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Healthcare

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Via Federal Express

July 20, 2006

Ms. Amy M. Snyder
Senior Project Manager
U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety and Safeguards
Division of Waste Management and Environmental Protection
Materials Decommissioning Section
Mail Stop T-7E-18
Washington, DC 20555-0001

Re: **NRC Docket 40-06563, NRC License STB - 401**
Mallinckrodt Inc. – C-T Phase II Decommissioning Plan
Appendix G and Chapter 5, "Dose Modeling"

Dear Ms. Snyder:

Mallinckrodt's response to NRC staff requests for information concerning the C-T Phase II Decommissioning Plan are enclosed. By teleconference call, Mark Thaggard requested that the source terms for derivation of concentration guideline level (DCGL) on pavement and attenuation effect of pavement from cinder fill beneath be based on radionuclides observed by sampling. Explanation of DCGL on pavement in equivalent, measurable units was also requested. A new Appendix G to CT 2 DP describing derivation of $DCGL_W$ on pavement and other explanations requested, a corresponding revision of CT 2 DP, section 5 Dose Modeling, §5.9, §5.10, and §5.11, and an updated Table of Contents of the Plan are enclosed.

If you have any further questions concerning the C-T Phase II Decommissioning Plan or concerning these responses, please contact me.

Sincerely,

Pat Duft
Patricia H. Duft

PHD:tob
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MALLINCKRODT C-T DECOMISSIONING PROJECT
C-T PHASE II DECOMISSIONING PLAN

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APPENDIX G

DERIVATION OF $DCGL_W$ ON PAVEMENT

Mallinckrodt, Inc.

C-T Phase II Decommissioning Plan
June 5, 2006

NRC Docket: 40-06563
NRC License: STB-401

APPENDIX G
DERIVATION OF $DCGL_W$ ON PAVEMENT

1. INTRODUCTION

Most land area in Plant 5 is covered by pavement, buildings, or building slabs. Characterization survey data indicate that only 3 of 1670 direct measurements [ref. CT 2 DP §4, Table 4-3] on pavement in Plant 5 exceeded the DCGL initially proposed for pavement in C-T Phase II DP §5, Dose Modeling. Only one scabble sample of pavement contained more than, 0.05 wt % source material, a threshold concentration for licensing according to 10 CFR Part 40.13(a) [ref. CT 2 DP §4.8.3]. It would be rational to survey the pavement and building slabs separately from underlying cinder fill in order to "clear" the pavement from survey and release considerations associated with the cinder fill. Since potential contamination on pavement and building slabs would be mainly on the surface and potential contamination in cinder fill would be within its volume it would be logical to derive and express DCGL in units of areal density and mass concentration respectively.

This appendix describes a revised derivation of DCGLw applicable to pavement and building slabs. Responses to NRC staff requests for additional information about this topic are also incorporated into this appendix.

2. COMPENSATION FOR GAMMA RADIATION FROM CINDER FILL THROUGH PAVEMENT

When deriving DCGL, one consideration is whether exposure to pavement and to soil beneath are independent. In essence, the scenario of exposure to bare soil, on which DCGL for soil were derived, and the scenario of exposure to pavement, on which DCGL for pavement are derived, cannot occur simultaneously. Without pavement, the source and exposure pathways to contamination on pavement are absent, and exposure to topsoil can occur. Thus, DCGL derived for soil are independent of presence of or contribution from pavement.

Alternatively, when pavement exists atop soil, it would be a complete barrier against airborne and ingestion pathways of exposure to conceivable residue in the soil and an incomplete shield against gamma radiation penetrating from conceivable residue in the soil beneath. If pavement were to erode or be removed, so would any source on or embedded in the pavement be removed. Analysis of the amount of radiological dose that could be caused by gamma radiation from C-T residue in soil penetrating pavement has been done by dose modeling. If the maximum amount of dose allowed from contamination on pavement surface is specified to be no more than 25 mrem/yr minus the contribution from residue in cinder fill beneath the pavement, the corresponding DCGL on pavement will be uncoupled from the DCGL in cinder fill.

2.1. <u>RADOINUCLIDE SOURCE IN CINDER FILL</u>

Determination of the relative concentration relation of C-T radionuclides above background concentration in cinder fill is reported in Phase II Decommissioning Plan (DP)

Appendix C. The geometric mean of each distribution shown in DP Appendix C, Figures C-1 through C-5 and in Appendix C, Attachment B, is presented as the best estimate of the ratio of the respective key radionuclides. The mean ratios are summarized as:

Table G-1. Ln Mean Ratio in Cinder Fill

Th^{230} / U^{238}	=	1.1
Ra^{226} / U^{238}	=	2.8
Th^{230} / Ra^{226}	=	0.66
Ra^{228} / Th^{232}	=	1.6
Th^{228} / Th^{232}	=	1.3
Th^{228} / Ra^{228}	=	0.8

Fifteen years since cessation of C-T processing is enough time to allow thorium series radionuclides to grow or decay within about 0.20 of radioactive equilibrium. Considering uncertainty in alpha spectrometry of separate radioelements at low concentration, the thorium series might rationally be assumed to be in radioactive equilibrium in Plant 5 soil samples.

The characterization survey data suggest that a reasonably representative range of source terms would be a U / Th ratio of approximately 3, with uranium isotopes in radioactive equilibrium, with thorium series in radioactive equilibrium, and with excess Th^{230} and Ra^{226}.

When assessing shielding effect of pavement on radiological dose caused by C-T residue in cinder fill, the relative concentration on long-lived radionuclides in cinder fill is represented by these ratios as:

Table G-2. Relative Radionuclide Concentration in Cinder Fill

Nuclide	Relative Concentration (pCi/g soil)			Concentration Causing 25 mrem/yr[A] (pCi/g soil)
U^{238}	3.0	=	3.0	9.959
U^{234}	3.0	=	3.0	9.959
U^{235}	3.0 x 0.0455	=	0.137	0.453
Ac^{227}	3.0 x 0.0455	=	0.137	0.453
Pa^{231}	3.0 x 0.0455	=	0.137	0.453
Th^{230}	3.0 x 1.1	=	3.3	10.96
Ra^{226}	3.0 x 2.8	=	8.4	27.89
Pb^{210}	3.0 x 2.8	=	8.4	27.89
Th^{232}	1.0	=	1.0	3.32
Ra^{228}	1.0	=	1.0	3.32
Th^{228}	1.0	=	1.0	3.32

[A] Concentration causing 25 mrem/yr = 3.32 x relative concentration of each radionuclide.

The "concentration causing 25 mrem/yr" of the source spectrum in cinder fill maintains the relative concentration of each radionuclide to each other while increasing each by a constant multiplier, 3.32, to describe a source that, altogether, causes 25 mrem/yr atop bare soil.

2.2. DOSE MODELING

As depth of C-T source material in cinder fill, beginning at bare land surface, increases, the cinder fill itself attenuates radiation from the intermingled source. With increasing depth of source, gamma radiation emanating from land surface asymptotically reaches a maximum, or plateau, intensity. Response to NRC Request for Additional Information, Figure 41 demonstrates that maximum dose rate reaches a plateau when the source is about 30 cm deep in the ground. Similarly, Figure G-2 confirms that only about 0.01 of gamma radiation would penetrate through 30 cm of pavement. Thus, assumption of a 100 cm deep zone of C-T source material in cinder fill is sufficient to produce maximum dose rate for the purpose of this modeling analysis.

2.3. ANALYSIS OF SHIELDING EFFECT OF PAVEMENT

Dose modeling to evaluate the effect of pavement on suppressing radiological dose was done by entering the same values of parameters into RESRAD version 6.3 as were used to derive DCGLw in bare soil except for the source radionuclide concentrations and pavement description. When entered into RESRAD version 6.3, as modeled to derive the DCGLw in bare soil, the spectrum of nuclide "concentration causing 25 mrem/yr" does yield a probabilistic peak of the mean dose = 25.0 mrem/yr. The time of the peak of the mean dose occurs during the first year of exposure. [ref. RESRAD case 446iuth]

Modeling to estimate the effect of pavement on attenuating dose from residual radionuclides in cinder fill soil was done by simulating a range of thicknesses of pavement atop the same one-meter-deep source of C-T residue in the cinder fill described in Table G-2. When pavement was assumed present, inhalation and ingestion pathways originating in the soil were assumed to be prevented by the pavement barrier. Pavement density was estimated to be 1.9 g/cm^3 to simulate a gravel-asphalt mix. (By comparison, concrete pavement density would be about 2.2 g/cm^3 and would increase attenuation). Erosion of pavement and soil was assumed to be practically negligible at 1.x 10^{-4} m/yr and would be of no effect since maximum potential dose occurs in the first year of exposure.

Results of the RESRAD simulations of effect of a range of pavement thickness on radiological dose are displayed graphically in Figures G-1 and G-2.

Figure G-1. Effect of Pavement Thickness on Radiological Dose from Cinder Fill

Source Spectrum is Ln Mean of Characterization Survey Data
Dose Modeling by RESRAD v. 6.3

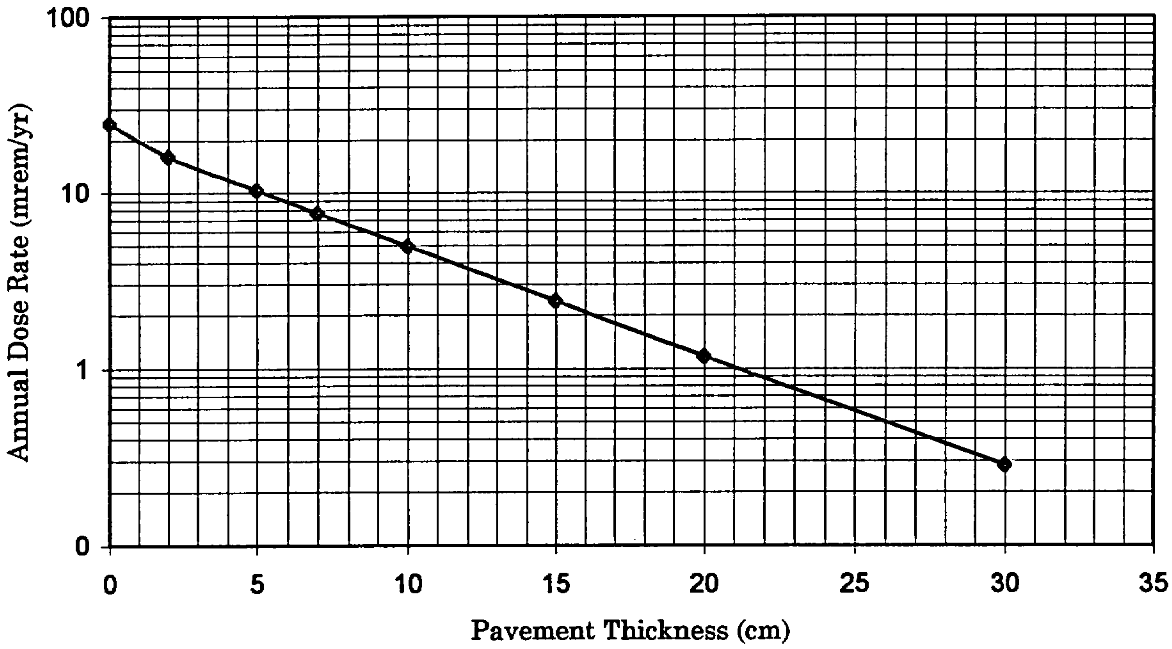
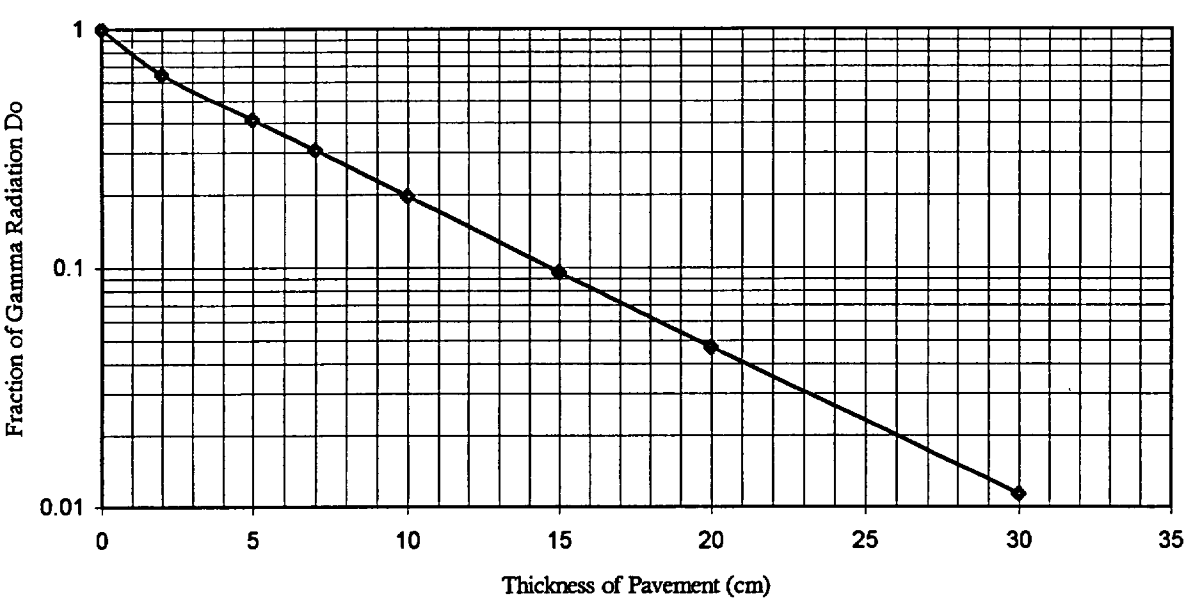


Figure G-2. Fraction of Gamma Radiation Penetrating Pavement

Source Spectrum is Ln Mean Radionuclide Concentration in Cinder Fill
Dose Modeling by RESRAD v. 6.3



When pavement is at a nominal 4-inch thickness, *i.e.*, 10 cm, potential radiological dose atop the pavement is 0.2 of the potential dose atop bare soil. That is, the spectrum of radionuclide concentrations in the characterization survey of cinder fill that would produce 25 mrem/yr atop bare cinder fill, would produce only 4.95 mrem/yr atop 4-inch-thick macadam pavement and even less atop concrete pavement.

Thus, with the aid of dose modeling of outdoor exposure to gamma radiation penetrating nominal 4-inch-thick pavement by RESRAD, one finds that one or more meters of soil containing $DCGL_W$ concentration of the source spectrum, i.e., relative concentration ratios, would be estimated to contribute 4.95 mrem/yr through the pavement. Subtracting that from 25 mrem/yr allotted to DCGL would imply reduction of conceivable contribution from residue on pavement itself to 20 mrem/yr and would eliminate question of allocation of maximum acceptable total dose.

Although it is unlikely that both soil and pavement would be contaminated to more than 0.80 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ on pavement in is being reduced by 0.20 to correspond to 20 mrem/yr. Together with revisions in response to NRC request for additional information item 48, values in Table G-7 herein become the revised $DCGL_W$ to be applied. As a consequence $DCGL_{EMC}$ will also be reduced to nominally 0.80 of 25 mrem/yr.

3. DERIVATION OF $DCGL_W$ ON PAVEMENT, COMPENSATED FOR GAMMA RADIATION FROM CINDER FILL

3.1. INTRODUCTION

The objective in dose modeling was to determine the maximum **areal density** of contaminant on or near the surface that would not cause more than 25 mrem/yr when potential gamma radiation from residue in underlying cinder fill is included.

Dose factors were computed by RESRAD for an industrial work scenario on pavement. The RESRAD output for each radionuclide can be interpreted as a dose factor (mrem/y per pCi/m^2), which in turn may be interpreted as a maximum acceptable average areal density of the radionuclide on a surface, also called the $DCGL_W$, corresponding to a maximum acceptable potential radiological dose equivalent.

3.2. MODELING EXPOSURE

In the industrial land use scenario and outdoor environment of interest with contaminant assumed on the surface of pavement, the potential exposure pathways would mainly be by direct gamma irradiation, inhalation of dust suspended into air, and ingestion of dust. Among these, the model simulating suspension of dust into outdoor air in RESRAD is appropriate; whereas the indoor ventilation model in RESRAD-BUILD would be less adaptable. The conceptual models for ingestion and inhalation in RESRAD are a function of radioactivity concentration in the surface dust or soil and not on its depth. Consequently, RESRAD was employed because it would be preferable for exposure to an outdoor source on pavement via these pathways. Inhalation was treated probabilistically [ref. RESRAD case 457putrae3].

Although it is unlikely that both soil and pavement would be contaminated to more than 0.8 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ on pavement is being reduced by 0.2 to the equivalent of 20 mrem/yr, which become the revised $DCGL_W$ to be applied. As a consequence, $DCGL_{EMC}$ will also be reduced to the equivalent of 20 mrem/yr.

3.3. RADIONUCLIDE SOURCE ON PAVEMENT

The Columbium-Tantalum Characterization Plan, described in Decommissioning Plan §4.0, provided for survey of paved surfaces in the former C-T process and support areas of Plant 5. Twenty-four scabble samples of pavement in the Plant 5 area were collected and analyzed for use in determination of release limits.[1] The locations of scabble sampling are shown in Decommissioning Plan §4, Figure 4-2. The data collected from the scabble results are reproduced in Table G-3 herein. They enabled the relative distribution of key radionuclide concentrations, or spectrum, to be interpreted.

Relative concentration of long-lived radionuclides in the scabble samples was determined by graphical analysis of their correlation. Figures G-3 thru G-6 display the relations, or ratios. The natural log mean ratio, at the 50th cumulative percent occurrence, provides the best single-valued representation of relative concentration of the principal radionuclides. Thereby, the relative concentrations of the principal radionuclides in pavement scabble samples are:

Table G-4. Ln Mean Ratio on Pavement

Radionuclide	Relative Concentration
U_{nat}/Th series	3
Th^{230}/U_{nat}	0.78
Ra^{226}/U_{nat}	1.4
Th^{230}/Ra^{226}	0.6

These ratios translate to relative concentrations in a source to model contamination on pavement by C-T residue in Table G-5. The relative radionuclide concentrations in this spectrum are entered into RESRAD to derive the dose factors (mrem/yr)/(pCi/g).

[1] Mallinckrodt Chemical, Inc. Radiological Characterization Data Set for the Mallinckrodt Chemical C-T Plant. Thermo Nutech, Oak Ridge, TN. Volume 1, "Results of Radiological Surveys for Background Radiation"; Volume 3, "Radiological Survey Data and Field Drawings"; and volumes 4 and 5, "Results of Radiological Analysis of Samples". October 1998.

Table G-3. Analytical Results of Scabble Samples from Plant 5 Street Surfaces
ref. CT Phase II Decommissioning Plan, Table 4-2

Location ID	Radionuclide Concentration										Percent by weight of source material
	U-234 (pCi/g)	U-235 (pCi/g)	U-238 (pCi/g)	U_{total} (pCi/g)	Th-230 (pCi/g)	Ra-226 (pCi/g)	Th-234 (pCi/g)	Th-232 (pCi/g)	Ra-228 (pCi/g)	Th-228 (pCi/g)	
SC-01	10.5	0.34	12.2	42.5	21	23.7	8.5	20.7	12.3	22	0.02
SC-02	25.2	1.6	27.2	74.5	5	34.7	22.5	1.9	1.5	2.8	0.01
SC-03	11.3	0.4	11.9	27.1	7.8	7.6	3.6	2.5	3	2.7	0.00
SC-04	6.4	0.31	6.7	4.5	3.8	2.8	1.6	3.7	3.4	4.5	0.00
SC-05	31.2	1.3	30.9	106.9	129.4	339.8	61	32.8	32.8	34.9	0.03
SC-06	91.4	3.6	91.3	256.7	66.6	106.7	30.7	28	19.7	29.9	0.04
SC-07	56.6	3.1	58.5	177.5	32.7	157.3	40.7	32.5	26.6	34.2	0.04
SC-08	21	1.2	21.8	70.7	17	89.9	12.8	10.2	5.7	11.7	0.01
SC-09	45	1.7	47.7	118.3	25.7	153.7	36.7	31.7	66.4	35.2	0.04
SC-10	122.2	7.5	125.2	339.9	58.2	978.7	73.1	57.4	42.1	68.9	0.07
SC-11	15.3	1.2	16.1	49.3	22.8	8.3	13.9	12.8	7.2	13.2	0.01
SC-12	19.6	1	17.8	72.7	51.3	32.9	49.2	7.5	6.3	9.8	0.01
SC-13	28.2	0.73	28.4	76.7	12.4	73.6	30.6	2.2	2.4	3	0.01
SC-14	18.8	0.73	18.1	41.7	14.6	40.7	25.9	8.1	9.9	8.1	0.01
SC-15	32.6	1.4	33.5	129.3	17.5	46.8	26.6	4.8	4.3	5.2	0.01
SC-16	17.4	1.1	16.9	48.5	36.6	104.4	30.7	5.6	5.6	5.9	0.01
SC-17	29.1	1.3	26.5	84.3	21.7	65.5	47.4	9.7	10.5	12.1	0.01
SC-18	8.6	0.31	8.5	31.5	5.4	3.6	5.5	1.4	1.3	1.8	0.00
SC-19	8.8	0.46	9.3	27.9	6.2	3.5	5.1	1.9	1.4	1.9	0.00
SC-20	29.9	1.4	32.9	82.3	20.2	10.8	26.5	6.1	4.8	6.3	0.01
SC-21	25.2	1.7	27.2	86.7	19.6	13.8	28.1	5.4	5.9	4.9	0.01
SC-22	215.8	9.9	204	530.96	94.1	263	161	15.4	16.5	17.8	0.04
SC-23	35.7	1.9	38.7	90.7	5.7	3.2	16.5	1.4	1.5	1.2	0.01
SC-24	4.5	0.23	5	9.8	13.5	6.6	5.2	3.4	2	3	0.00

Figure G-3

Distribution of Natural Uranium -to- Thorium Series Ratio in Pavement Scabble Samples

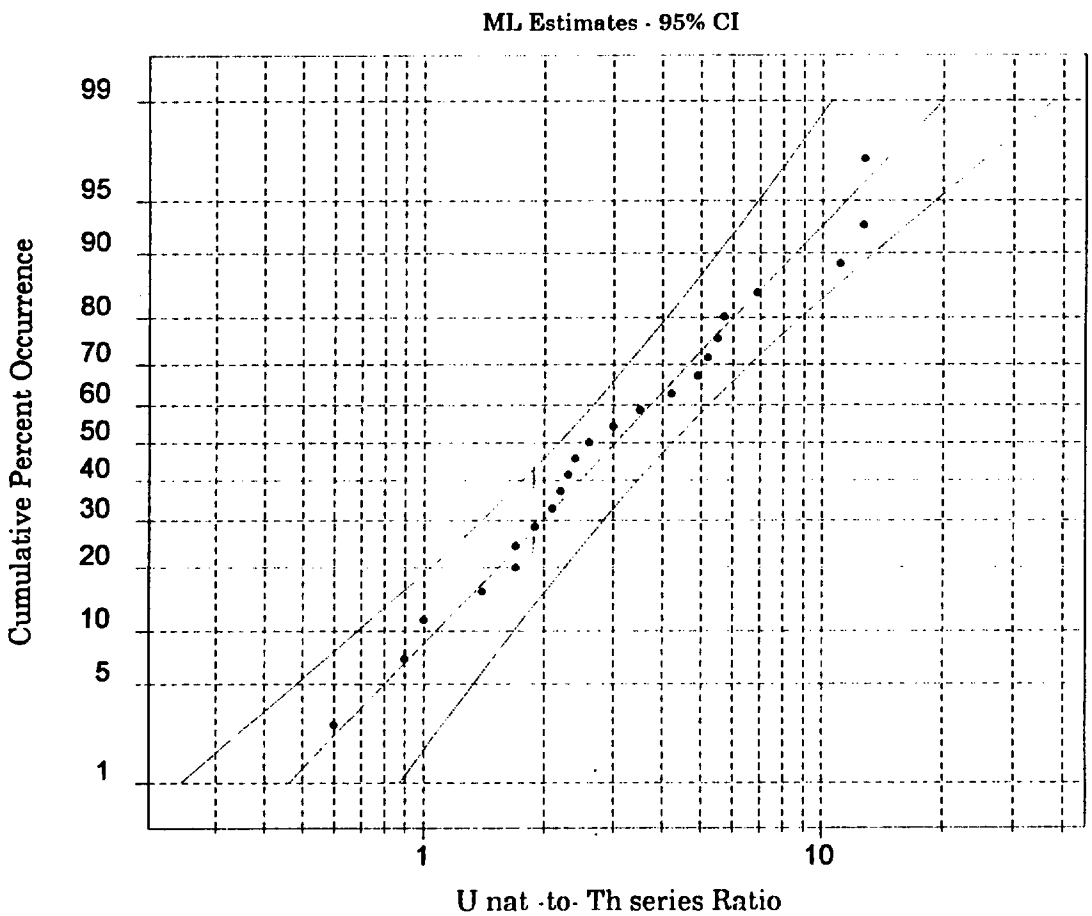


Figure G-4

Distribution of Thorium-230 -to- Natural Uranium Ratio in Pavement Scabble Samples

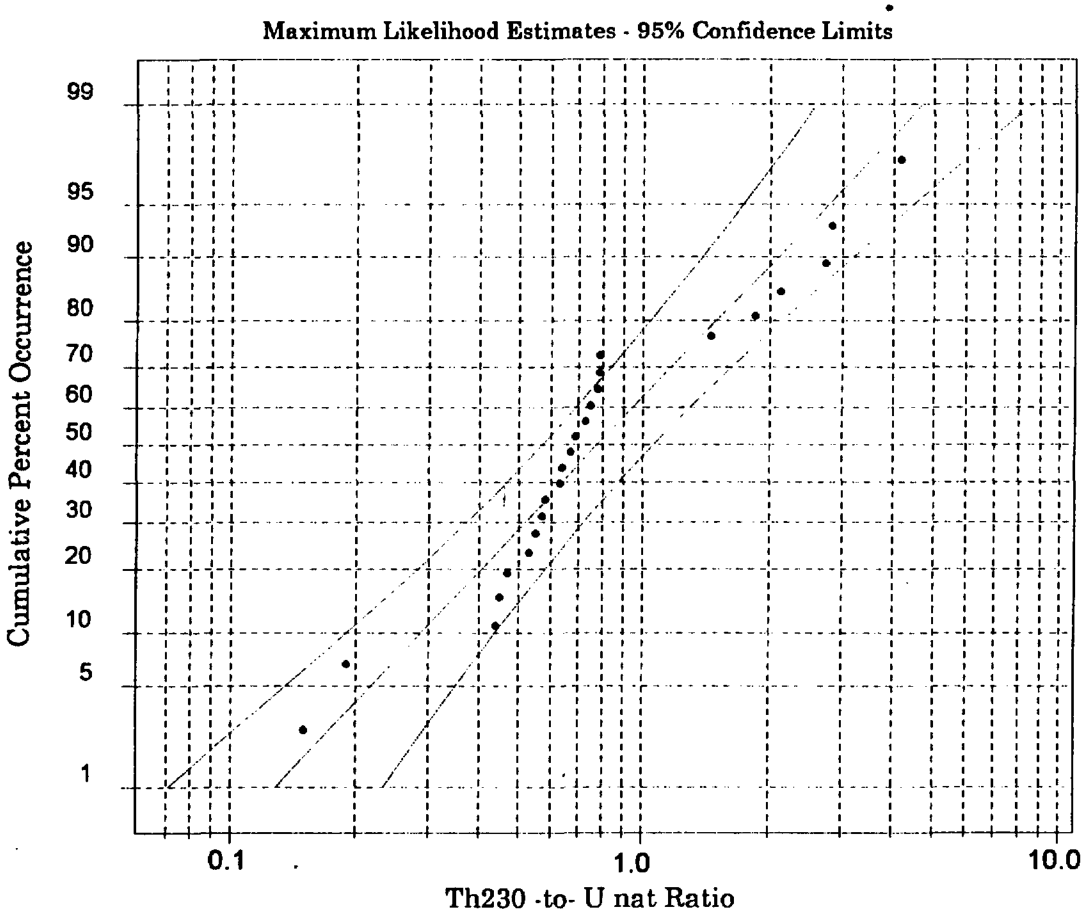


Figure G-5

Distribution of Radium-226 -to- Natural Uranium Ratio in Pavement Scabble Samples

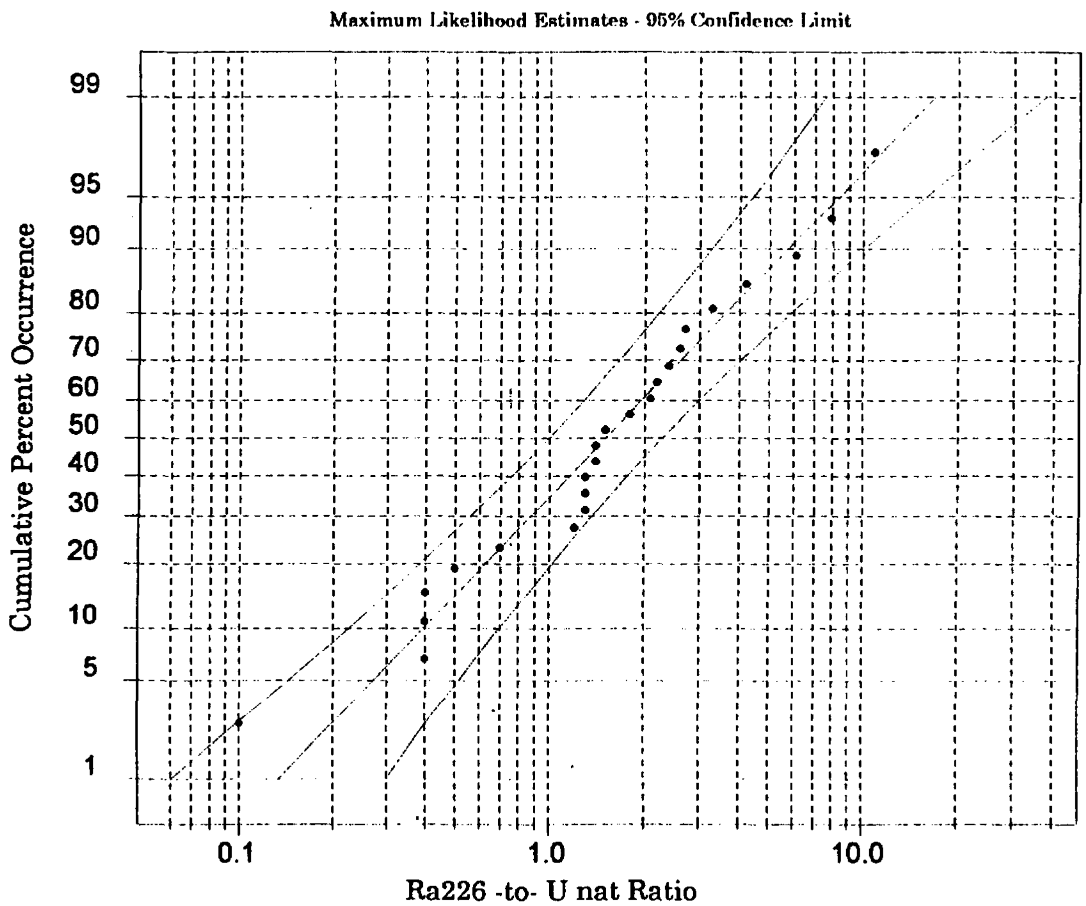
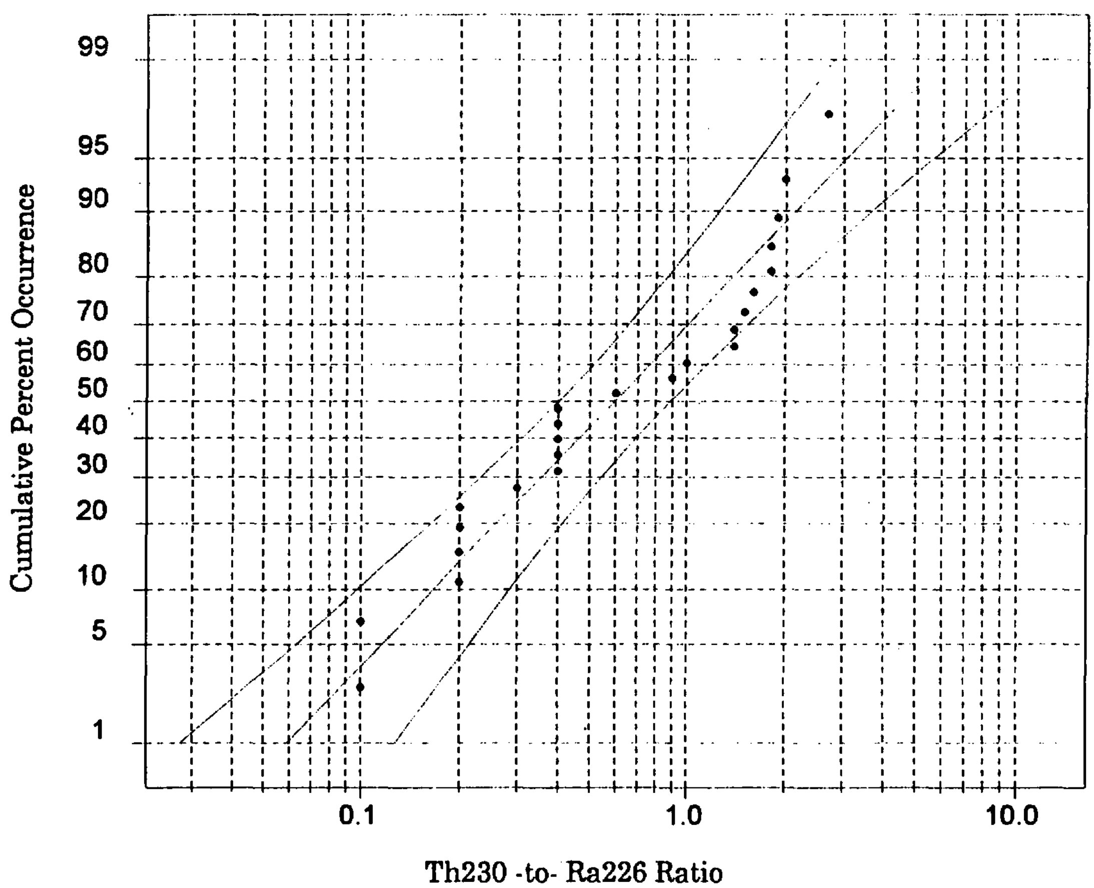


Figure G-6

Distribution of Thorium-230 -to- Radium-226 Ratio in Pavement Scabble Samples

ML Estimates - 95% CI



3.4. DOSE MODELING

3.4.1. Dose vs. Source Depth

RESRAD models simulate exposure to a source originating as a mass concentration in soil.[2] In order to simulate surficial contamination on pavement out-of-doors, a mass concentration equivalent of areal density of source material on pavement needs to be estimated. Assumption of as much as 0.1 cm source thickness is sufficient for contamination of worker hands or clothing and potential for ingestion and removal from the surface to become suspended in air for potential inhalation. That is, modeling removal for either ingestion or inhalation pathways does not depend on a thicker source.

A common sense perspective on the assumption of as much as 0.1 cm source thickness on pavement in Plant 5 may be realized by estimating the volume it would occupy. That volume would be 30 cubic yards, or three 10-cubic-yard, semi-trailer truck loads. Even if 2/3 of Plant 5 pavement were vacuum-cleaned (the remaining area occupied by structures), it would be quite unrealistic to expect to accumulate as much as two 10-cubic-yard, semi-trailer truck loads of sediment on the pavement remaining from more than 15 years ago.

Another interest is whether contamination might be beneath, or deeper than 0.1 cm thick surface contamination. The pertinent objective is to derive the maximum acceptable average areal density, or DCGLw, in units pCi/100 cm^2 or dis/(min·100 cm^2) of surficial contamination, regardless of its depth of embedment.

To examine this issue, modeling has been done assuming residual U and Th series as a function of source thickness or embedment into pavement. The objective is to derive the maximum areal density of CT residue **on or embedded in** an outdoor surface, including pavement and CT process building slabs, that would cause no more than 25 mrem/yr. Deterministic modeling was acceptable to examine this issue since the aim is relative optimization of dose as a function of source depth. Whether concentrating a source on a surface or assuming it is embedded into pavement or a building slab would produce maximum annual dose becomes a central question to be investigated. To do this,

- A reasonable spectrum of radionuclides in CT residue is represented by a ratio of 3 U series + 0.0455 x 3 U^{235} series + 1 Th series in radioactive equilibrium.
- The relative radioactivity fraction in this ratio and the basis dose factor[3] of each key radionuclide are used with a sum-of-fractions expression to derive the areal density and equivalent mass concentration in dust (soil at 1.5 pCi/g density) on pavement surface that would produce 25 mrem/yr.
- Enter this areal density equivalent mass concentration into RESRAD with the same parameter values otherwise used as a basis to derive the areal $DCGL_W$ in CT 2 DP §5, Table 5-3 to verify whether it calculates 25 mrem/yr maximum total dose rate.

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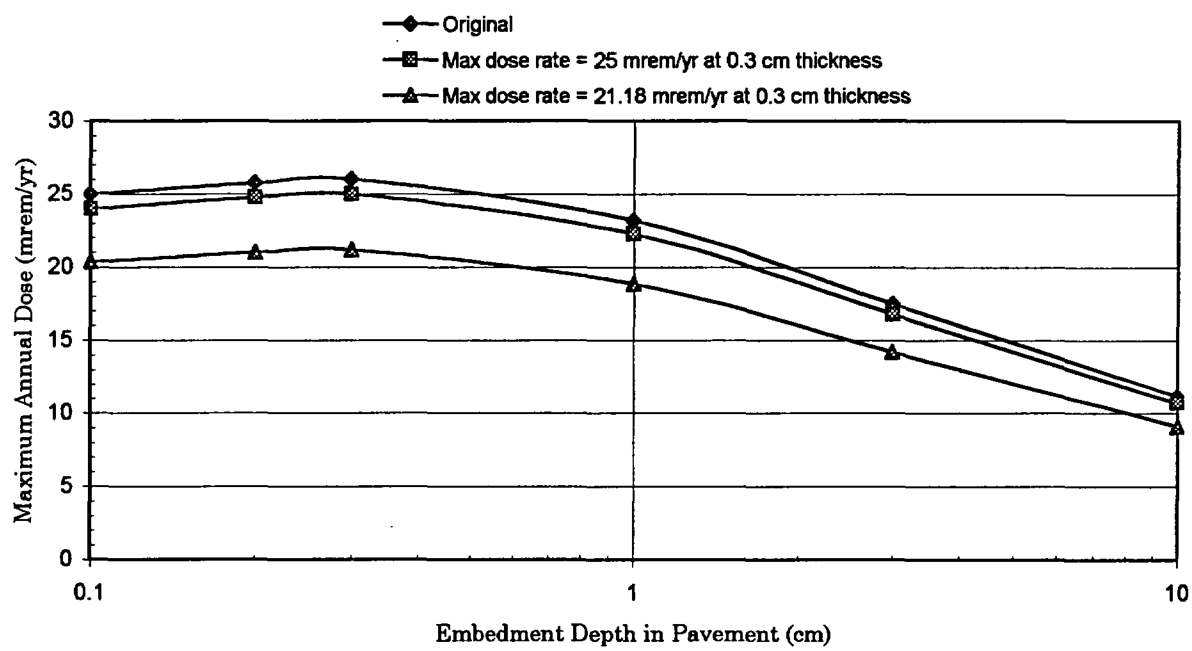
2 Whereas, RESRAD-BUILD simulates indoor contamination with indoor dust suspension and ventilation models. Both are inappropriate for outdoor airborne exposure modeling.

3 The basis dose factor (mrem/yr)/(pCi/g) on which the areal DCGLw in CT 2 DP is derived.

- Assume the same radionuclide spectrum at the same areal density were embedded into pavement (represented by 1.5 g/cm^3 soil). Use RESRAD to compute maximum total dose rate as a function of increasing depth of embedment.

A premise of CT 2 DP, §5, original Table 5-3 was that an equivalent areal density of CT residue would produce less dose when embedded than when accumulated on the surface; hence the source was originally modeled as concentrated into a 0.1 cm layer on the surface. Unexpectedly, maximum total dose occurs when the source is 0.2 to 0.3 cm thick, or deep, as illustrated in Figure G-7, curve "♦ Original." This observation prompted derivation of DCGLw assuming 0.3 cm contaminant thickness of the long-lived radionuclides in the uranium series, the actinium (U^{235}) series, and the thorium series, assuming short-lived nuclides (<180 day half-life) to be in transient radioactive equilibrium with their parent. The result of this refinement is illustrated in Figure G-7 by the curve, "■ Max. Dose Rate = 25 mrem/yr at 0.3 cm thickness". Thus, if contamination were on the surface or even if it were unevenly embedded into pavement or a building slab, assuming 0.3 cm source thickness when deriving DCGLw by dose modeling would assure maximum annual dose as a function of source areal density.

Figure G-7. Refinement of CT 2 DP §5 Model for Pavement



If the inventory corresponding to the areal DCGLw derived for the surface of pavement were embedded or migrated downward into pavement, the dose would diminish because of internal shielding of gamma radiation by pavement material. The inventory to be allowed on pavement surface corresponding to the areal DCGLw proposed in Table G-6 would be less than inventory in about 4 cm of topsoil at the DCGLw specified in CT 2 DP Table 5-1 (rev. March 20, 2006).

That is, in a nominally representative mixture of 3 U series -to- 1 Th series, the areal density at the $DCGL_W$ on pavement or a building slab is the same as the areal density equivalent of the $DCGL_W$ concentration in about 4 cm of soil. Or, if radioactive source material at the $DCGL_W$ in the top 4 cm of topsoil were concentrated at the surface, the areal density would be the same as the $DCGL_W$ applicable on the surface of pavement or a building slab. In perspective, then, the relation in radioactivity between the $DCGL_W$ derived for application on pavement or a building slab and separately in topsoil is a reasonable one.

3.4.2. Erosion of Pavement

Assumption that pavement does not erode was questioned. The reason for assuming no erosion of pavement was to simulate sustaining the surficial source in order to maximize potential dose. Else, source material on pavement would erode along with the pavement, thereby diminishing the source. Whereas, apparent concern of agency staff about maintenance of pavement for 1000 years seems to imagine it to be needed to shield against gamma irradiation by residue in soil beneath. Consider, however,

- $DCGL_W$ in topsoil was derived assuming bare soil.
- Gamma radiation from residual source in soil beneath pavement would, at its $DCGL_W$, contribute about 5.0 mrem/yr, or 0.80 of 25 mrem/yr, by irradiation through pavement.
- Weathering is likely to remove surficial residue from pavement, or if ever present, has already done so already.
- It is reasonable to expect surficial contamination on outdoor pavement to be removed by weathering more rapidly than erosion of pavement would allow gamma radiation penetrating from beneath it to increase.
- Even if a surficial source initially at its $DCGL_W$ were to migrate into pavement or a slab, it would diminish to the $DCGL_W$ appropriate for soil, specified in CT 2 DP §5, Table 5-1 (rev. March 20, 2006), within about 4 cm depth into the pavement or slab, such that the combined dose rate would be no greater than for soil alone, even as the pavement was eroding.

That the erosion rate of source sediment on pavement is assumed to be zero maintains the source in RESRAD simulation present on the pavement surface indefinitely in order to assess whether maximum dose might be greater in future than near the beginning time of simulation. Since the maximum dose occurs near the beginning time of simulation, the assumption of zero erosion rate of source from pavement surface is otherwise of no practical consequence to the $DCGL_W$ derived with the aid of RESRAD.

If the pavement were to erode, a surficial source would be expected to disappear more readily, or at least would disappear at the rate of erosion of the pavement. That is, as pavement erodes, dose from surficial source, even if embedded into pavement, would diminish more than dose from source in soil beneath would increase. In either prospect, the source inventory per unit area on or in pavement may be as much as allowed by Table G-6 and the 25 mrem/yr dose criterion would still be satisfied. Another perspective is that **modeling a source on pavement as a thin, surficial source maximizes potential radiological dose per unit areal density**. If the source were embedded into pavement, ease of removal for contamination of worker hands or clothing and potential for ingestion

would be diminished. Likewise, ease of removal from the surface to become suspended in air for potential inhalation would be diminished. Furthermore, unlike an embedded source, a surficial source is without shielding by its substrate.

3.4.3. Radionuclide Source

Subtracting 5 mrem/yr apportioned to C-T residue in cinder fill from 25 mrem/yr allotted to DCGL would imply reduction of conceivable contribution from residue on pavement alone itself to 0.8 of the DCGLw derived for pavement and would eliminate question of allocation of maximum acceptable total dose.

Table G-5. Relative Radioactivity Spectrum in Pavement Scabble Samples

Radionuclide	Relative Concentration (pCi/g)
U^{238}	3.0
U^{234}	3.0
U^{235}	0.0455 x 3.0 = 0.1365
Ac^{227}	0.0455 x 3.0 = 0.1365
Pa^{231}	0.0455 x 3.0 = 0.1365
Th^{230}	0.78 x 3.0 = 2.34
Ra^{226}	1.4 x 3.0 = 4.2
Pb^{210}	1.4 x 3.0 = 4.2
Th^{232}	1.0
Ra^{228}	1.0
Th^{228}	1.0

Although it is unlikely that both soil and pavement would be contaminated to more than 0.8 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ on pavement is being reduced by 0.2 to the equivalent of 20 mrem/yr, which become the revised $DCGL_W$ to be applied. As a consequence, $DCGL_{EMC}$ will also be reduced to the equivalent of 20 mrem/yr.

Relative concentrations of the principal radionuclides in the pavement scabble samples, in Table G-5 and Table G-6, column 2, were increased by a constant multiple, to the concentration in Table G-6, column 3 and entered into RESRAD.

3.4.4. Dose Factors

In the case of an areal source on pavement, RESRAD computed the peak of the mean dose from all contributing radionuclides to be 20 mrem/yr, occurring in the first year of

exposure. Contributions of principal radionuclides and, implicitly, their short-lived progeny to the dose are tabulated in Table G-6.

Table G-6. Scabble Sample Spectrum on Pavement

Radionuclide	Relative Concentration (pCi/g)	Concentration Entered into RESRAD (pCi/g)	Dose Computed by RESRAD (mrem/yr)
U^{238}	3.0	225.2	0.193
U^{234}	3.0	225.2	0.0158
U^{235}	0.1365	10.25	0.0459
Ac^{227}	0.1365	10.25	0.14
Pa^{231}	0.1365	10.25	0.0352
Th^{230}	2.34	175.7	0.0266
Ra^{226}	4.2	315.3	14.3
Pb^{210}	4.2	315.3	0.403
Th^{232}	1.0	75.08	0.178
Ra^{228}	1.0	75.08	2.24
Th^{228}	1.0	75.08	2.4
		total dose =	20.0

These dose factors are combined logically for U_{nat}, Th^{230} subseries, and Th series in Table G-7 in units (mrem/yr)/(pCi/g). The dose factor of the thorium series is the sum of doses caused by the principal radionuclides Th^{232}, Ra^{228}, Th^{228}, and their short-lived progeny, divided by the concentration of Th^{232}, the reference radionuclide. Specifically,

$$DF_{\text{Th series}} = \frac{\text{dose}_{Th232} + \text{dose}_{Ra228} + \text{dose}_{Th228}}{\text{concentration}_{Th232}}$$

$$DF_{\text{Th series}} = \frac{(0.178 + 2.24 + 2.4)\text{mrem}/\text{yr}}{75.08\ \text{pCi Th}^{232}/\text{g}} = 6.42 \times 10^{-2}\ \frac{\text{mrem}/\text{yr}}{\text{pCi Th}^{232}/\text{g}}$$

Similarly, the radiological dose computed by RESRAD for U^{238}, U^{234}, U^{235}, Ac^{227}, and Pa^{231} and their short-lived progeny, divided by the concentration of U^{238} derives the dose factor, 1.9 x10^{-3} (mrem/yr)/(pCi/g U^{238}) for U_{nat} referenced per pCi U^{238}/g source.

Likewise, the dose factor of the Th^{230} subseries is the sum of doses caused by Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny, divided by the concentration of Ra^{226}. Thereby, the dose factor for the Th^{230} subseries is referenced to Ra^{226} because Ra^{226} would be the most practical to measure and poses the most potential dose.

3.4.5. DCGLw

The next step is to express the areal density of radionuclide source that would cause 20 mrem/yr to an industrial worker. A formula for that is:

$$AD = \frac{\dfrac{20\ \text{mrem/yr}}{\text{DF mrem/yr}}}{\dfrac{\text{pCi}}{\text{g}} \times 1.5 \dfrac{\text{g}}{\text{cm}^3} \times \dfrac{0.3\ \text{cm} \times 100\ \text{cm}^2}{100\ \text{cm}^2}} = \frac{900}{\text{DF}} \frac{\text{pCi}}{100\ \text{cm}^2}$$

where: AD = areal density of source on pavement that produces 20 mrem/yr (pCi/100 cm^2)
DF = dose factor of radionuclide or nuclide series (mrem/yr)/(pCi/g)
1.5 = mass density of source (g/cm^3)
0.3 = thickness of radioactive source on pavement as modeled in RESRAD (cm)
100 = factor to normalize expression of areal density to standard area (cm^2)

Table G-7. Areal C-T Contamination Limits on Pavement Surface

Radionuclide	Dose Factor	Areal Density Equal to 20 mrem/yr	
	(mrem/yr)/(pCi/g)	(pCi/100 sq cm)	(dpm/100 sq cm)
U-238	8.57E-04	1.05E+06	2.33E+06
U-234	7.02E-05	1.28E+07	2.85E+07
U-235+DI	2.16E-02	4.17E+04	9.26E+04
Th-230	1.51E-04	5.94E+06	1.32E+07
Ra-226	4.54E-02	1.98E+04	4.41E+04
Pb-210	1.28E-03	7.04E+05	1.56E+06
Th-232	2.37E-03	3.80E+05	8.43E+05
Ra-228	2.98E-02	3.02E+04	6.70E+04
Th-228	3.20E-02	2.82E+04	6.25E+04
U nat [b, c]	1.91E-03	4.71E+05	1.05E+06
$Th^{230}+Ra^{226}+Pb^{210}$ [d]	4.67E-02	1.93E+04	4.28E+04
Th series [a]	6.42E-02	1.40E+04	3.11E+04

[a] Th^{232} series is the limit for Th^{232} with all its progeny nuclides present in equilibrium concentration (*i.e.*, radioactivity concentration of each equal to the Th^{232} concentration). Because Th^{232} progeny grows in to equilibrium within about 30 years, and because the C-T facilities have existed for nearly that long, Th^{232} progeny can be expected to be near equilibrium.

[b] U nat is the limit for U^{238} with U^{234}, and their short-lived progeny present in equilibrium and the U^{235} series is present in equilibrium in the proportion occurring in natural uranium.

[c] Radioactivity ratio of U^{235} -to- U^{238} = 0.0455 in natural uranium.

[d] Th^{230} series includes Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny and is referenced to Ra^{226} radioactivity concentration.

An areal density that produces 20 mrem/yr may be expressed in alternate units by the formula:

$$AD = \frac{900}{DF}\frac{pCi}{100\ cm^2} \times 2.22 \frac{dis}{min \cdot pCi} = \frac{2.00 \times 10^3}{DF}\frac{dis}{min \cdot 100\ cm^2}$$

Values of areal density derived by these formulae and that could cause 20 mrem/yr are tabulated in Table G-7. **These are the DCGLw for industrial work on outdoor pavement or slabs.**

When radioactivity of each long-lived radionuclide relative to each other is known, a **composite DCGLw** may be derived. In the pavement scabble samples in which principal radionuclides were measured and DCGLw has been derived for subseries, a composite DCGLw may be derived by the **sum-of-fractions** convention.

$$DCGL_W = \frac{3 + 4.2 + 1}{\frac{3}{1.05 \times 10^6} + \frac{4.2}{4.28 \times 10^4} + \frac{1}{3.11 \times 10^4}} = 6.16 \times 10^4 \frac{dis}{min \cdot 100\ cm^2}$$

where

DCGLw = composite DCGLw on pavement referenced per disintegration of parent U^{238}, Ra^{226}, or Th^{232} in the mixture (dis/(min·100 cm^2))

3 = relative concentration of U_{nat} referenced to U^{238} parent

4.2 = relative concentration of Th^{230} subseries referenced to Ra^{226}

1 = relative concentration of Th series referenced to parent Th^{232}

1.05×10^6 = DCGLw of U_{nat} referenced to U^{238} parent (dis/(min·100 cm^2))

4.28×10^4 = DCGLw of Th^{230} subseries referenced to Ra^{226} (dis/(min·100 cm^2))

3.11×10^4 = DCGLw of Th series referenced to parent Th^{232} (dis/(min·100 cm^2))

4. SPECIFICATION OF DCGLw IN MEASURABLE UNITS

The maximum acceptable average areal radioactivity density on a surface, or DCGLw, is expressed in units, pCi/100 cm^2, and in units, atomic disintegrations/(min·100 cm^2) in Table G-7 for components of the source. In order to assess compliance of surficial contamination with DCGL, a practical means of measurement is needed. It would be practical to state the contamination limit in units consistent with the measurement. Radioactive contamination on surfaces is often surveyed by gross activity detection and would be practical for the C-T source material.

Of the three common radiations emitted by naturally radioactive series, alpha rays are unable to penetrate sufficiently from rough or dirty surfaces while background gamma rays penetrate excessively from the substrate. Beta rays remain as the practical radiation to measure as an indication of the surficial source. A method of interpreting a surface radioactivity limit and gross beta measurement in comparable units is described in C-T Phase I Decommissioning Plan, Appendix D.

Note that the radionuclide source, in units, pCi/100 cm^2, is directly proportional to dose and thus is the parameter that must be limited. When the source is a mixture of

radionuclides, expressed in units, pCi/100 cm^2 or (dis/(min·100 cm^2)), a composite value is derived by the **sum-of-fractions** convention to assure that the mixture would cause no more than 20 mrem/yr. The number of beta (+ i.c.e.) per disintegration of a radionuclide is an indicator of the source but is not a direct indicator of the dose it causes; for there is not a one-to-one correlation between number of beta + i.c.e. per atomic tranformation among the radionuclides. Consequently, the corresponding number of beta + i.c.e. is derived separately from the DCGL for the radionuclide spectrum, or mixture, to correlate with the radionuclide mix that would produce 20 mrem/yr and not as a sum-of-fractions.

Since it is practical to measure total beta radiation, an essential step is to determine the total beta + internal conversion electron emission per atomic transformation of the source radionuclide spectrum or of a reference radionuclide.

4.1. RADIONUCLIDE SPECTRUM ON PAVEMENT

Principal radionuclides in the uranium series, thorium series, and actinium series were measured in 24 samples scabbled on pavement in Plant 5. Results are in CT Phase II DP Table 4-2 and are reproduced herein as Table G-3. Lognormal distribution graphics of analytical data, in CT Phase II DP, Table 4-2, indicate that the log mean U_{nat} -to- Th series activity ratio is about 3 -to- 1. Ra^{226} is about 1.5 times more abundant than the U_{nat} parent. Th^{230} averages about 0.8 of U_{nat} parent and about 0.6 of Ra^{226}, and for deriving $DCGL_W$, is conservatively be assumed exist in equal radioactivity with Ra^{226}.

Table G-8. Relative Concentration in Pavement Scabble Samples

Radionuclide	Relative Concentration (pCi/g sample) Factors	Value
U^{238}	3.0 =	3.0
U^{234}	3.0 =	3.0
U^{235} + d	.0455 x 3.0 =	0.1365
Th^{230}	078 x 3.0 =	2.34
Ra^{226}	1.4 x 3.0 =	4.2
Pb^{210}	1.4 x 3.0 =	4.2
Th^{232}	1.0 =	1.0
Ra^{228}	1.0 =	1.0
Th^{228}	1.0 =	1.0

4.2. BETA EMISSION

Naturally-occurring radioactive decay series each emit beta radiation and internal conversion electrons of sufficient energy to be detected by conventional radiation survey instrumentation. The number of beta plus internal conversion electrons (i.c.e.) having > 0.08 Mev energy, sufficient to penetrate a 9 mg/cm^2 detector window, are tabulated for each of the radioactive decay series of interest.

Table G-9. Beta + I.C.E. Emission by Radionuclides in the Uranium Series

Radionuclide	Probability of Creation per Decay	
	Beta	I.C. Electron[A]
U^{238}		0.0015
Th^{234}	0.98	0.038
Pa^{234m}	1.	0.004
U^{234}		0.0014
Th^{230}		<<
Ra^{226}		0.023
Rn^{222}		
Po^{218}		
Pb^{214}	1.	0.27
Bi^{214}	1.	0.015
Po^{214}		
Pb^{210}	<<	<<
Bi^{210}	1.	
Po^{210}		
total[B]	4.98	0.35

[A] I.C.E. = internal conversion electron
[B] total beta + i.c.e. = 5.33

Table G-10. Beta Emission by Radionuclides in the Actinium Series

Radionuclide	Probability of Creation per Decay	
	Beta	I.C. Electron[A]
U^{235}		
Th^{231}	1.	
Pa^{231}		
Ac^{227}		
Fr^{223}	0.0137[B]	
Ra^{223}		
Rn^{219}		
Po^{215}		
Pb^{211}	1.	
At^{215}		
Bi^{211}		
Po^{211}		
Tl^{207}	0.994[B]	
total[C]	3.008	

[A] internal conversion electron data not identified in available database
[B] branching fraction included
[C] total beta + i.c.e. = 3.008

Table G-11. Beta + I.C.E. Emission by Radionuclides in the Thorium Series

Radionuclide	Probability of Creation per Decay	
	Beta	I.C. Electron
Th^{232}		0.001
Ra^{228}	<<	<<
Ac^{228}	0.97	0.14
Th^{228}		0.019
Ra^{224}		0.011
Rn^{220}		
Po^{216}		
Pb^{212}	1.0	0.43
Bi^{212}	0.64	0.0012
Po^{212}		
Tl^{208}	0.36[A]	0.032[A]
total[B]	2.97	0.634

[A] branching fraction included
[B] total beta + i.c.e. = 3.604

The DCGLw of C-T source radionuclides has been combined into 3 decay sets:

- U_{nat} including U^{238}, Th^{234}, Pa^{234}, U^{234}, and in naturally-occurring proportion, the Actinide series
- Th^{230} subseries including Th^{230}, Ra^{226}, Pb^{210} and their short-lived progeny
- Th series including Th^{232}, Ra^{228}, Th^{228}, and their short-lived progeny

The number of beta + i.c.e. emitted by each of these decay sets is tallied in order to be able to estimate the number of beta + i.c.e. emitted by an identified proportion of each set in an entire source.

$$\beta \text{ by } U_{nat} = U^{238} \text{ thru } U^{234} + 0.0455\ U^{235} \text{ series}$$
$$= 2.2049 + 0.0455 \times 3.008\ \beta/U^{238} \text{ dis}$$
$$= 2.162\ \beta/U^{238} \text{ dis}$$
$$\beta \text{ by } Th^{230} \text{ subseries} = 3.308\ \beta/\ Ra^{226} \text{ dis}$$
$$\beta \text{ by Th series} = 3.604\ \beta/\ Th^{232} \text{ dis}$$

where the number of beta emitted is referenced to a principal parent radionuclide in the set whose radioactivity concentration is measurable and which is also the reference for statement of the DCGLw of the same set.

In the pavement scabble samples, the ratio of radioactivity of the principal reference radionuclides is:

U^{238} representing $U_{nat} = 3$

Ra^{226} representing Th^{230} subseries = 1.4 x 3 = 4.2

Th^{232} representing Th series = 1

One may estimate β_{limit}, the total number of beta emitted by this spectrum, capable of penetrating a 9 mg/cm² detector window, and corresponding to the DCGLw of this scabble sample mix.

4.2.1. First Method.

The β emission (+i.c.e. implied) corresponding to the DCGLw applicable to C-T contamination on pavement as represented by the set of scabble samples may be estimated by adding the three contributing nuclide groups. DCGLw = 6.16×10^4 dis/(min·100 cm²) was derived in §3.4.5 of this appendix for source ratios

3 = relative concentration of U_{nat} referenced to U^{238} parent

4.2 = relative concentration of Th^{230} subseries referenced to Ra^{226}

1 = relative concentration of Th series referenced to parent Th^{232}

Component contributions to the DCGLw are:

$$U_{nat} \text{ part ref to } U^{238} = \frac{3}{8.2} \times 6.16 \times 10^4 = 2.25 \times 10^4 \ \frac{\text{dis } U^{238}}{\text{min} \cdot 100 \text{ cm}^2}$$

$$Th^{230} \text{ subseries ref to } Ra^{226} = \frac{4.2}{8.2} \times 6.16 \times 10^4 = 3.15 \times 10^4 \ \frac{\text{dis } Ra^{226}}{\text{min} \cdot 100 \text{cm}^2}$$

$$\text{Th series ref to } Th^{232} = \frac{1}{8.2} \times 6.16 \times 10^4 = 7.51 \times 10^3 \ \frac{\text{dis } Th^{232}}{\text{min} \cdot 100 \text{ cm}^2}$$

Each component radionuclide group emits β +i.c.e. They add to produce total β (+i.c.e. implied) emission corresponding to the DCGLw. Thus,

$$\beta_{lim} = \beta(U_{nat}) + \beta(Th^{230} \text{ subseries}) + \beta(\text{Th series})$$

$$\beta_{lim} = 2.25 \times 10^4 \ \frac{\text{dis } U^{238}}{\text{min} \cdot 100 \text{ cm}^2} \times 2.162 \frac{\beta}{U^{238} \text{ dis}} + 3.15 \times 10^4 \ \frac{\text{dis } Ra^{226}}{\text{min} \cdot 100 \text{ cm}^2} \times 3.308 \frac{\beta}{Ra^{226} \text{ dis}} +$$

$$+ 7.51 \times 10^3 \ \frac{\text{dis } Th^{232}}{\text{min} \cdot 100 \text{ cm}^2} \times 3.604 \frac{\beta}{Th^{232} \text{ dis}}$$

$$\beta_{lim} = 1.80 \times 10^5 \ \beta/(\text{min} \cdot 100 \text{ cm}^2)$$

4.2.2. Second Method.

A variation on the method estimates the β emission corresponding to the DCGLw expressed by composite data. The composite number of beta emitted per a parent disintegration is:

$$\text{composite } \beta/\text{dis} = \beta(U_{nat}) + \beta(Th^{230} \text{ subseries}) + \beta(\text{Th series})$$

$$\text{composite } \beta/\text{dis} = \frac{3 \times 2.162 + 4.2 \times 3.308 + 1 \times 3.604}{3 + 4.2 + 1}$$

composite β/dis = 2.925 β/dis of one of the reference nuclides U^{238}, Ra^{226}, or Th^{232}

The composite β_{lim} of that mixture of radionuclides represented by pavement scabble samples is

$$\text{composite } \beta_{\text{lim}} \text{ of mix} = \text{DCGL}_\text{W} \text{ of mix} \frac{\text{dis}}{\text{min} \cdot 100\,\text{cm}^2} \times \text{composite } \frac{\beta}{\text{dis}}$$

$$\text{composite } \beta_{\text{lim}} \text{ of mix} = 6.16 \times 10^4 \frac{\text{dis}}{\text{min} \cdot 100\,\text{cm}^2} \times 2.925 \frac{\beta}{\text{dis}}$$

composite β_{lim} of mix = 1.80×10^5 $\beta/(\text{min} \cdot 100\ \text{cm}^2)$

4.3. SUMMARY

Applying the radionuclide distribution observed in pavement scabble samples estimate the areal density equal to 20 mrem/yr by dose modeling derives a composite

$DCGL_W = 6.2 \times 10^4$ dis/(min·100 cm^2),

where a *disintegration* is per atomic tranformation of principal radionuclide U^{238}, Ra^{226}, or Th^{232} while accounting for the contribution to dose of each radionuclide in each subseries.

This composite $DCGL_W$ may be expressed in measurable units to compare with total beta + internal conversion electrons emitted by the source.

$DCGL_W = 1.8 \times 10^5$ β/(min·100 cm^2)

The $DCGL_W$ is not very sensitive to radionuclide variability. If, for instance, the source were entirely uranium series + actinium series in natural proportion to uranium, both in radioactive equilibrium, the $DCGL_W$ would = 2.2×10^5 β/(min·100 cm^2); or if the source were entirely thorium series in equilibrium, the $DCGL_W$ would = 1.1×10^5 β/(min·100 cm^2). Thus, to enable practical survey by measuring gross beta radiation, $DCGL_W = 1.8 \times 10^5$ β/(min·100 cm^2) is proposed. Measurement methodology is described in C-T Phase I Decommissioning Plan, Appendix D, §3 "Beta Radiation Measurement."

SECTION 5

DOSE MODELING

Mallinckrodt, Inc.

C-T Phase II Decommissioning Plan

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NRC Docket: 40-06563

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5. DOSE MODELING

5.1. INTRODUCTION

Radiological dose criteria for decommissioning lands and structures[1] provide the basis of determining maximum acceptable residual radionuclide concentration for remediation of residual radioactivity at nuclear facilities undergoing decommissioning. These criteria determine the extent to which lands and structures must be remediated before decommissioning of a site can be considered complete and the license terminated. This chapter describes the derivation of soil concentration guideline levels, $DCGL_W$ [2] and $DCGL_{EMC}$ [3], for land affected by C-T process operation and areal contamination guideline levels for surficial contamination on pavement affected by C-T process operation. Criteria for buildings and structures were derived in the C-T Phase I Decommissioning Plan (Phase I Plan).

To help decide what actions are reasonable to mitigate potential exposure to residual radionuclides in soil and to assure the radiological dose limit is met, maximum acceptable levels of residual radioactivity concentration in soil must be derived for soil remaining after decommissioning. To do this one must estimate the quantitative relation between radionuclide concentration in the soil and potential radiation dose to an average person in the group who might be exposed the most to residual radionuclides in land in Plant 5. Radiological dose modeling by mathematical simulation is a way to describe this source-to-dose relation, thereby enabling one to derive maximum acceptable radionuclide concentration to guide decommissioning and/or decide compliance with the decommissioning regulation. Dose modeling involves:

1. the radioactive source term;
2. an exposure scenario considering the site environment and pathways of exposure;
3. relation of the source term and potential radiological dose; and
4. parameters in the model.

<u>Assessment Methodology</u>. An objective of an environmental exposure pathway analysis is to derive a maximum acceptable average concentration of residual, licensed radioactive material ($DCGL_W$) that will assure conformance with regulatory limit(s) on radiological dose. To derive a $DCGL_W$, one describes land use scenarios based on anticipated site conditions and uses. For each land use scenario, reasonably anticipated environmental radionuclide exposure pathways are described. A mathematical model with simplified representations of site physical conditions and the potentially maximally exposed group of people is used to calculate future exposures and radiation doses as a function of time and concentration of nuclides in the soil. The relationship between dose and radionuclide concentration in soil is computed with the mathematical model.

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[1] 10 CFR Part 20, subpart E

[2] $DCGL_W$ = derived concentration guideline level corresponding to the release criterion for the nonparametric statistical test. ref. MARSSIM.

[3] $DCGL_{EMC}$ = derived concentration guideline level corresponding to the acceptance criterion for elevated measurements comparison ref. MARSSIM.

Reasonable remediation alternatives are posed to clean the site to comply with the DCGL.

Under NRC regulation for decommissioning, pathway analysis includes the estimation of radiation doses that might be received by a typical member of a small group of people from future uses of the site as much as 1,000 years into the future. Thus, this analysis considers not only the current conditions at the site, but projected conditions as well. The analysis evaluates potential uses of the site and potential migration of radioactive materials through the environment over time, accounting for both natural processes and human activities that could be expected to alter the patterns or rates of contaminant movement. The primary objectives of the environmental radiation exposure analysis is to derive the concentration of uranium series and thorium series radionuclides in soil in Plant 5 that potentially produce a 25 mrem/yr radiological dose equivalent above background to an average member of the critical group.

5.2. SOURCE TERM

Residual radioactive sources from C-T processing are the thorium series, the uranium series, and the actinium (U^{235}) series. The thorium decay series may be assumed to be in secular radioactive equilibrium because Th^{232} progeny are relatively short-lived. U^{238} and U^{235} are presumed to be present at the ratio present in natural uranium ore.

The existing distributions of residual source material in soil and on pavement in Plant 5 are described in Section 4 of the C-T Phase II Decommissioning Plan (Phase II Plan). A remediation goal is that radioactivity concentrations exceeding the DCGL will be removed.

By deriving nuclide-specific concentration limits equivalent to the dose limit, *i.e.*, DCGL, and by removing soil containing more radioactivity than the DCGL, acceptable spatial variability of any remaining radioactive residue will be achieved by remedial action and confirmed by a final radiation status survey. This provides the best assurance before the fact that acceptable spatial variability of radioactive residue will be achieved.

5.3. LAND USE SCENARIO

Mallinckrodt's site is in an urban industrial area. Manufacturing and support buildings cover a large portion of the site, and the remainder of the area is typically paved with asphalt or concrete. Mallinckrodt has owned the site and has operated chemical manufacturing facilities on the site since 1867. It intends to continue industrial use of the site, including Plant 5 where C-T facilities are being decommissioned.

The site is in an area whose zoning by the City of St. Louis allows all uses except new or converted dwellings. Some uses allowed within this zone under conditional use permit are acid manufacture, petroleum refining, and stockyards.[4] Land use within a 1.6 km (1-mi) radius of the site reflects a mixture of commercial, industrial, and residential uses. The closest residential

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[4] St. Louis City Revised Code, Chapter 26.60, K UNRESTRICTED DISTRICT

dwelling is located on North Broadway, approximately 60 m (200 ft) south of the site.[5] The long-term plans for this area are to retain the industrial uses, encourage the wholesale produce district, and phase out any junkyards, truck storage lots, and the remaining marginal residential uses.

The foreseeable use of Mallinckrodt's St. Louis downtown site where C-T facilities are being decommissioned is for continued industrial or commercial use. This is reasonably assured without additional restrictions. Residential use is not expected because of historical and current land use and because of government land use zoning. Agricultural usage is not expected or likely because of the poor soil quality and the prevailing land use in the area.

5.4. CRITICAL GROUP

As a result of the land use scenario, workers are potentially subject to the most exposure in the future. Mallinckrodt limits access to its facilities to employees, subcontracting construction workers, and authorized visitors and maintains 24-hour security at the property. Labor laws prohibit employment of minors. The maximum exposure could occur in to a typical industrial worker who spends most of their time in a building and some time out-of-doors.

Radioactive contamination on interior and exterior surfaces of the buildings has been addressed in the Phase I Plan. The regulated sources of radiation exposure in the Phase II Plan would be in soil and or on pavement in Plant 5. An industrial work scenario involves employees who spend most of their time in a building and some time out-of-doors. This critical group could potentially be exposed to outdoor sources by direct irradiation, by ingestion of soil, and by inhalation of airborne dust. While indoors, they could be exposed to radiation penetrating the floor of a building or to airborne dust that enters the building.

5.5. ENVIRONMENTAL EXPOSURE PATHWAYS

Whereas decommissioning criteria for buildings was addressed in the C-T Phase I Plan, the Phase II Plan addresses decommissioning criteria for soil, pavement, and building slabs. Thus, environmental pathways from residual source material in soil or on surfaces of pavement or building slabs to potential exposure of people in the critical group of workers are of interest to derivation of DCGL.

5.5.1. Pathways to Industrial Worker

A typical industrial worker will spend most of their time in a building and some time out-of-doors. Such an *industrial worker* might be exposed to radionuclides in soil or on the surface of pavement or a building slab in the following ways.

1. Gamma radiation emitted by contaminated soil might irradiate a worker directly while out-of-doors.

[5] Feasibility Study for the St. Louis Downtown Site, St. Louis, Missouri, U.S. Army Corps of Engineers, St. Louis District, Formerly Utilized Sites Remedial Action Program, April 1998, page 2-4.

2. Contaminated soil might be suspended as airborne dust and inhaled by a worker while out-of doors.
3. Contaminated soil might get on a worker's clothing and/or hands and be eaten inadvertently.
4. Gamma radiation emitted by contaminated soil might penetrate the floor and or walls of a building and irradiate a worker while indoors.
5. Contaminated soil might be suspended as airborne dust; some fraction of that dust might enter a building in ventilation air, and be inhaled by a worker while inside a building.

Although credit was not taken in dose modeling to derive DCGL for contaminated soil, a mitigating factor is that pavement shields an industrial worker from some direct radiation from soil and from creation of airborne dust from soil beneath the pavement. Most of Plant 5 is covered by buildings or is paved with concrete or macadam. Characterization surveys have identified some radioactivity on pavement that is elevated above expected background. As a practical matter, a worker would not be exposed simultaneously to bare ground and to pavement. Thus, separately an industrial worker might be exposed by:

- direct irradiation by the surficial source while out-of-doors;
- inhalation of dust suspended from the surface while out-of-doors;
- ingestion of dust;
- direct irradiation while indoors; and
- inhalation while indoors of dust suspended from a surficial source.

5.5.2. Pathways Not Present

5.5.2.1. Surface Water.[6]

Site wastewater, storm water, and all other surface drainage flow via site sewers and drains to a combined municipal sewer system and then to the Metropolitan St. Louis Sewer District (MSD) Bissell Point Treatment Plant. The Bissell Point Plant is located approximately 1 km (0.7 mi.) north (upstream) of the site. Treated water is discharged to the Mississippi River. During storm periods, the combined sewer system serving the site is diverted directly to the Mississippi River. There are no surface streams or lakes on-site; industrial or commercial use would not be conducive to creation of either, thereby eliminating any reasonable anticipation of surface water use on-site to become a potential exposure pathway.

5.5.2.2. Groundwater.[7]

The groundwater beneath the site is not a current source of drinking water, nor will it be a source of drinking water in the future for the following reasons.[8, 9]

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[6] C-T Phase II Plan §3.6 Surface Water Hydrology.

[7] C-T Phase II DP §3.7 Groundwater Hydrology.

[8] Mallinckrodt. *RCRA Facility Investigation Report for AOC I (Site-Wide Groundwater)*, Mallinckrodt, Inc., St. Louis Facility, p. 5. April 6, 2001; prepared by URS Corporation.

[9] Ref. Appendix A herein.

1. All of the drinking water for the City of St. Louis is derived from the Mississippi and/or Missouri Rivers, and all of the drinking water intakes for the City of St. Louis are located upstream of the facility.

2. St. Louis City Ordinance 13,272, Section 3 (dated March 25, 1885), states that drinking water supply wells are prohibited within the City of St. Louis. The ordinance has restricted drinking water supply well installation in the City of St. Louis for over 100 years and will continue to restrict well installation for the foreseeable future.

3. There is no known drinking water well in the vicinity of the plant (DOE, 1990). According to information obtained from the Missouri Department of Natural Resources Division of Geology and Land Survey, two wells are located within a ½-mile radius of the facility (EPA, 1993). Neither of the wells is a drinking water well. Well No. 2798 is located in the SE¼ of Township 45N Range 7E. It was installed in 1933 to a depth of 185 feet and produced 30 gallons per minute. Fisher Chemical Company is listed as the well owner. Well No. 19835 is located in the SE¼ NE½ Township 45 N Range 7E and was installed in 1961. It is 180 feet deep and screened in the Mississippian alluvium. Well No. 19835 has produced 260 gallons per minute, but is located at an abandoned site.

4. The quality of perched groundwater in fill historically placed along the riverfront in the St. Louis area is naturally poor due to the presence of brick, glass, concrete rubble, coal cinder, and slag, and associated metals and PAH compounds (DOE, 1990). The perched zone is intermittent in nature and limited in its lateral continuity, saturated thickness, and transmissivity, which results in low water producing quality. For these reasons, the perched zone is not a realistic source of potable groundwater even in the absence of any contamination derived from the Mallinckrodt facility.

5. Groundwater in the lower zone (sandy alluvial unit) is locally saline and generally very hard, with high iron and manganese content. Groundwater found in the underlying bedrock is generally saline and non-potable. Groundwater in the site area is not withdrawn for potable, industrial, or agricultural purposes, and groundwater use is not anticipated to change in the future. Considering these unfavorable groundwater characteristics and that St. Louis has a municipal water system that serves this region, installation of a domestic water well is not reasonably foreseeable. Since the land is unsuitable for agriculture because it is coal cinder fill, withdrawal of groundwater for agricultural irrigation also is not a reasonable expectation.

6. Groundwater in the St. Louis area is generally of poor quality and does not meet drinking water standards without treatment. The expected future use of groundwater at the SLDS is minimal since in the Mississippi and Missouri Rivers constitute high-quality, large-quantity, readily available sources.[10]

[10] USACE. Record of Decision for St. Louis Downtown Site. p. 6, July 1998.

5.6. CONCEPTUAL AND MATHEMATICAL MODELS

Each environmental scenario and pathway of exposure can be described by a conceptual model and a mathematical model. A *conceptual model* is a simplified description of the environmental system, including the radioactive source, its movement in the environment to a receptor, and habits of the receptor of the exposure. A *mathematical model* reduces the conceptual model into equations that can quantify the relations between radioactive source and radiological dose.

5.6.1. Soil

The RESRAD computer program implements mathematical models that calculate total effective dose equivalent to an average member of the critical group from residual radionuclides in soil. RESRAD models simulate environmental pathways including transport in air, water, and biological media to an exposed person. Exposure is translated to radiological dose with ICRP models (ICRP 26, 30, and 48) for estimating total effective dose equivalent, which are the bases of NRC regulations. Mathematical models implemented in RESRAD v.6 have been described.[11] RESRAD v.6 includes perhaps the best available set of mathematical models to describe the environmental scenario and exposure pathways that might be anticipated in Plant 5 after C-T decommissioning.

5.6.2. Pavement

Land in Plant 5 that is not covered by a building is practically all paved with concrete or macadam. Characterization surveys have identified some radioactivity on pavement that is elevated above expected background. A conceptual model of this surficial source is described as 0.1 cm thick layer of contaminated soil at land surface. An industrial worker might be exposed to surficial contamination on pavement by:

- direct irradiation by the surficial source while out-of-doors;
- inhalation of suspended dust while out-of-doors;
- ingestion of dust;
- direct irradiation while indoors; and
- inhalation of suspended dust while indoors.

These potential exposure pathways are simulated by mathematical models in RESRAD v.6. An advantage of using RESRAD for exposure to contamination on pavement is consistency with the simulation of the conceptual model for exposure to bare soil. This is significant because the airborne dust loading model is used to estimate airborne concentration of respirable particulate for both the outdoor sources, soil and pavement.

[11] Yu, C., *et. al.*, *User's Manual for RESRAD* Version 6. ANL/EAD-4. July 2001.

5.7. INPUT PARAMETERS

Default values of parameters in RESRAD v. 6 have been developed and described.[12] Unless described herein, default values of parameters in RESRAD v.6 have been retained in the derivation of DCGL. The influence of parameters most pertinent to the scenario have been considered for appropriateness of value.

5.7.1. Industrial Worker Worker Exposed to Soil

5.7.1.1. Area of Contaminated Zone

For the purpose of deriving, DCGL in soil, the area of a contaminated zone should not be smaller than 2,000 m^2 the maximum area of a Class 1 survey unit; nor should it be larger than 10,000 m^2, the maximum area of a Class 2 survey unit. The RESRAD v.6 default value is 10,000 m^2. The larger assumed potential area increases dose by airborne dust inhalation and thereby diminishes the DCGL. Thus, the default value, 10,000 m^2 is retained.

5.7.1.2. Thickness of Contaminated Zone

The thickness of the contaminated zone is the depth distance between the uppermost and lowermost soil samples that have radionuclide concentration above background.

Probabilistic. An analysis of the effect of contaminated zone thickness on radiological dose during industrial land use was done to interpret the depth beyond which additional contribution from a representative source in soil to irradiation dose to a person would become negligible. Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinide (U^{235}) series, and 1 Th series together.
- bare land in which residual source contamination extends from land surface downward into the soil;
- indoor time fraction = 0.0 in order to simulate effect of irradiation on bare land;
- the same industrial land use scenario modeled to derive $DCGL_W$ originally, except absent ingestion of soil and inhalation of dust; (for the origin of inadvertently ingested dust and of dust suspended into air is surficial topsoil); and
- deterministic simulation using RESRAD to derive the effect of increasing contamination depth in soil on exposure to direct irradiation.

The result of this analysis is summarized graphically in Figure 5-1. It determined that, in representative simulation, maximum dose rate by direct irradiation is reached asymptotically when the depth of the contaminated zone in topsoil reaches about 30 cm. Additional source thickness would not produce significantly greater dose rate.

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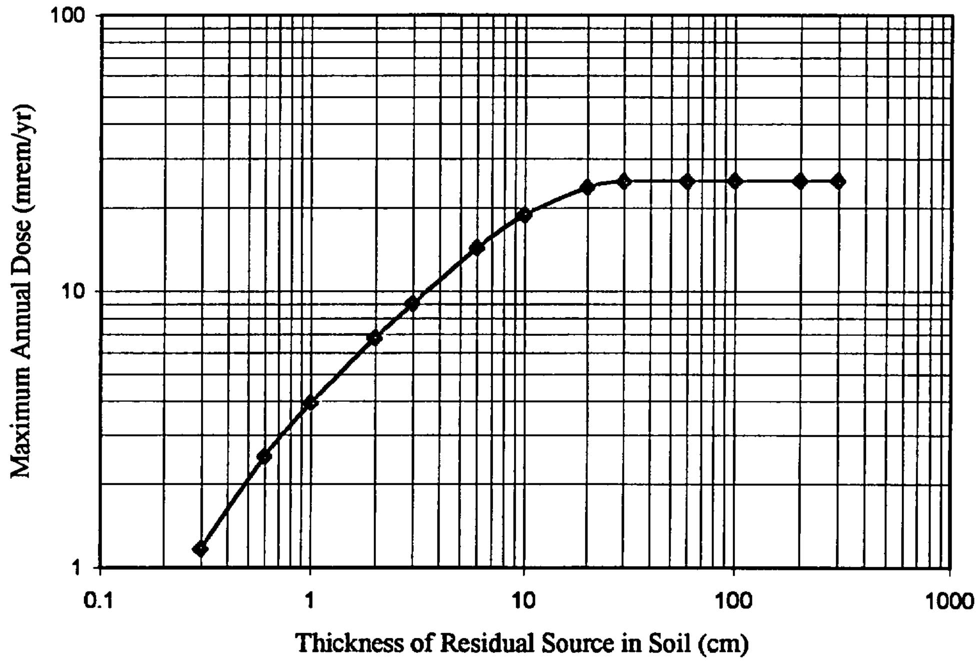
12 Biwer, B.M., *et. al.*, "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes." atch. C in *Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes.* NUREG/CR-6697. Dec. 2000.

Figure 5-1. Maximum Annual Radiological Dose Versus Source Depth in Soil
(infinitely-thick source ratio 3 U series + 1 Th series produces 25 mrem/yr)



As a result of this analysis, the thickness of contaminated zone parameter will be represented as a variable in probabilistic dose modeling. It is being represented as a uniform distribution ranging from 0 to 1 meter thick since characterization survey soil sampling intervals are insufficient to resolve a well-defined gradient within this range. A maximum depth of 1 meter is more than sufficient to be a conservative representation insofar as direct irradiation is concerned.

5.7.1.3. Cover Depth

Cover depth is the distance from ground surface to the contaminated zone. The default value in RESRAD is zero meters. Although Plant 5 is covered by pavement, when evaluating potential exposure to contaminated soil, it will be modeled as if there were no pavement and the land were bare.

5.7.1.4. Soil Mixing Layer Thickness

The soil mixing layer thickness is the thickness of the uppermost soil layer in which radioactive residue is mixed. It is estimated[13] to range from 0 to 0.6 meter, with the most likely thickness being 0.15 m. Since 0.15 m is also the default value, it will be assumed in DCGL calculations.

5.7.1.5. Occupancy Time

Occupancy times are described as the fraction of a year spent indoors and the fraction of a year spent outdoors in an area on-site that was previously contaminated. That would be the fraction

[13] *op. cit.*, Biwer, B.M., *et. al.*, pp. 3-42 & 3-43.

of an 8766 hour year spent in an industrial scenario within an affected area of Plant 5 or where the C-T incinerator or URO burials had been located.

An *industrial or commercial work* year is estimated to be 50 weeks x 40 hr/wk = 2000 hr. 0.8 of that time is estimated to be indoors and 0.2 is estimated to be out-of-doors. These amount to 0.1825 of time indoors and 0.04566 of time out-of-doors. These fractions, 0.1825 of time indoors and 0.04566 of time out-of-doors, are based on an estimated 2000 working hours per year and are entered into RESRAD as deterministic estimates of indoor and outdoor time fractions of 8766 hr/yr.

By comparison, the USACE estimated industrial worker occupancy 0.1969 of time indoors and 0.04566 out-of-doors on nearby Plant 2;[14] while the ANL staff estimated industrial worker occupancy indoors to be 0.17 of the time and occupancy out-of-doors to be 0.06 of the time.[15]

5.7.1.6. Inhalation Rate

It is necessary to estimate the volume of air inhaled by a worker while in an area on-site that was previously contaminated in order to estimate potential radiological dose to an industrial worker after C-T decommissioning. That volume is the product of occupancy time and inhalation rate. Resource data on inhalation rate have been reviewed.[17]

For the purpose of deriving DCGL in soil, industrial workers are assumed to spend time out-of-doors on affected land as well as indoors. The RESRAD model accepts a single inhalation rate, which should be weighted to represent both circumstances. The USACE[18] estimates an industrial worker breathes at an average rate of 1.2 m^3/hr. The ANL staff estimates that an industrial worker breathes at an average rate of 1.3 m^3/hr.[19] Short-term inhalation rates of adults[20] at 1.0 m^3/hr during light activity 1/3 of the time and at 1.6 m^3/hr during moderate activity 2/3 of the time produce a time and activity weighted inhalation rate of 1.4 m^3/hr. Similarly, if an outdoor worker[21] breathes 1.1 m^3/hr during slow activity 0.25 of the time and 1.5 m^3/hr during moderate activity 0.75 of the time, the weighted inhalation rate would also be estimated to be 1.4 m^3/hr. An inhalation rate of 1.4 m^3/hr has also been recommended as the default rate for commercial or industrial building occupancy.[22] An inhalation rate representing an *industrial* worker who spends some time out-of-doors and the majority indoors is represented by 1.4 m^3/hr in the industrial work scenario.

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14 USACE. Post-Remedial Action Report for the St. Louis Downtown Site Plant 2 Property. Table B-3. June 2001.

15 Yu, C., *et. al.*, ANL/EAD-4, Table 2-3, p. 2-22.

16 *ibid.*, USACE.

17 Biwer, B.M., *et. al.*, atch C, pp. 5-1 thru 5-5 in NUREG/CR-6697.

18 USACE. Post-Remedial Action Report for the St. Louis Downtown Site Plant 2 Property. Table B-3. June 2001.

19 Yu, C., *et. al.*, *User's Manual for RESRAD Version 6. ANL/EAC-4. p.2-22. July 2001.*

20 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-2.

21 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-2.

22 Biwer, B.M., *et. al.*, atch C, p. 5-3 in NUREG/CR-6697

Construction worker activity would seem to be most nearly similar to gardening, for which the recommended[23] default inhalation rate is 1.7 m^3/hr. This would correspond to an outdoor worker[24] whose activity is 0.8 moderate exertion at 1.5 m^3/hr breathing rate and 0.2 heavy exertion at 2.5 m^3/hr breathing rate. Since *construction* workers are assumed to work out-of-doors entirely, the inhalation rate of this critical group is estimated to be 1.7 m^3/hr without adjustment for any time indoors.

By comparison, the USACE estimates a breathing rate of 1.2 m^3/hr represents both industrial workers and construction workers on portions of Mallinckrodt's site being remediated under the FUSRAP.

5.7.1.7. Mass Loading for Inhalation

Estimation of intake by inhalation depends on the airborne concentration of contaminated airborne particulate matter, *i.e.*, soil, that is respirable. Respirable particles are those less than 10 μm in diameter. About 0.28 to 0.33 of airborne particles have been found to be respirable.[25, 26, 27, 28] The mass loading of respirable particulate in air may be estimated as the product of the total mass loading of airborne dust and the respirable fraction.

Deterministic. The total mass loading of airborne dust in an urban area has been estimated to range from 60 to 220 μg/m^3 by USHEW[29] and 33 to 254 by Gilbert, *et.al.*[30] A best geometric estimate is about 115 μg/m^3. Thus, a reasonable estimate of respirable mass loading for inhalation in an urban, industrial area is 0.3 x 115 μg/m^3 = 35 μg/m^3. (This is about the upper 90th percentile recommended for use in RESRAD in a residential environment.[31] Long-term measurements of mass loading in ambient air are 23 μg/m^3 at the 50th percentile.)

Probabilistic. The model of radionuclides in outdoor air subject to inhalation is the product of the radionuclide concentration in surface soil and the airborne density of particulates of respirable size in ambient air. Biwer, *et.al.*,[33] summarized the distribution of respirable

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23 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-3.
24 Biwer, B.M., *et. al.*, p. 5-4, Table 5.1-2.
25 USEPA. *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment.* EPA 520/4-77-016. pp. 31-32. Sept. 1977.
26 Chepil, W.S., "Sedimentary Characteristics of Dust Storms: III Composition of Suspended Dust." Am. J. Sci., 225, p. 206, 1957. in EPA 520/4-77-016, p. 57
27 Sehmel, G.A., *Radioactive Particle Resuspension Research Experiments on the Hanford Reservation*, BNWL-2081, 1977.
28 Willeke, K. *et.al.*, "Size Distribution of Denver Aerosols - A Comparison of Two Sites," Atm. Env., 8, p. 609, 1974.
29 USHEW. *Air Quality Criteria for Particulate Matter.* 1969. in NUREG/CR-5512, 1, p. 6.11.
30 Gilbert, T.L., *et.al.*, *Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites.* ORO-832 rev. Jan 1984. in Yu, C. *et.al.*, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil.* ANL/EAIS-8. pp. 110-111, Apr. 1983.
31 Biwer, *et.al.* atch C, p. c4-16 in NUREG/CR-6697.
32 NUREG/CR-5512, 1, p. 6.11.
33 Biwer, *et.al.* "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes." atch C, pp. C4-15 & C4-16 in NUREG/CR-6697. Dec. 2000.

particulate in ambient air reported by the EPA[34] for about 1790 air monitoring stations in a range of environments. At cumulative probability = 0.50, the most frequent respirable particulate density in the EPA distribution occurs at about 23 μg/m³ air.[35]

Three other sources of data were examined to get more comprehensive information about airborne particulate density in urban air. The total mass loading of airborne dust in an urban area has been estimated to range from 60 to 220 μg/m³ by USHEW[36] and 33 to 254 by Gilbert, *et.al.*[37] Their respective geometric means are approximately 115 and 92 μg/m³. Airborne particulates measured in 14494 urban and 3114 non-urban air samples in the National Air Sampling Network exhibited a geometric mean of 98 μg/m³.[38] A best geometric estimate of those is about 102 μg/m³.

Estimation of intake by inhalation depends on the airborne concentration of contaminated airborne particulate matter, *i.e.*, soil, that is respirable. About 0.28 to 0.33 of airborne particles have been found to be respirable, *i.e.*, less than 10 μm in diameter.[39, 40, 41, 42] The mass loading of respirable particulate in air may be estimated as the product of the total mass loading of airborne dust and the respirable fraction. Thus, a reasonable estimate of the geometric mean of respirable mass loading for inhalation in an urban, industrial area is about $0.3 \times 102\ \mu g/m^3 = 31\ \mu g/m^3$.

A distribution representing airborne particulate loading in urban air may be estimated by the shape of the distribution in NUREG/CR-6697, Table 4.6-1 and shifted upward by an increment representing the increase in dust in urban air relative to all ambient air. The result, in Figure 5-2, becomes the probabilistic distribution to replace the default distribution in RESRAD v. 6.3. This distribution represents careful, reasonable appraisal of values of airborne mass loading in an urban environment.

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34 USEPA. Aerometric Information Retrieval System. internet site http://www.epa.gov/airs/airs.html. 1999.

35 Biwer, *et.al.*, Table 4.6-1 and Fig. 4.6-1 in NUREG/CR-6697.

36 USHEW. *Air Quality Criteria for Particulate Matter*. 1969. in NUREG/CR-5512, 1, p. 6.11.

37 Gilbert, T.L., *et.al.*, *Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites*. ORO-832 rev. Jan 1984. in Yu, C. *et.al.*, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil*. ANL/EAIS-8. pp. 110-111, Apr. 1983.

38 Stern, A.C., ed. *Air Pollution*. 2nd ed. Academic Press. NY. 1968.

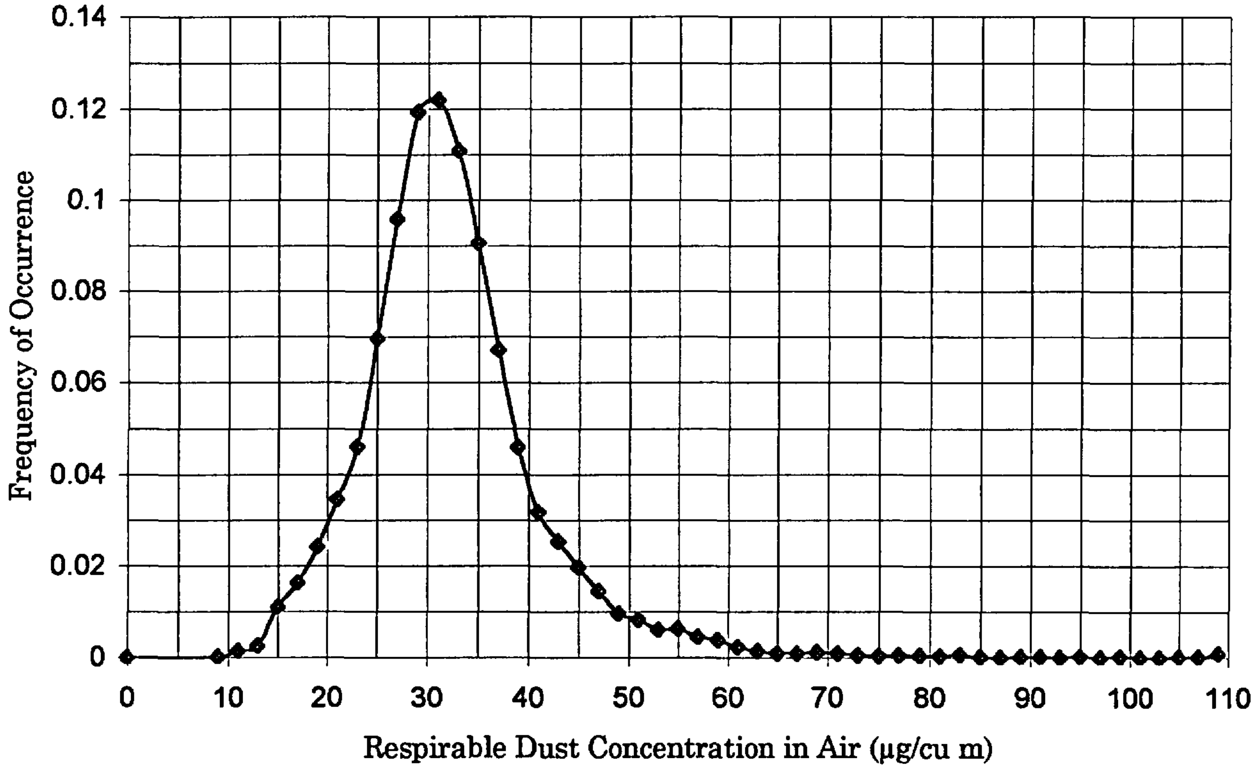
39 USEPA. *Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment*. EPA 520/4-77-016. pp. 31-32. Sept. 1977.

40 Chepil, W.S., "Sedimentary Characteristics of Dust Storms: III Composition of Suspended Dust." Am. J. Sci., 225, p. 206, 1957. in EPA 520/4-77-016, p. 57

41 Sehmel, G.A., *Radioactive Particle Resuspension Research Experiments on the Hanford Reservation*, BNWL-2081, 1977.

42 Willeke, K. *et.al.*, "Size Distribution of Denver Aerosols - A Comparison of Two Sites," Atm. Env., 8, p. 609, 1974.

Figure 5-2. Frequency Distribution of Respirable Dust in Urban Air
(EPA AIRS PM-10 data normalized to urban environment)



It is represented in RESRAD as a continuous linear distribution with entries in Table 5-1.

Table 5-1. Respirable Particulate in Urban Air

Respirable Particulate Concentration (µg/m³)	Frequency
0.	0.0
15.	0.0151
23.	0.1365
37.	0.8119
47.	0.9495
67.	0.9937
83.	0.9983
107.	0.9992

5.7.1.8. Soil Ingestion Rate

The quantity of contaminated soil ingested incidentally from outdoor activities annually is estimated to range from 0 to 36.5 g/yr.[43] The most likely amount is estimated to be 18.3 g/yr.[44] The recommended default value[45], 36.5 g/yr, is entered into RESRAD to represent an industrial worker.

5.7.1.9. Building Shielding Against Gamma Irradiation

The floor and walls of a building shield an occupant against some gamma rays entering from soil outside. Buildings in Plant 5 have concrete slab floors and brick or concrete block walls with few windows.

Probabilistic. An analysis of the effect of radiation attenuation by a building, especially floor thickness, on radiological dose for the portion of time a worker spends indoors during industrial occupation has been performed. Essential features of modeling to perform this analysis were:

- a reasonably representative source ratio of 3 U series, 0.0455 x 3 actinide (U^{235}) series, and 1 Th series together;
- residual source contamination extends from land surface downward one meter into the soil;
- outdoor time fraction = 0.0 in order to simulate effect of irradiation indoors;
- the same industrial land use scenario modeled to derive $DCGL_W$ originally, except absent ingestion of soil and inhalation of dust;
- deterministic simulation using RESRAD to derive the fraction of gamma dose rate as a function of concrete floor thickness; and
- combination of probable distribution of floor thickness and indoor gamma shielding factor to derive a probability distribution of indoor gamma shielding factor.
- The result of this analysis is summarized in Table 5-2 where indoor gamma shielding factor probability distribution is tabulated.

On the premise that a floor construction is likely to be specified in an integer thickness in units of inches, a *discrete cumulative* probability distribution of these data has been specified in RESRAD. Table 5-2 depicts the cumulative probability and indoor gamma shielding factor data entered into RESRAD for probabilistic evaluation of the effect of this parameter on radiological dose rate.

43 Biwer, *et.al.* atch C, pp. c5-19 thru c5-25 in NUREG/CR-6697.
44 *ibid.*
45 Yu, C., *et. al.*, NUREG/CR-6697, p. 18, Table 2.1.
46 Biwer, *et.al.* atch C, p. c7-36 in NUREG/CR-6697

Table 5-2. Indoor Gamma Shielding Factor Distribution

Shielding Thickness (cm)	(in)	Shielding Factor ("value")	Fractional Occurrence	Cumulative Distribution Indoor Only (cdf)
25.4	10	0.0084	0.01	0.01
20.3	8	0.022	0.08	0.09
17.8	7	0.035	0.12	0.21
15.2	6	0.055	0.18	0.39
12.7	5	0.088	0.24	0.63
10.2	4	0.14	0.25	0.88
7.6	3	0.23	0.07	0.95
0	0	1.0	0.05	1.0

5.7.1.10. Indoor Airborne Dust Filtration

The fraction of airborne dust out-of-doors that is available indoors has been reviewed.[47] When considering outdoor sources of respirable particulate indoors, Wallace[48] estimated the indoor-to-outdoor fraction to be close to 0.5. In residential housing, Wallace estimated the indoor-to-outdoor fraction of respirable particulate to average about 0.57. Biwer, *et. al.*,[49] estimated the same fraction to be 0.54. A value of 0.6 will be assumed when deriving DCGL for an industrial worker scenario.

5.7.1.11. Wind Speed

The average wind speed reported for St. Louis is 4.3 m/s (9.5 mi/hr);[50] whereas the default value in RESRAD v. 6 is 2 m/s. Although it makes little difference in dose modeling, an average wind speed = 4. m/s is entered into RESRAD to derive DCGL for C-T decommissioning.

5.7.2. Industrial Work on Pavement

The influences of parameters most pertinent to industrial work on pavement scenario are discussed below. Industrial worker characteristics are assumed to be the same whether the source is in soil or on pavement. Aside from parameters mentioned below, default values of parameters in RESRAD v.6 have been retained when deriving DCGL for surficial contamination on pavement.

5.7.2.1. Contaminated Zone

Surficial contamination on pavement may be simulated in RESRAD as a thin contaminated layer

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47 Biwer, *et.al.* atch C, pp. 7-1 thru 7-4 in NUREG/CR-6697

48 Wallace, L., "Indoor Particles: A Review." J. Air & Waste Mgt. Assoc., 46, pp. 98-126. 1996 in Biwer, *et.al.* atch C, pp. 7-1 thru 7-4 in NUREG/CR-6697.

49 Biwer, *et.al.* atch C, pp. 7-3 & 7-4 in NUREG/CR-6697.

50 C-T Phase II Decommissioning Plan, §3.4, Table 3-2.

of soil without cover and with zero erosion rate. Inhalation and ingestion models in RESRAD depend more on radionuclide concentration in soil than on thickness; while direct irradiation is more closely related to thickness, particularly when the source is thin. Physically, one would not expect as much as 0.1 cm of soil, on average, on pavement in Plant 5.

Consequently, an areal density of soil equivalent to 0.3 cm thickness of soil would adequately represent areal contamination on pavement for the purpose of estimating potential exposure of an industrial worker. Areal contamination on pavement is thus represented by 0.3 cm thick contaminated zone, zero cover depth, and zero erosion rate.

Although characterization survey data suggest surface contamination is unlikely to exceed an appropriate areal DCGL, assumption of 10,000 m^2 area of contamination will tend to maximize the dose factor and minimize the DCGL. Hence, the default value of the contaminated area, 10,000 m^2, is retained for pavement.

5.7.2.2. Wind Speed and Mass Loading for Inhalation

The average wind speed reported for St. Louis is 4.3 m/s (9.5 mi/hr);[51] whereas the default value in RESRAD v. 6 is 2 m/s. Thus, an average wind speed = 4. m/s is entered into RESRAD to derive an areal DCGL for decommissioning pavement affected by C-T.

A mass loading of respirable dust in outdoor air = 35 $\mu g/m^3$ has been entered into RESRAD to simulate an industrial work scenario in which the radioactive source is surficial contamination on pavement. The rationale of a dust concentration, 35 $\mu g/m^3$, in outdoor air is discussed in section 5.7.1.7.

While a worker is indoors, an indoor dust filtration factor = 0.6 will be assumed when deriving DCGL. The rationale for estimating this value is discussed in section 5.7.1.10.

5.7.2.3. Worker Characteristics

Industrial workers spend most of their time indoors. In Plant 5, an industrial worker is conservatively assumed to be on contaminated pavement 0.20 of their work time, which is an outdoor time fraction = 0.04563, and their remaining time indoors, an indoor time fraction = 0.1825. These estimates are discussed in section 5.7.1.5.

Where the source of contamination is on the surface of pavement, an industrial worker is assumed to ingest contaminated material at RESRAD's default rate, 36.5 grams per year.

A breathing rate representative of indoor and outdoor activities is estimated to be 1.4 m^3/hr, or 12270 m^3 during a 2000 work year. While indoors, an external gamma shielding factor = 0.17 of the outdoor gamma exposure rate is estimated to apply in Plant 5 buildings, which typically are constructed with a concrete slab floor and brick walls. These estimates are discussed in sections 5.7.1.6, 5.7.1.9, and 5.7.1.10.

[51] C-T Phase II Decommissioning Plan, §3.4, Table 3-2.

5.8. DCGL FOR INDUSTRIAL WORK ON SOIL

5.8.1. Radiological Dose Modeling

Models simulating environmental exposure pathways to estimate potential radiological dose to people are coded in the RESRAD computer program. With the aid of RESRAD, probabilistic modeling has been done to derive dose factors and DCGL at the *peak of the mean* dose as NRC guidance suggests.[52]

RESRAD is able to compute and tabulate the time of peak mean dose rate and the peak mean dose rate (mrem/yr). One may derive a composite dose factor for a related series of radionuclides by summing the average dose of each source radionuclide in the series at the time of the peak of the mean dose. Then one may derive the dose factor as the quotient of that sum and the concentration of the radionuclides to which it is referenced. For example, the composite dose factor of the thorium series would be the sum of doses of the principal radionuclides, including their short-lived progeny, at the time of the peak of the mean dose divided by the initial concentration of the reference, or parent Th^{232}.

In the probabilistic total dose summary, one can read the contribution by each long-lived radionuclide entered in the source term column corresponding to the time of peak mean dose. The *average (avg)* dose of each source radionuclide at the time of peak mean dose, summed over all of the source radionuclides, equals the peak of the mean dose. Having identified the contribution of each source radionuclide to the peak of the mean total dose, one may derive an appropriate probabilistic dose factor (mrem/yr per pCi/g) as the quotient of the average dose of each source radionuclide at the time of peak mean total dose and the concentration of that radionuclide entered into the source term in RESRAD.

5.8.2. Derivation of Thorium Series Dose Factor and $DCGL_W$

Thorium series nuclides associated with C-T processing have grown or decayed within about 0.20 of radioactive equilibrium. Considering that C-T feed was ore and that alpha spectrometry of separate radioelements poses some uncertainty at low concentration, the thorium series might rationally be assumed to be in radioactive equilibrium in Plant 5 soil samples. Especially for future estimation, the shorter radioactive half-lives of Ra^{228}, 6.7 yr, and of Th^{228}, 1.9 yr, imply that Th^{232} parent concentration is controlling. Characterization survey data also indicate the thorium series occurs at about a 1/3 of the uranium series concentration in soil.

Assuming the thorium series to be in radioactive equilibrium, a composite dose factor representing the series was derived probabilistically with RESRAD (ref. case 408guti in Appendix C). Equal concentrations of principal radionuclides, Th^{232}, Ra^{228}, and Th^{228}, entered into RESRAD, produce peak of the mean annual dose at year zero and corresponding peak of the mean composite dose factor, DF = 1.05 (mrem/yr)/(pCi Th^{232}/g soil). The corresponding $DCGL_W$ = 23.8 pCi Th^{232}/g soil for industrial land use.

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[52] NUREG-1757, 2, §5.

[53] Composite limit is also referred to as the derived concentration guideline level for the Wilcoxon test ($DCGL_W$).

5.8.3. Derivation of Uranium Dose Factor and $DCGL_W$

Since C-T residue includes natural uranium, it would be logical to consider U^{238} through U^{234} and include the actinium, or U^{235}, series in its naturally-occurring proportion to the uranium series. When these radionuclides are the source in a RESRAD probabilistic simulation of an industrial land use scenario, the peak of the mean annual dose occurs in the first year of exposure (ref. case 407guti in Appendix C). The composite dose factor,[54] corresponding to the peak of the mean annual dose rate = 0.0347 mrem/yr per pCi U^{238}/g soil. The corresponding $DCGL_W$ = 721 pCi U^{238}/g soil for industrial land use.

5.8.4. Derivation of the Dose Factor and $DCGL_W$ of Th^{230} and Ra^{226}

Since Th^{230} transmutes into Ra^{226}, is observed together with Ra^{226} in soil samples, and since the dose factor of Ra^{226} and its progeny, including Pb^{210}, exceed other radionuclides in the uranium series, it is logical to associate Th^{230} and Ra^{226} in dose estimation. Measurement of Th^{230} requires analysis that is slow, expensive, and separate from other key radionuclides. To the extent its presence in excess of uranium or Ra^{226} does not increase potential annual dose substantially and specific measurement is unnecessary, remediation can be done without undue delay. It would be desirable to adopt a conventional association that does not underestimate potential radiological dose and that allows measured Ra^{226} to represent the subseries. For this reason, it would be logical and useful to link Th^{230} with Ra^{226} in lieu of further measurement of Th^{230} itself.

A subseries beginning with Th^{230} and including Ra^{226}, Pb^{210}, and their short-lived progeny is a logical grouping. In soil, it would be reasonable to assume Ra^{226}, Pb^{210}, and their short-lived progeny are in radioactive equilibrium; although exhalation of Rn^{222} could even leave progeny below equilibrium. The relatively short half-life of Pb^{210}, 21 years, and its lower dose factor than of Ra^{226} justifies compositing the contributions of Ra^{226}, Pb^{210}, and their short-lived progeny to radiological dose.

A series of probabilistic dose modeling was computed with RESRAD to determine conditions in which a composite dose factor including principal radionuclides, Th^{230}, Ra^{226}, and Pb^{210} as the source, would not significantly underestimate radiological dose when applied to the range of characterization survey data. Within a population of more than 500 soil characterization samples and among the 41 pairs in which Ra^{226} and Th^{230} are above background mean by more than 1 standard deviation, only 3 samples, or 0.6 %, exhibit Th^{230} -to- U^{238} > 6. Adopting the composite dose factor representing Th^{230}, Ra^{226}, Pb^{210}, and their progeny, with Th^{230}/Ra^{226} ratio = 6, would be expected to encompass more than 99% of soil samples. The peak of the mean dose as a function of increasing Th^{230} -to- the peak of the mean dose when Th^{230} concentration equals Ra^{226} concentration only exceeds 1.1, or increases by as much as 11 percent only when the Th^{230} -to- U^{238} ratio exceeds 6. Thus, radiological dose is not very sensitive to increasing Th^{230} -to- Ra^{226} ratio.

Thus, it is reasonable to apply a composite dose factor = 0.852 (mrem/yr)/(pCi Ra^{226}/g soil) and

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[54] including all the principal radionuclides and their short-lived progeny

a $DCGL_W$ = 29.4 pCi Ra^{226}/g soil to represent the subseries including Th^{230}, Ra^{226}, and Pb^{210} for industrial land use.

5.8.5. Composite Dose Factors and $DCGL_W$

From the separate cases and source terms, recorded in Appendix D, composite dose factors and $DCGL_W$ in Table 5-3 were derived.

Table 5-3. Composite Dose Factor and DCGLw Derived Separately

Radionuclide Group	Composite Dose Factor[55] (mrem/yr)/(pCi/g)	$DCGL_W$[20] (pCi/g)	RESRAD case
Th series	1.05	23.9	408guti
Natural Uranium	0.0347	721.	407guti
6 Th^{230} + Ra^{226} + Pb^{210}	0.852	29.4	399guti

Dose factor and $DCGL_W$ of the thorium series is referenced to Th^{232}.
Dose factor and $DCGL_W$ of natural uranium is referenced to U^{238}.
Dose factor and $DCGL_W$ of Th^{230}, Ra^{226}, and Pb^{210} is referenced to Ra^{226}.

5.8.6. Compliance Model for Soil

In the uranium series, U^{238} through U^{234} will be assumed to be in radioactive equilibrium and will be represented by measurement of uranium isotope(s) or surrogate progeny. The actinium (U^{235}) series will be assumed to exist in its naturally-occurring proportion to the uranium series.

Radium-226 and its progeny, including Pb^{210}, will be assumed to be in radioactive equilibrium and will be referenced to measured Ra^{226} concentration. Th^{230} will be associated with Ra^{226} and Pb^{210} because the Ra^{226}, to which it decays, presents the dominant dose factor.

Thorium series radionuclides will be assumed to be in radioactive equilibrium and will be represented by measurement of a surrogate radionuclide, Ac^{228}, in the series.

Radiological **dose factors** of individual radionuclides in each subseries may then be composited and stated simply as

$$DF_U = [D(U^{238}) + D(U^{234}) + D(U^{235} + Ac^{227} + Pa^{231})] \div C(U^{238}) \qquad \text{eqn 1}$$

$$DF_{Ra226\ \&\ Th230} = [D(Ra^{226}) + D(Pb^{210}) + D(Th^{230}{=}6 \cdot Ra^{226})] \div C(Ra^{226}) \qquad \text{eqn 2}$$

$$DF_{Th\ series} = [D(Th^{232}) + D(Ra^{228}) + D(Th^{228})] \div C(Th^{232}) \qquad \text{eqn 3}$$

where D_i = annual dose rate of principal radionuclide *i* and its short-lived progeny at the time of the peak of the mean dose rate posed by the related group of radionuclides (mrem/yr)

C_i = concentration of reference radionuclide *i* in soil (pCi/g soil)

DF = radiological dose factor (mrem/yr)/(pCi/g soil)

Dose factors include long-lived radionuclides mentioned and their short-lived progeny.

The **derived concentration guideline level** may then be stated as

55 DF and $DCGL_W$ are referenced to Th^{232}, U^{238}, and Ra^{226} respectively.

$$DCGL_{W\,U} = \frac{25}{DF_U}$$ eqn 4

$$DCGL_{W\,Ra226} = \frac{25}{DF_{Ra226+Th230}}$$ eqn 5

$$DCGL_{W\,Th\,series} = \frac{25}{DF_{Th\,series}}$$ eqn 6

where 25 = maximum acceptable annual radiological dose (mrem/yr)

$DCGL_W$ = derived concentration guideline level of reference radionuclide (pCi/g soil)

This permits a simplified statement of the **sum-of-fractions** of the radionuclides encountered in C-T decommissioning to be:

$$SOF = \frac{C_{U238}}{DCGL_{W\,U}} + \frac{C_{Ra226}}{DCGL_{W\,Ra226}} + \frac{C_{Th232}}{DCGL_{W\,Th\,series}}$$ eqn 7

where: SOF = sum-of-fractions of $DCGL_W$

C_{U238} = concentration of U^{238} in soil (pCi/g)

C_{Ra226} = concentration of Ra^{226} in soil (pCi/g)

C_{Th232} = concentration of Th^{232} in soil (pCi/g)

$DCGL_{W\,U}$ = $DCGL_W$ of U^{238} + U^{234} + actinium (U^{235}) series in its naturally-occurring ratio to the uranium series (pCi/g)

$DCGL_{W\,Ra226}$ = $DCGL_W$ of 6 Th^{230} + Ra^{226} and its progeny, including Pb^{210}, in radioactive equilibrium (pCi/g)

$DCGL_{W\,Th\,series}$ = $DCGL_W$ of Th^{232} and its progeny, including Ra^{228} and Th^{228}, in radioactive equilibrium (pCi/g)

The index, or SOF, determined for each soil sample or location measured, will be the basis of testing compliance with population statistics and elevated measurements criteria.

5.8.7. Area Factor for Elevated Measurements in Soil

It is desirable to discover any small area of contamination that could cause more than 25 mrem/yr radiological dose. The magnitude by which the concentration within a small area of elevated radioactivity can exceed the $DCGL_w$ while maintaining compliance with the release criterion is defined as an *area factor*.[56] It may be calculated as the ratio

$$\text{Area Factor} = \frac{\text{composite dose factor for survey unit area}}{\text{composite dose factor for local area of contamination}}$$ eqn 8

Figure 5-3 is the *area factor* as a function of a localized area of radioactive contamination consisting separately of

- thorium series;
- natural uranium, including U^{234}, U^{235}, and actinium series in which uranium isotopes are in the ratio occurring in natural uranium; and
- Ra^{226}, Pb210, and 6 Th^{230}.

[56] MARSSIM, p. 5-36. Dec. 1997.

The maximum tolerable areal density of residual radioactive contamination by each of these groups, above background, within a small area of elevated radioactivity is derived by the relation

$$DCGL_{EMC} = \text{Area Factor} \times DCGL_w$$

where the maximum area factor considered corresponds to 10 m^2 area of elevated contamination.

An index representing radioactivity in a small area may be calculated with the sum-of-fractions relation:

$$\text{Index} = \frac{C_{U238}}{(AF \times DCGL_W)_U} + \frac{C_{Ra226}}{(AF \times DCGL_W)_{Ra226}} + \frac{C_{Th232}}{(AF \times DCGL_W)_{Th\,series}} \qquad \text{eqn 9}$$

where $DCGL_W$ are read from Table 5.1 and AF_U, AF_{Ra226}, and $AF_{Th\,series}$ are read from Figure 5-3. This Index represents the fraction or multiple of the $DCGL_{EMC}$. In effect, $DCGL_{EMC}$ occurs when this Index = 1 and is exceeded when the Index > 1.

Systematically distributed measurements and soil characterization survey measurements, together, are employed in each Class 1 survey unit to find such an area of contamination whose radioactivity concentration is elevated above the $DCGL_W$.

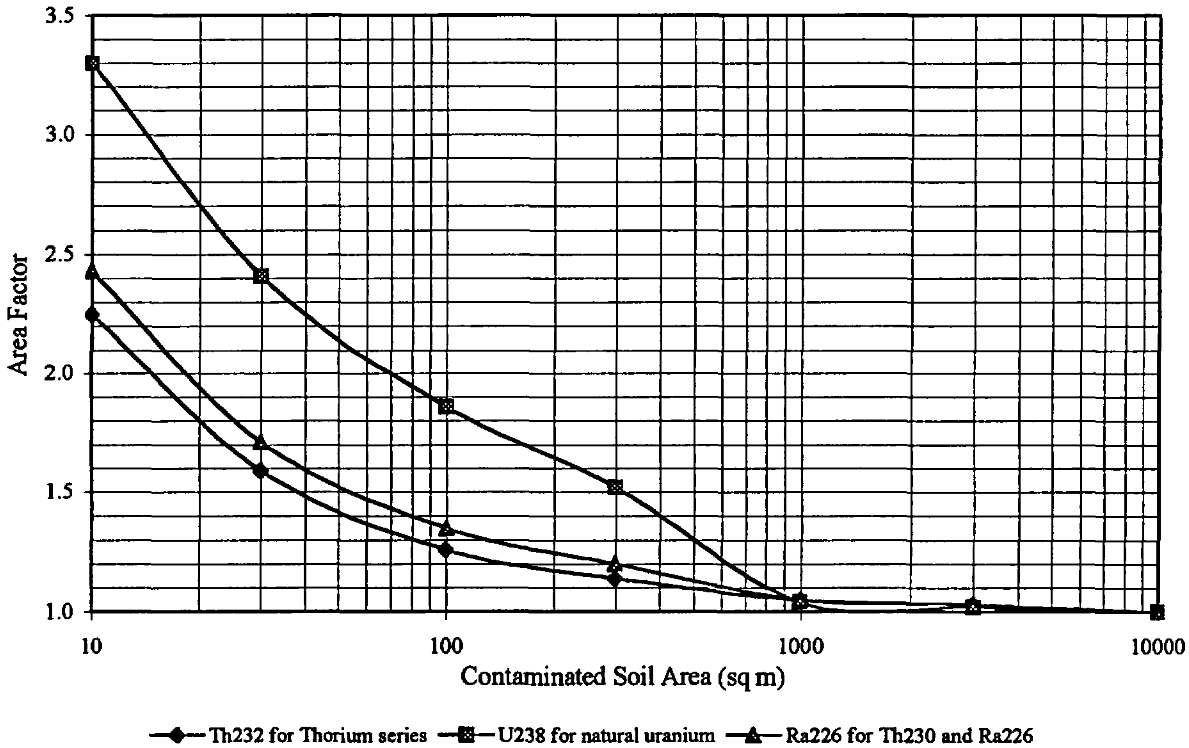


Figure 5-3. Area Factors for Elevated Measurements Criterion in Soil

5.9. INDUSTRIAL WORK ON PAVEMENT

5.9.1. $DCGL_W$ on Pavement

Dose factors were computed by RESRAD for an industrial work scenario on pavement. The RESRAD output for each radionuclide can be interpreted as a dose factor (mrem/y per pCi/m^2), which in turn may be interpreted as a maximum acceptable average areal density of the radionuclide on a surface, also called the $DCGL_w$, corresponding to a maximum acceptable potential radiological dose equivalent.

Exposure to bare soil and to pavement cannot occur simultaneously. The scenario assuming bare soil necessarily excludes pavement and any exposure to it. Thus, derivation of DCGL for work on soil is independent of exposure to pavement.

On the other hand, pavement would exist atop soil. When so, it would be a complete barrier against airborne and ingestion pathways of exposure to conceivable residue in the soil and an incomplete shield against gamma radiation penetrating from conceivable residue in the soil. With the aid of dose modeling of outdoor exposure to gamma radiation penetrating nominal 4-inch-thick pavement by RESRAD, a meter of soil containing a spectrum of radionuclides observed in soil [ref. Appendix C, §C.3.2] at the concentration corresponding to $DCGL_W$ in soil would be estimated to contribute 5.0 mrem/yr through the pavement. Subtracting that from 25 mrem/yr allotted to DCGL would imply reduction of conceivable contribution from residue on pavement itself to 20 mrem/yr, or 0.80 of the $DCGL_W$ derived and proposed for pavement.

Although it is unlikely that both soil and pavement would be contaminated to more than 0.80 of either $DCGL_W$, and thus are practically independent, $DCGL_W$ in Table 5-4 and consequently $DCGL_{EMC}$ are reduced to 0.80 of values that would produce 25 mrem/yr. Corresponding $DCGL_W$ were then derived as the quotient of 20 mrem/yr and each dose factor. They may be composited into logical groups, each of which may be represented by a practically measurable radionuclide:

U_{nat}	represents U^{238} thru U^{234} and the actinium (U^{235}) series in natural proportion to U^{238}; U^{238} is the reference radionuclide.
Th^{230} subseries	represents Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny, with Th^{230} and Ra^{226} in proportions measured in cinder fill samples and with Pb^{210} and its short-lived progeny assumed in radioactive equilibrium with Ra^{226}. Ra^{226} is the reference radionuclide.
Th series	represents the thorium series in radioactive equilibrium. Th^{232} is the reference radionuclide.

The adjusted $DCGL_W$ applicable to pavement are in Table 5-4. Derivation of Table 5-4 is explained in Appendix G of this Plan. Application of $DCGL_W$ in Table 5-4 absorbs any need to allocate potential radiological dose among soil and pavement later.

Table 5-4. Radioactivity on Pavement Surface Producing 20 mrem/yr

Radionuclide	Dose Factor	Areal Density Equal to 20 mrem/yr	
	(mrem/yr)/(pCi/g)	(pCi/100 sq cm)	(dpm/100 sq cm)
U-238	8.57E-04	1.05E+06	2.33E+06
U-234	7.02E-05	1.28E+07	2.85E+07
U-235+DI	2.16E-02	4.17E+04	9.26E+04
Th-230	1.51E-04	5.94E+06	1.32E+07
Ra-226	4.54E-02	1.98E+04	4.41E+04
Pb-210	1.28E-03	7.04E+05	1.56E+06
Th-232	2.37E-03	3.80E+05	8.43E+05
Ra-228	2.98E-02	3.02E+04	6.70E+04
Th-228	3.20E-02	2.82E+04	6.25E+04
U nat [b, c]	1.91E-03	4.71E+05	1.05E+06
Th^{230}+Ra^{226}+Pb^{210} [d]	4.67E-02	1.93E+04	4.28E+04
Th series [a]	6.42E-02	1.40E+04	3.11E+04

[a] Th^{232} series is the limit for Th^{232} with all its progeny nuclides present in equilibrium concentration (*i.e.*, radioactivity concentration of each equal to the Th^{232} concentration). Because Th^{232} progeny grows in to equilibrium within about 30 years, and because the C-T facilities have existed for nearly that long, Th^{232} progeny can be expected to be near equilibrium.

[b] U nat is the limit for U^{238} with U^{234}, and their short-lived progeny present in equilibrium and the U^{235} series is present in equilibrium in the proportion occurring in natural uranium.

[c] Radioactivity ratio of U^{235} -to- U^{238} = 0.0455 in natural uranium.

[d] Th^{230} series includes Th^{230}, Ra^{226}, Pb^{210}, and their short-lived progeny and is referenced to Ra^{226} radioactivity concentration.

Radioactive contamination on surfaces is often surveyed by gross activity detection. It is practical, then, to state the contamination limit in units consistent with the measurement. A method of interpreting a surface radioactivity limit and gross beta measurement in comparable units is described in C-T Phase I Decommissioning Plan, Appendix D. The maximum acceptable average areal radioactivity density on a surface, or $DCGL_W$, is expressed in units, pCi/ 100 cm^2, and in units, disintegrations/(min·100 cm^2) in Table 5-4 for components of the source.

Principal radionuclides in the uranium series, thorium series, and actinium series were measured in 24 samples scabbled on pavement in Plant 5. Lognormal distribution graphics of the analytical data in Table 4-2, indicate that the log mean radioactivity ratios are as in Appendix G, Tables G-4 and G-5 and in Table 5-5.

Table 5-5. Ln Mean Ratio on Pavement

Radionuclide	Relative Concentration
U_{nat}/Th series	3
Th^{230}/U_{nat}	0.78
Ra^{226}/U_{nat}	1.4
Th^{230}/Ra^{226}	0.6

Applying this distribution to the areal density equal to 20 mrem/yr, or $DCGL_W$, in Table 5-4 yields composite limits:

$$DCGL_W = 6.2 \times 10^4 \text{ dis/(min}\cdot 100 \text{ cm}^2)$$

or the corresponding β radiation limit:

$$\beta_{limit} = 1.8 \times 10^5 \ \beta\text{/(min}\cdot 100 \text{ cm}^2)$$

Derivation of these composite limits is explained in Appendix G.

To enable practical survey of the radionuclide spectrum observed on pavement by measuring gross beta radiation, $DCGL_W = 1.8 \times 10^5$ β/(min·100 cm^2) is proposed. Measurement methodology is described in C-T Phase I Decommissioning Plan, Appendix D, §3 "Beta Radiation Measurement."

5.9.2. Area Factor for Elevated Measurements on Pavement

It is desirable to discover any small area of contamination that could cause more than 25 mrem/yr radiological dose. The magnitude by which the concentration within a small area of elevated radioactivity can exceed the $DCGL_w$ while maintaining compliance with the release criterion is defined as an *area factor*.[57] Figure 5-4 provides the *area factor* separately for U series (including actinium series present in natural uranium) , Th series, and the ratios of principal radionuclide in pavement scabble samples as a function of a localized area of radioactive contamination on pavement. The actinium series is assumed present with the uranium series at the radioactivity ratio, U^{235}-to-U^{238} = 0.0455, that occurs naturally.

A composite area factor is calculated as the ratio of composite areal density limits, *i.e.*, DCGL, applicable to radionuclides in pavement scabble samples in ratios of principal radionuclides observed therein and reported in Table 5-5 and Appendix G, Tables G-4 and G-5.

$$\text{Area Factor} = \frac{\text{composite areal DCGL for survey unit area}}{\text{composite areal DCGL for local area of contamination}} \qquad \text{eqn 13}$$

[57] MARSSIM, p. 5-36. Dec. 1997. Biwer, *et.al.* atch C, pp. 7-1 thru 7-4 in NUREG/CR-6697

[58] Composite limit is also referred to as the derived concentration guideline level for the Wilcoxon test ($DCGL_W$).

The maximum tolerable areal density of residual radioactive contamination, above background, within a small area of elevated radioactivity is derived by the relation

$$DCGL_{EMC} = \text{Area Factor} \times DCGL_w \qquad \text{eqn 14}$$

where the maximum area factor considered corresponds to 10 m^2 area of elevated contamination. Since the area factors curves in Figure 5-4 are nearly coincident, it is reasonable to adopt the area factor curve representing the composite of the radionuclide distribution observed in scabble samples of pavement to apply to the $DCGL_W$ derived in §5.9.1.

Systematically distributed measurements and scanning, together, are employed in each Class 1 survey unit to find such an area of contamination whose areal radioactivity density is elevated above the $DCGL_w$. Measurement of gross beta radiation and interpretation as described in the CT Phase I Decommissioning Plan would be acceptable.

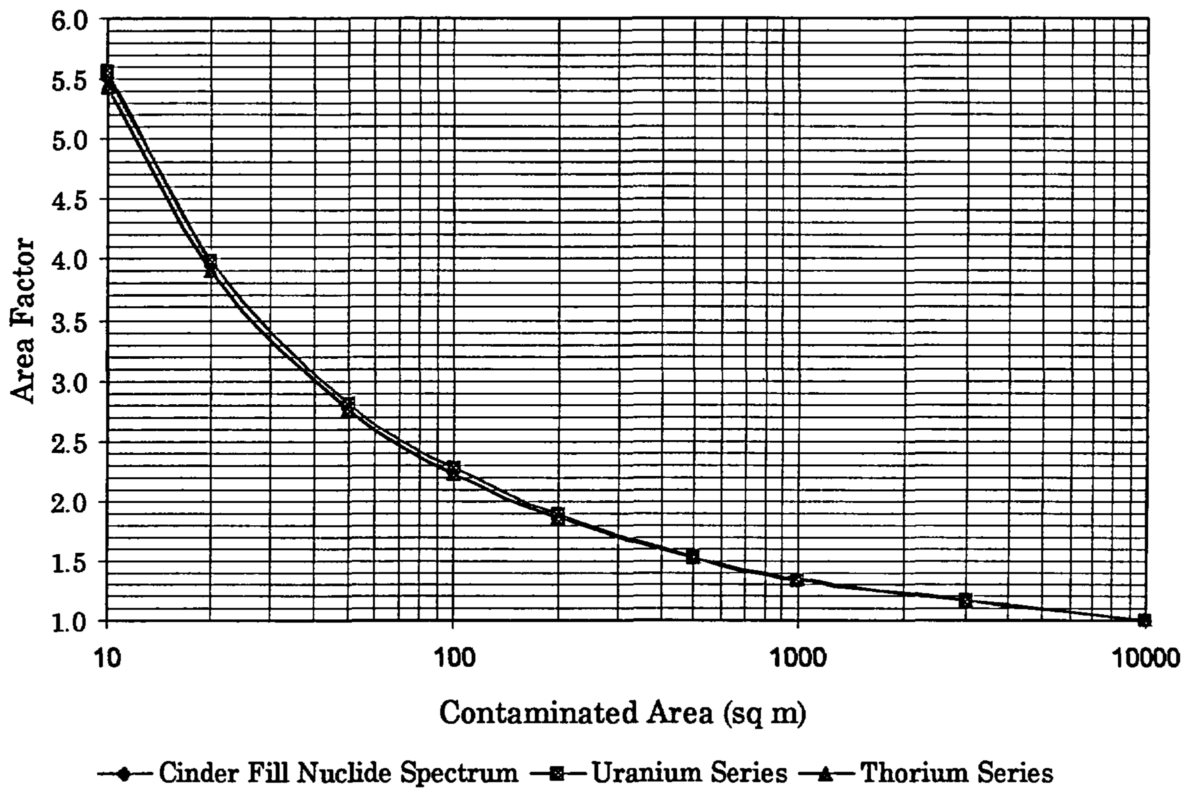


Figure 5-4. Area Factor for Elevated Measurements on Pavement

5.10. SENSITIVITY ANALYSIS

5.10.1. Ranking Parameters

An aim of conceptual and mathematical modeling to derive a DCGL is confidence that the modeling is unlikely to overestimate future radiological dose to an average member of the critical group of people exposed. That confidence is built on conceptual and mathematical simulation in which projected land use scenarios, environmental exposure models, and values of

parameters in the models, compounded together, are unlikely to overestimate dose consequence of residual radioactive material.

It is important to understand the effect on dose of values used in the assessment to represent the key parameters. In deterministic modeling,[59] sensitivity analysis calculates the change in the radiological dose, with respect to a small change in the independent variables, one at a time. In a deterministic analysis, it is recognized that the reported dose is one of a range of possible doses that could be calculated for the site. It is important to build confidence that the single reported estimate of the peak dose is likely to be an overestimation of the actual peak dose.

The primary aim of sensitivity analysis is to identify the important assumptions and input parameters that cause variation in the estimated dose. This helps a modeler to identify conservative land use scenarios, models, and values in order to make a convincing case for the acceptability of the DCGL.

Yu, *et. al.*,[60] have ranked RESRAD input parameters with respect to potential for affecting radiological dose, tendency to vary from site to site, parameter type, and ease of characterization using available literature. The impact on the radiation dose resulting from a change in a parameter value was a major factor in ranking the parameters for analysis.

Ranking of parameters in models used to derive DCGL for soil are in Table 5-6. Parameters ranked Priority 1 were expected to have the greatest potential for affecting radiological dose, tend to vary more from site to site, and are able to be characterized more easily than parameters of lower priority.

Table 5-6. ANL Ranking of Parameters in RESRAD That Are Used to Derive DCGL Herein

Priority 1 (higher)	Priority 2 (mid)	Priority 3 (lower)
Density of cover material *	Nuclide concentration	Time since placement of material*
Density of contaminated zone*	Area of contaminated zone*	Inhalation rate
	Thickness of contaminated zone*	Indoor time fraction
	Cover depth	Outdoor time fraction
	Cover erosion rate	Building foundation thickness*
	Wind speed	Building foundation density*
	Mass loading for inhalation	
	Indoor dust filtration factor	

59 NUREG-1727, Apx. C, §6.3.3, p. C60.

60 Yu, *et. al.*, NUREG/CR-6697. Table 4.2, p. 55.

Table 5-6 continued:

Priority 1 (higher)	Priority 2 (mid)	Priority 3 (lower)
	External gamma shielding factor Soil ingestion rate* A Depth of soil mixing layer*	

* Default value used for DCGL.

*, A Default value used for industrial worker.

In a particular scenario the sensitivity of derived dose to a change in parameter value depends on the influence of that parameter in each exposure pathway model and on the relative contribution of each pathway to total dose. Some parameters, like radionuclide concentration affect every pathway, whereas other parameters, such as mass loading of airborne dust affect only one or two inhalation pathways.

The Table 5-5 ranking of parameters and the fractional contribution by each pathway to total dose offer an efficient way to judge which are the most influential parameters.

In the industrial/commercial work scenario, most of potential dose would be caused by gamma irradiation directly from radionuclides in the soil. Minor fractions would be attributable to inadvertent ingestion of soil and inhalation of dust suspended from the soil. Parameters in RESRAD's direct radiation model to which dose is most sensitive to variation would be:

- density of cover material,
- density of contaminated zone,
- nuclide concentration in the contaminated zone,
- area of contaminated zone
- thickness of contaminated zone
- cover depth, and
- external gamma shielding factor while indoors.

Radiological dose by gamma irradiation directly from contaminated soil would be a direct, one-to-one, function of radionuclide concentration in the contaminated zone.

DCGL herein is derived on the basis of the default soil density, 1.5 g/cm^3, in the contaminated zone. Soil density in the contaminated zone does not affect source self-shielding because the contaminated zone is initially assumed to be an infinitely thick source relative to first collision of gamma rays and secondary photon buildup. The thickness of the contaminated zone, assumed to be 2 meters, is effectively an infinitely thick source, given the default soil density. That is, radiological dose would not be increased significantly by increasing the contaminated zone density or diminishing soil density within realistic bounds.

While radiological dose by direct irradiation is a function of the area of the contaminated zone, the 10000 m^2 default area assumed in deriving $DCGL_W$ is effectively infinite in areal extent.

5.10.2. Radionuclide Variability

The $DCGL_W$ of C-T source residue on pavement is not very sensitive to radionuclide variability. To evaluate this, boundary conditions could be reasonably represented by assumptions that the source were either all natural uranium series and actinium series in naturally-occurring proportion, or all thorium series, or all Th^{230} subseries. If, for instance, the source were entirely uranium series in equilibrium, the β limit equivalent to $DCGL_W$ would = 2.2 x 10^5 β/(min·100 cm^2); or if the source were entirely thorium series in equilibrium, the beta limit equivalent to $DCGL_W$ would = 1.1 x 10^5 β/(min·100 cm^2); or if the source were entirely the Th^{230} subseries mix represented in its $DCGL_W$, the beta limit equivalent to that $DCGL_W$ would = 1.4 x 10^5 β/(min·100 cm^2).

The radionuclide spectra in a set of 24 scabble samples collected on pavement are a mix of uranium series[61] and thorium series. The β limit equivalent to the $DCGL_W$ of the radionuclide spectrum (radionuclides in their relative concentrations) observed in this set of scabble samples is 1.8 x 10^5 β/(min·100 cm^2). Thus, the β limit equivalent to the $DCGL_W$ of the most representative radionuclide spectrum in these samples is a value between the extremes of all uranium series or all thorium series. In perspective, these boundary conditions indicate that the β limit to which measurements will be compared to assess compliance with the DCGL will not be very sensitive to variability in the spectrum of radionuclides on pavement.

5.10.3. Pavement

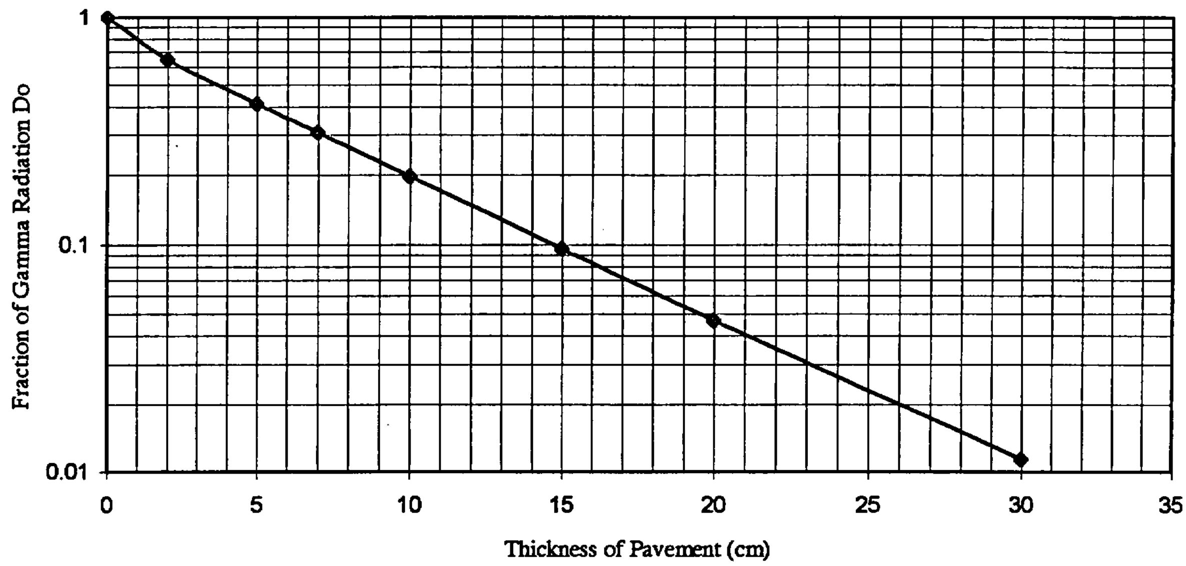
Radiological dose is sensitive to cover depth and density of cover material. The industrial/commercial work scenario assumes outdoor exposure to bare, contaminated land, *i.e.*, without cover on the contaminated zone. Whereas, practically all land in Plant 5 is paved or is covered by a concrete slab. Together, they conceptually exclude inhalation and ingestion of contaminated soil and would shield an industrial worker from most direct gamma radiation. If one were to assume 4-inch-thick pavement instead of bare land containing typical source spectrum observed in cinder fill samples it would diminish potential dose and increase the composite $DCGL_W$ derived by RESRAD for an industrial worker about 5 times more than if no pavement were present.

Thus, radiological dose from cinder fill would diminish with increasing depth and density of a pavement cover zone. This is evident in Figure 5-5.[63] Having assumed no pavement when deriving the DCGL in soil tended to overestimate radiological dose and conservatively estimate the $DCGL_W$ in the industrial/commercial scenario herein by a factor of about 5 for typical U series + Th series in cinder fill.

[61] including actinium series in naturally-occurring proportion to the uranium series

[63] CT 2 DP, Appendix G, Fig. G-2.

Figure 5-5. Fraction of Gamma Radiation Penetrating Pavement
Source Spectrum is Ln Mean Radionuclide Concentration in Cinder Fill
Dose Modeling by RESRAD v. 6.3



5.11. COMPLIANCE WITH REGULATORY CRITERIA

Mallinckrodt proposes to satisfy unrestricted release provisions of 10 CFR Part 20, Subpart E by evaluating final status survey data to demonstrate that

- $DCGL_W$ in §5.8.5 as interpreted in §5.8.6 and $DCGL_{EMC}$ in §5.8.7 are not exceeded in soil affected by C-T operation, and separately that
- $DCGL_W$ in §5.9.1 and $DCGL_{EMC}$ in §5.9.2 are not exceeded on pavement affected by C-T operations.

Final radiation status survey methods to assess compliance are described in §14, *Facility Radiation Surveys.*