APPENDIX A EXAMPLES AND SOLUTIONS USING VARSKIN+ (VERSION 1.3)

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 to calculate Deep Dose Equivalent, but simply to demonstrate the utility of the code for estimating energy absorption at various depths in tissue from skin contamination events.

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 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 applicable to the inputs shown.

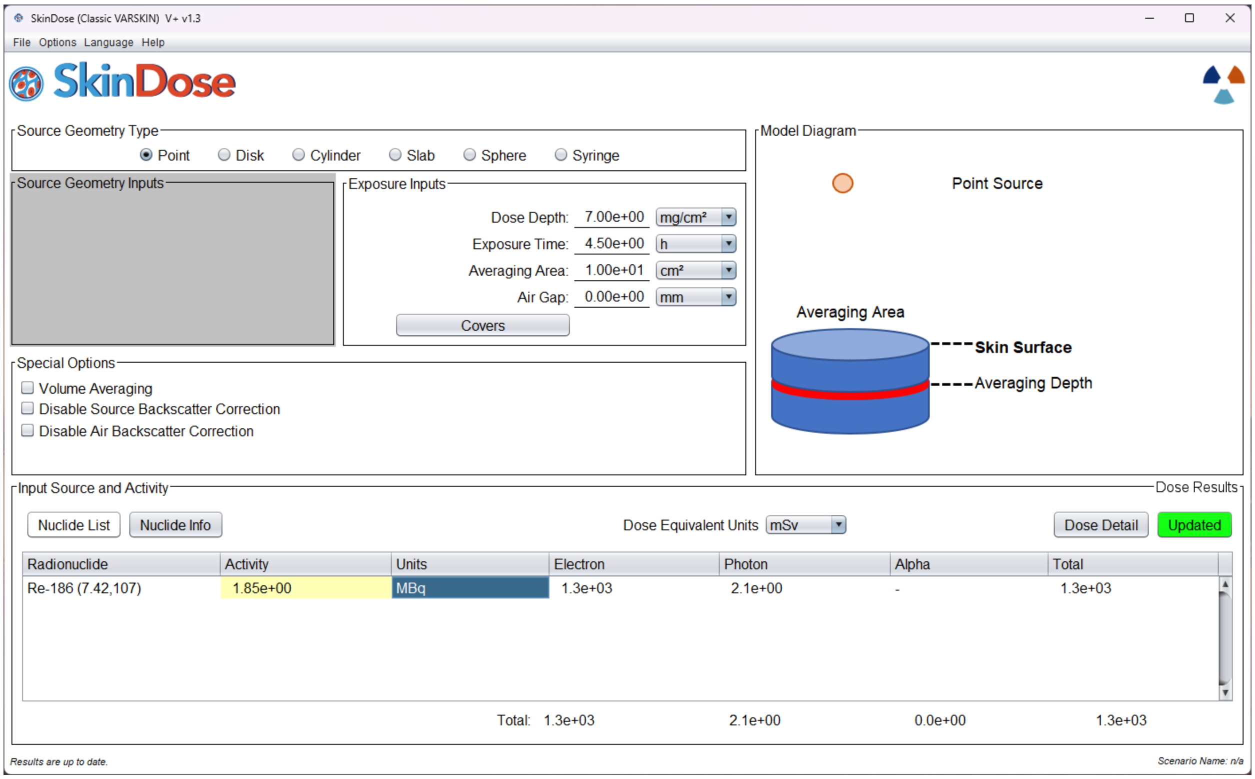

Figure A-1 Screenshot of SkinDose Module Main Window

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, **2.1 mSv** from photons, and no alpha emissions associated with this nuclide), 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 **0.0** (a calculated dose of zero), a photon dose equivalent of **0.074 mSv**, and no alpha emissions.

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**, a photon dose of **0.45 mSv**, and no alpha emissions.

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 (no alpha), 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 (no alpha). 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 (no alpha) 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 a depth of 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:

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

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 **130 mSv**, a photon dose of **130 mSv**, and a total dose (no alpha) of **270 mSv** (due to rounding the total dose appears to be greater than the sum). 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; users are cautioned not to rely too heavily on such calculations. 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 1 MBq/cm^2 will be assumed (232 MBq) 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 emissions. The activity concentration on the plate then can be found using,

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

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

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

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 Automatic 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 A-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 a large number of 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 Tables A-1 and A-2 (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.

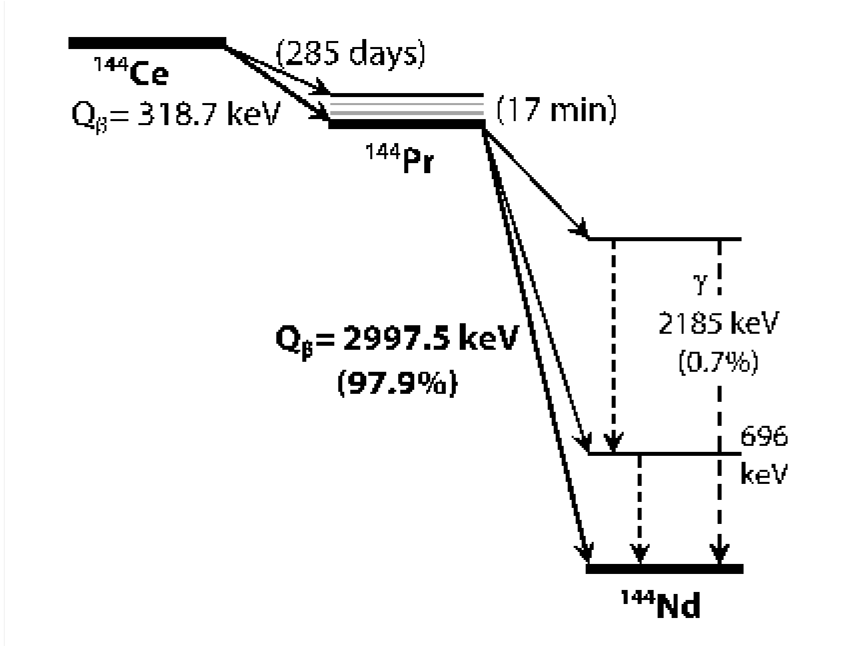

Figure A-2. The Decay Scheme of Ce-144 to Stable Nd-144

Table A-1a ICRP 38 Photon Emission Data for the 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
		0.2484	0.03357		0.2484	0.03357
		0.486	0.04093		0.486	0.04093
		0.1188	0.05341		0.1188	0.05341
		0.3456	0.0864999		0.3456	0.0864999
		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
		0.429454	0.0417924		0.429454	0.0417924
		0.550999	0.0406532		0.550999	0.0406532
		0.67266	0.00503329		0.67266	0.00503329
		0.439911	0.00548929		0.439911	0.00548929
		0.142402	0.00585109		0.142402	0.00585109
		0.128512	0.0055926		0.128512	0.0055926
Pr-144	0.9822	1.48	0.69649		1.4537	0.69649
		0.30044	1.48915		0.2951	1.48915
		0.77404	2.1857		0.7603	2.1857
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
		0.505078	0.0050132		0.00899	0.0050132
		1.63137	0.00548929		0.02903838	0.00548929
		0.959831	0.00585109		0.017085	0.00585109
		0.710227	0.0055926		0.012642	0.0055926
		0.421165	0.0054974		0.007497	0.0054974
		0.25531	0.0063272		0.004545	0.0063272
		0.110795	0.00659849		0.001972	0.00659849
		0.177557	0.00661719		0.003161	0.00661719
		0.149619	0.00445329		0.002663	0.00445329
Pr-144	0.999	1.48	0.69649		0.026318	0.69649
		0.30044	1.48915		0.005342	1.48915
		0.77404	2.1857		0.013764	2.1857

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

Table A-1b ICRP 38 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	6,823	116	0.0908	0.0279
Pr-144	0.288	100	1.21	0.696
Pr-144m	0.12	102	0.612	0.00412
Ce-144(D)	6,823	218	0.658	0.683

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

Table A-2a ICRP 107 Photon Emission Data for the 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
		0.578928	0.00501953		0.578928	0.00501953
		0.366352	0.00548692		0.366352	0.00548692
		0.19962	0.033568		0.19962	0.033568
		0.431743	0.0406843		0.431743	0.0406843
		0.835882	0.0407816		0.835882	0.0407816
		0.257288	0.04098		0.257288	0.04098
		0.179471	0.0417904		0.179471	0.0417904
Pr-144	0.99023	1.342	0.69651		1.32889	0.69651
		0.277794	1.48916		0.275078	1.48916

0.693814	2.18566		0.687035	2.18566

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

Table A-2b 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	113	0.0906	0.0286
Pr-144	0.288	100	1.21	0.696
Pr-144m	0.12	102.5	0.292	0.00412
Ce-144(D)	6837.84	212	0.654	0.684

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" (in secular equilibrium). On returning to the main SkinDose window, the user will note that the default activity value is 1 Bq; these inputs remain 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 A-3), a manual calculation of the total dose (SUM in Table A-3) can be compared with the automatic calculation using the progeny option (Ce-144(D) in Table A-3). The SUM is calculated using:

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

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

$$D = 6.9x10^{-9}\ mGy/nt$$

Table A-3 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		2.4×10^{-9}	5.9×10^{-12}
Pr-144	0.9822	4.5×10^{-9}	2.3×10^{-12}
Pr-144m	0.0178	5.7×10^{-13}	1.9×10^{-11}
Pr-144*	0.999	4.5×10^{-9}	2.3×10^{-12}
SUM		$\mathbf{6.9 \times 10^{-9}}$	$\mathbf{8.5 \times 10^{-12}}$
Ce-144(D)		6.9×10^{-9}	8.5×10^{-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".

The difference in the dose calculations using the automatic progeny consideration is shown to be within a rounding tolerance of 1 percent. 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 A-4 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. Note that a value of zero (0.0e+00) is indicated for alpha dose of the decay progeny selection (Ce-144(D)). This means that an alpha emission is somewhere in the decay chain, but no alpha energy reaches the dose averaging area.

Table A-4 Dose Results from SkinDose with Progeny using the ICRP 107 Decay Database

Nuclide	Branching Ratio	Electron Dose (mGy/nt)	Photon Dose (mGy/nt)
Ce-144		2.4×10^{-9}	4.8×10^{-12}
Pr-144	0.99023	4.5×10^{-9}	2.1×10^{-12}
SUM		$\mathbf{6.9 \times 10^{-9}}$	$\mathbf{6.9 \times 10^{-12}}$
Ce-144(D)		6.9×10^{-9}	7.1×10^{-12}

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

Examples Using the WoundDose Module

This section of the appendix describes three 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 database with no decay progeny.

Example 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. No alpha emissions are present.

	Shallow Dose		Local Dose		Systemic Dose
	Electron	Photon	Electron	Photon	CEDE
Point Source	0	15	90	16	0.033
Line Source	440	31	72	13	0.033

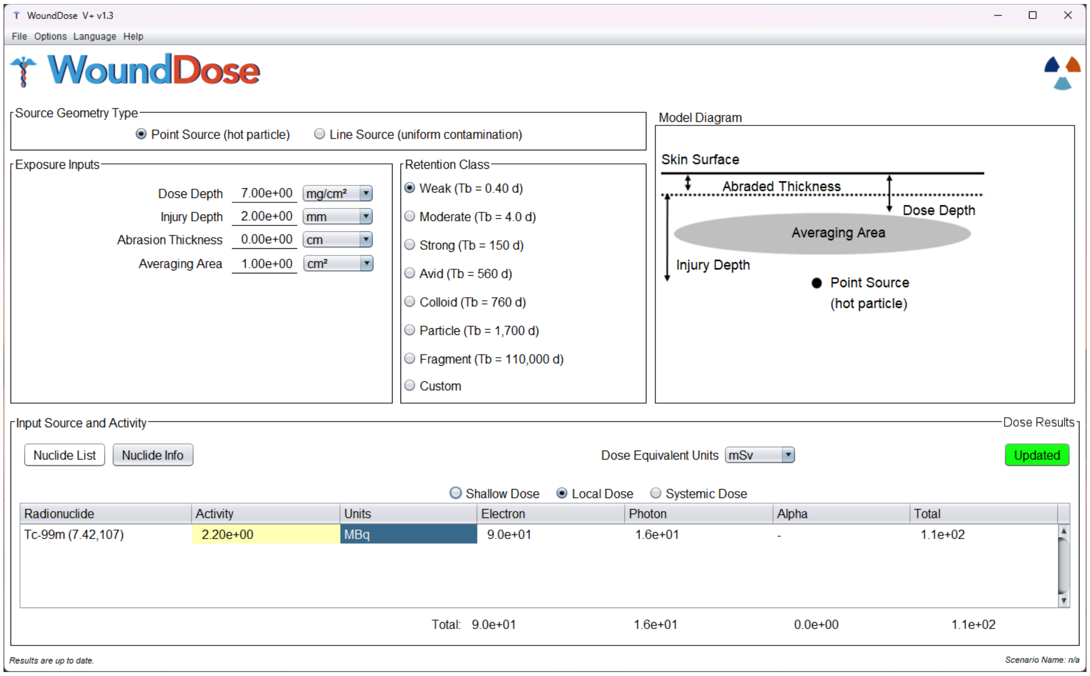

Figure A-3 Screenshot of the WoundDose Main Window

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 A-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 selecting the Calculate button, the user obtains the following results for the two assumptions of point source and line source.

	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	1.1E6	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:

	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	1,200	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 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.

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:

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

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. You choose 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:

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

Enter the NeutronDose data (Figure A-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**. No "Shielded" dose is displayed because no shielding has been selected (press the "Shield" button to implement shielding between the source and receptor). The user can select the "Spectrum" button to view the Cf-252 energy-dependent neutron emission probability.

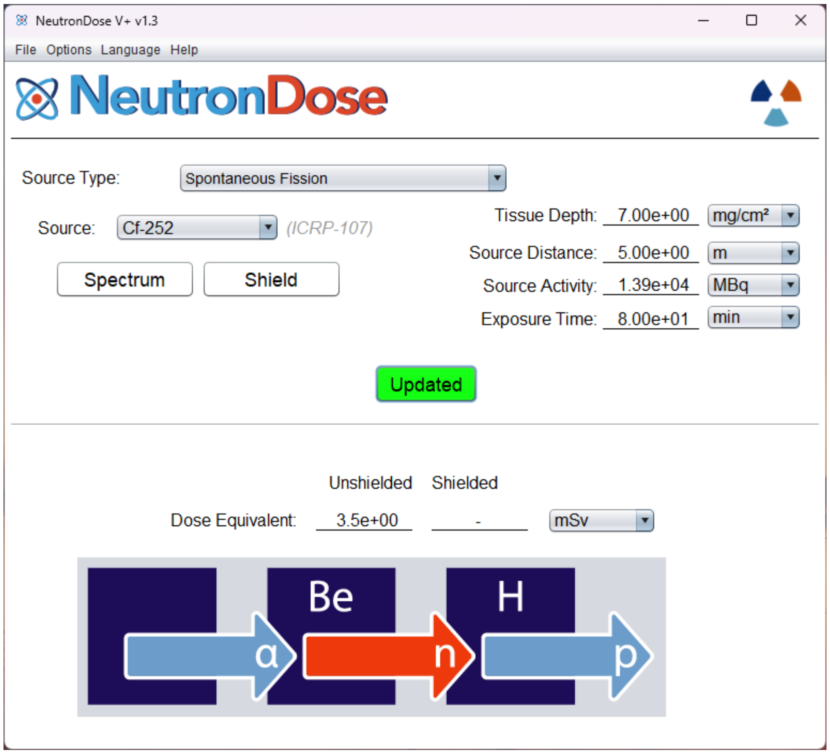

Figure A-4 Screenshot of NeutronDose Main Window

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

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

The energetics of the reaction are

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

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 shallow dose rate at 1, 2, and 3 meters from the PuBe source, the "Reaction (α, 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 equivalent rates 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

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

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 7 mg/cm^2, 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; essentially the same dose rates calculated above. The table below provides dose rates (**μSv/hr**) for this source with various assumptions about average neutron energy.

Distance	**Flux**	**1.0 MeV**	**4.0 MeV**	**4.5 MeV**	**5.0 MeV**	**11 MeV**
1 m	2,700	0.63	1.6	1.6	1.6	2.8
2 m	660	0.15	0.39	0.39	0.39	0.68
3 m	300	0.070	0.18	0.18	0.18	0.31

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:

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

The energetics of this reaction are as follows:

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

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 tissue depth of 7 mg/cm^2 to be **1.6** [$pSv\ m^2\ h^{-1}\ MBq^{-1}$].

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 A-5).

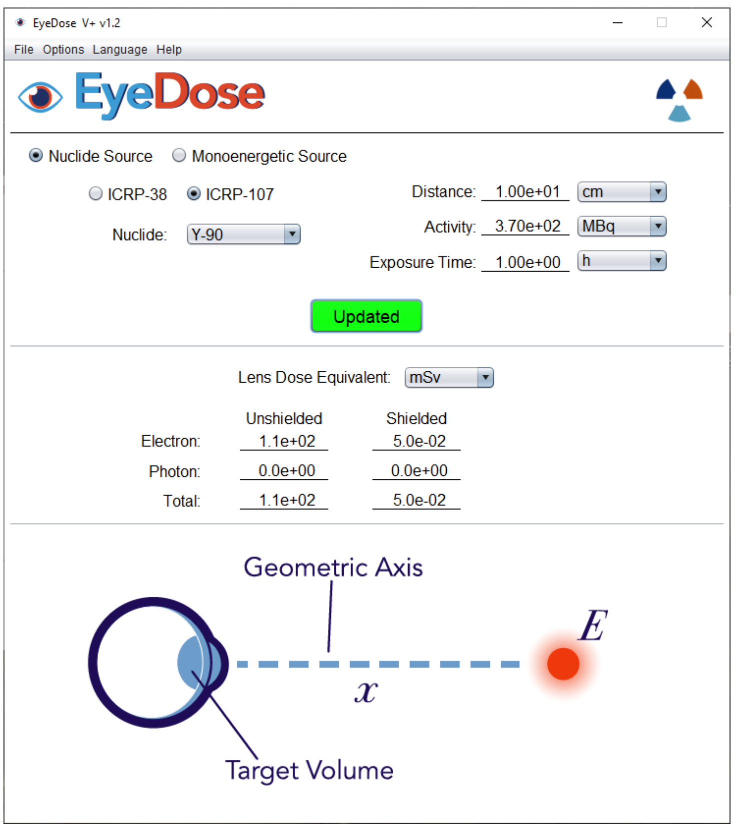

Figure A-5 Screenshot of the EyeDose Module Main Screen.

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

The table below shows the Sr/Y-90 (point source) 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**.

Unshielded	0.1 m	0.2 m	0.4 m	0.6 m	0.8 m	1 m
Y-90	$1.1x10^{2}$	$2.6x10^{1}$	$2.5x10^{0}$	$1.7x10^{-1}$	$3.4x10^{-2}$	$8.4x10^{-3}$
Sr-90	$1.9x10^{-3}$	$9.7x10^{-5}$	$1.8x10^{-6}$	$1.3x10^{-7}$	$2.6x10^{-8}$	$9.4x10^{-9}$

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

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 an electron dose rate of **120** mSv/h (compared to 110 mSv/h from EyeDose) 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.

In a separate incident, an individual is exposed to a 37 MBq source of Co-60 at a distance of 2.5 meters. The health physicist (HP) 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 (also **1.9 μSv**), 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; to maintain clarity she enters an electron energy of zero. After the Calculate button is pressed, a lens dose equivalent per source particle of **$7.2x10^{-12}$ μSv** is displayed for unshielded 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:

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

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

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

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 photon emissions from a 37 MBq source of Co-60. The user should actually 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.

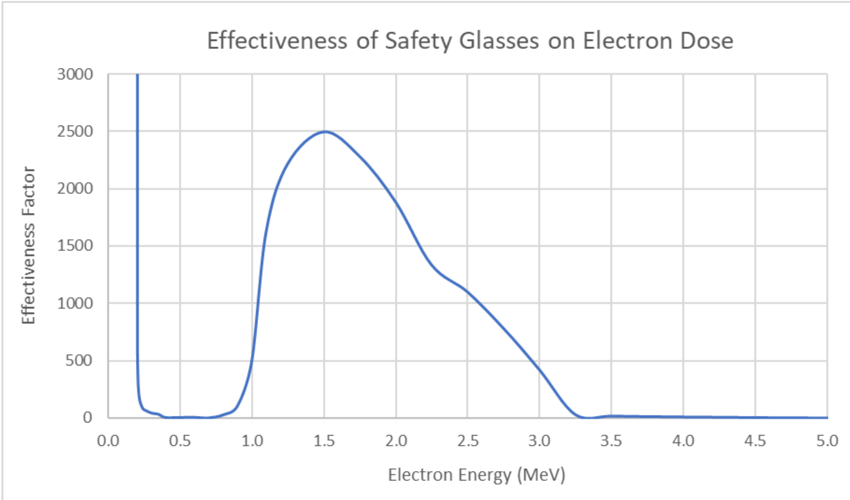

Figure A-6 Effectiveness Factor of 2 mm Leaded Safety Glasses on a Monoenergetic Beam of Electrons

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.

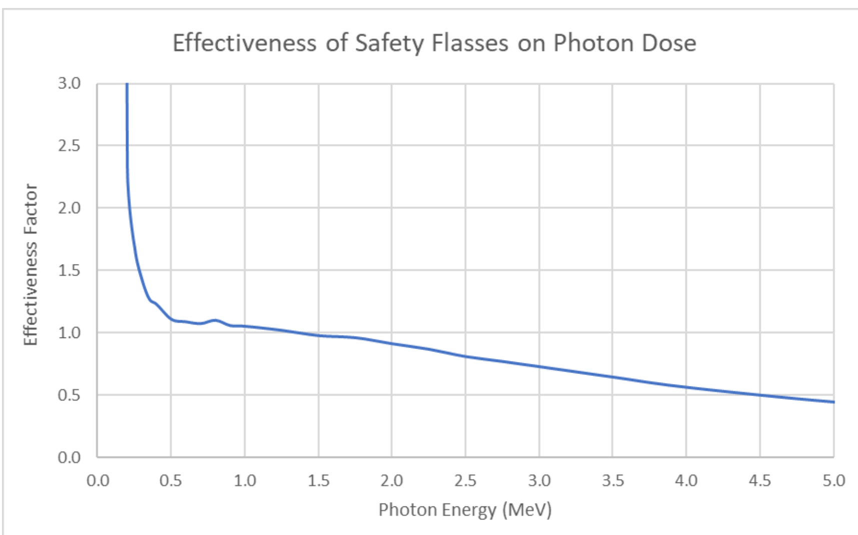

Figure A-7 Effectiveness Factor of 2 mm Leaded Safety Glasses on a Monoenergetic Beam of Photons