely fill that thickness. Adhering to this recommendation prevents splitting of a computational cell by a layer boundary (i.e., prevents the properties of two layers attributed to a single computational cell).
Default value: 5 mm
Input Limits: 1 – 10 mm; These input limits are hard limits to prevent unrealistically large problems from being generated. If a value is specified outside of this window the window value is set. There are additional limits based on the following requirements:

- The voxel size is limited such that there are less than 80,000 voxels modeled. This value is set to ensure a maximum memory usage of approximately 4GB. If a voxel size is specified that violates this limit a new value is automatically calculated based on the region width, length, and total thickness and is re-entered on the input screen.
- The voxel size is set to ensure that it is no larger than the thinnest specified layer. If a voxel size is specified that violates this limit a new value is automatically calculated and re-entered on the input screen.
- The voxel size will be set to ensure it fits into all layers perfectly by finding the least common denominator for the size that allows. Upon doing this it is possible the

limit minimum range of 1 mm to be violated in order to satisfy the user input geometry.

Rationale: Smallest computational cell size supported by the initial module. Long simulation times could be alleviated by increasing this parameter.

Category: This input is a modeling feature. Different values can influence the computational time for the simulation.

2.5.3 Executing Dose Calculations

The ed. calculation is initiated with the “Calculate” button. After the user clicks the “Calculate” button, the calculation begins, the button changes to “Cancel” (to cancel the calculation), and the trefoil in the lower right corner will begin spinning to indicate that Extravasation Dose is processing. When the trefoil finishes spinning, the calculation is complete.

Each calculation generates a large amount of spatial- and time-dependent information. To visualize this information, two-dimensional results for absorbed dose rates (or activity concentrations in tissue) are displayed at different depths in tissue. While activity concentration results indicate radioactive “source strength” in each computational cell, absorbed dose rate results combine dose contributions from radiation emitted within the same cell and surrounding cells. Figure 2-26 displays an example of the Results screen. Because these summary results pertain to the entire simulation, they are unaffected by user interactions with the output.

By selecting one of three radio buttons, the user can view a two-dimensional diagram of Accumulated Dose [Gy], Activity Concentration [MBq/cm^3] in each calculational cell or Absorbed Dose Rate [Gy/sec]. The accumulated dose displays absorbed dose integrated over time for each displayed voxel up to the current viewing time. As time progresses, accumulated dose continues to increase. The activity concentration provides a visual indication of the activity present in each voxel as a function of time over the entire analysis period. Likewise, the absorbed dose rate is summarized over time.

At the bottom of the Results screen, summary outputs are presented for:

- Extravasated Activity [MBq], A

$$A = V \cdot C \qquad [2.2]$$

C Activity concentration of radiopharmaceutical [MBq/mL]

- Extravasated Volume [mL], V

$$V = Q \cdot t \qquad [2.3]$$

Q Extravasation volumetric flow rate [mL/min]

t Elapsed time of extravasation [min]

- Maximum Voxel Dose [Gy];
- Maximum Voxel Dose Rate [Gy/sec];
- Time to Maximum Voxel Dose Rate [min];
- ROI Exceeding Threshold [%]; and

- Dose to ROI (Region of Interest) [Gy], D

$$D = \int_0^t \dot{D}\,dt \qquad [2.4]$$

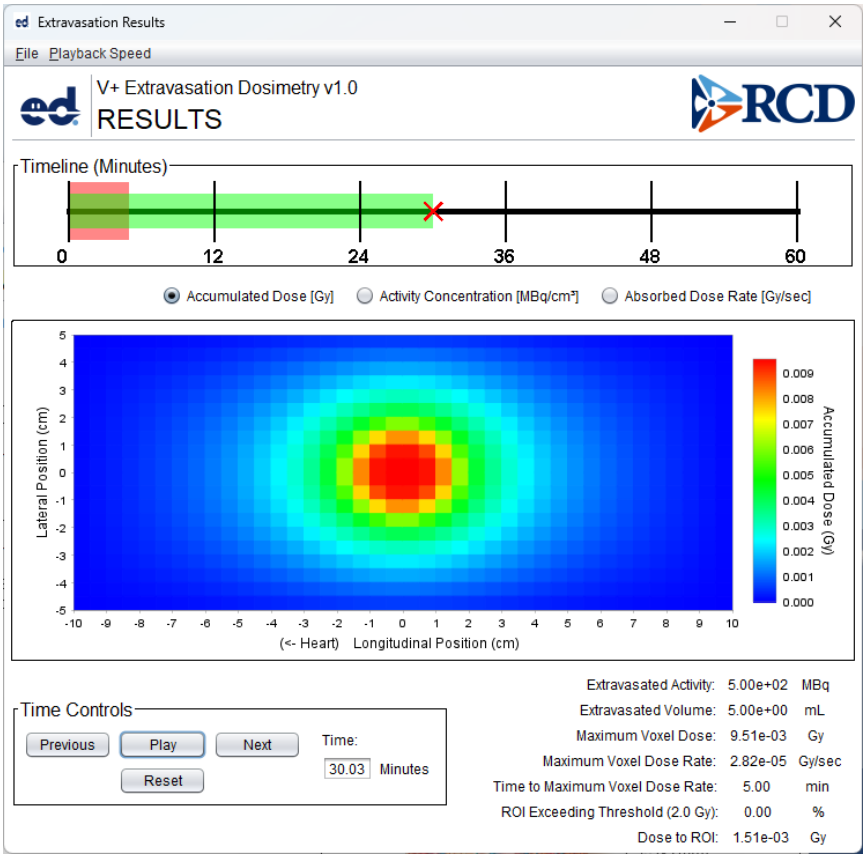


Figure 2-26 Example Output Screen for the Extravasation Dosimetry Module.

To the right of the image, the user can increment the view to a particular depth of interest, and to the lower left, time increments can be adjusted. The auto feature (Play) for time begins a time progression of results for a given depth in tissue. As time progresses, a red X moves from the left to the right on the timeline at the top of the screen, and the time index updates at the bottom of the screen.

2.6 Running Radiological ToolBox

Version 3.0.0 of the Radiological ToolBox (Figure 2-27) is dropped into V+ in its compiled state. When the user selects Rad ToolBox from the opening window, the software is executed. ToolBox is currently written in Visual Basic without support. The user is directed to the Radiological ToolBox documentation (Eckerman and Sjoreen 2013) for information regarding the execution and use of the software. Toolbox updates will appear in future versions of V+.

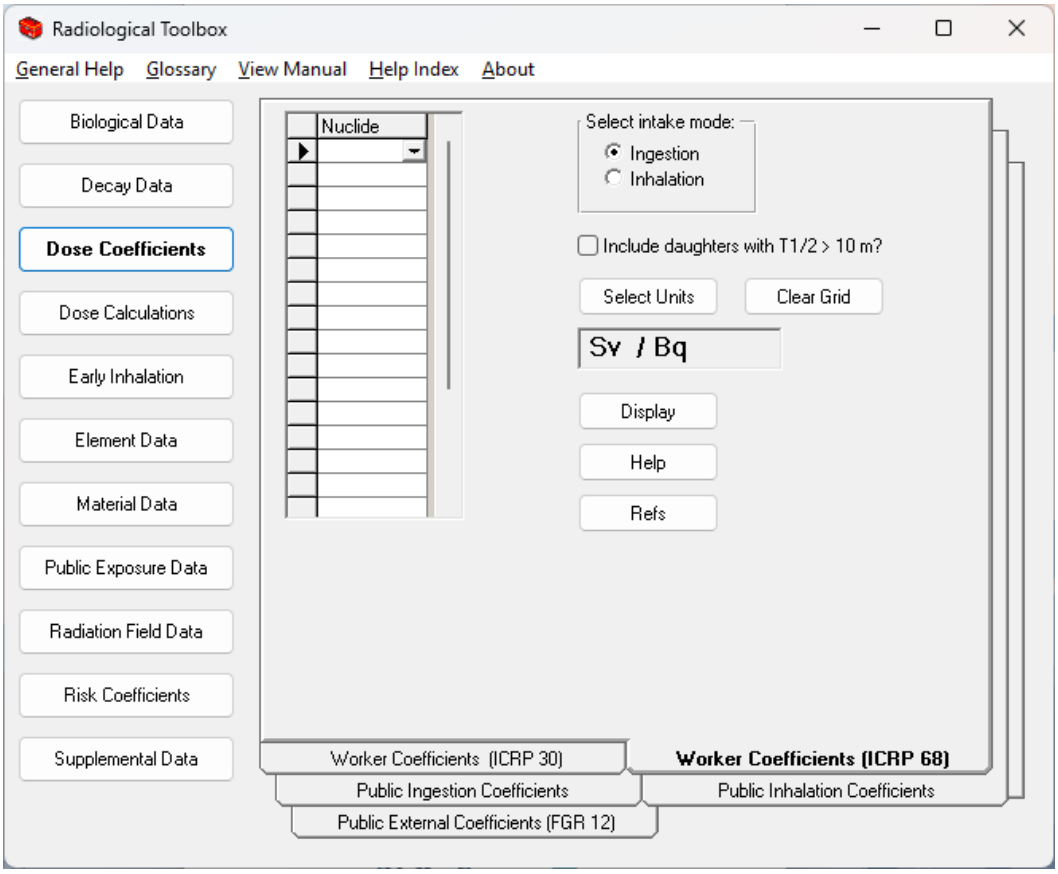


Figure 2-27 Radiological Toolbox opening window.

3 EXAMPLES AND SOLUTIONS USING VARSKIN+

3.1 Examples Using the SkinDose Module

This appendix describes four different practical applications of SkinDose using an example/solution format. Each example describes a situation followed by a solution that involves the use of SkinDose to estimate shallow dose at 7 mg/cm^2 and dose at a depth of 1,000 mg/cm^2. The purpose of these examples is to lead a new user of SkinDose through several calculations that highlight many of its features. Because SkinDose is a flexible tool, there are always several ways to calculate the dose for a given example. The solutions presented here reflect the recommendations that are provided throughout the user's manual. With some experience, most SkinDose users will not need to perform all the steps described in the solution in an actual situation. It is suggested that the user complete all four examples in the order in which they are presented to become familiar with SkinDose.

It is important to note that, even though SkinDose is used to calculate dose at depths other than 7 mg/cm^2, these values do not ensure compliance with the requirements of Title 10 of the Code of Federal Regulations (10 CFR) Part 20, "Standards for protection against radiation". The examples here simply change the tissue depth from 7 mg/cm^2 to some different value without changing other pertinent parameters of the dose-averaging calculation. Note that when, in the following scenarios, the depth is changed from 7 mg/cm^2 to 1,000 mg/cm^2, for example, the purpose is not necessarily to calculate deep dose equivalent, but simply to demonstrate the utility of the code for estimating energy absorption at various depths in tissue.

Example 1: Radiopharmaceutical *Technologist in Nuclear Medicine*

At a research hospital, a doctor prescribes a 5-milliliter (mL) administration from a stock solution containing 370 kiloBequerels per milliliter (kBq/mL) of rhenium (Re)-186 for a clinical research study at 1 p.m. that day. Around 12:30 p.m., a lab technologist loads the dose under the hood. Subsequently, a fellow employee bumps into her, and the needle slips out of its container. The entire 5 mL of the solution is spilled on the arm of her cloth lab coat in a circular shape with an area of approximately 50 square centimeters (cm^2). She is unaware of the accident and continues with her work until the end of the day. Around 5 p.m., a routine survey discovers the contamination.

Solution 1: Radiopharmaceutical Technologist in Nuclear Medicine

The point source geometry is suggested as a starting point to estimate the magnitude of the dose and to collect some other useful information. Run SkinDose and select the "Nuclide List" button. If ^{186}Re does not appear in the radionuclide library (in the "Available in Database" window), add Re-186 by selecting the database radio button for International Commission on Radiation Protection (ICRP) Publication 107, "Nuclear Decay Data for Dosimetric Calculations", issued in 2008, confirming the effective Z of 7.42, and double-click on "Re-186". When "Re-186 (7.42, 107)" appears in the "Selected for Analysis" box, return to the SkinDose window. Confirm the Dose Depth of 7 mg/cm^2. Enter the

Exposure Time as 4.5 followed by the Tab key and change the time unit to hours using the dropdown menu. Confirm that the dose-averaging area is 10 cm^2 and that there is zero airgap. Also, confirm that the Volume Averaging and Backscatter disable radio buttons are NOT selected and that the Dose Equivalent Units are in "mSv".

Because the point source geometry is being used, it is necessary to calculate the source strength by multiplying the concentration of the stock solution (370 kBq/mL) by the size of the administration (5 mL) to get a total source strength of 1.85 MBq.

For the Re-186 entry in the Radionuclide table at the bottom of the window, select the source strength units of MBq, then enter an activity value of 1.85. Click the red "Calculate" button. After the calculation is performed, the red Calculate button changes to green and indicates "Updated" to inform the user that the results (appearing in the lower third of the SkinDose window) are in fact applicable to the inputs shown.

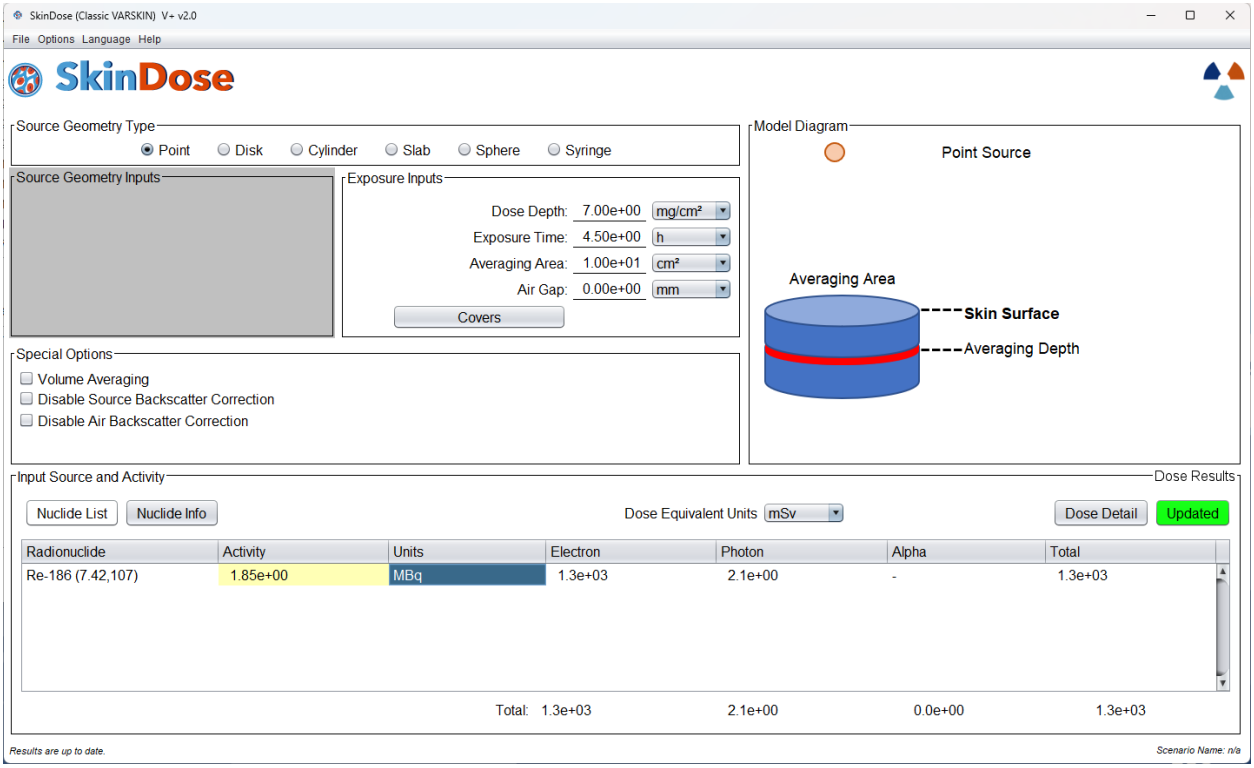


Figure 3-1 Screenshot of SkinDose Module Main Window

The results table shows dose equivalent for electrons, photons, and alpha as well as the total equivalent dose for all nuclides and for all radiation types. Examination of the SkinDose results table shows that the total effective dose is **1,300 mSv** (**1,300 mSv** from electrons and **2.1 mSv** from photons), a total dose that exceeds regulatory limits. To calculate the dose at a 1 cm depth, for example, go back to the top of the SkinDose window and change the value of "Dose Depth" to 1,000 milligrams per square centimeter (mg/cm^2), and click "Calculate." The SkinDose results table now displays an electron dose equivalent of **0** (zero) and a photon dose equivalent of **0.074 mSv**.

The total shallow dose calculated using the point geometry was above regulatory limits. However, the situation described in this example will obviously be more accurately modeled using the disk or cylinder geometries. A more realistic, yet conservative approach would be to use the disk geometry and calculate the dose as if all of the contamination were directly on the skin. Return your attention to the top of the SkinDose window and choose the "Disk" radio button in the Source Geometry Type frame. Enter a source Diameter of 8 cm (resulting in a source area of 50 cm^2), enter a Dose Depth value of 7 mg/cm^2, and confirm the Exposure Time of 4.5 hours and an Averaging Area of 10 cm^2. Select the red "Calculate" button. The Calculate button turns to green and the results table shows an electron dose of **260 mSv** and a photon dose of **0.45 mSv**.

Using the cylinder model to simulate contamination that is uniformly distributed throughout the thickness of the lab coat introduces even more realism. In this case, the lab coat is assumed to soak up the contamination instead of acting as a protective cover material. In Table 2-2 of the main report, the data for a cloth lab coat indicates a thickness of 0.04 centimeters (cm) and a density of 0.9 g/cm^3. Select "Cylinder" in the Source Geometry Type frame. Confirm the source Diameter is 8 cm, enter a Thickness of 0.04 cm and a Density of 0.9 g/cm^3 (confirm the use of the appropriate units). Confirm the Dose Depth is 7 mg/cm^3, the Exposure Time is 4.5 hours, and the Averaging Area is 10 cm^2. Do not use the Covers function in this example. Click the red "Calculate" button; the SkinDose results will display **160 mSv** and **0.42 mSv** as the electron and photon dose equivalent, respectively.

It is interesting to see what the electron dose would be if the lab coat were impervious to the liquid contamination, and the contamination resided as an infinitely thin layer of contamination on the plastic coat. In this case, the plastic lab coat acts as a cover material instead of defining the size and density of the source. To perform this calculation, return to the top of the SkinDose window and select Disk as the Source Geometry Type. Confirm that the source Diameter is 8 cm, the Dose Depth is 7 mg/cm^2, the Exposure Time of 4.5 hours, and the dose-averaging Area is 10 cm^2. Select the "Covers" button to enter a cover Density of 0.36 g/cm^3 and a cover Thickness of 0.02 cm. Select the "Apply" button to accept the cover parameters and return to the SkinDose window. You will notice in the Model Diagram frame that a single cover has been added to the picture. Select "Calculate" and the SkinDose results table will display doses of **180 mSv** for electrons and **0.41 mSv** for photons. It can be concluded from the above calculations, that a thicker, absorbent lab coat will give more protection against electron dose than a thin, impervious material; photon dose is essentially unchanged.

Example 2: Radiation Worker in Reactor Containment

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

- radioactive contaminant: Co-60
- source strength: 92.5 MBq
- particle thickness and density: 50 μm; 8.3 g/cm^3
- particle size: 80 microns x 70 microns
- stellite assumed atomic number (cobalt-chromium alloy): 25.5
- glove thickness: 0.03 cm
- glove density: 0.6 g/cm^3

Solution 2: Radiation Worker in Reactor Containment

The first step is to use the point source geometry to estimate the magnitude of the dose and to collect some other useful information. Start SkinDose or select "Reset Window" from its file dropdown menu. Select the "Nuclide List" button. If Co-60 does not appear in the "Available in Database" frame, enter an Effective Z of 25.5, selecting the ICRP 107 radio button and double-click "Co-60" in the radionuclide listing. Once loaded, go the SkinDose main window. For a Point source, confirm a Dose Depth of 7 mg/cm^2, enter an Exposure Time of 15 minutes, and confirm an Averaging Area of 10 cm^2. Enter 92.5 MBq for Co-60. Select "Covers" and enter a Density of 0.6 g/cm^3 and a Thickness of 0.03 cm; press "Apply". After you click "Calculate" the SkinDose results table will display an electron dose equivalent of **330 mSv**, a photon dose of **100 mSv,** and a total dose of **430 mSv**, a value approaching the regulatory limit. Thus, a more realistic calculation is desirable. In addition, because there is a photon component to the dose, a dose calculation at 1 cm may be desired.

Using the cylinder model will result in a more realistic calculation because the effects of self-shielding of the electron particles will be considered. As described previously, the slab and cylinder models can be used for a particle that is known to be rectangular. Return to the top of the SkinDose window and choose the cylinder as the Source Geometry Type. The diameter of a disk source, with the same area as the rectangular source, is found by:

$$d = 2\sqrt{X \cdot Y/\pi} = 2\sqrt{80\ \mu m \cdot 70\ \mu m/\pi} = 84\ \mu m \qquad [3.1]$$

Enter 84 μm for the source Diameter, 50 μm for the source Thickness, and 8.3 g/cm^3 for the Source Density. Confirm a 7 mg/cm^2 Dose Depth, a 15-minute Exposure Time, and an Averaging Area of 10 cm^2. Select "Covers" and confirm 0.6 g/cm^3 as the Density and 0.03 cm as the Thickness. Click "Calculate". The SkinDose results table displays an electron dose of **120 mSv**, a photon dose of **130 mSv**, and a total dose of **260 mSv** (the total dose appears to be greater than the sum, but this is because of rounding). Including the effects of self-shielding greatly reduced the electron dose and resulted in a dose that is now below regulatory limits. To investigate the dosimetric influence of tissue depth, calculate dose at 1 cm by returning to the top of the window, and changing the Dose Depth to 1,000 mg/cm^2. Click "Calculate". The SkinDose results table displays a dose at 1 cm of **32 mSv**, all from photons.

Example 3: Contaminated Metal in a University Laboratory Hood

During a radiation survey of a fume hood, a new radiation safety officer (RSO) at a university discovers a contaminated aluminum plate inside the hood. Further investigation found that the plate was used to hold beakers of solution containing carbon (C)-14 for use in radiobiology experiments. The RSO decides that the plate should be disposed of as low-level radioactive waste and that the activity of C-14 on the plate must be determined. The plate is 15.24 centimeters (cm) by 15.24 cm and is uniformly contaminated over the entire surface. The RSO uses a calibrated circular detector with an area of 50 cm^2 and a window thickness of 3 mg/cm^2 to measure a dose rate of 1.90 mGy/hr on contact and 0.60 mGy/hr at a distance of 2.54 cm. The RSO uses these dose-rate measurements and SkinDose results to estimate the activity of C-14 on the plate. SkinDose must be configured to mimic the measurements.

Solution 3: Contaminated Metal in a University Laboratory Hood

The solution to this example demonstrates a method in which SkinDose might be used for applications other than skin contamination events where rough estimations may be of use. For this solution, first select "Reset Window" and choose the "Disk" geometry. Select the "Nuclide List" button and add C-14 with an effective Z of 7.42 from the ICRP 107 database. Set the Dose Depth to 3 mg/cm^2 to correspond to the thickness of the probe window, the Averaging Area to 50 cm^2 to correspond to the area of the probe, and the source Diameter to 17.2 cm to correspond to the area of the contaminated plate (232 cm^2). Dose rate per hour is of interest, so set the exposure Time to 1 hour. An initial source strength of 232 MBq will be assumed (1 MBq/cm^2) for the calculation, and the results then scaled to the measurements taken by the RSO; enter an Activity of 232 and set the Units to MBq. Click "Calculate"; the SkinDose results table displays an electron dose of **1,200 mSv in one hour**, with no photon or alpha dose. The activity concentration on the plate then can be found using,

$$\frac{[A_{act}]}{[A_{cal}]} = \frac{\dot{D}_{meas}}{\dot{D}_{cal}} \qquad [3.2]$$

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

$$\frac{\left(1\ {}^{MBq}/_{cm^2}\right)\left(1.90\ {}^{mGy}/_{hr}\right)}{1{,}200\ {}^{mGy}/_{hr}} = 0.0016\ {}^{MBq}/_{cm^2} \qquad [3.3]$$

Multiplying the activity concentration by the area of the plate (232 cm^2) results in a total activity of 0.37 MBq. The measurement at a distance of 2.54 cm can be used to verify this result. Return to the top center of the SkinDose window, enter an Air Gap of 2.54 cm (note the Model Diagram frame), and change the activity to 0.37 MBq. Click "Calculate" and the SkinDose results table displays an electron dose of **0.62 mSv in one hour**, compared to the measurement of 0.60 mGy/hr with the calibrated detector.

Example 4: Use of Decay Databases and Auto*matic Progeny Selection*

This example is not specific to a particular contamination scenario but is provided here to demonstrate the internal calculations of SkinDose as it automatically includes decay progeny in the calculation of skin dose, and to give the user an appreciation of the possible differences between the two ICRP decay databases. The simulation itself is quite simply modeled as an infinite plane source of Ce-144 on the skin surface. The shallow skin dose is calculated at a depth of 7 mg/cm^2, normalized to an activity of 1 Bq for a 1 second exposure, resulting in a dose prediction per decay of Ce-144. The calculation is executed using data from ICRP 38 in the first case, and then using ICRP 107 data in the second case. The photon and electron data are provided explicitly so that the user can better understand the origin of differences in the dose predictions.

Cerium-144 decays by β^- emission (see Figure 3-2), with a half-life of about 285 days, through several energetic routes to praseodymium-144. One of the Ce-144 decay routes stops at the metastable state Pr-144m (~1 percent yield), with a half-life of about 7 minutes. Praseodymium-144 then decays again by β^- decay, with a half-life of about 17 minutes, to neodymium-144. They are not all shown in the figure, but several gamma-ray photons, conversion electrons, characteristic X rays, and Auger electrons are also emitted during these decay processes. The emission data, as extracted by SkinDose (and displayed by selecting the "Nuclide Info" button), are provided in Table 3-1 to Table 3-4 (divided by (a) photons and (b) electrons) according to both ICRP 38 and ICRP 107, respectively. It is evident from the data that there will be differences in the dose calculations using the two datasets.

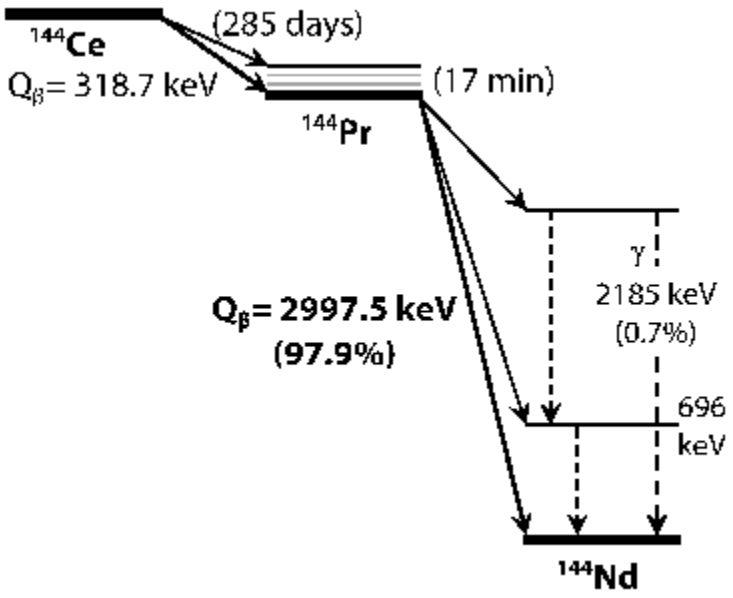


Figure 3-2 The Decay Scheme of Ce-144 to Stable Nd-144

Table 3-1 ICRP 38 Photon Emission Data for Decay of Ce-144 to Stable Nd-144

Nuclide	Branching Ratio	Photon Yield (%)	Photon Energy (MeV)	Nuclide	Photon Yield (%)	Photon Energy (MeV)
Ce-144		1.6416	0.0801199	Ce-144(D)	1.6416	0.0801199
		10.8	0.13353		10.8	0.13353
		5.40195	0.0360263		5.40195	0.0360263
		2.95756	0.0355502		2.95756	0.0355502
		1.06958	0.0407484		1.06958	0.0407484
Pr-144	0.9822	1.48	0.69649		1.45366	0.69649
Pr-144m	0.0178	15.7456	0.0360263		0.280272	0.0360263
		8.62071	0.0355502		0.153449	0.0355502
		3.11763	0.0407484		0.05549381	0.0407484
		1.25177	0.0417924		0.02228151	0.0417924
		1.60605	0.0406532		0.02858769	0.0406532
		4.53392	0.00503329		0.08070377	0.00503329
		1.63137	0.00548929		0.02903838	0.00548929
Pr-144	0.999	1.48	0.69649		0.02631766	0.69649

Ce-144(D) represents the combined "nuclide" in SkinDose having selected the option to include progeny.

Table 3-2 ICRP 38 Electron Emission Data for Decay of Ce-144 to Stable Nd-144

Nuclide	Half-life (hours)	Electron Yield (%)	Electron Avg Energy (MeV)	Electron X90 (cm)
Ce-144	6,823	157.344	0.09230879	0.02774469
Pr-144	0.288	100.06	1.2079	0.695699
Pr-144m	0.12	337.682	0.617	0.004115152
Ce-144(D)	6,823	263.4	0.659	0.683

Ce-144(D) represents the combined "nuclide" in SkinDose when the option to include progeny is selected.

Table 3-3 ICRP 107 Photon Emission Data for Decay of Ce-144 to Stable Nd-144

Nuclide	Branching Ratio	Photon Yield (%)	Photon Energy (MeV)	Nuclide	Photon Yield (%)	Photon Energy (MeV)
Ce-144		1.36407	0.08012	Ce-144(D)	1.36407	0.08012
		11.09	0.133515		11.09	0.133515
		4.40559	0.0360557		4.40559	0.0360557
		2.41237	0.0355671		2.41237	0.0355671
Pr-144	0.99023	1.342	0.69651		1.32889	0.69651

Ce-144(D) represents the combined "nuclide" in SkinDose when the option to include progeny is selected.

Table 3-4 ICRP 107 Electron Emission Data for the Decay of Ce-144 to Stable Nd-144

Nuclide	Half-life (hours)	Electron Yield (%)	Electron Avg Energy (MeV)	Electron X90 (cm)
Ce-144	6837.84	234.621	0.09170876	0.0285164
Pr-144	0.288	234.621	1.20882	0.696917
Pr-144m	0.12	1023.1	0.296957	0.004116936
Ce-144(D)	6837.84	333.7	0.655	0.683

Ce-144(D) represents the combined "nuclide" in when the option to include progeny is selected.

Solution 4: Use of Decay Databases and Automatic Progeny Selection

This example begins with selection of the scenario, along with the manual selection of parent and progeny nuclides using the ICRP 38 decay database. It continues with the selection of automatic decay progeny inclusion and a comparison of shallow skin dose predictions.

For this solution, first select "Reset Window" in SkinDose and choose the Disk geometry. Select a source Diameter of 11.3 cm (for an area of 100 cm^2), confirm a Dose Depth of 7 mg/cm^2, choose an Exposure Time of 1 second, and confirm an Averaging Area of 10 cm^2. Creating a source area much greater than the averaging area, the source essentially appears as an "infinite plane".

An examination of the decay scheme for Ce-144 shows that its decay progeny includes Pr-144 and Pr-144m. Therefore, those nuclides must be in the nuclide list as well. Click the "Nuclide List" button and add Ce-144, Pr-144, and Pr-144m from the ICRP 38 library (Z = 7.42). Additionally, to add Ce-144 with its decay progeny, select the "ICRP 38D" bubble and double-click "Ce-144". When the decay information window appears, click the Secular Equilibrium box and hit OK. On returning to the main SkinDose window, the user will note that the default activity value is 1 Bq; the input remains at the default value.

Recheck the input window to see that all parameters contain the appropriate values, including the four nuclides listed in the Input Source and Activity frame, and then click the red "Calculate" button to generate the SkinDose results. With these results (reproduced in Table 3-5), a manual calculation of the total dose (SUM in Table 3-5) can be compared with the automatic calculation using the progeny option (Ce-144(D) in Table 3-5). The SUM is calculated using:

$$D = D_{Ce} + (BR_{Pr}D_{Pr}) + (BR_m D_m) + (BR_m BR_{\mathrm{Pr}*} D_{Pr}) \quad [3.4]$$

$$D = 2.4x10^{-9} + (0.9822 \cdot 4.5x10^{-9}) + (0.0178 \cdot 5.7x10^{-13}) + (0.0178 \cdot 0.999 \cdot 4.5x10^{-9}) \quad [3.5]$$

$$D = 6.9x10^{-9}\ mSv/nt \quad [3.6]$$

Table 3-5 Dose Results from SkinDose with Progeny using the ICRP 38 Decay Database

Nuclide	Branching Ratio	Electron Dose (mSv/nt)	Photon Dose (mSv/nt)
Ce-144		$2.4x10^{-9}$	$5.9x10^{-12}$
Pr-144	0.9822	$4.5x10^{-9}$	$2.3x10^{-12}$
Pr-144m	0.0178	$5.7x10^{-13}$	$1.9x10^{-11}$
Pr-144m	0.999	$4.5x10^{-9}$	$2.3x10^{-12}$
SUM		$6.9x10^{-9}$	$8.5x10^{-12}$
Ce-144(D)		$6.9x10^{-9}$	$8.5x10^{-12}$

Ce-144(D) is the combined "nuclide" in SkinDose when the option to include progeny is selected.
**This entry represents Pr-144 as the decay product of Pr-144m.*
Note: "nt" is the abbreviation for "nuclear transition".

To execute SkinDose with the ICRP 107 decay database, simply "Add" the proper nuclides in the same fashion as above, except this time select the "ICRP 107" and "ICRP 107D" bubbles, where appropriate. ICRP 107 does not provide branching for Pr-144m, therefore, the calculation does not include the metastable state of Pr-144. Table 3-6 gives the dose results for the ICRP 107 comparison. In the comparisons of the manual and automatic progeny selection, electron and photon dose estimates give results within rounding.

Table 3-6 Dose Results from SkinDose with Progeny using the ICRP 107 Decay Database

Nuclide	Branching Ratio	Electron Dose (mSv/nt)	Photon Dose (mSv/nt)
Ce-144		$2.4x10^{-9}$	$4.8x10^{-12}$
Pr-144	0.99023	$4.5x10^{-9}$	$2.1x10^{-12}$
Ce-144(D)		$6.9x10^{-9}$	$6.9x10^{-12}$
Ce-144(D)		$6.9x10^{-9}$	$7.1x10^{-12}$

Ce-144(D) represents the combined "nuclide" in SkinDose when the option to include progeny is selected.

3.2 Examples Using the WoundDose Module

This appendix describes three different practical applications of WoundDose using an example/solution format. Each example describes a situation followed by a solution that involves the use of WoundDose to estimate skin dose at 7 mg/cm^2 and dose at a depth of 1,000 mg/cm^2. The purpose of these examples is to lead a new user of WoundDose through several calculations that highlight many of its features. Because WoundDose is a flexible tool, there are always several ways to calculate the dose for a given example. The solutions presented here reflect the recommendations provided throughout the user manual. With some experience, most WoundDose users will not need to perform all of

the steps described in the solution in an actual situation. It is suggested that the user complete all three examples in the order in which they are presented to become familiar with WoundDose. The examples given below all use the ICRP 38 (no decay progeny) database.

E*xample 1: Estimation of Dose from a Tc-99m Needlestick*

A nuclear medicine technologist accidentally sustained a needlestick in his right hand during MAG3 radiopharmaceutical production. It is estimated that a volume of about 5 μL of Tc-99m was left in the skin at a depth of about 2 mm. The concentration of radioactivity in the needle was 0.44 GBq/mL.

Solution 1: Estimation of Dose from a Tc-99m Needlestick

With the provided concentration and volume, it is determined that approximately 2.2 MBq of Tc-99m is assumed to have been injected at a depth of 2 mm. The WoundDose module is called on to estimate shallow, local, and systemic dose as a result of the needlestick. The WoundDose inputs include a shallow dose depth of 7 mg/cm^2, an injury depth of 2 mm, no abrasion, and an averaging area of 1 cm^2 to model the size of a finger. To determine the influence of wound geometry, the dose is calculated assuming a point source and then a line source. Select 2.2 MBq of Tc-99m (ICRP 107) and the Weak retention class.

The only difference in the wound inputs when accessing the line source is that an abrasion depth is not needed. As noted in the WoundDose diagram, the line source is assumed to pass from the surface, through the averaging disk, and ending at the injury depth.

The two models are executed, and the following dose (**mSv**) results are obtained:

Table 3-7 Shallow, Local, and System Dose Result for Tc-99m Needlestick

	Shallow Dose		**Local Dose**		**Systemic Dose**
	Electron	**Photon**	**Electron**	**Photon**	**CEDE**
Point Source	440	31	72	13	0.033
Line Source	440	31	72	13	0.033

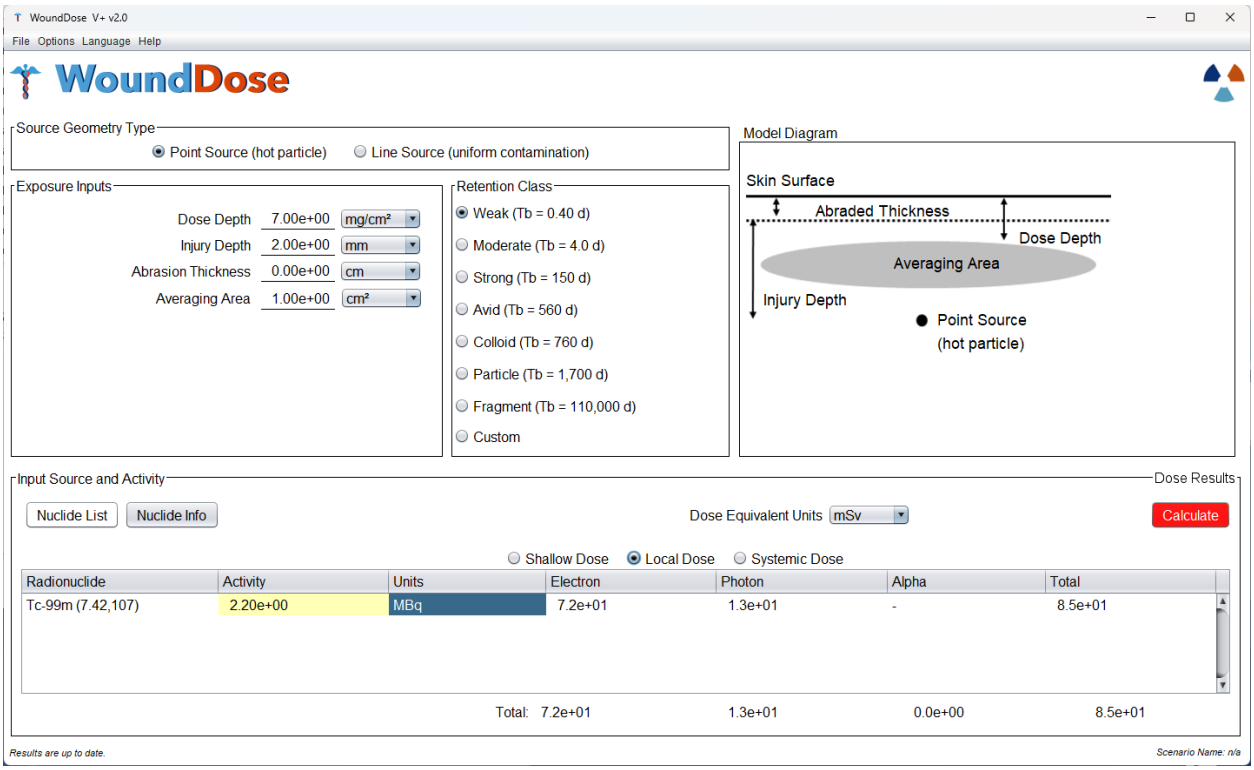


Figure 3-3 Screenshot of the WoundDose Main Window

Example 2: Puncture Wound Involving Pu-238 at Los Alamos

On a weekend day in 2018, while performing overtime work in a glovebox, an employee experienced a skin puncture contamination with Pu-238 (Klumpp et al. 2020). The employee was attempting to remove a knot in a 1/16th inch braided steel cable. The employee felt the glove breach and reported feeling a "poke" on the side of the left ring finger. After various investigative techniques, urinalysis, excision, and other measurements. It was determined that the "Avid" retention model (NCRP 156) was appropriate for the wound site and that the employee had an initial uptake of 392 Bq of Pu-238. Excisions removed approximately 302 Bq, and analysis showed that chelation therapy removed an additional 20 Bq from the body. The Los Alamos National Laboratory (LANL) Radiation Protection Division reported pretreatment and posttreatment estimates of committed effective dose of 163.8 mSv and 29.6 mSv, respectively.

Solution 2: Puncture Wound Involving Pu-238 at Los Alamos

The WoundDose module can be used to estimate shallow dose equivalent (SDE), local dose equivalent, and committed effective dose equivalent (CEDE) for this wound contamination incident. As in the first example, the user calculates dose assuming both point and line source geometries (Figure 3-3). After a window reset (or the selection of "New File"), the user confirms a Dose Depth of 7 mg/cm^2 and enters an assumed Injury Depth of 1 mm (the depth is unknown), an Abrasion Thickness of zero, and an Averaging Area of 1 cm^2 to estimate dose to the finger. The user selects the "Avid" retention class and enter the Pu-238 radionuclide from the ICRP 107 database and an assumed effective

Z of 7.42 (default). The user keeps the default activity unit of “Bq” and enters an activity value of 70 (392 initial activity less 322 removed by excision and chelation). On pressing the red Calculate button, the user obtains the following results for the two assumptions of point source and line source.

Table 3-8 Shallow, Local, and Systemic Dose (mSv) for Pu-238 Puncture Wound

	Shallow Dose			**Local Dose**			**Systemic Dose**	
	Electron	**Photon**	**Alpha**	**Electron**	**Photon**	**Alpha**	**CEDE**	**CODE***
Point Source	0	0.89	0	7.2	0.62	85,000	29	970
Line Source	210	2.1	1.1E06	6.5	0.56	77,000	29	970

*Committed Organ Dose Equivalent

Note that LANL staff determined a post-treatment CEDE of 29.6 mSv, compared to the WoundDose value of 29 mSv. Without chemical chelation or medical excision, the employee would have been committed to an activity of 392 Bq. The user now executes WoundDose for the initial uptake to determine how well the treatments reduced the employee’s radiation dose. Executing the same calculation as above but with an activity of 392 Bq, w the following results are obtained:

Table 3-9 Shallow, Local, and System Dose (mSv) for Pu-238 Puncture Wound with Increased Activity

	Shallow Dose			**Local Dose**			**Systemic Dose**	
	Electron	**Photon**	**Alpha**	**Electron**	**Photon**	**Alpha**	**CEDE**	**CODE***
Point Source	0	5.0	0	40	3.5	480,000	160	5,400
Line Source	1200	12	6.3E6	36	3.1	430,000	160	5,400

*Committed Organ Dose Equivalent

As above, w the pretreatment LANL CEDE estimate of 163.8 mSv and the WoundDose estimate of 160 mSv are noted. The very high values of local dose due to alpha emissions (nearly 500 Sv) is of particular note. These values are high due to high-energy absorption in a fairly small volume (1 cm^3). The likelihood of cancer induction at the wound site (due to alpha) is actually quite small even though radiation dose is high; the concentrated energy absorption will result in a high probability of cell killing as opposed to cell mutation.

3.3 Examples Using the NeutronDose Module

This example set provides three applications of NeutronDose using an example and solution format. Each example describes a situation followed by a solution that involves the use of NeutronDose to estimate dose equivalent at various depths in tissue from exposure to neutrons. The purpose of these examples is to lead a new user of NeutronDose through several calculations that highlight its features. With some experience, most NeutronDose users will not need to perform all the steps described in

the solution in an actual situation. It is suggested that the user complete all three examples in the order in which they are presented to become familiar with NeutronDose.

Example 1: Exposure to ^{252}Cf During a Laboratory Assignment

A health physics student is conducting a laboratory experiment using Bonner spheres to predict the neutron energy spectrum from a Cf-252 source. The experiment is conducted in a large rectangular laboratory space of approximately 25 x 40 feet. The source is maintained in a 55-gallon drum filled with paraffin. The student sets up the shielded source and a Lithium-Fluoride (LiF) detector (to be covered with Bonner spheres) in such a way as to minimize scatter. The resulting distance between source and detector is about 5 meters. After quickly raising the source, the student moves to the detector position and remains there for the duration of the experiment. The source was certified 500 days ago to contain 1 mg of Cf-252 (2.65 yr half-life). The student requires 1 hour and 20 minutes to complete the laboratory assignment. What dose equivalent does the student expect to receive as a result of the lab work?

Solution 1: Exposure to Cf-252 During a Laboratory Assignment

Californium-252 undergoes alpha decay during 96.9 percent of its transitions and spontaneous fission 3.1 percent of the time. These fission neutrons have an energy range from essentially 0 to 13 MeV, with a mean value of 2.3 MeV and a most probable value of 1 MeV. This isotope of californium produces high neutron energy emissions and can be used for applications in industries such as nuclear energy, medicine, and petrochemical exploration. Intrinsic specific activity is calculated by:

$$ISA = \frac{N_A\,\lambda}{M} = \frac{6.022x10^{23}\ \left[\frac{atoms}{mol}\right] \cdot 8.310x10^{-9}\ [s^{-1}]}{252\ \left[\frac{g}{mol}\right] \cdot 10^{12}\ \left[\frac{Bq}{TBq}\right]} = 19.86\ \left[\frac{TBq}{g}\right] \qquad [3.7]$$

Therefore, this californium isotope has an intrinsic specific activity of 19.86 TBq/g.
In this example, assume that the Cf-252 is removed from the paraffin shielding and is thereafter a bare source. Open V+ and select NeutronDose from the startup window. Select Spontaneous Fission from the Source Type dropdown list. Note that ICRP 107 decay data are employed and choose Cf-252 from the Source dropdown list. The other four inputs are as follows: the depth in tissue at which neutron dose will be estimated; the distance between source and receptor; the source activity on the day of exposure; and the total time of exposure. The user chooses to determine neutron dose at the shallow dose depth of 7 mg/cm^2 and, separately, at a depth of 1 cm in tissue. The Source Distance is set to 5 meters and Exposure Time is 80 minutes. The activity of the Cf-252 source is determined by first converting 500 days to years (1.37 years) and calculating its radiological decay constant (ln(2)/2.645 y = 0.2621 y^{-1}), and then using:

$$A = 1.985x10^{7}\left[\frac{MBq}{g}\right] \cdot 0.001\,[g] \cdot e^{-0.2621 \cdot 1.37} = 13{,}860\,[MBq] \qquad [3.8]$$

Enter the NeutronDose data (Figure 3-4) and select the Calculate button. The student's SDE is estimated to be **3.5 mSv**. Likewise, the tissue dose equivalent at a depth of 1 cm is estimated as **3.6 mSv**.

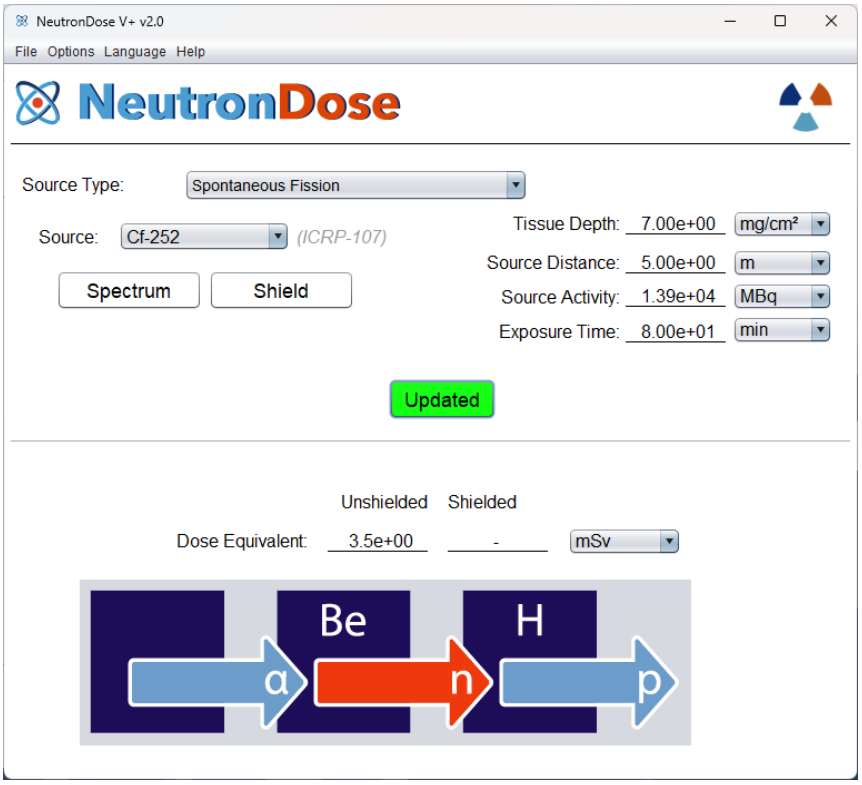


Figure 3-4 Screenshot of NeutronDose Main Window

Example 2: Neutron Dose Rate from a Plutonium-Beryllium Reaction Source

A plutonium-beryllium (PuBe) source is used in a portable density gauge. Dose-rate as a function of distance (1, 2, and 3 meters) is to be determined for this 1.85 GBq Pu-239-Be reaction source. In this type of neutron generator, the plutonium component provides a source of alpha particles (~5.1 MeV) that can initiate a nuclear reaction with beryllium, resulting in the emission of near-monoenergetic neutrons. The nuclear reaction of importance is

$$^{9}_{4}Be\ (^{4}_{2}\alpha, ^{1}_{0}n)\ ^{12}_{6}C. \qquad [3.9]$$

The energetics of the reaction are

$$Q = [(9.012182\ [amu] + 4.001506) - (1.008664 + 12.000000)] \cdot 931.5\left[\frac{MeV}{amu}\right] = 4.68\ MeV. \quad [3.10]$$

Combining the interaction rest energy with the kinetic energy of the incoming alpha particle (after self-absorption in the PuBe mixture), neutrons emitted are between thermal and about 11 MeV with an average energy between 4 and 5 MeV.

Solution 2: Dose Rate from a Plutonium-Beryllium Reaction Source

To estimate the dose at 1, 2, and 3 meters from the PuBe source, the "Reaction (alpha, n)" source type is selected along with the "Pu239-Be9" source. An activity of 1,850 MBq is entered for an exposure period of 1 hour (to determine dose rate). NeutronDose predicts the dose equivalents of **4.9, 1.2, and 0.55 μSv/h** for the three distances, respectively.

Alternatively, an investigation of the emission rate of a typical PuBe source indicates that approximately 50,000 neutrons per second (n/s) are emitted per GBq of plutonium. Given that the half-life of Pu-239 is thousands of years, estimate the emission rate as 1.85 GBq x 50,000 n/s/GBq = 92,500 n/s. Assuming the source is small enough to call it a point source at a distance of 1 meter, the fluence rates at 1, 2, and 3 meters are

$$\phi = \frac{92{,}500\ \left[\frac{n}{s}\right] \cdot 3600\ \left[\frac{s}{h}\right]}{4\pi(100\ [cm])^2} = 2{,}650\ \left[\frac{n}{cm^2\ h}\right], \quad [3.11]$$

conservatively assumed to be 2,700, 660, and 300 [n cm^{-2} h^{-1}], respectively. In this case, neutron dose must be estimated for a monoenergetic source. For a 4.5 MeV neutron, a tissue depth of 70 microns, and a fluence rate (flux) as specified above, the dose equivalent rates at the three distances are estimated to be **1.6, 0.39, and 0.18 μSv/h**, respectively; about a factor of 3 less than the dose rates calculated above.

Example 3: Neutron Dose Rate from an Antimony-Beryllium Reaction Source

This example is different than the previous in that Sb-124 is mixed with beryllium to provide a photoneutron source, i.e., a photon is absorbed by the beryllium to cause a neutron emission. In this example the dose rate factor is determined for a typical Sb-124-Be reaction source. This source provides two nearly monoenergetic neutrons of about 22 keV and 380 keV. In this case, assume the activity of the source is unknown and will be included in the dose-rate factor. The nuclear reaction of importance is:

$$^{9}_{4}Be\ (\gamma, ^{1}_{0}n)\ ^{8}_{4}Be \quad [3.12]$$

The energetics of this reaction are as follows:

$$Q = [(9.012182\ [amu]) - (1.008664 + 8.005305)] \cdot 931.5 \left[\frac{MeV}{amu}\right] \quad [3.13]$$
$$= -1.67\ MeV$$

meaning that the reaction is endothermic and additional energy is needed for production of the neutron. Antimony-124 (with a half-life of 60.2 days) emits two photons of 1.691 and 2.091 MeV with photon emission yields of 49 and 5.7 percent, respectively. When Sb-124 is mixed with stable beryllium the possibility exists that an emitted photon will be captured by a beryllium atom and release a neutron with energy equal to the excess. This results in an emission yield of about 5.1×10^{-6} neutrons emitted per disintegration of Sb-124 (Shultis and Faw 2000).

Solution 3: Dose Rate from an Antimony-Beryllium Reaction Source

The NeutronDose module is employed to determine a dose rate factor for a typical SbBe source. The "Reaction (γ, n)" source type is selected along with the "Sb124-Be9" source. An activity of 1 MBq is entered for an exposure period of 1 hour at an exposure distance of 1 meter (to determine dose rate factor). NeutronDose predicts the dose rate factor at a 70-micron depth in tissue to be **1.6 [pSv m^2 h^{-1} MBq^{-1}]**.

Alternatively, using the neutron emission yield above (5.1×10^{-6} n/dis) and assuming the source is a point with negligible self-absorption, the fluence factor is

$$\phi = \frac{5.1\ \left[\frac{n}{s\ MBq}\right] \cdot 3600\ \left[\frac{s}{h}\right]}{4\pi(100\ [cm])^2} = 0.14\ \left[\frac{n}{cm^2}\right]\ per\ hour\ per\ MBq \quad [3.14]$$

Using the monoenergetic feature of NeutronDose for each neutron emitted (22 and 380 keV), combined with the original photon emission yields of 0.490 and 0.057 (for a total of 0.547 photons per disintegration), a tissue depth of 70 microns, and a fluence of 0.14 [n cm^{-2}], the energy-specific dose rate factors of **0.027** and **7.6 [pSv m^2 h^{-1} MBq^{-1}]**, respectively, are determined. Weighing each of those contributions by their photon emission yield as a fraction of total photon emissions results in a dose rate factor for SbBe comparable to the value calculated above:

$$DRF = 0.027\left(\frac{0.490}{0.547}\right) + 7.6\left(\frac{0.057}{0.547}\right) = \mathbf{0.82}\ [\boldsymbol{pSv\ m^2\ h^{-1}\ MBq^{-1}}] \quad [3.15]$$

3.4 Examples Using the EyeDose Module

This example set provides three applications of EyeDose. Each example describes a situation followed by a solution that involves the use of EyeDose to estimate dose equivalent to the lens of the human eye from exposure to photons and/or electrons. The

purpose of these examples is to lead a new user of EyeDose through several calculations that highlight its features. With some experience, most EyeDose users will not need to perform all the steps described in the solution in an actual situation. It is suggested that the user complete all three examples in the order in which they are presented to become familiar with EyeDose.

Example 1: Exposure to Sr/Y-90 in the Laboratory

A 370 MBq source of Sr/Y-90 is in equilibrium and there is interest in knowing the dose rate to the human lens as a function of distance from the source. The ICRP 107 database is selected (Figure 3-5).

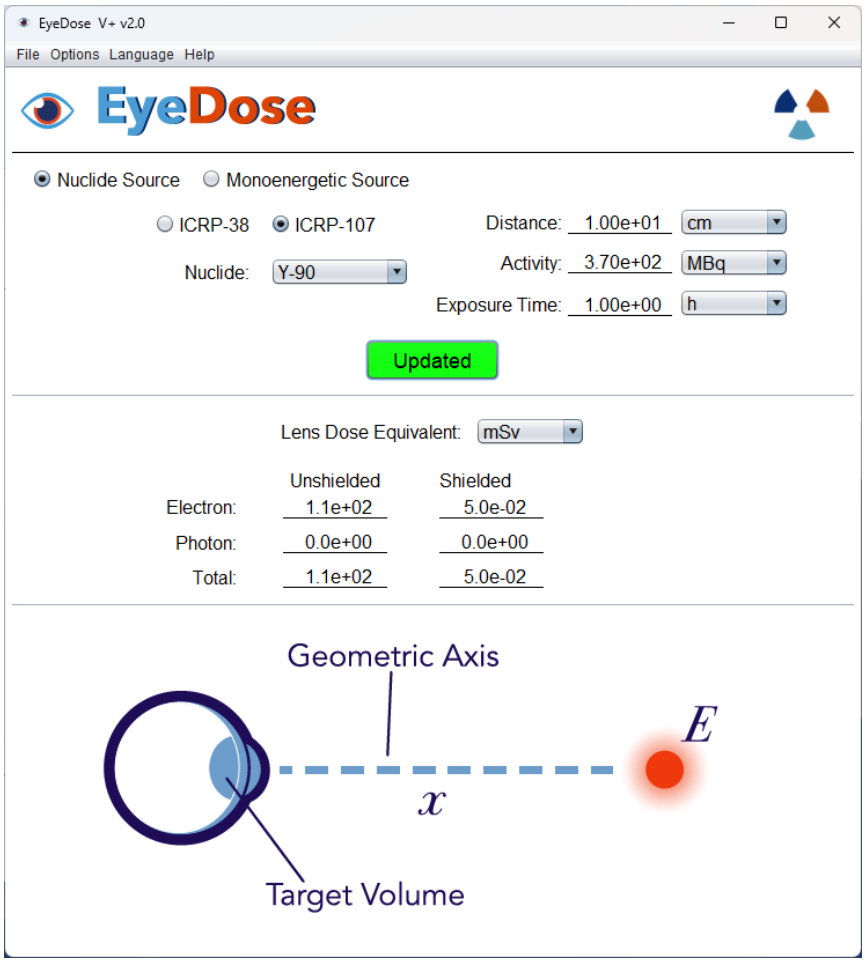


Figure 3-5 Screenshot of the EyeDose Module Main Screen.

Solution 1: Exposure to Sr/Y-90 in the Laboratory

The table below shows the Sr/Y-90 electron dose rate as a function of distance, both with and without 2 mm leaded safety glasses. Dose rates below are given in units of mSv/h.

Note that in the dose rate calculations, the safety glasses provide a dose reduction of about 2,000-fold for Y-90, but only about 5-fold for Sr-90. Also note that for the unshielded

case, the electron dose rate from Y-90 is five to six orders of magnitude greater than that for Sr-90. However, for the shielded case the two dose rates vary by two to three orders of magnitude.

As a note of comparison, using SkinDose with an averaging area of 1 cm^2, a volume-averaged depth of 300 – 700 mg/cm^2 and an airgap of 10 cm results in a dose rate of 120 mSv/h for a 370 MBq source of Sr/Y-90 in secular equilibrium. The dose rate obtained from EyeDose is believed to be a better estimate of lens dose (than the SkinDose) result because of the complexities modeled in the underlying probabilistic eye dosimetry method.

Table 3-10 Unshielded beta dose (mSv/h) to the lens of the eye at varying distance.

Unshielded	**0.1 m**	**0.2 m**	**0.4 m**	**0.6 m**	**0.8 m**	**1 m**
Y-90	$1.1x10^{2}$	$2.6x10^{1}$	$2.5x10^{0}$	$1.7x10^{-1}$	$3.4x10^{-2}$	$8.3x10^{-3}$
Sr-90	$1.9x10^{-3}$	$9.7x10^{-5}$	$1.8x10^{-6}$	$1.3x10^{-7}$	$2.6x10^{-8}$	$9.4x10^{-9}$

Table 3-11 Shielded beta dose (mSv/h) to the lens of the eye at varying distance.

Shielded	**0.1 m**	**0.2 m**	**0.4 m**	**0.6 m**	**0.8 m**	**1 m**
Y-90	$5.0x10^{-2}$	$8.7x10^{-3}$	$7.4x10^{-4}$	$1.0x10^{-4}$	$1.8x10^{-5}$	$3.8x10^{-6}$
Sr-90	$3.4x10^{-4}$	$1.8x10^{-5}$	$2.3x10^{-7}$	$9.5x10^{-9}$	$2.1x10^{-9}$	$1.1x10^{-9}$

Example 2: Estimation of Dose Rate to the Lens from a Co-60 Source

An individual is exposed to a 37 MBq source of Co-60 at a distance of 2.5 meters. The health physicist provides an estimate of whole-body dose and is now asked for a prediction of dose rate to the human lens. She uses the EyeDose module in V+ for this estimate.

Solution 2: Estimation of Dose Rate to the Lens from a ^{60}Co Source

Selecting the EyeDose option, the HP is presented with the initial user interface. For the first calculation, the HP selects the Nuclide Source radio button. Using the ICRP 107 database, she selects Co-60 from the Nuclide dropdown menu, enters a distance of 2.5 meters, an Activity of 37 MBq, and an Exposure Time of 1 hour. She also selects the Lens Dose Equivalent unit to display as μSv. She selects the Calculate button and the result of **1.9 μSv** is displayed for unshielded photons. By examining the dose from shielded photons, the HP notes that wearing 2 mm leaded safety glasses would provide no protection for this source. She also notes that at this distance the dose from electrons is eight orders of magnitude less than the photon dose, and that the safety glasses do provide about a third reduction in dose from electrons.

Out of curiosity, the HP now selects the Monoenergetic Source radio button to check the nuclide calculation. She enters a photon energy of 1.25 MeV (average of the two Co-60 photons) and confirms the distance of 2.5 m. After the Calculate button is pressed, an unshielded lens dose equivalent per source particle of **$7.2x10^{-12}$ μSv** is displayed for photons. She must now convert the dose per photon into the expected lens dose rate for

a 37 MBq source (and considering that two photons are emitted per disintegration). The calculation is straightforward and appears as:

$$\dot{D} = 7.2x10^{-12}\left[\frac{\mu Sv}{\gamma}\right]\cdot 37x10^{6}\left[\frac{dis}{s}\right]\cdot 2\left[\frac{\gamma}{dis}\right]\cdot 3600\left[\frac{s}{h}\right] = 1.9\left[\frac{\mu Sv}{h}\right] \quad [3.16]$$

She further checks her answer by making a hand calculation. The hand calculation is carried out as follows:

$$\dot{D} = 1.25\,[MeV]\cdot 2\left[\frac{\gamma}{dis}\right]\cdot\frac{37x10^{6}\left[dis/_{s}\right]}{4\pi(250\,[cm])^{2}}\cdot 0.0297\left[\frac{cm^{2}}{g}\right] \cdot 1.6x10^{-10}\left[\frac{J\,g}{MeV\,kg}\right]\cdot 3.6x10^{9}\left[\frac{s\,\mu Sv}{h\,sv}\right] = 2.0\left[\frac{\mu Sv}{h}\right] \quad [3.17]$$

The HP notes the similarity in the three answers, observes that the hand calculation exceeds the EyeDose estimate as expected (see below), and is therefore confident in reporting a dose rate to the lens of **1.9 μSv/h**.

The hand calculation is conservative and fundamental. The assumptions underlying this calculation are that the source is small enough to be considered a point; the exposed person is staring at the source; there is no attenuation, buildup, or scatter of photons in the air between the source and the eye; there is no shielding by the cornea; and the lens is a point precisely 2.5 m from the source.

Dose to the lens as calculated by EyeDose is expected to be less than the hand calculation results because the EyeDose model considers air attenuation, buildup, and scatter; curvature of the eyeball; attenuation by the cornea; and total deposition of energy in the volume of the lens.

As in Example 1, the lens dose estimate can be compared with a similar calculation in SkinDose. With an exposure time of 1 hour, an averaging area of 1 cm^2, a volume-averaged depth of 300 – 700 mg/cm^2, and an airgap of 250 cm (the user will get a warning that the airgap is greater than the limit, but the code will still estimate a dose), the SkinDose results indicate a lens dose rate of 2.0 μSv/h for a 37 MBq source of Co-60. The user should interpret this finding to mean that photon dosimetry in SkinDose is quite accurate at this separation distance (2.5 m), even though SkinDose warns that the airgap is out of bounds. The SkinDose estimate for electron dose is equal to zero because the dose depth is beyond the CSDA range of Co-60 electrons; EyeDose, however, accounts for various electron scatter possibilities in its estimate of electron dose.

Example 3: The Effectiveness of 2 mm Leaded Safety Glasses on Dose to the Lens

The dose reduction achieved by wearing safety glasses is demonstrated in the figures below. The data were obtained using the EyeDose module for monoenergetic sources

of electrons and photons at an exposure distance of 1 m. The effectiveness factor is defined as the ratio of unshielded lens dose to shielded lens dose, where the shield is 2 mm leaded safety glass.

Solution 3: The Effectiveness of 2 mm Leaded Safety Glasses on Dose to the Lens

Using the Monoenergetic Source inputs, and a distance from source to eye of 1 m, the analysis obtained the data below. The results show that the safety glasses are quite effective for electrons between about 1 and 3 MeV, with a peak effectiveness at 1.5 MeV. Outside those bounds the wearing of safety glasses seems to have no effect on lens dose, although the factor is never less than 1. The effectiveness factor increases dramatically for electron energies less than about 0.2 MeV; this energy relates to the electron energy required to penetrate the thickness of leaded glass and the thickness of the cornea.

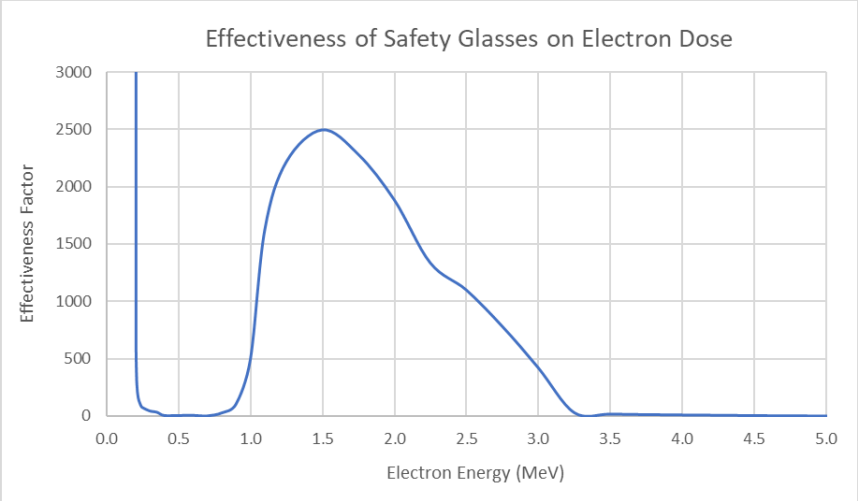


Figure 3-6 Effectiveness Factor of 2 mm Leaded Safety Glasses on a Monoenergetic Beam of Electrons

The effectiveness factor as a function of energy for photons shielded by 2 mm leaded safety glass is entirely different than that for electrons. The figure below indicates that the effectiveness in dose reduction for photons less than about 1 MeV is much reduced over that for electrons. It also shows that for energies greater than about 1.3 MeV, wearing safety glasses can actually increase the photon dose to the lens and the glasses are therefore potentially more harmful than helpful. Lens dose is increased by at least a factor of two for photons greater than 4.5 MeV.

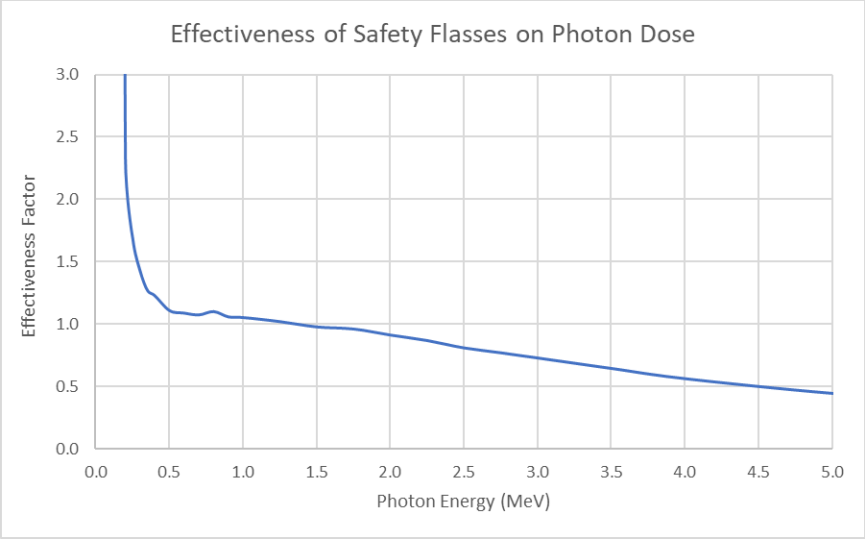


Figure 3-7 Effectiveness Factor of 2 mm Leaded Safety Glasses on a Monoenergetic Beam of Photons

3.5 Examples Using Extravasation Dose

This example set provides three applications of the new Extravasation Dosimetry module. As above, each example describes a situation followed by a solution that involves the use of extravasation dosimetry to estimate one's equivalent dose (alpha, electron, photon) to the tissues surrounding an injection point from exposure due to an extravasation event.

Example 1: Extravasation of Tc-99m During Intravenous Injection

A simulation for 100 MBq/mL of Tc-99m administered by injection at a rate of 1 mL/min over 5 minutes is assessed. Decay data is obtained from the ICRP 107 database. It is determined that extravasation occurred during the entire procedure. A basic, default dose assessment is modeled which lasts 30 minutes after the extravasation began.

Solution 1: Tc-99m Extravasation

A simulation is run in the Basic mode (Figure 3-8). The analyst must select the Timeline button to invoke the default events (Figure 3-9) and then select the Calculate button to begin the calculation. On completion of the calculation (requiring a clock time of about 45 seconds), the Total Dose 2D plot presents the following. Note that the event timeline is displayed at the top of the Results window.

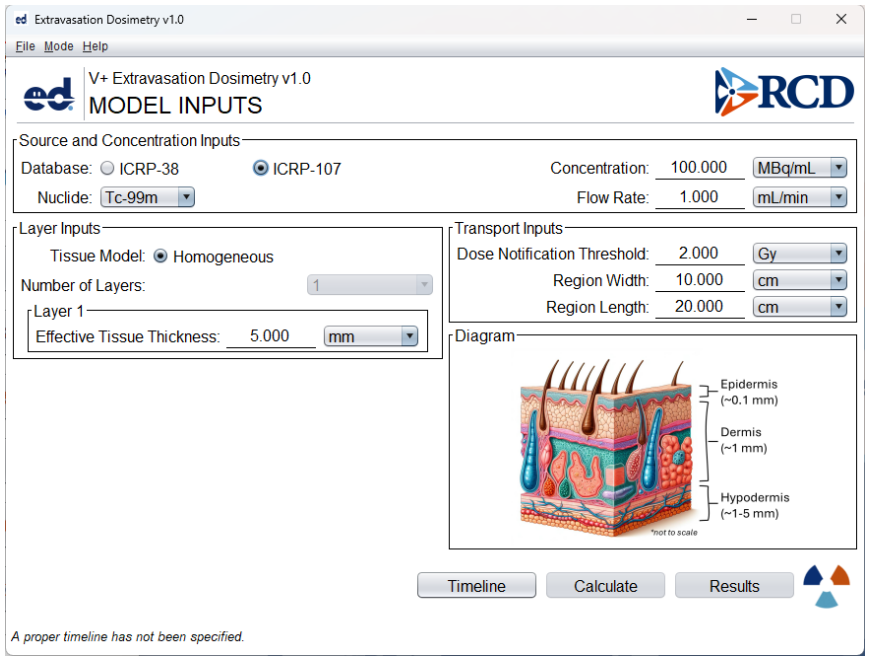


Figure 3-8 Extravasation Dose Basic Mode input screen for Solution 1.

Figure 3-9 Extravasation Dose Timeline input screen for Solution 1.

Output data (Figure 3-10) show the Maximum Voxel Dose is 9.67 mGy, Dose to ROI (Region of Interest) is 3.04 mGy, and the threshold dose of 2 Gy is exceeded in none of the 800 calculation cells contained in the ROI (10 cm x 20 cm x 0.5 cm) with a cubic side length of 0.5 cm. Additionally, the Maximum Voxel Dose Rate occurs 5.00 minutes after the beginning of extravasation and the Maximum Voxel Dose Rate to any voxel is 28.3 µGy/sec.

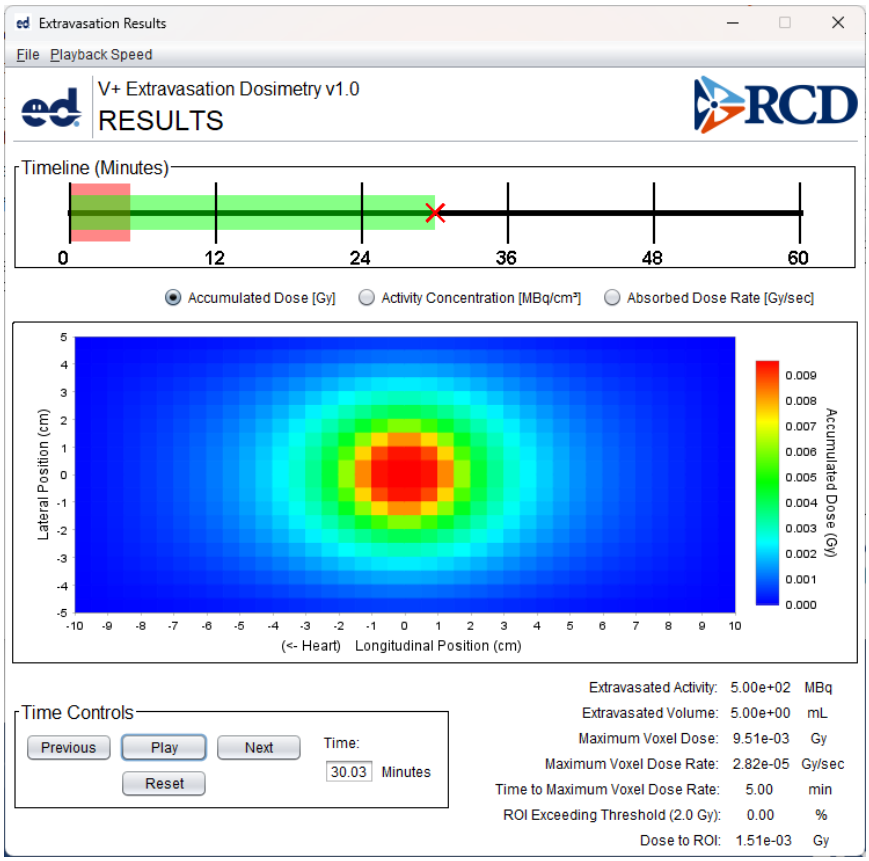


Figure 3-10 Extravasation results for Accumulated Dose at end of the 30-min analysis period for Solution 1, the default simulation.

Example 2: Extravasation of Lu-177 During Intravenous Injection

A 10 mCi/mL concentration of Lu-177 is administered by injection at a rate of 3 mL/min over twenty-five minutes. Decay data is obtained from the ICRP 107 database. Near the end of the procedure, it is estimated that extravasation of the Lu-177 occurred during the last 5 minutes. Five minutes later the clinician established a limb elevation at 80 degrees held in place for 30 minutes. An advanced dose assessment was conducted examining 40 minutes after extravasation ceased (Figure 3-11).

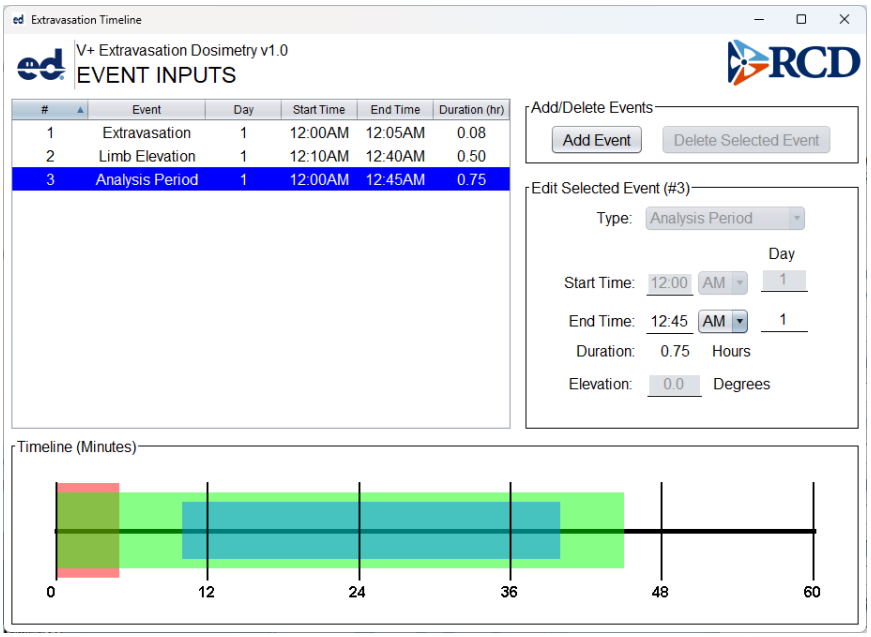


Figure 3-11 Extravasation timeline event inputs for Solution 2.

Solution 2: Lu-177 Extravasation

The Advanced mode of input values will be used to parameterize this simulation. The administered concentration is changed as given above, but other parameters are kept at their default values.

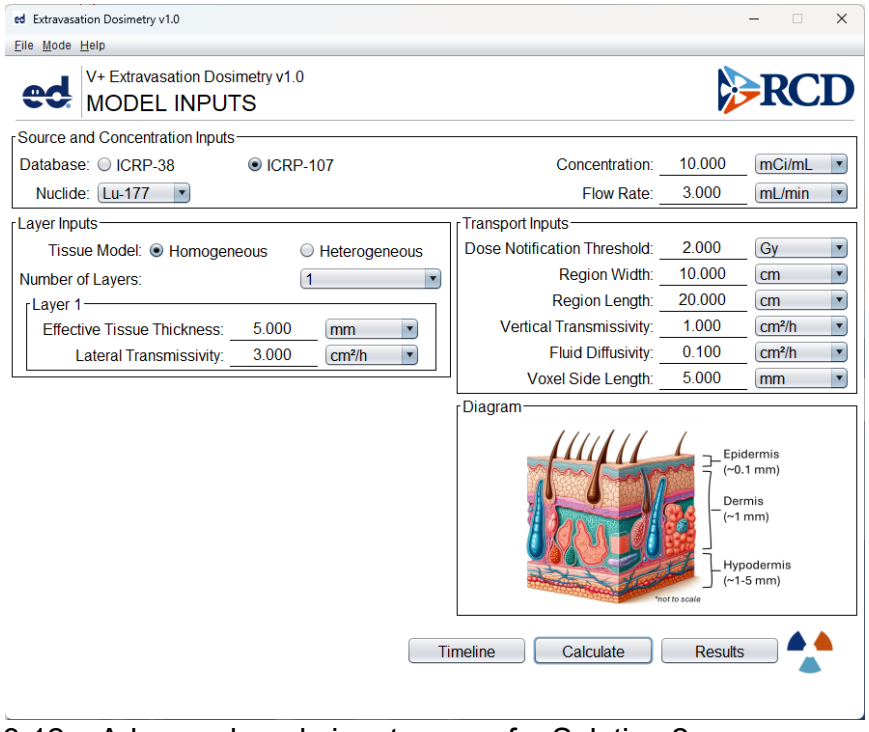


Figure 3-12 Advanced mode input screen for Solution 2.

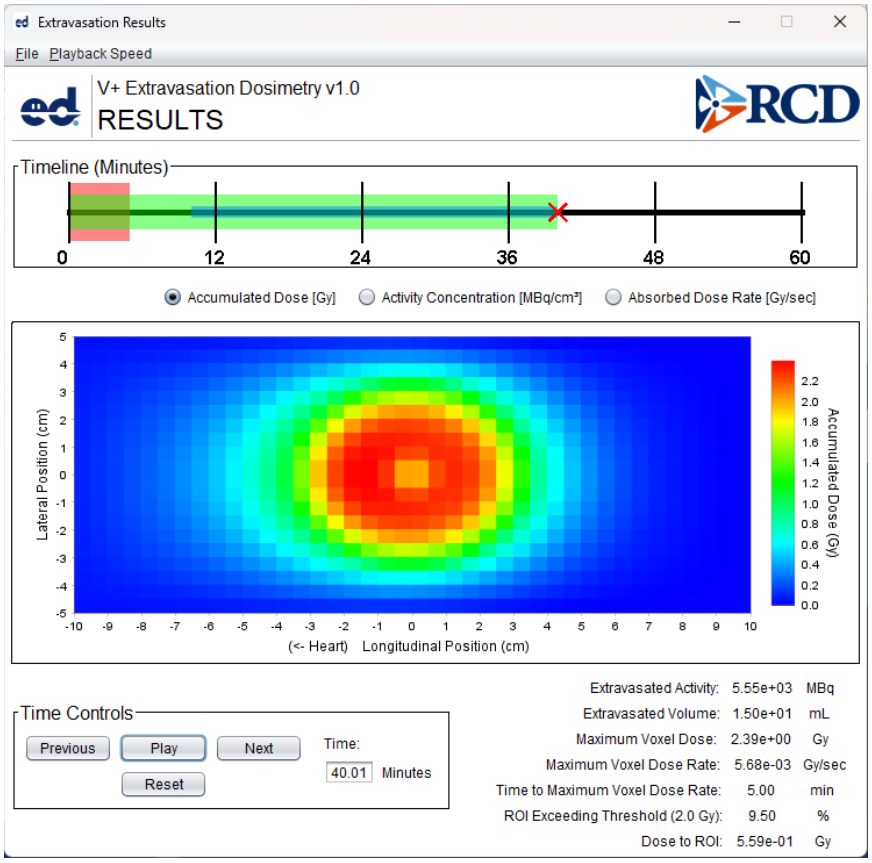


Figure 3-13 Extravasation Accumulated Dose (Gy) results for Solution 2.

In this instance, the output data show (Figure 3-13) the maximum voxel dose is 2.39 Gy, the dose to the entire region of interest is 0.559 Gy, and threshold dose of 2 Gy was exceeded in 9.5% of the 800 calculational cells. Additionally, the maximum voxel dose rate occurs at 5 minutes after the beginning of extravasation and the maximum dose rate to any voxel is 5.68 mGy/sec (Figure 3-14). On review of the time-incremented data (activity concentration and dose rate series), the majority of extravasated activity leaves the region to the left (toward the heart) within about 15 minutes because of the raised arm (Figure 3-15). The simulation requires a clock time of about 70 seconds to run.

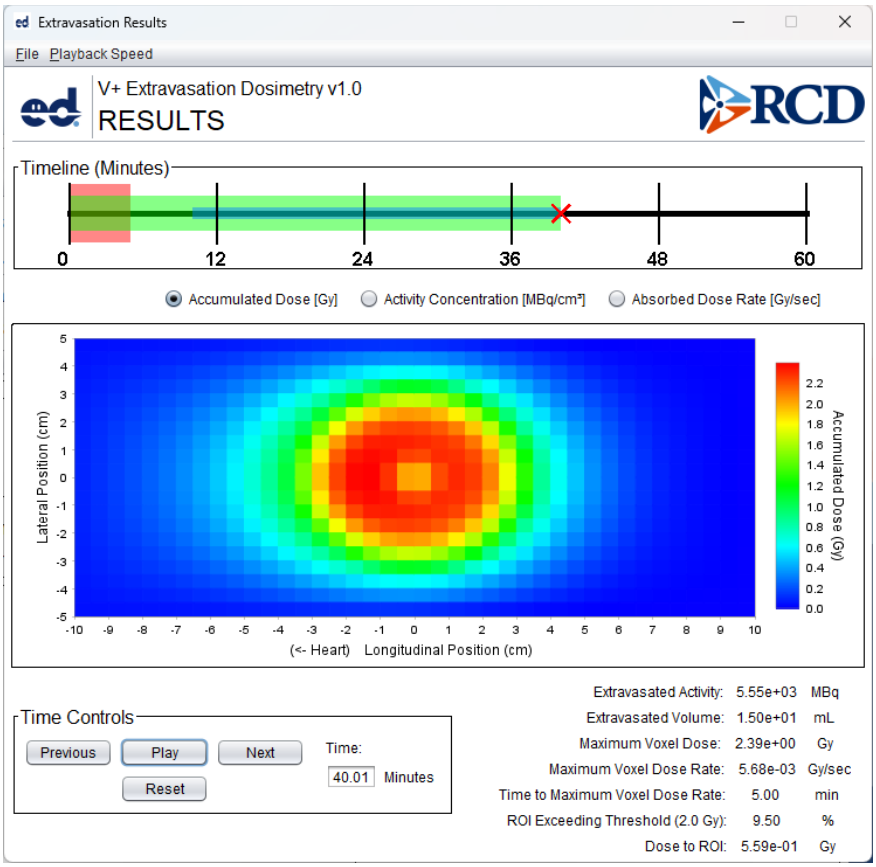


Figure 3-14 Extravasation Absorbed Dose Rate results at end of the analysis period for Solution 2.

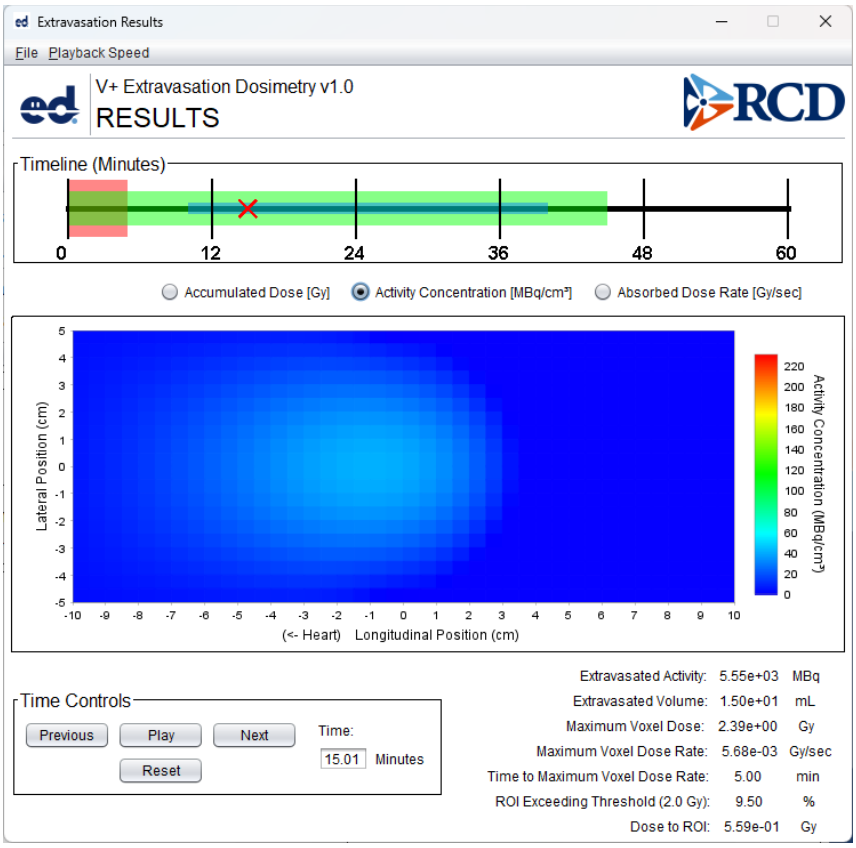


Figure 3-15 Remaining activity after 15 minutes seen moving toward the heart (to the left).

Example 3: Extravasation of F-18 During Intravenous Injection

A 370 MBq/mL concentration of F-18 is extravasated during an injection in 1 min at a rate of 1 mL/min. Decay data is obtained from the ICRP 107 database. The clinician immediately applies a warm compress, which is held in place for 30 min. An advanced dose assessment was conducted for the first hour to capture the highest radioactivity concentrations in tissue close to the site of extravasation. The user is reminded that F-18 has a radiological half-life of just under 2 h.

Solution 3: F-18 Extravasation

The Advanced mode inputs reflect changes to several inputs (Figure 3-16) and the application of a warm compress (Figure 3-17). User specifications include calculations with a smaller voxel size and multiple layers. Thinner tissue layers and a smaller voxel size justify reductions in lateral transmissivity. In this case, the upper 6 mm of tissue is assumed to have the same lateral transmissivity with the deepest 3 mm of tissue exhibiting a greater resistance to flow and threefold smaller lateral transmissivity. The simulation finishes in 20 seconds.

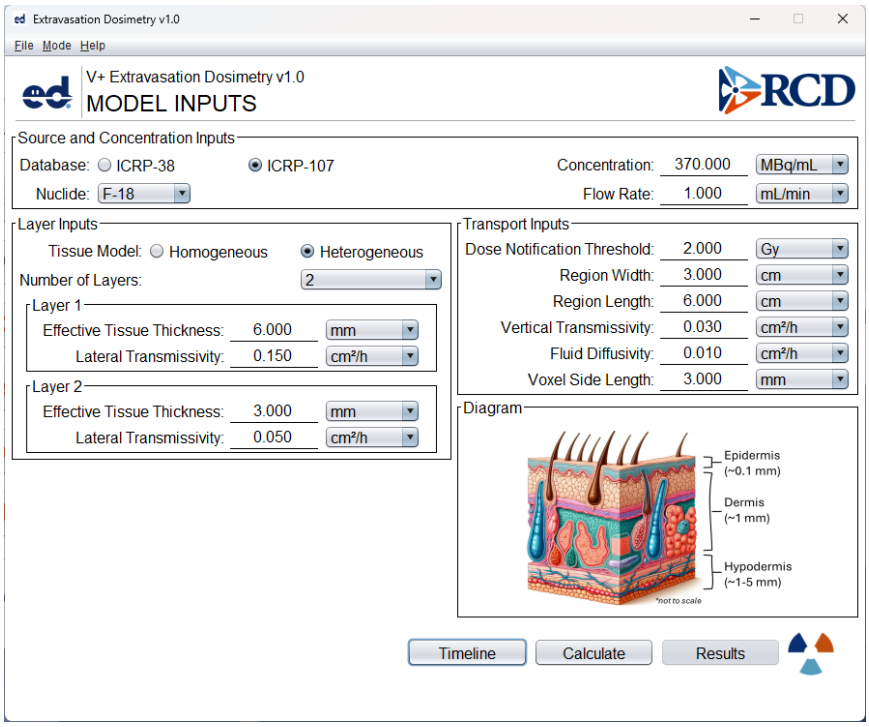


Figure 3-16 Extravasation Advanced Mode Main Screen for Solution 3.

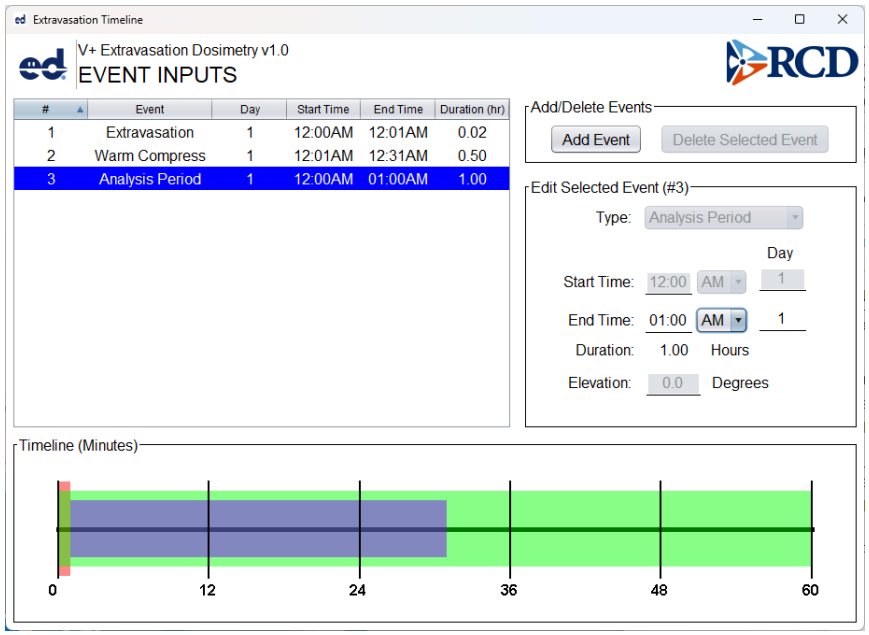
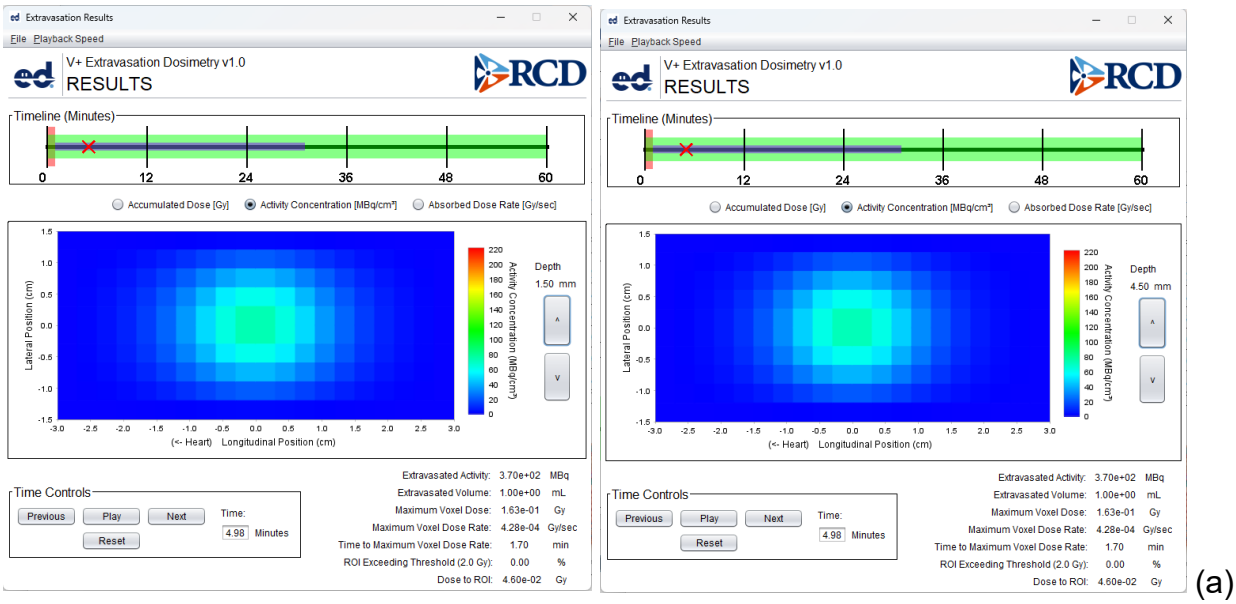
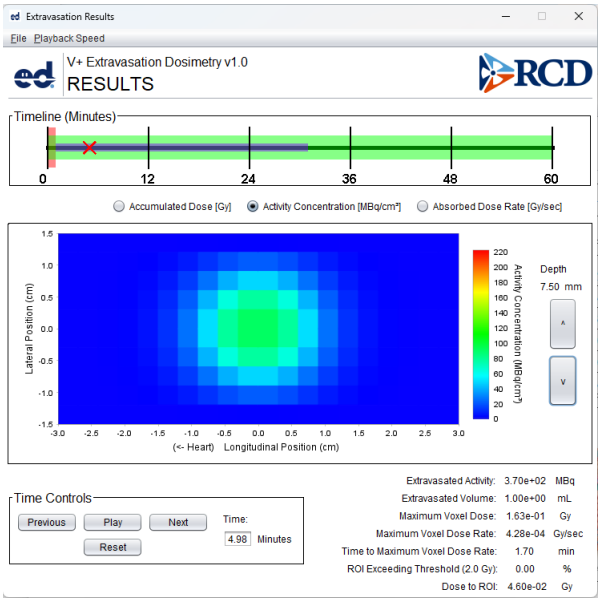


Figure 3-17 Extravasation timeline event inputs for Solution 3.

Figure 3-18 displays the 3D activity distribution of F-18 in tissue at about 5 min. The accumulated dose distribution to local tissue for the 1-h simulation is shown in Figure 3-19. The maximum voxel dose and dose to the entire region of interest are 0.163 Gy and 0.0460 Gy, respectively. Both results are well below the 2-Gy notification threshold.

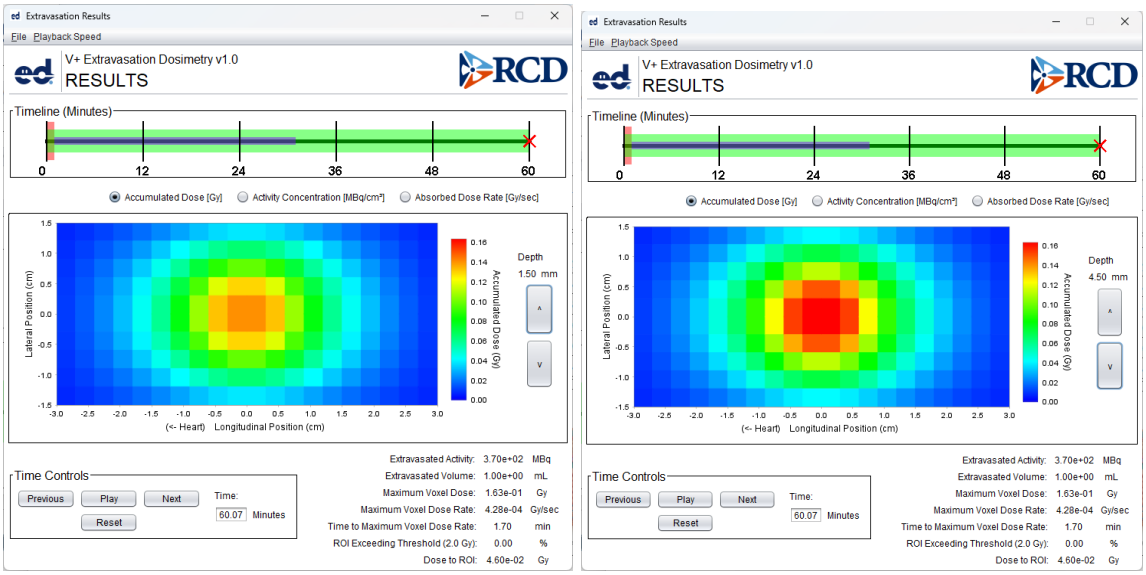


(a)

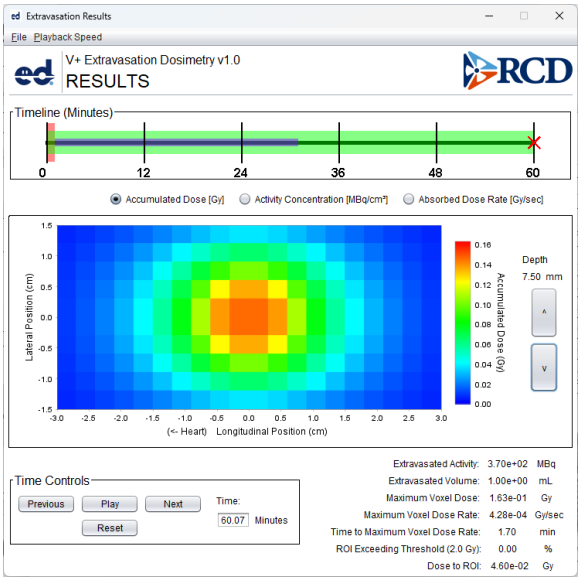


(b)

Figure 3-18 F-18 activity concentrations in tissue at 5 min for (a) the upper 6 mm of tissue with midpoint depths of 1.5 and 4.5 mm and (b) the deepest 3 mm of tissue with a midpoint depth of 7.5 cm.



(a)



(b)

Figure 3-19 Accumulated tissue dose from F-18 at 1 h for (a) the upper 6 mm of tissue with midpoint depths of 1.5 and 4.5 mm and (b) the deepest 3 mm of tissue with a midpoint depth of 7.5 cm.

Example 4: Extravasation of O-15 Intravenous Injection

A 2,300 MBq/mL concentration of short-lived O-15 is administered by 1-mL injection within 1 min. The analyst assumes complete extravasation and proceeds with default inputs for a 30-min Basic calculation with data from the ICRP 107 database.

Solution 4: O-15 Extravasation

Basic mode inputs in Figure 3-20 and timeline detail in Figure 3-21 show changes to the concentration and extravasation time. Figure 3-22 displays accumulated dose results at the end of analysis.

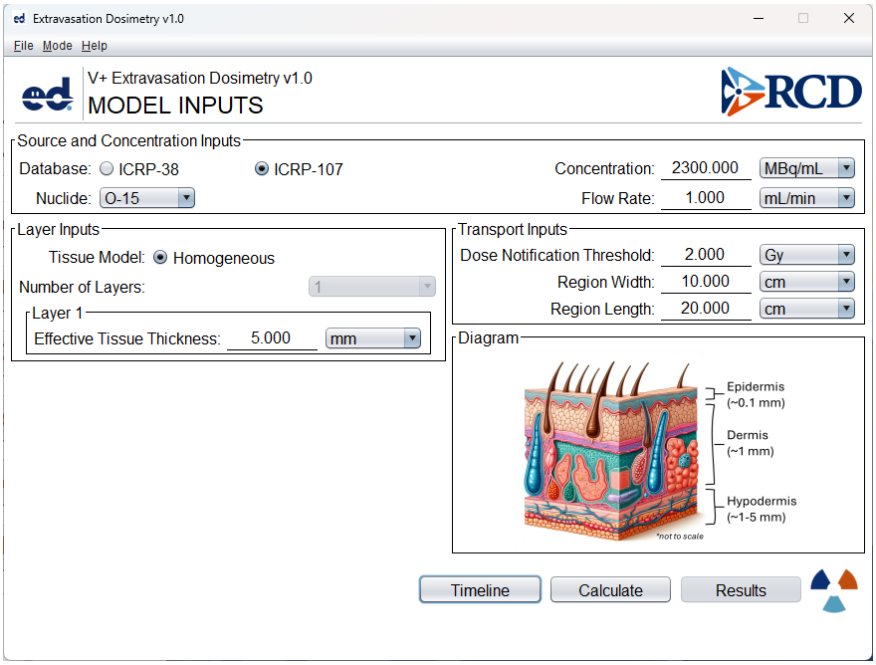


Figure 3-20 Extravasation Advanced Mode input screen for Solution 4.

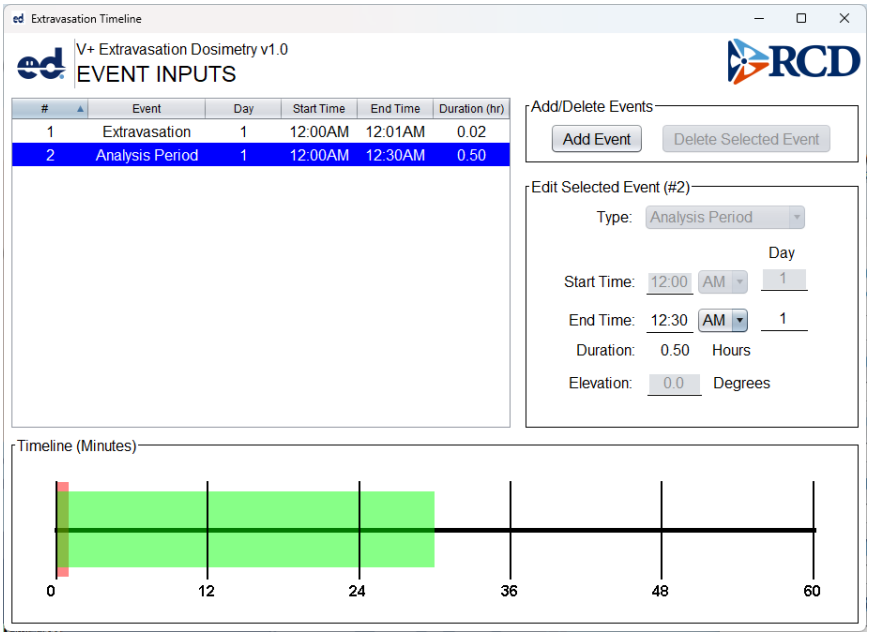


Figure 3-21 Extravasation timeline event inputs for Solution 4.

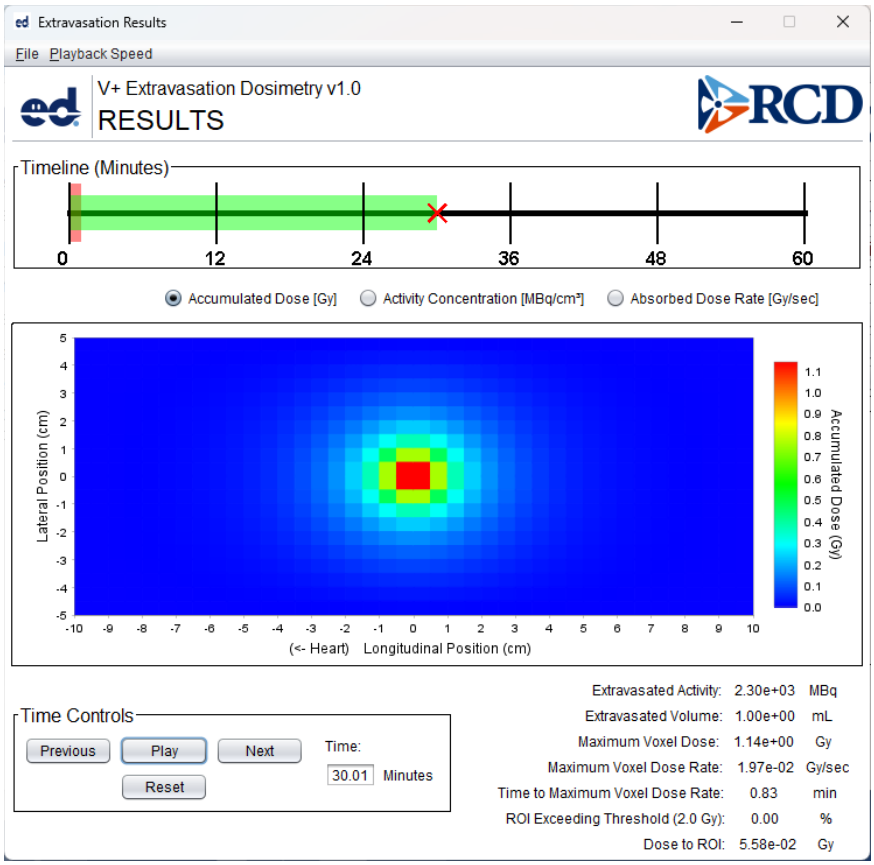


Figure 3-22 Extravasation Accumulated Dose results for Solution 4.

In this instance, the output data show the maximum voxel dose is 1.14 Gy with a dose to the entire region of interest of 55.8 mGy. The default notification threshold of 2 Gy is not exceeded in any of the calculational cells. The maximum voxel dose to the patient is on the order of the bounding dose estimates “approaching 1 mSv” to the technologist’s fingers during administration summarized by ICRP (2008b).

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