October 25, 2021

VARSKIN+ Examples

Fall 2021 RAMP Users Group Meeting

D.M. Hamby and C.D. Mangini
Developed by Renaissance Code Development for the U.S. NRC

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

TABLE OF CONTENTS

Example Problems *1*

Example 1 – SkinDose: Liquid Contaminant Spilled on Lab Coat **2**

Example 2 – SkinDose: Hot Particle on Gloved Hand **3**

Example 3 – SkinDose: Determination of a Depth-Dose Profile **4**

Example 4 – SkinDose: Use of the Air Gap Model **5**

Example 5 – SkinDose: Use of Decay-Correction and Progeny (D) Option **6**

Example 6 – SkinDose*: Point Kernel Photon Dose Calculation **7**

Example 7 – SkinDose*: Determination of Contaminant Activity on a Metal Plate **8**

Example 8 – SkinDose*: Exposure to a High-Activity ^{192}Ir Source **9**

Example 9 – NeutronDose: Exposure to ^{252}Cf During a Laboratory Assignment **10**

Example 10 – NeutronDose: Neutron Dose Rate from a Plutonium-Beryllium Reaction Source **11**

Example 11 – NeutronDose: Neutron Dose Rate from an Antimony-Beryllium Reaction Source **12**

Example 12 – EyeDose: Exposure to Sr/Y-90 in the Laboratory **13**

Example 13 – EyeDose: Estimation of Dose Rate to the Lens from a Co-60 Source **14**

Example 14 – EyeDose: The Effectiveness of 2 mm Leaded Safety Glasses on Dose to the Lens **15**

Example 15 – WoundDose: Estimation of Dose from a Tc-99m Needlestick **16**

Example 16 – WoundDose: Puncture Wound Involving Pu-238 at Los Alamos **17**

Example 17 – WoundDose: Liquid Source Directly on Open Wound **18**

Appendix: Detailed Explanations and Answers to Examples *1*

Example 1 – SkinDose: Liquid Contaminant Spilled on Lab Coat 3
Example 2 – SkinDose: Hot Particle on Gloved Hand 6
Example 3 – SkinDose: Determination of a Depth-Dose Profile 8
Example 4 – SkinDose: Use of the Air Gap Model 10
Example 5 – SkinDose: Use of Decay-Correction and Progeny (D) Options 11
Example 6 – SkinDose*: Point Kernel Photon Dose Calculation 14
Example 7 – SkinDose*: Determination of Contaminant Activity on a Metal Plate 15
Example 8 – SkinDose*: Exposure to a High-Activity ^{192}Ir Source 16
Example 9 – NeutronDose: Exposure to ^{252}Cf During a Laboratory Assignment 19
Example 10 – NeutronDose: Neutron Dose Rate from a Plutonium-Beryllium Reaction Source 21
Example 11 – NeutronDose: Neutron Dose Rate from an Antimony-Beryllium Reaction Source 22
Example 12 – EyeDose: Exposure to Sr/Y-90 in the Laboratory 23
Example 13 – EyeDose: Estimation of Dose Rate to the Lens from a Co-60 Source 24
Example 14 – EyeDose: The Effectiveness of 2 mm Leaded Safety Glasses on Dose to the Lens . 26
Example 15 – WoundDose: Estimation of Dose from a Tc-99m Needlestick 28
Example 16 – WoundDose: Puncture Wound Involving Pu-238 at Los Alamos 29
Example 17 – WoundDose: Liquid Source Directly on Open Wound 31

Example Problems

This workbook provides a tutorial for both novice and experienced users and serves as a resource for VARSKIN+ training sessions which have been offered during annual RAMP User's Meetings. Examples are provided for SkinDose (* examples are intended for advanced users), NeutronDose, EyeDose, and WoundDose. Each example describes an exposure situation followed by a solution that involves the use of pertinent VARSKIN+ modules to estimate doses of interest. The purpose of these examples is to lead the trainee through several calculations that require in-depth knowledge of dosimetry and also highlight many features of the VARSKIN+ software modules. Detailed explanations and answers are provided in the Appendix.

Example 1 – SkinDose: Liquid Contaminant Spilled on Lab Coat

At a research hospital, a doctor prescribes a 10-milliliter (mL) administration from a stock solution containing 370 kilo-Becquerels per milliliter (kBq/mL) of rhenium-186 (^{186}Re) for a clinical research study at 1 p.m. that day. Around 12:30 p.m., a lab technician loads the dose under the hood. Subsequently, a fellow employee bumps into her, and the needle slips out of its container and deposits 5 mL of the solution onto 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 is performed, and the contamination is discovered.

a) By hand, calculate the activity of the source in MBq.

b) Use SkinDose to calculate decay-corrected electron and photon shallow doses using a standard point source geometry, directly on the skin. Given that this is a conservative model of the scenario, what do we learn from performing this step?

c) Calculate decay-corrected electron and photon doses using a thin disk source geometry, directly on the skin.

d) Assume that the cloth lab coat soaks up the contamination, thereby acting as a volumetric source directly on the skin. What geometry would this resemble? Use the density and thickness values found in the VARSKIN+ NUREG for a cotton lab coat ($t = 0.4$ mm; $\rho = 0.9$ g/cm^3), calculate the decay-corrected electron and photon doses.

SkinDose DOSIMETRY	Electron Dose (mSv)	Photon Dose (mSv)	Total Dose (mSv)
Point on Skin			
Disk on Skin			
Cylinder in Cloth			

Example 2 – SkinDose: Hot Particle on Gloved Hand

An employee 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 an exit survey, contamination is detected on the surgeon's glove, and the glove (0.3 mm thick; ρ = 0.6 g/cm^3) is removed and taken to the laboratory for analysis. The laboratory report concludes that the contamination is a slab-shaped stellite hot particle with the following characteristics:

- Stellite atomic number (cobalt-chromium alloy): 25.5
- Stellite density: 8.3 g/cm^3
- Radioactive contaminant: ^{60}Co
- Source strength: 92.5 MBq
- Particle size: 80 x 70 microns (5.6x10^{-5} cm^2) and 50 microns thick

a) Calculate the shallow-skin dose from electrons and photons including the presence of the cover material. How does this compare to the regulatory limit?

b) Calculate shallow dose using a cylindrical source geometry. [Hint: use the following formula to find the diameter for the cylindrical source using the given dimensions of the stellite: $d = 2\sqrt{(\frac{X \cdot Y}{\pi})}$]

c) Investigate the dosimetric influence of tissue depth by calculating dose at 1 cm from the slab source (by changing the skin density thickness to 1,000 mg/cm^2). Discuss the reasoning behind the difference between the results for photon and electron doses.

SkinDose DOSIMETRY (with cover)	Electron Dose (mSv)	Photon Dose (mSv)	Total Dose (mSv)
Slab Source Shallow Dose			
Cylindrical Shallow Dose			
Dose @ 1 cm			

Example 3 – SkinDose: Determination of a Depth-Dose Profile

A hot particle was found on an employee's plastic lab coat (ρ = 0.36 g/cm^3). The lab coat is 0.2 mm thick and separated from the skin by a 3 mm air gap. The particle has not been "captured" (i.e., separated from the lab coat), therefore, we know very little about its physical size and shape. By analysis of the coat, however, we do know that the particle contains six different radionuclides with all their associated emissions. The analysis indicates the presence of 3.6 μCi of ^{57}Co, 1920 μCi of ^{106}Ru (with ^{106}Rh in equilibrium), 2.8 μCi of ^{134}Cs, and 3.6 μCi of ^{137}Cs (with ^{137m}Ba in equilibrium). By experience we know that both electrons and photons are emitted from these nuclides and we are concerned about the potential dose delivered to the employee's skin. Because our procedures require determination of the electron and photon depth-dose profiles, we will calculate dose at various tissue depths and plot the result.

For this example, we will use ICRP 107 data. Since we do not know the dimensions of the source, we will assume a point.

a) Calculate the electron and photon dose rates, as well as total dose rate, for each separate nuclide present in the source at a standard depth of 7 mg/cm^2.

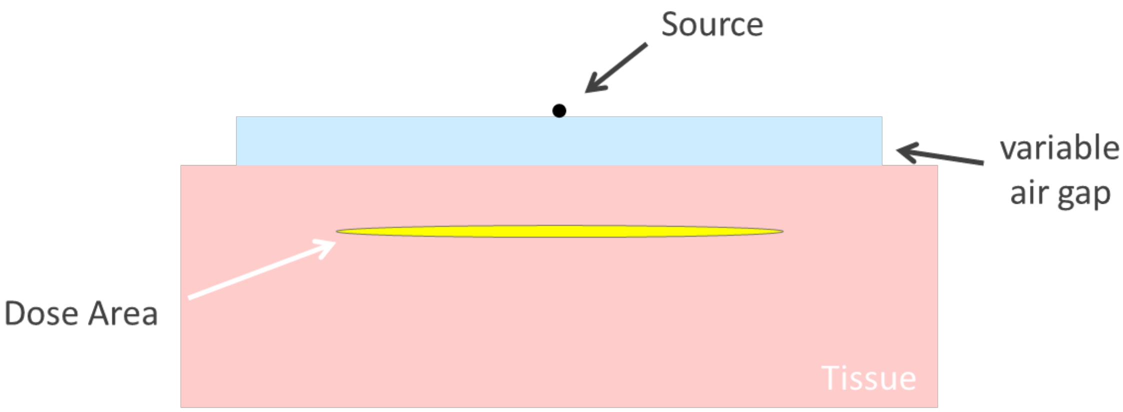
b) Investigate the influence of tissue depth on dose by repeating the calculations in part a) for the range of tissue depths in the table below. Fill out the table using the sums of the nuclides' individual results. Discuss the effect of tissue depth on electron and photon dose for these nuclides.

SkinDose DOSIMETRY (ICRP 107) @ 7 mg/cm^2	Electron Dose Rate (mSv/hr)	Photon Dose Rate (mSv/hr)	Total Dose Rate (mSv/hr)
Co-57			
Ru-106(D)			
Cs-134			
Cs-137(D)			
TOTAL			

SkinDose DOSIMETRY (ICRP 107)	Electron Dose Rate (mSv/hr)	Photon Dose Rate (mSv/hr)	Total Dose Rate (mSv/hr)
7 mg/cm^2			
30			
50			
75			
100			
150			
200			
300			
500			
750			
1000			

Example 4 – SkinDose: Use of the Air Gap Model

Consider a 100 kBq ^{60}Co point source skin contaminant separated from the skin by a variable air gap. The source serves as a contaminant for 15 minutes. Fill out the table below, wherein you calculate the effect of an air gap on shallow skin dose from a point source. Use a 0.01 cm^2 skin dose averaging area to show how interactions in the air gap influence the dose at 7 mg/cm^2.



a) Calculate electron and photon dose for each air gap in the table. The values were chosen to support a large range of SkinDose's air gap modeling boundaries.

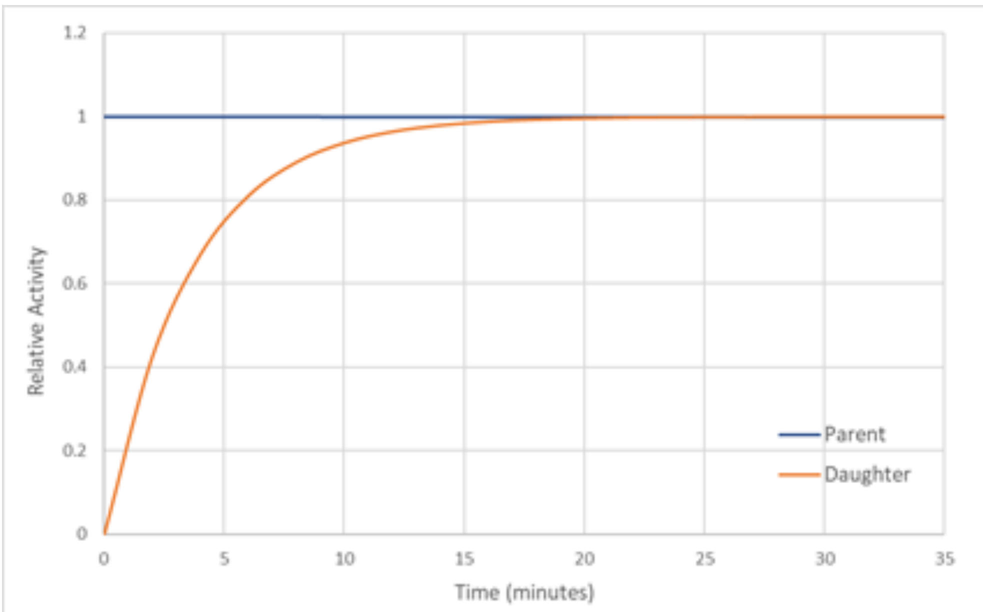
Airgap (cm)	Electron Dose (mSv)	Photon Dose (mSv)
0.1		
0.2		
0.5		
0.7		
1		
2		
5		
7		
10		

b) Create a logarithmic plot comparing the air gap length to both electron and photon doses. Is there any part of this plot that could be considered not as expected? What may cause these deviations?

Example 5 – SkinDose: Use of Decay-Correction and Progeny (D) Option

SkinDose ow provides three main radiation dose estimates: (1) initial dose rate; (2) dose (no decay); and (3) decay-corrected dose. At first glance, the user may think that it is odd for a total dose to be calculated that does not consider radioactive decay. SkinDose, however, has this feature so that decay progeny in secular equilibrium with its parent can receive full consideration in the dose calculation.

One such example is ^{137}Cs (half-life of 30 yrs) and its progeny ^{137m}Ba (half-life of about 2.5 minutes). Using a 10-half-life rule of thumb (chart below), the ^{137m}Ba activity will be fully in-grown from a pure ^{137}Cs source within about 25 minutes, after which the activity of both parent and progeny will be equal (secular equilibrium).



Calculate dose for a ^{137}Cs point source of 1 MBq, an exposure time of 1 hour, and a 10 cm^2 averaging area at a depth of 7 mg/cm^2.

a) Model the scenario in SkinDose and calculate dose using ICRP 107 parameters. Select the option (D) that will include the decay progeny. What do you observe about the initial dose rate, no-decay dose, and decay-corrected dose?

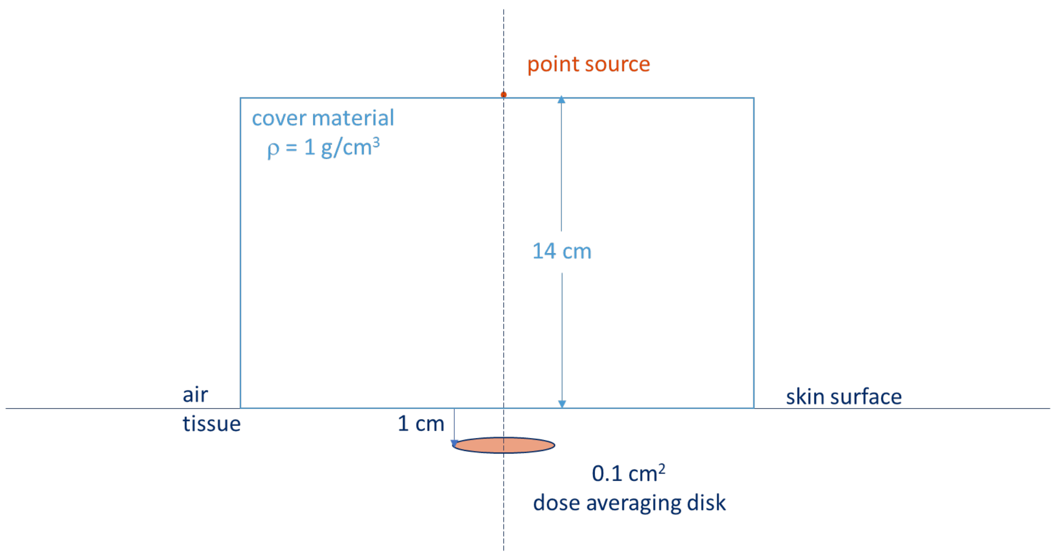
b) Calculate dose using ICRP 107 parameters where the decay products are not included. You will need to include both nuclides separately. What do you now notice about the initial dose rate, no-decay dose, and decay-corrected dose, compared to part a)? What SkinDose input causes these differences?

c) How might the branching ratio for ^{137m}Ba (94.7%) affect dose calculations?

Example 6 – SkinDose*: Point Kernel Photon Dose Calculation

Consider a 3.7 GBq ^{137}Cs point source that is separated from a skin point receptor by 14 cm of water. The point receptor is located 1 cm beneath the skin surface, as in the diagram below.

(a) Calculate the point kernel *photon dose rate* using SkinDose. HINT: SkinDose does not have point receptor modeling capabilities, so different measures must be taken to closely model a skin point receptor.



Example 7 – SkinDose*: Determination of Contaminant Activity on a Metal Plate

This example demonstrates an alternative application for SkinDose other than skin contamination assessments. Users are cautioned, however, not to rely heavily on such calculations.

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.

Model the scenario in SkinDose. Consider what serves as the "skin averaging area" (i.e., where the dose is calculated) and density thickness in this scenario? What constitutes the source, and what geometry should be used? Once you have calculated a dose rate, use the following:

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

to determine the actual activity concentration on the plate: _______________ kBq/cm^2.

Example 8 – SkinDose*: Exposure to a High-Activity ^{192}Ir Source

A radiographer failed to crank in the source at the conclusion of an exposure; failed to observe the radiation actuated visible alarm; bypassed the audible alarm feature of the shooting room; and failed to observe his survey meter upon entry into the shooting room. In addition to a whole-body exposure, the radiographer's hands were exposed at close range to a high-activity (50 Curie) source of ^{192}Ir. The skin exposure to his hands is of interest here.

Iridium-192 decays about 95% of the time through beta-minus decay to ^{192}Pt and about 5% of the time through electron capture to ^{192}Os. As ^{192}Ir transitions, several high-energy beta particles are emitted, along with a number of low- and moderate-energy photons (energy transitions of which may also result in the emission of conversion electrons).

The ^{192}Ir source is encapsulated in stainless steel (Z = 26; x = 0.8 mm; ρ = 8 g/cm^3) which shields electron emissions (yet, potential significant bremsstrahlung production) such that human exposure is from photons alone. Electron emissions include two primary beta decay mechanisms with maximum energy of 672 keV and 535 keV, with an average energy for all electrons (beta and conversion electrons) of 227 keV and a 338% yield.

(a) One publication (HHPRH 1998) states that the ^{192}Ir gamma-ray dose constant is 0.00016 mSv hr^{-1} MBq^{-1} at 1 meter. Convert the units of this constant to a dose-rate factor at 1 inch for our 50 Ci source. Use this value to approximate dose to the left and right hand; record your answers below.

(b) The previous estimate assumes that the dose is calculated to deep tissue (i.e., charged particle equilibrium, CPE, has been established). The development of CPE in shallow media is quite complex. Because of its primary purpose, SkinDose specifically handles this calculation. Use SkinDose to estimate the shallow and deep dose at 7 mg/cm^2 and 1000 mg/cm^2, respectively. Considering encapsulation, and a dose averaging disk of 10 cm^2, what is the dose to the left hand and the right hand?

SkinDose Photon Dose	Depth (mg/cm^2)	Dose (mSv)
Left Hand (4", 19 sec)		
	7	
	1000	
HHPRH	air*	
Right Hand (7", 12 sec)		
	7	
	1000	
HHPRH	air*	

*refers to the gamma constant being defined for a homogeneous volume of air

Example 9 – NeutronDose: 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.

(a) Determine the intrinsic specific activity of the Cf-252 source and its activity at the time of exposure.

(b) What dose equivalent does the student expect to receive as a result of the lab work?

Example 10 – NeutronDose: Neutron Dose Rate from a Plutonium-Beryllium Reaction Source

A 1.85 GBq plutonium-beryllium (PuBe) source is used in a portable density gauge. 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.

(a) Determine dose-rate as a function of distance (1, 2, and 3 meters) for this 1.85 GBq Pu-239-Be reaction source.

(b) Repeat the calculation using a monoenergetic source of 4.5 MeV. Is there a significant difference? Assume that approximately 50,000 neutrons per second (n/s) are emitted per GBq of plutonium.

Example 11 – NeutronDose: 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. This source provides two nearly monoenergetic neutrons of about 22 keV and 380 keV. 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).

Assume that the activity of the source is unknown. Calculate the dose rate factor for a typical Sb-124-Be reaction source.

Example 12 – EyeDose: 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. Use the ICRP 107 decay data for each radionuclide. Use the distances of 0.1 m, 0.2 m, 0.4 m, 0.6 m ,0.8 m and 1 m. Note that the "D" option is not available in the EyeDose model to include progeny.

Example 13 – EyeDose: 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 (HP) provides an estimate of whole-body dose and is now asked for a prediction of dose rate to the human lens.

(a) Estimate the dose to the lens of the eye using the ICRP 107 Co-60 decay data.

(b) Estimate the dose to the lens of the eye using a monoenergetic source of the same activity with an energy of 1.25 MeV.

(c) Estimate the dose using SkinDose assuming that the lens of the eye sits at a depth between 300 – 700 mg/cm^2. You may ignore the warning regarding the chosen air gap.

Example 14 – EyeDose: The Effectiveness of 2 mm Leaded Safety Glasses on Dose to the Lens

The dose reduction achieved by wearing 2 mm leaded safety glasses needs to be documented at your institution for an upcoming license renewal. Use EyeDose to perform the analysis for the energies below assuming a source distance of 1 m. As a reminder, 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. Plot the results for both electron dose and gamma dose.

Energy (MeV	Electron Effectiveness Factor	Photon Effectiveness Factor
0.2		
0.4		
0.6		
0.8		
1.0		
1.5		
2.0		
2.5		
3.0		
3.5		
4.0		
4.5		
5.0		

Example 15 – WoundDose: 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.

(a) Estimate the shallow dose, local dose and systemic dose using both a point source and a line source geometry. Assume a "Weak" retention class.

(b) Assuming that the wound depth is 0 mm (not realistic), how does the point source result for shallow dose compare to what SkinDose would calculate for the same set of inputs?

Example 16 – WoundDose: 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.

Use WoundDose to estimate shallow dose equivalent (SDE), local dose equivalent, and committed effective dose equivalent (CEDE) for this wound contamination incident.

Example 17 – WoundDose: Liquid Source Directly on Open Wound

A NM lab technician working with a 100 μCi solution of ^{141}Ce spills half of the of the vial directly onto her forearm. The solution gets absorbed by a bandage from a recent abrasion. Analysis by the RSO estimates that the bandage contained 90 μCi. Conservatively, the RSO estimates that the remaining 10 μCi has contaminated the open abrasion. Prior to an attempt at decontaminating the abrasion, the RSO wants to estimate the resulting shallow dose.

(a) Assuming an abrasion depth of zero, a wound depth of zero and point source geometry, what is the shallow dose for a "Weak" retention class.

(b) Determine the dose if biological removal is ignored (i.e., only decay removal is possible). How does this compare to a comparable SkinDose calculation?

HINT: The exposure time, or residence time (τ) of material remaining at the wound site, is determined by

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

where T_r and T_b are the radiological and biological half-lives, respectively.

Appendix: Detailed Explanations and Answers to Examples

RENAISSANCE CODE DEVELOPMENT, LLC

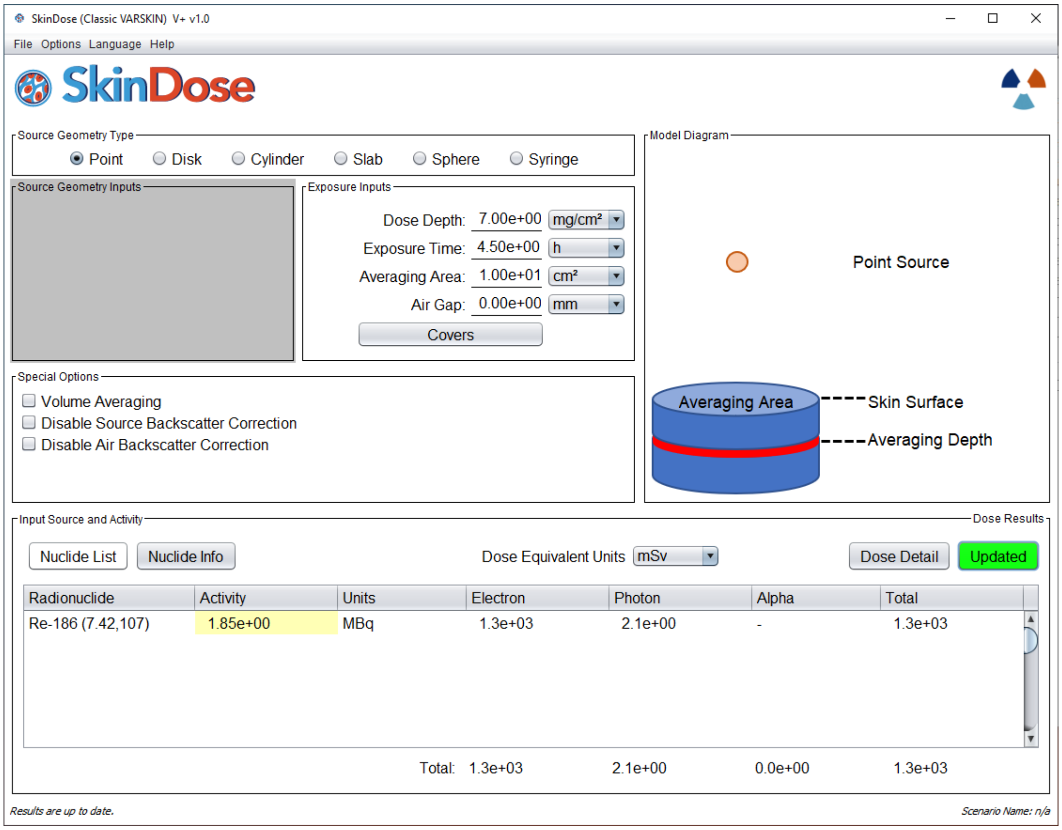
United States Nuclear Regulatory Commission
Protecting People and the Environment

Example 1 – SkinDose: Liquid Contaminant Spilled on Lab Coat

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.

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 in fact applicable to the inputs shown.



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 **250 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.

SkinDose DOSIMETRY	Electron Dose (mSv)	Photon Dose (mSv)	Total Dose (mSv)
Point on Skin	**1300**	**2.1**	**1302**
Disk on Skin	**270**	**0.45**	**270**
Cylinder in Cloth	**160**	**0.42**	**160**

Example 2 – SkinDose: Hot Particle on Gloved Hand

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

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.

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 **100 mSv**, and a total dose of **240 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.

SkinDoseDOSIMETRY (with cover)	Electron Dose (mSv)	Photon Dose (mSv)	Total Dose (mSv)
Point Source Shallow Dose	**330**	**100**	**430**
Cylindrical Shallow Dose	**130**	**100**	**240**
Dose @ 1 cm depth	**0**	**32**	**32**

Example 3 – SkinDose: Determination of a Depth-Dose Profile

In this example, we have a situation where a hot particle was found on an employee's plastic lab coat. The particle has not been "captured" (i.e., separated from the lab coat); therefore, we know very little about its physical size and shape. By analysis of the coat, however, we do know that the particle contains six different radionuclides with all their associated emissions. The analysis indicates the presence of 3.6 μCi of ^{60}Co, 1920 μCi of ^{106}Ru (with ^{106}Rh in equilibrium), 2.8 μCi of ^{134}Cs, and 3.6 μCi of ^{137}Cs (with ^{137m}Ba in equilibrium). By experience we know that both electrons and photons are emitted from these nuclides and we are concerned about the potential dose delivered to the patient's skin. Because our procedures require determination of the electron and photon depth-dose profiles, we will calculate dose at various depths into tissue and plot the result.

We begin by developing the exposure scenario with an initial thought of modeling the source as a point. The lab coat worn by the employee is 0.2 mm thick with a density of 0.36 g/cm^3. We assume that the coat is not stuck to the employee's skin, but that there is an air gap of an arbitrary distance of 3 mm. Additionally, we will take advantage of SkinDose's ability to include daughter products and will apply the ICRP 107 decay database for the dose profile calculations. Our initial calculation is conducted for a shallow dose estimate at 7 mg/cm^2. The skin averaging area should be set to 10 cm^2 and exposure time at 60 min. The Z_{eff} for each nuclide should be set 7.42 (default) for this example.

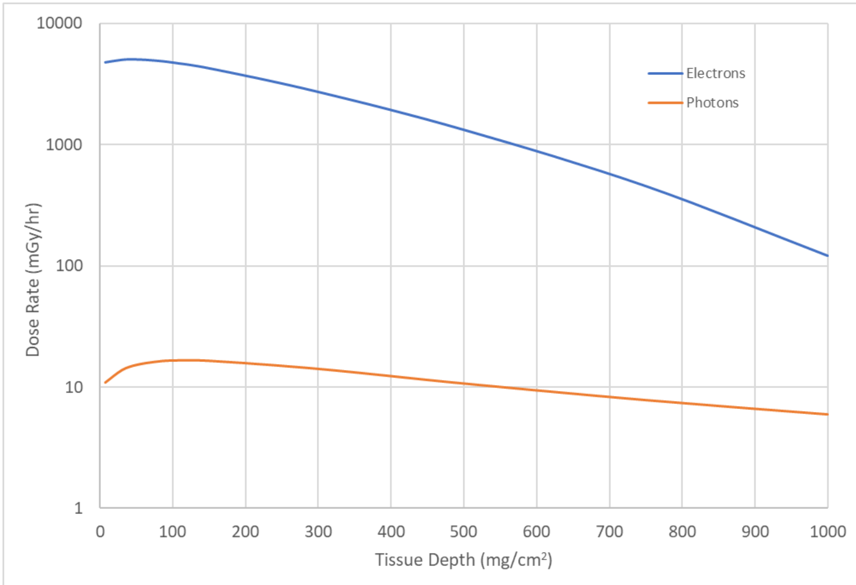
The dose rate at a depth of 7 mg/cm^2 is tabulated below for each nuclide. We see that ^{106}Ru and its progeny result in the greatest contribution to dose for both electrons and photons at that depth.

SkinDose DOSIMETRY (ICRP 107) @ 7 mg/cm^2	Electron Dose Rate (mSv/hr)	Photon Dose Rate (mSv/hr)	Total Dose Rate (mSv/hr)
Co-60	5	0.22	5.2
Ru-106(D)	4700	10.4	4710
Cs-134	6.2	0.13	6.4
Cs-137(D)	110	0.065	110
TOTAL	**4700**	**12**	**4712**

Then, the calculations are repeated for greater tissue depths. Tabular and plotted results are below.

SkinDose DOSIMETRY (ICRP 107)	Electron Dose Rate (mSv/hr)	Photon Dose Rate (mSv/hr)	Total Dose Rate (mSv/hr)
7 g/cm^2	**4700**	**12**	**4712**
30	**4900**	**15**	**4900**
50	**4900**	**17**	**4900**
75	**4800**	**18**	**4800**
100	**4600**	**18**	**4600**
150	**4100**	**18**	**4200**
200	**3600**	**17**	**3600**

300	**2600**	**15**	**2600**
500	**1200**	**12**	**1300**
750	**410**	**8.6**	**410**
1000	**96**	**6.6**	**100**



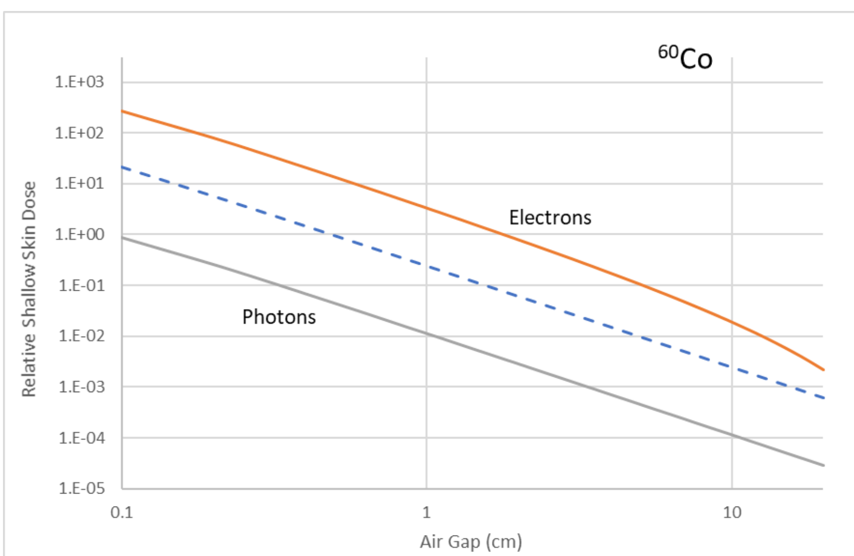
The data show that the maximum electron dose rate occurs at a depth of about 50 mg/cm^2 and the maximum photon dose rate occurs at about 100 mg/cm^2. The initial dose increase with depth is due to increased production of charged particles and the decrease of dose with depth occurs due to energy degradation of electrons and attenuation of photons.

Example 4 – SkinDose: Use of the Air Gap Model

In this example, we will demonstrate how air between the source and the skin may impact the shallow dose estimate. For this scenario, we'll assume that 100 kBq of ^{60}Co exists as a point source skin contaminant for 15 minutes and investigate various air gap distances for the point source from the skin surface. By calculating dose to a 0.01 cm^2 averaging disk, we attempt to show how interactions in the air gap influence the dose at 7 mg/cm^2. In a hand calculation that does not include material attenuation in the air gap, one may consider the effects of geometric attenuation on dose such that we would expect the reduction as a function of air gap, a, to follow the inverse square law.

Airgap (cm)	Electron Dose (mSv)	Photon Dose (mSv)
0.1	**270**	**0.88**
0.2	**80**	**0.26**
0.5	**14**	**0.045**
0.7	**6.9**	**0.023**
1	**3.4**	**0.011**
2	**0.8**	**0.003**
5	**0.11**	**0.0005**
7	**0.05**	**0.00023**
10	**0.02**	**0.00012**

If we plot electron and photon dose for the scenario above, we see a similar reduction in dose for the most part, but with a bit of deviation at distances greater than about 5 cm. Photon dose estimates seem to follow the inverse square law, but at larger air gaps, the electron dose decreases faster than expected by inverse-square alone. These loses are likely due to significant energy degradation of the electrons at the larger distances. Recall that ^{60}Co has an average electron energy of about 0.5 MeV and energetic photon emissions at 1.17 and 1.33 MeV.



Example 5 – SkinDose: Use of Decay-Correction and Progeny (D) Options

The SkinDose provides three main radiation dose estimates: (1) initial dose rate; (2) dose (no decay); and (3) decay-corrected dose. The code first estimates dose rate at the start of exposure and then calculates the other two estimates from that value based on different handlings of exposure time. The dose (no decay) is calculated as simply the product of initial dose rate and exposure time (i.e., assumes that dose rate stays constant during exposure):

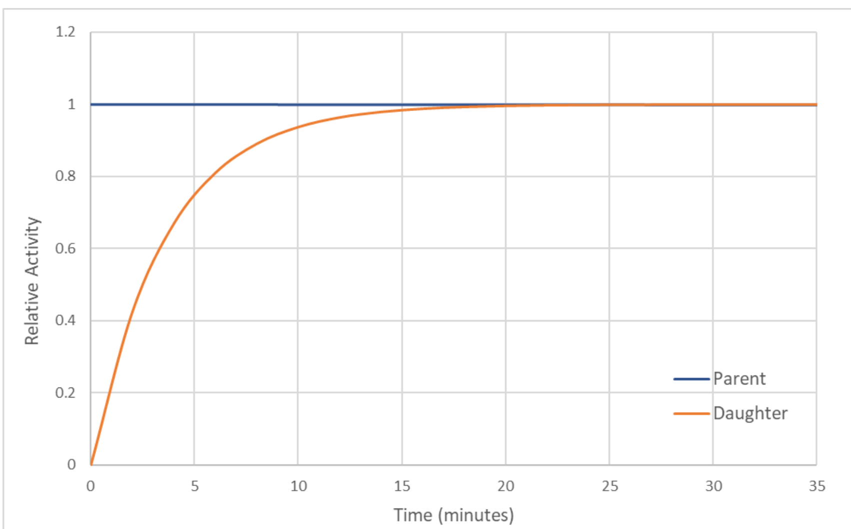
$$D(t) = \dot{D}(0) \cdot t$$

and, decay-corrected dose is calculated by time-integrating the changing dose rate:

$$D_{dc} = \int_0^T \dot{D}(t)\,dt = \dot{D}(0)\int_0^T e^{-\lambda t}\,dt$$

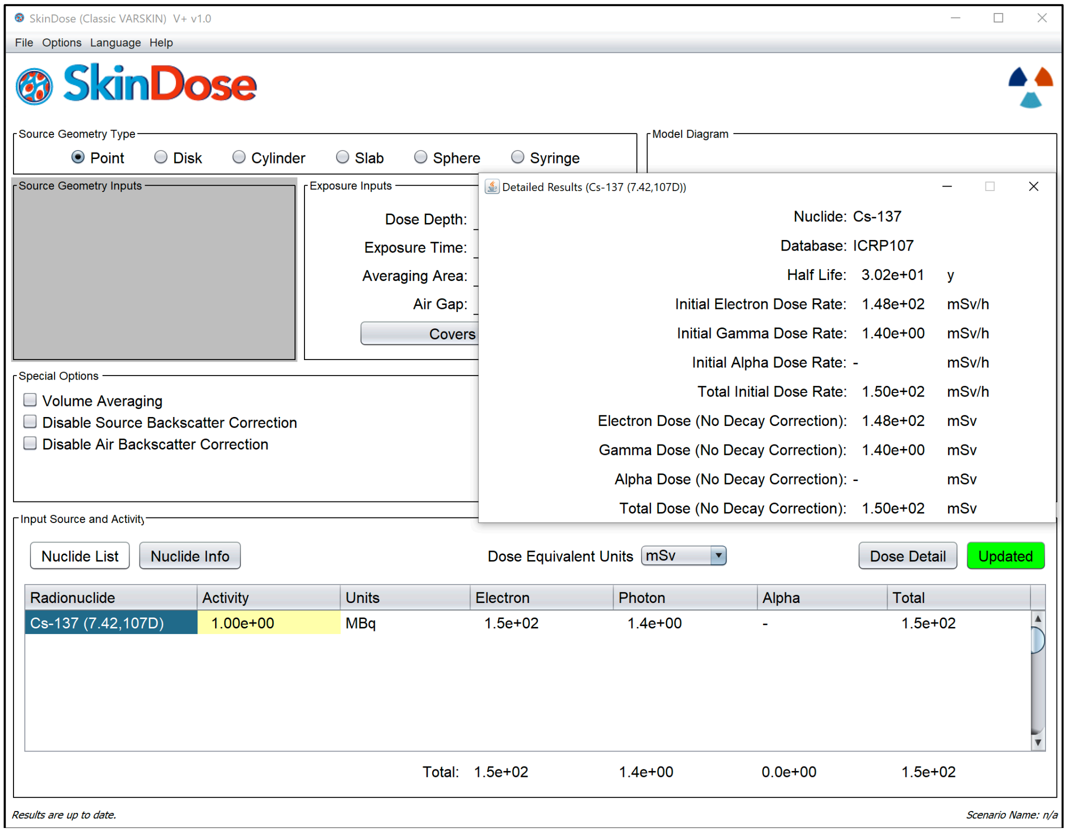
At first glance, the user may think that it is odd for a total dose to be calculated that does not consider radioactive decay. SkinDose, however, has this feature so that a daughter product in secular equilibrium with its parent can receive full consideration in the dose calculation.

Consider ^{137}Cs (half-life of 30 yrs) and its daughter product ^{137m}Ba (half-life of about 2.5 minutes). Using a 10-half-life rule of thumb (and the figure below), the ^{137m}Ba daughter activity will be fully ingrown from a pure ^{137}Cs source within about 25 minutes, after which the activity of both parent and daughter will be equal (secular equilibrium).

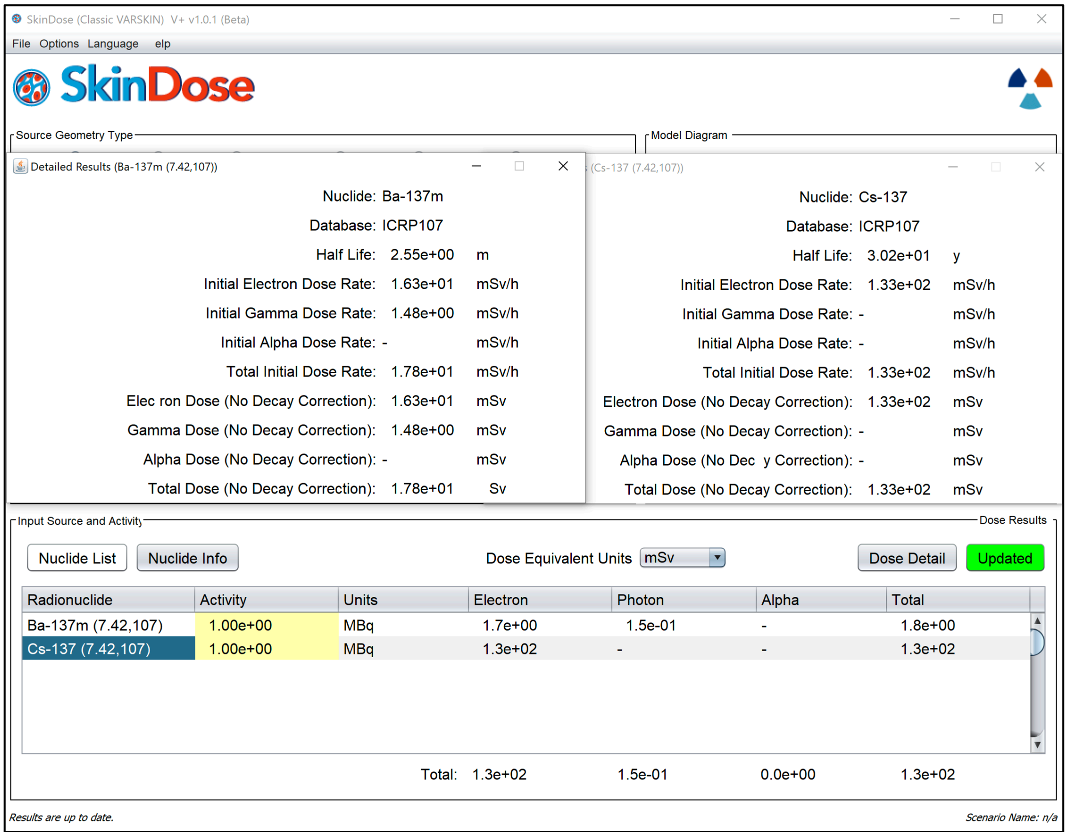


If we use SkinDose with progeny automatically selected (i.e., using the 38D or 107D database), there will be no issue with no-decay dose and its value will be equal to the decay-corrected dose. However, if the user is looking specifically at dose contribution by nuclide and selects one of the standard databases (i.e., 38 or 107), the no-decay dose values become very important. Our scenario for this example will be simple, a point source of 1 MBq, an exposure time of 1 hour, and dose estimated at a depth of 7 mg/cm^2 over a 10 cm^2 averaging disk.

In the first example, we're using the ICRP 107D database and selecting ^{137}Cs. SkinDose will automatically include the ^{137m}Ba daughter product and we note below that the Dose (No Decay) is equal to the Decay-Corrected Dose.



In the next example, we run SkinDose using the ICRP 107 database without automatic inclusion of daughter products. We, therefore, must select both ^{137}Cs and ^{137m}Ba from the database. For this VARSKIN execution, we assume that ^{137}Cs and ^{137m}Ba are in secular equilibrium (the activities are the same). We examine the output for each nuclide separately.



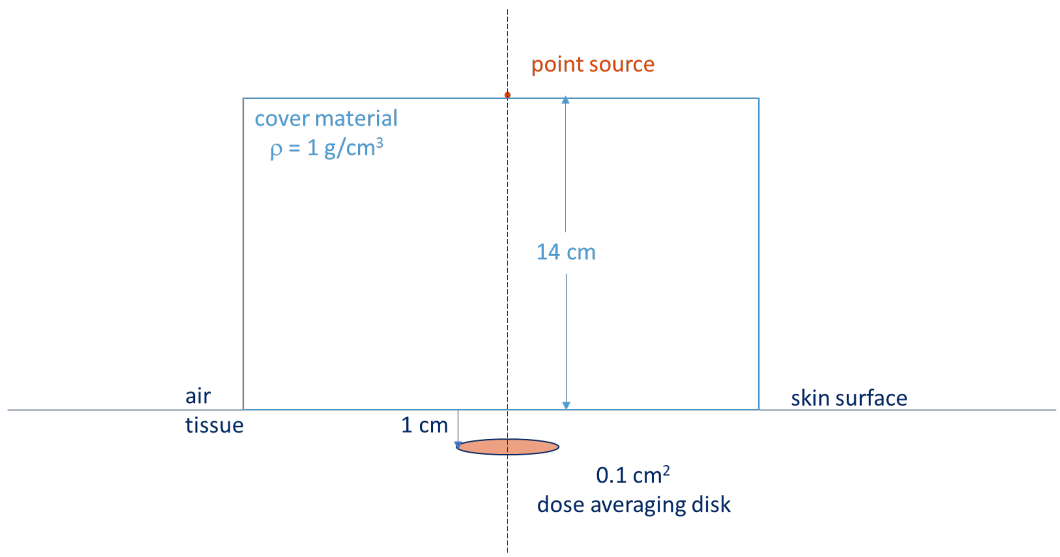
In screenshot above we observe that the dose from ^{137}Cs is purely an electron dose (no contributing photons) and that the no-decay and decayed doses are the same; the ^{137}Cs half-life is very long compared to a 1-hour exposure and decay over that hour is insignificant. The ^{137m}Ba results indicates a difference of more than an order of magnitude in the no-decay versus decayed doses. Recall the half-life is 2.5 minutes and over the course of an hour, decay is very significant, i.e., the activity is gone in about 25 minutes.

When selecting a nuclide and calculating its dose as we've done for ^{137m}Ba in the second example, SkinDose assumes that the nuclide activity is equal to the input value (1 MBq in this case) at the beginning of the exposure time. Since ^{137}Cs constantly replenishes ^{137m}Ba, and the activity remains essentially constant throughout the 1-hour exposure, we want to report the dose value for ^{137m}Ba assuming no decay of that nuclide. Choosing the decay-corrected dose implies that ^{137m}Ba irradiates the skin without replenishment from the decaying ^{137}Cs.

The trainee should consider the appropriate branching ratio for ^{137m}Ba and sum the doses provided in the second set of results. How does this sum compare with the results in using the ICRP 107D data?

Example 6 – SkinDose*: Point Kernel Photon Dose Calculation

In this first example, we will calculate the fundamental point-kernel dose for a point source and point receptor in water, separated by 15 cm. SkinDose does not model point receptors, so we will use a very small dose averaging disk (0.1 cm^2) to simulate a point. The photons emanating from the source will be attenuated and we allow for CPE buildup. Let's look at how we might force SkinDose into a comparable scenario.



SkinDose inputs should indicate a point source of 3.7 GBq of ^{137}Cs, with its progeny ^{137m}Ba, exposing a small, infinitely thin tissue area (0.1 cm^2) at a depth of 10 mm for one second. This tissue depth is sufficient to establish CPE. Further, we assumed the source to be on a cover that is 14 cm thick with unit density (1 g/cm^2) to simulate water. After pressing "Calculate", the SkinDose results table will update with the decay-corrected doses.

The table should indicate that the photon dose is **1.1×10^{-3} mSv** for the 1 second exposure, i.e., a dose rate of **1.11 μGy/s**

Example 7 – SkinDose*: Determination of Contaminant Activity on a Metal Plate

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.

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 dose. The activity concentration on the plate then can be found using,

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

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

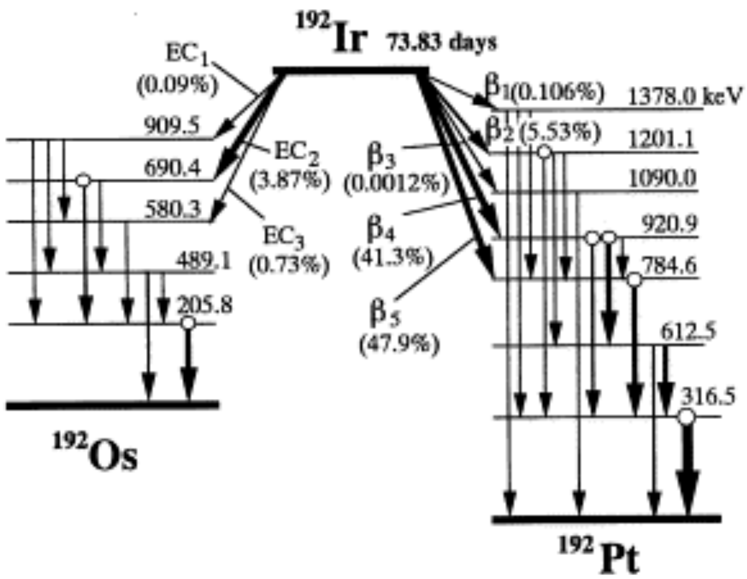
$$\frac{\left(1 \, {}^{MBq}/_{cm^2}\right)\left(1.90 \, {}^{mGy}/_{hr}\right)}{1{,}200 \, {}^{mGy}/_{hr}} = 0.0016 \, {}^{MBq}/_{cm^2}$$

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 8 – SkinDose*: Exposure to a High-Activity ^{192}Ir Source

A radiographer failed to crank in the source at the conclusion of the exposure; failed to observe the radiation actuated visible alarm; bypassed the audible alarm feature of the shooting room; and failed to observe his survey meter upon entry into the shooting room. In addition to a whole-body exposure, the radiographer's hands were exposed at close range to a high-activity (50 Curie) source of ^{192}Ir photons and electrons. The exposure to his hands is of interest here.

Iridium-192 decays about 95% of the time through beta-minus decay to ^{192}Pt and about 5% of the time through electron capture to ^{192}Os. As ^{192}Ir transitions, several high-energy beta particles are emitted, along with a number of low- and moderate-energy photons (energy transitions of which may also result in the emission of conversion electrons).



The prominent photon emissions from ^{192}Ir include:

^{192}Ir Photons (ICRP 107 Database)	Energy (keV)	Yield (%)
Gamma rays	612	5.34
	604	8.20
	589	4.52
	485	3.19
	468	47.8
	317	82.7
	308	29.7
	296	28.7
	206	3.34
X rays	67.0	4.58
	65.3	2.68
	63.2	2.13

	61.6	1.24
	11.1	1.35
	9.4	1.62

The ^{192}Ir source is created by activation of pure iridium, and then encapsulated in stainless steel. The encapsulation (x = 0.8 mm; ρ = 8 g/cm^3) provides shielding of electron emissions (yet, potential significant bremsstrahlung production) such that human exposure is from photons alone.

Electron emissions include two primary beta decay mechanisms with maximum energy of 672 keV and 535 keV, with an average energy for all electrons (beta and conversion electrons) of 227 keV and a 338% yield.

An investigation of exposure time and distance to the hands reveals that the right hand was exposed to the source at a distance of about 7" for 12 seconds, and the left hand was exposed at a distance of about 4" for 19 seconds. Using the dose-rate factor and the exposure estimates, we calculate doses to the hands.

One publication (HHPRH 1998) states that the ^{192}Ir gamma-ray dose constant (calculated in a manner similar to what we just completed) is 0.00016 mSv hr^{-1} MBq^{-1} at 1 meter. We can convert the units of this constant so that we have a dose-rate factor at 1 inch for our 50 Ci source:

$$0.00016\ \frac{mSv\ m^2}{hr\ MBq}\left(\frac{1\ MBq}{0.000027\ Ci}\right)(50\ Ci)\left(\frac{1\ hr}{3600\ sec}\right)\left(\frac{39.4\ in}{1\ m}\right)^2\left(\frac{1\ mGy}{1\ mSv}\right) = 130\ \frac{mGy\ in^2}{sec}$$

Using this factor, our estimate of dose to the left hand is:

$$D(LH) = 130\ \frac{mGy\ in^2}{sec} \cdot \frac{19\ sec}{(4\ in)^2} = 150\ mGy$$

And, for the right hand:

$$D(RH) = 130\ \frac{mGy\ in^2}{sec} \cdot \frac{12\ sec}{(7\ in)^2} = 32\ mGy$$

This estimate assume that the dose is calculated to deep tissue (i.e., charged particle equilibrium, CPE, has been established). The development of CPE in shallow media is quite complex; because of its primary purpose, SkinDose specifically handles this calculation. We, therefore, will turn to SkinDose for a confirmatory calculation of dose to hands and to estimate the shallow dose at 7 mg/cm^2, accounting for the encapsulation and using a dose averaging disk of 10 cm^2 (per the regulation).

Note that the SkinDose dose is for tissue and is averaged at depth over a 10 cm^2 disk, whereas the hand calculation is a point-kernel, in-air calculation. Additionally, SkinDose accounts for buildup and attenuation (albeit slight) in tissue, whereas the dose rate factor assumes a homogeneous medium without attenuation from source to receptor. We also see that the shallow dose is about 70% that of the dose calculated at 1 cm deep. This indicates that CPE is not yet reached at the shallow depths.

The dose estimates are as follows:

VARSKIN Photon Dose	Depth (mg/cm^2)	Dose (mSv)
Left Hand (4”, 19 sec)		
	7	**62**
	1000	**80**
HHPRH	air*	**150**
Right Hand (7”, 12 sec)		
	7	**13**
	1000	**18**
HHPRH	air*	**32**

*refers to the gamma constant being defined for a homogeneous volume of air

Example 9 – NeutronDose: 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?

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:

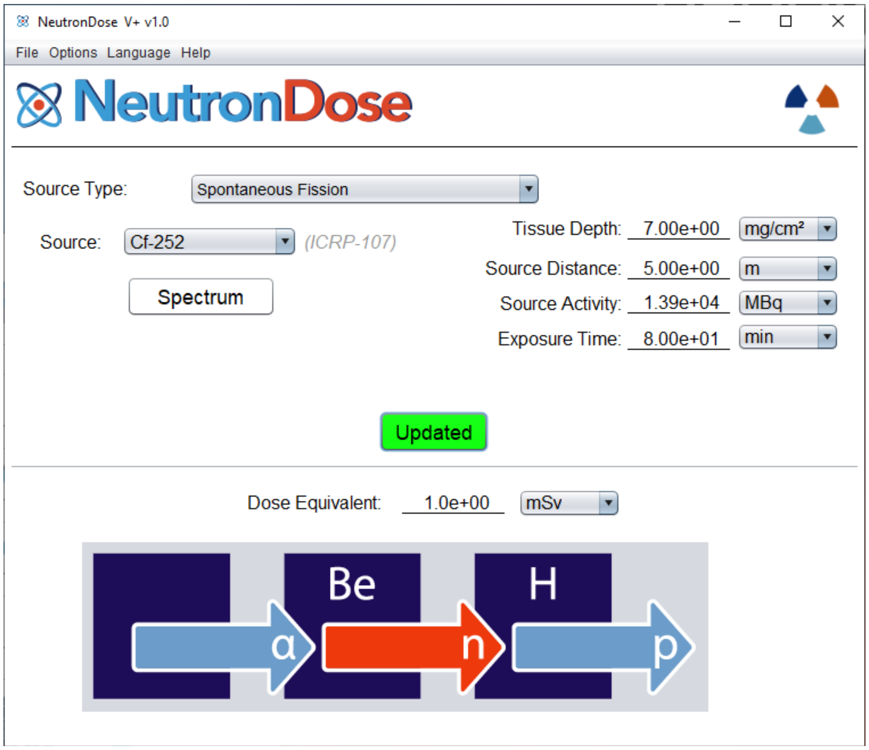
$$ISA = \frac{N_A\,\lambda}{M} = \frac{6.022x10^{23}\ \left[\frac{atoms}{mol}\right] \cdot 8.310x10^{-9}\ [s^{-1}]}{252\ \left[\frac{g}{mol}\right] \cdot 10^{12}\ \left[\frac{Bq}{TBq}\right]} = 19.86\ \left[\frac{TBq}{g}\right]$$

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:

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

Enter the NeutronDose data (below) and select the Calculate button. The student's SDE is estimated to be **1.0 mSv**. Likewise, the tissue dose equivalent at a depth of 1 cm is estimated as **0.91 mSv**.



NeutronDose V+ v1.0
File Options Language Help
NeutronDose
Source Type: Spontaneous Fission
Source: Cf-252 (ICRP-107)
Spectrum
Tissue Depth: 7.00e+00 mg/cm²
Source Distance: 5.00e+00 m
Source Activity: 1.39e+04 MBq
Exposure Time: 8.00e+01 min
Updated
Dose Equivalent: 1.0e+00 mSv
Be
H
α
n
p

Example 10 – NeutronDose: 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.

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 **0.87, 0.22, and 0.096 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 70 microns, and a fluence rate (flux) as specified above, the dose equivalent rates at the three distances are estimated to be **0.86, 0.21, and 0.095 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	1.4	0.97	0.86	0.74	0.48
2 m	660	0.34	0.24	0.21	0.18	0.12
3 m	300	0.16	0.11	0.095	0.082	0.053

Example 11 – NeutronDose: 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).

The NeutronDose module is employed to determine a dose rate factor for a typical SbBe source. The "Reaction (gamma, 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 **5.0 [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

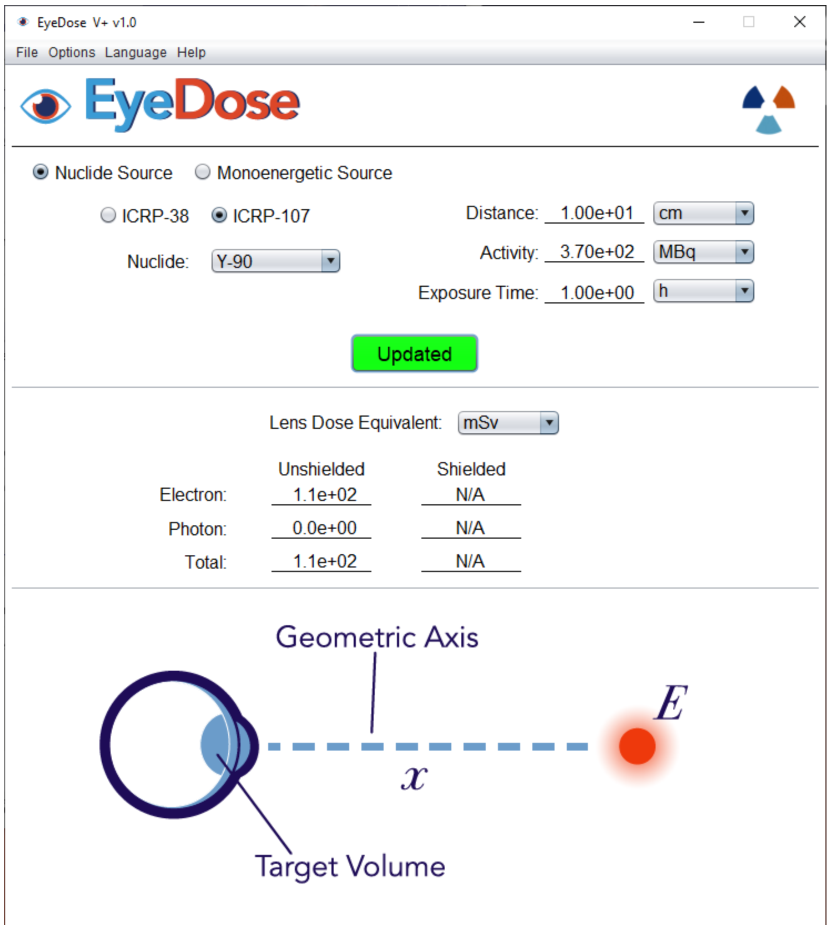
$$\phi = \frac{5.1\ \left[\frac{n}{s\ MBq}\right] \cdot 3600\ \left[\frac{s}{h}\right]}{4\pi(100\ [cm])^2} = 0.14\ \left[\frac{n}{cm^2}\right]\ per\ hour\ per\ MBq$$

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 1.1 and 36 [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:

$$DRF = 1.1\left(\frac{0.490}{0.547}\right) + 36\left(\frac{0.057}{0.547}\right) = \mathbf{4.7}\ [\boldsymbol{pSv\ m^2\ h^{-1}\ MBq^{-1}}]$$

Example 12 – EyeDose: 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



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.

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	$1.9x10^{-3}$	$9.7x10^{-5}$	$1.8x10^{-6}$	$1.3x10^{-7}$	$2.6x10^{-8}$	$9.4x10^{-9}$

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 13 – EyeDose: 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 (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.

For the first calculation, select the Nuclide Source radio button. Use the ICRP 107 database, and select Co-60 from the Nuclide dropdown menu, enter a Distance of 2.5 meters, an Activity of 37 MBq, and an Exposure Time of 1 hour. Selects the Lens Dose Equivalent unit to display as μSv. The select the Calculate button and the result of **1.9 μSv** is displayed for unshielded photons. By examining the dose from shielded photons, note that wearing 2 mm leaded safety glasses would provide no protection for this source. Also note 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.

Now, select the Monoenergetic Source radio button to check the nuclide calculation. Enter a photon energy of 1.25 MeV (average of the two Co-60 photons) and confirm the distance of 2.5 m. After the Calculate button is pressed, a lens dose equivalent per source particle of **7.2x10^{-12} μSv** is displayed for photons. 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:

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

One can further check the answer by making a hand calculation. The hand calculation is carried out as follows:

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

Note the similarity in the three answers and observe 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.

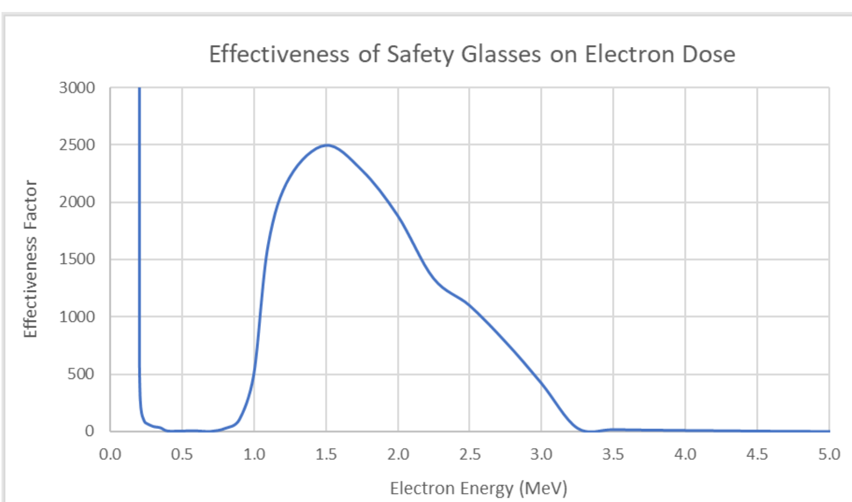
The lens dose estimate can be compared with a similar calculation in SkinDose. With an exposure time of 1 hour, an averaging area of 1 cm^2, a volume-averaged depth of 300 – 700 mg/cm^2, and an airgap of 250 cm (the user will get a warning that the airgap is greater than the limit, but the code will 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 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 14 – EyeDose: The Effectiveness of 2 mm Leaded Safety Glasses on Dose to the Lens

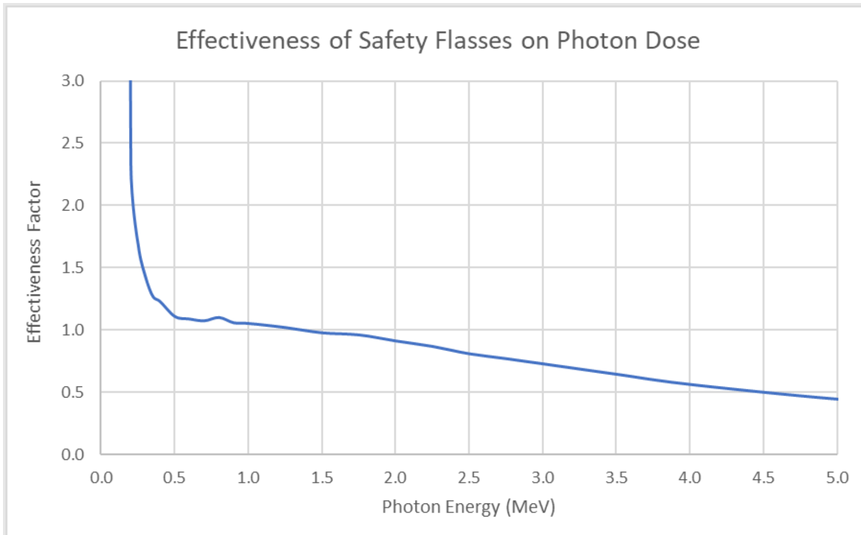
The dose reduction achieved by wearing safety glasses is demonstrated in the figures below. The data were obtained using the EyeDose module for monoenergetic sources of electrons and photons at an exposure distance of 1 m. The effectiveness factor is defined as the ratio of unshielded lens dose to shielded lens dose, where the shield is 2 mm leaded safety glass.

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.

Energy (MeV)	Electron Effectiveness Factor	Photon Effectiveness Factor
0.2	**3.33E+06**	**2.34E+00**
0.4	**8.00E+00**	**1.23E+00**
0.6	**9.17E+00**	**1.09E+00**
0.8	**3.06E+01**	**1.10E+00**
1.0	**5.00E+02**	**1.06E+00**
1.5	**2.50E+03**	**9.80E-01**
2.0	**1.89E+03**	**9.15E-01**
2.5	**1.10E+03**	**8.13E-01**
3.0	**4.24E+02**	**7.31E-01**
3.5	**2.02E+01**	**6.48E-01**
4.0	**1.26E+01**	**5.66E-01**
4.5	**4.56E+00**	**5.06E-01**
5.0	**3.36E+00**	**4.48E-01**



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.



Example 15 – WoundDose: Estimation of Dose from a Tc-99m Needlestick

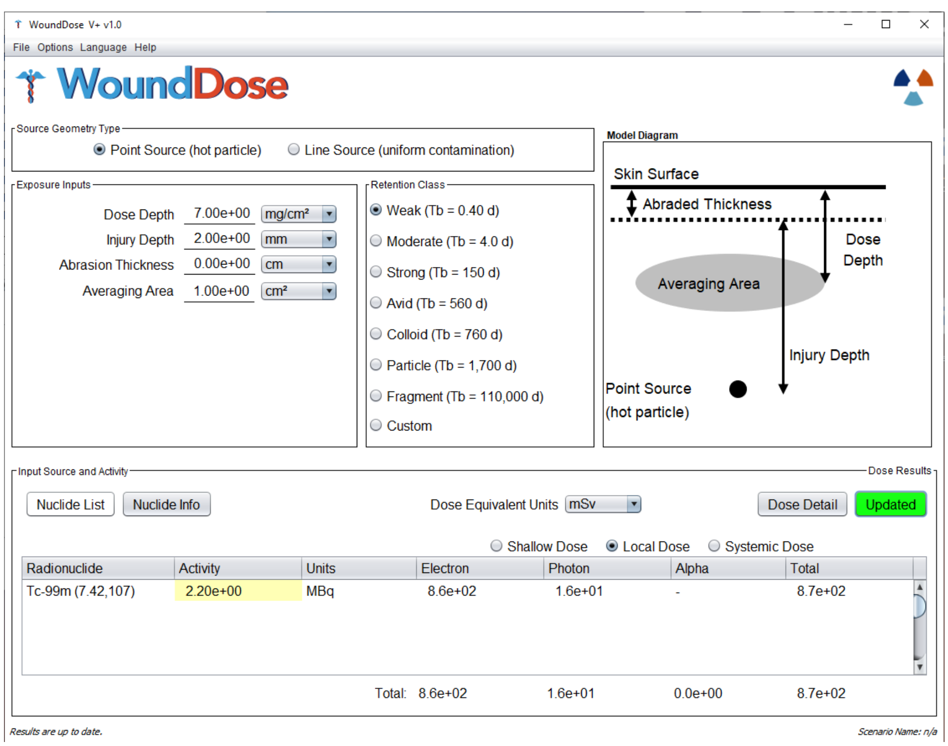
A nuclear medicine technologist accidentally sustained a needlestick in his right hand during MAG3 radiopharmaceutical production. It is estimated that a volume of about 5 μL of Tc-99m was left in the skin at a depth of about 2 mm. The concentration of radioactivity in the needle was 0.44 GBq/mL.

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:

	Shallow Dose		Local Dose		Systemic Dose
	Electron	Photon	Electron	Photon	CEDE
Point Source	**0**	**11**	**860**	**16**	**0.033**
Line Source	**0**	**0.072**	**690**	**13**	**0.033**



Example 16 – WoundDose: 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.

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. 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. Doses in the tables below are in **mSv**.

	Shallow Dose			Local Dose			Systemic Dose	
	Electron	Photon	Alpha	Electron	Photon	Alpha	CEDE	CODE*
Point Source	**0**	**0.88**	**0**	**760**	**0.62**	**85,000**	**29**	**970**
Line Source	**0**	**0.011**	**0**	**680**	**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**	**4.9**	**0**	**4,200**	**3.5**	**480,000**	**160**	**5,400**
Line Source	**0**	**0.061**	**0**	**3,800**	**3.1**	**430,000**	**160**	**5,400**

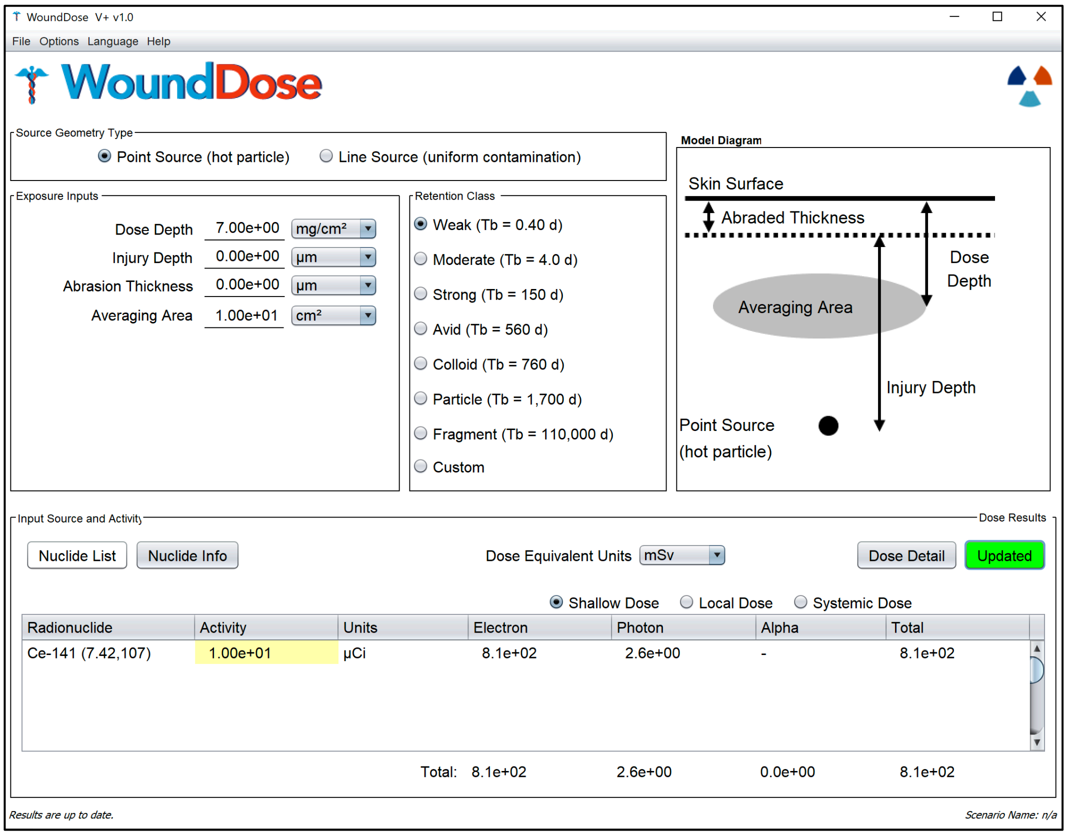
*Committed Organ Dose Equivalent

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.

Example 17 – WoundDose: Liquid Source Directly on Open Wound

In this exercise, a NM lab technician working with a 100 µCi solution of ^{141}Ce spills half of the of the vial directly onto her forearm and 10 µCi gets into an open wound. Prior to the abrasion, the RSO wants to estimate the resulting shallow dose assuming an abrasion depth of zero, a wound depth of zero, point source geometry, and a “Weak” retention class.

Using the ICRP 107 decay data, the shallow dose is found to be **8.1 E+02 mSv**:



The exposure time, or residence time (τ) of material remaining at the wound site, is determined by

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

where T_r and T_b are the radiological and biological half-lives, respectively. When $T_b \gg T_r$, then $\tau = 1.44\, T_r$. Given that the T_r for ^{141}Ce is 32.5 days, choosing the Particle or Fragment retention class will force the problem to be modeled using simple radiological removal. Doing so results in a shallow dose of **4.2E+04 mSv.**

Due to the assumptions of abrasion and wound depths of zero, this problem can be modeled in SkinDose if biological removal is ignored. Using the half-live of 32.5 days, the exposure time is simply 1.44 x 32.5 days, or 46.8 days. As can be seen below, the SkinDose is exactly the same as the WoundDose estimate for this specific scenario. If the contamination were to be specified at a depth greater than zero, SkinDose wouldn't be as accurate due to the presence of tissue above the contamination site.