Determining the Need For External Radiation Monitoring at FUSRAP Projects Using Soil Characterization Data

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Introduction

According to Regulatory Guide 8.34 *Monitoring Criteria and Methods to Calculate Occupational Radiation Doses*, monitoring an individual's external radiation exposure is required if the occupational dose is likely to exceed 10% of the appropriate dose limit. Monitoring is also required if the individual enters a high radiation area or a very high radiation area (1). These terms are defined in Table 1. According to 10 CFR 835.402 monitoring is required for workers who are likely to be exposed to greater than 100 mrem effective dose equivalent to the whole body (2). Although these limits are based on contributions from both internal and external exposure, only external radiation exposure will be considered here. Some limits have been compiled and are summarized in Table 1: *External Radiation Exposure Limits*. The values listed in the Limit column are the dose limits. The values listed in the Monitoring Limit column are the limits at which monitoring must begin.

Table 1: External Radiation Exposure Limits

Requirement	Limit	Monitoring Limit
Deep Dose Equivalent Limit (yearly)	5 rem (0.05 Sv)	500 mrem (5 mSv)
DOE Effective Dose Equivalent (yearly)	-	100 mrem (1 mSv)
Declared Pregnant Worker (gestation)	0.5 rem	50 mrem (0.5 mSv)
High Radiation Area	100 mrem/h at 0.3 m	100 mrem/h at 0.3 m
Very High Radiation Area	500 mrem/h at 1 m	500 mrem/h at 1 m
USACE Administrative Limit	500 mrem (1 mSv)	-
Detection Limit for a typical Thermoluminescent Dosimeter (TLD)	10 mrem (0.1 mSv)	-

The objective of this paper is to calculate the specific activity limits for various nuclides that mark the threshold where external radiation monitoring must begin. These values can then be compared to soil characterization data for a Formerly Utilized Sites Remedial Action Program (FUSRAP) project to demonstrate whether the threshold has been approached or exceeded at that particular site. If the monitoring threshold is approached or exceeded, engineering controls can be added, external monitoring can be used, or administrative controls can be reworked. The calculation uses the gamma constant and linear attenuation coefficient of each nuclide to determine its specific activity limit.

Method

It is assumed that the FUSRAP project has contamination or waste that is either made up of source material or byproduct material, but is not special nuclear material. That is, only the nuclides from the uranium series, the actinium series, or the thorium series are considered. The radioactive nuclide of potassium can also be considered because the data for this nuclide is typically available, as it is a common constituent of soil. It is assumed that the only operation that occurred at the project was the processing of uranium ore into uranium metal. In this case, there are only a handful of prime nuclides for which this process requires the soil characterization data. These prime nuclides are the nuclides that are at the top of the chain, or are long-lived daughters that have been chemically separated from the rest of the chain, and have not had enough time to reestablish equilibrium. The prime nuclides for three natural decay series are U-238, Th-230, and Ra-226 for the uranium series; U-235, Pa-231, and Ac-227 for the actinium series; and Th-232 for the thorium series. If curiosity demands, K-40 can also be considered as a prime nuclide. Specific activity limits were found for the prime nuclides only.

It is also assumed that the soil characterization data is analyzed by gamma spectrometry. Because several of the prime nuclides are in secular equilibrium with their daughters, the dose contribution from each daughter are considered with that of the prime nuclide when calculating the specific activity limits. The reciprocal of the specific activity limit from each daughter or parent that emits gamma radiation are summed, then the reciprocal of this sum of reciprocals is used as the specific activity limit for the prime nuclide. For example, U-238 is a prime nuclide with the contributing daughters Th-234, Pa-234^{m}, Pa-234, and U-234. When looking for the specific activity which causes monitoring to begin for a typical worker, the reciprocal of the specific activity limits for U-238, Th-234, Pa-234^m, Pa-234, and U-234 nuclides are found and summed. The reciprocal of this sum is the specific activity limit used to compare with the specific activity of U-238 and its gamma emitting daughters. Because there is a specific activity limit for each of these prime nuclides, a sum of ratios (SOR) must be used to determine if there is an overall problem. This is shown in the following equation.

$$SOR = \sum_{1}^{j} \frac{A_i}{SA_i}$$

A_i is the specific activity of prime nuclide *i* in pCi/g, and SA_i is the specific activity limit of prime nuclide *i* in pCi/g, and *j* is the total number of prime nuclides. If the SOR is greater than or equal to one, then the threshold for monitoring has been exceeded.

Table 2: *Data For the Prime Nuclides* lists the prime nuclides and their contributing daughters if there are any, as well as the energies of the gamma rays that are actually detected to generate the soil characterization data. The energy in the table listed in *Italics* is that which was used when finding the value for the linear attenuation coefficient.

Table 2: Data For the Prime Nuclides

	Prime nuclide	Contributor	Gamma energy, MeV (yield, %)
Uranium series	U-238 *plus four daughters*	U-238	*0.0496 (0.07)*
		Th-234	*0.0663 (3.8)*, 0.0924 (2.7), 0.0928 (2.7), 0.1128 (0.24)
		Pa-234^m	0.766 (0.207), *1.001 (0.59)*
		Pa-234	*0.132 (19.7)*, 0.570 (10.7), 0.883 (11.8), 0.926 (10.9), 0.946 (12)
		U-234	*0.053 (0.12)*, 0.121 (0.04)
	Th-230	Th-230	*0.0677 (0.37)*, 0.142 (0.07), 0.144 (0.045)
	Ra-226 *plus six daughters*	Ra-226	*0.186 (3.28)*
		Rn-222	*0.510 (0.078)*
		Pb-214	0.2419 (7.5), 0.295 (19.2), *0.352(37.1)*
		Bi-214	*0.609 (46.1)*, 1.12 (15.0), 1.765 (15.9), 2.204 (5.0)
		Po-214	*0.7997 (0.010)*
		Pb-210	*0.0465 (4)*
		Po-210	*0.802 (0.0011)*
Actinium series	U-235 *plus one daughter*	U-235	0.1438 (10.5), 0.163 (4.7), *0.1857 (54)*, 0.205 (4.7)
		Th-231	*0.0256 (14.8)*, 0.0842 (6.5)
	Pa-231	Pa-231	*0.0274 (9.3)*, 0.2837 (1.6), 0.300 (2.3), 0.3027 (4.6), 0.33 (1.3)
	Ac-227 *plus nine daughters*	Ac-227	0.07 (0.017), *0.1 (0.032)*, 0.16 (0.019)
		Th-227	0.05 (8.5), *0.236 (11.2)*, 0.3 (2.0), 0.304 (1.1), 0.33 (2.7)
		Fr-223	*0.05 (34)*, 0.0798 (9.2), 0.2349 (3.4)
		Ra-223	0.144 (3.3), 0.154 (5.6), *0.269 (13.6)*, 0.324 (3.9), 0.338 (2.8)
		Rn-219	*0.271 (9.9)*, 0.4018 (6.6)
		Po-215	*0.4388 (0.04)*
		Pb-211	*0.405 (3.0)*, 0.427 (1.38), 0.832 (2.8)
		Bi-211	*0.351 (12.7)*
		Po-211	*0.57 (0.54)*, 0.898 (0.52)
		Tl-207	*0.897 (0.24)*
Thorium series	Th-232 *plus eight daughters*	Th-232	*0.059 (0.19)*, 0.126 (0.04)
		Ac-228	0.338 (11.4), *0.911 (27.7)*, 0.969 (16.6), 1.588 (3.5)
		Th-228	*0.084 (1.19)*, 0.132 (0.11), 0.166 (0.08), 0.216 (0.27)
		Ra-224	*0.241 (3.9)*
		Rn-220	*0.55 (0.07)*
		Po-216	*0.128 (0.002)*
		Pb-212	*0.239 (44.6)*, 0.300 (3.4)
		Bi-212	0.040 (1.0), *0.727 (11.8)*, 1.62 (2.75)
		Tl-208	0.277 (6.8), 0.5108 (21.6), 0.583 (85.8), 0.86 (12), *2.614 (100)*
	K-40	K-40	*1.46 (0.0118)*

Scenarios

The following scenarios involve cases where a radiation worker is most likely exposed to external radiation while working at a FUSRAP site.

Scenario 1: Working in a contaminated region—use of a volume source

A worker may be required to walk in a controlled region over contaminated soil, tailings, debris, etc. Please refer to Figure 1: *Working On a Volume Source.* The controlled region shall be assumed to be a homogeneous, level planar surface with an amount of radioactive material on the surface and below the surface which contributes a dose to the worker. Buildup of the gamma radiation from a broad-beam geometry will be ignored. The actual depth of interest, x, shall be calculated by using ten relaxation lengths in concrete of the most penetrating radiation. The values in concrete have been used due its similarity to soil. Note that the relaxation length is the thickness of material that will attenuate a beam of gamma rays to 1/*e* of its original intensity. It is numerically equal to the reciprocal of the attenuation coefficient. Ten relaxation lengths have been used for the thickness of the radioactive material because this is a good thumb rule for phenomenon which follow exponential decay. After ten relaxation lengths, the intensity of the radiation of a beam has been attenuated by the absorbing material and has dropped to less than 5/100000 of its original intensity. From Appendix C, Table C: *Nuclide Data* it is seen that the largest relaxation length is 10.78 cm from the 2.614 MeV gamma ray. It should be noted that although this gamma ray should not be a problem at most uranium sites (because this gamma comes from Tl-208--the last radioactive daughter of Th-232), using its penetrating abilities should provide for a very conservative approach. Ten relaxation lengths are equal to 107.8 cm, or 1.078 m. The attenuation coefficients of air have been used to provide a conservative approach to describe the action of the gamma radiation. The radiation will be attenuated in soil much more readily than in air. However, if the attenuation coefficients for air are used, the dose from the gamma rays that actually reach the target will be overestimated.

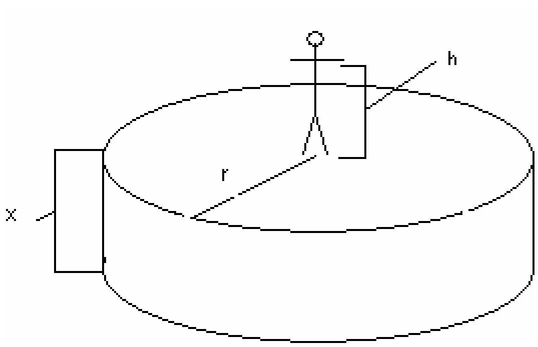

Figure 1: Working On a Volume Source

The dose rate of a volume source is given by the following equation.

$$\hat{H} = p\Gamma \frac{C_v}{m}(1 - e^{-mx}) \ln\left(\frac{r^2 + h^2}{h^2}\right)\frac{\text{mSv}}{\text{h}}$$

- H is the dose rate in mSv/h.
- Γ is the gamma constant or source strength, in mSv m^2/MBq h. The values were taken from reference 3, Table 6.2.2.
- C_v is the volumetric activity in MBq/m^3.
- μ is the linear attenuation coefficient for air, in m^{-1}. The values of μ (for both air and concrete) for each nuclide were interpolated or extrapolated from reference 4, Table 5.2.
- x is the thickness of the volume source in m. The value of 1.078 m was calculated as noted above.
- r is the radius of the cylinder of the volume source in m, 1.078 m. This was set to be identical to the value for x.

- h is the height of the target (TLD badge) above the top surface of the cylinder, assumed to be 1.00 m

If a limiting dose is chosen and a value for exposure time, t, is considered, then the equation can be solved for the volumetric activity,

$$C_v = \frac{\hat{H}\, mt}{p\Gamma(1-e^{-mx})\ln\left(\frac{r^2+h^2}{h^2}\right)} \frac{\text{MBq}}{\text{m}^3}$$

The value of t is measured in h. The volumetric activity limit can be converted into the specific activity limit by dividing by the density of the soil.

$$SA = \frac{C_v}{r} \frac{\text{MBq}}{\text{g}}$$

- ρ is the density of the volume source, 1.60E+06 g/m^3. This value is the density of typical soil. This value was converted from 100 lb/ft^3 (5).

This specific activity limit can easily be converted to units of pCi/g, which is the unit typically used at the FUSRAP projects.

For this scenario, there are three sets of limits to calculate. To determine the monitoring limit for a declared pregnant worker, the value of dose was chosen to be 50 mrem (0.5 mSv) and the time for the gestation is given as a 40 week period times 40 hours per week, or 1600 hours. To determine the same limit for a typical radiation worker, the chosen dose was 500 mrem (5 mSv) and the time for working for an entire year is 50 weeks times 40 hours per week or 2000 hours. For determining the detection limit on a typical TLD, a value of 10 mrem was used. Furthermore, because the TLDs are typically sent for analysis once per quarter, it can be assumed that the TLD has an exposure time of only 13 weeks multiplied by 40 hours per week, or 520 hours. The values of Γ, μ , C_v, and SA have been found for each of the nuclides and are shown in Appendix A, Table A-1: *Monitoring Limits For a Declared Pregnant Worker With a Volume Source*, Table A-2: *Monitoring Limits For a Typical Radiation Worker With a Volume Source*, and Table A-3: *Detection Limit for a Typical TLD With a Volume Source*.

Scenario 2: Handling individual radioactive samples—use of point source

A radiation worker may have to handle samples at a FUSRAP site or associated laboratory sites. The samples are assumed to be a homogeneous point source. Also assume that the gamma rays can penetrate the sample container as readily as they can penetrate air, and that the sample will typically be held no closer than 30 cm from the radiation worker. Finally, the mass of the sample is assumed to be 1000 grams.

The dose rate of a point source is given by the following equation.

$$\hat{H} = \frac{\Gamma A}{d^2} \frac{\text{mSv}}{\text{h}}$$

- H is the dose rate in mSv/h,
- A is the activity in MBq, and
- d is the distance from the source to the target in cm.

Rearranging,

$$A = \frac{\hat{H}\, d^2}{\Gamma} \text{MBq}$$

Finally, the specific activity limit can be found by dividing by the mass, m, of the sample.

$$SA = \frac{A}{m} \frac{\text{MBq}}{g}$$

Again the specific activity limits for this scenario can easily be converted to the more commonly used units of pCi/g. A dose rate of 10 mrem/h (0.1 mSv/h) is the limit that was chosen to find the specific activity threshold for monitoring to begin. The values of Γ, A, and SA have been found for each of the nuclides and are shown in Appendix B, Table B: *Monitoring Limits For Handling Radioactive Samples*.

Limits

The specific activity limits from the two scenarios are summarized in Table 3: *Specific Activity Limit Where External Monitoring Must Begin*. Note that these limits are the average specific activity that a worker must be exposed to for the entire time of interest. The likelihood of needing external monitoring for radiation workers at FUSRAP sites is rather low. For the scenario of working in a contaminated area, the limiting prime nuclide from the uranium series is U-238. If the work done at the FUSRAP site involves the processing of natural thorium, then Th-232 will likely be the limiting factor.

Table 3: Specific Activity Limit (in pCi/g) Where External Monitoring Must Begin

Prime Nuclide	Declared Pregnant Worker	Typical Worker	TLD Detection Limit	Sampler/ Lab Worker
U-238	8.54E+06	1.07E+08	5.55E+05	4.07E+05
Th-230	2.75E+08	3.43E+09	1.79E+07	1.31E+07
Ra-226	1.32E+07	1.65E+08	8.58E+05	6.30E+05
U-235	2.14E+07	2.67E+08	1.39E+06	1.02E+06
Pa-231	5.06E+07	6.32E+08	3.29E+06	2.40E+06
Ac-227	1.53E+07	1.92E+08	9.96E+05	7.31E+05
Th-232	5.91E+06	7.39E+07	3.84E+05	2.83E+05
K-40	2.31E+08	2.89E+09	1.50E+07	1.10E+07

Note that the specific activity threshold for a sampler or laboratory worker is smaller than that for typical radiation worker.

Case 1

Below are data from a hypothetical sample that could be taken to a FUSRAP laboratory for analysis. Gamma spectrometry would be performed on the sample giving the results listed in Table 4: *Gamma Spectrometry Results For a Hypothetical Sample*. The value in the third column is the activity from the prime nuclide as well as the daughters (if any) that are in secular equilibrium with the parent.

Table 4: Gamma Spectrometry Results For a Hypothetical Sample

Prime nuclide	Activity pCi/g	Activity with daughters (pCi/g)
U-238	2000	10000
Th-230	110000	110000
Ra-226	18000	126000
U-235	300	600
Pa-231	5000	5000
Ac-227	5000	50000
Th-232	100	900
K-40	25	25

These hypothetical results were compared to the specific activity limits for a sampler or laboratory worker because that scenario had the lowest limits. The SOR of the dose contributions for the prime nuclides was calculated as follows.

$$SOR = \frac{10000}{4.07E+05} + \frac{110000}{1.31E+07} + \frac{126000}{6.30E+05} + \frac{600}{1.02E+06} + \frac{5000}{2.40E+06} + \frac{50000}{7.31E+05} + \frac{900}{2.83E+05} + \frac{25}{1.10E+07}$$

$$SOR = 2.46E-02 + 8.42E-3 + 2.00E-1 + 5.88E-4 + 2.08E-3 + 6.84E-2 + 3.18E-3 + 2.27E-6$$

$$SOR = 0.307$$

Note that the limits used are designed to keep the dose rate under 10 mrem/h when a 1000 g sample is held at a distance of 30 cm. Even in the unlikely event that the sampler or laboratory worker held the sample at a distance closer than 30 cm, or handled the sample for longer than one hour, the chance for a TLD to acquire enough energy to register a dose is small.

Also note that the limits listed in Table 3 for the declared pregnant worker and for a typical radiation worker are the average specific activity that the worker must be exposed to for the entire period of time used in the calculation to reach the dose used in the calculation. For example, for a declared pregnant worker, the exposure time must be 1600 hours and the limiting dose be equal to 50 mrem for the specific activity limits to be used. If the worker's exposed for one half of the 1600 hours, then the specific activity limit would be one half of the tabulated value. This method's usefulness for tracking dose to a worker is clearly limited when using the dose limit and time factors that were used in the above scenarios.

Discussion

As shown, it is unlikely that external radiation monitoring for personnel will be needed at a typical FUSRAP project. If soils with high specific activity are uncovered at a FUSRAP Project, this method could be used to determine the dose to an individual on a daily or weekly basis, particularly if the means of monitoring using a dosimeter is unreliable. To do this, specific activity limits would be established based upon a dose of unity (1 mrem or 1 mSv). The dose could then be tracked on a daily basis simply by dividing the average soil concentration by the specific activity limits. The daily doses could then be summed over some time period.

The following are some suggestions that would improve this process or generalize it for all FUSRAP sites.

- These limits could be used at other FUSRAP sites by establishing dose limits for the site and by using soil density data from that site. Although the dose limit established by a site may change the calculated specific activity limits, the density of soil should not change much more than ± 20%.
- Other scenarios can be established. Another scenario that may be useful involves surrounding the radiation worker with a volume of radioactive material, for example, when the worker is inside a 5-foot deep trench.
- The linear attenuation coefficients of soil could be calculated if the elemental composition of the soil is known or measured. This would make the gamma ray penetration of the volume source more realistic but the values for the specific activity limits would be less conservative.
- A more accurate depiction of the volume source would have the worker standing on a hemisphere of radioactive material instead of a cylinder of radioactive material. The hemisphere would realistically be centered at the center of mass of the worker's body. For convenience the center of the hemisphere could be the point where the TLD of the worker would be. Again this increase in accuracy would take away some of the conservatism of using a cylinder-shaped source.
- For a very conservative approach, the radius of the volume source could be changed to a much larger number. This radius, which was set equal to ten relaxation lengths of the Tl-208 gamma in concrete, could be changed to ten relaxation lengths of the Tl-208 gamma in air. This would cause the volume source to approximate a plane source. Although the distance of ten relaxation lengths of the Tl-208 gamma is unreasonably large at 1980 m, the values of the specific activity limits calculated from it only decrease by a factor of approximately 20. These limits are shown in Appendix D, Table D: *Detection Limit For a Typical TLD With a*

Very Large Volume Source. The specific activities of most material at FUSRAP sites do not approach these limits.

References

1 *Regulatory Guide 8.34 Monitoring Criteria and Methods to Calculate Occupational Radiation Doses.* US NRC. 1992
2 *Code of Federal Regulations, Title 10: Energy.* 2001.
3 *Handbook of Health Physics and Radiological Health, 3rd Edition.* Eds. Schleien, Slaback, Birky. Williams & Wilkins. Baltimore. 1998
4 *Introduction to Health Physics, 3rd Edition*, Herman Cember, Ph. D. McGraw-Hill, New York. 1996.
5 *Trenching and Excavation Safety.* Zomar Productions, Ltd. 1987.
6 *USACE Radiation Protection Manual.* EM-385-1-80, 1999.

Appendix A
Factors and Limits for Working in a Contaminated Region

Attachments:
Table A1: Monitoring Limits For a Declared Pregnant Worker With a Volume Source
Table A2: Monitoring Limits For a Typical Radiation Worker With a Volume Source
Table A3: Detection Limit For a Typical TLD With a Volume Source

Table A-1 Monitoring Limits For a Declared Pregnant Worker With a Volume Source

	Nuclide	Γ mSv/h MBq	μ_{air} cm^{-1}	C_v MBq/m^3	SA pCi/g	1/SA g/pCi	SA Limit pCi/g
Uranium series	U-238	1.760E-05	2.17E-04	1.75E+07	2.953E+08	3.39E-09	8.684E+06
	Th-234	2.038E-05	2.11E-04	1.51E+07	2.549E+08	3.92E-09	
	$Pa-234^m$	2.776E-06	8.45E-05	1.10E+08	1.859E+09	5.38E-10	
	Pa-234	5.356E-04	1.81E-04	5.75E+05	9.684E+06	1.03E-07	
	U-234	2.097E-05	2.16E-04	1.47E+07	2.478E+08	4.04E-09	
	Th-230	1.861E-05	2.09E-04	1.66E+07	2.791E+08	3.58E-09	2.791E+08
	Ra-226	3.274E-06	1.63E-04	9.40E+07	1.583E+09	6.32E-10	1.341E+07
	Rn-222	7.390E-08	1.11E-04	4.15E+09	6.992E+10	1.43E-11	
	Pb-214	8.742E-05	1.31E-04	3.51E+06	5.917E+07	1.69E-08	
	Bi-214	2.268E-04	1.04E-04	1.35E+06	2.277E+07	4.39E-08	
	Po-214	1.398E-08	9.12E-05	2.19E+10	3.692E+11	2.71E-12	
	Pb-210	6.801E-05	2.19E-04	4.54E+06	7.642E+07	1.31E-08	
	Po-210	1.424E-09	9.11E-05	2.15E+11	3.625E+12	2.76E-13	
Actinium series	U-235	9.159E-05	1.63E-04	3.36E+06	5.657E+07	1.77E-08	2.174E+07
	Th-231	1.473E-04	2.28E-04	2.10E+06	3.530E+07	2.83E-08	
	Pa-231	1.011E-04	2.27E-04	3.05E+06	5.143E+07	1.94E-08	5.143E+07
	Ac-227	2.364E-06	1.95E-04	1.30E+08	2.196E+09	4.55E-10	1.558E+07
	Th-227	1.145E-04	1.51E-04	2.69E+06	4.523E+07	2.21E-08	
	Fr-223	8.930E-05	2.17E-04	3.46E+06	5.819E+07	1.72E-08	
	Ra-223	8.789E-05	1.44E-04	3.50E+06	5.890E+07	1.70E-08	
	Rn-219	1.419E-05	1.43E-04	2.17E+07	3.648E+08	2.74E-09	
	Po-215	2.861E-08	1.20E-04	1.07E+10	1.807E+11	5.53E-12	
	Pb-211	9.836E-06	1.24E-04	3.12E+07	5.257E+08	1.90E-09	
	Bi-211	1.274E-05	1.31E-04	2.41E+07	4.060E+08	2.46E-09	
	Po-211	1.328E-06	1.07E-04	2.31E+08	3.890E+09	2.57E-10	
	Tl-207	3.524E-07	8.80E-05	8.70E+08	1.464E+10	6.83E-11	
Thorium series	Th-232	1.848E-05	2.13E-04	1.67E+07	2.811E+08	3.56E-09	6.011E+06
	Ac-228	2.281E-04	8.75E-05	1.34E+06	2.262E+07	4.42E-08	
	Th-228	2.142E-05	2.02E-04	1.44E+07	2.424E+08	4.13E-09	
	Ra-224	2.967E-06	1.50E-04	1.04E+08	1.745E+09	5.73E-10	
	Rn-220	9.720E-08	1.09E-04	3.16E+09	5.315E+10	1.88E-11	
	Po-216	2.424E-09	1.83E-04	1.27E+11	2.140E+12	4.67E-13	
	Pb-212	7.389E-05	1.50E-04	4.16E+06	7.008E+07	1.43E-08	
	Bi-212	5.264E-05	9.63E-05	5.82E+06	9.808E+07	1.02E-08	
	Tl-208	4.605E-04	5.04E-05	6.64E+05	1.118E+07	8.94E-08	
	K-40	2.208E-05	1.75E-04	1.39E+07	2.348E+08	4.26E-09	2.348E+08

H = 0.5 mSv

r = 1.08 m

h = 1 m

x = 1.08 m

ρ = 1.60E+06 g/m^3

t = 1600 h

Table A-2 Monitoring Limits For a Typical Radiation Worker With a Volume Source

Series	Nuclide	Γ mSv/h MBq	μ_{air} cm^{-1}	C_v MBq/m^3	SA pCi/g	1/SA g/pCi	SA Limit pCi/g
Uranium series	U-238	1.760E-05	2.17E-04	2.19E+08	3.691E+09	2.71E-10	1.086E+08
	Th-234	2.038E-05	2.11E-04	1.89E+08	3.186E+09	3.14E-10	
	Pa-234^m	2.776E-06	8.45E-05	1.38E+09	2.323E+10	4.30E-11	
	Pa-234	5.356E-04	1.81E-04	7.19E+06	1.210E+08	8.26E-09	
	U-234	2.097E-05	2.16E-04	1.84E+08	3.097E+09	3.23E-10	
	Th-230	1.861E-05	2.09E-04	2.07E+08	3.489E+09	2.87E-10	3.489E+09
	Ra-226	3.274E-06	1.63E-04	1.17E+09	1.978E+10	5.05E-11	1.677E+08
	Rn-222	7.390E-08	1.11E-04	5.19E+10	8.740E+11	1.14E-12	
	Pb-214	8.742E-05	1.31E-04	4.39E+07	7.396E+08	1.35E-09	
	Bi-214	2.268E-04	1.04E-04	1.69E+07	2.847E+08	3.51E-09	
	Po-214	1.398E-08	9.12E-05	2.74E+11	4.615E+12	2.17E-13	
	Pb-210	6.801E-05	2.19E-04	5.67E+07	9.552E+08	1.05E-09	
	Po-210	1.424E-09	9.11E-05	2.69E+12	4.531E+13	2.21E-14	
Actinium series	U-235	9.159E-05	1.63E-04	4.20E+07	7.072E+08	1.41E-09	2.717E+08
	Th-231	1.473E-04	2.28E-04	2.62E+07	4.413E+08	2.27E-09	
	Pa-231	1.011E-04	2.27E-04	3.82E+07	6.429E+08	1.56E-09	6.429E+08
	Ac-227	2.364E-06	1.95E-04	1.63E+09	2.745E+10	3.64E-11	1.948E+08
	Th-227	1.145E-04	1.51E-04	3.36E+07	5.653E+08	1.77E-09	
	Fr-223	8.930E-05	2.17E-04	4.32E+07	7.274E+08	1.37E-09	
	Ra-223	8.789E-05	1.44E-04	4.37E+07	7.362E+08	1.36E-09	
	Rn-219	1.419E-05	1.43E-04	2.71E+08	4.560E+09	2.19E-10	
	Po-215	2.861E-08	1.20E-04	1.34E+11	2.259E+12	4.43E-13	
	Pb-211	9.836E-06	1.24E-04	3.90E+08	6.571E+09	1.52E-10	
	Bi-211	1.274E-05	1.31E-04	3.01E+08	5.075E+09	1.97E-10	
	Po-211	1.328E-06	1.07E-04	2.89E+09	4.863E+10	2.06E-11	
	Tl-207	3.524E-07	8.80E-05	1.09E+10	1.831E+11	5.46E-12	
Thorium series	Th-232	1.848E-05	2.13E-04	2.09E+08	3.514E+09	2.85E-10	7.514E+07
	Ac-228	2.281E-04	8.75E-05	1.68E+07	2.828E+08	3.54E-09	
	Th-228	2.142E-05	2.02E-04	1.80E+08	3.030E+09	3.30E-10	
	Ra-224	2.967E-06	1.50E-04	1.30E+09	2.182E+10	4.58E-11	
	Rn-220	9.720E-08	1.09E-04	3.95E+10	6.644E+11	1.51E-12	
	Po-216	2.424E-09	1.83E-04	1.59E+12	2.675E+13	3.74E-14	
	Pb-212	7.389E-05	1.50E-04	5.20E+07	8.760E+08	1.14E-09	
	Bi-212	5.264E-05	9.63E-05	7.28E+07	1.226E+09	8.16E-10	
	Tl-208	4.605E-04	5.04E-05	8.30E+06	1.398E+08	7.15E-09	
	K-40	2.208E-05	1.75E-04	1.74E+08	2.935E+09	3.41E-10	2.935E+09

H =	5	mSv
r =	1.08	m
h =	1	m
x =	1.08	m
ρ =	1.60E+06	g/m^3
t =	2000	h

Table A-3 Detection Limit For a Typical TLD With a Volume Source

Series	Nuclide	Γ mSv/h MBq	μ_{air} cm^{-1}	C_v MBq/m^3	SA pCi/g	1/SA g/pCi	SA Limit pCi/g
Uranium series	U-238	1.760E-05	2.17E-04	1.14E+06	1.919E+07	5.21E-08	5.645E+05
	Th-234	2.038E-05	2.11E-04	9.84E+05	1.657E+07	6.04E-08	
	$Pa-234^m$	2.776E-06	8.45E-05	7.17E+06	1.208E+08	8.28E-09	
	Pa-234	5.356E-04	1.81E-04	3.74E+04	6.294E+05	1.59E-06	
	U-234	2.097E-05	2.16E-04	9.56E+05	1.611E+07	6.21E-08	
	Th-230	1.861E-05	2.09E-04	1.08E+06	1.814E+07	5.51E-08	1.814E+07
	Ra-226	3.274E-06	1.63E-04	6.11E+06	1.029E+08	9.72E-09	8.720E+05
	Rn-222	7.390E-08	1.11E-04	2.70E+08	4.545E+09	2.20E-10	
	Pb-214	8.742E-05	1.31E-04	2.28E+05	3.846E+06	2.60E-07	
	Bi-214	2.268E-04	1.04E-04	8.79E+04	1.480E+06	6.76E-07	
	Po-214	1.398E-08	9.12E-05	1.43E+09	2.400E+10	4.17E-11	
	Pb-210	6.801E-05	2.19E-04	2.95E+05	4.967E+06	2.01E-07	
	Po-210	1.424E-09	9.11E-05	1.40E+10	2.356E+11	4.24E-12	
Actinium series	U-235	9.159E-05	1.63E-04	2.18E+05	3.677E+06	2.72E-07	1.413E+06
	Th-231	1.473E-04	2.28E-04	1.36E+05	2.295E+06	4.36E-07	
	Pa-231	1.011E-04	2.27E-04	1.99E+05	3.343E+06	2.99E-07	3.343E+06
	Ac-227	2.364E-06	1.95E-04	8.47E+06	1.427E+08	7.01E-09	1.013E+06
	Th-227	1.145E-04	1.51E-04	1.75E+05	2.940E+06	3.40E-07	
	Fr-223	8.930E-05	2.17E-04	2.25E+05	3.783E+06	2.64E-07	
	Ra-223	8.789E-05	1.44E-04	2.27E+05	3.828E+06	2.61E-07	
	Rn-219	1.419E-05	1.43E-04	1.41E+06	2.371E+07	4.22E-08	
	Po-215	2.861E-08	1.20E-04	6.97E+08	1.174E+10	8.51E-11	
	Pb-211	9.836E-06	1.24E-04	2.03E+06	3.417E+07	2.93E-08	
	Bi-211	1.274E-05	1.31E-04	1.57E+06	2.639E+07	3.79E-08	
	Po-211	1.328E-06	1.07E-04	1.50E+07	2.529E+08	3.95E-09	
	Tl-207	3.524E-07	8.80E-05	5.65E+07	9.519E+08	1.05E-09	
Thorium series	Th-232	1.848E-05	2.13E-04	1.09E+06	1.827E+07	5.47E-08	3.907E+05
	Ac-228	2.281E-04	8.75E-05	8.73E+04	1.471E+06	6.80E-07	
	Th-228	2.142E-05	2.02E-04	9.36E+05	1.576E+07	6.35E-08	
	Ra-224	2.967E-06	1.50E-04	6.74E+06	1.134E+08	8.82E-09	
	Rn-220	9.720E-08	1.09E-04	2.05E+08	3.455E+09	2.89E-10	
	Po-216	2.424E-09	1.83E-04	8.26E+09	1.391E+11	7.19E-12	
	Pb-212	7.389E-05	1.50E-04	2.70E+05	4.555E+06	2.20E-07	
	Bi-212	5.264E-05	9.63E-05	3.79E+05	6.375E+06	1.57E-07	
	Tl-208	4.605E-04	5.04E-05	4.32E+04	7.270E+05	1.38E-06	
	K-40	2.208E-05	1.75E-04	9.06E+05	1.526E+07	6.55E-08	1.526E+07

H = 0.1 mSv
r = 1.08 m
h = 1 m
x = 1.08 m
ρ = 1.60E+06 g/m^3
t = 520 h

Appendix B
Factors and Limits for Handling Individual Radioactive Samples

Attachments:
Table B: Monitoring Limits For Handling Radioactive Samples

Table B: Monitoring Limits For Handling Radioactive Samples

	Nuclide	Γ mSv m^2/MBq h	A MBq	SA pCi/g	1/SA g/pCi	Prime Nuclides
Uranium series	U-238	1.760E-05	5.114E+02	1.381E+07	7.243E-08	4.068E+05
	Th-234	2.038E-05	4.416E+02	1.192E+07	8.387E-08	
	$Pa-234^m$	2.776E-06	3.242E+03	8.754E+07	1.142E-08	
	Pa-234	5.356E-04	1.680E+01	4.537E+05	2.204E-06	
	U-234	2.097E-05	4.292E+02	1.159E+07	8.630E-08	
	Th-230	1.861E-05	4.836E+02	1.306E+07	7.658E-08	1.306E+07
	Ra-226	3.274E-06	2.749E+03	7.422E+07	1.347E-08	6.302E+05
	Rn-222	7.390E-08	1.218E+05	3.288E+09	3.041E-10	
	Pb-214	8.742E-05	1.030E+02	2.780E+06	3.598E-07	
	Bi-214	2.268E-04	3.968E+01	1.071E+06	9.333E-07	
	Po-214	1.398E-08	6.438E+05	1.738E+10	5.753E-11	
	Pb-210	6.801E-05	1.323E+02	3.573E+06	2.799E-07	
	Po-210	1.424E-09	6.320E+06	1.706E+11	5.860E-12	
Actinium series	U-235	9.159E-05	9.826E+01	2.653E+06	3.769E-07	1.017E+06
	Th-231	1.473E-04	6.110E+01	1.650E+06	6.062E-07	
	Pa-231	1.011E-04	8.902E+01	2.404E+06	4.160E-07	2.404E+06
	Ac-227	2.364E-06	3.807E+03	1.028E+08	9.728E-09	7.308E+05
	Th-227	1.145E-04	7.860E+01	2.122E+06	4.712E-07	
	Fr-223	8.930E-05	1.008E+02	2.721E+06	3.675E-07	
	Ra-223	8.789E-05	1.024E+02	2.765E+06	3.617E-07	
	Rn-219	1.419E-05	6.342E+02	1.712E+07	5.840E-08	
	Po-215	2.861E-08	3.146E+05	8.494E+09	1.177E-10	
	Pb-211	9.836E-06	9.150E+02	2.471E+07	4.048E-08	
	Bi-211	1.274E-05	7.064E+02	1.907E+07	5.243E-08	
	Po-211	1.328E-06	6.777E+03	1.830E+08	5.465E-09	
	Tl-207	3.524E-07	2.554E+04	6.896E+08	1.450E-09	
Thorium series	Th-232	1.848E-05	4.870E+02	1.315E+07	7.605E-08	2.832E+05
	Ac-228	2.281E-04	3.946E+01	1.065E+06	9.387E-07	
	Th-228	2.142E-05	4.202E+02	1.134E+07	8.815E-08	
	Ra-224	2.967E-06	3.033E+03	8.190E+07	1.221E-08	
	Rn-220	9.720E-08	9.259E+04	2.500E+09	4.000E-10	
	Po-216	2.424E-09	3.713E+06	1.002E+11	9.975E-12	
	Pb-212	7.389E-05	1.218E+02	3.289E+06	3.041E-07	
	Bi-212	5.264E-05	1.710E+02	4.616E+06	2.166E-07	
	Tl-208	4.605E-04	1.954E+01	5.277E+05	1.895E-06	
	K-40	2.208E-05	4.076E+02	1.101E+07	9.086E-08	1.101E+07

threshold for monitoring

H = 0.1 mSv/h

d = 0.3 m

m = 1000 g

Appendix C
Nuclide Data

Attachments:
Table C: Nuclide Data

Table C: Nuclide Data

Series	Nuclide	Half-life	[1] Γ mSv/h MBq	[2] μ_{conc} cm^{-1}	[2] μ_{air} cm^{-1}	[3] E MeV					$1/\mu_{conc}$ cm	$1/\mu_{air}$ cm
Uranium Series	U-238	4.47E+09 y	1.760E-05	0.468568	2.17E-04	*0.0496*					2.134	4.60E+03
	Th-234	24.1 d	2.038E-05	0.449114	2.11E-04	*0.0633*	0.0924	0.0928	0.1128		2.227	4.74E+03
	Pa-234m	1.2 m	2.776E-06	0.148946	8.45E-05	0.766	*1.001*				6.714	1.18E+04
	Pa-234	6.7 h	5.356E-04	0.35156	1.81E-04	*0.132*	0.57	0.883	0.926	0.946	2.844	5.53E+03
	U-234	2.44E+05 y	2.097E-05	0.46374	2.16E-04	*0.053*	0.121				2.156	4.64E+03
	Th-230	7.54E+04 y	1.861E-05	0.442866	2.09E-04	*0.0677*	0.142	0.144			2.258	4.78E+03
	Ra-226	1600 y	3.274E-06	0.3008	1.63E-04	*0.186*					3.324	6.14E+03
	Rn-222	3.82 d	7.390E-08	0.2027333	1.11E-04	*0.51*					4.933	8.98E+03
	Pb-214	26.8 m	8.742E-05	0.239015	1.31E-04	0.2419	0.295	*0.352*			4.184	7.66E+03
	Bi-214	19.9 m	2.268E-04	0.1901933	1.04E-04	*0.609*	1.12	1.765	2.204		5.258	9.57E+03
	Po-214	4 s	1.398E-08	0.166038	9.12E-05	*0.7997*					6.023	1.10E+04
	Pb-210	22.3 y	6.801E-05	0.47297	2.19E-04	*0.0465*					2.114	4.58E+03
	Po-210	138 d	1.424E-09	0.16583	9.11E-05	*0.802*					6.030	1.10E+04
Actinium series	U-235	7.04E+08 y	9.159E-05	0.30101	1.63E-04	0.1438	0.163	*0.1857*	0.205		3.322	6.13E+03
	Th-231	1.1 d	1.473E-04	0.502648	2.28E-04	*0.0256*	0.0842				1.989	4.39E+03
	Pa-231	3.28E+04 y	1.011E-04	0.500092	2.27E-04	*0.0274*	0.2837	0.3	0.3027	0.33	2.000	4.41E+03
	Ac-227	21.8 y	2.364E-06	0.397	1.95E-04	0.07	*0.1*	0.16			2.519	5.13E+03
	Th-227	18.7 d	1.145E-04	0.2766	1.51E-04	0.05	*0.236*	0.3	0.304	0.33	3.615	6.62E+03
	Fr-223	21.8 m	8.930E-05	0.468	2.17E-04	*0.05*	0.0798	0.2349			2.137	4.61E+03
	Ra-223	11.4 d	8.789E-05	0.2634	1.44E-04	0.144	0.154	*0.269*	0.324	0.338	3.797	6.95E+03
	Rn-219	4 s	1.419E-05	0.2626	1.43E-04	*0.271*	0.4018				3.808	6.97E+03
	Po-215	3 s	2.861E-08	0.218382	1.20E-04	*0.4388*					4.579	8.36E+03
	Pb-211	36.1 m	9.836E-06	0.226325	1.24E-04	*0.405*	0.427	0.832			4.418	8.07E+03
	Bi-211	2.1 m	1.274E-05	0.239015	1.31E-04	*0.351*					4.184	7.66E+03
	Po-211	0.5 s	1.328E-06	0.1951333	1.07E-04	*0.57*	0.898				5.125	9.33E+03
	Tl-207	4.8 m	3.524E-07	0.157755	8.80E-05	*0.897*					6.339	1.14E+04
Thorium series	Th-232	1.40E+10 y	1.848E-05	0.45522	2.13E-04	*0.059*	0.126				2.197	4.69E+03
	Ac-228	6.1 h	2.281E-04	0.156565	8.75E-05	0.338	*0.911*	0.969	1.588		6.387	1.14E+04
	Th-228	1.9 y	2.142E-05	0.41972	2.02E-04	*0.084*	0.132	0.166	0.216		2.383	4.95E+03
	Ra-224	3.6 d	2.967E-06	0.2746	1.50E-04	*0.241*					3.642	6.67E+03
	Rn-220	55.6 s	9.720E-08	0.1976667	1.09E-04	*0.55*					5.059	9.21E+03
	Po-216	0.1 s	2.424E-09	0.35724	1.83E-04	*0.128*					2.799	5.47E+03
	Pb-212	10.6 h	7.389E-05	0.2754	1.50E-04	*0.239*	0.3				3.631	6.65E+03
	Bi-212	1 h	5.264E-05	0.1752467	9.63E-05	0.04	*0.727*	1.62			5.706	1.04E+04
	Tl-208	3.1 m	4.605E-04	0.09272	5.04E-05	0.277	0.5108	0.583	0.86	*2.614*	10.785	1.98E+04
	K-40		2.208E-05	0.124	1.75E-04	*0.146*					8.054	5.72E+03

[1] The values for Γ were taken from Table 6.2.2 of the Health Physics and Radiological Health Handbook.

[2] The values for μ_{conc} and μ_{air} were interpolated and extrapolated from Cember, Table 5.2 p 137.

[3] The energy listed in italics was the energy used in finding the value for μ_{conc} and μ_{air}.

The shaded cell contains the maximum value for relaxation length.

Appendix D
Detection Limit For a Typical TLD With a Very Large Volume Source

Attachments:
Table D: Detection Limit For a Typical TLD With a Very Large Volume Source

Table D Detection Limit For a Typical TLD With a Very Large Volume Source

Series	Nuclide	Γ mSv/h MBq	μ_{air} cm^{-1}	C_v MBq/m^3	SA pCi/g	1/SA g/pCi	SA Limit pCi/g	SA Limit pCi/g
Uranium series	U-238	1.760E-05	2.17E-04	5.80E+04	9.793E+05	1.02E-06	2.880E+04	5.656E+05
	Th-234	2.038E-05	2.11E-04	5.01E+04	8.455E+05	1.18E-06		
	$Pa\text{-}234^m$	2.776E-06	8.45E-05	3.65E+05	6.165E+06	1.62E-07		
	Pa-234	5.356E-04	1.81E-04	1.90E+03	3.212E+04	3.11E-05		
	U-234	2.097E-05	2.16E-04	4.87E+04	8.219E+05	1.22E-06		
	Th-230	1.861E-05	2.09E-04	5.49E+04	9.258E+05	1.08E-06	9.258E+05	1.818E+07
	Ra-226	3.274E-06	1.63E-04	3.11E+05	5.249E+06	1.91E-07	4.449E+04	8.738E+05
	Rn-222	7.390E-08	1.11E-04	1.37E+07	2.319E+08	4.31E-09		
	Pb-214	8.742E-05	1.31E-04	1.16E+04	1.962E+05	5.10E-06		
	Bi-214	2.268E-04	1.04E-04	4.48E+03	7.554E+04	1.32E-05		
	Po-214	1.398E-08	9.12E-05	7.26E+07	1.225E+09	8.17E-10		
	Pb-210	6.801E-05	2.19E-04	1.50E+04	2.535E+05	3.95E-06		
	Po-210	1.424E-09	9.11E-05	7.12E+08	1.202E+10	8.32E-11		
Actinium series	U-235	9.159E-05	1.63E-04	1.11E+04	1.876E+05	5.33E-06	7.209E+04	1.416E+06
	Th-231	1.473E-04	2.28E-04	6.94E+03	1.171E+05	8.54E-06		
	Pa-231	1.011E-04	2.27E-04	1.01E+04	1.706E+05	5.86E-06	1.706E+05	3.350E+06
	Ac-227	2.364E-06	1.95E-04	4.32E+05	7.282E+06	1.37E-07	5.169E+04	1.015E+06
	Th-227	1.145E-04	1.51E-04	8.89E+03	1.500E+05	6.67E-06		
	Fr-223	8.930E-05	2.17E-04	1.14E+04	1.930E+05	5.18E-06		
	Ra-223	8.789E-05	1.44E-04	1.16E+04	1.953E+05	5.12E-06		
	Rn-219	1.419E-05	1.43E-04	7.17E+04	1.210E+06	8.27E-07		
	Po-215	2.861E-08	1.20E-04	3.55E+07	5.993E+08	1.67E-09		
	Pb-211	9.836E-06	1.24E-04	1.03E+05	1.744E+06	5.74E-07		
	Bi-211	1.274E-05	1.31E-04	7.98E+04	1.347E+06	7.43E-07		
	Po-211	1.328E-06	1.07E-04	7.65E+05	1.290E+07	7.75E-08		
	Tl-207	3.524E-07	8.80E-05	2.88E+06	4.857E+07	2.06E-08		
Thorium series	Th-232	1.848E-05	2.13E-04	5.53E+04	9.325E+05	1.07E-06	1.994E+04	3.915E+05
	Ac-228	2.281E-04	8.75E-05	4.45E+03	7.504E+04	1.33E-05		
	Th-228	2.142E-05	2.02E-04	4.76E+04	8.040E+05	1.24E-06		
	Ra-224	2.967E-06	1.50E-04	3.43E+05	5.788E+06	1.73E-07		
	Rn-220	9.720E-08	1.09E-04	1.04E+07	1.763E+08	5.67E-09		
	Po-216	2.424E-09	1.83E-04	4.21E+08	7.097E+09	1.41E-10		
	Pb-212	7.389E-05	1.50E-04	1.38E+04	2.324E+05	4.30E-06		
	Bi-212	5.264E-05	9.63E-05	1.93E+04	3.253E+05	3.07E-06		
	Tl-208	4.605E-04	5.04E-05	2.20E+03	3.709E+04	2.70E-05		
	K-40	2.208E-05	1.75E-04	4.62E+04	7.788E+05	1.28E-06	7.788E+05	1.529E+07

H =	0.1	mSv
r =	1980	m
h =	1	m
x =	1.08	m
ρ =	1.60E+06	g/m^3
t =	520	h

The gray shaded cells are the SA limit that was calculated when r = 1.08 m.