Development of Generic Standards for Remediation of Radioactively Contaminated Soils in New Jersey

A Pathways Analysis Approach

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Technical Basis Document for N.J.A.C. 7:28-12 (proposed)

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NOTICE

This document represents the technical basis for determining soil remediation standards proposed in NJAC 7:28-12, "Soil Remediation Standards for Radioactive Materials" and should not be used to determine compliance. The soil standards presented in the proposed rule, NJAC 7:28-12.9, require mixing of the uncontaminated surface soil and vertical extent of residual contamination for unrestricted and limited restricted use (to avoid a requirement for maintenance of the uncontaminated surface soil, which the NJDEP Site Remediation Program considers an engineering control). Contact the NJ DEP Bureau of Environmental Radiation (6090984-5400) for a copy of the rule proposal or it may be downloaded from the Radiation Protection Programs web site at http://www.state.nj.us/dep/rpp/index.htm.

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Chapter 1
GENERAL METHODOLOGY

1.1 GENERAL APPROACH TO STANDARD SETTING

The clean-up standards for radioactive materials are based on the Industrial Site Recovery Act (ISRA), N.J.A.C. 13:1K-6 et seq., and the Brownfield and Contaminated Site Remediation Act (BaCSRA), N.J.A.C 58:10B-1 et seq.. These laws establish cleanup criteria for contaminated sites in New Jersey and direct the Department to promulgate generic remediation standards that could be consistently applied across the State. The intent was to move the department away from establishing cleanup standards on a case-by-case basis, while allowing the use of alternative standards for significantly different site circumstances.

In order to establish soil remediation standards, the Department had to consider the term "contaminant" as defined in Section 23 of ISRA. For the purpose of this rule, "radiation" is considered the contaminant which must be controlled, and not each individual radionuclide. This position is based on the fact that it is the collective radiation, not the individual radionuclide, that causes the harmful health effect. Additionally, radiation from different sources may vary in energy intensity and physical state (e.g., gamma ray vs. alpha particle), and cause different degrees of harm to the body. Only the use of established measures of radiation dose can reduce these differences to a common measure of relevance. Furthermore, because "terrestrial" and "in the body" natural background radiation is the sum of all available ambient radionuclides, and because natural background is the soil remediation goal, it is logical to establish "radiation" as the contaminant for this application.

Section 35 d.(1) of ISRA tasks the Department with establishing remediation standards that will not result in more than an additional cancer risk of one in one million. While some controversy exists regarding the magnitude of risks from exposure to levels of radioactivity as low as natural background radiation, the risk estimates published by the National Research Council's Committee on the Biological Effects of Ionizing Radiation[1] and the International Commission on Radiation Protection[2] have not been replaced by any new consensus in the scientific community. Using the estimates from the previously cited publications, the risks associated with naturally occurring background radiation substantially exceed one in one million

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[1] National Academy of Sciences. 1990. *Health Effects of Exposure to Low Levels of Ionizing Radiation*. BEIR V Report. National Academy Press. Washington, D.C..

[2] ICRP Publication 60. 1990. *1990 Recommendations of the International Commission on Radiological Protection*. Annals of the ICRP 21(1-3).

cancer deaths. Therefore, the Department has looked to Section 35 g.(4) of ISRA for legislative direction. That section states that remediation shall not be required beyond the regional natural background levels for any particular contaminant. ISRA further defines regional natural background levels as the concentration of a contaminant consistently present in the environment of the region of the site and which has not been influenced by localized human activities.

For the reasons stated above, risk of fatal cancer cannot be used as a cleanup criteria; as directed by ISRA, the Department has used natural background as the remediation criteria for radioactive materials. In doing so, the Department has recognized that background radiation varies with time and from place to place, and has utilized the naturally occurring variability in radiation that people encounter in their day to day lives as the radiation dose increment to be achieved by a remediation. Further, ISRA directs that regional natural background should be defined as the levels "consistently" found in the region of the site. Recognizing the statistical nature of background radiation, the Department has utilized a one-standard deviation, or approximation thereto, as the measure of the variation that is "consistently" encountered. The radiation from soil remediated to a one standard deviation standard, when added to the average natural background radiation, is less than or equal to the natural background radiation experienced by 16% of the population.

Consequently, the approach taken in this rule is to define the one-standard deviation in naturally occurring background radiation doses from each of the three major pathways of radiation; external gamma radiation, internal deposition of radionuclides, and inhalation of radon gas. The standard deviations of the doses from external gamma and internal deposition were then summed statistically to approximate a one standard deviation value for both pathways. Radon was kept separate because of its unique character. The resulting one standard deviation for the sum of the external and internal background doses is the Total Dose Increment (above background); this was used as the fundamental criteria for soil standard setting. For Ra226, the one standard deviation of background indoor radon concentration was also used as a constraining criteria.

To translate the radiation dose criteria into generic soil standards, the Department has calculated individual Dose Factors, for both Unrestricted Use and Limited Restricted Use, as a function of:

1. the vertical extent (depth) of the contaminated material (VertXtnt); and
2. the depth of uncontaminated soil left or placed on the surface (USS).

Dose Factors are expressed as the maximum individual dose received (mrem/yr) divided by the residual radionuclide concentration in remediated soil (pCi/g). Dose Factors are then divided into the Total Dose Increment to determine the allowed soil concentration increments:

$$C(pCi/g) = \frac{TDI(mrem/yr)}{DF\left(\frac{mrem/yr}{pCi/g}\right)}$$

where:
C = allowable soil Concentration above background
TDI = Total Dose Increment
DF = Dose Factor

For a given combination of residual contamination depth (VertXtnt) and uncontaminated surface soil depth (USS), the maximum value of residual concentration (C)[3] that does not cause either theTotal Dose Increment (TDI) or the Radon Concentration Increment (RCI) to be exceeded is then selected as the standard.

Dose Factors, as described above, were calculated for each radioactive subchain in the three principal naturally-occurring decay chains (Table 1). However, in order to account for ingrowth of progeny, the Dose Factors for certain decay chains were combined. Specifically:

- Pb210+D was combined with Ra226+D;
- Pa231 was combined with Ac227+D; and
- Th228+D and Ra228+D were combined with Th232.

By combining the Dose Factors, the resultant soil standard can then be expressed as the maximum activity concentration of the parent nuclide. In the case of Pa231 and Ac227+D, the resultant standard is expressed in terms of Ac227 because it is easier to measure than Pa231.

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[3] Soil concentration may be averaged over a 1000 ft² area for Unrestricted Use sites or 2400 ft² for Limited Restricted Use (non-residential) sites; also, concentration may be averaged over the depth of vertical extent.

Table 1 Radioactive decay chains in NORM series

Principal Decay Chain	Subchain	Members	Half-life
Uranium-238	U238+D	uranium-238	4.468×10^{9} years
		thorium-234	24.10 days
		proactinium-234m	1.170 minutes
		proactinium-234 (0.13%)	6.75 hours
	U234	uranium-234	2.445×10^{5} years
	Th230	thorium-230	7.700×10^{4} years
	Ra226+D	radium-226	1,600 years
		radon-222	3.823 days
		polonium-218	3.050 minutes
		lead-214 (99.98%)	26.80 minutes
		astatine-218 (0.02%)	~2 seconds
		bismuth-214	19.90 minutes
		polonium-214 (99.98%)	1.637×10^{-4} seconds
		thallium-210 (0.02%)	1.3 minutes
	Pb210+D	lead-210	22.26 years
		bismuth-210	5.013 days
		polonium-210	138.4 days
		lead-206	stable
Uranium-235	U235+D	uranium-235	7.038×10^{8} years
		thorium-231	25.52 hours
	Pa231	proactinium-231	3.726×10^{4} years
	Ac227+D	actinium-227	21.77 years
		thorium-227 (98.6%)	18.72 days
		francium-223 (1.4%)	22 minutes
		radium-233	11.43 days
		radon-219	3.960 seconds
		polonium-215	1.778×10^{-3} seconds
		lead-211	36.10 minutes
		bismuth-211	2.130 minutes
		thallium-207 (99.7%)	4.770 minutes
		polonium-211 (0.28%)	0.52 seconds
		lead-207	stable
Thorium-232	Th232	thorium-232	1.405×10^{10} years
	Ra228+D	radium-228	5.750 years
		actinium-228	6.130 hours
	Th228+D	thorium-228	1.930 years
		radium-224	3.620 days
		radon-220	55.61 seconds
		polonium-216	0.146 seconds
		lead-212	10.64 hours
		bismuth-212	60.55 minutes
		polonium-212 (64%)	2.980×10^{-7} seconds
		thallium-208 (36%)	3.053 minutes
		lead-208	stable

1.2 SITE USE SCENARIOS

The Department performed generic dose calculations for both Unrestricted Use and Limited Restricted Use sites. The assumptions for Unrestricted Use were based on residential building construction, while the assumptions for Limited Restricted Use were based on commercial building construction. For each use, it considered a building excavation scenario that would result in contaminated material being brought to the surface (Figure 1). Two types of construction - slab on grade and basement - were used to evaluate the building excavation scenario (Figure 2). Allowable soil concentration increments (generic cleanup standards) were calculated for both slab on grade and basement excavation scenarios. The more restrictive concentration increment (or set of increments when the contamination consists of more than one subchain) defines the applicable standards for a particular site. Thus, adherence to that standard would allow any type of construction on site. By selecting the more restrictive construction scenario for all applicable subchains together rather than independently, the Department avoids a potentially important source of redundant conservatism: selecting the more restrictive scenario for each subchain independently when in reality only one construction scenario can result in the maximum exposure for a given site. See section 4.2 for an example of how the applicable standards are determined for a site contaminated with more than one subchain.

BaCSRA also allows an applicant or licensee to propose alternatives to the generically derived soil concentrations based on unique site or contamination characteristics, or alternative site uses. Any such alternative soil remediation standards shall be based on a Department approved dose assessment and be as protective of human health and the environment as the generic standards established in this rule. In other words, the alternative soil remediation standards must not exceed the Total Dose Increment (TDI) or Radon Concentration Increment (RCI) as defined previously and quantified later in Chapter 2.

For instance, an applicant may wish to propose an alternate use for the site, such as a golf course. As another example, an applicant may stipulate that the drinking water pathway does not exist because the underlying groundwater is not capable of yielding a drinking water supply. Other uses and scenarios are of course possible and can also be dealt with in the alternate standards section of the rule. Alternate standards can be based on modifications to the Department's generic analyses or the applicant's own analysis pursuant to N.J.A.C. 7:28-12.12. The spreadsheet that implements the Department's methodology can accommodate many simple alternative scenarios by changing input parameters (where justified) or "turning off" irrelevant pathways. Alternative risk assessment methodologies shall be consistent with those developed by the U.S. Environmental Protection Agency pursuant to the "Comprehensive Environmental Response, Compensation and Liability Act," 42 U.S.C. §9601 et seq. and other statutory authorities as applicable.

Figure 1 Building excavation scenario

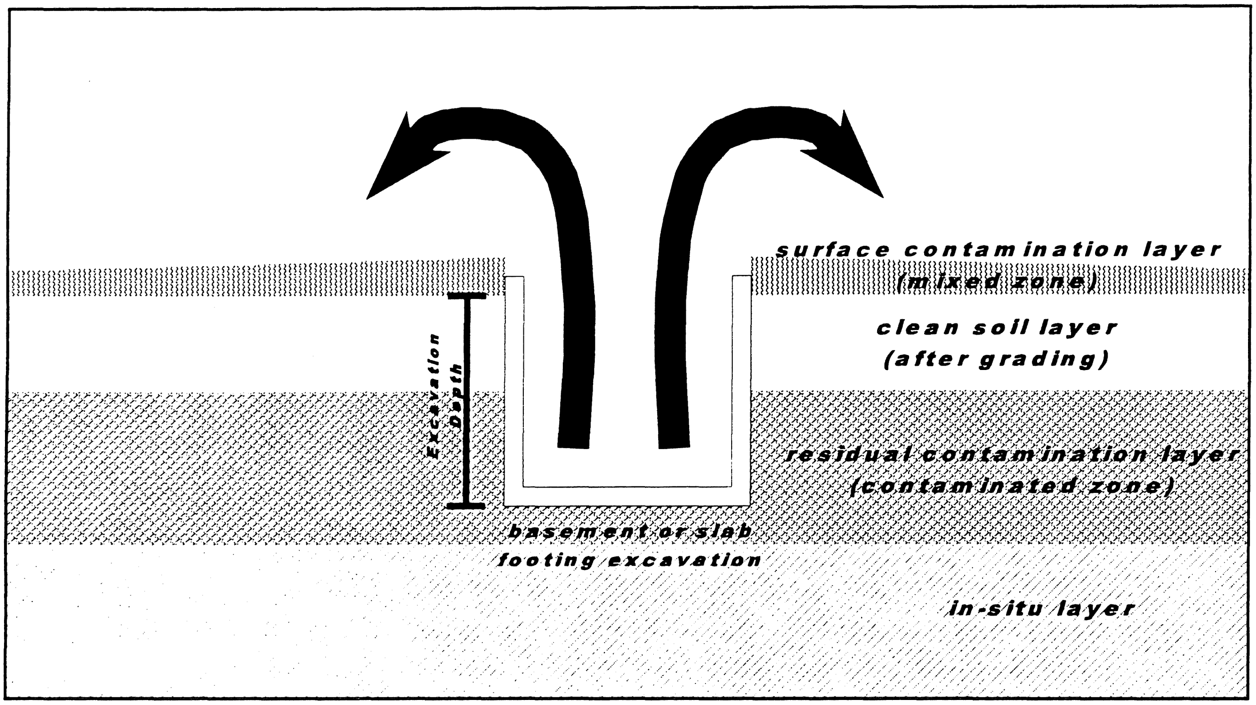

Figure 2 Construction scenarios

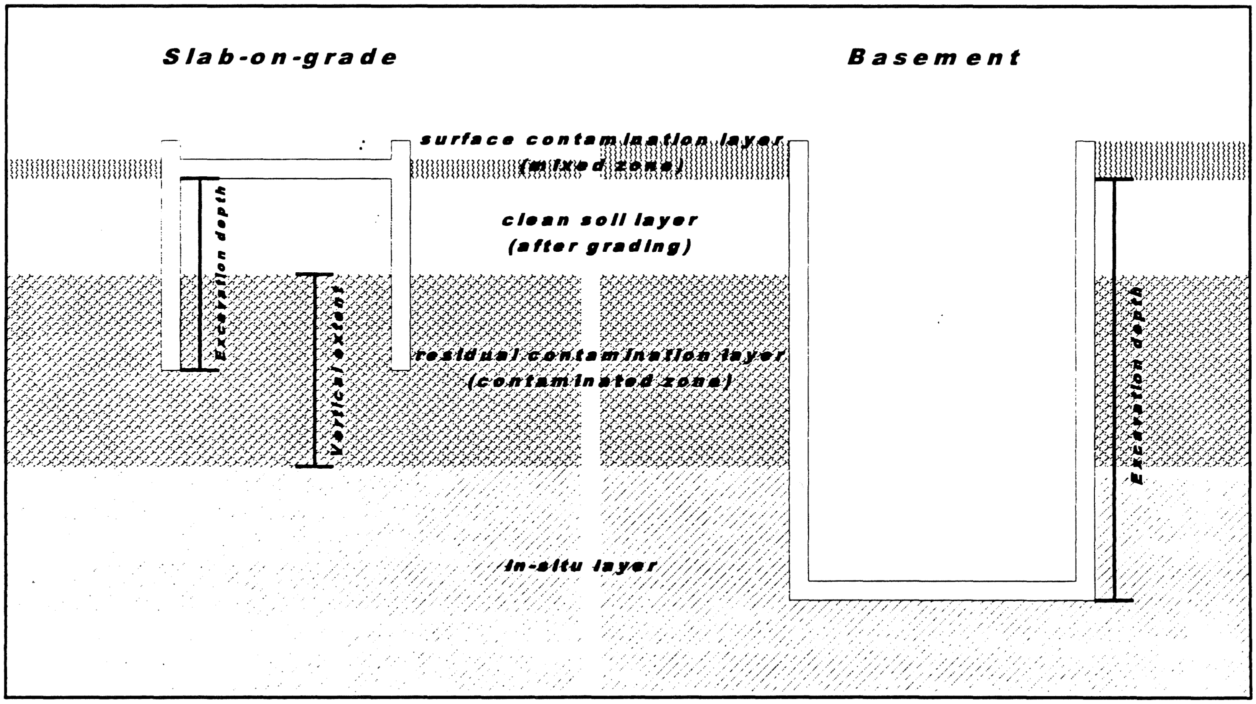

Table 2 Assumed Parameters for Pathway Analyses

ASSUMPTIONS PERTAINING TO EXCAVATION SCENARIO		
cover lost from grading (ft):	1.0	
Parameters Specific to Construction Scenario	**Basement**	**Slab on Grade**
depth of excavation (ft):	7.0	4.0
width of excavation (ft):		2.0
Parameters Specific to Site Use Scenario	**Residential**	**Commercial**
building length (ft):	40	60
building width (ft):	25	40
lot size ((ft^2):	5,000	10,890
fraction of time spent indoors on site:	70%	18%
fraction of time spent outdoors on site:	5%	5%
ASSUMPTIONS PERTAINING TO EXTERNAL GAMMA PATHWAY		
shielding factor through basement or slab:	0.20	
shielding factor through walls:	0.80	
shielding factor outside:	1.00	
cover coefficient (% through 1 ft clean soil):	10%	
Parameters Specific to Site Use Scenario	**Residential**	**Commercial**
area factor for under basement or slab:	0.54	0.63
area factor for side contribution:	0.24	0.32
area factor for four basement walls:	1.32	1.66
area factor for outside:	0.78	0.95
ASSUMPTIONS PERTAINING TO INTAKE PATHWAYS		
indoor dust level as percent of outdoor:	40%	
resuspension dilution length (ft):	10	
drinking water consumption rate (l/yr):	700	
root depth (ft):	3	
Parameters Specific to Site Use Scenario	**Residential**	**Commercial**
soil ingestion rate (g/yr):	70	12.5
outdoor mass loading ($\mu g/m^3$):	100	200
indoor on site breathing rate of adult (m^3/hr):	0.63	1.20
outdoor on site breathing rate of adult (m^3/hr):	1.40	1.20
homegrown crop ingestion rate (g/yr):	14,235	0
ASSUMPTIONS PERTAINING TO RADON PATHWAY		
radon to radium ratio (pCi/l per pCi/g):	1.5	

1.3 ASSUMED PARAMETERS

The parameters assumed for the various pathway analyses are listed in Tables 2 and 3.[4] ISRA directs the Department to make use of the guidance and regulations for exposure assessment developed by the federal Environmental Protection Agency. Such guidance was obtained from the EPA Exposure Factors Handbook[5] and the supplemental Superfund guidance, Standard Default Exposure Factors[6]. For those parameters that were not included in EPA guidance, the Department turned to the Nuclear Regulatory Commission[7] and the Department of Energy[8].

1.3.1 ASSUMPTIONS PERTAINING TO EXCAVATION SCENARIO

It was assumed that one foot of uncontaminated surface soil would be removed from grading prior to construction. For slab on grade construction, a footing excavation around the perimeter of the house four feet deep and two feet wide was assumed; for basement construction, a seven feet depth of excavation was assumed over the full area of the structure. Recall that the assumptions for Unrestricted Use were based on residential building construction, while the assumptions for Limited Restricted Use were based on commercial building construction. For residential construction, a house of 25'×40' and a plot size of 50'×100' were assumed; for commercial construction, a building of 40'×60' and a plot size of ¼ acre were assumed.

Exposure calculations for both residential and commercial scenarios also require the fraction of time spent indoors on site and the fraction of time spent outdoors on site. Values have been suggested by federal agencies for a residential scenario:

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[4] Note that the parameters for the drinking water pathway are presented in Appendix A since they are inseparably related to the drinking water methodology.

[5] U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043.

[6] U.S. Environmental Protection Agency. 1991. *Risk Assessment Guidance for Superfund: Volume 1: Human Health Evaluation Manual Supplemental Guidance: Standard Default Exposure Factors: Interim Final..* OSWER Directive: 9285.603.

[7] U.S. Nuclear Regulatory Commission. 1994. *Scenarios for Assessing Potential Doses Associated with Residual Radioactivity.* Policy and Guidance Directive PG-8-08.

[8] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8.

Residential Scenario

	EPA[9]					
	adults	women	children	NRC[10]	DOE[11]	NJDEP
time spent indoors at home	62%	68%	73%	40%	50%	70%
time spent outdoors at home	2%	1%	7%	10%	25%	5%
time spent away from home	36%	31%	20%	50%	25%	25%

EPA's values were based on time use data for adult men and women as well as children (ages 3 to 17 during the school year). No data were cited for the NRC or DOE values. Because EPA's values are based on real data and because ISRA directs the Department to use EPA Superfund guidance when appropriate, the Department looked primarily to the EPA for residential occupancy values. However, EPA's time use data for adults included working residents. The Department, desiring to achieve a standard protective for children as well as adults, chose 75% as the fraction of total time spent at home and selected 5% as the fraction of total time spent outdoors at home. The total time spent at home (75%) is equivalent to the DOE's value, and is about halfway between the EPA's value for women (69%) and the EPA's value for children (80%). The time outdoors at home (5%) is between EPA's value for adults of 2% and NRC's value of 10%, and corresponds to an average of 1.2 hours per day outside at home. As a "sanity check" on the value for time spent outdoors at home, the Department asked a mother who stays at home with pre-school children to estimate the time her children spend outside at home on a seasonal basis:

3 months summer	4 hrs/day	5 days/wk
6 months spring/fall	2.5 hrs/day	4 days/wk
3 months winter	¾ hrs/day	4 days/wk

These seasonal estimates include time spent at the pool and are intended to account for inclement weather and time away from home, excluding vacation. Assuming annual occupancy of 350 days per year, the "sanity check" is equivalent to about 6% time spent outdoors at home. This provides an additional level of confidence that the value of 5% selected by the Department is reasonable.

Occupancy values for the commercial scenario (18% indoors; 5% outdoors) were taken from the NRC because neither the EPA nor DOE offer comparable guidance. Fraction of total

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[9] U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043. Part I, pp.5-25 to 5-28.

[10] U.S. Nuclear Regulatory Commission. 1994. *Scenarios for Assessing Potential Doses Associated with Residual Radioactivity.* Policy and Guidance Directive PG-8-08. p.7.

[11] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp.96-97.

time spent at work is assumed to be 23%, corresponding to 8 hours/day × 5 days/week × 50 weeks/year. Of the time spent at work, 20% is assumed to be outdoors.

1.3.2 ASSUMPTIONS PERTAINING TO EXTERNAL GAMMA PATHWAY

Shielding factors are simply unitless values between 0 and 1 that estimate the fraction of gamma radiation that penetrates a given barrier. Not having specific site information, the Department made the typical[12] assumption that outside terrain and vegetation do not provide shielding; the outside shielding factor was therefore set equal to 1. Comparable values for inside gamma shielding factors were difficult to obtain because the Department's methodology required separating indoor gamma into components from two sources:

1. radiation from excavated surface contamination penetrating through the exterior walls to a receptor in the building; and
2. radiation from buried contamination penetrating through the basement to a receptor in the building.

On the other hand, indoor shielding factors in the literature are usually presented as a composite that includes both basement floor and interior wall shielding. The Department's literature search discovered a wide range of values and several inconsistencies. Shielding factors were therefore estimated using general shielding software (QUAD-CGCP). Using Ra-226 as the source, the analysis was performed by calculating the exposure from under the house and from the surrounding area with a structure present and with no structure present. The ratio of the two is the shielding factor. The contaminated area was 10,000 m^2, which was contaminated to a depth of 2m. The home was assumed to have a 1500 ft^2 footprint. The walls were assumed to be 1.25 inches thick made of wood and plaster. The basement floor and slab were assumed to be 4 inches of concrete. The results of the model indicate shielding factors of 0.8 for walls and 0.2 for basement or slab. As expected, published composite indoor shielding factors of 0.70[13] and 0.33[14] fall between these values.

Similar to shielding factors, cover factor estimates the fraction of radiation penetrating clean soil. It is calculated by multiplying a cover coefficient to the power of soil depth in feet. A

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[12] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. p.129.

Kennedy, W.E. Jr. and D.L. Strenge. 1992. *Residual Radioactive Contamination from Decommissioning.* NUREG/CR-5512, PNL-7994, Vol. 1.. p. 6.37.

[13] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. p.129.

[14] Kennedy, W.E. Jr. and D.L. Strenge. 1992. *Residual Radioactive Contamination from Decommissioning.* NUREG/CR-5512, PNL-7994, Vol. 1. p. 6.37.

rule of thumb value of 0.1 was used for soil cover coefficient. In other words, each foot of clean soil reduces gamma exposure by 90%. While both shielding factor and cover coefficient technically vary with radionuclide, the external gamma pathway calculations are not sensitive enough to these parameters (shielding factor and cover factor) to warrant varying them. In other words, within the ranges in which these parameters are known to vary, it does not matter what value is selected because it makes little difference in the resultant dose factor.

Area factors correct for the degree to which the source area is smaller than infinite in lateral extent. Using dimensions from the residential and commercial scenarios, area factors were linearly interpolated from the values in Table 50.1 of the DOE Data Collection Handbook[15]. While area factors for a given source vary between 0 and 1, the values for soil adjacent to the basement walls are greater than one because they include the contributions from all four walls. The detailed derivation of area factors is related to the external gamma methodology and is therefore presented in the Pathway Analyses chapter (3.1) of this document.

1.3.3 ASSUMPTIONS PERTAINING TO INTAKE PATHWAYS

1.3.3.1 Soil Ingestion

Numerous attempts have been made to estimate the soil ingestion rates for both children and adults[16]. Initially, soil ingestion studies were based on observations of mouthing behaviors

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[15] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp.131-132.

[16] Lepow,M.L., L.Bruckman, M.Gillette, S.Markowitz, R.Robino, and J.Kapish. 1975 *Investigations into Sources of Lead in the Environment of Urban Children.* Environmental Research 10:415-426.

Binder, S., D.Sokoal, and D.Maughan. 1986. *Estimating Soil Ingestion: The Use of Tracer Elements in Estimating the Amounts of Soil Ingested by Young Children.* Archives of Environmental Health 41:341-345.

Kimbraugh,R, H.Falk, P.Stehr, and G.Fries. 1984. *Health Implications of TCDD Contamination of Residential Soil.* Journal of Toxicology and Environmental Health 14:47-93.

Calabrese,E., R.Barnes, E.Stanek, H.Pastides, C.Gilbert, P.Veneman, X.Wang, A.Lasztity and K.Kostecki. 1989. *How Much Soil Do Young Children Ingest: An Epidemiological Study.* Regulatory Toxicology and Pharmacology 10:123-137.

Calabrese,E., E.Stanek, C.Gilbert, and R,Barnes. 1990. *Preliminary Adult Soil Ingestion Estimates: Results of a Pilot Study.* Regulatory Toxicology and Pharmacology 12:88-95.

Calabrese,E., and E.Stanek. 1991. *A Guide to Interpreting Soil Ingestion Studies.* Regulatory Toxicology and Pharmacology 13:278-292.

Hixson,E., R.Jennings, and S.Smith. 1992. *Contribution of Childhood Ingestion of Contaminated Soil to Lifetime Carcinogenic Risk: Guidance for Inclusion in Risk Assessment.* Superfund Risk Assessment in Soil Contamination Studies. ASTM STP 1158. K.Hoddinott,ed. American Society for Testing and Materials, Philadelphia, PA.

U.S.E.P.A. 1989. *Interim Final Guidance on Soil Ingestion Rates.* USEPA, Washington, DC.

in children. There were orders of magnitude variation in the results derived from these qualitative evaluations and the risk assessment community showed little confidence in the findings. Attempting to reduce the subjectivity in the findings, studies were later designed to track the movement of various elements (aluminum, silicon and titanium) through the digestive tracts of test subjects. These elements are found in varying abundance in soil and make good tracers because they are not readily absorbed by the human digestive tract. By establishing the concentrations of these elements in soils and then measuring their levels in feces, a quantitative analysis is made that more closely reflects the actual soil ingestion rate. However, even these methods have shortcomings such as small sample groups and the difficulty in determining the contribution of these elements from foodstuffs consumed during the study. Although ingestion rates as high as 10,000 mg/d have been reported for children exhibiting pica, the consumption of abnormally high amounts of non-foodstuffs, the mean soil intakes for children are reported to be between 180-250 mg/d. The USEPA recommends a daily ingestion rate of 200 mg/d for children. The data for adults are somewhat limited with values in the 50 to 100 mg/d range. The USEPA uses 100 mg/d in its risk assessments for adults.[17]

In this proposal, soil standards for internally deposited radionuclides are based on one standard deviation of the mean natural background dose determined from national data (NCRP 94). This approach differs from that of the USEPA,[18] which uses a lifetime excess cancer risk based analysis for determining allowable incremental soil concentrations. Such an approach requires that a time weighted average for soil ingestion be taken in account. EPA uses a thirty year average in its calculation of soil ingestion rates, acknowledging that soil intakes vary over the age of the individual. In addition, EPA has developed a Soil Ingestion Factor that takes into account the body weights of individuals over time to establish the soil ingestion input. The purpose is to account for the higher body burden that children, due to their lower body weights, experience when they consume toxic materials. The proposed soil ingestion pathway analysis herein does not consider the lifetime risk, but the annual dose, thereby negating the need to calculate soil ingestion rates for a lifetime. In this instance, because children are at the greatest risk from soil ingestion, and to insure that DEP considers the reasonable maximally exposed individual, the soil rate used in this analysis is 70 g/yr (200 mg/d for 350 d/yr) for the residential scenario. For the commercial scenario, the USEPA recommended value of 12.5 g/yr (50 mg/d for 250 d/yr) is used.

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[17] U.S. Environmental Protection Agency. 1991. *Risk Assessment Guidance for Superfund: Volume 1: Human Health Evaluation Manual Supplemental Guidance: Standard Default Exposure Factors: Interim Final.*. OSWER Directive: 9285.603.

[18] U.S.E.P.A. 1991. *Human Health Evaluation Manual - Volume 1 (Part B), Development of Risk-based Preliminary Remediation Goals*. EPA/540/R-92/003.

1.3.3.2 Inhalation

Most of the inhalation parameters used by the Department were taken from DOE guidance[19], which was based on extensive literature review. The value for indoor dust level (40% of outdoor level) is comparable to the 50% value used by the NRC.[20] The generic value for dilution length (used by both DOE and NRC) accounts for dilution of suspended dust from "clean" soil off-site. An outdoor mass loading of 200 $\mu g/m^3$, the generic value suggested by both DOE and NRC, was used for the commercial scenario. However, since that value was based on industrial and agricultural data, the Department sought a more realistic value for the residential scenario. The outdoor mass loading of 100 $\mu g/m^3$ was therefore selected for the residential scenario based on NRC decommissioning guidance.[21]

Estimates of daily inhalation rate range from 15 to 30 m^3/day, with 20 m^3/day being considered a "reasonably conservative inhalation rate for total exposures at home and in the workplace."[22] If activity levels inside the home, outside the home, and away from home were the same, the daily rate of 20 m^3/day would correspond to an average hourly rate of 0.83 m^3/hr. In order to avoid "redundant conservatism," the Department chose to account for the substantially different inhalation rates between activities performed inside versus outside, as well as home versus work. Average inhalation rates for indoor and outdoor activities (0.63 and 1.4 m^3/hr, respectively[23]) were used for the residential scenario. Since the EPA guidance for the worker scenario included time spent away from work, it could not be used to determine the average inhalation rate while actually at work. The Department presumed that activity levels at work would be higher than the total average, which includes time spent at rest. Therefore the

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[19] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8, 36.2. pp.110-112.

Yu., C., *et al.* 1993. *Manual for Implementating Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2. pp.141-145.

[20] U.S. Nuclear Regulatory Commission. 1994. *Scenarios for Assessing Potential Doses Associated with Residual Radioactivity.* Policy and Guidance Directive PG-8-08. p.7.

[21] Kennedy, W.E. Jr. and D.L. Strenge. 1992. *Residual Radioactive Contamination from Decommissioning.* NUREG/CR-5512, PNL-7994, Vol. 1. pp.6.10-6.12.

[22] U.S. Environmental Protection Agency. 1991. *Risk Assessment Guidance for Superfund: Volume 1: Human Health Evaluation Manual Supplemental Guidance: Standard Default Exposure Factors: Interim Final..* OSWER Directive: 9285.603. Attachment A.

[23] U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043. Part I, p.3-8.

Department chose to use the NRC's inhalation rate of 1.2 m^3/hr[24] for the commercial scenario indoor and outdoor breathing rates. For comparison, the DOE's default average inhalation rate is 0.96 m^3/hr.[25]

1.3.3.3 Crop ingestion

Root depth is used to calculate the fraction of root within the the mixed surface layer and the buried contaminated layer. DOE uses a similar approach and estimates root depth to be 0.9m (3ft.). DOE notes that while root depth varies by more than an order of magnitude among plant species, "most of the plant roots from which nutrients are obtained, however, usually extend to less than 1 m below the surface."[26]

Homegrown crop ingestion rate (g/yr) was calculated from EPA guidance presented in the Exposure Factors Handbook[27] (see Appendix A for other sources considered). The average amounts of total fruits and total vegetables consumed were estimated to be 140 and 200 g/d, respectively. Furthermore, the average homegrown fraction was estimated to be 20% for fruits and 25% for vegetables. EPA noted that the number of days per year homegrown fruits and vegetables are consumed depends on the length of the particular harvesting seasons and whether they are preserved (canned). While offering no data, EPA estimated that homegrown fruits and vegetables are eaten 20-50% of the year. The Department chose to use 50% of the year in order to account for the practice of canning homegrown produce. Homegrown grains, which were included by both DOE[28] and NRC[29], were excluded from consideration because they are not commonly grown in residential gardens. The annual homegrown crop ingestion rate of 14,235 g/yr was therefore obtained by adding 20% of 140 to 25% of 200, and then multiplying by 50% of 365 days.

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[24] U.S. Nuclear Regulatory Commission. 1994. *Scenarios for Assessing Potential Doses Associated with Residual Radioactivity.* Policy and Guidance Directive PG-8-08. p.7.

[25] Yu., C., *et al.* 1993. *Manual for Implementating Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2. p.144.

[26] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8, 36.2. pp.113.

[27] U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043. Part I, pp.2-10 to 2-24 and Part II, pp.1-8 to 1-10.

[28] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8, 36.2. pp.121-122.

[29] U.S. Nuclear Regulatory Commission. 1994. *Scenarios for Assessing Potential Doses Associated with Residual Radioactivity.* Policy and Guidance Directive PG-8-08. p.A3.

1.3.4 ASSUMPTIONS PERTAINING TO RADON PATHWAY

Radon gas is a direct progeny of radium and therefore dependent on radium. Radon concentration in the home depends on many factors, including the soil radium concentration, the radon emanation fraction, soil texture, and specific house conditions. In order to support a standard that is generic for any site in New Jersey, factors other than soil radium concentration and depth must be ignored or held constant. As a first approximation, the Department compared the average New Jersey soil radium content to the average New Jersey indoor radon concentration. Limited data on New Jersey's soil radium content suggest an average soil radium concentration of about 0.9 pCi/g.[30] According to radon screening test data maintained by the Department's Radon Program, the statewide average geometric mean Radon concentration in New Jersey homes is about 1.35 pCi/l. Taken together, these data suggest an indoor radon to soil radium ratio of 1.5 pCi/l per pCi/g. Radon to radium ratios range from less than 0.2 to more than 2, with values greater than 1 being typical for the sandy soils found throughout many parts of New Jersey.[31]

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[30] Myrick, T.E., B.A. Berven, and F.F. Haywood. 1983. *Determination of Concentrations of Selected Radionuclides in Surface Soil in the U.S.*. Health Physics 45(3):631-642.

[31] Nielson, K.K. and V.C. Rogers. 1996. *Soil Radium Standards based on Radon/Radium Ratios*. Rogers & Associates Engineering Corporation.

Table 3 Subchain-Specific Factors

Subchain	$\mathrm{DCF}^{a}_{\mathrm{external}\,\infty}$	$\mathrm{DCF}^{a}_{\mathrm{external\,5cm}}$	$\mathrm{DCF}^{b}_{\mathrm{ingestion}}$	$\mathrm{DCF}^{b}_{\mathrm{inhalation}}$	Transfer Factor^{c}
U238+D	1.289E-01	7.881E-02	2.682E-04	1.184E-01	2.500E-03
U234	4.016E-04	3.400E-04	2.834E-04	1.325E-01	2.500E-03
Th230	1.209E-03	9.751E-04	5.476E-04	3.256E-01	1.000E-03
Ra226+D	1.118E+01	5.864E+00	1.326E-03	8.598E-03	4.000E-02
Pb210+D	6.105E-03	5.016E-03	7.273E-03	2.317E-02	7.647E-03
U235+D	7.575E-01	5.247E-01	2.674E-04	1.228E-01	2.500E-03
Pa231	1.905E-01	1.207E-01	1.058E-02	1.284E+00	1.000E-02
Ac227+D	2.012E+00	1.285E+00	1.476E-02	6.721E+00	2.500E-03
Th232	5.212E-04	4.408E-04	2.731E-03	1.639E+00	1.000E-03
Ra228+D	5.978E+00	3.232E+00	1.438E-03	5.081E-03	4.000E-02
Th228+D	1.021E+01	5.031E+00	8.084E-04	3.449E-01	1.000E-03

^{a}external Dose Conversion Factors expressed in mrem/yr per pCi/g

^{b}internal Dose Conversion Factors expressed in mrem per pCi

^{c}Transfer Factors expressed in pCi/g wet crop per pCi/g dry soil

1.3.5 SUBCHAIN-SPECIFIC FACTORS

Dose calculations were performed through the use of a simple ratio between effective dose and exposure. These ratios, called Effective Dose Conversion Factors (DCFs), are specific to each radionuclide as well as to the mode of exposure (internal, external, or inhalation); they account for the efficacy of the radionuclide as well as its distribution and residence time in the body. DCFs were obtained from applicable EPA Federal Guidance Reports[32] (see Appendix A for other sources considered). DCFs for subchains were obtained by adding together the DCFs for individual member nuclides, consistent with the assumption that they are in secular equilibrium with the subchain parent. In cases where member nuclides are in equilibrium at concentrations less than 100% of the subchain parent, the individual DCF was multiplied by that percentage. For ingestion and inhalation, more than one DCF is frequently listed to account for

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[32] Eckerman, K.F., A.B. Wolbarst, and A.C.B. Richardson. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.* Federal Guidance Report No. 11. EPA-520/1-88-020.

Eckerman, K.F. and J.C. Ryman. 1993. *External Exposure to Radionuclides in Air, Water, and Soil.* Federal Guidance Report No. 12. EPA 402-R-93-081.

various common chemical forms. The highest effective DCFs were selected so that the resultant standard would be protective for most chemical forms of contamination.

Uptake of radionuclides by crops was calculated using Vegetative Transfer Factors, which are simply ratios between the radionuclide concentration in vegetation and soil; they are specific to chemical forms of each element, type of vegetation, and soil environment. Transfer Factors were obtained from the suggested default RESRAD values published in the most recent compilation performed by the DOE[33] (see Appendix A for other sources considered). With one exception, Transfer Factors for the parent element of each subchain were used to estimate vegetative transfer for the entire subchain. This is consistent with the assumption that the presence of progeny in the vegetation is dependent on decay of the subchain parent taken up into the vegetation, not by transfer of progeny directly from the soil. Such an assumption is valid for progeny with small half-lives relative to the time between uptake and consumption. All the progeny have half-lives less than 30 days except polonium-210, which has a half-life of 138.4 days. Clearly, polonium-210 concentration would be driven by direct uptake from the soil rather than decay of bismuth-210 in the vegetation. To account for the direct uptake of polonium-210, the Transfer Factor for the lead-210 subchain was modified by calculating the average between the Transfer Factors of lead-210 and polonium-210 weighted by their respective DCFs.

1.4 CALCULATED PARAMETERS

Conceptually, the excavation scenario depicted in Figure 1 results in contaminated material being brought to the surface during building excavation and spread over the site at a certain depth and concentration. Since the excavated contamination is mixed with "clean" soil as it is spread over the top of the site, it can be referred to as the "mixed zone" to distinguish it from the buried "contaminated zone." The following two calculated parameters are used to define the mixed zone so that its contribution to each dose pathway can be analyzed.

1.4.1 MIXING FACTOR

"Mixing Factor" is the concentration of contamination in the mixed zone expressed as a fraction of the contamination concentration in the contaminated zone. A Mixing Factor of 0.25, for instance, means that the contamination concentration in the mixed zone is 25% of the residual concentration left in the contaminated zone. Since it is a function of the depth of excavation, Mixing Factor varies with excavation scenario (basement/slab). Notice that the Mixing Factor must be a number between zero and one, and that it varies with both the depth of uncontaminated

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[33] Wang, Y.-Y., B.M. Biwer, and C. Yu. 1993. *A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code*. ANL/EAIS/TM-103. pp. 22-24.

surface soil and the vertical extent of contamination. Also, the Mixing Factor is set to 1 (no dilution) if there is no uncontaminated surface soil, since it would no longer be conservative to assume that the excavated material would cover the entire property.

$$MF=\begin{cases} 0 & \text{if } Clean \geq ExcvDpth \\ \dfrac{VertXtnt}{ExcvDpth} & \text{if } (Clean+VertXtnt) \leq ExcvDpth \text{ and } USS>0 \\ \dfrac{(ExcvDpth-Clean)}{ExcvDpth} & \text{if } (Clean+VertXtnt)>ExcvDpth>Clean \text{ and } USS>0 \\ 1 & \text{if } USS=0 \end{cases}$$

where:

MF = Mixing Factor (MF_{base} or MF_{slab})
Clean = depth of "Clean" soil left on surface after grading (ft.)
ExcvDpth = Depth of Excavation ($ExcvDpth_{base}$=7ft., $ExcvDpth_{slab}$=4ft.)
VerXtnt = Vertical eXtent of contamination (ft.)
USS = depth of "Clean" soil left on surface after remediation (ft.)

1.4.2 MIXING DEPTH

"Mixing Depth" is the depth of excavated material spread on the surface. Since it is a function of both excavated volume and lot size, Mixing Depth varies with excavation scenario (basement/slab) as well as site use scenario (residential/commercial). However, since Mixing Depth does not vary with either cover depth or vertical extent, its values are fixed for a given scenario.

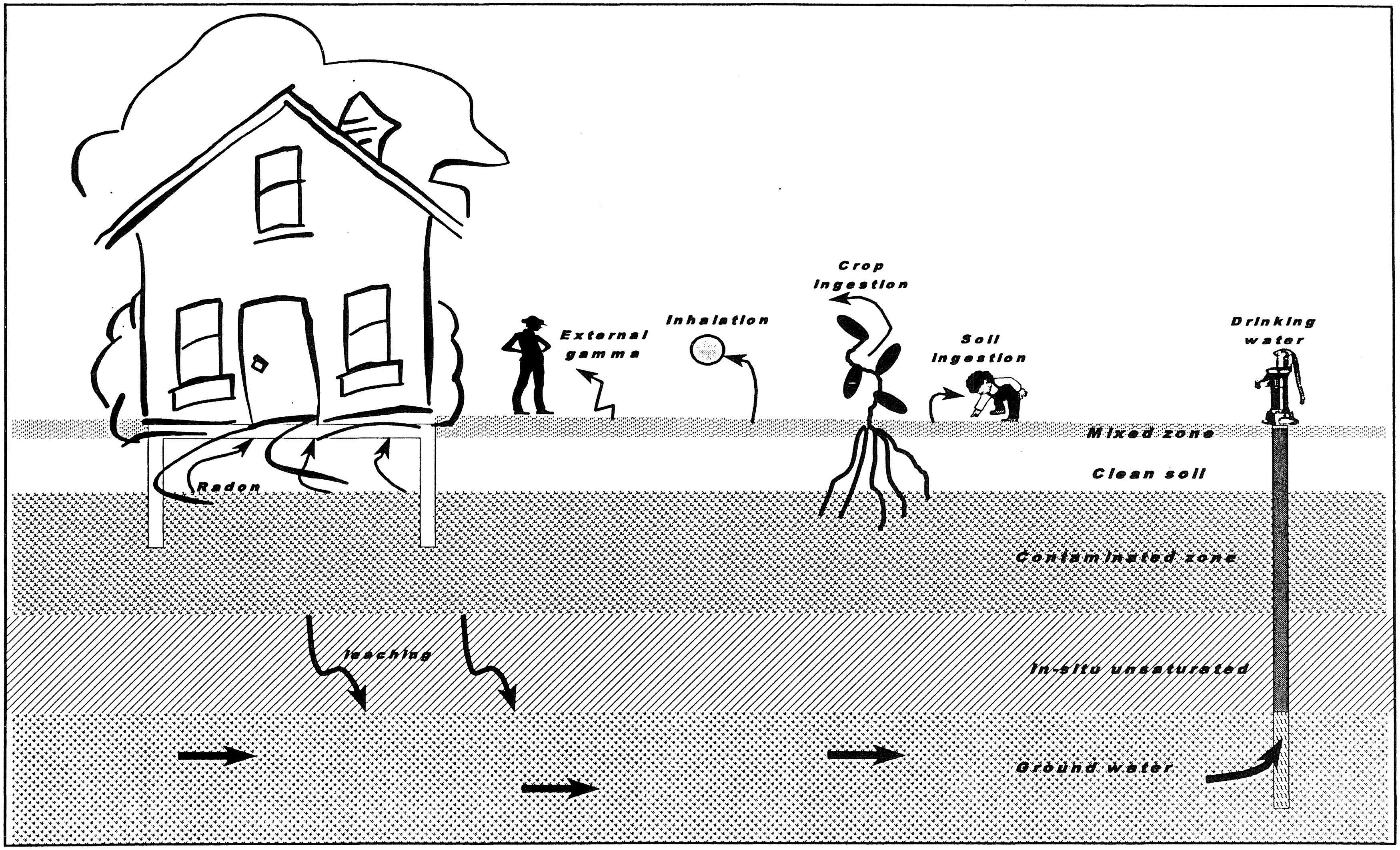
$$MD=\frac{ExcvVol}{(LotArea-BldgArea)}$$

where:

MD = Mixing Depth (MD_{Rbase}=1.75ft., MD_{Rslab}=0.26ft., MD_{Cbase}=1.98ft., MD_{Cslab}=0.19ft.)
ExcvVol = Excavated Volume ($ExcvVol_{Rbase}$=7,000ft^3, $ExcvVol_{Rslab}$=1,040ft^3, $ExcvVol_{Cbase}$=16,800ft^3, $ExcvVol_{Cslab}$=1,600ft^3)

LotArea = total Area of Lot ($LotArea_R$=5,000ft^2, $LotArea_C$=10,890ft^2)
BldgArea = total Area of Building ($BldgArea_R$=1,000ft^2, $BldgArea_C$=2,400ft^2)

Figure 3 Radiation exposure pathways



Chapter 2
ALLOWABLE RADIATION INCREMENTS

In response to the provision in ISRA stipulating that remediation not be required beyond regional natural background levels for any contaminant, the department analyzed the radiation from relevant sources of natural background. As discussed in Chapter 1, allowable radiation increments were based on a one standard deviation of the variation in natural radiation levels. Three pathways for natural radiation exposure were considered: 1) external gamma radiation; 2) internally deposited radionuclides; and 3) indoor radon. The derivation of allowable radiation increments for the sum of the external gamma and intake pathways, and for the radon pathway, are described below. These pathways are depicted in Figure 3.

2.1 TOTAL DOSE INCREMENT

2.1.1 EXTERNAL GAMMA

For external gamma background, the department used terrestrial background radiation data as reported in the National Council of Radiation Protection (NCRP) Report Number 94. National data were used because:

1. they were readily available;
2. terrestrial radiation data specific to New Jersey are very limited; and
3. it is difficult to measure terrestrial radiation separate from cosmic radiation.

Natural background for terrestrial gamma radiation is therefore being defined as one standard deviation from the national mean value of 40 millirad/year (mrad/yr). Based on the distribution of the NCRP data,[34] one standard deviation is approximately 21.3 mrad/yr. Expressed in terms of effective dose equivalent, the allowable external dose increment equals:

$$\begin{aligned} EDI &= 1\sigma \cdot BSF \cdot (Inside \cdot SFI + Outside \cdot SFO) \\ &= 21.3 \cdot 0.7 \cdot (92\% \cdot 0.7 + 8\% \cdot 1.0) \\ &= 10.8\ mrem/yr \end{aligned}$$

where:
EDI = External Dose Increment
1F = one standard deviation of mean exposure, 21.3 mrad/yr (NCRP 94 data)

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[34] National Council on Radiation Protection and Measurements. 1987. *Exposure of the Population in the United States and Canada from Natural Background Radiation*. NCRP Report No. 94. Figure 5.4, p.78. (NOTE: the mean of 44 mrad/yr shown in Figure 5.4 is population-weighted over the parts of the country covered by the aerial survey; when population-weighted over the entire country, the mean is estimated to be 40 mrad/yr, as explained on p.89)

BSF = Body Shielding Factor, 0.7[35]
Inside = percentage of total time spent indoors, 92%[36]
SFI = indoor shielding factor, 0.7[37]
Outside = percentage of total time spent outdoors, (100% - Inside) = 8%
SFO = outdoor shielding factor, 1.0[38]

2.1.2 INTERNAL RADIONUCLIDES

Human intake of radionuclides occurs from three main sources; drinking water consumption, food intake, and air inhalation. The average radiation dose (effective dose equivalent) from such intakes in the U.S. is estimated to be 40 mrem per year; most of that dose comes from potassium-40 and the lead-210 - polonium-210 chain, each contributing about 20 mrem per year.[39]

Data on variations of internal dose are more limited than that for external gamma radiation. For potassium-40, Figure 7.1 in NCRP 94 illustrates the variations in concentration as functions of sex and age. Potassium is homoeostatically regulated in the body. Variations among people are not related to intake as much as biological factors such as body build, age, and sex. Since the potassium-40 variation is small and mostly unrelated to intake, it was not included in the internal dose increment. In other words, people do not receive different doses of radiation from potassium-40 by moving to or through different regions of New Jersey. Rather, the different potassium-40 doses experienced by people are due to biological differences such as body build, age, and sex.

The variation for the lead-210 - polonium-210 component is greater. The standard deviation of Pb210 and Po210 in human bone ash is about 50% of the mean based on New York

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[35] National Council on Radiation Protection and Measurements. 1987. *Exposure of the Population in the United States and Canada from Natural Background Radiation.* NCRP Report No. 94. p.89.

[36] U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043. p.5-28.

[37] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. p.129.

[38] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. p.129.

[39] National Council on Radiation Protection and Measurements. 1987. *Exposure of the Population in the United States and Canada from Natural Background Radiation.* NCRP Report No. 94. p.140-149.

area data.[40] The effective dose equivalent corresponding to a one standard deviation variation is therefore about $0.5 \times 20 = 10$ mrem/year.

The allowable internal dose increment is therefore equal to 10 mrem/yr.

2.1.3 SUM OF EXTERNAL AND INTERNAL DOSE INCREMENTS

To provide more flexibility in terms of remediation alternatives, the Department summed the allowable radiation dose increments for the external and internal pathways. Since the dose increments are based on standard deviations, the sum of the dose increments is equal to the standard deviation of the sum of the external and internal pathways. Furthermore, since the distributions for these pathways are statistically independent, the standard deviation of their sum can be expressed in terms of the standard deviations of the individual pathways as follows:

$$\begin{aligned} TDI &= \sqrt{EDI^2 + IDI^2} \\ &= \sqrt{10.8^2 + 10^2} \\ &= 14.7 \\ &\cong 15 \ mrem/yr \end{aligned}$$

where =
TDI = Total Dose Increment
EDI = External Dose Increment
IDI = Internal Dose Increment

Therefore, the Department has adopted a Total Dose Increment (TDI) of 15 mrem/yr (0.15 mSv/yr) above background. In other words, radioactively contaminated soils must be remediated such that any soil concentrations above background must not lead to an effective dose equivalent to any individual greater than 15 mrem/yr via the external and internal pathways, not including radon inhalation.

2.2 RADON

Radon levels tend to be distributed log-normally. In other words there are a large number of low activity samples and a small number of high activity samples. The department maintains a database of radon test results since the start of the mandatory certification regulations N.J.A.C. 7:28-27 (Certification of Radon Testers and Mitigators) on May 13, 1991. These regulations require certified radon measurement businesses to submit monthly reports containing the county and incorporated municipality in which the radon test was deployed; the measurement device used (charcoal canister, alpha track, electret, etc.); building level tested; testing purpose (real

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[40] Fisenne, I.M.. 1993. *Long-Lived Radionuclides in the Environment, in Food and in Human Beings.* in Fifth International Symposium on the Natural Environment - Tutorial Sessions. Commission of European Communities. Report EUR 14411 EN. pp.187-255. Table 9, p.241.

estate, screening, follow-up, pre-mitigation, post-mitigation, diagnostic, blank or duplicate): dates and times the measurement device was deployed; and the radon/radon progeny test result.

New Jersey has six distinct geo-provincial regions; Valley and Ridge, Highlands, Innercoastal Plain, Outercoastal Plain, Southern Piedmont and Northern Piedmont. All 567 incorporated municipalities in New Jersey were classified according to the geo-province in which they are affiliated. For this study, the Department analyzed results from radon screening tests deployed on the lowest house level tested. When these radon screening test results were analyzed according to geo-province, the following geometric means and standard deviations were obtained:

Geological Province	Geometric Mean (pCi/l)	Geometric Standard Deviation (pCi/l)
Valley and Ridge	2.25	3.21
Highlands	2.00	3.13
Innercoastal Plain	1.17	3.01
Outercoastal Plain	0.80	2.52
Southern Piedmont	1.88	3.12
Northern Piedmont	1.07	2.50
Statewide Average	**1.35**	**2.95**

As seen in the above table, the geometric mean varies by geo-province from 0.8 pCi/l to 2.25 pCi/L. However, the geometric standard deviation in all provinces tends to be close to 3.0 pCi/L. The allowable Radon Concentration Increment (RCI) was therefore set equal to 3.0 pCi/l (111mBq/l). Since the radon pathway was kept separate from other pathways, there was no need to translate the increment to an effective dose equivalent.

2.3 GROUNDWATER CRITERIA

It should be noted that compliance with the Total Dose Increment (TDI) and the Radon Concentration Increment (RCI) does not supersede any applicable New Jersey Groundwater Criteria.[41] These Criteria require that the concentrations of residual contamination not cause the

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[41] NJ DEPE. 1993. *Ground Water Criteria Standards* (N.J.A.C. 7:9-6). Water Supply Element, Department of Environmental Protection and Energy, State of New Jersey.

NJ DEP. 1989. *A Ground Water Strategy for New Jersey.* Division of Water Resources, Department of Environmental Protection, State of New Jersey.

groundwater of certain aquifers to exceed the Maximum Contaminant Levels (MCLs) specified in the U.S. Safe Drinking Water Act.[42]

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[42] US EPA. 1976. *National Interim Primary Drinking Water Regulations.* Office of Water Supply.

Chapter 3
PATHWAY ANALYSES

In order to determine what residual soil concentration will result in the allowed radiation increments defined in the previous chapter, individual pathways of potential human exposure (Figure 3) must be analyzed for each subchain. In the case of external and internal pathways, the analyses must establish ratios between annual effective dose equivalent and subchain soil concentrations. These ratios, called dose factors (mrem/yr per pCi/g), are specific to:

1. each pathway;
2. each subchain;
3. vertical extent (depth) of contaminated soil (VertXtnt);
4. depth of uncontaminated soil left or placed on the surface after remediation (USS);
5. site use designation, Unrestricted (residential) or Limited Restricted (commercial); and
6. construction scenario (basement or slab-on-grade).

In the case of the radon pathway, the analysis simply relates radium soil concentration and vertical extent of contamination to indoor radon concentration (pCi/l per pCi/g). The methodologies used to calculate dose factors and radon concentration factor are presented in this chapter. Note that the parameters assumed for the various pathway analyses are listed in Tables 2 and 3 and explained in section 1.3 of this document.[43] Also, the calculations used to define the Mixed Zone are developed in section 1.4.

3.1 EXTERNAL GAMMA PATHWAY

The contributions to external gamma dose were separated into four components (see Figure 4):

1. dose that is received outside the building from the mixed zone;
2. dose that is received inside the building from the mixed zone penetrating the sides of the building;
3. dose that is received inside the building from the contaminated zone directly under the building; and
4. dose that is received inside the building from the contaminated zone adjacent to the basement walls of the building.

All of these components are then added together to determine the total external dose equivalent. It is necessary to separate the dose into these components to account for the external gamma

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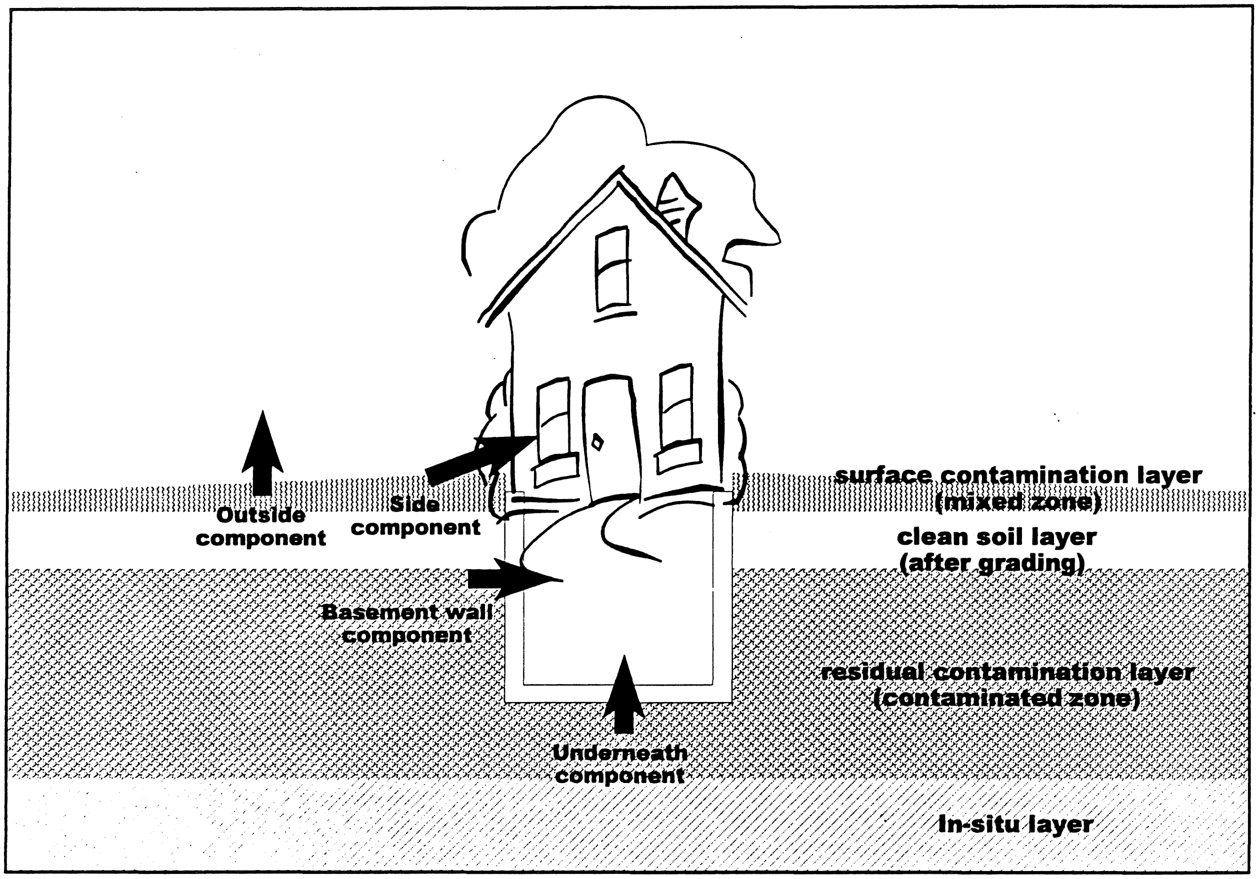
[43] Note that the parameters for the drinking water pathway are presented in the Drinking Water Pathway section (4.4) because they are inseparable related to the drinking water methodology..

contributions from both the contaminated zone and the mixed zone. The equations below are expressed in terms of dose factors (mrem/yr per pCi/g) by dividing the soil concentration out of the dose equations.

Figure 4 Components of External Gamma pathway



The total external dose factor is simply the sum of the various external gamma components:

$$DF_E = DF_{Eo} + DF_{Es} + DF_{Eu} + DF_{Eb}$$

where:
DF_E = External Dose Factor (mrem/yr per pCi/g)
DF_{Eo} = External Dose Factor from outside component (mrem/yr per pCi/g)
DF_{Es} = External Dose Factor from side component from mixed zone (mrem/yr per pCi/g)
DF_{Eu} = External Dose Factor from underneath component (mrem/yr per pCi/g)
DF_{Eb} = External Dose Factor from basement wall component from contaminated zone (mrem/yr per pCi/g)

The generalized equation for any component of external dose factor can be expressed as:

$$DF_{Ec}=DCF_{Ec}\cdot T_{Ec}\cdot SF_{Ec}\cdot AF_{Ec}\cdot CF_{Ec}$$

where:
DF_{Ec} = External Dose Factor for a given component
DCF_{Ec} = Dose Conversion Factor appropriate for a given component
T_{Ec} = fraction of total time spent exposed to a given component
SF_{Ec} = Shielding Factor appropriate for a given component
AF_{Ec} = Area Factor appropriate for a given component
CF_{Ec} = Cover Factor appropriate for a given component: $CF=K_c^{soil\ cover\ depth}$
where K_c = soil cover coefficient

The specific dose factor equations for each external gamma component for both basement and slab-on-grade construction scenarios are:

component	**basement**	**slab-on-grade**
outside: DF_{Eo} =	$(DCF_{\infty}\cdot MF_{base})\cdot T_o\cdot SF_o\cdot AF_o$	$(DCF_5\cdot MF_{slab})\cdot T_o\cdot SF_o\cdot AF_o$
side walls: DF_{Es} =	$(DCF_{\infty}\cdot MF_{base})\cdot T_i\cdot SF_w\cdot AF_s$	$(DCF_5\cdot MF_{slab})\cdot T_i\cdot SF_w\cdot AF_s$
underneath: DF_{Eu} =	$DCF_{\infty}\cdot T_i\cdot SF_b\cdot AF_u\cdot B_{Cub}\cdot CF_{base}$	$DCF_{\infty}\cdot T_i\cdot SF_b\cdot AF_u\cdot CF_{slab}$
basement walls: DF_{Eb} =	$DCF_{\infty}\cdot T_i\cdot SF_b\cdot AF_b\cdot FBW$	0
Sum of all Components: DF_E =	$DCF_{\infty}\cdot\left[\begin{array}{l} MF_{base}\cdot\left(\begin{array}{l} T_o\cdot SF_o\cdot AF_o \\ +T_i\cdot SF_w\cdot AF_s \end{array}\right) \\ +T_i\cdot SF_b\cdot\left(\begin{array}{l} AF_u\cdot B_{Cub}\cdot CF_{base} \\ +AF_b\cdot FBW \end{array}\right) \end{array}\right]$	$\left[\begin{array}{l} DCF_5\cdot MF_{slab}\cdot\left(\begin{array}{l} T_o\cdot SF_o\cdot AF_o \\ +T_i\cdot SF_w\cdot AF_s \end{array}\right) \\ +DCF_{\infty}\cdot T_i\cdot SF_b\cdot AF_u\cdot CF_{slab} \end{array}\right]$

where:

DCF_{∞} , DCF_5 = Effective Dose Conversion Factors (mrem/yr per pCi/g) for infinite depth and 5 cm depth of contamination, respectively. Values are listed in Table 3 and discussed in section 1.3.5. The 5 cm depth DFCs were used for the mixed zone slab construction because the mixing depths (section 1.4.2) for residential and commercial slab construction are 8 and 6 cm, respectively. By contrast, the mixing depths for residential and commercial basement construction are 53 and 60 cm, respectively. Note that if USS is 0, the infinite DCF is used instead of the 5cm DCF (see section 1.4.1). Depth Factors, which can be used to modify the DCF to account for the actual depth of contamination, were calculated to be very close to 1 and therefore not included. In other words, the actual mixing depths for basement construction are deep enough that the infinite-depth DCFs are adequate. The same would apply to contaminated zone depths, since they are typically estimated in feet not centimeters.

MF_{base} , MF_{slab} = Mixing Factor for basement and slab construction scenarios, respectively. Mixing Factor is the concentration of contamination in the mixed zone expressed as a fraction of the contamination concentration in the contaminated zone. The equation for Mixing Factor is presented in section 1.4.1

T_o , T_i = Fraction of time spent outdoors on site and indoors on site, respectively. Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.1.

SF_o , SF_w , SF_b = Shielding Factor outside, through building walls, and through basement or slab, respectively. Values are listed in Table 2 and discussed in section 1.3.2.

AF_o , AF_s , AF_u , AF_b = Area Factor outside, inside from around building sides, inside from underneath basement or slab, and inside from around basement walls, respectively (see Figure 4). Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.2. Dimensions for both residential and commercial scenarios were used to interpolate area factors. Lot size was used for outside area factor; building area was used for underneath area factor; and lot size minus building size was used for inside area factor from surrounding mixed zone contamination. Area factor for contaminated zone adjacent to basement walls was determined by assuming four basement walls, interpolating area factors for values for each, and adding them together. Contaminated zone soil adjacent to basement walls will result in four simultaneous vertical source planes. Specific calculations of area factors are presented in Appendix A.

CF_{base} , CF_{slab} = Cover Factor for basement and slab construction scenarios, respectively. Cover factor accounts for the shielding provided by clean soil underneath the basement or slab. It is calculated as a function of soil cover coefficient and depth of clean soil underneath basement or slab:

$$CF_{base} = K_c^{\left[B_{Club} \cdot \left(Clean - ExcvDpth_{base}\right)\right]}$$

$$CF_{slab} = K_c^{Clean}$$

where:

K_c = soil cover coefficient. Value is listed in Table 2 and discussed in section 1.3.2.

B_{club} = Boolean flag (1 indicates "yes;" 0 indicates "no") to indicate that clean layer extends underneath basement: Clean > $ExcvDpth_{base}$. Only if the clean soil layer extends beneath the basement will there be any soil cover between the contaminated zone and the basement.

Clean = depth (ft.) of "Clean" soil left on surface after grading (uncontaminated surface soil minus 1' grading). For the slab construction scenario, excavated soil is assumed to be placed outside building perimeter, leaving the clean soil (after grading) intact underneath the slab.

$ExcvDpth_{base}$ = Depth of excavation for basement (ft.). Value is listed in Table 2 and discussed in section 1.3.1.

B_{Cub} = Boolean flag (1 indicates "yes;" 0 indicates "no") to indicate that contaminated zone extends underneath the basement: Clean + VertXtnt > $ExcvDpth_{base}$, where VertXtnt = vertical extent of contamination (ft.).

FBW = Fraction of Basement Wall adjacent to contaminated zone. This calculated parameter is used to linearly reduce the basement wall gamma component acording to the fraction of basement wall that is adjacent to the contaminated zone soil. Except for cases where there is no uncontaminated surface soil, it happens to be equivalent to the Mixing Factor for the basement scenario (section 1.4.1):

$$FBW=\begin{cases} 0 & \text{if } Clean \geq ExcvDpth_{base} \\ \dfrac{VertXtnt}{ExcvDpth_{base}} & \text{if } (Clean+VertXtnt) \leq ExcvDpth_{base} \\ \dfrac{(ExcvDpth_{base}-Clean)}{ExcvDpth_{base}} & \text{if } (Clean+VertXtnt) > ExcvDpth_{base} > Clean \end{cases}$$

3.2 INTERNAL PATHWAYS

Four pathways by which radioactivity in soil can contribute to internal dose are considered:

1. direct soil ingestion;
2. inhalation of resuspended particles;
3. leaching followed by drinking water intake; and
4. vegetative uptake followed by consumption.

3.2.1 SOIL INGESTION

The dose factor (mrem/yr per pCi/g) from soil ingestion is calculated as a simple function of soil ingestion rate:

$$DF_{SI}=DCF_{ing}\cdot MF\cdot SI$$

where:

DF_{SI} = Soil Ingestion Dose Factor (mrem/yr per pCi/g)

DCF_{ing} = Effective Dose Conversion Factor (mrem per pCi) for ingestion of radioactive subchains. Values are listed in Table 3 and discussed in section 1.3.5.

MF = Mixing Factor (MF_{base} or MF_{slab}). Mixing Factor is the concentration of contamination in the mixed zone expressed as a fraction of the contamination concentration in the contaminated zone. Only the mixed zone is assumed to be susceptible to soil ingestion. The equation for mixing factor is presented in section 1.4.1

SI = Soil Ingestion rate (g/yr). Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.3.1.

3.2.2 INHALATION PATHWAY

Evaluating the impact of inhaled resuspended contaminated soil involves several factors that can vary significantly depending on the specific site. After reviewing the various models for determining resuspension of deposited contaminated soil, it was determined that the Mass Loading (ML) model[44] was the most appropriate. The ML approach, in which an average value of the airborne dust concentration is specified on the basis of empirical data, eliminates the need to evaluate in detail the resuspension mechanism or the effective depth of the distribution layer:

$$DF_I = ML \cdot DCF_{inh} \cdot MF \cdot \left(I_o \cdot T_o + I_i \cdot T_i \cdot SF_i\right) \cdot AF_I \cdot UnitConv$$

where:

DF_I = Inhalation Dose Factor (mrem/yr per pCi/g)

ML = outdoor Mass Loading ($\mu g/m^3$), the concentration of resuspended soil. Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.3.2.

DCF_{inh} = Effective Dose Conversion Factor (mrem per pCi) for inhalation of radioactive subchains. Values are listed in Table 3 and discussed in section 1.3.5

MF = Mixing Factor (MF_{base} or MF_{slab}). Mixing Factor is the concentration of contamination in the mixed zone expressed as a fraction of the contamination concentration in the contaminated zone. Only the mixed zone is assumed to be susceptible to resuspension followed by inhalation. The equation for mixing factor is presented in section 1.4.1

I_o , I_i = outdoor and indoor Inhalation rates (m^3/hr), respectively. Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.3.2.

T_o , T_i = Fraction of time spent outdoors on site and indoors on site, respectively. Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.1.

SF_i = indoor Shielding Factor for resuspension; indoor dust level expressed as percent of outdoor dust level. Value is listed in Table 2 and discussed in section 1.3.3.2.

AF_I = Area Factor for inhalation pathway. Area factor in this context accounts for the degree to which resuspended dust is comprised of off-site soil (presumably "clean"). It can be calculated as a function of lot size:[45]

$$AF_I = \frac{\sqrt{LotArea}}{\sqrt{LotArea} + DL}$$

where:

LotArea = total area of lot (ft^2). Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.1.

DL = resuspension dilution length (ft). Value is listed in Table 2 and discussed in section 1.3.3.2.

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[44] Yu., C., *et al.* 1993. *Manual for Implementating Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2. p.141-145.

[45] Yu., C., *et al.* 1993. *Manual for Implementating Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2. p.143.

$$\text{UnitConv} = \frac{1\cdot 10^{-6} g}{\mu g} \cdot \frac{24 hr}{day} \cdot \frac{365 days}{year} = 8.76\cdot 10^{-3}$$

3.2.3 DRINKING WATER PATHWAY

The drinking water component of the intake dose was evaluated by assuming the groundwater pathway is the primary route by which radioactive contaminants can potentially reach drinking water. Surface water pathways result in greater dilution than the groundwater pathway. Therefore, it is conservative to assume that all residual contamination is susceptible to processes involved in the groundwater pathway. Conceptually, the groundwater pathway refers to the following scenario:

1. contaminants in the soil leach into water as it percolates through the contamination zone;
2. contaminants travel through the unsaturated zone to an aquifer, where they are susceptible to saturated transport processes;
3. a well is eventually placed in the aquifer, providing a primary source of drinking water.

The expectation under BaCSRA is that generic cleanup standards be developed for application to any site in New Jersey. Furthermore, while the standards are specific to each radionuclide subchain, they are expected to be applied to any chemical form in which the radionuclides may be found. The expectations of generic standards pose some difficulty, since leach and transport rates are strongly influenced by the physicochemical properties of both the contamination and the soil.

In order to overcome the difficulties inherent in developing generic cleanup standards, a conservative bounding approach was used to assess the groundwater pathway. The approach estimated the maximum groundwater contamination that could reasonably be expected over a wide range of site characteristics and chemical forms of contamination. Care was taken in the development of these standards to avoid "redundant conservatism." Given current knowledge regarding leach and transport processes for near surface contamination, it is expected that actual groundwater concentrations and associated doses resulting from radioactively contaminated soil for most sites in New Jersey would not exceed the dose factors developed using this methodology (Table 4).

Details of the methodology are presented in Appendix A. Residential assumptions, such as water consumption of 2 liters/day for 350 days/year[46], were also used for the commercial scenario since commercial land use on the surface could not preclude residential use of drinking

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[46] U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043. Part I, p.2-1.

water from the underlying aquifer. For the residential (Unrestricted Use) scenario analyses, the drinking water well was assumed to be placed in the aquifer under the contaminated soil; the well was placed at the edge of the contaminated soil for the commercial (Limited Restricted Use) scenario analyses. Placing the hypothetical well on the edge of the contaminated soil instead of directly under the contamination did not significantly affect the resultant dose factors, since the subchains important to the groundwater pathway are very long-lived even compared to groundwater travel times. The peak groundwater concentrations calculated to occur between 1-1,000 years were used for all dose analyses. Even conservative bounding calculations become tenuous when carried out over long periods of time. Other pathways may remove residual contamination substantially over the course of a millennium. To calculate peak concentration from the groundwater pathway over longer periods of time without considering other removal processes would unreasonably overestimate the drinking water component. Since uncertainties preclude quantifying such loss mechanisms, it is reasonably conservative to calculate peak concentrations from 1-1,000 years. Therefore it was decided to limit the calculations to 1,000 years.

Results, shown in Table 4, are expressed as dose to soil concentration ratios (dose factors) for various vertical extents of contamination. Notice that vertical extent of contamination affects dose factors differently for different subchains. Dose Factors for any vertical extent can be interpolated or linearly regressed from Table 4.

Table 4 Groundwater Pathway Dose Factors (mrem/yr per pCi/g) for Various Vertical Extents of Contamination

		Vertical Extent of Contamination (VertXtnt in feet)								
	subchain	1	2	3	4	5	6	7	8	9
Unrestricted (Residential)	U238+D[b]	1.62E-01	3.22E-01	4.82E-01	6.40E-01	7.94E-01	9.46E-01	1.09E+00	1.24E+00	1.37E+00
	U234[b]	1.71E-01	3.40E-01	5.08E-01	6.75E-01	8.39E-01	9.99E-01	1.16E+00	1.31E+00	1.45E+00
	Th230[a,b]	6.43E-03	6.98E-03	7.15E-03	7.26E-03	7.32E-03	7.32E-03	7.37E-03	7.37E-03	7.43E-03
	Ra226+D[b]	1.39E-01	1.53E-01	1.57E-01	1.60E-01	1.63E-01	1.64E-01	1.64E-01	1.65E-01	1.65E-01
	Pb210+D[c]	2.82E-05	2.89E-05	2.91E-05	2.92E-05	2.92E-05	2.93E-05	2.93E-05	2.93E-05	2.94E-05
	U235+D[b]	1.67E-01	3.41E-01	5.20E-01	6.98E-01	8.75E-01	1.05E+00	1.22E+00	1.38E+00	1.53E+00
	Pa231[b]	2.16E-01	2.29E-01	2.34E-01	2.36E-01	2.37E-01	2.38E-01	2.38E-01	2.39E-01	2.40E-01
	Ac227+D[c]	9.37E-06	9.54E-06	9.63E-06	9.67E-06	9.68E-06	9.69E-06	9.69E-06	9.71E-06	9.71E-06
	Th232[b]	DOES NOT REACH AQUIFER AFTER 1000 YEARS								
	Ra228+D[c]	2.69E-05	2.71E-05	2.71E-05	2.72E-05	2.72E-05	2.72E-05	2.72E-05	2.72E-05	2.72E-05
	Th228+D[c]	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09
Restricted (Commercial)	U238+D[b]	1.46E-01	2.90E-01	4.33E-01	5.72E-01	7.08E-01	8.38E-01	9.62E-01	1.08E+00	1.19E+00
	U234[b]	1.54E-01	3.07E-01	4.57E-01	6.05E-01	7.49E-01	8.86E-01	1.02E+00	1.14E+00	1.26E+00
	Th230[a,b]	3.45E-03	3.71E-03	3.81E-03	3.86E-03	3.89E-03	3.90E-03	3.92E-03	3.93E-03	3.94E-03
	Ra226+D[b]	7.54E-02	8.27E-02	8.55E-02	8.71E-02	8.77E-02	8.83E-02	8.88E-02	8.94E-02	8.94E-02
	Pb210+D[c]	1.46E-05	1.50E-05	1.51E-05	1.52E-05	1.52E-05	1.52E-05	1.52E-05	1.53E-05	1.53E-05
	U235+D[b]	1.63E-01	3.24E-01	4.84E-01	6.39E-01	7.91E-01	9.36E-01	1.08E+00	1.21E+00	1.33E+00
	Pa231[b]	1.15E-01	1.22E-01	1.24E-01	1.25E-01	1.26E-01	1.26E-01	1.26E-01	1.27E-01	1.27E-01
	Ac227+D[c]	9.37E-06	9.54E-06	9.63E-06	9.67E-06	9.68E-06	9.69E-06	9.69E-06	9.71E-06	9.71E-06
	Th232[b]	DOES NOT REACH AQUIFER AFTER 1000 YEARS								
	Ra228+D[c]	2.69E-05	2.71E-05	2.71E-05	2.72E-05	2.72E-05	2.72E-05	2.72E-05	2.72E-05	2.72E-05
	Th228+D[c]	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09	6.05E-09

[a] Thorium is essentially immobile and would not reach the aquifer in 1000 years. The leach rate of Ra226 produced by Th230 was calculated over time and manually input as the source term for the groundwater model, thereby allowing the Ra226 to move independently from its parent Th230 in the unsaturated zone.

[b] For peak times occuring after 1,000 years, maximum dose between 1-1,000 was used.

[c] The thickness of the unsaturated zone was reduced in order to fulfill the unsaturated zone model condition that the transit time be less than ten times the half-life of the contaminant.

3.2.4 CROP INGESTION

The dose factor (mrem/yr per pCi/g) from crop ingestion is calculated as a function of the rate of transfer from soil to crops and the crop ingestion rate:[47]

$$DF_{CI}=TF\cdot RF\cdot DCF_{ing}\cdot CI$$

where:

DF_{CI} = Crop Ingestion Dose Factor (mrem/yr per pCi/g)

TF = vegetative Transfer Factor, the plant to soil radionuclide concentration ratio. Values are listed in Table 3 and discussed in section 1.3.5.

RF = Root Factor,[48] the fraction of plant root depth in contaminated soil. Since the Department's excavation scenario (Figure 1) includes two layers with differing levels of contamination (mixed zone and contaminated zone), root factor must be calculated accordingly:

$$RF=\left(RF_m\cdot MF+RF_c\right)$$

$$RF_m=\begin{cases}\dfrac{MD}{RD} & if\ MD\le RD\\ 1 & if\ MD>RD\end{cases}$$

$$RF_c=\begin{cases}0 & if\ \left(MD+Clean\right)\ge RD\\ \dfrac{VertXtnt}{RD} & if\ \left(MD+Clean+VertXtnt\right)\le RD\\ \dfrac{\left(RD-MD-Clean\right)}{RD} & if\ \left(MD+Clean\right)<RD<\left(MD+Clean+VertXtnt\right)\end{cases}$$

where:

RF_m , RF_c = fraction of plant root depth in the mixed and contaminated zones, respectively.

MF = Mixing Factor (MF_{base} or MF_{slab}). Mixing Factor is the concentration of contamination in the mixed zone expressed as a fraction of the contamination concentration in the contaminated zone. The equation for mixing factor is presented in section 1.4.1

MD = Mixing Depth (MD_{base} or MD_{slab} , ft.), depth of mixed zone. Equation for mixing depth is presented in section 1.4.2.

RD = Root Depth (ft). Value is listed in Table 2 and discussed in section 1.3.3.3.

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[47] Yu., C., *et al.* 1993. *Manual for Implementating Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2. p.177.

[48] Yu., C., *et al.* 1993. *Manual for Implementating Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2. p.180.

Clean = depth (ft.) of "Clean" soil left on surface after grading (uncontaminated surface soil minus 1' grading).
VertXtnt = Vertical eXtent (depth in feet) of contaminated soil.
DCF_{ing} = Effective Dose Conversion Factor (mrem per pCi) for ingestion of radioactive subchains. Values are listed in Table 3 and discussed in section 1.3.5
CI = homegrown Crop Ingestion rate (g/yr). Values for both residential and commercial scenarios are listed in Table 2 and discussed in section 1.3.3.3.

3.3 RADON PATHWAY

Since the allowable radiation increment for the radon pathway is expressed in terms of indoor radon concentration, the goal of the radon pathway analysis is simply to relate radium soil concentration to indoor radon concentration. This is accomplished through the use of a radon to radium ratio modified by a factor to account for the vertical extent of the radium contamination:

$$RCF = RRR \cdot (VEF \cdot CLF)$$

where:
RCF = Radon Concentration Factor (pCi/l indoor radon per pCi/g radium).
RRR = Radon to Radium Ratio (pCi/l indoor radon per pCi/g radium), a simple correlation between radium soil concentration and indoor radon concentration. Value is listed in Table 2 and discussed in section 1.3.4.
VEF = Vertical Extent Factor, a calculated factor between zero and one that that reduces the indoor radon concentration according to the thinness of the vertical extent of radium contamination;
CLF = Clean Layer Factor, a calculated factor between zero and one that reduces the indoor radon concentration according to the thickness of the layer of clean soil that might exist between the basement or slab and the radium contamination:

$$VEF=\begin{cases} 0\ (set\ to\ 1e^{-6}\ to\ avoid\ DivBy0) & if\ VertXtnt=0 \\ \sqrt{\left(VEF_b+VEF_m\cdot\log_2(VertXtnt)\right)} & if\ VertXtnt>1 \\ \sqrt{\left(VEF_b+VEF_m\cdot\log_2(1)\right)}\ =0.27 & if\ 0\leq VertXtnt\leq 1 \end{cases}$$

$$CLF_{base}=\begin{cases} 1 & if\ \left(Clean-ExcvDpth_{base}\right)<1 \\ 1-\sqrt{\left(VEF_b+VEF_m\cdot\log_2\left(Clean-ExcvDpth_{base}\right)\right)} & if\ \left(Clean-ExcvDpth_{base}\right)\geq 1 \end{cases}$$

$$CLF_{slab}=\begin{cases} 1 & if\ Clean<1 \\ 1-\sqrt{\left(VEF_b+VEF_m\cdot\log_2\left(Clean\right)\right)} & if\ Clean\geq 1 \end{cases}$$

where:

$VEF < 1$

$CLF > 0$

VEF_b,VEF_m = intercept and slope for linear relationship between $\log_2$(VertXtnt) and VEF^2 = 0.07112 and 0.2483, respectively. Data taken from modeling study analyzing the effects that discrete contaminated soil layers have on indoor radon concentrations.[49] Development of the equation and methodology is presented in detail in Appendix A.

VertXtnt = Vertical eXtent (depth in feet) of contaminated soil.

Clean = depth (ft.) of "Clean" soil left on surface after grading (uncontaminated surface soil minus 1' grading).

$ExcvDpth_{base}$ = Depth of excavation for basement (ft.). Value is listed in Table 2 and discussed in section 1.3.1.

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[49] Rogers, V., K.K. Nelson, and V.C. Rogers. 1992. *Foundation Soil Cleanup Depths and Radium Limits for Avoiding Elevated Indoor Radon.* Prepared by Rogers and Associates Engineering Corporation for U.S. Environmental Protection Agency. RAE-8964/18-2. Figure 5-1 and pp.5-1 to 5-3.

Chapter 4
RESULTS

4.1 ALLOWABLE SOIL CONCENTRATION INCREMENTS

For any combination of vertical extent, uncontaminated surface soil depth, construction scenario (basement or slab-on-grade), and site use designation (Unrestricted Use or Limited Restricted Use), dose factors for all 11 subchains can be calculated for each pathway using the equations presented in the previous chapter. Similarly, radon concentration factors can be calculated for any combination of vertical extent, uncontaminated surface soil depth, and construction scenario (basement or slab-on-grade) using the equations presented in section 3.3. Such calculations were performed for vertical extents of one to nine feet and uncontaminated surface soil depths of one to five feet. Dose factors for individual pathways were summed to obtain the total dose factor for each subchain. Recall from section 1.1 that in order to account for ingrowth of progeny, the total dose factors for certain decay chains were combined. Specifically:

- Pb210+D was combined with Ra226+D;
- Pa231 was combined with Ac227+D; and
- Th228+D and Ra228+D were combined with Th232.

Total dose factors for the seven remaining subchains were divided into the Total Dose Increment of 15 mrem (Chapter 2.1) to obtain the allowable soil concentration increments above background. Also, the radon concentration factors were divided into the Radon Concentration Increment (Chapter 2.2) of 3 pCi/l to obtain allowable radium concentration increments.

For sites with only one of the seven long-lived subchains in soil concentrations above background, the minimum (most restrictive) concentration increment between basement and slab-on-grade construction scenarios and also between dose-based and radon-based values must be selected as the incremental cleanup standard. Shown in Table 5, these cleanup standards[50] allow for either type of building construction, and also meet both the Total Dose Increment as well as the Radon Concentration Increment.

4.2 SUM OF FRACTIONS

For sites with more than one of the seven long-lived subchains in soil concentrations above background, the sum of fractions rule must be applied. To demonstrate compliance with the Total Dose Increment, the sum of fractions rule must be applied to the Allowable Soil

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[50] The cleanup standards are presented in this chapter using traditional units (pCi/g). Appendix B repeats the tables in this chapter using SI units (Bq/g).

Table 5 Allowable Soil Concentration Increments (pCi/g)
Most Restrictive (for sites where only one subchain is present above background)

VE*, USS**		Commercial (Limited Restricted Use)									Residential (Unrestricted Use)								
		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
U238	USS0	71	44	32	25	20	17	15	13	12	59	37	27	21	17	15	13	11	10
	USS1	84	47	33	25	21	17	15	13	12	74	40	28	21	18	15	13	11	10
	USS2	85	47	33	25	21	17	15	13	12	77	41	28	22	18	15	13	11	10
	USS3	85	47	33	25	21	17	15	13	12	78	42	29	22	18	15	13	11	10
	USS4	85	48	33	25	21	18	15	13	12	79	42	29	22	18	15	13	12	10
	USS5	86	48	33	26	21	18	15	14	12	79	42	29	22	18	15	13	12	10
U234	USS0	72	43	31	24	20	17	14	13	11	63	37	27	21	17	14	12	11	10
	USS1	81	45	31	24	20	17	14	13	11	75	40	27	21	17	14	12	11	10
	USS2	81	45	31	24	20	17	14	13	11	75	40	27	21	17	15	13	11	10
	USS3	81	45	32	25	20	17	15	13	11	75	40	28	22	17	15	13	11	10
	USS4	81	46	32	25	20	17	15	13	11	76	42	28	22	18	15	13	11	10
	USS5	83	46	32	25	20	17	15	13	12	78	42	28	22	18	15	13	11	10
Ra226	USS0	7	4	3	3	2	2	2	2	2	3	3	3	3	2	2	2	2	2
	USS1	7	4	3	3	2	2	2	2	2	7	4	3	3	2	2	2	2	2
	USS2	7	4	3	3	2	2	2	2	2	7	4	3	3	2	2	2	2	2
	USS3	7	4	3	3	2	2	2	2	2	7	4	3	3	2	2	2	2	2
	USS4	7	4	3	3	2	2	2	2	2	7	4	3	3	2	2	2	2	2
	USS5	7	4	3	3	2	2	2	2	2	7	4	3	3	2	2	2	2	2
U235	USS0	50	33	25	20	17	14	12	11	10	36	26	20	16	13	11	10	9	8
	USS1	67	39	27	21	17	14	12	11	10	55	31	22	17	14	11	10	9	8
	USS2	72	40	28	21	17	14	12	11	10	67	34	23	17	14	11	10	9	8
	USS3	73	40	28	21	17	14	13	11	10	68	34	23	17	14	11	10	9	8
	USS4	73	40	28	21	17	15	13	11	10	68	34	23	17	14	12	10	9	8
	USS5	73	40	28	21	18	15	13	12	10	68	34	23	17	14	12	11	10	9
Ac227	USS0	6	6	6	6	6	6	6	6	6	3	2	2	2	2	2	2	2	2
	USS1	20	11	8	6	6	6	6	6	6	8	4	3	3	3	3	2	2	2
	USS2	22	12	8	8	8	7	7	7	7	8	5	4	4	4	3	3	3	3
	USS3	22	12	12	10	8	8	8	8	8	9	6	6	5	4	4	4	4	4
	USS4	22	18	13	10	9	9	9	9	9	13	9	6	5	4	4	4	4	4
	USS5	32	18	13	12	12	12	12	12	12	15	9	6	6	6	6	6	6	6
Th232	USS0	6	6	6	6	6	5	5	5	5	3	3	3	2	2	2	2	2	2
	USS1	22	15	11	9	7	6	5	5	5	7	5	4	3	3	2	2	2	2
	USS2	36	18	12	9	7	6	5	5	5	14	7	5	4	3	2	2	2	2
	USS3	36	18	12	9	7	6	6	6	6	15	7	5	4	3	2	2	2	2
	USS4	36	18	12	9	7	7	7	7	7	15	7	5	4	3	3	3	3	3
	USS5	36	18	12	9	9	9	9	9	9	15	7	5	4	4	4	4	4	4

*VE = vertical extent of contamination in feet
**USS = uncontaminated surface soil depth in feet

Concentration Increments for both the basement (Table 7) and slab-on-grade (Table 8) construction scenarios; both sum of fractions must be less than or equal to one. By applying the sum of fractions to each construction scenario, the Department avoids a potentially important source of redundant conservatism: selecting the more restrictive scenario for each subchain independently when in reality only one construction scenario can occur on the same site.

The residual radium concentration must also be compared with the radon-based Allowable Soil Concentration Increments shown in Table 8 to demonstrate compliance with the Radon Concentration Increment. While the radon-based standards for slab-on-grade are never more restrictive than those for basement construction, they are shown nevertheless in Table 8 to facilitate the development of alternative standards pursuant to N.J.A.C. 7:28-12.12.

4.2.1 SAMPLE CALCULATION

Consider the following hypothetical site: Limited Restricted Use (Deed of Environmental Restriction indicating non-residential use only); the vertical extent of contamination where uranium and thorium subchains are present in concentrations exceeding background is 3 feet; such contamination starts 2 feet below ground surface (i.e., 2 feet uncontaminated surface soil); background soil concentration of uranium and thorium subchains is demonstrated to be 1 pCi/g; field concentrations of the uranium and thorium subchains averaged over the three feet of vertical extent and over any 2400 ft^2 area are not more than 12 pCi/g for U238, 7 pCi/g for U234, 4 pCi/g for Ra226, and 4 pCi/g for Th232.

Subchain	proposed residual soil concentration	background soil concentration	basement standard (Table 6)	slab-on-grade standard (Table 7)	fraction of basement standard	fraction of slab-on-grade standard	radon standard (Table 8)
U238	12	1.0	33	33	0.33	0.33	
U234	7	1.0	32	31	0.19	0.19	
Ra226	4	1.0	18	25	0.18	0.13	3
Th232	4	1.0	12	15	0.25	0.20	
				Sum of fractions	0.98	0.90	

It should be emphasized that the remediation standards are incremental to the natural background radionuclide concentration. The calculations shown above for a hypothetical site would indicate that the site complies with the remediation standard: the sums of fractions for both basement and slab-on-grade construction scenarios are less than one; and the radium-226 field concentration over background is equal to but not greater than the radon-based standard of 3 pCi/g.

Table 6 Allowable Soil Concentration Increments (pCi/g)
Basement construction scenario

VE*, USS**		Commercial (Limited Restricted Use)									Residential (Unrestricted Use)								
		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
U238	USS0	72	44	32	25	20	17	15	13	12	60	37	27	21	17	15	13	11	10
	USS1	86	48	33	25	21	17	15	13	12	78	42	29	22	18	15	13	11	10
	USS2	86	48	33	25	21	17	15	13	12	79	42	29	22	18	15	13	11	10
	USS3	86	48	33	25	21	17	15	13	12	79	42	29	22	18	15	13	11	10
	USS4	86	48	33	25	21	18	15	13	12	79	42	29	22	18	15	13	12	10
	USS5	86	48	33	26	21	18	15	14	12	79	42	29	22	18	15	13	12	10
U234	USS0	72	43	31	24	20	17	14	13	11	63	37	27	21	17	14	12	11	10
	USS1	83	46	32	25	20	17	14	13	11	77	41	28	21	17	14	12	11	10
	USS2	83	46	32	25	20	17	14	13	11	78	42	28	22	17	15	13	11	10
	USS3	83	46	32	25	20	17	15	13	11	78	42	28	22	17	15	13	11	10
	USS4	83	46	32	25	20	17	15	13	11	78	42	28	22	18	15	13	11	10
	USS5	83	46	32	25	20	17	15	13	12	78	42	28	22	18	15	13	11	10
Ra226	USS0	12	11	10	9	9	8	8	7	7	3	3	3	3	3	2	2	2	2
	USS1	44	25	18	13	11	9	8	7	7	10	6	5	4	3	3	2	2	2
	USS2	44	25	18	13	11	9	8	8	8	14	8	6	4	4	3	3	3	3
	USS3	44	25	18	13	11	9	9	9	9	16	9	6	5	4	3	3	3	3
	USS4	44	25	18	13	11	11	11	11	11	16	9	6	5	4	4	4	4	4
	USS5	44	25	18	13	13	13	13	13	13	16	9	6	4	4	4	4	4	4
U235	USS0	51	34	25	20	17	14	12	11	10	40	26	20	16	13	11	10	9	8
	USS1	73	40	28	21	17	14	12	11	10	67	34	23	17	14	11	10	9	8
	USS2	73	40	28	21	17	14	12	11	10	67	34	23	17	14	11	10	9	8
	USS3	73	40	28	21	17	14	13	11	10	68	34	23	17	14	11	10	9	8
	USS4	73	40	28	21	17	15	13	11	10	68	34	23	17	14	12	10	9	8
	USS5	73	40	28	21	18	15	13	12	10	68	34	23	17	14	12	11	10	9
Ac227	USS0	6	6	6	6	6	6	6	6	6	3	2	2	2	2	2	2	2	2
	USS1	32	18	13	10	8	7	6	6	6	9	6	5	4	3	3	2	2	2
	USS2	32	18	13	10	8	7	7	7	7	13	8	6	4	4	3	3	3	3
	USS3	32	18	13	10	8	8	8	8	8	15	9	6	5	4	4	4	4	4
	USS4	32	18	13	10	9	9	9	9	9	15	9	6	5	4	4	4	4	4
	USS5	32	18	13	12	12	12	12	12	12	15	9	6	6	6	6	6	6	6
Th232	USS0	7	7	6	6	6	5	5	5	5	3	3	3	2	2	2	2	2	2
	USS1	36	18	12	9	7	6	5	5	5	12	6	4	3	3	2	2	2	2
	USS2	36	18	12	9	7	6	5	5	5	14	7	5	4	3	2	2	2	2
	USS3	36	18	12	9	7	6	6	6	6	15	7	5	4	3	2	2	2	2
	USS4	36	18	12	9	7	7	7	7	7	15	7	5	4	3	3	3	3	3
	USS5	36	18	12	9	9	9	9	9	9	15	7	5	4	4	4	4	4	4

*VE = vertical extent of contamination in feet
**USS = uncontaminated surface soil depth in feet

Table 7 Allowable Soil Concentration Increments (pCi/g)
Slab-on-grade construction scenario

VE*, USS**	Commercial (Limited Restricted Use)									Residential (Unrestricted Use)								
	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
U238 USS0	71	44	32	25	20	17	15	13	12	59	37	27	21	17	15	13	11	10
USS1	84	47	33	25	21	17	15	13	12	74	40	28	21	18	15	13	11	10
USS2	85	47	33	26	21	18	15	13	12	77	41	28	22	18	15	13	12	10
USS3	85	47	34	26	21	18	15	14	12	78	42	29	23	18	16	13	12	11
USS4	85	49	34	26	21	18	16	14	12	79	44	30	23	19	16	14	12	11
USS5	90	50	35	27	22	18	16	14	12	85	46	31	24	19	16	14	12	11
U234 USS0	72	43	31	24	20	17	14	13	11	64	38	27	21	17	14	12	11	10
USS1	81	45	31	24	20	17	14	13	11	75	40	27	21	17	14	12	11	10
USS2	81	45	31	24	20	17	15	13	11	75	40	27	21	17	15	13	11	10
USS3	81	45	32	25	20	17	15	13	12	75	40	28	22	18	15	13	11	10
USS4	81	46	32	25	20	17	15	13	12	76	42	29	22	18	15	13	11	10
USS5	85	48	33	25	21	17	15	13	12	81	43	30	23	18	15	13	11	10
Ra226 USS0	10	10	10	10	10	10	10	10	10	4	3	3	3	3	3	3	3	3
USS1	30	23	18	15	15	15	15	15	15	8	5	4	4	4	4	4	4	4
USS2	56	35	25	25	25	25	25	25	25	13	7	6	6	6	6	6	6	6
USS3	61	37	37	37	37	36	36	36	36	15	11	11	11	10	10	10	10	10
USS4	62	62	61	61	61	60	60	60	59	25	25	25	25	25	25	25	25	25
USS5	186	183	180	177	174	172	169	166	164	101	99	98	96	94	93	91	90	88
U235 USS0	50	33	25	20	17	14	13	11	10	36	26	20	16	14	12	10	9	8
USS1	67	39	27	21	17	15	13	11	10	55	31	22	17	14	12	11	9	9
USS2	72	40	28	22	18	15	13	12	11	69	35	24	19	15	13	11	10	9
USS3	73	40	29	23	18	16	14	12	11	70	36	25	20	16	14	12	10	9
USS4	73	43	30	23	19	16	14	12	11	71	39	27	21	17	14	12	11	9
USS5	81	45	31	24	19	16	14	12	11	85	43	29	22	17	14	12	11	10
Ac227 USS0	6	6	6	6	6	6	6	6	6	3	3	2	2	2	2	2	2	2
USS1	20	11	8	6	6	6	6	6	6	8	4	3	3	3	3	3	3	3
USS2	22	12	8	8	8	8	8	8	8	8	5	4	4	4	4	4	4	4
USS3	22	12	12	12	12	12	12	12	12	9	6	6	6	6	6	6	6	6
USS4	22	22	22	22	22	22	22	22	22	13	13	13	13	13	13	13	13	13
USS5	125	124	123	122	121	120	119	118	116	67	66	65	65	64	63	63	62	62
Th232 USS0	6	6	6	6	6	6	6	6	6	3	3	3	3	3	3	3	3	3
USS1	22	15	11	9	9	9	9	9	9	7	5	4	4	4	4	4	4	4
USS2	43	22	15	15	15	15	15	15	15	15	9	7	7	7	7	7	7	7
USS3	47	24	24	24	24	24	24	24	24	19	11	11	11	11	11	11	11	11
USS4	48	48	48	48	48	48	48	48	48	27	27	27	27	27	27	27	27	27
USS5	greater than 999									greater than 999								

*VE = vertical extent of contamination in feet
**USS = uncontaminated surface soil depth in feet

Table 8 Allowable Soil Concentration Increments (pCi/g)
Radon-based standards

VE*, USS*		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
Ra226 (basement)	USS0	7	4	3	3	2	2	2	2	2
	USS1	7	4	3	3	2	2	2	2	2
	USS2	7	4	3	3	2	2	2	2	2
	USS3	7	4	3	3	2	2	2	2	2
	USS4	7	4	3	3	2	2	2	2	2
	USS5	7	4	3	3	2	2	2	2	2
Ra226 (slab-on-grade)	USS0	7	4	3	3	2	2	2	2	2
	USS1	7	4	3	3	2	2	2	2	2
	USS2	10	5	4	4	3	3	3	3	3
	USS3	17	8	7	6	6	5	5	5	5
	USS4	24	11	9	8	8	7	7	7	7
	USS5	30	14	12	11	10	10	9	9	9

*VE = vertical extent of contamination in feet
**USS = uncontaminated surface soil depth in feet

4.3 SPREADSHEET IMPLEMENTATION

A spreadsheet program (NJRaSoRS.xls, Excel97 format) that implements the methodology described herein for the development of generic standards for remediation of radioactively contaminated sites is available to interested parties (contact information listed on page ii). The spreadsheet can be used to quickly perform sum of fraction calculations for a site with any combination of vertical extent, uncontaminated surface soil depth, site use designation, residual concentrations of subchains, and background concentrations of subchains. Additionally, the spreadsheet can be a helpful tool to help develop alternative soil remediation standards (pursuant to N.J.A.C. 7:28-12.12) as described in section 1.2. For instance, the spreadsheet can accommodate many simple alternative scenarios by changing input parameters (where justified) or "turning off" irrelevant pathways. Also, the spreadsheet can help direct the development of alternative soil remediation standards by identifying which pathways are most important, thereby focussing the applicant's own analyses. Any such alternative soil remediation standards shall be based on a department approved dose assessment and be as protective of human health and the environment as the generic standards established in this rule.

Appendix A

Homegrown Crop Ingestion Rate

Eight publications,[51] dating from 1987-1993, which contain values for vegetative intake were reviewed. These reports in turn cite eight further references[52] published over the period 1974-1989. The primary publications report similar values for total consumption of a particular group of foods; however, they vary greatly on their estimates of the percentage of food consumed that is grown on contaminated soil. It seems unlikely that 100% of a persons diet would be homegrown (grown on contaminated soil), therefore a reasonable assumption of the percentage of consumed homegrown food must be ascertained.

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[51] Till, J.E. and R.E. Moore. 1988. *A Pathway Approach for Determining Acceptable Levels of Contamination of Radionuclides in Soil.* Health Physics 55(3):541-548.

Kennedy, W.E. and R.A. Peloquin. 1990. *Residual Radioactive contamination from Decommissioning.* Draft Report for Comment. NUREG/CR-5512, PNL-7212.

Wang, Y.-Y., B.M. Biwer, and C. Yu. 1993. *A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code.* ANL/EAIS/TM-103.

Kennedy, W.E. Jr. and D.L. Strenge. 1992. *Residual Radioactive Contamination from Decommissioning.* NUREG/CR-5512, PNL-7994.

Center for Disease Control. 1987. *Health Assessment for Montclair, Glen Ridge and West Orange, N.J.*

U.S. Environmental Protection Agency. 1989. *Risk Assessment Methodology: Environmental Impact Statement: NESHAPS for Radionuclides: Background Information Document.* Volume 1. EPA 520 1-89-005.

U.S. Environmental Protection Agency. 1991. *Risk Assessment Guidance for Superfund: Volume 1: Human Health Evaluation Manual Supplemental Guidance: Standard Default Exposure Factors: Interim Final.* OSWER Directive: 9285.603.

U.S.E.P.A. 1991. *Human Health Evaluation Manual - Volume 1 (Part B), Development of Risk-based Preliminary Remediation Goals.* EPA/540/R-92/003.

[52] Oztunali, O.I., G.C. Re, P.M. Moskowitz, E.D. Picazo, and C.J. Pitt. 1981. *Data Base for Radioactive Waste Management: Impacts Analyses Methodology Report*. Volume 3. NUREG/CR-4370.

U.S. Department of Agriculture. 1974. *Food Consumption, Prices and Expenditures.* AER-138.

Rupp, E.M.. 1979. *Dietary Intake and Inhalation Rates, U_{ap},* in Hoffman, F.O. and C.F. Baes III (eds.). A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides. ORNL/NUREG/TM-282.

U.S. Department of Agriculture. 1980. *Food and Nutrient Intakes of Individuals in One Day in the United States: Spring 1977.* Nationwide Food Consumption Survey 1977-1978. Preliminary Report No. 2.

Pao, E.M., et al.. 1982. *Foods Commonly Eaten by Individuals: Amount Per Day and Per Eating Occasion.* Home Economics Report No. 44. U.S. Department of Agriculture, Washington, D.C.

Brodsky, A.. 1982. *CRC Handbook of Environmental Radiation.* 475 p..

U.S. Department of Agriculture. 1983. *Food Consumption: Households in the United States, Seasons, and Year 1977-1978.* Government Printing Office, Washington, D.C.

U.S. Environmental Protection Agency. 1989. *Exposure Factors Handbook.* EPA/600/8-89-043.

Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8.

EPA's *Exposure Factors Handbook* is the only publication which attempts to provide a logical justification for a particular vegetative intake value. This publication utilizes national survey data reported in USDA (1980) on the average amounts of total fruits and vegetables consumed on any one day. It is not known how representative these estimates are of consumption during the entire year. It is known that consumption rates vary by region. Information from USDA (1983) on the weight ratio of homegrown to total fruits and vegetables consumed was also examined. These ratios vary from 0.1 to 0.7 for various types of vegetables and fruits and for the rural, city and suburban populations. The overall average homegrown fraction was determined to be 0.25 for vegetables and 0.2 for fruits.

Ingestion Dose Conversion Factors

Seven publications,[53] dating 1979-1993, were reviewed which contain ingestion dose conversion factors. These reports in turn cite six further references[54] published over the period 1977-1988. Table 9 shows that the dose conversion factor values presented in the reviewed publications are essentially the same except for those values reported in Kennedy and Peloquin

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[53] Till, J.E. and R.E. Moore. 1988. *A Pathway Approach for Determining Acceptable Levels of Contamination of Radionuclides in Soil.* Health Physics 55(3):541-548.

International Commission on Radiological Protection. 1979. *Limits for Intakes of Radionuclides by Workers.* ICRP Publication 30, Part 1. Ann. ICRP 2(3/4).

Eckerman, K.F., A.B. Wolbarst, and A.C.B. Richardson. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.* Federal Guidance Report No. 11. EPA-520/1-88-020.

Yu., C., *et al.* 1993. *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2.

Kennedy, W.E. and R.A. Peloquin. 1990. *Residual Radioactive contamination from Decommissioning.* Draft Report for Comment. NUREG/CR-5512, PNL-7212.

Wang, Y.-Y., B.M. Biwer, and C. Yu. 1993. *A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code.* ANL/EAIS/TM-103.

Kennedy, W.E. Jr. and D.L. Strenge. 1992. *Residual Radioactive Contamination from Decommissioning.* NUREG/CR-5512, PNL-7994.

[54] International Commission on Radiological Protection. 1977. *Recommendations of the International Commission on Radiological Protection.* ICRP Publication 26. Ann. ICRP 1(4).

U.S. Nuclear Regulatory Commission. 1977. *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR 50, Appendix 2.* Regulatory Guide 1.109. Office of Standards Development, Rev. 1. Washington, D.C.

Oztunali, O.I., G.C. Re, P.M. Moskowitz, E.D. Picazo, and C.J. Pitt. 1981. *Data Base for Radioactive Waste Management: Impacts Analyses Methodology Report*. Volume 3. NUREG/CR-4370.

Johnson, J.R. and D.W. Dunford. 1983. *Dose Conversion Factors for Intakes of Selected Radionuclides by Infants and Adults.* Atomic Energy of Canada Limited Report. AECL-7919.

Corley, J.P. (ed.). 1986. *Committed Dose Equivalent Tables for U.S. Department of Energy Population Dose Calculations.* Appendix C.

U.S. Department of Energy. 1988. *Internal Dose Conversion Factors for Calculation of Dose to the Public.* DOE/EH-0071.

(1990). The author of this publication stated that the dose factors presented in the paper were not presented in the normal manner in which dose factors are usually presented. Specifically, ingestion dose conversion factors were presented in mrem/yr per pCi/g of soil instead of mrem/pCi. Therefore, it was decided that these values were inappropriate for use as inputs. The dose conversion factors from E.P.A. Federal Guidance Report No. 11 (Eckerman *et al*, 1988) were used for the ingestion dose calculations.

Table 9 Ingestion Dose Conversion Factors (mrem/pCi)

Radionuclide	ICRP , 1979	Eckerman, *et al* (1988)	Till and Moore (1988)	Yu, *et al* (1993) Wang, *et al* (1993)	Kennedy and Peloquin (1990)*	Kennedy and Strenge (1992)
Th 228+D		4×10^{-4}		7.5×10^{-4}	1×10^{-1}	4×10^{-4}
Th 229+D	3.5×10^{-3}	3.5×10^{-3}		4.3×10^{-3}	4.3×10^{-1}	3.5×10^{-3}
Th 230		5.5×10^{-4}		5.3×10^{-4}	4.2×10^{-1}	5.5×10^{-4}
Th 232		2.7×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	2.2	2.7×10^{-3}
Ra 226+D	1.2×10^{-3}	1.3×10^{-3}		1.1×10^{-3}	8.6×10^{-1}	1.3×10^{-3}
Ra 228+D		1.4×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	3.4×10^{-1}	1.4×10^{-3}
Pb 210+D		5.4×10^{-3}		6.7×10^{-3}	1.7	5.4×10^{-3}
U 238+D	2.3×10^{-4}	2.5×10^{-4}	2.3×10^{-4}	2.5×10^{-4}	7.3×10^{-3}	2.5×10^{-4}
U 234		2.8×10^{-4}	2.6×10^{-4}	2.6×10^{-4}	1.3×10^{-2}	2.8×10^{-4}
U 235+D		2.7×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	7×10^{-3}	2.7×10^{-4}

*these values are reported in mrem/yr per pCi/g instead of mrem/pCi

Vegetative Transfer Factors

Eight publications,[55] dating 1982-1993, which contain soil to vegetable transfer factors were reviewed. These publications in turn cite at least two additional references[56] published over the period 1977-1987. [Please note that Baes *et al* (1984) references a rather lengthy list of publications on which the paper is based; those references are not included here.] Table 10 shows that the soil to vegetation transfer factor values presented in the reviewed publications vary by approximately two orders of magnitude depending on the radionuclide and whether it is a composite value or a value for a particular type of vegetation, i.e. vegetable transfer factor versus a fruit transfer factor.

In 1993, Wang *et al* published a review document on the soil to vegetable transfer factor. This report discusses three considerations when reviewing soil to vegetable transfer factors from various sources. First, it is difficult to compare the soil to vegetable factors for root uptake used in the various publications because this factor can be reported in one of two different formats. The transfer factor can be reported as the ratio: pCi per gram plant (wet)/pCi per gram soil (dry) or pCi per gram plant (dry)/pCi per gram soil (dry). The Wang et al. (1993) document uses the wet plant factors since vegetation consumed by humans is most frequently reported in fresh weight.

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[55] Till, J.E. and R.E. Moore. 1988. *A Pathway Approach for Determining Acceptable Levels of Contamination of Radionuclides in Soil.* Health Physics 55(3):541-548.

Yu., C., *et al.* 1993. *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.* ANL/EAD/LD-2.

Kennedy, W.E. and R.A. Peloquin. 1990. *Residual Radioactive contamination from Decommissioning.* Draft Report for Comment. NUREG/CR-5512, PNL-7212.

Wang, Y.-Y., B.M. Biwer, and C. Yu. 1993. *A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code.* ANL/EAIS/TM-103.

U.S. Environmental Protection Agency. 1989. *Risk Assessment Methodology: Environmental Impact Statement: NESHAPS for Radionuclides: Background Information Document.* Volume 1. EPA 520 1-89-005.

International Atomic Energy Agency. 1982. *Generic Models and Parameters for Assessing the Environmental Transfer of Radionuclides from Routine Releases; Exposure of Critical Groups.* Safety Series No. 57.

Baes, C.F., R.D. Sharp, A.L. Sjoreen, and R.W. Shor. 1984. *A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture.* DE85-000287/ORNL-5786.

National Council on Radiation Protection and Measurements. 1991. unpublished data. referenced in Wang *et al.*, 1993.

[56] Oztunali, O.I., G.C. Re, P.M. Moskowitz, E.D. Picazo, and C.J. Pitt. 1981. *Data Base for Radioactive Waste Management: Impacts Analyses Methodology Report*. Volume 3. NUREG/CR-4370.

King, C.M., W.L. Marter, B.B. Looney, and J.B. Pickett. 1987. *Methodology and Parameters for Assessing Human Health Effects for Waste Sites at the Savannah River Plant.* DPST-86298. E.I. DuPont de Nemours and Co., Savannah River Plant, Aiken, SC 29408.

A second consideration associated with transfer factors is that comprehensive data in the literature is available for relatively few nuclides in different crops grown on various soils. Data for radionuclides for which little or no experimental information exists have been customarily estimated on the basis of the assumption that chemically similar elements act similarly in the soil-plant environment[57]. Relationships between transfer factors for an element and those for other elements of the same or adjacent periods or groups were established and examined for possible trends. Investigators often extrapolate such trends to the element in question.

A third consideration for transfer factors is whether the value represents a composite value from various food and feed crops or separate values for forage vegetation and edible portions of various vegetables and produce. If doses were being calculated for a particular vegetation type it might be advantageous to use the factor for that vegetation type. However, given the sparsity of data on which any of these factors are based, and that we do not know what kind of vegetation might be grown on a reclaimed site, it seems reasonable to use a composite factor.

Wang et al's (1993) composite transfer factors were chosen as input values because of the thorough, recent literature review which the authors conducted and the reasonable assumptions they made in proposing their values. These values are in good agreement with the composite values published in other references.[58]

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[57] Baes, C.F., R.D. Sharp, A.L. Sjoreen, and R.W. Shor. 1984. *A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture*. DE85-000287/ORNL-5786.

[58] Kennedy, W.E. and R.A. Peloquin. 1990. *Residual Radioactive contamination from Decommissioning*. Draft Report for Comment. NUREG/CR-5512, PNL-7212.

International Atomic Energy Agency. 1982. *Generic Models and Parameters for Assessing the Environmental Transfer of Radionuclides from Routine Releases; Exposure of Critical Groups*. Safety Series No. 57.

National Council on Radiation Protection and Measurements. 1991. unpublished data. referenced in Wang *et al*., 1993.

Table 10 Soil to Vegetation Transfer Factors

	IAEA* (1982)	Baes** *et al* (1984)		Till and Moore (1988)		EPA (1989)	
Element	Composite	Vegetable	Fruit	Edible[1]	Pasture[2]	Produce[1]	Pasture[2]
Th	5×10^{-4}	8.5×10^{-4}	8.5×10^{-5}	3.6×10^{-5}	8.5×10^{-4}	3.6×10^{-5}	8.5×10^{-4}
Ra	4×10^{-2}	1.5×10^{-2}	1.5×10^{-3}	6×10^{-3}	1.5×10^{-2}	6.4×10^{-4}	1.5×10^{-2}
Pb	1×10^{-2}	4.5×10^{-2}	9×10^{-3}			3.9×10^{-3}	4.5×10^{-2}
Po	2×10^{-4}	2.5×10^{-3}	4×10^{-4}			1.7×10^{-3}	2.5×10^{-2}
U	2×10^{-3}	8.5×10^{-3}	4×10^{-3}	1.7×10^{-3}	8.5×10^{-3}	1.7×10^{-3}	8.5×10^{-3}
Ac	1×10^{-3}	3.5×10^{-3}	3.5×10^{-4}			1.5×10^{-4}	3.5×10^{-3}
Pa	4×10^{-2}	2.5×10^{-3}	2.5×10^{-4}			1.1×10^{-4}	2.5×10^{-3}
Bi	1×10^{-1}	3.5×10^{-2}	5×10^{-3}			2.1×10^{-3}	3.5×10^{-2}
Tl		4.3×10^{-3}	4×10^{-4}			1.7×10^{-4}	4×10^{-3}

	Yu *et al* (1989)	Kennedy and Peloquin* (1990)		NCRP* (1991)	Wang* *et al* (1993)
Element		Leafy Vegetable	Root Vegetable	Composite	Composite
Th	4.2×10^{-3}	4.2×10^{-2}	1.7×10^{-2}	1×10^{-3}	1×10^{-3}
Ra	1.4×10^{-3}	1.4×10^{-1}	5.6×10^{-2}	4×10^{-2}	4×10^{-2}
Pb	6.8×10^{-2}	4×10^{-2}	1.6×10^{-2}	4×10^{-3}	1×10^{-2}
Po	9×10^{-3}	1×10^{-2}	1×10^{-2}	1×10^{-3}	1×10^{-3}
U	2.5×10^{-3}	2.5×10^{-2}	1×10^{-2}	2×10^{-3}	2.5×10^{-3}
Ac	2.5×10^{-3}	1×10^{-2}	1×10^{-2}	1×10^{-3}	2.5×10^{-3}
Pa	2.5×10^{-3}	5×10^{-2}	5×10^{-2}	1×10^{-2}	1×10^{-2}
Bi	1.5×10^{-1}	1.5	6×10^{-1}	1×10^{-1}	1×10^{-1}
Tl		9.9×10^{-4}	9.9×10^{-4}		

*wet plant weight to dry soil weight

**dry plant weight to dry soil weight

Area Factor Calculations

Using dimensions from the residential and commercial scenarios, area factors were linearly interpolated from the values in Table 50.1 of the DOE Data Collection Handbook[59]. Lot size was used for outside area factor; building area was used for underneath area factor; and lot size minus building size was used for inside area factor from surrounding mixed zone contamination. Area factor for contaminated zone adjacent to basement walls was determined by assuming four basement walls, interpolating area factors for values for each, and adding them together.[60] Contaminated zone soil adjacent to basement walls will result in four simultaneous vertical source planes.

Table 11 Area Factor Calculations

Gamma component		**area (ft²)**	**area (m²)**	**Area Factor**
outside	residential	5,000	465	0.78
	commercial	10,890	1,012	0.95
under basement	residential	1,000	93	0.54
	commercial	2,400	223	0.63
side contribution	residential	outside minus under basement		0.24
	commercial			0.32
each long basement wall	residential	280	26	0.40
	commercial	420	39	0.43
each short basement wall	residential	175	16	0.26
	commercial	280	26	0.40
all four basement walls	residential	2×long + 2×short		1.32
	commercial			1.66

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[59] Yu., C., *et al.* 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp.131-132.

[60] Personal communication with Dr. C. Yu corroborated the concept of accounting for all four vertical basement walls through additive area factors.

Drinking Water Pathway

Methodology

A semi-analytical code, GWSCREEN Version 2.03,[61] was used to estimate the groundwater activity concentrations and ingestion doses resulting from near surface contamination. GWSCREEN was developed to assess the groundwater pathway from leaching of radioactive and non-radioactive substances from surface or buried sources. The model makes several simplifying assumptions that are designed to assess the groundwater pathway when field data are limited. A mass balance approach was used to model three processes: contaminant release from a source volume, contaminant transport in the unsaturated zone, and contaminant transport in the saturated zone. None of the models in the code are novel; they are in fact textbook analytical simplifications. Contaminant transport in the saturated zone (and its associated uncertainty) was minimized by placing the drinking water well under the source material at the point of discharge from the unsaturated zone to the aquifer. Committed Effective Dose Equivalent was then calculated from the resultant well water concentrations.

Release from the source volume was modeled as a first-order leaching process that accounts for decay and sorption (distribution between solid and liquid media). Solubility-limited release was assumed to be negligible. This assumption is accurate for diffuse waste and conservative for more concentrated sources. Site parameters important to the leaching model include net water percolation rate (m/yr), volumetric moisture content and bulk density of source volume, thickness of source volume, and contaminant half-life (years). A sorption coefficient (also called distribution coefficient, ml/g) was assumed for each subchain.

Dispersion in the unsaturated zone was assumed to be negligible, leaving a simple plug-flow model. As long as the transport time in the unsaturated zone is less than ten times the half-life of the contaminant, dispersion will have the effect of lowering the peak concentration slightly. Therefore, it is conservative to consider dispersion negligible. The thickness of the unsaturated zone was reduced when necessary to fulfill the condition of the transit time being less than ten times the half-life of the contaminant. Contaminant flux to the aquifer was obtained by calculating the fraction of activity that remains after transit through the unsaturated zone. Site parameters important to the unsaturated transport model include thickness of unsaturated zone

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[61] Rood, A.S.. 1994. *GWSCREEN: a semi-analytical model for assessment of the groundwater pathway from surface or buried contamination: version 2.0* Theory and User's Manual, Revision 2. Idaho National Engineering Laboratory. EGG-GEO-10797.

Rood, A.S.. 1994. *GWSCREEN: a model for assessment of the groundwater pathway from surface or buried contamination.* The Environmental Professional 16:196-210.

MacKinnon, R.J. and T.M. Sullivan. 1994. *A review of GWSCREEN Version 2.0, with an emphasis on physical and chemical processes important to groundwater pathway assessments.* Risk Analysis 14(6):1109-1121.

(distance from base of source volume to top of aquifer, m), percolation rate (m/yr), volumetric moisture content, and bulk density in the unsaturated zone. Sorption coefficients were assumed to be the same as in the source volume for each subchain.

Assuming uniform steady flow in homogeneous isotropic media, the advection-dispersion equation for contaminant transport in saturated soil was approximated using a textbook analytical solution.[62] The activity concentration in the aquifer at some point downgradient from the center of the area source was solved in terms of Green's functions and vertically averaged over the well screen thickness. Aquifer parameters important to the saturated transport model include groundwater pore velocity (m/yr), dispersivity (m),effective porosity (m^3/m^3),well screen thickness, and bulk density. Sorption coefficients for each subchain were assumed to be the same in the aquifer as in the source volume and unsaturated zone.

Due to the long time frames involved, subchains within the same decay series were allowed to decay into one another. The concentration of individual subchains in a decay chain was calculated as a function of the parent concentration. Partitioning differences (as reflected in the sorption coefficients) among subchain species were taken into account. Decay-ingrowth factors were calculated based on the decay constants of the parent and subchain progeny.

Assumptions

A number of simplifying assumptions are implicit in the code (GWSCREEN) used to make calculations for the groundwater pathway analyses. For instance, the contaminant is assumed to be homogeneously mixed in a finite volume, and a constant infiltration rate is assumed. Recall that the code is not a predictive tool, but is intended to provide bounding calculations when field data are limited. For more information on the uses and limitations of GWSCREEN, refer to Rood (1994).

The peak concentrations calculated to occur between 1-1,000 years were used for all analyses. Even conservative bounding calculations become tenuous when carried out over long periods of time. Therefore it was decided to limit the calculations to 1,000 years. The thorium subchains (Th230 and Th232) were calculated to take over 5,000 years to move through ½ meter of unsaturated soil. Consequently, none of the thorium had reached the aquifer after the 1,000 year calculations. Also, Ra226+D, Pa231, and uranium subchains had not reached their peak concentrations after 1000 years. Transit times for Ra226+D and Pa231 were calculated to be 800 and 900 years, respectively. The long transit times of these contaminants reflects their strong tendency to sorb onto soil instead of desorbing into water.

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[62] Till, J.E. and H.R. Meyer. 1983. *Radiological Assessment: A Textbook on Environmental Dose Analysis.* U.S. Nuclear Regulatory Commission. NUREG/CR-3332, ORNL-5968. p. 4-29 to 4-33.

The model implicitly assumes that progeny travel with the parent through the unsaturated zone. This assumption is adequate as long as the progeny are short-lived relative to their transit times through the unsaturated zone, since the presence of progeny species in the unsaturated zone will be dependent on decay of the parent in the soil column. The production of Ra226 by the decay of Th230 must be handled differently. While the thorium species is essentially immobile (transit time greater than 5,000 through ½ meter), it will decay into Ra226 which persists and will travel, albeit slowly. In order to account for the independent movement of Ra226 produced by the Th230, the leach rate of Ra226 produced by Th230 was calculated over time externally and manually input as the source term for the groundwater model.

Though the simplifying assumptions in GWSCREEN are intended to yield conservative bounding approximations, the degree of conservatism depends in great part on the input parameters used in the analyses. Table 12 lists the generic site input parameters. The unsaturated zone was assumed to extend only ½ meter below the contaminated soil. There was no need to develop a more realistic depth to groundwater because the subchains of concern for the groundwater pathway have such long half-lives that the model is not at all sensitive to depth to groundwater. In other words, a larger depth to groundwater increases the travel time in the unsaturated zone, but the concentration of the very long-lived subchains will not have changed substantially over that time. The combination of relatively slow pore velocity in the aquifer and small well screen thickness ensures conservatism for most New Jersey sites. The drinking water well was assumed to be placed in the aquifer under the contaminated soil: 25 meters downstream from center for the residential scenario and at the downstream edge (50 meters from center) for the commercial scenario.

Table 12 Generic Site Input Parameters for Groundwater Pathway Analysis

Dimensions of contaminated zone, LxW (m):	100x100
Percolation rate (vertical Darcy velocity, m/yr):	0.5
Volumetric water content in contaminated zone (m^3/m^3):	0.35
Volumetric water content in unsaturated zone (m^3/m^3):	0.2
Bulk density of contaminated zone (g/cm^3):	1.6
Bulk density of unsaturated zone (g/cm^3):	1.6
Bulk density of saturated zone (g/cm^3):	1.6
Unsaturated zone thickness (distance from bottom of source to aquifer, m):	0.5
Porosity of aquifer:	0.45
Longitudinal dispersivity in aquifer (m):	9
Transverse dispersivity in aquifer (m):	4
Pore velocity in aquifer (m/yr):	4
Well screen thickness (mixing depth, m):	10
Horizontal distance to well (m) for residential, commercial scenarios:	25, 50

Subchains in each of the three naturally occurring radioactive material (NORM) decay series were evaluated as if they decayed directly into one another. For instance, the Uranium decay series was simplified as follows: U238+D⇒U234⇒Th230⇒Ra226+D⇒Pb210+D⇒Pb206. Progeny of each subchain parent were assumed to be in secular equilibrium with the subchain parent.

Sorption coefficients for subchain parents (also called distribution coefficients), listed in Table 13, were taken from the geometric mean of typical sorption coefficients in sand.[63] Sorption coefficients represent the tendency of a contaminant to remain bound (sorbed) in the soil; the lower the sorption coefficient, the greater tendency has the contaminant to leach (desorb) into the groundwater. Sorption coefficients vary greatly with chemical form and site characteristics such as soil type. Using the geometric mean for sand provides a conservative sorption coefficient relative to the range observed over many soil types and conditions.

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[63] Sheppard, M.I. and D.H. Thibault. 1990. *Default soil solid/liquid partition coefficients, K_ds, for four major soil types: a compendium.* Health Physics 59:471-482.

Sensitivity analyses indicate that the sorption coefficient is the single most important parameter affecting the potential dose via the drinking water pathway for the NORM subchains evaluated.

As explained in section 1.3.5, effective dose conversion factors[64] for ingestion were summed for all progeny in each subchain. This approach is consistent with the assumption of secular equilibrium. Dose calculations were performed assuming residential consumption of 2 liters/day intake for 350 days/year. Residential assumptions were also used for the commercial scenario since commercial land use on the surface could not preclude residential use of drinking water from the underlying aquifer. The hypothetical well for the commercial scenario was placed at the downstream edge of the contamination rather than directly underneath.

Table 13 Sorption Coefficients used for Groundwater Pathway Analysis

isotopes	Kd (mg/l)
uranium	35
thorium	3,200
radium	500
lead	270
proactinium	550
actinium	450

Radon Pathway

Vertical Extent Factor (VEF)

The Radon to Radium Ratio (RRR) assumes the radium concentration extends throughout the soil column. Indoor radon modeling studies indicate that "much greater radium concentrations can be tolerated if the contaminated zones are relatively thin."[65] Since data from New Jersey do not currently exist to support a relationship between radium thickness (vertical extent) and indoor radon concentration, the Department turned to the modeling output from the above-referenced study. Specifically, VEFs were taken from a modeling study analyzing the

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[64] Eckerman, K.F., A.B. Wolbarst, and A.C.B. Richardson. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.* Federal Guidance Report No. 11. EPA-520/1-88-020.

[65] Rogers, V., K.K. Nelson, and V.C. Rogers. 1992. *Foundation Soil Cleanup Depths and Radium Limits for Avoiding Elevated Indoor Radon.* Prepared by Rogers and Associates Engineering Corporation for U.S. Environmental Protection Agency. RAE-8964/18-2. p. 5-1.

effects of discrete contaminated soil layers on indoor radon concentrations.[66] While indoor radon potential will vary widely over different site and house scenarios (and probably vary even more in reality), the relative radon potential of discrete layers of radium contamination (i.e. VEFs) will not vary as much. VEFs were calculated from the model output by dividing the RRR modeled at various vertical extents by the maximum RRR, which was modeled at 16 feet vertical extent:

VE (ft.)	VEF (RRR/RRR_{max})
1	0.29
2	0.52
4	0.75
8	0.96
16	1

These data essentially mean that the radium in the first foot under a slab will produce 29% of the indoor radon that would be produced if the radium extended throughout the soil column; similarly, the first four feet of radium will produce 75% of the indoor radon. Transformations were performed to linearize these data, as follows: the independent variable VE was transformed using $\log_2(VE)$; the dependent variable VEF was transformed using VEF^2. Linear regression of $\log_2(VE)$ versus VEF^2 produced the following relationship: $VEF^2 = 0.07112 + 0.2483 \cdot \log_2(VE)$, where 0.07112 is the y-intercept (VEF_b) and 0.2483 is the slope (VEF_m). The r^2 value for this regression is 0.972, indicating a strong linearity. Solving for VEF in terms of VE results in the following: $VEF = \sqrt{(VEF_b + VEF_m \cdot \log_2(VE))}$. Vertical extents of contamination less than 1 foot were set equal to one foot to match the approach used in the reference modeling study.

Clean Layer Factor (CLF)

Using the same VEF function developed above, an expression was developed to account for clean soil between the slab and the radium contamination. Expressing the VEF equation as a function, let $f_{VEF}(X) = \sqrt{(VEF_b + VEF_m \cdot \log_2(X))}$. How would a layer of clean soil between the slab and the radium contamination affect the VEF? Two expressions were proposed to calculate VEF as a function of both vertical extent and clean layer depth (Clean).

The first expression (difference model) proposes that the VEF can be calculated by taking the VEF of both the Clean and VE layers and then subtracting off the VEF of the Clean layer: $VEF = f_{VEF}(VE + Clean) - f_{VEF}(Clean)$. The second expression (rate model) proposes instead that

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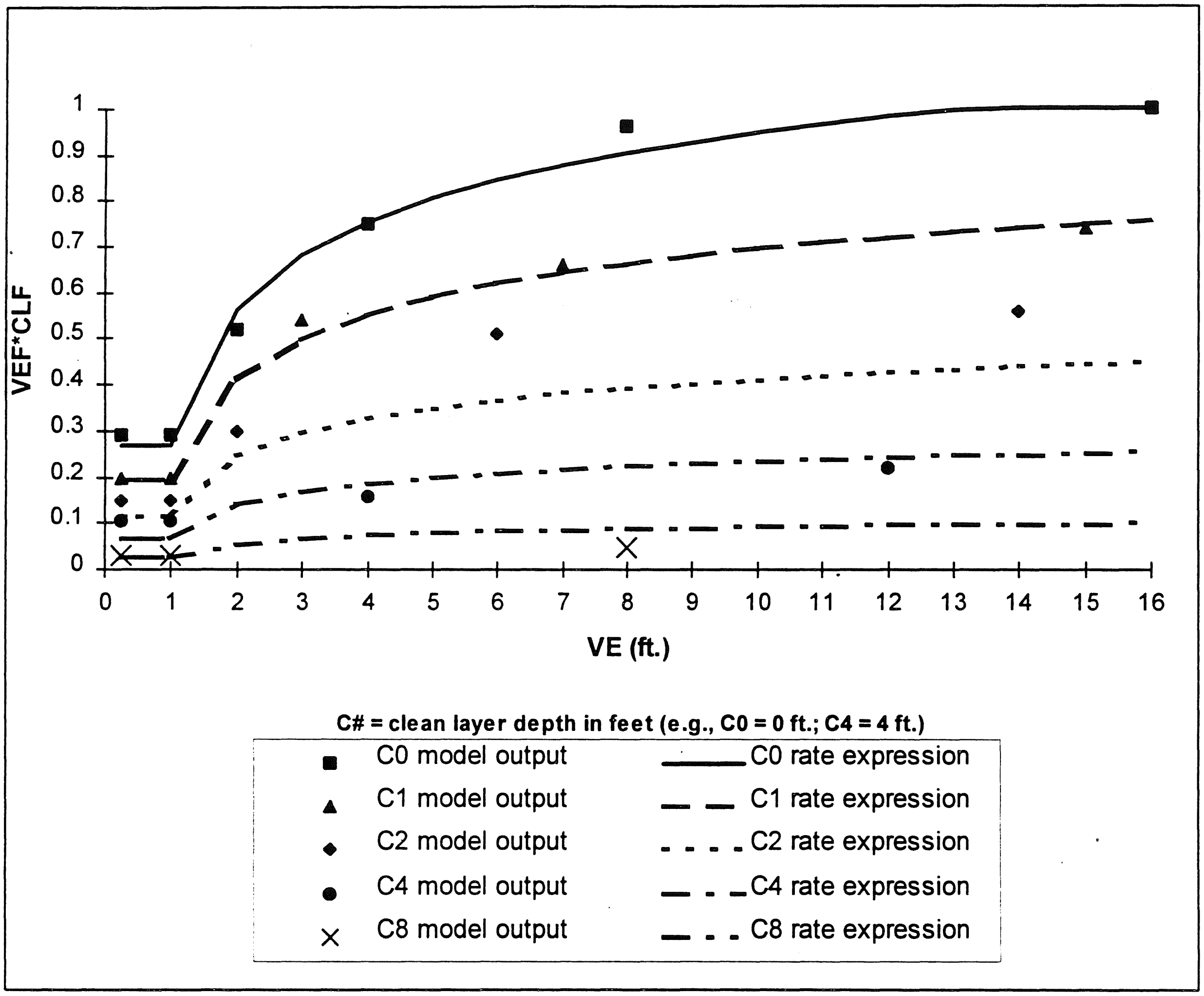
[66] Rogers, V., K.K. Nelson, and V.C. Rogers. 1992. *Foundation Soil Cleanup Depths and Radium Limits for Avoiding Elevated Indoor Radon.* Prepared by Rogers and Associates Engineering Corporation for U.S. Environmental Protection Agency. RAE-8964/18-2. Figure 5-1 and pp.5-1 to 5-3.

the VEF can be calculated by multiplying the VEF of the VE layer by one minus the VEF of the Clean layer: $VEF = f_{VEF}(VE)\cdot\left[1 - f_{VEF}(Clean)\right]$. Both expressions were implemented and compared with the output in the reference modeling study.[67] The rate expression reproduced the modeling output adequately (Figure 5), and was therefore selected. Clean layer depths less than 1 foot were set equal to zero feet to match the approach used in the reference modeling study.

Figure 5 Rate Expression for modifying Radon to Radium Ratio to account for vertical extent and clean layer depth (VEF*CLF)



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[67] Rogers, V., K.K. Nelson, and V.C. Rogers. 1992. *Foundation Soil Cleanup Depths and Radium Limits for Avoiding Elevated Indoor Radon.* Prepared by Rogers and Associates Engineering Corporation for U.S. Environmental Protection Agency. RAE-8964/18-2. p. 5-1.

For clarity of presentation, the rate expression that accounts for both vertical extent and clean layer depth was divided into two terms, VEF and CLF (Clean Layer Factor). Also, it should be noted that the modeling study was based on slab-on-grade residential construction. In the absence of a similar study for basement construction, the department chose to allow "credit" for clean layer depth only if the clean layer extends beneath the basement.

Appendix B

The following tables repeat the cleanup standards presented in Chapter 4, except that the values are given in SI units (Bq/g). Due to rounding errors, the pCi/g numbers from Chapter 4 cannot always be directly converted to Bq/g using a multiplier of 0.037. Also, again due to rounding errors, the same pCi/g value will not always be converted to the same Bq/g value. To minimize rounding errors, Bq/g values are rounded to the nearest hundredth.

Table 14 Allowable Soil Concentration Increments (Bq/g)
Most Restrictive (for sites where only one subchain is present above background)

VE*, USS**		Commercial (Limited Restricted Use)									Residential (Unrestricted Use)								
		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
U238	USS0	2.63	1.62	1.17	0.92	0.75	0.64	0.55	0.49	0.44	2.19	1.36	0.99	0.77	0.64	0.54	0.47	0.41	0.37
	USS1	3.11	1.74	1.21	0.92	0.76	0.64	0.55	0.49	0.44	2.73	1.49	1.03	0.79	0.65	0.55	0.47	0.41	0.37
	USS2	3.15	1.75	1.21	0.94	0.76	0.64	0.56	0.49	0.44	2.86	1.53	1.05	0.81	0.65	0.55	0.47	0.42	0.38
	USS3	3.16	1.75	1.23	0.94	0.76	0.64	0.56	0.49	0.44	2.88	1.55	1.07	0.81	0.65	0.55	0.48	0.42	0.38
	USS4	3.16	1.78	1.23	0.94	0.77	0.65	0.56	0.50	0.45	2.92	1.57	1.07	0.81	0.66	0.56	0.48	0.43	0.38
	USS5	3.20	1.78	1.23	0.95	0.78	0.66	0.57	0.50	0.45	2.93	1.57	1.07	0.82	0.67	0.56	0.49	0.43	0.39
U234	USS0	2.65	1.59	1.14	0.89	0.73	0.61	0.53	0.47	0.42	2.32	1.38	0.99	0.77	0.63	0.53	0.46	0.41	0.36
	USS1	3.01	1.67	1.16	0.89	0.73	0.61	0.53	0.47	0.42	2.77	1.48	1.01	0.77	0.63	0.53	0.46	0.41	0.36
	USS2	3.01	1.67	1.16	0.90	0.73	0.62	0.54	0.47	0.42	2.77	1.48	1.02	0.79	0.64	0.54	0.47	0.41	0.37
	USS3	3.01	1.67	1.18	0.91	0.74	0.62	0.54	0.47	0.42	2.78	1.50	1.04	0.80	0.64	0.54	0.47	0.41	0.37
	USS4	3.01	1.71	1.19	0.91	0.74	0.62	0.54	0.48	0.43	2.82	1.54	1.05	0.80	0.65	0.55	0.47	0.42	0.37
	USS5	3.07	1.71	1.19	0.92	0.74	0.63	0.54	0.48	0.43	2.88	1.54	1.05	0.81	0.65	0.55	0.47	0.42	0.37
Ra226	USS0	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.13	0.11	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS1	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS2	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS3	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS4	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS5	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
U235	USS0	1.83	1.24	0.93	0.74	0.61	0.52	0.46	0.40	0.36	1.35	0.95	0.73	0.58	0.48	0.41	0.36	0.32	0.29
	USS1	2.49	1.43	1.00	0.77	0.63	0.53	0.46	0.40	0.36	2.05	1.16	0.81	0.62	0.51	0.42	0.36	0.32	0.29
	USS2	2.68	1.48	1.03	0.78	0.63	0.53	0.46	0.41	0.37	2.49	1.26	0.84	0.63	0.51	0.42	0.36	0.32	0.29
	USS3	2.69	1.48	1.03	0.78	0.63	0.53	0.47	0.42	0.38	2.50	1.26	0.84	0.63	0.51	0.42	0.37	0.33	0.30
	USS4	2.69	1.48	1.03	0.78	0.64	0.54	0.48	0.42	0.38	2.50	1.26	0.84	0.63	0.50	0.43	0.38	0.34	0.31
	USS5	2.69	1.48	1.03	0.79	0.65	0.56	0.48	0.43	0.39	2.50	1.26	0.84	0.63	0.52	0.45	0.40	0.35	0.32
Ac227	USS0	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	USS1	0.75	0.43	0.30	0.23	0.23	0.23	0.21	0.21	0.21	0.28	0.15	0.11	0.09	0.09	0.09	0.09	0.09	0.09
	USS2	0.80	0.44	0.30	0.30	0.29	0.25	0.24	0.24	0.24	0.30	0.17	0.13	0.13	0.13	0.11	0.11	0.11	0.11
	USS3	0.81	0.44	0.44	0.36	0.29	0.29	0.29	0.29	0.29	0.34	0.21	0.21	0.17	0.14	0.13	0.13	0.13	0.13
	USS4	0.81	0.67	0.47	0.36	0.35	0.35	0.35	0.35	0.35	0.48	0.32	0.22	0.17	0.16	0.16	0.16	0.16	0.16
	USS5	1.17	0.67	0.47	0.45	0.45	0.45	0.45	0.45	0.45	0.57	0.32	0.22	0.21	0.21	0.21	0.21	0.21	0.21
Th232	USS0	0.24	0.24	0.23	0.22	0.21	0.20	0.19	0.17	0.17	0.11	0.10	0.10	0.09	0.08	0.08	0.08	0.06	0.06
	USS1	0.81	0.55	0.42	0.33	0.26	0.22	0.19	0.17	0.17	0.27	0.19	0.15	0.13	0.10	0.09	0.08	0.06	0.06
	USS2	1.31	0.66	0.44	0.33	0.26	0.22	0.19	0.19	0.19	0.52	0.27	0.18	0.14	0.11	0.09	0.08	0.08	0.08
	USS3	1.31	0.66	0.44	0.33	0.26	0.22	0.22	0.22	0.22	0.55	0.28	0.18	0.14	0.11	0.09	0.09	0.09	0.09
	USS4	1.31	0.66	0.44	0.33	0.27	0.27	0.27	0.27	0.27	0.55	0.28	0.18	0.14	0.11	0.11	0.11	0.11	0.11
	USS5	1.31	0.66	0.44	0.34	0.34	0.34	0.34	0.34	0.34	0.55	0.28	0.18	0.13	0.13	0.13	0.13	0.13	0.13

*VE = vertical extent of contamination in feet

**USS = uncontaminated surface soil depth in feet

Table 15 Allowable Soil Concentration Increments (Bq/g)
Basement construction scenario

VE*, USS**		Commercial (Limited Restricted Use)									Residential (Unrestricted Use)								
		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
U238	USS0	2.65	1.62	1.17	0.92	0.75	0.64	0.55	0.49	0.44	2.20	1.36	0.99	0.77	0.64	0.54	0.47	0.41	0.37
	USS1	3.20	1.78	1.23	0.94	0.76	0.64	0.55	0.49	0.44	2.88	1.55	1.06	0.81	0.65	0.55	0.47	0.41	0.37
	USS2	3.20	1.78	1.23	0.94	0.76	0.64	0.56	0.49	0.44	2.92	1.56	1.07	0.81	0.65	0.55	0.47	0.42	0.38
	USS3	3.20	1.78	1.23	0.94	0.76	0.64	0.56	0.49	0.44	2.93	1.57	1.07	0.81	0.65	0.55	0.48	0.42	0.38
	USS4	3.20	1.78	1.23	0.94	0.77	0.65	0.56	0.50	0.45	2.93	1.57	1.07	0.81	0.66	0.56	0.48	0.43	0.38
	USS5	3.20	1.78	1.23	0.95	0.78	0.66	0.57	0.50	0.45	2.93	1.57	1.07	0.82	0.67	0.56	0.49	0.43	0.39
U234	USS0	2.65	1.59	1.14	0.89	0.73	0.61	0.53	0.47	0.42	2.32	1.38	0.99	0.77	0.63	0.53	0.46	0.41	0.36
	USS1	3.07	1.71	1.19	0.91	0.74	0.62	0.53	0.47	0.42	2.83	1.52	1.04	0.79	0.64	0.54	0.46	0.41	0.36
	USS2	3.07	1.71	1.19	0.91	0.74	0.62	0.54	0.47	0.42	2.87	1.54	1.05	0.80	0.64	0.54	0.47	0.41	0.37
	USS3	3.07	1.71	1.19	0.91	0.74	0.62	0.54	0.47	0.42	2.88	1.54	1.05	0.80	0.64	0.54	0.47	0.41	0.37
	USS4	3.07	1.71	1.19	0.91	0.74	0.62	0.54	0.48	0.43	2.88	1.54	1.05	0.80	0.65	0.55	0.47	0.42	0.37
	USS5	3.07	1.71	1.19	0.92	0.74	0.63	0.54	0.48	0.43	2.88	1.54	1.05	0.81	0.65	0.55	0.47	0.42	0.37
Ra226	USS0	0.43	0.40	0.37	0.35	0.33	0.31	0.29	0.26	0.26	0.13	0.11	0.11	0.10	0.10	0.09	0.09	0.08	0.08
	USS1	1.64	0.93	0.65	0.50	0.40	0.34	0.29	0.26	0.26	0.38	0.23	0.18	0.14	0.12	0.10	0.09	0.08	0.08
	USS2	1.64	0.93	0.65	0.50	0.40	0.34	0.29	0.29	0.29	0.52	0.30	0.21	0.16	0.13	0.11	0.09	0.09	0.09
	USS3	1.64	0.93	0.65	0.50	0.40	0.34	0.34	0.34	0.34	0.59	0.32	0.22	0.17	0.14	0.11	0.11	0.11	0.11
	USS4	1.64	0.93	0.65	0.50	0.40	0.40	0.40	0.40	0.40	0.59	0.32	0.22	0.17	0.13	0.13	0.13	0.13	0.13
	USS5	1.64	0.93	0.65	0.50	0.50	0.50	0.50	0.50	0.49	0.59	0.32	0.22	0.16	0.16	0.16	0.16	0.16	0.16
U235	USS0	1.90	1.25	0.93	0.74	0.61	0.52	0.46	0.40	0.36	1.47	0.97	0.73	0.58	0.48	0.41	0.36	0.32	0.29
	USS1	2.69	1.48	1.03	0.78	0.63	0.53	0.46	0.40	0.36	2.46	1.25	0.84	0.63	0.51	0.42	0.36	0.32	0.29
	USS2	2.69	1.48	1.03	0.78	0.63	0.53	0.46	0.41	0.37	2.49	1.26	0.84	0.63	0.51	0.42	0.36	0.32	0.29
	USS3	2.69	1.48	1.03	0.78	0.63	0.53	0.47	0.42	0.38	2.50	1.26	0.84	0.63	0.51	0.42	0.37	0.33	0.30
	USS4	2.69	1.48	1.03	0.78	0.64	0.54	0.48	0.42	0.38	2.50	1.26	0.84	0.63	0.50	0.43	0.38	0.34	0.31
	USS5	2.69	1.48	1.03	0.79	0.65	0.56	0.48	0.43	0.39	2.50	1.26	0.84	0.63	0.52	0.45	0.40	0.35	0.32
Ac227	USS0	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	USS1	1.17	0.67	0.47	0.36	0.29	0.25	0.21	0.21	0.21	0.34	0.22	0.17	0.14	0.11	0.10	0.09	0.09	0.09
	USS2	1.17	0.67	0.47	0.36	0.29	0.25	0.24	0.24	0.24	0.48	0.29	0.21	0.16	0.13	0.11	0.11	0.11	0.11
	USS3	1.17	0.67	0.47	0.36	0.29	0.29	0.29	0.29	0.29	0.57	0.32	0.22	0.17	0.14	0.13	0.13	0.13	0.13
	USS4	1.17	0.67	0.47	0.36	0.35	0.35	0.35	0.35	0.35	0.57	0.32	0.22	0.17	0.16	0.16	0.16	0.16	0.16
	USS5	1.17	0.67	0.47	0.45	0.45	0.45	0.45	0.45	0.45	0.57	0.32	0.22	0.21	0.21	0.21	0.21	0.21	0.21
Th232	USS0	0.26	0.25	0.23	0.22	0.21	0.20	0.19	0.17	0.17	0.12	0.11	0.10	0.09	0.08	0.08	0.08	0.06	0.06
	USS1	1.31	0.66	0.44	0.33	0.26	0.22	0.19	0.17	0.17	0.43	0.23	0.16	0.13	0.10	0.09	0.08	0.06	0.06
	USS2	1.31	0.66	0.44	0.33	0.26	0.22	0.19	0.19	0.19	0.52	0.27	0.18	0.14	0.11	0.09	0.08	0.08	0.08
	USS3	1.31	0.66	0.44	0.33	0.26	0.22	0.22	0.22	0.22	0.55	0.28	0.18	0.14	0.11	0.09	0.09	0.09	0.09
	USS4	1.31	0.66	0.44	0.33	0.27	0.27	0.27	0.27	0.27	0.55	0.28	0.18	0.14	0.11	0.11	0.11	0.11	0.11
	USS5	1.31	0.66	0.44	0.34	0.34	0.34	0.34	0.34	0.34	0.55	0.28	0.18	0.13	0.13	0.13	0.13	0.13	0.13

*VE = vertical extent of contamination in feet

**USS = uncontaminated surface soil depth in feet

Table 16 Allowable Soil Concentration Increments (Bq/g)
Slab-on-grade construction scenario

VE*, USS**		Commercial (Limited Restricted Use)									Residential (Unrestricted Use)								
		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9	VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
U238	USS0	2.63	1.62	1.17	0.92	0.75	0.64	0.56	0.49	0.44	2.19	1.36	0.99	0.78	0.64	0.55	0.47	0.42	0.38
	USS1	3.11	1.74	1.21	0.92	0.76	0.64	0.56	0.49	0.44	2.73	1.49	1.03	0.79	0.65	0.55	0.48	0.42	0.38
	USS2	3.15	1.75	1.21	0.94	0.77	0.65	0.57	0.50	0.45	2.86	1.53	1.05	0.82	0.67	0.56	0.49	0.43	0.39
	USS3	3.16	1.75	1.24	0.96	0.78	0.66	0.57	0.50	0.45	2.88	1.55	1.09	0.84	0.68	0.58	0.50	0.44	0.39
	USS4	3.16	1.81	1.27	0.98	0.79	0.67	0.58	0.51	0.45	2.92	1.62	1.12	0.86	0.70	0.59	0.50	0.44	0.40
	USS5	3.33	1.87	1.29	0.99	0.80	0.68	0.58	0.51	0.46	3.15	1.69	1.16	0.88	0.71	0.59	0.51	0.45	0.40
U234	USS0	2.65	1.59	1.14	0.89	0.73	0.61	0.53	0.47	0.42	2.37	1.39	0.99	0.77	0.63	0.53	0.46	0.41	0.36
	USS1	3.01	1.67	1.16	0.89	0.73	0.61	0.53	0.47	0.42	2.77	1.48	1.01	0.77	0.63	0.53	0.46	0.41	0.36
	USS2	3.01	1.67	1.16	0.90	0.73	0.62	0.54	0.47	0.42	2.77	1.48	1.02	0.79	0.64	0.54	0.47	0.41	0.37
	USS3	3.01	1.67	1.18	0.91	0.74	0.63	0.54	0.48	0.43	2.78	1.50	1.04	0.80	0.65	0.55	0.47	0.42	0.37
	USS4	3.01	1.72	1.20	0.92	0.75	0.63	0.55	0.48	0.43	2.82	1.55	1.07	0.82	0.66	0.56	0.48	0.42	0.38
	USS5	3.15	1.76	1.22	0.94	0.76	0.64	0.55	0.48	0.43	2.99	1.61	1.10	0.83	0.67	0.56	0.48	0.42	0.38
Ra226	USS0	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.13	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11
	USS1	1.11	0.84	0.67	0.56	0.56	0.56	0.56	0.56	0.56	0.28	0.19	0.15	0.13	0.13	0.13	0.13	0.13	0.13
	USS2	2.08	1.29	0.94	0.94	0.93	0.93	0.93	0.93	0.92	0.47	0.28	0.23	0.23	0.23	0.23	0.23	0.22	0.22
	USS3	2.27	1.37	1.36	1.36	1.35	1.35	1.34	1.34	1.33	0.57	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
	USS4	2.30	2.28	2.27	2.26	2.24	2.23	2.22	2.21	2.20	0.94	0.94	0.93	0.93	0.93	0.92	0.92	0.91	0.91
	USS5	6.90	6.78	6.66	6.55	6.45	6.35	6.25	6.15	6.06	3.74	3.68	3.61	3.55	3.49	3.43	3.38	3.32	3.27
U235	USS0	1.83	1.24	0.93	0.75	0.62	0.54	0.47	0.42	0.38	1.35	0.95	0.73	0.59	0.50	0.43	0.38	0.34	0.31
	USS1	2.49	1.43	1.00	0.77	0.64	0.55	0.48	0.42	0.38	2.05	1.16	0.81	0.62	0.52	0.45	0.39	0.35	0.32
	USS2	2.68	1.49	1.03	0.81	0.67	0.57	0.49	0.44	0.39	2.54	1.30	0.88	0.69	0.57	0.48	0.42	0.37	0.33
	USS3	2.70	1.49	1.07	0.83	0.68	0.58	0.50	0.44	0.40	2.61	1.33	0.94	0.73	0.59	0.50	0.43	0.38	0.34
	USS4	2.70	1.58	1.11	0.86	0.70	0.59	0.51	0.45	0.40	2.64	1.45	1.00	0.76	0.62	0.52	0.45	0.39	0.35
	USS5	2.99	1.67	1.16	0.89	0.72	0.60	0.52	0.46	0.41	3.14	1.59	1.07	0.80	0.64	0.54	0.46	0.40	0.36
Ac227	USS0	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.11	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	USS1	0.75	0.43	0.30	0.23	0.23	0.23	0.23	0.23	0.23	0.28	0.15	0.11	0.09	0.09	0.09	0.09	0.09	0.09
	USS2	0.80	0.44	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.17	0.13	0.13	0.13	0.13	0.13	0.13	0.13
	USS3	0.81	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.34	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
	USS4	0.81	0.81	0.81	0.80	0.80	0.80	0.80	0.80	0.80	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.47
	USS5	4.64	4.59	4.55	4.51	4.47	4.43	4.39	4.35	4.31	2.46	2.44	2.42	2.39	2.37	2.35	2.33	2.30	2.28
Th232	USS0	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	USS1	0.81	0.55	0.42	0.34	0.34	0.34	0.34	0.34	0.34	0.27	0.19	0.15	0.13	0.13	0.13	0.13	0.13	0.13
	USS2	1.58	0.83	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.57	0.32	0.24	0.24	0.24	0.24	0.24	0.24	0.24
	USS3	1.74	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.71	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
	USS4	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
	USS5	greater than 99									greater than 99								

*VE = vertical extent of contamination in feet

**USS = uncontaminated surface soil depth in feet

Table 17 Allowable Soil Concentration Increments (Bq/g)
Radon-based standards

VE*, USS**		VE1	VE2	VE3	VE4	VE5	VE6	VE7	VE8	VE9
Ra226	USS0	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
(basement)	USS1	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS2	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS3	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS4	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS5	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
Ra226	USS0	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
(slab-on-grade)	USS1	0.28	0.13	0.11	0.10	0.09	0.09	0.08	0.08	0.08
	USS2	0.38	0.18	0.15	0.13	0.13	0.12	0.12	0.11	0.11
	USS3	0.64	0.30	0.25	0.23	0.21	0.20	0.19	0.19	0.18
	USS4	0.87	0.41	0.34	0.31	0.29	0.28	0.27	0.26	0.25
	USS5	1.13	0.53	0.44	0.40	0.37	0.36	0.34	0.33	0.32

*VE = vertical extent of contamination in feet
**USS = uncontaminated surface soil depth in feet