HNF-2418

Soil Contamination Standards for Protection of Personnel

Prepared for the U.S. Department of Energy

Fluor Daniel Hanford, Inc.
Richland, Washington

Hanford Management and Integration Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

HNF-2418
UC-630

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Date Published
May 1997

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- [ ] Journal Article
- [ ] Internet
- [ ] Software
- [X] Report

B. Document Number HNF-2418

C. Title
Soil Contamination Standards for Protection of Personnel

D. Internet Address

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1. Is document potentially Classified? [X] No [ ] Yes (MANDATORY)

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6. Release Level? [X] Public [ ] Limited

7. Charge Code D1210

F. Complete for a Journal Article

1. Title of Journal N/A

G. Complete for a Presentation

1. Title for Conference or Meeting N/A
2. Group Sponsoring ______
3. Date of Conference ______
4. City/State ______
5. Will Information be Published in Proceedings? [ ] No [ ] Yes
6. Will Material be Handed Out? [ ] No [ ] Yes

H. Author/Requestor

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(Print and Sign)

Responsible Manager

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Document Number:	HNF-2418
Document Title:	Soil Contamination Standards for Protection of Personnel

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Soil Contamination Standards for Protection of Personnel
by Paul D. Rittmann, PhD CHP May 14, 1997

1.0 Introduction

The objective of this report is to recommend soil contamination levels that will ensure that radionuclide intakes by unprotected workers are likely to give internal doses below selected dose limits during the working year. The three internal dose limits are 1, 100, and 500 mrem per year. In addition, photon, beta, and alpha instrument readings are estimated for these soil concentration limits.

Two exposure pathways are considered: the first is inhalation of resuspended dust and the second is ingestion of trace amounts of soil. In addition, radioactive decay and ingrowth of progeny during the year of exposure is included. External dose from the soil contamination is not included because monitoring and control of external exposures is carried out independently from internal exposures, which are the focus of this report. The methods used are similar to those used by Carbaugh and Bihl (1993) to set bioassay criteria for such workers.

2.0 Summary of Methods

The inhalation dose from resuspended dust is calculated using a mass loading approach. The air breathed by the worker is assumed to have an average dust loading of 5 mg/m³ of respirable sized particles, i.e., less than 10 μm AMAD. The worker is assumed to breathe this dust for 2000 hours at the light activity breathing rate for reference man (ICRP 1975), 1.2 m³/hour. The total amount of dust inhaled is therefore 12 grams over the course of the year. It is assumed that the radionuclide concentration in the airborne dust is the same as it is in the contaminated soil. Technically, this is incorrect. The soil contamination is normally found in the soil fines so that the radionuclide concentration in the airborne dust is far greater than in the bulk soil. However, the assumed average air concentration of 5 mg/m³ is also very large. It is the OSHA limit for workplace dust. In addition, the assumed exposure time of 2000 hours per year at this high concentration also leads to large intakes. Therefore, it will be assumed that the above combination of assumptions represent a reasonable worst case inhalation model.

The ingestion dose from eating trace amounts of soil is based on the EPA soil ingestion value of 100 mg/day for adults. The ingestion takes place through licking the lips and similar motions. The worker is assumed to consume soil at this rate for 250 days during the year. The total amount ingested in a year is therefore 25 grams of soil.

Appendix A summarizes the data used in these calculations. The 128 distinct radionuclides have half-lives greater than 33 days. Implicit daughters shown in Table A-2 have been included in the calculations of dose. It is assumed that these short-lived nuclides are in secular equilibrium with the parent at all times. The radioactive decay information is from Kocher (1981). This was used to determine the relative amounts of the short-lived progeny, as well as the decay and ingrowth of longer-lived progeny during the year of exposure. The specific decay chains used during the year of exposure are listed in Table A-1.

The internal dose factors used in the dose calculations are from EPA (1988). These dose factors are use the methods of ICRP 26 (1977) and are based on a 50 year dose commitment period. Organ doses are not considered in this report. Only the weighted sum of the organ doses, known as the effective dose equivalent is used. Table A-3 lists the inhalation and ingestion dose factors along with the lung solubility class and gut absorption factors which were assumed. The inhalation dose factors use 1 μm AMAD particles. The worst-case dose factors were used, except for strontium and uranium. For both elements, the class Y compounds give the largest doses per unit intake. However, these class Y compounds have never been handled or produced in the 200 Areas. For the 300 Areas, there has been some class Y uranium handled. This was treated separately, for comparison.

The external dose rate factors used in the dose calculations are from EPA (1993). These dose factors are use the weighting factors from ICRP 26 (1977). Table A-3 lists the external dose rate factors for an infinitely thick layer of contaminated soil at the surface. The soil density is 1.6 g/cc.

The method for estimating instrument response is described in Appendix B. This method assumes the soil contamination is very uniformly mixed and is at the surface. Due to the non-uniform nature of soil, this is never the exactly the case. For higher energy beta-emitters, the assumed homogenous distribution of contamination in the surface soil introduces little error, except in rocky soils. However, readings from alpha-emitters and low energy beta-emitters are strongly affected by non-uniformities in the distribution of contamination in the surface soil. The estimated readings for these nuclides could be high by orders of magnitude. The users of these soil contamination standards must take into account this weakness on the readings given for alpha and low-energy beta emitting nuclides.

The minimum CP reading is assumed to be 1 mR/h, window closed. Window open readings were not estimated because the GM would give a more sensitive indication of contamination. The minimum GM reading is assumed to be 100 cpm with a 15 cm^2 probe face. The PAM has a face area of 50 cm^2. The minimum PAM reading for a 2 inch per second scan rate is assumed to be 35 cpm. If the PAM registers anything, it is assumed that a static count will be done, which offers a minimum PAM reading of 6 cpm. The 6 cpm value is used in the summary tables for the PAM readings. Both the GM and the PAM are assumed to be held about 1 cm above the soil surface during the scan.

3.0 Summary of Results

Table 1 shows the effective dose equivalent (EDE) the worker could receive in the inhalation and ingestion scenario described above. The 50 year dose commitments shown on the table accumulate over the course of one working year. Next to the column with doses is a column showing whether the inhalation or ingestion pathway gives most of the total dose.

Nuclides which have implicit daughters are identified with the letters "+D" after the name. For these nuclides, the activity in the table is only that of the parent nuclide. For example, 1 pCi/g of Sr-90+D will also have 1 pCi/g of Y-90. The implicit daughters represent additional activity.

The last three columns of Table 1 give soil concentration limits for individual nuclides based on the three annual dose limits, 1, 100, or 500 mrem.

Tables 2, 3, and 4 repeat the soil concentration limits shown on Table 1 and also give the estimated instrument reading at the limit. The instruments considered are the window-closed CP, the GM with a pancake probe (15 cm^2 face area), and the Portable Alpha Monitor (PAM) (50 cm^2 face area). It was assumed that the detection limits are 1 mR/h for the CP, 100 cpm for the GM, and 6 cpm for the PAM. The detection efficiencies depend on the energy of the radiation emitted. Appendix B describes the method used to estimate detector response.

For both the GM and the PAM, the detection limit as well as the detection efficiency depend strongly on the condition of the soil. For example, soil moisture reduces the ability of an instrument to detect alpha particles and low-energy electrons. In addition, the granular nature of soil could lead to readings which are much higher or lower, depending on whether the contamination lies above or below the soil grains.

The last column of Tables 2, 3, and 4 shows which instruments (CP, GM, or PAM) would detect the radionuclide at the concentration given in the second column. For nuclides which undergo significant decay during the year, the concentration shown is at the beginning of the work year. The number after the instrument identifier is the order of magnitude above the assumed detection limit. Thus, "CP0" or "GM0" or "PAM0" all mean that the estimated instrument reading is somewhere between the minimum detectable and 10 times the minimum detectable. Similarly, "CP1" or "GM1" or "PAM1" all mean that the estimated instrument reading is somewhere between 10 and 100 times the minimum detectable. In some cases the estimated reading would be off scale, but no notation to this effect is made, since the focus here is on detecting the suggested soil contamination standard.

Nearly all of the beta-emitting nuclides are detectable with field instruments at the 100 mrem/y level. The few nuclides that are not detectable are normally found with nuclides that can be readily detected. Note that the alpha-emitting nuclides are largely undetectable at the soil contamination limits derived here.

Note also that the instrument readings will give little indication of the depth of contamination. All of the beta particles will come from the upper 4 centimeters of soil. Most of the photon reading (greater than 80 percent) is from the upper 15 centimeters. These thicknesses of soil are also adequate to conceal subsurface contamination. When soil is being excavated, the radiological conditions at the work site can change rapidly as contamination is uncovered.

4.0 Treatment of Mixtures

After a few months or years, some nuclides shown on the table will be in secular equilibrium with longer-lived progeny. Two examples are the Zr-95 to Nb-95 chain and the Sb-125 to Te-125m chain. With the chains in equilibrium they could be combined much the way the short-lived implicit daughters were. These combinations are listed in the last several lines at the end of the tables. The special identifier "old" is used for these chains. As before, the activity concentration shown is only the activity of the parent nuclide. For example, 1 pCi/g of "Zr-95 old" means the concentration of the Zr-95 is 1 pCi/g. There is also the equilibrium amount of 2.21 pCi/g of Nb-95. As with the implicit daughters, the activity of the progeny in equilibrium is not shown.

The mixture "Pb-210 old" includes both the short-lived Bi-210 as well as Po-210. The "Ra-226 old" includes every nuclide down to Po-210 in secular equilibrium. The radionuclide mixtures "Th-Nat" and "U-Nat" are for the complete decay chains of U-238 and Th-232 in secular equilibrium. This is approximately how they are found in nature. Note that background soil concentrations normally range from 0.5 to 1 pCi/g.

Plutonium is normally found as a mixture of isotopes. A typical mixture at Hanford has about 6 percent Pu-240 by mass. This is the mixture labelled "Pu 6%" at the end of the tables. This mixture was also aged 10 years and recomputed. This is was labelled "Pu 6% Aged" on the tables. The results differ only slightly from the fresh plutonium.

Other mixtures of radionuclides can be evaluated by summing the products of the soil concentrations and the unit concentration dose factor in the first column of Table 1. For example, a mixture of 5,000 pCi/g Sr-90 and 15,000 pCi/g Cs-137 would produce the annual dose shown below. Note that the EDE is given in mrem/y to indicate that the intakes occur over one working year. The dose commitment period is still 50 years. The units are thus the dose commitment per year of exposure.

$$\begin{aligned}\text{Sr \& Cs Mixture} &= (5000\ \text{pCi/g})(0.00672\ \text{mrem/y per pCi/g}) + \\ &\quad (15000\ \text{pCi/g})(0.00161\ \text{mrem/y per pCi/g}) \\ &= 33.6 + 24.2\ \text{mrem/y} \\ &= 57.8\ \text{mrem/y}\end{aligned}$$

Table 1. Unit Dose Factors and Soil Concentration Limits

Nuclide	TEDE mrem/y at 1 pCi/g	Max Pathway	pCi/g to give the annual doses 1 mrem	100 mrem	500 mrem
H-3	2.68E-06	Ingest	3.74E+05	3.74E+07	1.87E+08
Be-7	1.47E-06	Inhale	6.79E+05	6.79E+07	3.40E+08
Be-10	4.37E-03	Inhale	2.29E+02	2.29E+04	1.14E+05
C-14	7.72E-05	Ingest	1.30E+04	1.30E+06	6.48E+06
Na-22	3.32E-04	Ingest	3.01E+03	3.01E+05	1.50E+06
S-35	1.57E-05	Inhale	6.39E+04	6.39E+06	3.19E+07
Cl-36	3.39E-04	Inhale	2.95E+03	2.95E+05	1.48E+06
K-40	6.13E-04	Ingest	1.63E+03	1.63E+05	8.16E+05
Ca-41	4.80E-05	Ingest	2.08E+04	2.08E+06	1.04E+07
Ca-45	8.05E-05	Inhale	1.24E+04	1.24E+06	6.21E+06
Sc-46	1.62E-04	Inhale	6.16E+03	6.16E+05	3.08E+06
V-49	3.96E-06	Inhale	2.52E+05	2.52E+07	1.26E+08
Mn-54	1.03E-04	Inhale	9.75E+03	9.75E+05	4.88E+06
Fe-55	4.18E-05	Inhale	2.39E+04	2.39E+06	1.20E+07
Fe-59	6.06E-05	Inhale	1.65E+04	1.65E+06	8.25E+06
Co-57	8.99E-05	Inhale	1.11E+04	1.11E+06	5.56E+06
Co-58	5.98E-05	Inhale	1.67E+04	1.67E+06	8.36E+06
Co-60	3.09E-03	Inhale	3.24E+02	3.24E+04	1.62E+05
Ni-59	2.11E-05	Inhale	4.73E+04	4.73E+06	2.36E+07
Ni-63	5.15E-05	Inhale	1.94E+04	1.94E+06	9.71E+06
Zn-65	3.77E-04	Ingest	2.65E+03	2.65E+05	1.33E+06
Se-75	1.43E-04	Ingest	7.02E+03	7.02E+05	3.51E+06
Se-79	3.35E-04	Ingest	2.98E+03	2.98E+05	1.49E+06
Rb-87	1.62E-04	Ingest	6.18E+03	6.18E+05	3.09E+06
Sr-89	6.14E-05	Ingest	1.63E+04	1.63E+06	8.14E+06
Sr-90+D	6.72E-03	Ingest	1.49E+02	1.49E+04	7.44E+04
Y-88	1.86E-04	Inhale	5.38E+03	5.38E+05	2.69E+06
Y-91	1.88E-04	Inhale	5.32E+03	5.32E+05	2.66E+06
Zr-93	3.90E-03	Inhale	2.56E+02	2.56E+04	1.28E+05
Zr-95+D	1.26E-04	Inhale	7.91E+03	7.91E+05	3.96E+06
Nb-93m	3.55E-04	Inhale	2.81E+03	2.81E+05	1.41E+06
Nb-94	5.15E-03	Inhale	1.94E+02	1.94E+04	9.71E+04
Nb-95	1.86E-05	Inhale	5.39E+04	5.39E+06	2.69E+07
Mo-93	3.83E-04	Inhale	2.61E+03	2.61E+05	1.30E+06
Tc-99	1.36E-04	Inhale	7.33E+03	7.33E+05	3.66E+06
Ru-103+D	2.86E-05	Inhale	3.50E+04	3.50E+06	1.75E+07
Ru-106+D	4.65E-03	Inhale	2.15E+02	2.15E+04	1.08E+05
Pd-107	1.57E-04	Inhale	6.37E+03	6.37E+05	3.19E+06
Ag-108m+D	3.58E-03	Inhale	2.79E+02	2.79E+04	1.40E+05
Ag-110m+D	7.76E-04	Inhale	1.29E+03	1.29E+05	6.45E+05
Cd-109	1.31E-03	Inhale	7.63E+02	7.63E+04	3.82E+05
Cd-113m	2.18E-02	Inhale	4.59E+01	4.59E+03	2.29E+04
Cd-115m	2.23E-04	Inhale	4.48E+03	4.48E+05	2.24E+06
In-114m+D	2.90E-04	Inhale	3.45E+03	3.45E+05	1.72E+06
In-115	4.88E-02	Inhale	2.05E+01	2.05E+03	1.02E+04
Sn-113+D	8.41E-05	Inhale	1.19E+04	1.19E+06	5.95E+06
Sn-119m	7.35E-05	Inhale	1.36E+04	1.36E+06	6.80E+06

Table 1. Unit Dose Factors and Soil Concentration Limits, Continued

Nuclide	TEDE mrem/y at 1 pCi/g	Max Pathway	pCi/g to give the annual doses 1 mrem	100 mrem	500 mrem
Sn-121m+D	1.98E-04	Inhale	5.05E+03	5.05E+05	2.53E+06
Sn-123	2.63E-04	Inhale	3.80E+03	3.80E+05	1.90E+06
Sn-126+D	1.74E-03	Inhale	5.74E+02	5.74E+04	2.87E+05
Sb-124	1.30E-04	Inhale	7.69E+03	7.69E+05	3.84E+06
Sb-125	2.21E-04	Inhale	4.53E+03	4.53E+05	2.27E+06
Te-123m	1.12E-04	Ingest	8.96E+03	8.96E+05	4.48E+06
Te-125m	4.05E-05	Ingest	2.47E+04	2.47E+06	1.23E+07
Te-127m+D	1.88E-04	Inhale	5.31E+03	5.31E+05	2.65E+06
Te-129m+D	7.41E-05	Inhale	1.35E+04	1.35E+06	6.75E+06
I-125	2.93E-04	Ingest	3.42E+03	3.42E+05	1.71E+06
I-129	8.98E-03	Ingest	1.11E+02	1.11E+04	5.57E+04
Cs-134	2.03E-03	Ingest	4.93E+02	4.93E+04	2.47E+05
Cs-135	2.31E-04	Ingest	4.32E+03	4.32E+05	2.16E+06
Cs-137+D	1.61E-03	Ingest	6.20E+02	6.20E+04	3.10E+05
Ba-133	1.73E-04	Inhale	5.78E+03	5.78E+05	2.89E+06
Ce-144+D	3.32E-03	Inhale	3.01E+02	3.01E+04	1.51E+05
Pm-147	4.37E-04	Inhale	2.29E+03	2.29E+05	1.15E+06
Pm-148m+D	7.84E-05	Inhale	1.28E+04	1.28E+06	6.38E+06
Sm-147	9.02E-01	Inhale	1.11E+00	1.11E+02	5.55E+02
Sm-151	3.68E-04	Inhale	2.72E+03	2.72E+05	1.36E+06
Eu-150	3.35E-03	Inhale	2.99E+02	2.99E+04	1.49E+05
Eu-152	2.74E-03	Inhale	3.65E+02	3.65E+04	1.82E+05
Eu-154	3.53E-03	Inhale	2.83E+02	2.83E+04	1.42E+05
Eu-155	5.00E-04	Inhale	2.00E+03	2.00E+05	1.00E+06
Gd-152	2.93E+00	Inhale	3.42E-01	3.42E+01	1.71E+02
Gd-153	1.95E-04	Inhale	5.12E+03	5.12E+05	2.56E+06
Tb-158	3.17E-03	Inhale	3.15E+02	3.15E+04	1.58E+05
Tb-160	1.30E-04	Inhale	7.71E+03	7.71E+05	3.86E+06
Ho-166m	9.48E-03	Inhale	1.06E+02	1.06E+04	5.28E+04
Tm-170	1.96E-04	Inhale	5.10E+03	5.10E+05	2.55E+06
Ta-182	2.83E-04	Inhale	3.54E+03	3.54E+05	1.77E+06
W-181	4.37E-06	Ingest	2.29E+05	2.29E+07	1.14E+08
W-185	1.68E-05	Ingest	5.94E+04	5.94E+06	2.97E+07
Re-187	8.90E-07	Inhale	1.12E+06	1.12E+08	5.62E+08
Os-185	6.24E-05	Inhale	1.60E+04	1.60E+06	8.01E+06
Ir-192	1.36E-04	Inhale	7.35E+03	7.35E+05	3.67E+06
Pt-193	5.66E-06	Ingest	1.77E+05	1.77E+07	8.84E+07
Au-195	9.85E-05	Inhale	1.01E+04	1.01E+06	5.07E+06
Hg-203	6.85E-05	Ingest	1.46E+04	1.46E+06	7.30E+06
Tl-204	1.03E-04	Ingest	9.70E+03	9.70E+05	4.85E+06
Pb-210+D	3.81E-01	Inhale	2.63E+00	2.63E+02	1.31E+03
Bi-207	3.73E-04	Inhale	2.68E+03	2.68E+05	1.34E+06
Po-209	2.00E-01	Inhale	5.00E+00	5.00E+02	2.50E+03
Po-210	7.36E-02	Inhale	1.36E+01	1.36E+03	6.80E+03
Ra-226+D	1.42E-01	Inhale	7.04E+00	7.04E+02	3.52E+03
Ra-228+D	7.35E-01	Inhale	1.36E+00	1.36E+02	6.81E+02
Ac-227+D	7.97E+01	Inhale	1.25E-02	1.25E+00	6.27E+00
Th-228+D	3.49E+00	Inhale	2.87E-01	2.87E+01	1.43E+02

Table 1. Unit Dose Factors and Soil Concentration Limits, Continued

Nuclide	TEDE mrem/y at 1 pCi/g	Max Pathway	pCi/g to give the annual doses 1 mrem	100 mrem	500 mrem
Th-229+D	2.61E+01	Inhale	3.83E-02	3.83E+00	1.92E+01
Th-230	3.92E+00	Inhale	2.55E-01	2.55E+01	1.28E+02
Th-232	1.98E+01	Inhale	5.06E-02	5.06E+00	2.53E+01
Pa-231	1.69E+01	Inhale	5.90E-02	5.90E+00	2.95E+01
U-232	8.78E-01	Inhale	1.14E+00	1.14E+02	5.69E+02
U-233	1.04E-01	Inhale	9.58E+00	9.58E+02	4.79E+03
U-234	1.02E-01	Inhale	9.84E+00	9.84E+02	4.92E+03
U-235+D	9.43E-02	Inhale	1.06E+01	1.06E+03	5.30E+03
U-236	9.60E-02	Inhale	1.04E+01	1.04E+03	5.21E+03
U-238+D	9.14E-02	Inhale	1.09E+01	1.09E+03	5.47E+03
Np-236	1.29E+00	Inhale	7.77E-01	7.77E+01	3.88E+02
Np-237+D	6.59E+00	Inhale	1.52E-01	1.52E+01	7.58E+01
Pu-236	1.57E+00	Inhale	6.37E-01	6.37E+01	3.18E+02
Pu-237	6.50E-06	Inhale	1.54E+05	1.54E+07	7.70E+07
Pu-238	4.77E+00	Inhale	2.10E-01	2.10E+01	1.05E+02
Pu-239	5.24E+00	Inhale	1.91E-01	1.91E+01	9.54E+01
Pu-240	5.24E+00	Inhale	1.91E-01	1.91E+01	9.54E+01
Pu-241+D	1.03E-01	Inhale	9.75E+00	9.75E+02	4.87E+03
Pu-242	5.01E+00	Inhale	2.00E-01	2.00E+01	9.98E+01
Pu-244+D	4.92E+00	Inhale	2.03E-01	2.03E+01	1.02E+02
Am-241	5.41E+00	Inhale	1.85E-01	1.85E+01	9.23E+01
Am-242m+D	5.27E+00	Inhale	1.90E-01	1.90E+01	9.48E+01
Am-243+D	5.37E+00	Inhale	1.86E-01	1.86E+01	9.30E+01
Cm-242	1.19E-01	Inhale	8.43E+00	8.43E+02	4.21E+03
Cm-243	3.70E+00	Inhale	2.70E-01	2.70E+01	1.35E+02
Cm-244	2.97E+00	Inhale	3.37E-01	3.37E+01	1.68E+02
Cm-245	5.56E+00	Inhale	1.80E-01	1.80E+01	9.00E+01
Cm-246	5.51E+00	Inhale	1.82E-01	1.82E+01	9.08E+01
Cm-247+D	5.06E+00	Inhale	1.98E-01	1.98E+01	9.88E+01
Cm-248	2.02E+01	Inhale	4.95E-02	4.95E+00	2.48E+01
Cf-250	3.11E+00	Inhale	3.21E-01	3.21E+01	1.61E+02
Cf-252	1.68E+00	Inhale	5.95E-01	5.95E+01	2.98E+02
Es-254+D	3.90E-01	Inhale	2.56E+00	2.56E+02	1.28E+03
Zr-95 old	1.67E-04	Inhale	5.97E+03	5.97E+05	2.99E+06
Sb-125 old	2.31E-04	Inhale	4.34E+03	4.34E+05	2.17E+06
Pb-210 old	4.55E-01	Inhale	2.20E+00	2.20E+02	1.10E+03
Ra-226 old	6.03E-01	Inhale	1.66E+00	1.66E+02	8.30E+02
Th-Nat	2.40E+01	Inhale	4.17E-02	4.17E+00	2.08E+01
U-Nat	4.71E+00	Inhale	2.12E-01	2.12E+01	1.06E+02
Pu 6%	5.95E+00	Inhale	1.68E-01	1.68E+01	8.41E+01
Pu 6% 10yr	5.65E+00	Inhale	1.77E-01	1.77E+01	8.84E+01
U-232 Y	8.57E+00	Inhale	1.17E-01	1.17E+01	5.84E+01
U-233 Y	1.63E+00	Inhale	6.12E-01	6.12E+01	3.06E+02
U-234 Y	1.60E+00	Inhale	6.26E-01	6.26E+01	3.13E+02
U-235+D Y	1.48E+00	Inhale	6.75E-01	6.75E+01	3.38E+02
U-236 Y	1.51E+00	Inhale	6.62E-01	6.62E+01	3.31E+02
U-238+D Y	1.43E+00	Inhale	7.01E-01	7.01E+01	3.50E+02

Note: See discussion in Section 3.0 for explanation of table.

Table 2. Soil Limits and Instrument Response - 1 mrem/y

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
H-3	3.74E+05	0.0E+00	0.0E+00	0.0E+00	
Be-7	6.79E+05	3.4E+01	0.0E+00	0.0E+00	CP1
Be-10	2.29E+02	5.2E-05	6.2E+01	0.0E+00	
C-14	1.30E+04	4.1E-05	1.1E+02	0.0E+00	GM0
Na-22	3.01E+03	6.7E+00	8.1E+02	0.0E+00	CP0 GM0
S-35	6.39E+04	2.3E-04	6.2E+02	0.0E+00	GM0
Cl-36	2.95E+03	1.5E-03	1.2E+03	0.0E+00	GM1
K-40	1.63E+03	2.6E-01	1.6E+03	0.0E+00	GM1
Ca-41	2.08E+04	0.0E+00	0.0E+00	0.0E+00	
Ca-45	1.24E+04	1.8E-04	5.1E+02	0.0E+00	GM0
Sc-46	6.16E+03	1.2E+01	5.8E+02	0.0E+00	CP1 GM0
V-49	2.52E+05	0.0E+00	0.0E+00	0.0E+00	
Mn-54	9.75E+03	8.2E+00	0.0E+00	0.0E+00	CP0
Fe-55	2.39E+04	0.0E+00	0.0E+00	0.0E+00	
Fe-59	1.65E+04	2.0E+01	1.9E+03	0.0E+00	CP1 GM1
Co-57	1.11E+04	1.1E+00	3.1E+01	0.0E+00	CP0
Co-58	1.67E+04	1.7E+01	6.4E+02	0.0E+00	CP1 GM0
Co-60	3.24E+02	8.2E-01	2.2E+01	0.0E+00	
Ni-59	4.73E+04	0.0E+00	0.0E+00	0.0E+00	
Ni-63	1.94E+04	0.0E+00	0.0E+00	0.0E+00	
Zn-65	2.65E+03	1.5E+00	5.1E+00	0.0E+00	CP0
Se-75	7.02E+03	2.7E+00	3.1E+01	0.0E+00	CP0
Se-79	2.98E+03	1.3E-05	1.5E+01	0.0E+00	
Rb-87	6.18E+03	2.0E-04	2.7E+02	0.0E+00	GM0
Sr-89	1.63E+04	2.9E-02	2.2E+04	0.0E+00	GM2
Sr-90+D	1.49E+02	7.0E-04	4.1E+02	0.0E+00	GM0
Y-88	5.38E+03	1.5E+01	6.8E+00	0.0E+00	CP1
Y-91	5.32E+03	3.0E-02	7.4E+03	0.0E+00	GM1
Zr-93	2.56E+02	0.0E+00	0.0E+00	0.0E+00	
Zr-95+D	7.91E+03	5.9E+00	8.5E+02	0.0E+00	CP0 GM0
Nb-93m	2.81E+03	8.9E-05	0.0E+00	0.0E+00	
Nb-94	1.94E+02	3.1E-01	3.2E+01	0.0E+00	
Nb-95	5.39E+04	4.2E+01	5.0E+02	0.0E+00	CP1 GM0
Mo-93	2.61E+03	4.7E-04	0.0E+00	0.0E+00	
Tc-99	7.33E+03	2.1E-04	3.9E+02	0.0E+00	GM0
Ru-103+D	3.50E+04	1.7E+01	1.4E+03	0.0E+00	CP1 GM1
Ru-106+D	2.15E+02	4.8E-02	9.3E+02	0.0E+00	GM0
Pd-107	6.37E+03	0.0E+00	0.0E+00	0.0E+00	
Ag-108m+D	2.79E+02	4.6E-01	4.2E+01	0.0E+00	
Ag-110m+D	1.29E+03	3.6E+00	1.4E+02	0.0E+00	CP0 GM0
Cd-109	7.63E+02	3.2E-03	0.0E+00	0.0E+00	
Cd-113m	4.59E+01	6.3E-06	1.1E+01	0.0E+00	
Cd-115m	4.48E+03	1.1E-01	6.5E+03	0.0E+00	GM1
In-114m+D	3.45E+03	3.1E-01	7.1E+03	0.0E+00	GM1
In-115	2.05E+01	1.8E-06	3.6E+00	0.0E+00	
Sn-113+D	1.19E+04	3.2E+00	2.7E+03	0.0E+00	CP0 GM1
Sn-119m	1.36E+04	1.1E-02	0.0E+00	0.0E+00	

Table 2. Soil Limits and Instrument Response - 1 mrem/y, Continued

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
Sn-121m+D	5.05E+03	2.8E-03	1.3E+02	0.0E+00	GM0
Sn-123	3.80E+03	3.2E-02	4.4E+03	0.0E+00	GM1
Sn-126+D	5.74E+02	1.2E+00	9.1E+02	0.0E+00	CP0 GM0
Sb-124	7.69E+03	1.4E+01	6.5E+03	0.0E+00	CP1 GM1
Sb-125	4.53E+03	1.9E+00	3.4E+02	0.0E+00	CP0 GM0
Te-123m	8.96E+03	1.1E+00	2.2E+02	0.0E+00	CP0 GM0
Te-125m	2.47E+04	9.9E-02	6.7E+02	0.0E+00	GM0
Te-127m+D	5.31E+03	3.4E-02	1.8E+03	0.0E+00	GM1
Te-129m+D	1.35E+04	9.2E-01	1.7E+04	0.0E+00	GM2
I-125	3.42E+03	1.6E-02	0.0E+00	0.0E+00	--
I-129	1.11E+02	3.9E-04	5.8E-01	0.0E+00	
Cs-134	4.93E+02	7.9E-01	1.1E+02	0.0E+00	GM0
Cs-135	4.32E+03	3.8E-05	7.6E+01	0.0E+00	
Cs-137+D	6.20E+02	3.6E-01	2.2E+02	0.0E+00	GM0
Ba-133	5.78E+03	2.2E+00	7.5E+01	0.0E+00	CP0
Ce-144+D	3.01E+02	1.7E-02	1.1E+03	0.0E+00	GM1
Pm-147	2.29E+03	2.6E-05	5.4E+01	0.0E+00	
Pm-148m+D	1.28E+04	2.6E+01	3.7E+03	0.0E+00	CP1 GM1
Sm-147	1.11E+00	0.0E+00	0.0E+00	0.0E+00	
Sm-151	2.72E+03	7.5E-07	4.0E-04	0.0E+00	
Eu-150	2.99E+02	4.5E-01	0.0E+00	0.0E+00	
Eu-152	3.65E+02	4.1E-01	6.4E+01	0.0E+00	
Eu-154	2.83E+02	3.5E-01	1.2E+02	0.0E+00	GM0
Eu-155	2.00E+03	7.9E-02	2.1E+01	0.0E+00	
Gd-152	3.42E-01	0.0E+00	0.0E+00	0.0E+00	
Gd-153	5.12E+03	2.7E-01	1.3E+01	0.0E+00	
Tb-158	3.15E+02	2.4E-01	2.9E+01	0.0E+00	
Tb-160	7.71E+03	8.7E+00	2.8E+03	0.0E+00	CP0 GM1
Ho-166m	1.06E+02	1.9E-01	1.0E+01	0.0E+00	
Tm-170	5.10E+03	1.7E-02	2.9E+03	0.0E+00	GM1
Ta-182	3.54E+03	4.5E+00	5.2E+02	0.0E+00	CP0 GM0
W-181	2.29E+05	4.1E+00	0.0E+00	0.0E+00	CP0
W-185	5.94E+04	5.5E-03	7.4E+03	0.0E+00	GM1
Re-187	1.12E+06	0.0E+00	0.0E+00	0.0E+00	
Os-185	1.60E+04	1.1E+01	2.0E+02	0.0E+00	CP1 GM0
Ir-192	7.35E+03	6.2E+00	2.1E+03	0.0E+00	CP0 GM1
Pt-193	1.77E+05	0.0E+00	0.0E+00	0.0E+00	
Au-195	1.01E+04	4.7E-01	3.8E+01	0.0E+00	
Hg-203	1.46E+04	3.5E+00	1.1E+03	0.0E+00	CP0 GM1
Tl-204	9.70E+03	8.6E-03	3.6E+03	0.0E+00	GM1
Pb-210+D	2.63E+00	3.4E-06	2.1E+00	0.0E+00	
Bi-207	2.68E+03	4.1E+00	7.3E+02	0.0E+00	CP0 GM0
Po-209	5.00E+00	1.5E-01	1.1E-03	2.6E-01	
Po-210	1.36E+01	1.2E-07	0.0E+00	8.8E-01	
Ra-226+D	7.04E+00	1.3E-02	1.5E+01	2.5E+00	
Ra-228+D	1.36E+00	1.3E-03	1.1E+00	0.0E+00	
Ac-227+D	1.25E-02	4.8E-06	2.8E-02	6.7E-03	
Th-228+D	2.87E-01	4.6E-04	5.4E-01	1.5E-01	

Table 2. Soil Limits and Instrument Response - 1 mrem/y, Continued

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
Th-229+D	3.83E-02	1.1E-05	5.2E-02	2.1E-02	
Th-230	2.55E-01	6.6E-08	0.0E+00	1.1E-02	
Th-232	5.06E-02	5.8E-09	2.7E-06	1.3E-03	
Pa-231	5.90E-02	2.1E-06	4.2E-04	3.4E-03	
U-232	1.14E+00	2.2E-07	1.1E-04	7.4E-02	
U-233	9.58E+00	2.7E-06	9.6E-05	4.7E-01	
U-234	9.84E+00	8.7E-07	5.7E-04	4.7E-01	
U-235+D	1.06E+01	1.6E-03	5.4E-01	3.9E-01	
U-236	1.04E+01	5.2E-07	4.7E-04	4.1E-01	
U-238+D	1.09E+01	2.6E-04	2.5E+01	3.4E-01	
Np-236	7.77E-01	7.3E-05	6.0E-02	0.0E+00	
Np-237+D	1.52E-01	3.2E-05	2.3E-02	7.3E-03	
Pu-236	6.37E-01	3.5E-08	0.0E+00	5.1E-02	
Pu-237	1.54E+05	5.2E+00	2.4E+00	0.0E+00	CPO
Pu-238	2.10E-01	8.2E-09	0.0E+00	1.5E-02	
Pu-239	1.91E-01	1.1E-08	0.0E+00	1.1E-02	
Pu-240	1.91E-01	6.7E-09	0.0E+00	1.1E-02	
Pu-241+D	9.75E+00	3.8E-08	1.9E-05	0.0E+00	
Pu-242	2.00E-01	6.5E-09	0.0E+00	1.0E-02	
Pu-244+D	2.03E-01	6.9E-05	3.2E-01	8.6E-03	
Am-241	1.85E-01	1.9E-06	8.1E-06	1.3E-02	
Am-242m+D	1.90E-01	2.6E-06	4.2E-02	5.6E-05	
Am-243+D	1.86E-01	3.4E-05	3.5E-02	1.2E-02	
Cm-242	8.43E+00	3.8E-07	0.0E+00	7.8E-01	
Cm-243	2.70E-01	3.1E-05	2.0E-02	2.2E-02	
Cm-244	3.37E-01	1.1E-08	0.0E+00	2.7E-02	
Cm-245	1.80E-01	1.3E-05	4.7E-03	1.2E-02	
Cm-246	1.82E-01	6.1E-09	0.0E+00	1.2E-02	
Cm-247+D	1.98E-01	6.8E-05	4.2E-02	1.1E-02	
Cm-248	4.95E-02	1.1E-09	0.0E+00	2.6E-03	
Cf-250	3.21E-01	9.0E-09	1.4E-06	2.9E-02	
Cf-252	5.95E-01	2.6E-08	3.9E-06	5.3E-02	
Es-254+D	2.56E+00	2.3E-03	1.3E+00	2.6E-01	
Zr-95 old	5.97E+03	1.5E+01	7.6E+02	0.0E+00	CPI GMO
Sb-125 old	4.34E+03	1.9E+00	3.5E+02	0.0E+00	CPO GMO
Pb-210 old	2.20E+00	2.8E-06	1.7E+00	1.4E-01	
Ra-226 old	1.66E+00	3.0E-03	4.7E+00	7.1E-01	
Th-Nat	4.17E-02	1.1E-04	1.1E-01	2.3E-02	
U-Nat	2.12E-01	3.9E-04	1.1E+00	1.2E-01	
Pu 6%	1.68E-01	1.3E-07	2.8E-06	1.0E-02	
Pu 6% 10yr	1.77E-01	2.7E-07	2.5E-06	1.1E-02	
U-232 Y	1.17E-01	2.2E-08	1.1E-05	7.6E-03	
U-233 Y	6.12E-01	1.8E-07	6.1E-06	3.0E-02	
U-234 Y	6.26E-01	5.5E-08	3.6E-05	3.0E-02	
U-235+D Y	6.75E-01	1.0E-04	3.5E-02	2.5E-02	
U-236 Y	6.62E-01	3.3E-08	3.0E-05	2.6E-02	
U-238+D Y	7.01E-01	1.7E-05	1.6E+00	2.2E-02	

Table 3. Soil Limits and Instrument Response - 100 mrem/y

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
H-3	3.74E+07	0.0E+00	0.0E+00	0.0E+00	
Be-7	6.79E+07	3.4E+03	0.0E+00	0.0E+00	CP3
Be-10	2.29E+04	5.2E-03	6.2E+03	0.0E+00	GM1
C-14	1.30E+06	4.1E-03	1.1E+04	0.0E+00	GM2
Na-22	3.01E+05	6.7E+02	8.1E+04	0.0E+00	CP2 GM2
S-35	6.39E+06	2.3E-02	6.2E+04	0.0E+00	GM2
Cl-36	2.95E+05	1.5E-01	1.2E+05	0.0E+00	GM3
K-40	1.63E+05	2.6E+01	1.6E+05	0.0E+00	CP1 GM3
Ca-41	2.08E+06	0.0E+00	0.0E+00	0.0E+00	
Ca-45	1.24E+06	1.8E-02	5.1E+04	0.0E+00	GM2
Sc-46	6.16E+05	1.2E+03	5.8E+04	0.0E+00	CP3 GM2
V-49	2.52E+07	0.0E+00	0.0E+00	0.0E+00	
Mn-54	9.75E+05	8.2E+02	0.0E+00	0.0E+00	CP2
Fe-55	2.39E+06	0.0E+00	0.0E+00	0.0E+00	
Fe-59	1.65E+06	2.0E+03	1.9E+05	0.0E+00	CP3 GM3
Co-57	1.11E+06	1.1E+02	3.1E+03	0.0E+00	CP2 GM1
Co-58	1.67E+06	1.7E+03	6.4E+04	0.0E+00	CP3 GM2
Co-60	3.24E+04	8.2E+01	2.2E+03	0.0E+00	CP1 GM1
Ni-59	4.73E+06	0.0E+00	0.0E+00	0.0E+00	
Ni-63	1.94E+06	0.0E+00	0.0E+00	0.0E+00	
Zn-65	2.65E+05	1.5E+02	5.1E+02	0.0E+00	CP2 GM0
Se-75	7.02E+05	2.7E+02	3.1E+03	0.0E+00	CP2 GM1
Se-79	2.98E+05	1.3E-03	1.5E+03	0.0E+00	GM1
Rb-87	6.18E+05	2.0E-02	2.7E+04	0.0E+00	GM2
Sr-89	1.63E+06	2.9E+00	2.2E+06	0.0E+00	CP0 GM4
Sr-90+D	1.49E+04	7.0E-02	4.1E+04	0.0E+00	GM2
Y-88	5.38E+05	1.5E+03	6.8E+02	0.0E+00	CP3 GM0
Y-91	5.32E+05	3.0E+00	7.4E+05	0.0E+00	CP0 GM3
Zr-93	2.56E+04	0.0E+00	0.0E+00	0.0E+00	
Zr-95+D	7.91E+05	5.9E+02	8.5E+04	0.0E+00	CP2 GM2
Nb-93m	2.81E+05	8.9E-03	0.0E+00	0.0E+00	
Nb-94	1.94E+04	3.1E+01	3.2E+03	0.0E+00	CP1 GM1
Nb-95	5.39E+06	4.2E+03	5.0E+04	0.0E+00	CP3 GM2
Mo-93	2.61E+05	4.7E-02	0.0E+00	0.0E+00	
Tc-99	7.33E+05	2.1E-02	3.9E+04	0.0E+00	GM2
Ru-103+D	3.50E+06	1.7E+03	1.4E+05	0.0E+00	CP3 GM3
Ru-106+D	2.15E+04	4.8E+00	9.3E+04	0.0E+00	CP0 GM2
Pd-107	6.37E+05	0.0E+00	0.0E+00	0.0E+00	
Ag-108m+D	2.79E+04	4.6E+01	4.2E+03	0.0E+00	CP1 GM1
Ag-110m+D	1.29E+05	3.6E+02	1.4E+04	0.0E+00	CP2 GM2
Cd-109	7.63E+04	3.2E-01	0.0E+00	0.0E+00	
Cd-113m	4.59E+03	6.3E-04	1.1E+03	0.0E+00	GM1
Cd-115m	4.48E+05	1.1E+01	6.5E+05	0.0E+00	CP1 GM3
In-114m+D	3.45E+05	3.1E+01	7.1E+05	0.0E+00	CP1 GM3
In-115	2.05E+03	1.8E-04	3.6E+02	0.0E+00	GM0
Sn-113+D	1.19E+06	3.2E+02	2.7E+05	0.0E+00	CP2 GM3
Sn-119m	1.36E+06	1.1E+00	0.0E+00	0.0E+00	CP0

Table 3. Soil Limits and Instrument Response - 100 mrem/y, Continued

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
Sn-121m+D	5.05E+05	2.8E-01	1.3E+04	0.0E+00	GM2
Sn-123	3.80E+05	3.2E+00	4.4E+05	0.0E+00	CP0 GM3
Sn-126+D	5.74E+04	1.2E+02	9.1E+04	0.0E+00	CP2 GM2
Sb-124	7.69E+05	1.4E+03	6.5E+05	0.0E+00	CP3 GM3
Sb-125	4.53E+05	1.9E+02	3.4E+04	0.0E+00	CP2 GM2
Te-123m	8.96E+05	1.1E+02	2.2E+04	0.0E+00	CP2 GM2
Te-125m	2.47E+06	9.9E+00	6.7E+04	0.0E+00	CP0 GM2
Te-127m+D	5.31E+05	3.4E+00	1.8E+05	0.0E+00	CP0 GM3
Te-129m+D	1.35E+06	9.2E+01	1.7E+06	0.0E+00	CP1 GM4
I-125	3.42E+05	1.6E+00	0.0E+00	0.0E+00	CP0 --
I-129	1.11E+04	3.9E-02	5.8E+01	0.0E+00	
Cs-134	4.93E+04	7.9E+01	1.1E+04	0.0E+00	CP1 GM2
Cs-135	4.32E+05	3.8E-03	7.6E+03	0.0E+00	GM1
Cs-137+D	6.20E+04	3.6E+01	2.2E+04	0.0E+00	CP1 GM2
Ba-133	5.78E+05	2.2E+02	7.5E+03	0.0E+00	CP2 GM1
Ce-144+D	3.01E+04	1.7E+00	1.1E+05	0.0E+00	CP0 GM3
Pm-147	2.29E+05	2.6E-03	5.4E+03	0.0E+00	GM1
Pm-148m+D	1.28E+06	2.6E+03	3.7E+05	0.0E+00	CP3 GM3
Sm-147	1.11E+02	0.0E+00	0.0E+00	0.0E+00	
Sm-151	2.72E+05	7.5E-05	4.0E-02	0.0E+00	
Eu-150	2.99E+04	4.5E+01	0.0E+00	0.0E+00	CP1
Eu-152	3.65E+04	4.1E+01	6.4E+03	0.0E+00	CP1 GM1
Eu-154	2.83E+04	3.5E+01	1.2E+04	0.0E+00	CP1 GM2
Eu-155	2.00E+05	7.9E+00	2.1E+03	0.0E+00	CP0 GM1
Gd-152	3.42E+01	0.0E+00	0.0E+00	0.0E+00	
Gd-153	5.12E+05	2.7E+01	1.3E+03	0.0E+00	CP1 GM1
Tb-158	3.15E+04	2.4E+01	2.9E+03	0.0E+00	CP1 GM1
Tb-160	7.71E+05	8.7E+02	2.8E+05	0.0E+00	CP2 GM3
Ho-166m	1.06E+04	1.9E+01	1.0E+03	0.0E+00	CP1 GM1
Tm-170	5.10E+05	1.7E+00	2.9E+05	0.0E+00	CP0 GM3
Ta-182	3.54E+05	4.5E+02	5.2E+04	0.0E+00	CP2 GM2
W-181	2.29E+07	4.1E+02	0.0E+00	0.0E+00	CP2
W-185	5.94E+06	5.5E-01	7.4E+05	0.0E+00	GM3
Re-187	1.12E+08	0.0E+00	0.0E+00	0.0E+00	
Os-185	1.60E+06	1.1E+03	2.0E+04	0.0E+00	CP3 GM2
Ir-192	7.35E+05	6.2E+02	2.1E+05	0.0E+00	CP2 GM3
Pt-193	1.77E+07	0.0E+00	0.0E+00	0.0E+00	
Au-195	1.01E+06	4.7E+01	3.8E+03	0.0E+00	CP1 GM1
Hg-203	1.46E+06	3.5E+02	1.1E+05	0.0E+00	CP2 GM3
Tl-204	9.70E+05	8.6E-01	3.6E+05	0.0E+00	GM3
Pb-210+D	2.63E+02	3.4E-04	2.1E+02	0.0E+00	GM0
Bi-207	2.68E+05	4.1E+02	7.3E+04	0.0E+00	CP2 GM2
Po-209	5.00E+02	1.5E+01	1.1E-01	2.6E+01	CP1
Po-210	1.36E+03	1.2E-05	0.0E+00	8.8E+01	
Ra-226+D	7.04E+02	1.3E+00	1.5E+03	2.5E+02	CP0 GM1 PAM0
Ra-228+D	1.36E+02	1.3E-01	1.1E+02	0.0E+00	GM0
Ac-227+D	1.25E+00	4.8E-04	2.8E+00	6.7E-01	
Th-228+D	2.87E+01	4.6E-02	5.4E+01	1.5E+01	

Table 3. Soil Limits and Instrument Response - 100 mrem/y, Continued

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
Th-229+D	3.83E+00	1.1E-03	5.2E+00	2.1E+00	
Th-230	2.55E+01	6.6E-06	0.0E+00	1.1E+00	
Th-232	5.06E+00	5.8E-07	2.7E-04	1.3E-01	
Pa-231	5.90E+00	2.1E-04	4.2E-02	3.4E-01	
U-232	1.14E+02	2.2E-05	1.1E-02	7.4E+00	
U-233	9.58E+02	2.7E-04	9.6E-03	4.7E+01	
U-234	9.84E+02	8.7E-05	5.7E-02	4.7E+01	
U-235+D	1.06E+03	1.6E-01	5.4E+01	3.9E+01	
U-236	1.04E+03	5.2E-05	4.7E-02	4.1E+01	
U-238+D	1.09E+03	2.6E-02	2.5E+03	3.4E+01	GM1
Np-236	7.77E+01	7.3E-03	6.0E+00	0.0E+00	
Np-237+D	1.52E+01	3.2E-03	2.3E+00	7.3E-01	
Pu-236	6.37E+01	3.5E-06	0.0E+00	5.1E+00	
Pu-237	1.54E+07	5.2E+02	2.4E+02	0.0E+00	CP2 GM0
Pu-238	2.10E+01	8.2E-07	0.0E+00	1.5E+00	
Pu-239	1.91E+01	1.1E-06	0.0E+00	1.1E+00	
Pu-240	1.91E+01	6.7E-07	0.0E+00	1.1E+00	
Pu-241+D	9.75E+02	3.8E-06	1.9E-03	0.0E+00	
Pu-242	2.00E+01	6.5E-07	0.0E+00	1.0E+00	
Pu-244+D	2.03E+01	6.9E-03	3.2E+01	8.6E-01	
Am-241	1.85E+01	1.9E-04	8.1E-04	1.3E+00	
Am-242m+D	1.90E+01	2.6E-04	4.2E+00	5.6E-03	
Am-243+D	1.86E+01	3.4E-03	3.5E+00	1.2E+00	
Cm-242	8.43E+02	3.8E-05	0.0E+00	7.8E+01	
Cm-243	2.70E+01	3.1E-03	2.0E+00	2.2E+00	
Cm-244	3.37E+01	1.1E-06	0.0E+00	2.7E+00	
Cm-245	1.80E+01	1.3E-03	4.7E-01	1.2E+00	
Cm-246	1.82E+01	6.1E-07	0.0E+00	1.2E+00	
Cm-247+D	1.98E+01	6.8E-03	4.2E+00	1.1E+00	
Cm-248	4.95E+00	1.1E-07	0.0E+00	2.6E-01	
Cf-250	3.21E+01	9.0E-07	1.4E-04	2.9E+00	
Cf-252	5.95E+01	2.6E-06	3.9E-04	5.3E+00	
Es-254+D	2.56E+02	2.3E-01	1.3E+02	2.6E+01	GM0
Zr-95 old	5.97E+05	1.5E+03	7.6E+04	0.0E+00	CP3 GM2
Sb-125 old	4.34E+05	1.9E+02	3.5E+04	0.0E+00	CP2 GM2
Pb-210 old	2.20E+02	2.8E-04	1.7E+02	1.4E+01	GM0
Ra-226 old	1.66E+02	3.0E-01	4.7E+02	7.1E+01	GM0
Th-Nat	4.17E+00	1.1E-02	1.1E+01	2.3E+00	
U-Nat	2.12E+01	3.9E-02	1.1E+02	1.2E+01	GM0
Pu 6%	1.68E+01	1.3E-05	2.8E-04	1.0E+00	
Pu 6% 10yr	1.77E+01	2.7E-05	2.5E-04	1.1E+00	
U-232 Y	1.17E+01	2.2E-06	1.1E-03	7.6E-01	
U-233 Y	6.12E+01	1.8E-05	6.1E-04	3.0E+00	
U-234 Y	6.26E+01	5.5E-06	3.6E-03	3.0E+00	
U-235+D Y	6.75E+01	1.0E-02	3.5E+00	2.5E+00	
U-236 Y	6.62E+01	3.3E-06	3.0E-03	2.6E+00	
U-238+D Y	7.01E+01	1.7E-03	1.6E+02	2.2E+00	GM0

Table 4. Soil Limits and Instrument Response - 500 mrem/y

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
H-3	1.87E+08	0.0E+00	0.0E+00	0.0E+00	
Be-7	3.40E+08	1.7E+04	0.0E+00	0.0E+00	CP4
Be-10	1.14E+05	2.6E-02	3.1E+04	0.0E+00	GM2
C-14	6.48E+06	2.1E-02	5.4E+04	0.0E+00	GM2
Na-22	1.50E+06	3.3E+03	4.0E+05	0.0E+00	CP3 GM3
S-35	3.19E+07	1.1E-01	3.1E+05	0.0E+00	GM3
Cl-36	1.48E+06	7.3E-01	5.8E+05	0.0E+00	GM3
K-40	8.16E+05	1.3E+02	8.2E+05	0.0E+00	CP2 GM3
Ca-41	1.04E+07	0.0E+00	0.0E+00	0.0E+00	
Ca-45	6.21E+06	8.8E-02	2.5E+05	0.0E+00	GM3
Sc-46	3.08E+06	6.2E+03	2.9E+05	0.0E+00	CP3 GM3
V-49	1.26E+08	0.0E+00	0.0E+00	0.0E+00	
Mn-54	4.88E+06	4.1E+03	0.0E+00	0.0E+00	CP3
Fe-55	1.20E+07	0.0E+00	0.0E+00	0.0E+00	
Fe-59	8.25E+06	9.8E+03	9.3E+05	0.0E+00	CP3 GM3
Co-57	5.56E+06	5.7E+02	1.6E+04	0.0E+00	CP2 GM2
Co-58	8.36E+06	8.3E+03	3.2E+05	0.0E+00	CP3 GM3
Co-60	1.62E+05	4.1E+02	1.1E+04	0.0E+00	CP2 GM2
Ni-59	2.36E+07	0.0E+00	0.0E+00	0.0E+00	
Ni-63	9.71E+06	0.0E+00	0.0E+00	0.0E+00	
Zn-65	1.33E+06	7.7E+02	2.5E+03	0.0E+00	CP2 GM1
Se-75	3.51E+06	1.3E+03	1.5E+04	0.0E+00	CP3 GM2
Se-79	1.49E+06	6.7E-03	7.3E+03	0.0E+00	GM1
Rb-87	3.09E+06	9.8E-02	1.4E+05	0.0E+00	GM3
Sr-89	8.14E+06	1.4E+01	1.1E+07	0.0E+00	CP1 GM5
Sr-90+D	7.44E+04	3.5E-01	2.1E+05	0.0E+00	GM3
Y-88	2.69E+06	7.3E+03	3.4E+03	0.0E+00	CP3 GM1
Y-91	2.66E+06	1.5E+01	3.7E+06	0.0E+00	CP1 GM4
Zr-93	1.28E+05	0.0E+00	0.0E+00	0.0E+00	
Zr-95+D	3.96E+06	3.0E+03	4.2E+05	0.0E+00	CP3 GM3
Nb-93m	1.41E+06	4.4E-02	0.0E+00	0.0E+00	
Nb-94	9.71E+04	1.6E+02	1.6E+04	0.0E+00	CP2 GM2
Nb-95	2.69E+07	2.1E+04	2.5E+05	0.0E+00	CP4 GM3
Mo-93	1.30E+06	2.3E-01	0.0E+00	0.0E+00	
Tc-99	3.66E+06	1.0E-01	1.9E+05	0.0E+00	GM3
Ru-103+D	1.75E+07	8.4E+03	6.9E+05	0.0E+00	CP3 GM3
Ru-106+D	1.08E+05	2.4E+01	4.6E+05	0.0E+00	CP1 GM3
Pd-107	3.19E+06	0.0E+00	0.0E+00	0.0E+00	
Ag-108m+D	1.40E+05	2.3E+02	2.1E+04	0.0E+00	CP2 GM2
Ag-110m+D	6.45E+05	1.8E+03	7.2E+04	0.0E+00	CP3 GM2
Cd-109	3.82E+05	1.6E+00	0.0E+00	0.0E+00	CP0
Cd-113m	2.29E+04	3.1E-03	5.6E+03	0.0E+00	GM1
Cd-115m	2.24E+06	5.5E+01	3.3E+06	0.0E+00	CP1 GM4
In-114m+D	1.72E+06	1.5E+02	3.6E+06	0.0E+00	CP2 GM4
In-115	1.02E+04	8.8E-04	1.8E+03	0.0E+00	GM1
Sn-113+D	5.95E+06	1.6E+03	1.4E+06	0.0E+00	CP3 GM4
Sn-119m	6.80E+06	5.7E+00	0.0E+00	0.0E+00	CP0

Table 4. Soil Limits and Instrument Response - 500 mrem/y, Continued

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
Sn-121m+D	2.53E+06	1.4E+00	6.5E+04	0.0E+00	CP0 GM2
Sn-123	1.90E+06	1.6E+01	2.2E+06	0.0E+00	CP1 GM4
Sn-126+D	2.87E+05	5.9E+02	4.6E+05	0.0E+00	CP2 GM3
Sb-124	3.84E+06	7.1E+03	3.3E+06	0.0E+00	CP3 GM4
Sb-125	2.27E+06	9.7E+02	1.7E+05	0.0E+00	CP2 GM3
Te-123m	4.48E+06	5.5E+02	1.1E+05	0.0E+00	CP2 GM3
Te-125m	1.23E+07	4.9E+01	3.4E+05	0.0E+00	CP1 GM3
Te-127m+D	2.65E+06	1.7E+01	9.1E+05	0.0E+00	CP1 GM3
Te-129m+D	6.75E+06	4.6E+02	8.5E+06	0.0E+00	CP2 GM4
I-125	1.71E+06	7.9E+00	0.0E+00	0.0E+00	CP0
I-129	5.57E+04	1.9E-01	2.9E+02	0.0E+00	GM0
Cs-134	2.47E+05	3.9E+02	5.6E+04	0.0E+00	CP2 GM2
Cs-135	2.16E+06	1.9E-02	3.8E+04	0.0E+00	GM2
Cs-137+D	3.10E+05	1.8E+02	1.1E+05	0.0E+00	CP2 GM3
Ba-133	2.89E+06	1.1E+03	3.7E+04	0.0E+00	CP3 GM2
Ce-144+D	1.51E+05	8.4E+00	5.4E+05	0.0E+00	CP0 GM3
Pm-147	1.15E+06	1.3E-02	2.7E+04	0.0E+00	GM2
Pm-148m+D	6.38E+06	1.3E+04	1.8E+06	0.0E+00	CP4 GM4
Sm-147	5.55E+02	0.0E+00	0.0E+00	0.0E+00	
Sm-151	1.36E+06	3.8E-04	2.0E-01	0.0E+00	
Eu-150	1.49E+05	2.2E+02	0.0E+00	0.0E+00	CP2
Eu-152	1.82E+05	2.1E+02	3.2E+04	0.0E+00	CP2 GM2
Eu-154	1.42E+05	1.7E+02	5.8E+04	0.0E+00	CP2 GM2
Eu-155	1.00E+06	3.9E+01	1.0E+04	0.0E+00	CP1 GM2
Gd-152	1.71E+02	0.0E+00	0.0E+00	0.0E+00	
Gd-153	2.56E+06	1.4E+02	6.6E+03	0.0E+00	CP2 GM1
Tb-158	1.58E+05	1.2E+02	1.4E+04	0.0E+00	CP2 GM2
Tb-160	3.86E+06	4.3E+03	1.4E+06	0.0E+00	CP3 GM4
Ho-166m	5.28E+04	9.3E+01	5.1E+03	0.0E+00	CP1 GM1
Tm-170	2.55E+06	8.3E+00	1.5E+06	0.0E+00	CP0 GM4
Ta-182	1.77E+06	2.2E+03	2.6E+05	0.0E+00	CP3 GM3
W-181	1.14E+08	2.0E+03	0.0E+00	0.0E+00	CP3
W-185	2.97E+07	2.7E+00	3.7E+06	0.0E+00	CP0 GM4
Re-187	5.62E+08	0.0E+00	0.0E+00	0.0E+00	
Os-185	8.01E+06	5.7E+03	9.8E+04	0.0E+00	CP3 GM2
Ir-192	3.67E+06	3.1E+03	1.1E+06	0.0E+00	CP3 GM4
Pt-193	8.84E+07	0.0E+00	0.0E+00	0.0E+00	
Au-195	5.07E+06	2.3E+02	1.9E+04	0.0E+00	CP2 GM2
Hg-203	7.30E+06	1.7E+03	5.7E+05	0.0E+00	CP3 GM3
Tl-204	4.85E+06	4.3E+00	1.8E+06	0.0E+00	CP0 GM4
Pb-210+D	1.31E+03	1.7E-03	1.0E+03	0.0E+00	GM1
Bi-207	1.34E+06	2.1E+03	3.7E+05	0.0E+00	CP3 GM3
Po-209	2.50E+03	7.7E+01	5.6E-01	1.3E+02	CP1 PAM0
Po-210	6.80E+03	5.9E-05	0.0E+00	4.4E+02	PAM0
Ra-226+D	3.52E+03	6.3E+00	7.3E+03	1.3E+03	CP0 GM1 PAM1
Ra-228+D	6.81E+02	6.6E-01	5.4E+02	0.0E+00	GM0
Ac-227+D	6.27E+00	2.4E-03	1.4E+01	3.3E+00	
Th-228+D	1.43E+02	2.3E-01	2.7E+02	7.5E+01	GM0

Table 4. Soil Limits and Instrument Response - 500 mrem/y, Continued

Nuclide	Soil Limit pCi/g	Estimated Instrument Readings CP W/C (mR/h)	GM P-11 (cpm)	PAM (cpm)	How Detectable
Th-229+D	1.92E+01	5.7E-03	2.6E+01	1.0E+01	
Th-230	1.28E+02	3.3E-05	0.0E+00	5.7E+00	
Th-232	2.53E+01	2.9E-06	1.4E-03	6.5E-01	
Pa-231	2.95E+01	1.1E-03	2.1E-01	1.7E+00	
U-232	5.69E+02	1.1E-04	5.5E-02	3.7E+01	
U-233	4.79E+03	1.4E-03	4.8E-02	2.4E+02	PAM0
U-234	4.92E+03	4.4E-04	2.9E-01	2.4E+02	PAM0
U-235+D	5.30E+03	7.9E-01	2.7E+02	1.9E+02	GM0 PAM0
U-236	5.21E+03	2.6E-04	2.3E-01	2.0E+02	PAM0
U-238+D	5.47E+03	1.3E-01	1.2E+04	1.7E+02	GM2 PAM0
Np-236	3.88E+02	3.7E-02	3.0E+01	0.0E+00	
Np-237+D	7.58E+01	1.6E-02	1.2E+01	3.6E+00	
Pu-236	3.18E+02	1.8E-05	0.0E+00	2.5E+01	
Pu-237	7.70E+07	2.6E+03	1.2E+03	0.0E+00	CP3 GM1
Pu-238	1.05E+02	4.1E-06	0.0E+00	7.4E+00	
Pu-239	9.54E+01	5.6E-06	0.0E+00	5.7E+00	
Pu-240	9.54E+01	3.4E-06	0.0E+00	5.7E+00	
Pu-241+D	4.87E+03	1.9E-05	9.3E-03	0.0E+00	
Pu-242	9.98E+01	3.3E-06	0.0E+00	5.2E+00	
Pu-244+D	1.02E+02	3.5E-02	1.6E+02	4.3E+00	GM0
Am-241	9.23E+01	9.5E-04	4.0E-03	6.5E+00	
Am-242m+D	9.48E+01	1.3E-03	2.1E+01	2.8E-02	
Am-243+D	9.30E+01	1.7E-02	1.7E+01	5.9E+00	
Cm-242	4.21E+03	1.9E-04	0.0E+00	3.9E+02	PAM0
Cm-243	1.35E+02	1.6E-02	1.0E+01	1.1E+01	
Cm-244	1.68E+02	5.6E-06	0.0E+00	1.4E+01	
Cm-245	9.00E+01	6.3E-03	2.4E+00	6.0E+00	
Cm-246	9.08E+01	3.0E-06	0.0E+00	6.1E+00	
Cm-247+D	9.88E+01	3.4E-02	2.1E+01	5.3E+00	
Cm-248	2.48E+01	5.7E-07	0.0E+00	1.3E+00	
Cf-250	1.61E+02	4.5E-06	7.2E-04	1.4E+01	
Cf-252	2.98E+02	1.3E-05	1.9E-03	2.7E+01	
Es-254+D	1.28E+03	1.1E+00	6.4E+02	1.3E+02	CP0 GM0 PAM0
Zr-95 old	2.99E+06	7.4E+03	3.8E+05	0.0E+00	CP3 GM3
Sb-125 old	2.17E+06	9.3E+02	1.8E+05	0.0E+00	CP2 GM3
Pb-210 old	1.10E+03	1.4E-03	8.6E+02	7.2E+01	GM0
Ra-226 old	8.30E+02	1.5E+00	2.4E+03	3.5E+02	CP0 GM1 PAM0
Th-Nat	2.08E+01	5.3E-02	5.6E+01	1.1E+01	
U-Nat	1.06E+02	1.9E-01	5.4E+02	5.8E+01	GM0
Pu 6%	8.41E+01	6.3E-05	1.4E-03	5.1E+00	
Pu 6% 10yr	8.84E+01	1.4E-04	1.2E-03	5.5E+00	
U-232 Y	5.84E+01	1.1E-05	5.6E-03	3.8E+00	
U-233 Y	3.06E+02	8.8E-05	3.1E-03	1.5E+01	
U-234 Y	3.13E+02	2.8E-05	1.8E-02	1.5E+01	
U-235+D Y	3.38E+02	5.0E-02	1.7E+01	1.2E+01	
U-236 Y	3.31E+02	1.6E-05	1.5E-02	1.3E+01	
U-238+D Y	3.50E+02	8.4E-03	7.8E+02	1.1E+01	GM0

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Appendix A. Data and Formulas Used in the Calculations

RADIOACTIVE DECAY METHOD

A spreadsheet was used for these calculations. The specific decay chains used by the spreadsheet are shown in Table A-1 below. The longest decay chain considered has 5 members. Some chains end even though there are significant members further down the chain. An example of this approximation is the Am-241, which ends at U-233 instead of including Th-229. Due to the long half-lives of the omitted nuclides there will be little ingrowth of these progeny for decay times less than 1000 years. Hence they can be omitted.

The "+D" designator means that there are short half-live progeny nuclides produced by the decay of this nuclide. Table A-2 lists the short-lived progeny which were lumped with the parent nuclide. These are sometimes called "implicit daughters". The numbers in parentheses are the effective branching ratios for that nuclide when it is in secular equilibrium with its parent nuclide. The dose factors for all nuclides with implicit daughters were computed by adding the appropriate dose factors, weighted by the equilibrium branching ratios.

The parent nuclides shown on the leftmost column of Table A-1 generate additional nuclides which also contribute to the annual dose. At the start of the year of exposure the concentration of the Table A-1 parent nuclides has a unit value. The progeny nuclides shown on Table A-1 have zero activity. Note that the Table A-2 progeny are present in equilibrium amounts even at the beginning of the exposure scenario due to their short half-lives. As the year progresses, the parent nuclide concentration decreases according to the half-life of that nuclide. In addition, the progeny nuclides shown in Table A-1 begin to accumulate in the soil.

Radioactive decay of the source as well as the ingrowth of any progeny nuclides is computed using the ordinary decay chain equations. The actual decay chains computed by the spreadsheet are shown in Table A-1 below. The decay equations shown below describe the decay of nuclide 1 (the parent) to nuclide 2, then nuclide 3, and finally nuclide 4.

$$A_1 = A_1^0 \, \mathrm{Exp}(-\lambda_1 T)$$

$$A_2 = A_2^0 \, \mathrm{Exp}(-\lambda_2 T) + A_1^0 \, \lambda_2 \left\{ \mathrm{Exp}(-\lambda_1 T)/(\lambda_2-\lambda_1) + \mathrm{Exp}(-\lambda_2 T)/(\lambda_1-\lambda_2) \right\}$$

$$\begin{aligned} A_3 = {} & A_3^0 \, \mathrm{Exp}(-\lambda_3 T) + A_2^0 \, \lambda_3 \left\{ \mathrm{Exp}(-\lambda_2 T)/(\lambda_3-\lambda_2) + \mathrm{Exp}(-\lambda_3 T)/(\lambda_2-\lambda_3) \right\} \\ & + A_1^0 \, \lambda_2\lambda_3 \{ \mathrm{Exp}(-\lambda_1 T)/(\lambda_2-\lambda_1)/(\lambda_3-\lambda_1) + \mathrm{Exp}(-\lambda_2 T)/(\lambda_1-\lambda_2)/(\lambda_3-\lambda_2) \\ & \quad + \mathrm{Exp}(-\lambda_3 T)/(\lambda_1-\lambda_3)/(\lambda_2-\lambda_3) \} \end{aligned}$$

$$\begin{aligned} A_4 = {} & A_4^0 \, \mathrm{Exp}(-\lambda_4 T) + A_3^0 \, \lambda_4 \left\{ \mathrm{Exp}(-\lambda_3 T)/(\lambda_4-\lambda_3) + \mathrm{Exp}(-\lambda_4 T)/(\lambda_3-\lambda_4) \right\} \\ & + A_2^0 \, \lambda_3\lambda_4 \{ \mathrm{Exp}(-\lambda_2 T)/(\lambda_3-\lambda_2)/(\lambda_4-\lambda_2) + \mathrm{Exp}(-\lambda_3 T)/(\lambda_2-\lambda_3)/(\lambda_4-\lambda_3) \\ & \quad + \mathrm{Exp}(-\lambda_4 T)/(\lambda_2-\lambda_4)/(\lambda_3-\lambda_4) \} \\ & + A_1^0 \, \lambda_2\lambda_3\lambda_4 \{ \mathrm{Exp}(-\lambda_1 T)/(\lambda_2-\lambda_1)/(\lambda_3-\lambda_1)/(\lambda_4-\lambda_1) \\ & \quad + \mathrm{Exp}(-\lambda_2 T)/(\lambda_1-\lambda_2)/(\lambda_3-\lambda_2)/(\lambda_4-\lambda_2) \\ & \quad + \mathrm{Exp}(-\lambda_3 T)/(\lambda_1-\lambda_3)/(\lambda_2-\lambda_3)/(\lambda_4-\lambda_3) \\ & \quad + \mathrm{Exp}(-\lambda_4 T)/(\lambda_1-\lambda_4)/(\lambda_2-\lambda_4)/(\lambda_3-\lambda_4) \} \end{aligned}$$

where,

$A_1^0, A_2^0, A_3^0, A_4^0$ = initial activity of nuclides 1, 2, 3, and 4 (T=0).

A_1, A_2, A_3, A_4 = activity of nuclides 1, 2, 3, and 4 at time T.

$\lambda_1, \lambda_2, \lambda_3, \lambda_4$ = decay constants for nuclides 1, 2, 3, and 4. Note that the decay constant is the natural logarithm of 2 divided by the half-life of the nuclide. Note also that the decay constants in a decay chain are all different so the denominators will never be zero.

The accumulated dose at time T is the time integral of the activity equations. These integrations are simply the integral of each exponential. In other words, each exponential in the decay equations, Exp($-\lambda$T) is replaced with its integral, [1 - Exp($-\lambda$T)]/λ.

Table A-3 shows the half-lives of nuclides used in the spreadsheet. The half-lives are from Kocher (1981). Table A-3 also shows the internal dose factors for each nuclide from EPA (1988 and 1993). Information on the implicit daughters for nuclides with the "+D" are listed at the end of Table A-3. The solubility classes of these nuclides are also shown for reference. The dose factors for the implicit daughters are multiplied by the branching ratios listed in Table A-2 before being added to the parent dose factor.

In Table A-3 the "Lung" column refers to the rate of clearance from the pulmonary region of the lung according to the ICRP lung model. There are only three possibilities, "D" means days, "W" means weeks, and "Y" means years. Carbon (C-14) may be present as carbon dioxide, which is a gas. The ICRP uses a special model for carbon isotopes in this chemical form. These lung model choices are the worst-case assumptions, except for strontium, which uses class D rather than class Y.

The "f1" column refers to the fraction of a stable element reaching body fluids following ingestion. These were also determined in ICRP 30. A few elements (eg. cobalt an plutonium) have more than one value for f1, so the value which produces the largest internal dose was selected.

DOSE AND SOIL LIMIT CALCULATION METHODS

Over the course of a year, the worker is assumed to inhale the radioactivity in 12 grams of soil, and to ingest the radioactivity in 25 grams of soil. Starting with a soil concentration of 1 pCi/g for each nuclide, the worker inhales 12 pCi and ingests 25 pCi of each nuclide. The internal dose commitment is shown in the equation below.

$$\text{Dose} = [(12\ \text{pCi})(\text{DF inhale}) + (25\ \text{pCi})(\text{DF ingest})](\text{Decay Factor})$$

The inhalation and ingestion dose factors are shown on Table A-3. The decay factor is computed from the decay equations (integral form) where the initial activity of the parent is 1 and the initial activity of any progeny nuclides is zero. The decay and ingrowth period is 365.25 days. The computed annual dose factors for a unit soil concentration are shown in the first column of numbers in Table 1.

The soil concentration limits were computed by dividing the annual dose limit by the dose from a unit soil concentration. Results were shown in the last three columns of Table 1.

Table A-1. Decay Chains Computed in the Spreadsheet

Parent	Progeny*
Zr-93	→ Nb-93m
Zr-95	→ Nb-95
Mo-93	→ Nb-93m
Cd-115m	→ In-115
Sb-125	→ Te-125m (0.231)
Te-129m	→ I-129
Pm-147	→ Sm-147
Eu-152	→ Gd-152 (0.278)
Pb-210	→ Po-210
Ra-226	→ Pb-210 → Po-210
Ra-228	→ Th-228
Th-230	→ Ra-226 → Pb-210 → Po-210
Th-232	→ Ra-228 → Th-228
Pa-231	→ Ac-227
U-232	→ Th-228
U-233	→ Th-229
U-234	→ Th-230 → Ra-226 → Pb-210 → Po-210
U-235	→ Pa-231 → Ac-227
U-236	→ Th-232 → Ra-228 → Th-228
U-238	→ U-234 → Th-230 → Ra-226
Np-236	→ Pu-236 → U-232 → Th-228
	→ U-236 (0.911)
Np-237	→ U-233 → Th-229
Pu-236	→ U-232 → Th-228
Pu-237	→ Np-237 → U-233 → Th-229
Pu-238	→ U-234 → Th-230
Pu-239	→ U-235
Pu-240	→ U-236
Pu-241	→ Am-241 → Np-237
Pu-242	→ U-238
Pu-244	→ Pu-240
Am-241	→ Np-237 → U-233
Am-242m	→ Cm-242 → Pu-238 → U-234
	→ Pu-242 (0.173)
Am-243	→ Pu-239 → U-235
Cm-242	→ Pu-238 → U-234 → Th-230
Cm-243	→ Pu-239 → U-235
	→ Am-243 (0.0024)
Cm-244	→ Pu-240 → U-236
Cm-245	→ Pu-241 → Am-241 → Np-237
Cm-246	→ Pu-242 → U-238
Cm-247	→ Am-243 → Pu-239 → U-235
Cm-248	→ Pu-244 → Pu-240
Cf-250	→ Cm-246 → Pu-242
Cf-252	→ Cm-248
Es-254	→ Cf-250 → Cm-246 → Pu-242

*The initial concentrations of these progeny are zero. During the exposure scenario (one year), their concentration increases.

Table A-2. Composition of the "+D" Nuclides

Nuclide	Short-Lived Progeny Lumped With Parent
Sr-90+D	Y-90 (1.00026)
Zr-95+D	Nb-95m (0.00742)
Ru-103+D	Rh-103m (0.99799)
Ru-106+D	Rh-106
Ag-108m+D	Ag-108 (0.0930)
Ag-110m+D	Ag-110 (0.0133)
In-114m+D	In-114 (0.955)
Sn-113+D	In-113m(1.0006)
Sn-121m+D	Sn-121 (0.776)
Sn-126+D	Sb-126m, Sb-126 (0.14)
Te-127m+D	Te-127 (0.9852)
Te-129m+D	Te-129 (0.6299)
Cs-137+D	Ba-137m (0.946)
Ce-144+D	Pr-144m (0.0143), Pr-144
Pm-148m+D	Pm-148 (0.04828)
Pb-210+D	Bi-210 (1.0006)
Ra-226+D	Rn-222, Po-218, Pb-214, Bi-214, Po-214
Ra-228+D	Ac-228 (1.0001)
Ac-227+D	Th-227(0.9885), Fr-223(0.0138), Ra-223(1.0038), Rn-219(1.0038), Po-215(1.0038), Pb-211(1.0038), Bi-211(1.0038), Po-211(0.00274), Tl-207(1.0010)
Th-228+D	Ra-224(1.0052), Rn-220(1.0052), Po-216(1.0052), Pb-212(1.0058), Bi-212(1.0058), Po-212(0.6444), Tl-208(0.3614)
Th-229+D	Ra-225, Ac-225, Fr-221, At-217, Bi-213, Po-213 (0.9784), Tl-209 (0.0216), Pb-209
U-235+D	Th-231
U-238+D	Th-234, Pa-234m, Pa-234 (0.0016)
Np-237	Pa-233
Pu-241+D	U-237 (2.45E-5)
Pu-244+D	U-240, Np-240m, Np-240 (0.0011)
Am-242m+D	Am-242 (0.99524), Np-238 (0.00476)
Am-243+D	Np-239
Cm-247+D	Pu-243
Es-254+D	Bk-250 (1.0005)

Any branching ratios different from 1.0 are shown in parentheses.
The decay chain corrections are included.
These implicit daughters are assumed to be in equilibrium with the parent nuclide at all times.
Decay chains computed by the spreadsheet are shown in Table A-1.

Table A-3. Solubility Assumptions, Half Lives and Dose Factors

Nuclide	Lung	f1	Half-life	mrem/pCi Intake Ingest	mrem/pCi Intake Inhale	mrem/hour per pCi/g External
H-3		1	12.28 Y	6.40E-08	9.60E-08	0.00E+00
Be-7	Y	0.005	53.44 D	1.28E-07	3.21E-07	3.28E-05
Be-10	W	0.005	1.600E+06 Y	4.66E-06	3.55E-04	1.23E-07
C-14	CO_2	1	5,730 Y	2.09E-06	2.09E-06	1.53E-09
Na-22	D	1	2.602 Y	1.15E-05	7.66E-06	1.56E-03
S-35	W	0.1	87.44 D	7.33E-07	2.48E-06	1.70E-09
Cl-36	W	1	301,000 Y	3.03E-06	2.19E-05	2.73E-07
K-40	D	1	1.277E+09 Y	1.86E-05	1.24E-05	1.19E-04
Ca-41	W	0.3	103,000 Y	1.27E-06	1.35E-06	0.00E+00
Ca-45	W	0.3	162.7 D	3.16E-06	6.62E-06	7.14E-09
Sc-46	Y	0.0001	83.8 D	6.40E-06	2.96E-05	1.45E-03
V-49	W	0.01	330 D	6.14E-08	3.45E-07	0.00E+00
Mn-54	W	0.1	312.7 D	2.77E-06	6.70E-06	5.88E-04
Fe-55	D	0.1	2.7 Y	6.07E-07	2.69E-06	0.00E+00
Fe-59	D	0.1	44.63 D	6.70E-06	1.48E-05	8.72E-04
Co-57	Y	0.3	270.9 D	1.18E-06	9.07E-06	5.71E-05
Co-58	Y	0.3	70.8 D	3.58E-06	1.09E-05	6.80E-04
Co-60	Y	0.3	5.271 Y	2.69E-05	2.19E-04	1.85E-03
Ni-59	D	0.05	75,000 Y	2.10E-07	1.33E-06	0.00E+00
Ni-63	D	0.05	100.1 Y	5.77E-07	3.10E-06	0.00E+00
Zn-65	Y	0.5	244.4 D	1.44E-05	2.04E-05	4.22E-04
Se-75	W	0.8	119.78 D	9.62E-06	8.47E-06	2.26E-04
Se-79	W	0.8	65,000 Y	8.70E-06	9.84E-06	2.12E-09
Rb-87	D	1	4.730E+10 Y	4.92E-06	3.23E-06	1.61E-08
Sr-89	D	0.3	50.55 D	9.25E-06	6.51E-06	1.04E-06
Sr-90+D	D	0.3	28.6 Y	1.53E-04	2.48E-04	2.81E-06
Y-88	Y	0.0001	106.6 D	5.99E-06	2.81E-05	2.03E-03
Y-91	Y	0.0001	58.51 D	9.51E-06	4.88E-05	3.71E-06
Zr-93	D	0.002	1.530E+06 Y	1.66E-06	3.21E-04	0.00E+00
Zr-95+D	D	0.002	64.02 D	3.79E-06	2.37E-05	5.16E-04
Nb-93m	Y	0.01	14.6 Y	5.22E-07	2.92E-05	1.19E-08
Nb-94	Y	0.01	20,300 Y	7.14E-06	4.14E-04	1.10E-03
Nb-95	Y	0.01	35.06 D	2.57E-06	5.81E-06	5.35E-04
Mo-93	Y	0.8	3,500 Y	1.35E-06	2.84E-05	6.74E-08
Tc-99	W	0.8	213,000 Y	1.46E-06	8.33E-06	1.43E-08
Ru-103+D	Y	0.05	39.35 D	3.06E-06	8.96E-06	3.13E-04
Ru-106+D	Y	0.05	368.2 D	2.80E-05	4.78E-04	1.47E-04
Pd-107	Y	0.005	6.500E+06 Y	1.50E-07	1.28E-05	0.00E+00
Ag-108m+D	Y	0.05	127 Y	7.62E-06	2.83E-04	1.10E-03
Ag-110m+D	Y	0.05	249.85 D	1.08E-05	8.03E-05	1.96E-03
Cd-109	D	0.05	464 D	1.31E-05	1.14E-04	1.68E-06
Cd-113m	D	0.05	13.7 Y	1.61E-04	1.53E-03	7.40E-08
Cd-115m	D	0.05	44.6 D	1.62E-05	7.22E-05	1.69E-05
In-114m+D	D	0.02	49.51 D	1.71E-05	8.88E-05	5.71E-05
In-115	D	0.02	4.600E+15 Y	1.58E-04	3.74E-03	4.58E-08
Sn-113+D	W	0.02	115.1 D	3.19E-06	1.07E-05	1.67E-04
Sn-119m	W	0.02	293 D	1.39E-06	6.25E-06	3.43E-07

Table A-3. Solubility Assumptions, Half Lives and Dose Factors, Continued

Nuclide	Lung	f1	Half-life	mrem/pCi Intake Ingest	mrem/pCi Intake Inhale	mrem/hour per pCi/g External
Sn-121m+D	W	0.02	55 Y	2.25E-06	1.19E-05	2.41E-07
Sn-123	W	0.02	129.2 D	8.40E-06	3.25E-05	5.78E-06
Sn-126+D	W	0.02	100,000 Y	2.11E-05	1.01E-04	1.35E-03
Sb-124	W	0.1	60.2 D	1.01E-05	2.52E-05	1.33E-03
Sb-125	W	0.1	2.77 Y	2.81E-06	1.22E-05	2.79E-04
Te-123m	W	0.2	119.7 D	5.66E-06	1.06E-05	7.16E-05
Te-125m	W	0.2	58 D	3.67E-06	7.29E-06	1.73E-06
Te-127m+D	W	0.2	109 D	8.93E-06	2.18E-05	3.84E-06
Te-129m+D	W	0.2	33.6 D	1.08E-05	2.40E-05	4.49E-05
I-125	D	1	60.14 D	3.85E-05	2.42E-05	1.89E-06
I-129	D	1	1.570E+07 Y	2.76E-04	1.74E-04	1.48E-06
Cs-134	D	1	2.062 Y	7.33E-05	4.63E-05	1.08E-03
Cs-135	D	1	2.300E+06 Y	7.07E-06	4.55E-06	4.37E-09
Cs-137+D	D	1	30.17 Y	5.00E-05	3.19E-05	3.89E-04
Ba-133	D	0.1	10.5 Y	3.40E-06	7.81E-06	2.26E-04
Ce-144+D	Y	0.0003	284.3 D	2.11E-05	3.74E-04	3.70E-05
Pm-147	Y	0.0003	2.6234 Y	1.05E-06	3.92E-05	5.71E-09
Pm-148m+D	Y	0.0003	41.3 D	8.18E-06	2.31E-05	1.39E-03
Sm-147	W	0.0003	1.069E+11 Y	1.85E-04	7.47E-02	0.00E+00
Sm-151	W	0.0003	90 Y	3.89E-07	3.00E-05	1.12E-10
Eu-150	W	0.001	35.8 Y	6.36E-06	2.68E-04	9.95E-04
Eu-152	W	0.001	13.6 Y	6.48E-06	2.21E-04	7.99E-04
Eu-154	W	0.001	8.8 Y	9.55E-06	2.86E-04	8.76E-04
Eu-155	W	0.001	4.96 Y	1.53E-06	4.14E-05	2.08E-05
Gd-152	D	0.0003	1.100E+14 Y	1.61E-04	2.44E-01	0.00E+00
Gd-153	D	0.0003	241.6 D	1.17E-06	2.38E-05	2.79E-05
Tb-158	W	0.0003	150 Y	4.40E-06	2.56E-04	5.39E-04
Tb-160	W	0.0003	72.3 D	6.73E-06	2.50E-05	7.89E-04
Ho-166m	W	0.0003	1200 Y	8.07E-06	7.73E-04	1.17E-03
Tm-170	W	0.0003	128.6 D	5.29E-06	2.63E-05	1.71E-06
Ta-182	Y	0.001	114.74 D	6.51E-06	4.48E-05	9.06E-04
W-181	D	0.01	120.95 D	3.45E-07	1.51E-07	8.72E-06
W-185	D	0.01	75.1 D	1.99E-06	7.51E-07	4.94E-08
Re-187	W	0.8	4.700E+10 Y	9.51E-09	5.44E-08	0.00E+00
Os-185	D	0.01	93.6 D	2.26E-06	1.04E-05	4.75E-04
Ir-192	Y	0.01	74.02 D	5.74E-06	2.82E-05	5.26E-04
Pt-193	D	0.01	50 Y	1.19E-07	2.27E-07	6.46E-10
Au-195	Y	0.1	183 D	1.06E-06	1.30E-05	2.37E-05
Hg-203	D	1	46.6 D	1.14E-05	7.33E-06	1.44E-04
Tl-204	D	1	3.779 Y	3.36E-06	2.41E-06	4.63E-07
Pb-210+D	D	0.2	22.26 Y	5.37E-03	1.38E-02	6.91E-07
Bi-207	W	0.05	33.4 Y	5.48E-06	2.00E-05	1.07E-03
Po-209	D	0.1	102 Y	2.38E-03	1.18E-02	2.04E-02
Po-210	D	0.1	138.378 D	1.90E-03	9.40E-03	5.97E-09
Ra-226+D	W	0.2	1600 Y	1.33E-03	8.61E-03	1.28E-03
Ra-228+D	W	0.2	5.75 Y	1.44E-03	5.08E-03	6.82E-04
Ac-227+D	D	0.001	21.773 Y	1.48E-02	6.72E+00	2.30E-04
Th-228+D	Y	0.0002	1.9132 Y	8.11E-04	3.45E-01	1.17E-03

Table A-3. Solubility Assumptions, Half Lives and Dose Factors, Continued

Nuclide	Lung	f1	Half-life	mrem/pCi Intake Ingest	mrem/pCi Intake Inhale	mrem/hour per pCi/g External
Th-229+D	W	0.0002	7340 Y	4.03E-03	2.17E+00	1.82E-04
Th-230	W	0.0002	77,000 Y	5.48E-04	3.26E-01	1.38E-07
Th-232	W	0.0002	1.405E+10 Y	2.73E-03	1.64E+00	5.95E-08
Pa-231	W	0.001	32,760 Y	1.06E-02	1.28E+00	2.17E-05
U-232	W	0.05	72 Y	1.31E-03	1.49E-02	1.03E-07
U-233	W	0.05	159,200 Y	2.89E-04	7.99E-03	1.59E-07
U-234	W	0.05	244,500 Y	2.83E-04	7.88E-03	4.58E-08
U-235+D	W	0.05	7.038E+08 Y	2.67E-04	7.29E-03	8.64E-05
U-236	W	0.05	2.342E+07 Y	2.69E-04	7.44E-03	2.45E-08
U-238+D	W	0.05	4.468E+09 Y	2.68E-04	7.06E-03	1.51E-05
U-232	Y	0.05	72 Y	1.31E-03	6.59E-01	1.03E-07
U-233	Y	0.05	159,200 Y	2.89E-04	1.35E-01	1.59E-07
U-234	Y	0.05	244,500 Y	2.83E-04	1.33E-01	4.58E-08
U-235+D	Y	0.05	7.038E+08 Y	2.67E-04	1.23E-01	8.64E-05
U-236	Y	0.05	2.342E+07 Y	2.69E-04	1.25E-01	2.45E-08
U-238+D	Y	0.05	4.468E+09 Y	2.68E-04	1.18E-01	1.51E-05
Np-236	W	0.001	115,000 Y	8.66E-04	1.04E-01	5.26E-05
Np-237+D	W	0.001	2.140E+06 Y	4.44E-03	5.40E-01	1.25E-04
Pu-236	W	0.001	2.851 Y	1.17E-03	1.45E-01	2.60E-08
Pu-237	Y	0.001	45.3 D	4.44E-07	1.97E-06	1.85E-05
Pu-238	W	0.001	87.75 Y	3.20E-03	3.92E-01	1.73E-08
Pu-239	W	0.001	24,131 Y	3.54E-03	4.29E-01	3.37E-08
Pu-240	W	0.001	6,537 Y	3.54E-03	4.29E-01	1.67E-08
Pu-241+D	W	0.001	14.4 Y	6.85E-05	8.25E-03	2.16E-09
Pu-242	W	0.001	375,800 Y	3.36E-03	4.11E-01	1.46E-08
Pu-244+D	W	0.001	8.260E+07 Y	3.32E-03	4.03E-01	2.31E-04
Am-241	W	0.001	432.2 Y	3.64E-03	4.44E-01	4.99E-06
Am-242m+D	W	0.001	152 Y	3.52E-03	4.26E-01	7.72E-06
Am-243+D	W	0.001	7,380 Y	3.63E-03	4.40E-01	1.02E-04
Cm-242	W	0.001	163.2 D	1.15E-04	1.73E-02	1.95E-08
Cm-243	W	0.001	28.5 Y	2.51E-03	3.07E-01	6.65E-05
Cm-244	W	0.001	18.11 Y	2.02E-03	2.48E-01	1.44E-08
Cm-245	W	0.001	8,500 Y	3.74E-03	4.55E-01	3.88E-05
Cm-246	W	0.001	4,750 Y	3.70E-03	4.51E-01	1.33E-08
Cm-247+D	W	0.001	1.560E+07 Y	3.42E-03	4.14E-01	2.12E-04
Cm-248	W	0.001	339,000 Y	1.36E-02	1.65E+00	1.00E-08
Cf-250	W	0.001	13.08 Y	2.13E-03	2.62E-01	1.35E-08
Cf-252	Y	0.001	2.639 Y	1.08E-03	1.57E-01	2.01E-08
Es-254+D	W	0.001	275.7 D	3.14E-04	4.11E-02	6.35E-04
Sr-90+D						
Sr-90	D	0.3	28.6 Y	1.42E-04	2.39E-04	8.03E-08
Y-90	Y	0.0001	64.1 H	1.08E-05	8.44E-06	2.73E-06
Zr-95+D						
Zr-95	D	0.002	64.02 D	3.77E-06	2.36E-05	5.16E-04
Nb-95m	Y	0.01	86.6 H	2.30E-06	2.44E-06	3.64E-05
Ru-103+D						
Ru-103	Y	0.05	39.35 D	3.05E-06	8.95E-06	3.13E-04
Rh-103m	D	0.05	56.1 M	1.16E-08	5.11E-09	2.77E-08

Table A-3. Solubility Assumptions, Half Lives and Dose Factors, Continued

Nuclide	Lung	f1	Half-life	mrem/pCi Intake Ingest	mrem/pCi Intake Inhale	mrem/hour per pCi/g External
Ru-106+D						
Ru-106	Y	0.05	368.2 D	2.74E-05	4.77E-04	0.00E+00
Rh-106	D	0.05	29.9 S	6.44E-07	2.13E-07	1.47E-04
Ag-108m+D						
Ag-108m	Y	0.05	127 Y	7.62E-06	2.83E-04	1.10E-03
Ag-108	Y	0.05	2.37 M			1.30E-05
Ag-110m+D						
Ag-110m	Y	0.05	249.85 D	1.08E-05	8.03E-05	1.96E-03
Ag-110	Y	0.05	24.6 S			2.56E-05
In-114m+D						
In-114m	D	0.02	49.51 D	1.71E-05	8.88E-05	5.52E-05
In-114	D	0.02	71.9 S	0.00E+00	0.00E+00	2.02E-06
Sn-113+D						
Sn-113	W	0.02	115.1 D	3.08E-06	1.07E-05	3.39E-06
In-113m	D	0.02	1.66 H	1.05E-07	4.11E-08	1.64E-04
Sn-121m+D						
Sn-121m	W	0.02	55.5 Y	1.55E-06	1.15E-05	2.24E-07
Sn-121	W	0.02	27.1 H	9.03E-07	5.11E-07	2.24E-08
Sn-126+D						
Sn-126	W	0.02	100,000 Y	1.95E-05	9.95E-05	1.68E-05
Sb-126m	D	0.1	19 M	9.40E-08	3.39E-08	1.06E-03
Sb-126	W	0.1	12.4 D	1.07E-05	1.17E-05	1.95E-03
Te-127m+D						
Te-127m	W	0.2	109 D	8.25E-06	2.15E-05	6.22E-07
Te-127	W	0.2	9.35 H	6.92E-07	3.18E-07	3.26E-06
Te-129m+D						
Te-129m	W	0.2	33.6 D	1.07E-05	2.39E-05	2.11E-05
Te-129	D	0.2	69.6 M	2.02E-07	8.95E-08	3.77E-05
Cs-137+D						
Cs-137	D	1	30.17 Y	5.00E-05	3.19E-05	8.57E-08
Ba-137m	D	0.1	2.552 M	0.00E+00	0.00E+00	4.11E-04
Ce-144+D						
Ce-144	Y	0.0003	284.3 D	2.10E-05	3.74E-04	8.18E-06
Pr-144m	Y	0.0003	7.2 M	0.00E+00	0.00E+00	1.64E-06
Pr-144	Y	0.0003	17.3 M	1.17E-07	4.33E-08	2.88E-05
Pm-148m+D						
Pm-148m	Y	0.0003	41.3 D	7.66E-06	2.26E-05	1.37E-03
Pm-148	Y	0.0003	5.37 D	1.09E-05	1.09E-05	4.20E-04
Pb-210+D						
Pb-210	D	0.2	22.26 Y	5.37E-03	1.36E-02	2.79E-07
Bi-210	W	0.05	5.013 D	6.40E-06	1.96E-04	4.11E-07
Ra-226+D						
Ra-226	W	0.2	1,600 Y	1.32E-03	8.58E-03	3.62E-06
Rn-222		1	3.8235 D	9.08E-07	1.44E-05	2.69E-07
Po-218	W	0.1	3.05 M	0.00E+00	0.00E+00	6.44E-09
Pb-214	D	0.2	26.8 M	6.25E-07	7.81E-06	1.53E-04
Bi-214	D	0.05	19.9 M	2.83E-07	6.59E-06	1.12E-03
Po-214	W	0.1	0.0001637 S	0.00E+00	0.00E+00	5.86E-08

Table A-3. Solubility Assumptions, Half Lives and Dose Factors, Continued

Nuclide	Lung	fl	Half-life	mrem/pCi Intake Ingest	mrem/pCi Intake Inhale	mrem/hour per pCi/g External
Ra-228+D						
Ra-228	W	0.2	5.75 Y	1.44E-03	4.77E-03	0.00E+00
Ac-228	D	0.001	6.13 H	2.16E-06	3.08E-04	6.82E-04
Ac-227+D						
Ac-227	D	0.001	21.773 Y	1.41E-02	6.70E+00	5.65E-08
Th-227	Y	0.0002	18.718 D	3.81E-05	1.62E-02	5.95E-05
Fr-223	D	1	21.8 M	8.25E-06	6.22E-06	2.26E-05
Ra-223	W	0.2	11.434 D	6.59E-04	7.84E-03	6.88E-05
Rn-219		1	3.96 S	0.00E+00	0.00E+00	3.52E-05
Po-215	W	0.1	0.001778 S	0.00E+00	0.00E+00	1.16E-07
Pb-211	D	0.2	36.1 M	5.25E-07	8.70E-06	3.50E-05
Bi-211	W	0.05	2.13 M	0.00E+00	0.00E+00	2.92E-05
Tl-207	D	1	4.77 M	0.00E+00	0.00E+00	2.26E-06
Po-211	W	0.1	0.516 S	0.00E+00	0.00E+00	5.43E-06
Th-228+D						
Th-228	Y	0.0002	1.9132 Y	3.96E-04	3.42E-01	9.06E-07
Ra-224	W	0.2	3.62 D	3.66E-04	3.16E-03	5.84E-06
Rn-220		1	55.61 S	0.00E+00	0.00E+00	2.62E-07
Po-216	W	0.1	0.146 S	0.00E+00	0.00E+00	1.19E-08
Pb-212	D	0.2	10.643 H	4.55E-05	1.69E-04	8.03E-05
Bi-212	D	0.05	60.55 M	1.06E-06	2.16E-05	1.34E-04
Po-212	W	0.1	2.98E-07 S	0.00E+00	0.00E+00	0.00E+00
Tl-208	D	1	3.053 M	0.00E+00	0.00E+00	2.62E-03
Th-229+D						
Th-229	W	0.0002	7,340 Y	3.53E-03	2.15E+00	3.67E-05
Ra-225	W	0.2	14.8 D	3.85E-04	7.77E-03	1.26E-06
Ac-225	D	0.001	10 D	1.11E-04	1.08E-02	7.27E-06
Fr-221	D	1	4.8 M	0.00E+00	0.00E+00	1.75E-05
At-217	D	1	0.0323 S	0.00E+00	0.00E+00	2.02E-07
Bi-213	D	0.05	45.65 M	0.00E+00	0.00E+00	8.74E-05
Po-213	W	0.1	4.2E-06 S	0.00E+00	0.00E+00	0.00E+00
Tl-209	D	1	2.2 M	0.00E+00	0.00E+00	1.47E-03
Pb-209	D	0.2	3.253 H	2.13E-07	9.47E-08	8.82E-08
U-235+D						
U-235	W	0.05	7.04E+08 Y	2.66E-04	7.29E-03	8.23E-05
Th-231	W	0.0002	25.52 H	1.35E-06	8.62E-07	4.16E-06
U-238+D						
U-238	W	0.05	4.47E+09 Y	2.55E-04	7.03E-03	1.18E-08
Th-234	W	0.0002	24.1 D	1.37E-05	2.98E-05	2.75E-06
Pa-234m	W	0.001	1.17 M	0.00E+00	0.00E+00	1.02E-05
Pa-234	W	0.001	6.7 H	3.46E-09	1.17E-09	1.32E-03
U-235+D						
U-235	Y	0.05	7.04E+08 Y	2.66E-04	1.23E-01	8.23E-05
Th-231	Y	0.0002	25.52 H	1.35E-06	8.77E-07	4.16E-06
U-238+D						
U-238	Y	0.05	4.47E+09 Y	2.55E-04	1.18E-01	1.18E-08
Th-234	Y	0.0002	24.1 D	1.37E-05	3.50E-05	2.75E-06
Pa-234m	Y	0.001	1.17 M	0.00E+00	0.00E+00	1.02E-05
Pa-234	Y	0.001	6.7 H	2.16E-06	8.14E-07	1.32E-03

Table A-3. Solubility Assumptions, Half Lives and Dose Factors, Continued

Nuclide	Lung	f1	Half-life	mrem/pCi Intake Ingest	mrem/pCi Intake Inhale	mrem/hour per pCi/g External
Np-237+D						
Np-237	W	0.001	2.14E+06 Y	4.44E-03	5.40E-01	8.89E-06
Pa-233	Y	0.001	27 D	3.63E-06	9.55E-06	1.16E-04
Pu-241+D						
Pu-241	W	0.001	14.4 Y	6.85E-05	8.25E-03	6.73E-10
U-237	Y	0.05	6.75 D	3.14E-06	3.53E-06	6.05E-05
Pu-244+D						
Pu-244	W	0.001	8.26E+07 Y	3.32E-03	4.03E-01	8.61E-09
U-240	Y	0.05	14.1 H	4.29E-06	2.27E-06	1.62E-07
Np-240m	W	0.001	7.4 M	0.00E+00	0.00E+00	2.30E-04
Np-240	W	0.001	65 M	2.37E-07	8.14E-08	8.82E-04
Am-242m+D						
Am-242m	W	0.001	152 Y	3.52E-03	4.26E-01	1.93E-07
Am-242	W	0.001	16.02 H	1.41E-06	5.85E-05	5.69E-06
Np-238	W	0.001	2.117 D	4.00E-06	3.70E-05	3.92E-04
Am-243+D						
Am-243	W	0.001	7,380 Y	3.62E-03	4.40E-01	1.62E-05
Np-239	W	0.001	2.355 D	3.26E-06	2.51E-06	8.59E-05
Cm-247+D						
Cm-247	W	0.001	1.56E+07 Y	3.42E-03	4.14E-01	2.03E-04
Pu-243	Y	0.001	4.956 H	3.33E-07	1.64E-07	9.08E-06
Es-254+D						
Es-254	W	0.001	275.5 D	3.13E-04	4.11E-02	1.47E-06
Bk-250	W	0.001	3.222 H	5.81E-07	7.55E-06	6.33E-04

Note: Half-life data is from Kocher (1981). Internal dose factors are from EPA (1988). External dose rate factors are from EPA (1993) for an infinite depth of soil with a density of 1.6 g/cc.

The composition of the "Pu 6%" is shown in Table A-4. It is a typical low-enrichment mixture of plutonium isotopes. The relative activity is as weighting factors when combining dose factors for individual plutonium isotopes to arrive at the unit dose factor for the mixture. Since the Pu-241 is a beta-emitting nuclide, its activity is not included in the total shown on the table.

Table A-4. Assumed Composition of Plutonium 6% Mixture

Isotope	Fresh Mixture Weight Percent	Fresh Mixture Relative Activity	Decayed 10 years Weight Percent	Decayed 10 years Relative Activity
Pu-238	0.0298	0.0623	0.0275	0.0531
Pu-239	93.1854	0.7051	93.1592	0.6498
Pu-240	6.0328	0.1670	6.0265	0.1538
Pu-241	0.5724	7.2000	0.3537	4.1010
Pu-242	0.0230	1.1E-5	0.0230	1.0E-5
Am-241	0.1566	0.0656	0.3709	0.1433
Total	100.0000	1.0000	99.9608	1.0000

Appendix B. Method for Estimating Field Instrument Readings

Three field instruments are considered in this report, the window-closed CP, the GM with a pancake probe (15 cm² face area), and the Portable Alpha Monitor (PAM) (50 cm² face area). To estimate the detector readings for particular soil contaminations, several assumptions were made about these detectors. The CP is assumed to respond only to photon radiation. The GM and PAM are assumed to ignore photons and respond only to charged particles. The GM is assumed to respond to any charged particle able to enter the active volume of the detector. The PAM is assumed to respond only to alpha particles with enough energy to enter the detector. All three detectors are assumed to respond equally to all radiation energies above 10 keV. In other words, the detectors are assumed to have a flat energy response.

PHOTON READINGS WITH A CP

The field reading for the CP are based on the computed external dose rate one meter above an infinite slab of contaminated soil which is quite thick. Contaminated areas larger than 100 m² produce nearly the same dose rates as the infinite layer. Examples computed with ISO-PC Version 1.98 are provided below in Table B-1.

Table B-1. Dose Rates 1 meter Above Various Circular Areas

Area m²	Radius cm	Dose Rates (rem/h per µCi/cc) for Various Photon Energies .02 MeV	.05 MeV	0.1 MeV	0.2 MeV	0.5 MeV	1 MeV	2 MeV
0.100	17.84	3.3E-06	9.9E-05	3.5E-04	1.0E-03	3.2E-03	6.4E-03	1.3E-02
0.215	26.19	6.9E-06	2.1E-04	7.4E-04	2.2E-03	6.8E-03	1.4E-02	2.7E-02
0.464	38.44	1.4E-05	4.3E-04	1.5E-03	4.5E-03	1.4E-02	2.8E-02	5.6E-02
1.00	56.42	2.7E-05	8.4E-04	3.0E-03	8.9E-03	2.8E-02	5.6E-02	1.1E-01
2.15	82.81	4.8E-05	1.5E-03	5.5E-03	1.6E-02	5.2E-02	1.0E-01	2.1E-01
4.64	121.6	7.6E-05	2.4E-03	8.9E-03	2.7E-02	8.6E-02	1.8E-01	3.6E-01
10.0	178.4	1.1E-04	3.4E-03	1.3E-02	3.9E-02	1.3E-01	2.6E-01	5.3E-01
21.5	261.9	1.3E-04	4.3E-03	1.6E-02	5.0E-02	1.6E-01	3.4E-01	7.0E-01
46.4	384.4	1.5E-04	5.0E-03	1.9E-02	5.9E-02	1.9E-01	4.0E-01	8.3E-01
100	564.2	1.7E-04	5.6E-03	2.1E-02	6.5E-02	2.1E-01	4.4E-01	9.2E-01
215	828.1	1.7E-04	5.9E-03	2.2E-02	6.9E-02	2.3E-01	4.7E-01	9.9E-01
464	1,216	1.8E-04	6.2E-03	2.3E-02	7.2E-02	2.4E-01	4.9E-01	1.0E+00
1,000	1,784	1.8E-04	6.3E-03	2.4E-02	7.4E-02	2.4E-01	5.1E-01	1.1E+00
10,000	5,642	1.9E-04	6.5E-03	2.5E-02	7.6E-02	2.5E-01	5.2E-01	1.1E+00
Infinite		1.9E-04	6.6E-03	2.5E-02	7.7E-02	2.5E-01	5.3E-01	1.1E+00

Note: The contamination thickness is 1.5 meters in all cases.

The external dose rates from EPA (1993) are preferred for estimating dose rates above contaminated soil because a more detailed calculation was carried out. However, the units are dose equivalent rather than exposure, which the CP uses. For this reason, the ISO-PC program was used with both sets of units to develop ratios between the two sets of units for each nuclide. The dose results and R/rem ratios are shown in Table B-2 below. These R/rem ratios were multiplied by the external dose rate factors in Table A-3 and also by the soil contamination level to give the estimated exposure rate which is assumed to represent the CP reading. The projected CP readings were shown in Tables 2, 3, and 4.

Table B-2. R/rem Ratios and Detection Fractions

Nuclide	Results per pCi/g mrem/h	mR/h	R/rem Ratio	Detection, g/cm² GM P-11	PAM
H-3	5.70E-15	1.59E-14	2.79	0.00E+00	0.00E+00
Be-7	3.65E-05	5.62E-05	1.54	0.00E+00	0.00E+00
Be-10	1.75E-07	3.24E-07	1.85	7.92E-03	0.00E+00
C-14	2.75E-09	5.74E-09	2.09	2.42E-04	0.00E+00
Na-22	1.64E-03	2.33E-03	1.42	7.78E-03	0.00E+00
S-35	3.33E-09	6.91E-09	2.08	2.80E-04	0.00E+00
Cl-36	3.15E-07	5.73E-07	1.82	1.14E-02	0.00E+00
K-40	1.26E-04	1.69E-04	1.34	2.93E-02	0.00E+00
Ca-41	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Ca-45	1.54E-08	3.04E-08	1.97	1.19E-03	0.00E+00
Sc-46	1.50E-03	2.10E-03	1.40	2.76E-03	0.00E+00
V-49	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Mn-54	6.37E-04	9.10E-04	1.43	0.00E+00	0.00E+00
Fe-55	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Fe-59	9.30E-04	1.27E-03	1.37	3.26E-03	0.00E+00
Co-57	6.63E-05	1.18E-04	1.78	8.21E-05	0.00E+00
Co-58	6.61E-04	9.70E-04	1.47	1.12E-03	0.00E+00
Co-60	1.87E-03	2.56E-03	1.37	2.01E-03	0.00E+00
Ni-59	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Ni-63	3.28E-11	7.86E-11	2.40	0.00E+00	0.00E+00
Zn-65	4.49E-04	6.20E-04	1.38	5.55E-05	0.00E+00
Se-75	2.44E-04	4.10E-04	1.68	1.28E-04	0.00E+00
Se-79	1.82E-09	3.83E-09	2.10	1.42E-04	0.00E+00
Rb-87	1.71E-08	3.37E-08	1.97	1.29E-03	0.00E+00
Sr-89	2.11E-06	3.61E-06	1.71	3.85E-02	0.00E+00
Sr-90+D	5.78E-06	9.64E-06	1.67	8.05E-02	0.00E+00
Y-88	1.97E-03	2.65E-03	1.35	3.68E-05	0.00E+00
Y-91	4.77E-06	7.33E-06	1.54	4.04E-02	0.00E+00
Zr-93	2.15E-11	5.20E-11	2.42	0.00E+00	0.00E+00
Zr-95+D	5.43E-04	7.90E-04	1.45	3.12E-03	0.00E+00
Nb-93m	9.40E-09	2.50E-08	2.66	0.00E+00	0.00E+00
Nb-94	1.11E-03	1.61E-03	1.45	4.76E-03	0.00E+00
Nb-95	5.47E-04	7.96E-04	1.46	2.68E-04	0.00E+00
Mo-93	5.27E-08	1.40E-07	2.66	0.00E+00	0.00E+00
Tc-99	2.16E-08	4.22E-08	1.95	1.54E-03	0.00E+00
Ru-103+D	3.39E-04	5.22E-04	1.54	1.15E-03	0.00E+00
Ru-106+D	1.55E-04	2.35E-04	1.52	1.25E-01	0.00E+00
Pd-107	4.36E-13	1.16E-12	2.66	0.00E+00	0.00E+00
Ag-108m+D	1.14E-03	1.71E-03	1.50	4.33E-03	0.00E+00
Ag-110m+D	2.00E-03	2.85E-03	1.43	3.26E-03	0.00E+00
Cd-109	2.27E-07	5.73E-07	2.52	0.00E+00	0.00E+00
Cd-113m	1.65E-07	3.06E-07	1.85	7.15E-03	0.00E+00
Cd-115m	1.81E-05	2.62E-05	1.45	4.23E-02	0.00E+00
In-114m+D	8.83E-05	1.37E-04	1.55	5.99E-02	0.00E+00
In-115	1.02E-07	1.91E-07	1.87	5.08E-03	0.00E+00
Sn-113+D	1.73E-04	2.77E-04	1.60	6.60E-03	0.00E+00
Sn-119m	2.40E-07	5.91E-07	2.46	0.00E+00	0.00E+00

Table B-2. R/rem Ratios and Detection Fractions, Continued

Nuclide	Results per pCi/g mrem/h	mR/h	R/rem Ratio	Detection, g/cm² GM P-11	PAM
Sn-121m+D	1.39E-06	3.25E-06	2.34	7.52E-04	0.00E+00
Sn-123	7.10E-06	1.04E-05	1.46	3.35E-02	0.00E+00
Sn-126+D	1.36E-03	2.06E-03	1.51	4.61E-02	0.00E+00
Sb-124	1.41E-03	1.95E-03	1.38	2.47E-02	0.00E+00
Sb-125	2.90E-04	4.46E-04	1.54	2.18E-03	0.00E+00
Te-123m	7.96E-05	1.37E-04	1.72	7.06E-04	0.00E+00
Te-125m	1.09E-06	2.53E-06	2.32	7.93E-04	0.00E+00
Te-127m+D	4.06E-06	6.75E-06	1.66	1.00E-02	0.00E+00
Te-129m+D	4.70E-05	7.15E-05	1.52	3.66E-02	0.00E+00
I-125	1.06E-06	2.60E-06	2.45	0.00E+00	0.00E+00
I-129	1.17E-06	2.76E-06	2.36	1.52E-04	0.00E+00
Cs-134	1.07E-03	1.58E-03	1.48	6.61E-03	0.00E+00
Cs-135	5.96E-09	1.21E-08	2.03	5.12E-04	0.00E+00
Cs-137+D	4.02E-04	5.96E-04	1.48	1.04E-02	0.00E+00
Ba-133	2.22E-04	3.67E-04	1.65	3.76E-04	0.00E+00
Ce-144+D	4.43E-05	6.64E-05	1.50	1.05E-01	0.00E+00
Pm-147	1.02E-08	2.01E-08	1.97	6.88E-04	0.00E+00
Pm-148m+D	1.47E-03	2.18E-03	1.48	8.37E-03	0.00E+00
Sm-147	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Sm-151	1.57E-10	3.87E-10	2.46	4.31E-09	0.00E+00
Eu-150	1.04E-03	1.57E-03	1.51	0.00E+00	0.00E+00
Eu-152	8.55E-04	1.21E-03	1.42	5.13E-03	0.00E+00
Eu-154	9.36E-04	1.32E-03	1.41	1.20E-02	0.00E+00
Eu-155	2.76E-05	5.23E-05	1.89	3.01E-04	0.00E+00
Gd-152	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Gd-153	3.81E-05	7.32E-05	1.92	7.53E-05	0.00E+00
Tb-158	5.70E-04	8.09E-04	1.42	2.63E-03	0.00E+00
Tb-160	7.92E-04	1.13E-03	1.43	1.07E-02	0.00E+00
Ho-166m	1.08E-03	1.63E-03	1.51	2.81E-03	0.00E+00
Tm-170	2.62E-06	5.02E-06	1.92	1.67E-02	0.00E+00
Ta-182	9.41E-04	1.32E-03	1.40	4.27E-03	0.00E+00
W-181	1.29E-05	2.63E-05	2.04	0.00E+00	0.00E+00
W-185	8.28E-08	1.54E-07	1.86	3.64E-03	0.00E+00
Re-187	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Os-185	4.95E-04	7.39E-04	1.49	3.56E-04	0.00E+00
Ir-192	5.47E-04	8.76E-04	1.60	8.45E-03	0.00E+00
Pt-193	0.00E+00	0.00E+00		0.00E+00	0.00E+00
Au-195	3.45E-05	6.75E-05	1.96	1.10E-04	0.00E+00
Hg-203	1.56E-04	2.59E-04	1.66	2.28E-03	0.00E+00
Tl-204	7.16E-07	1.37E-06	1.91	1.07E-02	0.00E+00
Pb-210+D	1.22E-06	2.27E-06	1.86	2.29E-02	0.00E+00
Bi-207	1.08E-03	1.56E-03	1.44	7.97E-03	0.00E+00
Po-209	2.33E-06	3.53E-06	1.52	6.52E-06	4.63E-04
Po-210	5.80E-09	8.44E-09	1.46	0.00E+00	5.84E-04
Ra-226+D	1.31E-03	1.84E-03	1.40	5.99E-02	3.25E-03
Ra-228+D	6.73E-04	9.62E-04	1.43	2.29E-02	0.00E+00
Ac-227+D	2.51E-04	4.17E-04	1.66	6.38E-02	4.78E-03
Th-228+D	1.20E-03	1.63E-03	1.36	5.46E-02	4.71E-03

Table B-2. R/rem Ratios and Detection Fractions, Continued

Nuclide	Results per pCi/g mrem/h	mR/h	R/rem Ratio	Detection, g/cm² GM P-11	PAM
Th-229+D	2.05E-04	3.33E-04	1.62	3.94E-02	4.87E-03
Th-230	1.71E-07	3.21E-07	1.88	0.00E+00	4.06E-04
Th-232	6.78E-08	1.30E-07	1.92	1.57E-06	2.31E-04
Pa-231	1.88E-05	3.14E-05	1.67	2.07E-04	5.23E-04
U-232	1.06E-07	1.97E-07	1.86	2.81E-06	5.84E-04
U-233	1.22E-07	2.19E-07	1.80	2.91E-07	4.46E-04
U-234	4.16E-08	8.04E-08	1.93	1.69E-06	4.31E-04
U-235+D	1.04E-04	1.79E-04	1.72	1.49E-03	3.29E-04
U-236	2.98E-08	6.06E-08	2.03	1.30E-06	3.54E-04
U-238+D	1.88E-05	2.99E-05	1.59	6.51E-02	2.78E-04
Np-236	7.27E-05	1.30E-04	1.79	2.26E-03	0.00E+00
Np-237+D	1.43E-04	2.42E-04	1.69	4.46E-03	4.32E-04
Pu-236	1.65E-08	3.52E-08	2.13	0.00E+00	7.19E-04
Pu-237	2.57E-05	4.73E-05	1.84	4.61E-07	0.00E+00
Pu-238	1.39E-08	3.13E-08	2.25	0.00E+00	6.36E-04
Pu-239	3.61E-08	6.31E-08	1.75	0.00E+00	5.39E-04
Pu-240	8.93E-09	1.88E-08	2.11	0.00E+00	5.42E-04
Pu-241+D	2.57E-09	4.63E-09	1.80	5.57E-08	0.00E+00
Pu-242	1.19E-08	2.67E-08	2.24	0.00E+00	4.69E-04
Pu-244+D	2.42E-04	3.57E-04	1.48	4.62E-02	3.81E-04
Am-241	6.52E-06	1.34E-05	2.06	1.27E-06	6.33E-04
Am-242m+D	9.38E-06	1.64E-05	1.75	6.41E-03	2.66E-06
Am-243+D	1.23E-04	2.20E-04	1.79	5.41E-03	5.74E-04
Cm-242	1.06E-08	2.42E-08	2.28	0.00E+00	8.29E-04
Cm-243	7.67E-05	1.33E-04	1.73	2.20E-03	7.39E-04
Cm-244	8.36E-09	1.94E-08	2.32	0.00E+00	7.31E-04
Cm-245	3.86E-05	6.96E-05	1.80	7.67E-04	6.00E-04
Cm-246	4.74E-09	1.20E-08	2.53	0.00E+00	6.04E-04
Cm-247+D	2.17E-04	3.52E-04	1.62	6.15E-03	4.83E-04
Cm-248	7.01E-09	1.60E-08	2.28	0.00E+00	4.75E-04
Cf-250	1.37E-08	2.85E-08	2.08	1.31E-07	8.02E-04
Cf-252	9.18E-09	2.00E-08	2.18	1.88E-07	8.07E-04
Es-254+D	6.50E-04	9.14E-04	1.41	1.45E-02	9.31E-04
Zr-95 old	1.75E-03	2.55E-03	1.46	3.71E-03	0.00E+00
Sb-125 old	2.90E-04	4.47E-04	1.54	2.37E-03	0.00E+00
Pb-210 old	1.23E-06	2.28E-06	1.86	2.29E-02	5.94E-04
Ra-226 old	1.31E-03	1.84E-03	1.41	8.31E-02	3.84E-03
Th-Nat	1.87E-03	2.59E-03	1.38	7.75E-02	4.94E-03
U-Nat	1.33E-03	1.87E-03	1.41	1.48E-01	4.95E-03
Pu 6%	4.74E-07	9.62E-07	2.03	4.84E-07	5.52E-04
Pu 6% 10yr	9.68E-07	1.98E-06	2.05	4.10E-07	5.58E-04

MONO-ENERGETIC CHARGED PARTICLE READINGS

Examples of mono-energetic charged particles are alphas, internal conversion electrons, and Auger electrons. They travel a given distance in matter (on the average) and then stop. The distance they travel depends on their initial kinetic energy.

The model for estimating instrument response begins with the radiation source uniformly distributed in soil, or some other reasonably dense, low atomic number material such as water. In order for a charged particle to be detected, it must have enough energy to pass through the soil, the air between the soil and the detector, and finally the window of the detector. The window thickness on the PAM is 0.5 mg/cm², while the window of the GM pancake probe is about 3 mg/cm². The density of air is such that each centimeter of thickness provides about 1.2 mg/cm² of shielding material.

The total shielding between the PAM and the soil is assumed to be about 2 mg/cm², based on an air thickness of about 1.7 cm. The shielding between the GM and the soil is assumed to be about 8 mg/cm² based on an air thickness of about 6.7 cm.

The total thickness that a charged particle can travel in low atomic number material was estimated from graphs found in the Radiological Health Handbook (HEW 1970) pages 123 and 125. One starts with a particular energy particle, such as the 5.15 MeV alpha particle emitted by Pu-239. From the graph, the alpha can penetrate 3.65 cm in air at STP, which corresponds to 4.7 mg/cm². Subtracting 2 mg/cm² for the air thickness and detector window means that alphas from a depth of 2.7 mg/cm² could reach the detector and be counted.

This needs to be adjusted for the detection geometry. The alphas are sent out from the source into all directions, but only certain directions will reach the detector. Due to the proximity of the soil and detector, it is assumed that 20 percent of the alphas could be detected. The geometry factor is therefore 0.20.

Detection Factor = (Soil Depth, mg/cm²)(Geometry Factor)

The detection factor in this case is 5.39E-4 g/cm², which matches the value shown on Table B-2. Knowing the probe face area and the soil contamination, one can now estimate the number of particles reaching the detector. (It is assumed that every charged particle entering the active volume of the detector will be counted.)

This detection factor is put to use by multiplying it by the effective face area of the detector and the soil concentration. The result is the number of detected particles per unit time. For example, the PAM probe area is 50 cm² and the 100 mrem/y soil limit for Pu-239 is 19.1 pCi/g, so the estimated alpha detection rate is shown below (and also on Table 3).

Detection Rate = (5.39E-4 g/cm²)(50 cm²)(19.1 pCi/g) = 0.51 per minute

Since the instrument operator needs to hear a rate of at least 100 per minute to notice the contamination, this particular Pu-239 soil limit will probably go undetected with the PAM. However, the granular nature of soil may allow detection if the plutonium particles are on the upper surfaces of the grains. Conversely, even higher levels could escape detection if the soil grains were covering the plutonium. Detecting alpha contamination in soil depends greatly on the condition of the soil.

The method for mono-energetic particles was automated with a computer program named DETECT which interpolates between values read from the graphs in the Handbook. The computer program uses the DRALIST nuclear data library (Kocher 1981) for the energies of the charged particles. The DETECT program is described in Appendix C.

BETA AND POSITRON READINGS

Beta decay and positron emission produce charged particles with energies ranging from zero up to a characteristic maximum, the endpoint energy for the decay. The same approach used for mono-energetic charged particles was extended to this case. The difference is that the detection factors for the various particle energies must be weighted by their probability and summed to calculate the overall detection factor.

Electrons and positrons emitted from a nucleus undergoing beta decay are produced with initial kinetic energies that range from zero to the endpoint energy, E_o. The probability of finding one of these particles with a total energy between W and (W+dW) is given by the equation below.

$$\mathrm{Prob}(W)\, dW = K\, \mathrm{Fermi}(\pm Z,W)\, p\, W\, (W_0-W)^2\, dW\, S_X$$

The Fermi function for electrons (+Z) and positrons (-Z) is calculated from tabulated values as shown in the next equation.

$$\mathrm{Fermi}(\pm Z,W) = K\, F_{NBS} / p^2$$

The values of F_{NBS} are listed in the National Bureau of Standards (NBS 1952) Mathematical Handbook. They were calculated from the formula shown below. The DETECT program described in Appendix C uses a data file which has the NBS values divided by the electron momentum. This combination is nearly linear with momentum, which ensures good accuracy when doing a simple linear interpolation between data points. The values for F_{NBS} for positrons are simply the electron values times $\mathrm{EXP}(-2\pi v)$.

$$F_{NBS} = p^{2g}\, \mathrm{Exp}(\pi v)\, \left| \Gamma(g+iv) \right|^2$$

The Shape factor (S_X) depends on the degree of "forbiddenness" of the particular decay mode. Shape factors for the first four degrees are shown below (Siegbahn 1968).

$$S_0 = 1$$

$$S_1 = p^2 + (W_0-W)^2$$

$$S_2 = p^4 + (W_0-W)^4 + 10/3\, p^2 (W_0-W)^2$$

$$S_3 = p^6 + (W_0-W)^6 + 7\, p^2\, (W_0-W)^2\, [p^2 + (W_0-W)^2]$$

The "g" and "v" variables used above are defined in the equation below.

$$g = \sqrt{1 - (\alpha Z)^2} \qquad v = \frac{\alpha Z W}{p}$$

The variables used in the above equations, as well as later ones are defined below.

E = beta particle kinetic energy, in MeV
W = total rest-mass energy, in units of mc^2, $W = 1 + E/(mc^2)$
p = beta particle momentum, $p^2 = W^2 + 1$
α = fine structure constant = 1/137.036
Z = atomic number of the daughter nucleus
K = a normalization factor which ensures the total probability is 1

The energy spectra defined above can be used to compute the momentum spectra using the relation shown in equation 6. Momentum spectra were frequently used to report beta spectra data measured in magnetic spectrometers since the product of the magnetic field strength and the radius of curvature is proportional to the particle momentum.

$$\text{Prob}(p)\, dp = \text{Prob}(E)\, dE\, (mc^2 p/W)$$

The DETECT program reads table values for the Fermi function at electron momenta ranging from 0.01 to 20 in 420 steps of varying length. The units of electron momentum are mc, where m is the mass of the electron and c is the speed of light. The values for the Fermi function were computed by numerical integration of the complex gamma function and stored in a binary file. This was done as a check on the NBS values and to avoid transposition errors when copying numbers.

The surface soil is divided into thin layers and the minimum energy electron which can travel from each layer to the detector is computed. The beta probability function, Prob(W), is used to determine the fraction of the electrons from each layer which would be counted. This fraction is the integral of the beta probability function from the minimum energy to the maximum energy. These fractions were weighted by the thickness of the soil layer and summed to give the total detection fraction.

Results for the detection factor for each nuclide were shown in Table B-2. These were computed by the DETECT program described in Appendix C.

Appendix C. The DETECT Program Version 2.0

USER'S GUIDE TO DETECT

The purpose of the program is to estimate detection factors for one or more lists of nuclides. A list of nuclides is a text file with individual nuclides or groups of nuclides which act together. The DETECT program reads through the nuclide list file and computes the detection factor for each nuclide and group of nuclides in the file. Scale factors may be applied to individual nuclides or groups of nuclides. Other inputs are the geometry factor, the initial air plus detector shielding thickness, and the thickness of the source. There is an option to calculate only alpha particle detection and omit electrons.

The files listed in Table C-1 are distributed as the DETECT software. The first six DRALIST files are the binary version of DRALIST (Kocher 1981) used by the DETECT program. These were created by the MAKE-DRA program. The SHOW-DRA program allows one to selectively display data in the DRALIST binary files to verify that it is correctly stored and read.

Table C-1. Files Distributed as the DETECT Software

FERMI.BIN	- Binary file with Fermi function values.
DRALIST.N	- DRALIST general data for each nuclide.
DRALIST.A	- DRALIST alpha emissions for each nuclide.
DRALIST.B	- DRALIST beta emissions for each nuclide.
DRALIST.P	- DRALIST positron emissions for each nuclide.
DRALIST.E	- DRALIST electron emissions for each nuclide.
DRALIST.G	- DRALIST gamma photon emissions for each nuclide.
DRALIST.SUM	- Data summary generated by MAKE-DRA.PAS.
MAKE-DRA.PAS	- Pascal source code to read the DRALIST.DAT file and create the DRALIST.? binary files.
SHOW-DRA.EXE	- Program to display nuclide data in the binary files.
SHOW-DRA.PAS	- Pascal source code for SHOW-DRA.EXE.
DETECT.EXE	- The executable for the DETECT program.
DETECT.PAS	- Pascal source code for DETECT.EXE.
DRALIST.PAS	- Pascal unit to read the DRALIST files.
GENERAL.PAS	- Pascal unit with general subroutines.
NUCLIST.PAS	- Pascal unit to read nuclide files.
SRCFRAC.PAS	- Pascal unit to generate beta spectrum and integrals.
TEST-DET.BAT	- Batch file to run the test cases and compare with valid output.
TEST.NUC	- Nuclide file for the test cases.
TEST.N3	- Test case output - 3 mg/cm² shielding and the default geometry factor of 0.5.
TEST.N5	- Test case output - default (5 mg/cm²) shielding and geometry factor (0.5).
TEST.N9	- Test case output - 9 mg/cm² shielding and the default geometry factor (0.5).
TEST.N8	- Test case output - 9 mg/cm² shielding and geometry factor of 0.25.
TEST.NA	- Test case output for alpha only, 3 mg/cm² shielding with the default geometry factor (0.5).

The test cases are run using the TEST-DET.BAT file. This creates five output files named TEST.E3, TEST.E5, TEST.E9, TEST.E8, and TEST.EA for comparison with the verified test case output files shown above.

The DETECT program is started using the command DETECT, at the DOS prompt. With no command line parameters, the program displays a summary of what it does and how it is run. This summary is shown in Table C-2 below.

Table C-2. Help Screen for DETECT

```
          DETECT Version 2.0  by Paul Rittmann PhD CHP

Purpose:  Estimate beta detection efficiency for one or more
          lists of nuclides.
Usage:    DETECT [/A/S--/T--/G--]  NucFile1  NucFile2  etc
          /A forces alpha detection only.  /S, /T, /G followed by
          a number are the Source thickness, the Thickness between
          source & detector, and the Geometry correction factor.
          Default values are 2000 mg/cm², 5.00 mg/cm², and 0.500.
          Nuclide files should have one nuclide per line.
          Unit input amounts will be used unless a number
          appears to the right of the nuclide.
          Groups of nuclides must be separated by a blank line.
          Comments begin with ":" and scale factors begin with "XX".
          The detection efficiencies are placed in files that end
          with the extension .EFF
Example:  If the nuclide files are named WAR.2 and PEACE.NUC, the source
          is 100 mg/cm² thick with 8 mg/cm² between source & detector
             DETECT  WAR.2  PEACE  /S100/T8
          The output files will be named WAR.EFF and PEACE.EFF
```

The command line controls the input to DETECT. There may be more than one file name on the command line. Typing the .NUC extension is optional. The program first looks for the filename you have entered. If it is found, it is used, otherwise the .NUC extension is added and a second attempt is made to find the nuclide file. If this is not successful, the program terminates with a message that the file in question could not be located.

Changes to the default soil thickness or geometry factor are indicated with the "/" character. One of the valid command options (A, S, T, or G) must immediately follow this character. The S, T and G options require a number. The A option must not have a number.

The TEST.NUC file shows the variety of input formats which are acceptable to the program. This input file is shown in Table C-3 below for reference. Line numbers have been added to facilitate a discussion of its contents.

Line 1 shows a comment. Lines beginning with non-alphabetic characters are assumed to be comments and are skipped.

Line 2 shows that leading spaces are ignored. Trailing spaces are also ignored, as are spaces between the element and the isotopic mass, as in Line 6.

The nuclide name can be in upper or lower case, the program makes the necessary conversions. In addition, the hyphen is optional.

Line 14 shows the addition of an adjustment factor using a line beginning with "XX". All input values after this are multiplied by the number which appears on the scale factor line. Line 22 shows another use of the scale factor line. This one has no value to the right. Therefore, the value 1.0 is assumed. The Ra-226 group are all adjusted by the factor 0.00432. However, Line 22 causes the Co-60 and other nuclides to be interpreted as having no adjustment (scale factor is 1.0). Line 36 changes the scale factor to 2.0, but the nuclides to which it would apply are fictitious. Line 43 returns the scale factor to 1.0 for doing K-40.

Table C-3. Contents of TEST.NUC with Line Numbers Added

```
 1>:  a test case for DETECT
 2>  C  14
 3>
 4>NA-22
 5>
 6>n  16
 7>
 8>ZN69
 9>
10>Po-212
11>
12>th230
13>
14>xx  .00432
15>ra226
16>rn222
17>po218
18>pb214
19>bi214
20>Po214
21>
22>xx
23>co 60
24>
25>tc 99
26>
27> cl 36
28>
29>sr 90
30>Qe-99
31>y  90
32>
33>cs137
34>ba137m    0.946
35>
36>xx  2
37>  Jc 78
38>
39>
40>Px95
41>Sx69
42>
43>XX
44>K-40
```

Line 34 shows how to include equilibrium factors for nuclides which are in secular equilibrium. Any number to the right of the nuclide name is interpreted as a second scale factor which only applies to that nuclide.

All output from DETECT is set to a file with the extension .EFF. The first part of the file name is the same as the nuclide list file. For example, output from TEST.NUC will be written to TEST.EFF. Since new output overwrites any existing output, the output file may need be copied to a file with a distinctive name to preserve it. This is the approach taken in the TEST-DET.BAT file to use the TEST.NUC file with various other inputs.

The output from DETECT is organized in two parts. The first part shows the adjusted amount for each nuclide, the detection factor and the type of particles contributing to that result. The notation is a=alpha, b=beta, p=positron, and e=electron. The second part shows the combined results for each nuclide or group of nuclides in the nuclide list. Groups of nuclides are indicated with a "+" sign between the name of the first nuclide in the group and the resulting detection efficiency. The sample file named TEST.N5 is shown below to illustrate this.

Table C-4. Output from TEST.NUC Using the Program Defaults

Output from DETECT Version 2.0 by Paul Rittmann PhD CHP

Source Nuclide Groups and Detected Fractions:

Geometry Factor: 0.500
Initial Thickness: 5.00 mg/cm²
Source Thickness: 2000 mg/cm²
Minimum Alpha, Beta keV: 5361, 57.0 source to detector
Minimum Alpha, Beta keV: 1110499, 3949 from back of source

Nuclides	Input Amount	Fraction gram/cm²	Particle Types
C-14	1.000E+00	1.06E-03	b
Na-22	1.000E+00	2.07E-02	p
N-16	1.000E+00	5.59E-01	b
Zn-69	1.000E+00	4.36E-02	b
Po-212	1.000E+00	2.95E-03	a
Th-230	1.000E+00	3.58E-05	e
Ra-226	4.320E-03	1.08E-06	e
Rn-222	4.320E-03	3.96E-07	a
Po-218	4.320E-03	2.11E-06	a
Pb-214	4.320E-03	1.37E-04	be
Bi-214	4.320E-03	5.20E-04	be
Po-214	4.320E-03	8.45E-06	a
Co-60	1.000E+00	5.92E-03	b
Tc-99	1.000E+00	4.67E-03	b
Cl-36	1.000E+00	2.97E-02	b
Sr-90	1.000E+00	1.72E-02	b
Qe-99	1.000E+00	Not Found!!	
Y-90	1.000E+00	1.87E-01	b
Cs-137	1.000E+00	1.72E-02	b
Ba-137m	9.460E-01	1.00E-02	e
Jc-78	2.000E+00	Not Found!!	

Px-95	2.000E+00	Not Found!!	
Sx-69	2.000E+00	Not Found!!	
K-40	1.000E+00	7.45E-02	b

Estimated Detected Fractions, gram per cm²:

Geometry Factor: 0.500
Initial Thickness: 5.00 mg/cm²
Source Thickness: 2000 mg/cm²
Minimum Alpha, Beta keV: 5361, 57.0 source to detector
Minimum Alpha, Beta keV: 1110499, 3949 from back of source

Nuclide(s)		Fraction gram/cm²
C-14		1.06E-03
Na-22		2.07E-02
N-16		5.59E-01
Zn-69		4.36E-02
Po-212		2.95E-03
Th-230		3.58E-05
Ra-226	+	6.69E-04
Co-60		5.92E-03
Tc-99		4.67E-03
Cl-36		2.97E-02
Sr-90	+	2.04E-01
Cs-137	+	2.72E-02
Jc-78		0.00E+00*
Px-95	+	0.00E+00*
K-40		7.45E-02

*Nuclide not in DRALIST.

To compute the particle detection rate, multiply the table values by the probe area (in cm²) and the source concentration in units of activity per gram.

MODELLING DETAILS

The DETECT program finds the range of a given energy particle (or the energy given the range) by interpolation on the values shown in Table C-5. The values were read from graphs in the Radiological Health Handbook (HEW 1970). Linear interpolation is used for alpha particles. The beta interpolation uses log scales for both energy and range. The minimum allowed initial thickness was chosen to be 1 mg/cm².

Table C-5. Range in Air for Various Alpha and Electron Energies

Alpha Particles

Range cm air	Range mg/cm²	Energy keV
0.50	0.647	1000
0.74	0.957	1500
1.00	1.293	2000
1.29	1.668	2500
1.63	2.108	3000
2.01	2.599	3500
2.44	3.155	4000
2.93	3.788	4500
3.47	4.487	5000
4.02	5.198	5500
4.62	5.974	6000
5.26	6.801	6500
5.95	7.693	7000
6.63	8.573	7500
7.33	9.478	8000

Beta Particles

Range mg/cm²	Energy keV
1	24.5
1.5	30.5
2	35.5
2.5	40
3	44
4	51
5	57
6	63
8	73
10	83
15	104
20	124
25	143
30	161
40	194
50	225
60	255
80	310
100	363
150	485
200	595
250	700
300	800
400	1000
500	1190
600	1370
800	1740
1000	2100
1500	3000
2000	3940
2500	4880
3000	5840
4000	7700
5000	9500
6000	11200

Numeric integration of the beta spectrum is carried out using Simpson's Rule. When the spectrum is computed from the endpoint energy, the nuclear transition is assumed to have a forbiddenness of 0, which tends to underestimate the detection factor. (Larger values for forbiddenness lead to larger detection factors.) The spectrum is computed at 500 equally spaced points. This large number is selected for two reasons. First, it ensures adequate accuracy near the endpoint energy where the probability function decreases rapidly with energy. Second, it allows a simplification during the numeric integration with soil depth to find the detection factor. At a given soil depth there is a minimum electron energy which is able to reach the detector. The beta integration begins at this energy and ends at the endpoint energy of the beta. To simplify the integration, it is assumed to begin at the next larger energy in this particle's probability function. Having a large number of points means that the small amount of area that is ignored will have no effect on the final answer.

The integration over soil depth is accomplished using the trapezoid rule on layers that increase exponentially in thickness. The first soil thickness is zero so that the beta particle range is the initial shield thickness. The second thickness is the first thickness multiplied by the factor shown below.

$$\text{Thickness Factor} = \left(\frac{6000 \text{ mg/cm}^2}{\text{Initial Shielding}} \right)^{0.005}$$

The thickness factor is computed so that after 200 applications of the factor, the range will be the maximum allowable range, 6000 mg/cm². Since the maximum beta energy in the DRALIST library is 10.419 MeV (N-16), no beta will ever exceed a range of 6000 mg/cm².

Since each successive thickness is this factor times the preceding thickness, integration by the trapezoid rule uses the equation shown below.

$$\text{Integral} = \sum_{K=1}^{N-1} (P_K + P_{K+1})(X_{K+1} - X_K)/2$$

$$= P_1 X_1 (f-1)/2 + P_N X_N (1-1/f)/2 + \sum_{K=2}^{N-1} P_K X_K (f-1/f)$$

where,
- N = Number of points to reach zero penetration.
- P = Probability function for the beta emission.
- X = Thickness of shielding between this layer and the detector.
- f = Thickness factor defined above.

PROGRAM LISTING - DETECT.PAS

```
Program Detection_Efficiency;

{ Author:  Paul D. Rittmann, PhD CHP
  Purpose: Computes the detected fraction of the alphas & betas emitted by
           uniformly distributed nuclides in some material.
           Beta spectra are computed using the method of WHC-SA-1435-FP,
           "BREMCALC -- A Computer Program for Calculating Electron and
           Positron Bremsstrahlung" by P. D. Rittmann, January, 1992.
           Bremsstrahlung is not computed.
           Version 2 adds the source thickness.
  Input:   Values of the linear Fermi Function used in BREMRAD and
              BREMCALC.  These are stored in the FERMI.BIN file.
           Values for electron and positron endpoint energies from DRALIST.BET,
              a binary file prepared from DRALIST.DAT.
           Names of nuclides and relative amounts in files supplied by the
              user on the command line.
           User may also change the default values for Geometry, Thick0, Rmax
              with the command line inputs /G--- and /T--- and /S---.
  Output:  One files of input parameters and output detection efficiencies for
           each nuclide list file supplied by the user.
}

Uses Crt, General, DRALIST, SrcFrac, NucList;

Const
  Chlp = 10;          { position of text on initial help screen }
  HlpN = 18;          { number of lines of text on the help screen }
  OutExtn = '.EFF';   { output file name extension }
  ProgID = 'DETECT Version 2.0  by Paul Rittmann PhD CHP';
  HlpSt : Array[1..HlpN] of ST79 = (
   'Estimate beta detection efficiency for one or more',
   'lists of nuclides.',
   'DETECT [/A/S--/T--/G--]  NucFile1  NucFile2  etc',
   '/A forces alpha detection only.  /S, /T, /G followed by',
   'a number are the Source thickness, the Thickness between',
   'source & detector, and the Geometry correction factor.',
   'Default values are',
   'Nuclide files should have one nuclide per line.',
   'Unit input amounts will be used unless a number',
   'appears to the right of the nuclide.',
   'Groups of nuclides must be separated by a blank line.',
   'Comments begin with ":" and scale factors begin with "XX".',
   'The detection efficiencies are placed in files that end',
   'with the extension '+OutExtn,
   'If the nuclide files are named WAR.2 and PEACE'+NucExtn+', the source',
   'is 100 mg/cm² thick with 8 mg/cm² between source & detector',
   '   DETECT  WAR.2  PEACE  /S100/T8',
   'The output files will be named WAR'+OutExtn+' and PEACE'+OutExtn);
Var
  NumNf,Nf   : Integer; { number of nuclide files }
  FileName   : Array[1..9] of ST45;   { input nuclide file names }
  AlphaOnly  : Boolean; { if true then ignore all other particles }


Procedure Print_Help;
{ Summary of how to use DETECT.EXE }
Var  I : Byte;
Begin
  TextAttr:= White;   ClrScr;
  Msg(Chlp,2,ProgID);
  OneLine:= Num3D(Rmax)+SrcUnit+Comma+Num3D(Thick0)+SrcUnit+', and'+Num3D(Geometry)+Period;
  For I:= 1 to HlpN Do Begin
    If (I=3) or (I=17) Then TextAttr:= Yellow
                       Else TextAttr:= LightCyan;
    Msg(Chlp,I+3,HlpSt[I]);
    If I = 7 Then Write(OneLine);
    End;
  TextAttr:= LightGreen;
  Msg(1, 4,'Purpose:');
  Msg(1, 6,'Usage:');
  Msg(1,18,'Example:');
  GotoXY(1,HlpN+3);  Halt;
End;
```

```
Procedure Check_Command_Line;
{ Reads the file names on the command line and looks for them.
  Also interprets changes in the initial thickness or geometry factor. }
Var  CH  : Char;
  I,K,J,        { string indices and file counter }
  Lng,N  : Byte;  { string length and command line parameter index }
  PST    : ST79;  { original command line input string }
  fi     : Text;
Procedure Quit_Msg(Msg:ST79);
{ Uses STo for the final message and halts execution.
  Displays the command line parameter which caused the error. }
Begin
  TextAttr:= LightMagenta;
  Writeln('  *** ',Msg,'  ',PST);
  Writeln('  Type DETECT for guidance on how to use this program.');
  Halt;
End;
Begin
  NumNf:= ParamCount;
  If NumNf = 0 Then Print_Help;
  J:= 0;    AlphaOnly:= false;     TextAttr:= Yellow;
  For N:= 1 to NumNf Do Begin
    PST:= ParamStr(N);        Lng:= Length(PST);
    CH:= PST[Lng];
    If (CH = '/') or (CH = '.') Then Dec(Lng);
    If Lng = 0 Then Quit_Msg('Invalid command line input:');
    For K:= 1 to Lng Do OneLine[K]:= UpCase(PST[K]);   OneLine[0]:= Chr(Lng);
    If (PST[1] = '/') and (Lng > 1) Then Begin { read one or more flags }
      K:= 1;
      Repeat  { loop starts with K positioned at the first / in ST }
        Inc(K);     CH:= OneLine[K];
        If CH = 'A' Then  AlphaOnly:= true    Else
        If (CH='T') or (CH='S') or (CH='G') Then Begin
          Inc(K);
          If K > Lng Then Quit_Msg('No number supplied in option string:');
          I:= K;
          While (OneLine[K] <> '/') and (K < Lng) Do Inc(K);
          If OneLine[K] = '/' Then Dec(K);
          If Valid_Number(I,K,Factor)
            Then If CH = 'G' Then Geometry:= Factor    Else
                 If CH = 'S' Then Rmax:= Factor
                              Else Thick0:= Factor
            Else Quit_Msg('Invalid number supplied in option string:');
          End
        Else Quit_Msg('Invalid program option:');
        Inc(K);
      Until K > Lng;
      If Thick0 < 1 Then Begin   PST:= '';
        Quit_Msg('Initial shielding must be greater than 1 mg/cm² !!');
        End;
      End
    Else Begin             { nuclide file name }
      Assign(fi,OneLine); {$I-} Reset(fi); {$I+}
      If IOResult > 0
        Then Begin
          OneLine:= OneLine + NucExtn;
          Assign(fi,OneLine); {$I-} Reset(fi); {$I+}
          If IOResult > 0
            Then Quit_Msg('Nuclide file could not be found:')
            Else Close(fi);
          End
        Else Close(fi);
      Inc(J);    FileName[J]:= OneLine;
      End;
    End;
  If J > 0 Then NumNf:= J
    Else Begin   PST:= '';
      Quit_Msg('No nuclide files were provided!!');
      End;
End;


Procedure Main_Calculations;
Var  f,fo    : Text;
  I, J, K    : Integer;
  WrkX,
  TotalDetect,
  NucDetect : Double;
  CH         : Char;
  BumNuc     : Boolean;
```

```
  PartFlg   : ST8;
  WrkSt     : ST79;
  Msg1,Msg2,Msg3,Msg4,Msg5,
  OutFile   : ST45;
Procedure Std_QA(Var Fqa:Text);
Begin
  Writeln(Fqa);          Writeln(Fqa,WrkSt);     Writeln(Fqa);
  Writeln(Fqa,Msg1);     Writeln(Fqa,Msg2);      Writeln(Fqa,Msg3);
  Writeln(Fqa,Msg4,' source to detector');
  If Rmax < RangB[REpt] Then Writeln(Fqa,Msg5,' from back of source');
  Writeln(fqa);
End;
Procedure Check_Particle(P:Byte);
{ Checks the running total (NucDetect) for increases.  An increase
  means that particles of that type were able to produce a reading
  and should be identified in the output. }
Begin
  If WrkX < NucDetect Then PartFlg:= PartFlg + PartAbb[P];
  WrkX:= NucDetect;
End;
Begin     Factor:= 1.0;       BumNuc:= false;
  Msg1:= 'Geometry Factor: '+Num3D(Geometry);
  Msg2:= 'Initial Thickness: '+Num3D(Thick0) + SrcUnit;
  Msg3:= 'Source Thickness: '+Num3D(Rmax) + SrcUnit;
  Msg4:= 'Minimum Alpha, Beta keV: '+Num3D(Ealpha0)+', '+Num3D(Ebeta[0]);
  Msg5:= 'Minimum Alpha, Beta keV: '+Num3D(EalphaR)+', '+Num3D(Ebeta[SrcNo]);
 { open the nuclide file }
  TextAttr:= LightCyan;        Writeln;
  Write('Reading nuclide file ',Filename[Nf]);
  Assign(fn,FileName[Nf]);    Reset(fn);       LineCount:= 0;
 { create temporary file for computed results }
  Assign(f,'DETECT.TMP');     Rewrite(f);
  Writeln(f);
  WrkSt:= 'Estimated Detected Fractions, gram per cm²:';
  Std_QA(f);
  Writeln(f,'                Fraction');
  Writeln(f,'Nuclide(s)   gram/cm²');
  Writeln(f,'──────────────────────');
 { begin the output file }
  OutFile:= FileName[Nf];     K:= Pos('.',OutFile);
  If K > 0 Then OutFile:= Copy(OutFile,1,Pred(K)) + OutExtn
          Else OutFile:= OutFile + '.' + OutExtn;
  Writeln('    Output goes to ',OutFile);
  Assign(fo,OutFile);         Rewrite(fo);
  Writeln(fo,'Output from ',ProgID);
  WrkSt:= 'Source Nuclide Groups and Detected Fractions:';
  Std_QA(fo);                                    LineSt[0]:= #54;
  Writeln(fo,'                Input       Fraction  Particle');
  Writeln(fo,'Nuclides        Amount      gram/cm²   Types');
  Writeln(fo,LineSt);
  Repeat
  While Nuclide_Block Do Begin
    TotalDetect:= 0.0;
    For K:= 1 to NucN Do Begin
      NucDetect:= 0.0;    WrkX:= NucDetect;        PartFlg:= '    ';
      WrkSt:= Nuclide[K]+'    '+Sci3D(AmtVal[K]);  { Write(WrkSt);  }
     { find the nuclide data }
      DraNuc[0].Name:= Nuclide[K];      Nuc:= NucD;
      While DraNuc[Nuc].Name <> Nuclide[K] Do Dec(Nuc);
      If Nuc = 0 Then Begin             CH:= '*';
        BumNuc:= true;
        Writeln(fo,Wrkst,'  Not Found!!');  { Writeln('  Not Found!!'); }
        End
      Else With DraNuc[Nuc] Do Begin   CH:= Space;
        If Aaa > 0 Then Begin  { use alpha particles }
          Positron:= true;
          For J:= Aaa to Azz Do
            NucDetect:= NucDetect + Afrac^[J]*Range_MonoE(Aengy^[J]);
          Check_Particle(1);
          End;
        If not AlphaOnly Then Begin
        Forbid:= 0; { assume allowed beta transitions }
        If Baa > 0 Then Begin  { use beta particles }
          Positron:= false;
          For J:= Baa to Bzz Do Begin
            Emax:= Bengy^[J];        Beta_Spectrum(Zno);
            NucDetect:= NucDetect + Bfrac^[J]*Combine_Beta_Layers;;
            End;
          Check_Particle(2);
          End;
```

```
          If Paa > 0 Then Begin  { use positrons }
            Positron:= true;
            For J:= Paa to Pzz Do Begin
              Emax:= Pengy^[J];
              Beta_Spectrum(Zno);
              NucDetect:= NucDetect + Pfrac^[J]*Combine_Beta_Layers;;
              End;
            Check_Particle(3);
            End;
          If Eaa > 0 Then Begin  { use Auger & IC electrons }
            Positron:= false;
            For J:= Eaa to Ezz Do
              NucDetect:= NucDetect + Efrac^[J]*Range_MonoE(Eengy^[J]);
            Check_Particle(4);
            End;
          End;
          NucDetect:= NucDetect*AmtVal[K]*Geometry;
          Msg1:= '     '+Sci2D(NucDetect);
          Writeln(fo,WrkSt,Msg1,PartFlg);
          End;
        TotalDetect:= TotalDetect + NucDetect;
        End; { of loop over nuclides in a group }
      If NucN > 1 Then WrkSt:= '+    '   Else WrkSt:= '     ';
      Writeln(f,Nuclide[1],WrkSt,Sci2D(TotalDetect),CH);
      End;
    Until Eof(fn);
    Writeln(fo,LineSt);                                        Close(fn);
    Writeln(f,'-------------------');
    If BumNuc Then Writeln(f,'*Nuclide not in DRALIST.');      Reset(f);
    While not Eof(f) Do Begin   { append the temporary file to the output }
      Readln(f,OneLine);  Writeln(fo,OneLine);  End;
    Writeln(fo);
    Writeln(fo,'To compute the particle detection rate, multiply the');
    Writeln(fo,'table values by the probe area (in cm²) and the source');
    Writeln(fo,'concentration in units of activity per gram.');
    Close(fo);    Close(f);     Erase(f);
  End;


  Begin
    Check_Command_Line;
    Init_Fermi;
    If AlphaOnly Then Get_Dralist(1,0,0,0,0)
                 Else Get_DRALIST(1,1,1,1,0);
    For Nf:= 1 to NumNf Do Main_Calculations;   { loop through nuclide files }
    Close(FF);
  End.
```

PROGRAM LISTING - GENERAL.PAS

```
Unit General;

{ Author:  Paul D. Rittmann, PhD CHP
  Purpose: General stuff for many calculations.
}

{=========================================================================}
                              Interface
{=========================================================================}

Uses Crt;

Const
  Space = ' ';   Blank8 = '        ';
  Colon = ':';   Comma = ',';   Period = '.';   Dash = '-';
  TopReal = 1.0E+37; { single precision }      Avogadro = 6.022137E+23;
  secMin = 60.0;           minHr = 60.0;            hrDay = 24.0;
  secHr = 3600.0;          minDay = minHr*hrDay;    dayYr = 365.0;
  secDay = secHr*hrDay;    minYr = minDay*dayYr;    hrYr = hrDay*dayYr;
  secYr = secDay*dayYr;    BqCi = 3.7E+10;          Svrem = 0.01;
  kilo = 1000.0;           Mega = 1.0E+6;
  Decimal : Array[0..15] of Char = '0123456789ABCDEF';

Type
  ST79 = String[79];
  ST45 = String[45];
  ST25 = String[25];
  ST15 = String[15];
  ST10 = String[10];
  ST8  = String[8];

Var
  LineSt : ST79;

Procedure  Beep;      { produces a randomly chosen tone to indicate errors }

Procedure Msg(X,Y:Integer; STR : ST79);{ displays STR at X,Y on the screen }

Function Num2S(X:Single) : ST10;
{ Returns a string with 1E-6 < X < 1E9 showing 2 significant digits. }
Function Num2D(X:Double) : ST10;

Function Num3S(X:Single) : ST10;
{ Returns a string with 1E-5 < X < 1E9 showing 3 significant digits. }
Function Num3D(X:Double) : ST10;

Function Sci2S(x:Single) : ST10;
{ Converts a number to a string in the format _a.bcE+xy  }
Function Sci2D(x:Double) : ST10;

Function Sci3S(x:Single) : ST10;
{ Converts a number to a string in the format _a.bcdE+xy  }
Function Sci3D(x:Double) : ST10;

{=========================================================================}
                             Implementation
{=========================================================================}

Procedure  Beep;    { produces a randomly chosen tone to indicate errors }
Begin    Sound(100+random(1000));  Delay(400);  NoSound   End;


Procedure Msg(X,Y:Integer; STR : ST79);{ displays STR at X,Y on the screen }
Begin
  GotoXY(X,Y); Write(STR)
End;


Function Num2S(X:Single) : ST10;
{ Returns a string with 1E-6 < X < 1E9 showing 2 significant digits. }
Var   WrkSt : String[11];
Begin
  If x > 9.9999999       Then Str(x:3:0,WrkSt)   Else
  If x > 0.99999999      Then Str(x:4:1,WrkSt)   Else
  If x > 0.099999999     Then Str(x:5:2,WrkSt)   Else
  If x > 0.009999999     Then Str(x:6:3,WrkSt)   Else
```

```
    If x > 0.0009999999   Then Str(x:7:4,WrkSt)   Else
    If x > 0.00009999999  Then Str(x:8:5,WrkSt)   Else
    If x > 0.000009999999 Then Str(x:9:6,WrkSt)
                          Else Str(x:10:7,WrkSt);
    If WrkSt[1] <> Space Then Insert(Space,WrkSt,1);
    Num2S:= WrkSt;
  End;

  Function Num2D(X:Double) : ST10;
  { Returns a string with 1E-6 < X < 1E9 showing 2 significant digits. }
  Var   WrkSt : String[11];
  Begin
    If x > 9.9999999      Then Str(x:3:0,WrkSt)   Else
    If x > 0.99999999     Then Str(x:4:1,WrkSt)   Else
    If x > 0.099999999    Then Str(x:5:2,WrkSt)   Else
    If x > 0.009999999    Then Str(x:6:3,WrkSt)   Else
    If x > 0.0009999999   Then Str(x:7:4,WrkSt)   Else
    If x > 0.00009999999  Then Str(x:8:5,WrkSt)   Else
    If x > 0.000009999999 Then Str(x:9:6,WrkSt)
                          Else Str(x:10:7,WrkSt);
    If WrkSt[1] <> Space Then Insert(Space,WrkSt,1);
    Num2D:= WrkSt;
  End;


  Function Num3S(X:Single) : ST10;
  { Returns a string with 1E-5 < X < 1E9 showing 3 significant digits. }
  Var   WrkSt : String[11];
  Begin
    If x > 99.999999     Then Str(x:4:0,WrkSt)   Else
    If x > 9.9999999     Then Str(x:5:1,WrkSt)   Else
    If x > 0.99999999    Then Str(x:5:2,WrkSt)   Else
    If x > 0.09999999    Then Str(x:6:3,WrkSt)   Else
    If x > 0.009999999   Then Str(x:7:4,WrkSt)   Else
    If x > 0.0009999999  Then Str(x:8:5,WrkSt)   Else
    If x > 0.00009999999 Then Str(x:9:6,WrkSt)
                         Else Str(x:10:7,WrkSt);
    If WrkSt[1] <> Space Then Insert(Space,WrkSt,1);
    Num3S:= WrkSt;
  End;

  Function Num3D(X:Double) : ST10;
  { Returns a string with 1E-5 < X < 1E9 showing 3 significant digits. }
  Var   WrkSt : String[11];
  Begin
    If x > 99.999999     Then Str(x:4:0,WrkSt)   Else
    If x > 9.9999999     Then Str(x:5:1,WrkSt)   Else
    If x > 0.99999999    Then Str(x:5:2,WrkSt)   Else
    If x > 0.09999999    Then Str(x:6:3,WrkSt)   Else
    If x > 0.009999999   Then Str(x:7:4,WrkSt)   Else
    If x > 0.0009999999  Then Str(x:8:5,WrkSt)   Else
    If x > 0.00009999999 Then Str(x:9:6,WrkSt)
                         Else Str(x:10:7,WrkSt);
    If WrkSt[1] <> Space Then Insert(Space,WrkSt,1);
    Num3D:= WrkSt;
  End;


  Function Sci2S(x:Single) : ST10;
  { Converts a number to a string in the format _a.bcE+xy  }
  Var   WrkSt : String[13];
  Begin
    Str(x:11,WrkSt);
    Delete(WrkSt,8,2);
    Sci2S:= WrkSt;
  End;

  Function Sci2D(x:Double) : ST10;
  { Converts a number to a string in the format _a.bcE+xy  }
  Var   WrkSt : String[13];
  Begin
    Str(x:11,WrkSt);
    Delete(WrkSt,8,2);
    Sci2D:= WrkSt;
  End;


  Function Sci3S(x:Single) : ST10;
  { Converts a number to a string in the format _a.bcdE+xy  }
  Var   WrkSt : String[13];
```

```
Begin
  Str(x:12,WrkSt);
  Delete(WrkSt,9,2);
  Sci3S:= WrkSt;
End;

Function Sci3D(x:Double) : ST10;
{ Converts a number to a string in the format _a.bcdE+xy  }
Var   WrkSt : String[13];
Begin
  Str(x:12,WrkSt);
  Delete(WrkSt,9,2);
  Sci3D:= WrkSt;
End;

Var  K : Byte;
Begin
  For K:= 1 to 79 Do LineSt[K]:= #196;    LineSt[0]:= #79;
End.
```

PROGRAM LISTING - DRALIST.PAS

```
Unit DRALIST;

{ Author:  Paul D. Rittmann, PhD CHP
  Purpose: Stuff to enable access to the DRALIST.DAT information.
}
{==========================================================================}
                                Interface
{==========================================================================}

Uses Crt, General;

Const
  DRABIN  = 'DRALIST.'; { A=alpha; B=beta; P=positron; E=IC electron; G=gamma }
  NucLmt = 505;

Type
  NucRec = Record     { 55 bytes per record }
    Name      : ST8;      { name in standard format, C-14, Co-60 }
    Zno       : Integer;  { atomic number of element }
    Ano,Spac,             { atomic mass number; specific activity (Ci/g) }
    Halflife  : Single;   { decay halflife (seconds) }
    HalfStr   : ST10;     { string with halflife from DRALIST }
    Aaa,Azz,              { alpha starting and ending indices }
    Baa,Bzz,              { beta starting and ending indices }
    Paa,Pzz,              { positron starting and ending indices }
    Eaa,Ezz,              { auger & internal conversion electron indices }
    Gaa,Gzz   : Integer;  { gamma starting and ending indices }
    NucFlag   : Boolean;  { general purpose flag }
    End;
  AlphaPtr   = ^AlphaArray;
  AlphaArray = Array[1..370] of Single;
  BetaPtr    = ^BetaArray;
  BetaArray  = Array[1..1750] of Single;
  PosiPtr    = ^PosiArray;
  PosiArray  = Array[1..150] of Single;
  ICPtr      = ^ICArray;
  ICArray    = Array[1..3400] of Single;
  GammaPtr   = ^GammaArray;
  GammaArray = Array[1..7500] of Single;

Const
  PartiSt : Array[1..5] of ST10 = ('Alpha','Beta','Positron','Auger & IC','Gamma');
  PartAbb : Array[1..5] of Char = ('a','b','p','e','g');

Var
  DraNuc  : Array[0..NucLmt] of NucRec; { nuclide data; zeroth record for sorting }
  Afrac,               { Alpha emission fractions }
  Aengy   : AlphaPtr; { Alpha energy data }
  Bfrac,               { Beta emission fractions }
  Bave,                { Beta average energy data }
  Bengy   : BetaPtr;  { Beta endpoint energy data }
  Pfrac,               { Positron emission fractions }
  Pave,                { Positron average energy data }
  Pengy   : PosiPtr;  { Positron endpoint energy data }
  Efrac,               { Auger emission fractions }
  Eengy   : ICPtr;    { Auger energy data }
  Gfrac,               { Gamma emission fractions }
  Gengy   : GammaPtr; { Gamma energy data }
  NucD,                { Number in DRALIST }
  Nuc     : Integer;  { Index for general use }

Procedure Get_DRALIST(A,B,P,IC,G:Byte);
{ Creates and initializes the requested arrays.
  For example, Get_DRALIST(0,1,1,1,0) will initialize only the beta,
  positron and IC electron arrays for fraction and energy.  The average
  energy arrays are only initialized if the number is >1.   }

{==========================================================================}
                             Implementation
{==========================================================================}

Procedure Get_DRALIST(A,B,P,IC,G:Byte);
{ Creates and initializes the requested arrays.
  For example, Get_DRALIST(0,1,1,1,0) will initialize only the beta,
  positron and IC electron arrays for fraction and energy.  The average
  energy arrays are only initialized if the number is >1.   }
```

```
Var
  Fd  : File of NucRec;
  Fa  : File of AlphaArray;
  Fb  : File of BetaArray;
  Fp  : File of PosiArray;
  Fe  : File of ICArray;
  Fg  : File of GammaArray;
  J   : Integer;
Begin
 { read DRALIST.N }
  Write('Reading General Nuclide Information      ');
  Assign(Fd,DRABIN+'N');    Reset(Fd);
  J:= -1;  While not Eof(Fd) Do Begin  Inc(J);  Read(Fd,DraNuc[J]);   End;
  Close(Fd);          NucD:= J;      Writeln(NucD:5,' nuclides were found');
  If A > 0 Then Begin  { read DRALIST.A }
    Writeln(Blank8,'Reading Alpha particles');
    New(Afrac);    New(Aengy);
    Assign(Fa,DRABIN+'A');      Reset(Fa);
    Read(Fa,Afrac^,Aengy^);     Close(Fa);
    End;
  If B > 0 Then Begin  { read DRALIST.B }
    Writeln(Blank8,'Reading Beta particles');
    New(Bfrac);    New(Bengy);      New(Bave);
    Assign(Fb,DRABIN+'B');          Reset(Fb);
    If B = 1 Then Read(Fb,Bfrac^,Bengy^)
             Else Read(Fb,Bfrac^,Bengy^,Bave^);
    Close(Fb);
    End;
  If P > 0 Then Begin  { read DRALIST.P }
    Writeln(Blank8,'Reading Positrons');
    New(Pfrac);    New(Pengy);      New(Pave);
    Assign(Fp,DRABIN+'P');          Reset(Fp);
    If P = 1 Then Read(Fp,Pfrac^,Pengy^)
             Else Read(Fp,Pfrac^,Pengy^,Pave^);
    Close(Fp);
    End;
  If IC > 0 Then Begin  { read DRALIST.E }
    Writeln(Blank8,'Reading Auger & IC electrons');
    New(Efrac);    New(Eengy);
    Assign(Fe,DRABIN+'E');      Reset(Fe);
    Read(Fe,Efrac^,Eengy^);     Close(Fe);
    End;
  If G > 0 Then Begin  { read DRALIST.G }
    Writeln(Blank8,'Reading Gamma rays');
    New(Gfrac);    New(Gengy);
    Assign(Fg,DRABIN+'G');     Reset(Fg);
    Read(Fg,Gfrac^,Gengy^);    Close(Fg);
    End;
End;

End.
```

PROGRAM LISTING - SRCFRAC.PAS

```
Unit SrcFrac;

{ Author:  Paul D. Rittmann, PhD CHP
  Purpose: Stuff to calculate the fraction of alphas, betas, positrons, and
           Auger/IC electrons emitted from a unit concentration in the source.
  Usage:   Calling program must call Init_Fermi to initialize variables
           and open FermiFile for reading.  Calling program should end
           by closing FermiFile.
}

{=====================================================================}
                                Interface
{=====================================================================}

Uses Crt, General;

Const
  FermiFile = 'FERMI.BIN'; { binary file with Fermi function values }
  alpha = 137.03599; { fine structure constant              }
  mc2 = 510.9991;     { rest mass energy of the electron, Kev }
  SourcDflt =2000;{ mg/cm² assumed source thickness }
  ThickDflt =  5; { mg/cm² assumed shielding thickness }
  GeomDflt = 0.5; { assumed efficiency for detection geometry }
  SpcN1= 500;       { number of points at which the spectrum is computed }
  SpcN = SpcN1-1; { constant in more frequent use than SpcN1 }
  REpt = 35;        { number of beta range-energy conversion data points }
  RApt = 15;        { number of alpha range-energy conversion data points }
  SrcNo = 200;      { number of thicknesses needed for source integration }
  NumZ = 100;       { number of elements }
  NumP = 420;       { number of electron momenta in the library }
  keVmin = 9.34;  { minimum acceptable beta particle energy }
  SrcUnit = ' mg/cm²';
Type
  REarray = Array[1..REpt] of Single; { electron range-energy from RHH p.123 }
  RAarray = Array[1..RApt] of Single; { Alpha range-energy from RHH p.125 }
  BetaSpec = Array[1..SpcN1] of Double;
  RangeArray = Array[0..SrcNo] of Double;
  DoubleArray = Array[1..NumP] of Double;
Const
  Symbol  : Array[1..NumZ,1..2] of Char =
     ('H ', 'He', 'Li', 'Be', 'B ', 'C ', 'N ', 'O ', 'F ', 'Ne',
      'Na', 'Mg', 'Al', 'Si', 'P ', 'S ', 'Cl', 'Ar', 'K ', 'Ca',
      'Sc', 'Ti', 'V ', 'Cr', 'Mn', 'Fe', 'Co', 'Ni', 'Cu', 'Zn',
      'Ga', 'Ge', 'As', 'Se', 'Br', 'Kr', 'Rb', 'Sr', 'Y ', 'Zr',
      'Nb', 'Mo', 'Tc', 'Ru', 'Rh', 'Pd', 'Ag', 'Cd', 'In', 'Sn',
      'Sb', 'Te', 'I ', 'Xe', 'Cs', 'Ba', 'La', 'Ce', 'Pr', 'Nd',
      'Pm', 'Sm', 'Eu', 'Gd', 'Tb', 'Dy', 'Ho', 'Er', 'Tm', 'Yb',
      'Lu', 'Hf', 'Ta', 'W ', 'Re', 'Os', 'Ir', 'Pt', 'Au', 'Hg',
      'Tl', 'Pb', 'Bi', 'Po', 'At', 'Rn', 'Fr', 'Ra', 'Ac', 'Th',
      'Pa', 'U ', 'Np', 'Pu', 'Am', 'Cm', 'Bk', 'Cf', 'Es', 'Fm');
  SgnSt : Array[false..true] of ST8 = ('Electron','Positron');

  RangA : RAarray = (0.647, 0.957, 1.293, 1.668, 2.108, 2.599, 3.155, 3.788,
 { mg/cm² }             4.487, 5.198, 5.974, 6.801, 7.693, 8.573, 9.478);
  EngyA : RAarray = (1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500,
 { keV }                5000, 5500, 6000, 6500, 7000, 7500, 8000);

  RangB : REarray = ( 1, 1.5,   2, 2.5,   3,   4,   5,   6,   8,  10,  15,  20,
 { mg/cm² }           25,  30,  40,  50,  60,  80, 100, 150, 200, 250, 300, 400,
                     500, 600, 800,1000,1500,2000,2500,3000,4000,5000,6000 );
  EngyB : REarray =(24.5,30.5,35.5,  40,  44,  51,  57,  63,  73,  83, 104, 124,
 { keV }             143, 161, 194, 225, 255, 310, 363, 485, 595, 700, 800,1000,
                    1190,1370,1740,2100,3000,3940,4880,5840,7700,9500,11200);

Var
  Forbid     : Integer; { forbiddeness, 0,1,2,3 }
  Positron,             { true if particle is an positron, false if electron }
  Allowed,              { Forbid < 2 }
  Maybe      : Boolean; { Forbid = 0 or 2 }
  Emax, Emin,           { limits on beta particle kinetic energy, keV }
  Wmax, Wmin,           { limits on total energy, mc² units }
  Tfctr,Tdelta1,        { factor to calculate successive source thicknesses }
  Tdelta2,              { integration factors used in Combine_Beta_Layers }
  Ealpha0,              { energy of alpha which penetrates to Thick0 }
  EalphaR,              { energy of alpha which penetrates to Thick0+Rmax }
  EbetaR,               { energy of beta which penetrates to Thick0+Rmax }
```

```
  DeltaE,              { spacing between beta spectrum points }
  Rmax,                { thickness of source itself }
  Geometry,            { geometry correction to detector efficiency }
  Thick0     : Double; { initial shielding thickness, mg/cm² }
  Aslp       : RAarray; { slope to convert thickness to alpha energy }
  Bslp       : REarray; { slope to convert thickness to electron energy }
  SpecSum,             { cumulative beta probabilities }
  SpecE,               { kinetic energy for beta spectrum array }
  SpecF      : BetaSpec;{ beta spectrum array }
  Ebeta,               { energies corresponding to source layer thicknesses }
  DepthB     : RangeArray; { source layer thicknesses used in integration }
  Pss,                   { electron momenta from FermiFile }
  FermD      : DoubleArray;{ values for the Fermi function divided by momentum }
  FF         : File of DoubleArray;


Procedure Init_Fermi;
{ Computes the values for the source integration process. }

Procedure Beta_Spectrum( Z : Integer );
{ Reads FermiFile to initialize the FermD array, computes and normalizes
  the beta spectrum.  Uses the global variables FF, Forbid (assigns values
  to Allowed and Maybe), Emax (computes Wmax), DeltaE, SpecE[], SpecF[]  }

Function Range_MonoE( Eal:Single ) : Double;
{ Computes the depth from which monoenergetic particles may be detected.
  The range for alpha particles uses linear interpolation; the range for
  IC electrons uses semi-log interpolation.
  The global variable Positron is used to tell them apart.
  Positron must be true for alphas and false for Auger & IC electrons.
  Also uses the global variables Ealpha0, Ebeta[], and DepthB[].
  Returns the value of the depth, in g/cm². }

Function Combine_Beta_Layers : Double;
{ Sums the contributions from increasingly deep source layers using the
  trapezoid rule on exponentially increasing source thicknesses.
  Simpsons rule is used to integrate the beta spectrum.
  Uses the global variables Emax, DeltaE, SpecE[], SpecF[], Ebeta[] and
  Depth[].  Returns the value of the sum, in g/cm². }

{=========================================================================}
                              Implementation
{=========================================================================}

Procedure Init_Fermi;
{ Computes the values for the source integration process. }
Var  I,K : Integer;
  Thick  : Double;
Begin
 { compute slopes for alpha range-energy data }
  For K:= 1 to Pred(RApt) Do
    Aslp[K]:= (EngyA[Succ(K)] - EngyA[K]) / (RangA[Succ(K)] - RangA[K]);
 { locate the alpha energy corresponding to Thick0 }
  I:= 2;      While (RangA[I] < Thick0) and (I < RApt) Do Inc(I);
  Dec(I);     Ealpha0:= EngyA[I]  +  Aslp[I]*(Thick0 - RangA[I]);
 { locate the alpha energy corresponding to Thick0+Rmax }
  Thick:= Thick0 + Rmax;
  I:= 2;      While (RangA[I] < Thick) and (I < RApt) Do Inc(I);
  Dec(I);     EalphaR:= EngyA[I]  +  Aslp[I]*(Thick - RangA[I]);
 { compute slopes for beta range-energy data }
  For K:= 1 to Pred(REpt) Do
    Bslp[K]:= Ln(EngyB[Succ(K)]/EngyB[K]) / Ln(RangB[Succ(K)]/RangB[K]);
 { compute factors for source depth integration for beta & positron }
  If Thick > RangB[REpt] Then Thick:= RangB[REpt];
  Tfctr:= Exp( Ln(Thick/Thick0) / SrcNo ); { logarithmic steps }
  Tdelta1:= 0.0005*(Tfctr - 1.0);
  Tdelta2:= 0.0005*(Tfctr - 1.0/Tfctr);
  Thick:= Thick0;
  For K:= 0 to SrcNo Do Begin
    DepthB[K]:= Thick;
   { locate the data points bracketting Thick and the cutoff beta energy }
    If Thick > RangB[REpt] Then I:= REpt
      Else Begin I:= 2;  While RangB[I] < Thick Do Inc(I);  End;
    Dec(I);
    Ebeta[K]:= EngyB[I] * Exp( Bslp[I] * Ln(Thick/RangB[I]) );
    Thick:= Thick * Tfctr;
    End;
  Assign(FF,FermiFile);      Reset(FF);
  Read(FF, Pss);      { read momentum table }
End;
```

```
Function FermiFunc( P : Double ) : Double;
{ Returns the unnormalized, weighted Fermi function, P*F(Z,W),
  at momentum P based on values stored in FERMI.BIN.  Note that FERMI.BIN
  actually has values for fnbs/P from P=0.01 up to P=20.
  If P is below 0.01, then a values is extrapolated from the lowest two.
  If P exceeds 20, then the function returns zero.  }
Var  Tmp, Wrk  : Extended;
     Low, High : Integer;
Begin
  If P < 0.01  { Pss[1] }
    Then Begin
      Tmp:= FermD[1];
      FermiFunc:= Tmp + (FermD[2]-Tmp)*(100.0*P - 1.0)
      End  Else
  If P < 1.0   { Pss[100] }
    Then Begin
      Wrk:= 100.0 * P;
      Low:=  Trunc(Wrk);
      High:= Trunc(Wrk + 0.99999999);
      Tmp:= FermD[Low];
      If Low = High
        Then FermiFunc:= Tmp
        Else FermiFunc:= Tmp + (FermD[High]-Tmp)*(Wrk - Low)
      End  Else
  If P < 3.0   { Pss[200] }
    Then Begin
      Wrk:= 50.0 * P ;
      Low:=  Trunc(Wrk) + 50;
      High:= Trunc(Wrk + 50.99999999);
      Tmp:= FermD[Low];
      If Low = High
        Then FermiFunc:= Tmp
        Else FermiFunc:= Tmp + (FermD[High]-Tmp)*(Wrk - 50.0*Pss[Low])
      End  Else
  If P < 8.0   { Pss[300] }
    Then Begin
      Wrk:= 20.0 * P ;
      Low:=  Trunc(Wrk) + 140;
      High:= Trunc(Wrk + 140.99999999);
      Tmp:= FermD[Low];
      If Low = High
        Then FermiFunc:= Tmp
        Else FermiFunc:= Tmp + (FermD[High]-Tmp)*(Wrk - 20.0*Pss[Low])
      End  Else
  If P < 20.0   { Pss[420] }
    Then Begin
      Wrk:= 10.0 * P ;
      Low:=  Trunc(Wrk) + 220;
      High:= Trunc(Wrk + 220.99999999);
      Tmp:= FermD[Low];
      If Low = High
        Then FermiFunc:= Tmp
        Else FermiFunc:= Tmp + (FermD[High]-Tmp)*(Wrk - 10.0*Pss[Low])
      End
    Else FermiFunc:= 0.0;
End;


Function pBeta ( Var We,Pe,Pe2 : Double ) : Double;
{ Computes the value of the beta probability function at a beta energy We,
  in units of electron rest mass.  Pe is the electron momentum and Pe2=Pe².
  Uses the global variables Wmax, Allowed, and Maybe.   Calls FermiFunc.  }
Var  Wdf2,PBt : Double;
Begin
  Wdf2:= Sqr( Wmax - We );
  PBt:= We * Wdf2 * FermiFunc( Pe );
  If ( Allowed ) Then
    If ( Maybe ) Then  PBeta:= PBt
                 Else  PBeta:= PBt * ( Pe2 + Wdf2 )
  Else
    If ( Maybe ) Then
      PBeta:= PBt*( Sqr(Pe2 + Wdf2) + 4.0/3.0*Pe2*Wdf2 )
    Else
      PBeta:= PBt*( Sqr(Pe2 + Wdf2) + 4.0*Pe2*Wdf2 ) * (Pe2 + Wdf2);
End;


Procedure Beta_Spectrum( Z : Integer );
{ Reads FermiFile to initialize the FermD array, computes and normalizes
```

```
  the beta spectrum.  Uses the global variables FF, Forbid (assigns values
  to Allowed and Maybe), Emax (computes Wmax), DeltaE, SpecE[], SpecF[].
  Z is the atomic number of the parent nuclide.  }
Var   I,FermZ : Integer;
  Winc,We,Wmx2,
  Pe,Pe2,PZA,Sum,Tmp : Double;
Begin
  If Positron Then FermZ:= Z - 1    Else FermZ:= Z + 1;
 { read Fermi function table for this atomic number }
  Seek(FF, FermZ);    Read(FF, FermD);
  Allowed:= Forbid < 2;        Maybe:= not Odd(Forbid);
  Wmax:= Emax/mc2 + 1.0;       Wmx2:= Sqr(Wmax);
  DeltaE:= Emax / SpcN1;
  Winc:= DeltaE / mc2;
  Sum:= 0.0;    PZA:= -2.0*Pi*FermZ/alpha;
  For I:= 1 to SpcN Do Begin
    Tmp:= I*Winc;                We:= 1.0 + Tmp;       SpecE[I]:= mc2*Tmp;
    Pe2:= Tmp*(We + 1.0);        Pe:= Sqrt(Pe2);
    Tmp:= pBeta ( We, Pe, Pe2 );
    If Positron Then Tmp:= Tmp * Exp(PZA*We/Pe);
    SpecF[I]:= Tmp;
    If Odd(I) Then Sum:= Sum + 4*Tmp     { Simpson's Rule }
              Else Sum:= Sum + 2*Tmp;
    End;
  PZA:= DeltaE / 3.0;        Sum:= Sum * PZA;
  SpecE[SpcN1]:= Emax;       SpecF[SpcN1]:= 0.0;
  SpecSum[SpcN1]:= 0.0;
  For I:= SpcN downto 1 Do Begin
    We:= SpecF[I] / Sum;     SpecF[I]:= We;  { store normalized probability }
    If I = SpcN Then Begin
      Pe:= We;           Pe2:= 4*We;
      SpecSum[SpcN]:= 0.5*We*DeltaE;
      End    Else
    If I = Pred(SpcN) Then Begin
      Pe:= Pe + 4*We;  Pe2:= Pe2 + We;       { Simpson's Rule }
      SpecSum[Pred(SpcN)]:= Pe2*PZA;
      End    Else
    If Odd(I) Then Begin
      Pe:= Pe + We;    Pe2:= Pe2 + SpecF[Succ(I)] + 4*We;
      SpecSum[I]:= Pe*PZA + SpecSum[SpcN];
      End
    Else Begin
      Pe2:= Pe2 + We;   Pe:= Pe + SpecF[Succ(I)] + 4*We;
      SpecSum[I]:= Pe2*PZA;
      End;
    End;
End;


Function Range_MonoE( Eal:Single ) : Double;
{ Computes the depth from which monoenergetic particles may be detected.
  The range for alpha particles uses linear interpolation; the range for
  IC electrons uses semi-log interpolation.
  The global variable Positron is used to tell them apart.
  Positron must be true for alphas and false for Auger & IC electrons.
  Also uses the global variables Ealpha0, Ebeta[], and DepthB[].
  Returns the value of the depth, in g/cm². }
Var      I : Integer;
  TotThick : Double; { fraction detected, g/cm² for one particle }
Begin
  TotThick:= 0.0;       I:= 2;
  If Positron
    Then Begin
      If Eal > EalphaR Then TotThick:= Thick0+Rmax   Else
      If Eal > Ealpha0 Then Begin
        While (EngyA[I] < Eal) and (I < RApt) Do Inc(I);
        Dec(I);
        TotThick:= RangA[I] + (Eal - EngyA[I])/Aslp[I];
      End  End
    Else
      If Eal > Ebeta[SrcNo] Then TotThick:= Thick0+Rmax    Else
      If Eal > Ebeta[0] Then Begin
        While (EngyB[I] < Eal) and (I < REpt) Do Inc(I);
        Dec(I);
        TotThick:= RangB[I] * Exp( Ln(Eal/EngyB[I]) / Bslp[I] );
      End;
  TotThick:= 0.001*(TotThick - Thick0);
  If TotThick < 0.0 Then TotThick:= 0.0;
  Range_MonoE:= TotThick;
End;
```

```
Function Combine_Beta_Layers : Double;
{ Sums the contributions from increasingly deep source layers using the
  trapezoid rule on exponentially increasing source thicknesses.
  Simpsons rule is used to integrate the beta spectrum.
  Uses the global variables Emax, DeltaE, SpecE[], SpecF[], Ebeta[] and
  Depth[].  Returns the value of the sum, in g/cm². }
Var
  I,J,K : Integer;
  Detect,   { fraction detected, mg/cm² for one particle }
  SumHi : Double;
Begin
  Detect:= 0.0;    I:= 0;
  Repeat
    Emin:= Ebeta[I];
   { do the integrals }
    If Emin < Emax Then Begin
     { locate the position of Emin in the beta spectrum }
      K:= 1;    While SpecE[K] < Emin Do Inc(K);
     { finally, add the contribution to the total fraction detected }
      If I = 1 Then SumHi:= SpecSum[K]*Tdelta1
               Else SumHi:= SpecSum[K]*Tdelta2;
      Detect:= Detect + SumHi*DepthB[I];
      End;
    Inc(I);
  Until (Emin > Emax) or (I > SrcNo);
  Combine_Beta_Layers:= Detect;
End;


Begin
  Geometry:= GeomDflt;      Thick0:= ThickDflt;      Rmax:= SourcDflt;
End.
```

PROGRAM LISTING - NUCLIST.PAS

```
Unit NucList;

{ Author:  Paul D. Rittmann, PhD CHP
  Purpose: Stuff to read a nuclide list file.
}

{==========================================================================}
                                Interface
{==========================================================================}

Uses Crt, General;

Const
  MaxNucs = 80;   { limit on number of nuclides in a group }
  NucExtn = '.NUC';  { default nuclide file name extension }

Var
  LineCount,          { position in nuclide file for reporting errors }
  NucN      : Integer; { number of nuclides in a group }
  fn        : Text;    { nuclide list file }
  Factor    : Double;  { scale factor in a nuclide file }
  OneLine   : ST79;    { general purpose string }
  Nuclide   : Array[1..MaxNucs] of ST8;    { nuclide name in standard format }
  AmtVal    : Array[1..MaxNucs] of Double; { values for each nuclide }


Function Valid_Number(Strt,Fini:Byte; Var NewVal:Double) : Boolean;
{ Looks through OneLine from Strt to Fini for the first valid number which
  is stored in NewVal.  Returns false if an invalid number was found.
  Exponential numbers without the E (FORTRAN notation) are accepted.
  Any commas are removed.  }

Function Nuclide_Block : Boolean;
{ Finds the information on one nuclide group from the nuclide list in fn.
  Returns true if a block was found.  Nuclide format is C-14, Co-60.
  Uses the global variables OneLine and fn.  Assigns values to the
  global variables NucN, Nuclide[], AmtVal[] and Factor.
  Called as part of a repeat loop, i.e.,
        Repeat
          If Nuclide_Block Then Begin [ process info about this block ]
            For Nuc:= 1 to NucN Do Begin
             [ process information obout this nuclide ]
             End;
            End;
        Until                           }

{==========================================================================}
                              Implementation
{==========================================================================}

Procedure ReadnTrim(Var f:Text; Var Wrds:Boolean; Var Lng:Byte);
{ Reads a line from f into OneLine, and checks for a blank line.
  Leading and trailing blank spaces are removed, as are any double spaces.
  The first character is made upper case while the second is made lower case.
  If the first character is not alphabetic, Wrds is set true to indicate
  a comment line must be skipped.  The length of the string (Lng) is set
  according to the table below.
          OneLine          Wrds     Lng
          ------------------------------
          Blank or empty   false     0
          Comment line     true    Length
          Nuclide line     false   Length
          Scale Factor     false   Length
          ------------------------------
  Note that Nuclide lines and Scale Factors may or may not be valid input.
  Note that the first character after the end of OneLine is blank.  }
Var  CH : Char;    J,K : Byte;
Begin
  If Eof(f) Then OneLine:= ''
           Else Readln(f,OneLine);
  Lng:= Length(OneLine);
 { remove leading spaces }
  While (OneLine[1] = Space) and (Lng > 0) Do Begin
    Delete(OneLine,1,1);  Lng:= Length(OneLine);
    End;
  If Lng = 0 Then Begin   { blank line }
```

```
    Wrds:= false;   Exit   End;
  { remove trailing blanks }
   While OneLine[Lng] = Space Do Dec(Lng);
   OneLine[0]:= Char(Lng);
  { remove any double spaces, leaving just one between words }
   K:= Pos(Space,OneLine);       J:= Succ(K);
   If K > 0 Then Begin    { at most two gaps are shortened }
     While OneLine[J] = Space Do Delete(OneLine,J,1);  { remove first extras }
     Lng:= Length(OneLine);
     While (OneLine[J] <> Space) and (J < Lng) Do Inc(J);{ look for second gap }
     K:= Succ(J);
     If K < Lng Then Begin
       While OneLine[K] = Space Do Delete(OneLine,K,1);
       Lng:= Length(OneLine)     End;
     End;
  { convert first characters to upper case }
   CH:= UpCase(OneLine[1]);
   Wrds:= (CH < 'A') or (CH > 'Z'); { non-alphabetic character denotes comment }
   OneLine[1]:= CH;
   CH:= OneLine[2];
   If (CH > '@') and (CH < '[') Then CH:= Chr(Ord(CH) + 32);
   OneLine[2]:= CH;
  { make sure the 1st character off the end of the string is a blank }
   OneLine[Succ(Lng)]:= Space;
 End;


 Function Valid_Number(Strt,Fini:Byte; Var NewVal:Double) : Boolean;
 { Looks through OneLine from Strt to Fini for the first valid number which
   is stored in NewVal.  Returns false if an invalid number was found.
   Exponential numbers without the E (FORTRAN notation) are accepted.
   Any commas are removed.  }
 Var  CH : Char;
   WrkSt : ST45;
   Ia    : Integer;
 Begin
   NewVal:= 1.0;   { default values for NewVal }
  { skip blanks before number }
   While OneLine[Strt] = Space Do Inc(Strt);
   WrkSt:= Copy(OneLine,Strt,Succ(Fini-Strt));
  { remove any commas }
   Repeat
     Ia:= Pos(Comma,WrkSt);
     Delete(WrkSt,Ia,1);
   Until Ia = 0;
  { Insert E if omitted, as in FORTRAN input }
   Ia:= Pos('-',WrkSt);
   If Ia < 2 Then Ia:= Pos('+',WrkSt);
   If Ia > 1 Then Begin   CH:= WrkSt[Pred(Ia)];
     If (CH <> 'e') and (CH <> 'E') Then Insert('E',WrkSt,Ia);
     End;
  { Insert zero before or after the decimal point, if omitted }
   Ia:= Pos('.',WrkSt);
   If Ia = 1  Then Insert('0',WrkSt,1)
     Else If Ia = Length(WrkSt)  Then WrkSt:= WrkSt + '0';
  { convert string into a real number }
   Val(WrkSt,NewVal,Ia);
   If Ia > 0  Then Begin
     Valid_Number:= false;
     Exit    End;
   Valid_Number:= true;
 End;


 Function Nuclide_Block : Boolean;
 { Finds the information on one nuclide group from the nuclide list in fn.
   Returns true if a block was found.  Nuclide format is C-14, Co-60.
   Uses the global variables OneLine and fn.  Assigns values to the
   global variables NucN, Nuclide[], AmtVal[] and Factor.
   Called as part of a repeat loop, i.e.,
         Repeat
           If Nuclide_Block Then Begin [ process info about this block ]
             For Nuc:= 1 to NucN Do Begin
               [ process information obout this nuclide ]
               End;
             End;
         Until                          }
 Var   CH         : Char;
   I,J,K,NumChar : Byte;
   NewVal        : Double;
```

```
  FctrLine,
  Comment       : Boolean;
Begin
  NucN:= 0;
  Repeat
    ReadnTrim(fn,Comment,NumChar);    Inc(LineCount);
    If (NumChar > 0) and not Comment Then Begin
      Inc(NucN);
      Nuclide[NucN]:= Blank8;
     { store nuclide name in standard format }
      Nuclide[NucN,1]:= OneLine[1];
      If OneLine[2] < 'a' Then Nuclide[NucN,2]:= Space
                          Else Nuclide[NucN,2]:= OneLine[2];
      FctrLine:= Copy(Nuclide[NucN],1,2) = 'Xx';
      If FctrLine
        Then Begin  I:= 3;   Dec(NucN);  End
        Else Begin  { read the atomic mass number }
          I:= 2;  { skip over non-numeric characters }
          While (OneLine[I] < '0') or (OneLine[I] > '9') Do Inc(I);
          Nuclide[NucN,3]:= Dash;
          J:= 4;  { store the numeric characters as atomic mass number }
          While (OneLine[I] > '/') and (OneLine[I] < ':') Do Begin
            Nuclide[NucN,J]:= OneLine[I];
            Inc(J);  Inc(I);   End;
          CH:= OneLine[I];
          If (CH = 'M') or (CH = '*') Then CH:= 'm';
          If CH > Space Then Begin  Nuclide[NucN,J]:= CH;  Inc(I);  End;
          If Nuclide[NucN,2] = Space Then Begin
            Delete(Nuclide[NucN],2,1);
            Nuclide[NucN]:= Nuclide[NucN] + Space;
            End;
          End;
      If I > NumChar   { no number on line }
        Then If FctrLine Then Factor:= 1.0
                         Else AmtVal[NucN]:= Factor
        Else If Valid_Number(I,NumChar,NewVal)
          Then If FctrLine Then Factor:= NewVal
                           Else AmtVal[NucN]:= Factor*NewVal
          Else Begin  TextAttr:= White;
            Writeln('Invalid number in nuclide list at line ',LineCount,':');
            Writeln(OneLine);   TextAttr:= Yellow;
            Writeln;  Writeln('Run Terminated!!  Correct the nuclide file!!');
            Halt;      End;
      End;
  Until NumChar = 0;   { empty line }
  Nuclide_Block:= NucN > 0;
End;


End.
```

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