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**DEVELOPMENT OF SITE-SPECIFIC
SOIL CLEANUP CRITERIA:
NEW BRUNSWICK LABORATORY,
NEW JERSEY SITE**

by

**V. R. Veluri, H. J. Moe,
M. J. Robinet, and R. A. Wynveen**

1983

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**OCCUPATIONAL HEALTH AND SAFETY DIVISION
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9700 South Cass Avenue
Argonne, Illinois 60439

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ABSTRACT

The potential human exposure which results from the residual soil radioactivity at a decommissioned site is a prime concern during D&D projects. To estimate this exposure, a pathway analysis approach is often used to arrive at the residual soil radioactivity criteria. The development of such a criteria for the decommissioning of the New Brunswick Laboratory, New Jersey site is discussed.

Contamination on this site was spotty and located in small soil pockets spread throughout the site area. Less than 1% of the relevant site area was contaminated. The major contaminants encountered at the site were ^{239}Pu , ^{241}Am , normal and natural uranium, and natural thorium. During the development of the pathway analysis to determine the site cleanup criteria, corrections for the inhomogeneity of the contamination was made. These correction factors and their effect upon the relevant pathway parameters are presented.

Major pathways by which radioactive material may reach an individual are identified and patterns of use are specified (scenario). Each pathway is modeled to estimate the transfer parameters along the given pathway, such as soil to air to man, etc. The transfer parameters are then combined with dose rate conversion factors (ICRP 30 methodology) to obtain soil concentration to dose rate conversion factors (pCi/g/mrem/yr). For an appropriate choice of annual dose equivalent rate, one can then arrive at a value for the residual soil concentration. Pathway modeling, transfer parameters, and dose rate factors for the three major pathways; inhalation, ingestion and external exposure, which are important for the NBL site, are discussed.

DEVELOPMENT OF SITE-SPECIFIC SOIL CLEANUP CRITERIA:

NEW BRUNSWICK LABORATORY, NEW JERSEY SITE

1.0 History of the Site:

The New Brunswick Laboratory, New Jersey (NBL-NJ) was comprised of a large main building, a plutonium laboratory complex, a hot-cell building, and nine ancillary structures on a 2.3 hectares (5.6 acres) site. The total floor area of the buildings was approximately 4100 m². The Laboratory was operated for the Department of Energy (DOE) and its predecessors from 1948 to 1977 as a general nuclear chemistry facility. Though one of its main functions was preparation of standards for performing assay of nuclear materials used on the Atomic Energy Commission (AEC) Reactor and Weapons Program, it also was involved in pilot-plant thorium extraction and UF₄ production. The lay-out of the buildings on the site prior to Decontamination and Decommissioning L&D is shown in Figure 1.

Because of the mission of the NBL-NJ, it was known that work was done with thorium and uranium ores, high purity plutonium, and uranium enriched in ²³³U and ²³⁵U. It was also known that there were periodic contamination incidents during the 29 years of operation and that contaminated liquid waste was discharged into the sanitary waste system in accordance with the then applicable AEC concentration guides.

In 1960 approximately 500 m³ of soil contaminated with Belgian Congo pitchblende was moved from the Middlesex, New Jersey, town dump to the NBL-NJ Site. This contaminated soil was mixed with some clean soil and used as fill (about 3100m³ total) in an unused railroad spur.

LEGEND

- A. HOT CELL
- B. PLUTONIUM LAB. (ADDITION)
- C. PLUTONIUM LAB. (EXISTING)
- D. SOLVENT STORAGE
- E. MISCELLANEOUS STORAGE
- F. MISCELLANEOUS STORAGE
- G. MISCELLANEOUS STORAGE
- H. MAINTENANCE
- I. MAIN LABORATORY
- J. STORAGE SHED
- K. COOLING TOWER
- L. GARAGE
- M. CHILLER BUILDING
- N. PARKING AREA

Fig. 1. New Brunswick Laboratory Prior to D&D
ANL-HP Dwg. No. 81-24

A preliminary decontamination of the Laboratory facilities was undertaken by a private contractor in 1978 with intentions of being able to release the property for unrestricted use. The preliminary decontamination involved removal of contaminated equipment, including exposed plumbing, benchtops and hoods. Contaminated portions of walls, floors, ceilings and plutonium waste hold-up tanks were also removed.

Following the preliminary decontamination of the Laboratory, radioactive contamination was detected in the plaster and foundation. As a consequence, it was decided that it would not be cost-effective to further decontaminate the structures for unrestricted use. The structures would instead be dismantled. A radiological characterization, done in late 1978 by Argonne National Laboratory, detected residual surface contamination up to a few thousand dis/min-cm² of uranium, thorium and americium, and trace amounts of cesium, strontium, radium and yttrium in several buildings. The characterization also indicated that the onsite sanitary sewer system was contaminated with low-levels of plutonium and americium. In addition, a loading dock associated with the main Laboratory (Building I, see Figure 1), as well as some roadway areas, were contaminated.

In 1980 an extensive direct radiation survey of the entire site, and analysis of surface soils and borings were done to determine the extent of soil contamination. In addition to the pitchblende area, some other areas were found contaminated (R. A. Wynveen, et al 1981).

Since the onsite sewer system was found to have been contaminated, it was decided to remove the sewer lines during the D&D effort and treat all of them as contaminated. This appeared to be the cost-effective approach. It was recognized that the soil under the sewer lines and probably the soil adjacent to the sewer lines may have been contaminated due to leaks in the sewer system.

As the concrete pad of the I building was removed, the surface soil under the pad was systematically surveyed. The sanitary sewer pipes were removed in an orderly manner, one section after the other, and the soil under the pipes and adjacent to the pipe lines were surveyed. In addition, a large number of soil samples were taken and analyzed for radioactive contamination. For every 30 foot section of the pipe trenches remaining after the pipe removal, a composite soil sample was obtained and analyzed. Based upon the results obtained from the soil samples taken under the sewer lines, it was estimated that the contaminated area of concern under the I pad represented not more than 1% of the total area of the I pad. The remainder of the NBL-NJ site-area, exclusive of the pitchblende contaminated region, was generally found to be a smaller percentage of contaminated area than was the case for the I pad. The only other region of the site which approached 1% of total area for the contaminated region was the area north of dashed line (345') in Figure 2. This area was conservatively estimated to be contaminated to the extent that about 1% of its total area was assumed to contain some measurable contamination. The limited areal extent of soil contamination became an important consideration when developing soil cleanup criteria.

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Fig. 2. Locations of Removed Sewer Lines and
Area Used for Pathway Analysis

2.0 Scenario for Pathway Analysis:

The radionuclide releases from contaminated soil and the subsequent human exposure determine the radiation dose of concern along with its potential consequent health effects. The projected future use of the site, therefore, becomes important. In order to carry out a "realistic" pathway analysis, the long-term patterns of use must be specified. Once the site is released for unrestricted use, it is difficult to predict the future human use of the site; viz: industrial, commercial, residential or agricultural. While these may be the potential near term patterns of use, radically different future patterns of use might emerge. Nevertheless, considering the potential near term patterns of site activity, credible "scenarios" can be constructed from which a worst case "scenario," for the purposes of pathway analysis, can be chosen. The worst case scenario for the future pattern of use must lead to the maximum individual dose.

A number of proposed "scenarios" were considered for the NBL-NJ site. Such scenarios have been used in recent studies (Murphy and Holter 1980, Lester et al 1981, Wiley 1981, U.S.N.R.C. 1982, Oztunali et al 1981). The "scenario" which was selected can be referred to as the 'Construction-Agriculture' (CA) scenario. It should be noted that current human activities neighboring the NBL-NJ site, which is located in an urban industrial area, make the scenario somewhat improbable, but certainly not impossible. The CA scenario is conservative and provides the largest individual dose from the relevant pathways. This scenario assumes that a family, unaware of any residual contamination, acquires the site, builds a dwelling on it, and raises most of its

food on the site. It is further assumed in this scenario that the residual waste is unprotected by soil cover and that the primary source of water is from a well on the site.

One is reminded that the development of soil cleanup guidelines, as presented in this document, is restricted to the soil under the former I building and other site areas, but does not address the known pitchblende contamination elsewhere on the site (see Figure 2). The pitchblende contamination was not a part of the current decommissioning project and will be addressed some time in the future.

3.0 Pathways of Exposure

The pathways of exposure considered under the CA scenario are (a) inhalation of dust, (b) ingestion of plants, meat and water and (c) external radiation from the contaminated soil. The other pathways of exposure such as immersion in air, in water, from a contaminated surface, ingestion of fish, milk and soil (pica) were considered. Their contributions to the dose turned out to be negligible (H. J. Moe, et al Soil-Cleanup Criteria, NBL-NJ Site: to be published).

3.1 Inhalation Pathway

The transfer of radioactivity from the contaminated soil to the human through the inhalation pathway occurs when dust is generated at the site due to human activities or due to natural phenomena. To assess the doses due to

inhalation of contaminated dust, the concentration of the contaminated dust in the atmosphere is estimated.

3.1.1 Methods of Estimation of Contaminated Dust Concentrations

There are, in general, three approaches which have been used to estimate the dust concentration due to human activities (Oztunali et al 1981, Gilbert et al 1983, Anspaugh 1974, Healy and Fuquay 1959, Healy 1974, Slinn 1974, Shinn et al 1974). They are:

- (a) the resuspension factor method,
- (b) the resuspension rate method and
- (c) the mass loading method.

The resuspension factor method and the resuspension rate method are not independent. They both require data on the surface-dependent mechanisms by which resuspension occurs. These factors are generally very poorly known or unavailable (Gilbert et al 1983). In contrast, the mass loading method, in which the mass loading is the concentration of dust particles in air, can be obtained from empirical data from similar site locations and under similar conditions. The EPA (U. S. EPA, 1977) uses the mass loading approach in deriving the screening level for transuranic elements in the general environment. The same approach is used in estimating the concentrations of radio-nuclides in the dust that would become airborne at NBL-NJ site.

The average ambient concentrations of dust particles range from ~30 to ~250 $\mu\text{g}/\text{m}^3$ in urban locations and from ~10 to ~80 $\mu\text{g}/\text{m}^3$ in non-urban locations (Health and Rodgers 1979). It is also known that plowing and cultivation can produce large local fluctuations in dust loading. Estimates of mass loading for various dust generating activities are ~600 $\mu\text{g}/\text{m}^3$ for construction and ~300 $\mu\text{g}/\text{m}^3$ for dust generated due to agricultural activities. Even higher values, up to 1.3 g/m^3 , have been estimated using very conservative assumptions (Oztunali et al 1981). In order to account for short periods of high mass loading along with sustained periods of normal farmyard activities, for which the dust level may be higher than ambient levels, a massloading value of 300 $\mu\text{g}/\text{m}^3$ was chosen for this analysis. This is more conservative than the value of 100 $\mu\text{g}/\text{m}^3$ used by other investigators (Anspaugh et al 1974, 1975; Healy and Rodgers 1979, EPA 1977). In addition, one notes that not all the transportable dust is respirable and that the radioactivity is not homogeneously distributed on all sizes of the dust particles. In our analysis, it is assumed that only 30% of the airborne dust is respirable (EPA 1977) and that the radioactivity is homogeneously distributed on all sizes of the soil particles.

3.1.2 Soil-Air-Human Transfer Parameter

The generic models found in the literature for this segment of the pathway analysis assume that an entire site is uniformly contaminated (see EPA 1977, Gilbert et al 1983) and is usually of infinite extent. Neither of these assumptions is valid for the case of NBL-NJ Site. The site area under consideration is finite and the contamination in the soil under the I pad is

known to be spotty. The areal extent of the contamination is estimated to be approximately 1% of the entire area under consideration, as previously stated. A multiplication factor of 0.01 has, therefore, been used in the calculation which follows, to correct for the estimated contaminated area. That is, the contaminated dust represents only 1% of the total dust loading. In addition, the respirable fraction was assumed to be 30%, as stated above.

The ratio, R, of radioactive concentration in resuspended dust to the radioactive concentration of the same radionuclide in soil at NBL-NJ Site is, given by

$$R = [\text{Mass loading}] \cdot [\text{respirable fraction}] \cdot [\text{area correction factor}] \quad (1)$$

$$= 3 \times 10^{-4} \left(\frac{\text{pCi/m}^3}{\text{pCi/g}} \right) (0.3) (0.01) = 9.0 \times 10^{-7} \left(\frac{\text{pCi}}{\text{m}^3} / \frac{\text{pCi}}{\text{g}} \right)$$

This value was applied to all identified radionuclides of concern at the site. A breathing rate of 23 m³/day (ICRP-23, 1974) is assumed. The soil-air-human transfer factor, I_{SAH}, is, thus, given by

$$I_{\text{SAH}} = 9.0 \times 10^{-7} \left(\frac{\text{pCi/m}^3}{\text{pCi/g}} \right) 23 \left(\text{m}^3/\text{day} \right) = 2.1 \times 10^{-5} \left(\frac{\text{pCi}}{\text{day}} / \frac{\text{pCi}}{\text{g}} \right) \quad (2)$$

3.2 Ingestion Pathway

The transfer of nuclides to humans from the soil can take place via several routes, such as soil to plant to human, soil to forage to animal to

human, soil to groundwater to human, etc. Site specific transfer fractions or transfer coefficients for these routes are not available. One notes that this is not a unique situation; in general, these transfer fractions for any site are poorly known quantities and rarely are available unless specific studies have been accomplished for a given site. Compiled values available in the literature (Boone et al 1981, Ng 1982, Peterson 1983) are a mixture of calculated and empirically determined numbers, which vary over a wide range. These coefficients are dependent on agricultural species, soil character, agricultural practices and chemical characteristics of radionuclide compounds. Of the available coefficients, instead of choosing nominal (NRC 1977) or median values, the highest and the lowest of the coefficient values listed (Ng 1982, Boone et al 1981) were used to determine the range of numbers.

The intake transfer parameters required for the evaluation of the ingestion pathways relevant to the NBL-NJ Site situation are soil-plant-human, soil-forage-animal-human and soil-groundwater-human. The various transfer coefficients which were used in determining the intake transfer parameters are defined and tabulated in Table 1. The animal and human ingestion rates are given in Table 2. The intake transfer parameters shown in Table 3 have the units of adult intake rate (pCi/day) per (pCi/g) soil concentration. One also notes that Table 3 provides external exposure parameters.

In the succeeding sections, dose rate† factors [(mrem/yr)/(pCi/day)] are calculated using ICRP-30 methodology (ICRP-30, 1979, 1981, 1982). Combining the intake transfer parameters (Table 3) with the dose rate factors (Table 4), one can compute the soil concentrations which relate to a given annual dose rate.

Sections 3.2.1 through 3.2.4 which follow demonstrate the calculation of intake transfer parameters listed in Table 3.

† The term dose rate is used throughout to mean dose equivalent rate.

TABLE 1
RANGES OF TRANSFER COEFFICIENTS[†]

Transfer Coefficient Symbol	²³⁹ Pu	Radionuclides ²⁴¹ Am	²³⁸ U	²³² Th
f _{SP}	1.5x10 ⁻³ - 6x10 ⁻³	1.0x10 ⁻³ - 4x10 ⁻²	9.0x10 ⁻⁵ - 1.1x10 ⁻³	9.0x10 ⁻³ - 1.1x10 ⁻³
f _{EH}	10 ⁻²	10 ⁻² - 3.0x10 ⁻²	10 ⁻² - 3.0x10 ⁻²	10 ⁻² - 3.0x10 ⁻²
f _P	0.25 - 1.0	0.2 - 1.0	0.2 - 1.0	0.2 - 1.0
f _{SF}	10 ⁻³	2.0x10 ⁻³	9.0x10 ⁻⁵ - 1.1x10 ⁻³	9.0x10 ⁻⁵ - 1.1x10 ⁻³
f _{EA}	1	1	1	1
f _{IA}	10 ⁻⁶ - 3.3x10 ⁻⁵	3.6x10 ⁻⁶ - 3.9x10 ⁻³	3.0x10 ⁻⁶ - 3.9x10 ⁻³	3.0x10 ⁻⁶ - 3.9x10 ⁻³

f_{SP}: soil-plant transfer coefficient: $\frac{\text{pCi/g-plant}}{\text{pCi/g-soil}}$

f_{EH}: human edible fraction of plant

f_P: fraction of activity remaining on the edible portion of the plant

f_{SF}: soil-forage transfer coefficient: $\frac{\text{pCi/g-forage}}{\text{pCi/g-soil}}$

f_{EA}: animal edible fraction of forage

f_O: occupancy factor: 0.75
f_S: shielding factor: 0.70 from NRC Reg Guide 1.109 (1977)

f_{IA}: fraction of nuclide ingested daily by the animal that is transferred to a kilogram of forage: day/kg

†: taken from Ng 1983 and Boone et al 1981 unless specified.

TABLE 2
ANIMAL AND HUMAN INGESTION RATES[†]

P_{IH}	Intake rate of plants by humans (g/day):	600 g/day
F_{IA} :	Forage consumption rate by animal (kg/day):	50 kg-wet/day.
A_{IH} :	Average human meat consumption rate (g/day):	300 g/day.
W_{IH} :	Water consumption rate by humans (l/day):	1.65 l/day*

[†]taken from, or averages calculated from, Boone et al 1981.

*From ICRP-23 (1977).

TABLE 3

PATHWAY INTAKE TRANSFER PARAMETER RANGES FOR NBL-NJ SITE

Pathway	Symbol	Units	Radionuclides				Remarks
			Pu	Am	U	Th	
Soil-Air-Human	I_{SAH}	$\frac{\text{pCi/day}}{\text{pCi/g-soil}}$	2.1×10^{-5}	2.1×10^{-5}	2.1×10^{-5}	2.1×10^{-5}	See text for calculation
Soil-Plant-Human	I_{SPH}	$\frac{\text{pCi/day}}{\text{pCi/g-soil}}$	2.3×10^{-5} 3.6×10^{-4}	1.2×10^{-5} 7.2×10^{-3}	1.1×10^{-6} 2.0×10^{-4}	1.1×10^{-6} 2.0×10^{-4}	Same coefficients are used for U and Th.
Soil-Forage-Animal-Human	I_{SFAH}	$\frac{\text{pCi/day}}{\text{pCi/g-soil}}$	1.5×10^{-7} 5.0×10^{-6}	1.1×10^{-6} 1.2×10^{-3}	4.1×10^{-8} 6.4×10^{-4}	4.1×10^{-8} 6.4×10^{-4}	
Soil-Groundwater-Human	I_{SWH}	$\frac{\text{pCi/day}}{\text{pCi/g-soil}}$	2.6×10^{-5} 1.1×10^{-3}	2.6×10^{-5} 1.1×10^{-3}	2.6×10^{-5} 1.1×10^{-3}	2.6×10^{-5} 1.1×10^{-3}	
External Exposure Parameters	F_E	-	5.25×10^{-2}	5.25×10^{-2}	5.25×10^{-2}	5.25×10^{-2}	

TABLE 4
DOSE RATE CONVERSION FACTORS

Radionuclide	Organ/Symbol	Inhalation [†] Pathway	Ingestion [†] Pathway	External Exposure ^{††} Pathway
Pu	Bone surface P_{BS}	7.96×10^{-4}	3.68	8.33×10^5
	Lung P_L	2.40×10^{-3}	4.16×10^8	2.22×10^6
	Total Body P_{TB}	8.58×10^{-3}	4.99×10^1	5.65×10^5
Am	P_{BS}	2.90×10^{-4}	6.97×10^{-2}	8.93×10^1
	P_L	4.08×10^{-2}	4.84×10^4	2.21×10^2
	P_{TB}	5.44×10^{-3}	1.33	1.53×10^2
Normal U	P_{BS}	3.3×10^{-1}	8.44	1.73×10^1
	P_L	1.28×10^{-3}	4.26×10^3	2.32×10^1
	P_{TB}	1.06×10^{-2}	2.71×10^1	2.12×10^1
Natural U	P_{BS}	2.35×10^{-2}	6.15×10^{-1}	1.95×10^{-1}
	P_L	3.09×10^{-4}	9.08×10^2	2.33×10^{-1}
	P_{TB}	2.57×10^{-3}	7.60	2.21×10^{-1}
Natural Th	P_{BS}	1.16×10^{-4}	2.75×10^{-2}	1.21×10^{-1}
	P_L	4.80×10^{-4}	3.78	1.07×10^{-1}
	P_{TB}	1.72×10^{-3}	6.62×10^{-1}	1.36×10^{-1}

[†] in units of $\frac{\text{pCi/day}}{\text{mrem/yr}}$

^{††} in units of $\frac{\text{pCi/g-soil}}{\text{mrem/yr}}$

3.2.1 Soil-Plant-Human Transfer Parameter

For a given concentration $\frac{(\text{pCi})}{(\text{g-soil})}$ of a radionuclide in the soil, a certain amount $\frac{(\text{pCi})}{(\text{g-plant})}$ will transfer via the root uptake to the plants which are grown in that soil. The ratio, f_{SP} , will be the fraction of the radionuclide transferred to the plant. For most plants which are consumed by humans, only a portion of the plant is edible. The edible fraction of the plant is designated as f_{EH} . In addition, many plants may be processed before they are consumed. The fraction of activity remaining in the edible portion of the plant is given by f_P . The adult intake rate of plants is designated by P_{IH} (g/day). These factors are combined to yield the Soil-Plant-Human intake transfer parameter, I'_{SPH} :

$$I'_{SPH} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} = f_{SP} f_{EH} f_P P_{IH} \quad (3)$$

As an example, using the high values shown in Table 1, for ^{241}Am , the maximum value of I'_{SPH} is given by

$$\begin{aligned} I'_{SPH} &= 4 \times 10^{-2} \frac{(\text{pCi/g-plant})}{(\text{pCi/g-Soil})} \times 3 \times 10^{-2} \times 1 \times 600 \frac{\text{g-plant}}{\text{day}} \\ &= 7.2 \times 10^{-1} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} \end{aligned} \quad (4)$$

For this analysis, we must also apply the contaminated areal correction factor, 0.01.

This then gives

$$I_{SPH} = (0.01) (I'_{SPH}) = 7.2 \times 10^{-3} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} \quad (5)$$

Using the low values shown in Table 1 for the transfer coefficients for ^{241}Am , the minimum value of I_{SPH} is also calculated. Similar calculations are performed to evaluate the minimum and maximum values of intake transfer parameters for all the radionuclides of concern. The results of these calculations are shown in Table 3.

3.2.2 Soil-Forage-Animal-Human Intake Transfer Parameter

For a given concentration $\left(\frac{\text{pCi}}{\text{g-soil}} \right)$ of a radionuclide in the soil, a certain amount $\left(\frac{\text{pCi}}{\text{g-forage}} \right)$ will transfer to the forage which is grown in that soil. The ratio, f_{SF} , will be the fraction of the radionuclide transferred to the forage. For most forages which are consumed by animals, only a portion of the forage is edible. The edible fraction of the forage is designated as f_{EA} . Usually, some part of the feed to the animal is not grown on the site, but in our study, it is conservatively assumed that all the feed is in forage form and is grown at the site. The forage consumption rate by the animal is denoted by $F_{\text{IA}} \left(\frac{\text{kg}}{\text{day}} \right)$. The fraction of the nuclide ingested daily by the livestock that is transferred to a kilogram of forage (day/kg) is given by f_{IA} . The average human ingestion rate of meat by humans is designated by A_{IH} . These factors are combined to yield the Soil-Forage-Animal-Human intake transfer parameter, I'_{SFAH} :

$$I'_{\text{SFAH}} \left(\frac{\text{pCi/day}}{\text{pCi/g-soil}} \right) = f_{\text{SF}} f_{\text{EA}} F_{\text{IA}} f_{\text{IA}} A_{\text{IH}} \quad (6)$$

As an example, using the high values shown in Table 1 for ^{241}Am , the maximum

value of I'_{SFAH} is found to be

$$\begin{aligned} I'_{\text{SFAH}} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} &= 2 \times 10^{-3} \times 1 \times 50 \times 3.9 \times 10^{-3} \times 300 \\ &= 1.2 \times 10^{-1} \left(\frac{\text{pCi/day}}{\text{pCi/g-soil}} \right) \end{aligned} \quad (7)$$

For this analysis, we must again apply the contaminated areal correction factor, 0.01.

This gives

$$I_{\text{SFAH}} = (0.01) (I'_{\text{SFAH}}) = 1.2 \times 10^{-3} \left(\frac{\text{pci/day}}{\text{pCi/g-soil}} \right), \quad (8)$$

the site specific intake transfer parameter. Using the low values shown in Table 1 for ^{241}Am , the minimum value of I_{SFAH} is also calculated. Similar calculations are performed to evaluate the minimum and maximum values of intake transfer parameters for all the radionuclides of concern. The results of these calculations are shown in Table 3.

3.2.3 Soil-Groundwater-Human Intake Transfer Parameter

The contamination levels in groundwater due to radioactive material contamination in the soil are dependent on the geology and hydrology of the NBL-NJ site. The geologic and hydrologic parameters of the site were not available for this analysis. Consequently, no attempt was made to apply any sophisticated groundwater transport models (see for example: Anderson 1979, Codell and Schreiber 1979, Faust and Mercer 1980, Gray 1976, Lewis and Goldstein 1982, Pinder and Gray 1977, Prickett and Lonquist 1971, Robertson 1974, Trescott et al 1976, Yeh and Tsai 1976, Yeh 1981; for more on models and references see Low-Level Radioactive Waste Management Handbook Series, DOE/LLW-13Tg, 1983 and Radiological Assessment U.S.N.R.C. 1983).

Utilizing empirical data (Oztunali, et al 1981) collected at the Maxey Flats and West Valley Waste Sites, a range of values for the ratio of leachate to radioactive waste under highly conservative conditions was obtained. The range of values was considered in estimating the fraction of contamination transferred from the contaminated soil to the groundwater. It is recognized that this approach ignores the transfer times, which are usually large for the isotopes of concern at the NBL-NJ Site, the retardation, the dilution and the vertical and lateral diffusion effects. In order to account for expected dilution an arbitrary, but seemingly "conservative" correction factor of 0.01 was applied to these values. Applying this correction factor, the adjusted range of values then becomes $\sim 4 \times 10^{-5}$ to $\sim 1 \times 10^{-6} \frac{(\text{pCi/L-leachate})}{(\text{pCi/L-waste})}$.

This range of values was applied to all the radionuclides of interest in this analysis. Assuming a density of 1.6g/cc for the waste the range of values will become

$$6.4 \cdot 10^{-2} \frac{(\text{pCi/L})}{(\text{pCi/g-soil})} \text{ to } 1.6 \times 10^{-3} \frac{(\text{pCi/L})}{(\text{pCi/g-soil})}$$

For an assumed intake rate of 1.65 liters of water per day by adult humans, (ICRP 1975) the maximum value for the intake transfer parameter from soil to water to humans, I'_{SWH} , is given by

$$\begin{aligned} I'_{\text{SWH}} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} &= 6.4 \times 10^{-2} \frac{(\text{pCi/L})}{(\text{pCi/g-soil})} \times 1.65 (\text{L/day}) \\ &= 1.1 \times 10^{-1} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} \end{aligned} \quad (9)$$

After applying the areal correction factor of 0.01, the maximum value for the water intake transfer parameter I_{SWH} is $I_{\text{SWH}} = I'_{\text{SWH}} (0.01)$

$$= 1.10 \times 10^{-3} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})} \quad (10)$$

Similarly the minimum value of the parameter is calculated to be

$$2.6 \times 10^{-5} \frac{(\text{pCi/day})}{(\text{pCi/g-soil})}$$

3.2.4 External Exposure Parameter

For the case of external radiation exposure due to a contaminated volume source (represented by a concentration of a radionuclide in soil), the transfer parameter obviously does not represent an intake over a given time period. In this case, exposure is received at a continuous rate during the actual time the individual remains in the radiation field. Factors which modify the total dose received in this case are the occupancy factor (f_o) and the shielding factor (f_s). Values for these factors were obtained from the Regulatory Guide 1.109 (USNRC 1977). The occupancy factor corrects for the fraction of time that the individual spends in the radiation field. The shielding factor corrects for the shielding effect provided by a structure such as a home when the individual is inside. The dosimetry model used to predict the external dose rates assumes an infinite volume source. Since the actual site consists of a few small contaminated regions which are widely separated, it is necessary to include an additional correction. Based upon the comparison of the flux density from a small contaminated volume to that from an essentially infinite volume (see External Dosimetry Section), a correction factor of 0.1 was used to correct for the case of a nonhomogeneous, finite volume source. The overall external exposure parameter is then given by

$$F_E = 0.1 f_o f_s = (0.1) (0.75)(0.7) = 5.25 \times 10^{-2}. \quad (11)$$

for all radionuclides in this analysis.

4.0 Dosimetry

The parameters developed above for the inhalation and ingestion pathways include the daily intake rate of the radionuclide via these routes. Once the radionuclide enters the body by a given pathway, the metabolic behavior of the inhaled or ingested material will determine its fate with respect to either incorporation in the various organs of the body or elimination from the body. The internal dose then, depends upon the intake, concentration and retention of material in the body, and can be conveniently treated independently of the pathway analysis. This section describes the metabolic and dosimetric models utilized to estimate the annual dose rate factors due to intake of material in the case of inhalation and ingestion, and exposure to photon radiation in the case of external exposure.

4.1 Internal Dosimetry

The approach used to compute internal dose utilizes the metabolic and dosimetric data and models contained in the ICRP 30 reports [(ICRP 1979), (ICRP (1981), (ICRP 30. Supp. (1979), (ICRP 30 Supp. B 1982))]. The metabolic model assumes that the body consists of a number of exponential compartments, that an organ may be comprised of one or more compartments, and that the retention in an organ may be expressed by a single exponential or a sum of exponential terms. Transfer of material between compartments, in most cases, assumes no feedback or recycling so that the model can be expressed as a linear chain of compartments which may be treated by systems of first order differential equations. Updated metabolic data for elements and their compounds are supplied in these reports. Physical characteristics and other

biological parameters used in the model are obtained from the "Reference Man" data (ICRP 1975). The dosimetric model assumes uniform deposition of the radionuclide in the organ, but uses different modeling of the organ dimensions from that in the previous ICRP internal dose report (ICRP 1960). Revised dosimetric models for the respiratory tract, digestive system and bone have been incorporated in the new publications, and contributions to the dose in one organ from photons emitted in nearby organs is accounted for. More recent radiation transformation data for radionuclides has been incorporated in the dosimetric data.

4.2 Inhalation Dosimetry Model

The lung model used in ICRP 30 divides the respiratory system into several regions (Figure 3). During inhalation of a contaminated atmosphere some of the intake will be immediately exhaled, some is trapped in the nasal-pharyngeal region of the lung (N-P) and swallowed, and some reaches the tracheo-bronchial tree (T-B) and pulmonary (P) regions of the lung. Considering the deposition of the standard size aerosol (1 μm), 37% is immediately exhaled and 63% initially reaches compartments (a-g) of the lung. (See Fig. 3.) Each of the compartments receives a fraction (F) of the material which is retained with a certain removal half-life T (Table 5). Depending upon the relative mobility of the material in the lung (class D, W or Y), the removal half-time and the fraction deposited for some of the compartments varies. Material which is cleared from the lung compartments goes to the body fluids or transfer compartment, the GI tract and the pulmonary lymph nodes. Some material in the body fluids is translocated to organs in the systemic system and some is excreted. A portion of the material which goes to the lymph

nodes, and some which goes through the GI tract, is routed back to the transfer compartment and on to the systemic system. The fraction of material which is transferred, and the systemic organ sites of deposition, are given by the metabolic data for the particular nuclide (see Figure 4 for a schematic representation of the ICRP 30 Pu metabolism model).

Fig. 3. Lung Model ICRP-30

Fig. 4. ICRP-30 Pu Metabolic Model. (Class Y Aerosol for Inhalation or Class Y for Ingestion.)

TABLE 5.
PARAMETERS OF THE LUNG MODEL - ICRP #30

REGION	COMPARTMENT	CLASS					
		D		W		Y	
		T	F	T	F	T	F
		(Day)		(Day)		(Day)	
N-P	a	0.01	0.5	0.01	0.1	0.01	0.01
($D_{N-P}=0.3$)	b	0.01	0.5	0.40	0.9	0.40	0.99
T-B	c	0.01	0.95	0.01	0.5	0.01	0.01
($D_{T-B}=0.08$)	d	0.2	0.05	0.2	0.5	0.2	0.99
P	e	0.5	0.8	50	0.15	500	0.05
($D_p = 0.25$)	f	n.a.	n.a.	1.0	0.4	1.0	0.40
	g	n.a.	n.a.	50	0.4	500	0.40
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1000	0.9
	j	n.a.	n.a.	n.a.	n.a.	∞	0.1

TABLE 6.

METABOLIC CONSTANTS FOR Pu - CLASS Y

$D_{N-P} = 0.3$	$\lambda_a = \lambda_c = \frac{\ln 2}{.01} d^{-1}$	$F_{GON} = \begin{matrix} 3.5 \times 10^{-4} \text{ male} \\ 1.1 \times 10^{-4} \text{ female} \end{matrix}$
$D_{T-B} = 0.08$	$\lambda_b = \frac{\ln 2}{.4} d^{-1}$	$f_1 = 1 \times 10^{-5}$
$D_P = 0.25$	$\lambda_d = \frac{\ln 2}{0.2} d^{-1}$	$\lambda_{LIV} = \frac{\ln 2}{40(365)} d^{-1}$
$a = .01 \lambda_a D_{N-P}$	$\lambda_e = \lambda_g = \lambda_h = \frac{\ln 2}{500} d^{-1}$	$\lambda_{BONE} = \frac{\ln 2}{100(365)} d^{-1}$
$b = .99 \lambda_b D_{N-P}$	$\lambda_f = \ln 2 d^{-1}$	$\lambda_{GON} = 0$
$c = .01 \lambda_c D_{T-B}$	$\lambda_i = \frac{\ln 2}{1000} d^{-1}$	$\lambda_{ST} = 24 d^{-1}$
$d = \text{includes components from F and G}$	$\lambda_{BF} = \frac{\ln 2}{0.25} d^{-1}$	$\lambda_{LLI} = 1 d^{-1}$
$e = .05 \lambda_e D_P$	$F_T = 0.1$	$\lambda_{SI} = 6 d^{-1}$
$h = 0.15 \lambda_h D_P$	$F_{LIV} = 0.45$	
$i = \text{includes component from H}$	$F_{BONE} = 0.45$	
$\lambda_B = \frac{6 f_1}{1-f_1}$		
$\lambda_{ULI} = \frac{24}{13} d^{-1} = 1.846 d^{-1}$		

For a continuous intake rate P (pCi/d), the amount $q_x(t)$ which is retained in lung compartment x is determined from

$$\frac{dq_x(t)}{dt} = P D_x F_x - (\lambda_x + \lambda_r) q_x(t), \quad (12)$$

in which D_x is the deposition fraction for the lung region (N-P, T-B or P) in which compartment x is located, F_x is the fraction of the inhaled material of the appropriate aerosol class (D, W or Y) which deposits in compartment x , λ_x is the removal rate constant for compartment x and λ_r is the radioactive transformation rate constant for the particular radionuclide. P , which is the intake rate for the inhalation pathway, is related to the transfer parameter previously developed in the Pathway Analysis Section. Solution of the above gives

$$q_x(t) = \frac{PD_x F_x}{\lambda_x + \lambda_r} \left(1 - e^{-(\lambda_x + \lambda_r)t} \right) \quad (13)$$

for the condition $q_x(0) = 0$.

The continuous intake retention function for the lung is given by the sum of the individual contributions from the compartments c through j . The ICRP respiratory dosimetry model excludes the contribution from the N-P region in determining lung dose, but includes the lymph compartment contributions.

The material present in the lung serves as the supply source for the body fluids (transfer compartment), lymph nodes and the GI tract. The contribution from a given lung compartment x , to the transfer compartment is found from

$$\frac{dq_{BF}(t)}{dt} = \lambda_x q_x(t) - (\lambda_{BF} + \lambda_r) q_{BF}(t), \quad (14)$$

which is similar in form to the differential equation above. Because of the chain nature of the model, a recursive relationship exists which may be applied to succeeding differential equations to aid in the solution. The solution of the above equation yields terms of the form

$$q_{BF}(t) = \frac{\lambda_x P D_x F_x}{(\lambda_x + \lambda_r)(\lambda_{BF} - \lambda_x)} \left[1 - e^{-(\lambda_x + \lambda_r)t} \right] - \frac{\lambda_x P D_x F_x}{(\lambda_{BF} + \lambda_r)(\lambda_{BF} - \lambda_x)} \left[1 - e^{-(\lambda_{BF} + \lambda_r)t} \right] \quad (15)$$

for $q_x(0) = 0$, for each of the lung compartments a, c, and e directly, b, d, f and g via the GI tract pathway, and h and i by way of the lymph node compartment. By combining terms with the same removal rate constant, the final expression, in the case of a class Y Pu aerosol, contains nine exponential terms.

The transfer compartment (body fluids) acts as the supply source for the systemic system. Referring to the schematic representation for Pu metabolism (Figure 4), one notes that bone is one of the systemic organs in which Pu will be deposited. Two new parameters, F_{BONE} and λ_{BONE} , are introduced. The solution of the differential equations gives terms of the form

$$q_{BONE}(t) = \frac{F_{BONE} \lambda_{BF} \lambda_x P D_x F_x}{(\lambda_x + \lambda_r)(\lambda_{BF} - \lambda_x)(\lambda_{BONE} - \lambda_x)} \left\{ 1 - e^{-(\lambda_x + \lambda_r)t} \right\} - \frac{F_{BONE} \lambda_{BF} \lambda_x P D_x F_x}{(\lambda_{BONE} + \lambda_r)(\lambda_{BF} - \lambda_x)(\lambda_{BONE} - \lambda_x)} \left\{ 1 - e^{-(\lambda_{BONE} + \lambda_r)t} \right\} \quad (16)$$

for each term of the body fluids retention function. By combining terms, and using the relevant parameter values for the ICRP approach, the final expression for $q_{BONE}(t)$ for ^{239}Pu for continuous inhalation of a class Y aerosol becomes:

$$\begin{aligned} \frac{q_{BONE}(t)}{P} = & 1.0279 \times 10^{-6} [1 - e^{-(\lambda_a + \lambda_r)t}] - 3.117 \times 10^{-6} [1 - e^{-(\lambda_b + \lambda_r)t}] + 7.7833 \times 10^{-7} \\ & [1 - e^{-(\lambda_d + \lambda_r)t}] + 6.99646 [1 - e^{-(\lambda_e + \lambda_r)t}] - 1.2597 \times 10^{-6} [1 - e^{-(\lambda_f + \lambda_r)t}] \\ & - 45.06179 [1 - e^{-(\lambda_i + \lambda_r)t}] + 2.937 \times 10^{-10} [1 - e^{-(\lambda_{st} + \lambda_r)t}] - 1.8128 \times 10^{-7} \\ & [1 - e^{-(\lambda_{SI} + \lambda_B + \lambda_r)t}] - 6.4052 \times 10^{-4} [1 - e^{-(\lambda_{BF} + \lambda_r)t}] + 1219.16 \\ & [1 - e^{-(\lambda_{BONE} + \lambda_r)t}], \end{aligned} \quad (17)$$

in which λ_a , λ_b , λ_d , λ_e , λ_f and λ_i refer to

the lung compartments, λ_{ST} and $\lambda_{SI} + \lambda_B$ refer to GI tract compartments, λ_{BF} to the transfer compartment and λ_{BONE} to the bone compartment.

For a long exposure period, the above expression reduces to:

$$q_{BONE}(t) \sim \left\{ -38.07 + 1219.16 [1 - e^{-(\lambda_{BONE} + \lambda_r)t}] \right\} P. \quad (18)$$

This expression may be solved for the amount, $q_{BONE}(t)$ of ^{239}Pu in bone at any time t following the onset of continuous intake at the rate of P (pCi/d). For example, for $t=50$ years, $q(50)$ will represent the activity (pCi) of ^{239}Pu present in bone at the end of 50 years of continuous intake. Since $T_{BONE}=100$ years and $T_r=2.41 \times 10^4$ years, $q(50) \sim 320.25 P$ (pCi). Since the activity in the organ, $q(t)$, is directly proportional to the organ dose rate, the intake rate P can then be determined for an appropriate choice of organ dose rate.

Expressions for the amount of activity present in the other organs of the systemic system due to deposition of ^{239}Pu following continuous intake by inhalation are developed in a similar manner.

4.2.1 Dose Equivalent Rate - Inhalation

The dose equivalent rate $\dot{H}_T$ (mrem/yr) in a target organ T , due to the activity of a radionuclide $q_S(t)$, present in a source organ S , is given by:

$$\begin{aligned} \dot{H}_T \left(\frac{\text{mrem}}{\text{yr}} \right) &= q_S(t) (\text{pCi}) 2.22 \left[\frac{\text{trans.}}{\text{m-pCi}} \right] \text{SEE}(T \leftarrow S) \left[\frac{\text{MeV}}{\text{g-trans}} \right] 1.6 \times 10^{-6} \left[\frac{\text{ergs}}{\text{MeV}} \right] \\ &\quad \frac{1}{100} \left[\frac{\text{g-rad}}{\text{erg}} \right] 10^3 \left[\frac{\text{mrem}}{\text{rem}} \right] 60 \left[\frac{\text{m}}{\text{h}} \right] 24 \left[\frac{\text{h}}{\text{d}} \right] 365 \left[\frac{\text{d}}{\text{yr}} \right] \\ &= 18.67 q_S(t) \text{SEE}(T \leftarrow S), \end{aligned} \quad (19)$$

in which $\text{SEE}(T \leftarrow S)$ is the Specific Effective Energy term, listed in the ICRP-30 Supplements. The $\text{SEE}(T \leftarrow S)$ term specifies the energy absorbed per gram in the

target (T), modified by an appropriate quality factor, due to each transformation of a radionuclide in a source organ (S). In addition to the dose rate in a target organ when that organ is both the source and the target, other nearby source organs may contribute to the dose rate to the target organ. When this is accounted for, the expression for $\dot{H}_T$ becomes:

$$\dot{H}_T \left[\frac{\text{mrem}}{\text{yr}} \right] = 18.67 \sum_i q_{S_i}(t) \text{ SEE } (T \leftarrow S_i) \quad (20)$$

Returning to our example of ^{239}Pu deposition in bone, the ICRP model for deposition distinguishes two types of bone depositors - surface and volume. For those radionuclides considered to be uniformly distributed over bone surfaces, the deposition is assumed to be equally distributed in cortical and trabecular bone. For bone volume depositors, 80% of the deposition is assumed to be in cortical bone, 20% in trabecular bone. In the bone dosimetry model, cortical and trabecular bone are considered to be the source organs. The target sites in the dosimetry model are the bone surfaces (BS) and red marrow (RM), which are the radiosensitive tissues of concern in bone. In the case of ^{239}Pu , the model assumes uniform distribution over the bone surfaces, and the deposition is considered to be equally distributed in cortical and trabecular bone.

In order to compute $\dot{H}_{BS}$ due to ^{239}Pu deposition at the end of the 50-year intake period, we must sum the contributions from all the source organs given in the metabolic model, so that the above expression for $\dot{H}_T$ becomes:

$$\begin{aligned} \dot{H}_{BS} \left[\frac{\text{mrem}}{\text{yr}} \right] = 18.67 & \left[\frac{q_{\text{BONE}}(50)}{2} \text{ SEE } (BS \leftarrow \text{CORT}) + \frac{q_{\text{BONE}}(50)}{2} \text{ SEE } (BS \leftarrow \text{TRAB}) \right. \\ & + q_{\text{LIV}}(50) \text{ SEE } (BS \leftarrow \text{LIV}) + q_{\text{LUNGS}}(50) \text{ SEE } (BS \leftarrow \text{LUNGS}) \\ & \left. + q_{\text{GON}}(50) \text{ SEE } (BS \leftarrow \text{GON}) \right] P \end{aligned} \quad (21)$$

Using the retention functions for the relevant organs in the metabolic model to find the appropriate values of $q(50)$ for liver, lung and gonads, and the dosimetric data for the Specific Effective Energy terms for ^{239}Pu (p.413 of ICRP-30, Supp. to Part 1), we construct the table below:

Source Organ	$q_s(50), \text{pCi}$	SEE(BS+S)
Cort. Bone	160.13 P	0.21
Trab. Bone	160.13 P	0.21
Liver	258 P	1×10^{-9}
Lungs	222.8 P	1.6×10^{-9}
Gonads	0.3 P	2.2×10^{-10}

Substituting these values into the expression for $\dot{H}_{BS}$, gives $\dot{H}_{BS}$ (mrem/yr) = $18.67[67.25]P = 1256 P$, and letting $\dot{H}_{BS} = 1$ mrem/yr gives P

$$= 7.96 \times 10^{-4} \frac{(\text{pCi/d})}{(\text{mrem/yr.})}$$

This value along with other dose rate conversion factors is tabulated in Table 4. Proceeding as above for all the other target organs of interest, namely red marrow, liver, lungs and gonads, values for the inhalation intake rate to dose rate conversion factors for these organs can be generated. Representative values of these factors for bone surfaces and lung are listed in Table 4. The dose rate conversion factors shown in Table 4 for the total body were obtained with the use of the ICRP 26 (ICRP 1977) weighting factors, w_T , to arrive at an effective weighted dose equivalent for the significantly exposed organs. That is

$$\dot{H}_{WB} = \sum w_T \dot{H}_T = w_{BS} \dot{H}_{BS} + w_{RM} \dot{H}_{RM} + w_{LIV} \dot{H}_{LIV} + w_{LUNG} \dot{H}_{LUNG}, \quad (22)$$

in which the weighting factor w_T for a given organ is the ratio of the stochastic risk in tissue T to the total risk for uniform whole body radiation.

This becomes:

$$\dot{H}_{WB} = 0.03 \dot{H}_{BS} + 0.12 \dot{H}_{RM} + 0.06 \dot{H}_{LIV} + 0.12 \dot{H}_{LUNG} \quad (23)$$

and when the values are substituted for the dose equivalent rates:

$$\begin{aligned}\dot{H}_{WB} &= 0.03(1265 \text{ P}) + 0.12 (101.6 \text{ P}) + 0.06 (279.4 \text{ P}) + 0.12 (416 \text{ P}) \\ &= 116.6 \text{ P, and for}\end{aligned}$$

$$\begin{aligned}\dot{H}_{WB} &= 1 \text{ mrem/yr,} \\ P &= 8.58 \times 10^{-3} \left(\frac{\text{pCi/d}}{\text{mrem/yr}} \right)\end{aligned}$$

In ICRP-26 (ICRP 1977), the Commission recommends the use of the whole body dose equivalent as a more significant index of stochastic risk than any of the individual organ doses. The effective weighted whole body dose equivalent, found by weighting the individual organ doses and summing the results, represents the same relative stochastic risk to the individual for non-uniform irradiation as that for uniform whole body irradiation. Based upon the ICRP recommendation, final values for the soil cleanup criteria were chosen on the basis of the effective weighted whole body doses. Table 4 contains the values obtained for the dose rate conversion factors for bone, lung, and whole body for intake by the inhalation pathway.

4.3 Ingestion Dosimetry Model

The ICRP-30 gastrointestinal (GI) tract model is based upon the biological model presented by I. S. Eve (Eve 1966). During ingestion, material passes through the four sections of the GI tract: stomach, small intestine, upper large intestine and lower large intestine (Fig. 5). Each section is considered to be a single compartment so that the entire system may be treated as a linear chain of first order differential equations. In general, a portion of the material is assumed to be absorbed from the small intestine to the body fluids, and this transfer is described by the rate constant λ_B . Values of λ_B are estimated from the metabolic data for f_1 , the fraction of the stable element reaching the body fluids following ingestion, from the relation:

SECTION OF G I TRACT	MASS OF WALLS (g)	MASS OF CONTENTS (g)	MEAN RESIDENCE TIME (day)	λ (day ⁻¹)
STOMACH (ST)	150	250	1/24	24
SMALL INTESTINE (SI)	640	400	4/24	6
UPPER LARGE INTESTINE (ULI)	210	220	13/24	1.8
LOWER LARGE INTESTINE (LLI)	160	135	24/24	1

Fig. 5. GI-Tract Model ICRP-30

$$\lambda_B = \frac{f_1 \lambda_{SI}}{1 - f_1} \quad (24)$$

The value of the fraction depends upon the radionuclide compound involved since absorption of material from the GI tract varies for different compounds. Material which is cleared from the small intestine goes to the transfer compartment (Fig. 5), while the remainder moves through the GI tract and is excreted in the feces. Of the material in the transfer compartment, a fraction is translocated to organs in the systemic system, as designated by the metabolic model, and the remainder is excreted.

For a continuous intake rate P (pCi/d), the amount $q_{ST}(t)$ which is retained in the stomach compartment (ST) is determined from:

$$\frac{dq_{ST}(t)}{dt} = P - (\lambda_{ST} + \lambda_r) q_{ST}(t) \quad (25)$$

and the solution, for the condition $q_{ST}(0) = 0$ is

$$q_{ST}(t) = \frac{P}{\lambda_{ST} + \lambda_r} (1 - e^{-(\lambda_{ST} + \lambda_r)t}). \quad (26)$$

Material in the stomach passes on to the small intestine (SI), where the amount at any time is determined from:

$$\frac{dq_{SI}(t)}{dt} = \lambda_{ST} q_{ST} - (\lambda_{SI} + \lambda_B + \lambda_r) q_{SI}(t) \quad (27)$$

As in the case of the differential equations for inhalation, this form yields the solution:

$$q_{SI}(t) = \frac{\lambda_{ST} P}{(\lambda_{ST} + \lambda_r)(\lambda_{SI} + \lambda_B - \lambda_{ST})} \left[1 - e^{-(\lambda_{ST} + \lambda_r)t} \right] - \frac{\lambda_{ST} P}{(\lambda_{SI} + \lambda_B + \lambda_r)(\lambda_{SI} + \lambda_B - \lambda_{ST})} \left[1 - e^{-(\lambda_{SI} + \lambda_B + \lambda_r)t} \right] \quad (28)$$

for the initial condition of $q_{SI}(0) = 0$. The recursive relationship, as was

noted previously, can then be used to develop the retention equations for the succeeding chain members. Note that the chain continues in two separate pathways (Fig. 5), a fraction going to body fluids and a fraction going on to the upper large intestine.

Once material is in the transfer compartment, it will distribute in the systemic system as shown in the metabolic model (Fig. 4). Using the relevant parameter values, the derived expression for $q_{\text{BONE}}(t)$ for continuous ingestion of ^{239}Pu , assuming Class Y material, becomes:

$$\frac{q_{\text{BONE}}(t)}{P} = -8.1633 \times 10^{-9} \left\{ 1 - e^{-\left[\lambda_{\text{ST}} + \lambda_r \right] t} \right\} + 8.5904 \times 10^{-7} \left\{ 1 - e^{-\left[\lambda_{\text{SI}} + \lambda_{\text{B}} + \lambda_r \right] t} \right\} \\ - 3.414 \times 10^{-6} \left\{ 1 - e^{-\left[\lambda_{\text{BF}} + \lambda_r \right] t} \right\} + 2.3599 \times 10^{-1} \left\{ 1 - e^{-\left[\lambda_{\text{BONE}} + \lambda_r \right] t} \right\} \quad (29)$$

Assuming a long exposure period, the above reduces to :

$$q_{\text{BONE}}(t) = \left\{ -2.56 \times 10^{-6} + 2.3599 \times 10^{-1} \left[1 - e^{-(\lambda_{\text{BONE}} + \lambda_r)t} \right] \right\} P. \quad (30)$$

Solving the above for $t = 50$ years, gives $q_{\text{BONE}}(50) = 6.94 \times 10^{-2} P$ (pCi). Similar expressions for the retention functions and the activity in the other relevant organs of the metabolic model are then developed in order to estimate $q(50)$ for these organs.

4.3.1 Dose Equivalent Rate - Ingestion

Utilizing the relationship developed in the section on the dose equivalent rate from inhalation, $\dot{H}_T$ is given by

$$\dot{H}_T \left(\frac{\text{mrem}}{\text{yr}} \right) = 18.67 \sum_i q_{\text{S}_i}(t) \text{ SEE } (T+S). \quad (31)$$

In the case of ingestion, the relevant parameter values become

Source Organ	$q_S(50)$	SEE(BS+S)
Cort. Bone	$3.47 \times 10^{-2} P$	0.21
Trab. Bone	$3.47 \times 10^{-2} P$	0.21
Liver	$5.49 \times 10^{-2} P$	1×10^{-9}
ULI	$5.42 \times 10^{-1} P$	7.3×10^{-10}
LLI	1 P	2.4×10^{-9}

Substituting these values in the above expression gives

$$\dot{H}_{BS} \left(\frac{\text{mrem}}{\text{yr}} \right) = 18.67 (1.46 \times 10^{-2}) = 2.72 \times 10^{-1} P, \text{ and setting}$$

$$\dot{H}_{BS} = 1 \text{ mrem/yr yields } P = 3.68 \left(\frac{\text{pCi/d}}{\text{mrem/yr}} \right)$$

This value is tabulated in Table 4. Following the same general procedure as used for the case of intake by inhalation, one can arrive at a value of P for the case of the effective weighted whole body exposure. Table 4 contains the values obtained for the dose rate conversion factors for bone, lung and whole body for intake by ingestion.

4.4 External Dosimetry

The approach used to compute the external dose utilized a model which initially considers the contaminated soil volume to be infinite in areal extent and of infinite depth. Contributions to the flux density at a point 1 meter above the ground surface were obtained by integration of the point kernel expression over the source volume, including a buildup correction for scattered radiation (Rockwell 1956). Recent radionuclide decay data (Kocher 1981) were used to estimate photon emissions from the various radionuclides involved. Flux density results were converted to dose rate in air and estimates of the dose equivalent rates in the relevant body organs were

obtained by the method suggested by Kocher (Kocher 1980). As indicated previously, a site specific correction factor, to account for the reduced flux density from a nonhomogeneous, finite volume source was estimated by comparing the flux density from a small contaminated volume to that from an infinite volume.

4.4.1 External Dosimetry Model

Consider a volume source as indicated in Fig. 6, the differential flux density at the point P, one meter above the ground surface, from the volume element dV in the contaminated soil source, will be given by

$$d\phi_P = \frac{S_V dV}{4\pi r^2} e^{-[b_1 + \mu_s (h-x)]} \sec \theta \quad (32)$$

in which $S_V \frac{(\text{ph})}{(\text{cc-s})}$ is the photon emission rate, $b_1 = \mu_{\text{air}} a$, and μ_s is the attenuation coefficient for the medium, soil. The expression neglects buildup, but the buildup factor, which is a function of the energy E , may be written as the sum of two exponentials:

$$B(E, \mu_s x) = A_1 e^{-\alpha_1 \mu_s x} + A_2 e^{-\alpha_2 \mu_s x} \quad (33)$$

in which $A_2 = 1 - A_1$.

This is known as Taylor's form for the buildup factor (Taylor 1954). Values for the constants A_1 , α_1 and α_2 , which are functions of the photon energy and the scattering medium, are available in the literature (ANL 1963, Schaeffer 1973, Rockwell 1956).

Including this expression for buildup due to scattered radiation, and expressing the differential volume element as $dV = 2\pi r dr dx$, gives

Fig. 6. Geometry for Volume Source of Contaminated Soil

$$\frac{d\phi}{P} = \frac{2\pi r dr dx S_V}{4\pi \rho} \left(A_1 e^{-\alpha_1 \mu_s (h-x) \sec \theta} + A_2 e^{-\alpha_2 \mu_s (h-x) \sec \theta} \right) e^{-[b_1 + \mu_s (h-x) \sec \theta]} \quad (34)$$

Combining terms, and making use of these relationships:

$\rho^2 = r^2 + [a+(h-x)]^2$; $\rho dp = r dr$, we arrive at

$$\phi_p = \frac{S_V}{2} \int_0^h dx \int_{a+(h-x)}^{\infty} \frac{dp}{\rho} \left[A_1 e^{-[b_1+(1+\alpha_1)\mu_s(h-x)]\sec\theta} + A_2 e^{-[b_1+(1+\alpha_2)\mu_s(h-x)]\sec\theta} \right] \quad (35)$$

Noting that $\rho = [a + (h-x)]\sec\theta$ and $\frac{dp}{\rho} = \tan \theta d\theta$, these can

be substituted into the above expression:

$$\phi_p = \frac{S_V}{2} \int_0^h dx \int_0^{\frac{\pi}{2}} \tan \theta d\theta \left[A_1 e^{-[b_1+(1+\alpha_1)\mu_s(h-x)]\sec\theta} + A_2 e^{-[b_1+(1+\alpha_2)\mu_s(h-x)]\sec\theta} \right] \quad (36)$$

which expresses the terms in the second integral as functions of the same variable θ . The limits of integration are for the case of infinite extent in the areal direction.

To obtain a form which allows integration, the following substitutions are made:

let $y = [b_1 + (1+\alpha_1)\mu_s(h-x)]\sec\theta$ and $y' = [b_1 + (1+\alpha_2)\mu_s(h-x)]\sec\theta$

$dy = [b_1 + (1+\alpha_1)\mu_s(h-x)]\sec\theta \tan \theta d\theta$ and $dy' = [b_1 + (1+\alpha_2)\mu_s(h-x)]\sec\theta \tan \theta d\theta$

$$\frac{dy}{y} = \tan \theta d\theta, \quad \frac{dy'}{y'} = \tan \theta d\theta \quad (37)$$

so that

$$\phi_p = \frac{S_V A_1}{2} \int_0^h dx \int_{b_1+(1+\alpha_1)\mu_s(h-x)}^{\infty} \frac{e^{-y}}{y} dy + \frac{S_V A_2}{2} \int_0^h dx \int_{b_1+(1+\alpha_2)\mu_s(h-x)}^{\infty} \frac{e^{-y'}}{y'} dy' \quad (38)$$

and since $E_1(b) \equiv \int_b^{\infty} \frac{e^{-y}}{y} dy$, the expression for ϕ_p becomes

$$\phi_p = \frac{S_V A_1}{2} \int_0^h E_1[b_1 + (1+\alpha_1)\mu_s(h-x)] dx + \frac{S_V A_2}{2} \int_0^h E_1[b_1 + (1+\alpha_2)\mu_s(h-x)] dx. \quad (39)$$

The set of functions $E_n(b)$ are called the exponential integral functions and values for $E_1(b)$ and $E_2(b)$ are plotted in Rockwell (Rockwell 1956). This function is also discussed in that reference. A further useful property of the exponential integral functions is that

$$\frac{dE_n(b)}{db} = -E_{n-1}(b). \quad (40)$$

For the remaining integrals above, we may write

$$\frac{\partial E_2(b)}{\partial x} = \frac{dE_2(b)}{db} \frac{(\partial b)}{(\partial x)} = -E_1(b) \frac{(\partial b)}{(\partial x)} \quad (41)$$

$$\begin{aligned} \text{and } \frac{\partial E_2[b_1 + (1+\alpha_1)\mu_s(h-x)]}{\partial x} &= -E_1[b_1 + (1+\alpha_1)\mu_s(h-x)] [-\mu_s(1+\alpha_1)] \\ &= (1+\alpha_1) \mu_s E_1[b_1 + (1+\alpha_1)\mu_s(h-x)], \end{aligned} \quad (42)$$

and similarly for the expression in the second integral, so that

$$\phi_p = \frac{S_V A_1}{2(1+\alpha_1)\mu_s} \int_0^h \partial E_2[b_1 + (1+\alpha_1)\mu_s(h-x)] + \frac{S_V A_2}{2(1+\alpha_2)\mu_s} \int_0^h \partial E_2[b_1 + (1+\alpha_2)\mu_s(h-x)] \quad (43)$$

which gives

$$\phi_p = \frac{S_V}{2\mu_s} \left[\frac{A_1}{1+\alpha_1} \left(E_2(b_1) - E_2[b_1 + (1+\alpha_1)\mu_s h] \right) + \frac{A_2}{1+\alpha_2} \left(E_2(b_1) - E_2[b_1 + (1+\alpha_2)\mu_s h] \right) \right] \quad (44)$$

For small distances in air, such as 1 m, $\mu_{\text{air}} \approx 0$, so that $b_1 \approx 0$ and

$E_2(0) = 1$, and

$$\phi_p = \frac{S_V}{2\mu_s} \left[\frac{A_1}{1+\alpha_1} \left(1 - E_2[(1+\alpha_1)\mu_s h] \right) + \frac{A_2}{1+\alpha_2} \left(1 - E_2[(1+\alpha_2)\mu_s h] \right) \right] \quad (45)$$

Values for μ_s , the attenuation coefficient in soil, were estimated by using the

values for SiO_2 , taken from the Radiological Health Handbook (Bur. Rad. Hlth. 1970). Values of A_1 , α_1 , and α_2 were obtained from ANL-5800, which contains values for buildup in Al. Al was chosen since its buildup closely approximates the buildup in sand (Schaeffer 1973) and should approximate buildup in soil.

Assuming the depth h is essentially infinite, which obtains for

$\mu_s h > 3$, $E_2(\infty) = 0$ and the expression reduces to

$$\phi_p = \frac{S_V}{2\mu_s} \left[\frac{A_1}{1+\alpha_1} + \frac{A_2}{1+\alpha_2} \right] \quad (46)$$

The expression in the brackets corrects for the buildup in the flux density, while $\frac{S_V}{2\mu_s}$ represents the uncollided flux density from the semi-infinite slab

source. Figure 7 is a plot of the buildup correction factor in Al as a function of photon energy. Data from this figure was used to obtain estimates of the flux density buildup in soil for this analysis, for photons >250 keV.

Now, S_V is related to the soil concentration, C_g ($\frac{\text{pCi}}{\text{g}}$), by

$$S_V \left(\frac{\text{ph}}{\text{cc-s}} \right) = C_g \left(\frac{\text{pCi}}{\text{g}} \right) \frac{1.6 \left(\frac{\text{g}}{\text{cc}} \right) 3.7 \times 10^{-2} \left(\frac{\text{trans.}}{\text{s-pCi}} \right) n_Y \left(\frac{\text{ph}}{\text{trans.}} \right)}{8} = 5.92 \times 10^{-2} n_Y C_g \quad (47)$$

in which $n_Y \left(\frac{\text{ph}}{\text{trans.}} \right)$ was obtained from DOE/TIC-11026 (Kocher 1981). Flux

density values were converted to mR/h using Fig. 8, and exposure rates in air were converted to mrem/yr in tissue, assuming the quality factor $Q = 1$, so that the final expression becomes:

$$\dot{H} \left(\frac{\text{mrem}}{\text{yr}} \right) = \frac{248 n_Y C_g}{K_\phi \mu_s} \left[\frac{A_1}{1+\alpha_1} + \frac{A_2}{1+\alpha_2} \right] \quad (48)$$

in which K_ϕ is the

Fig. 7. Buildup Factor for Semi-Infinite
Slab Source. (Values for Al from
ANL-5800.)

Fig. 8. Flux Density for 1 mR/h

factor which converts flux density to mR/h. This expression gives the dose equivalent rate to a small mass of tissue in air. It is necessary to relate this dose, which is similar to the photon dose at the body surface, to the dose delivered to individual organs, when an individual is exposed at the same point. Using the correction suggested by Kocher (Kocher 1980), and the values in his tables, the ratios, for the photon dose rate at the body surface to that of the relevant organs, were found. These ratios were then used to correct the computed dose equivalent rate given above to obtain estimates of the dose equivalent rates to individual organs.

In the case of ^{239}Pu , for example, the nuclide data lists only weak photon emissions. The average for 173 different photon energies is given as 113 keV and n_γ is 5×10^{-4} . Using the average energy value, $\mu_s = 0.37 \text{ cm}^{-1}$ and $K_\phi = 5.6 \times 10^3 \frac{(\text{ph/cm}^2\text{-s})}{(\text{mR/h})}$, and neglecting buildup for this case of low energy photons, $\dot{H} \frac{(\text{mrem})}{(\text{yr})}$ is given by

$$\dot{H} \frac{(\text{mrem})}{(\text{yr})} = \frac{248 (5 \times 10^{-4}) \text{ Cg}}{5.6 \times 10^3 (.37)} (1) = 5.98 \times 10^{-5} \text{ Cg} \sim 6 \times 10^{-5} \text{ Cg}. \quad (49)$$

The ratio of the photon dose to bone surfaces to the photon dose at the body surface from ^{239}Pu , obtained from data in the tables of Kocher (Kocher 1980), is 0.02. Then,

$$\dot{H}_{\text{BS}} = 0.02 (6 \times 10^{-5} \text{ Cg}) = 1.2 \times 10^{-6} \text{ Cg} \text{ and setting } \dot{H}_{\text{BS}} = 1 \frac{\text{mrem}}{\text{yr}}$$

gives $\text{Cg} = 8.33 \times 10^5 \frac{(\text{pCi/g})}{(\text{mrem/yr})}$, which is the value listed in Table 4.

The factors in Table 4 for inhalation, ingestion and external exposure were

developed for the radionuclides specific to the NBL-NJ Site. The dose rate factors for natural uranium and natural thorium include contributions from all the radionuclides in the chain, i.e., 15 in the uranium chain and 10 in the thorium chain, since characterization measurements at the site indicated the presence of these chains as contaminants. In addition, processed uranium (normal uranium) was identified - this is uranium from which the daughter products below ^{234}U have been removed.

4.5 Site Specific Correction Factor

For the NBL-NJ Site, the contamination was found to consist of a few small contaminated regions which are widely separated. Assuming a semi-infinite slab source greatly overestimates the actual flux density at the dose point and thus the computed values should be corrected. Returning to the expression for the flux density from the semi-infinite slab source,

$$\phi_p = \frac{S_v}{2\mu_s} \left[\frac{A_1}{1+\alpha_1} + \frac{A_1}{1+\alpha_2} \right], \text{ the flux density value does not}$$

change greatly with photon energy, in the range 0.25 - 2 MeV, which is the range of interest at the NBL-NJ Site. For this reason, a nominal 1 MeV gamma emitter was assumed to be representative of the photons emitted at the site for the purpose of comparing finite-sized sources to the infinite source result.

In the case of a finite source, using the same geometry as in Fig. 6, the flux density expression is

$$\phi_p = \frac{S_v}{2} \int_0^h dx \int_0^\theta \tan \theta \, d\theta \left[A_1 e^{-[b_1 + (1+\alpha_1)\mu_s(h-x)] \sec \theta} + A_2 e^{-[b_1 + (1+\alpha_2)\mu_s(h-x)] \sec \theta} \right] \quad (50)$$

Using the same methodology as before, the final expression becomes

$$\begin{aligned} \Phi_P = \frac{S_V}{2\mu_S} \left(\frac{A_1}{1+\alpha_1} \right) & \left[E_2(b_1) - \frac{E_2(b_1 \sec \theta)}{\sec \theta} - E_2[b_1 + \alpha_1) \mu_S h] \right. \\ & \left. + \frac{E_2([b_1 + (1+\alpha_1) \mu_S h] \sec \theta)}{\sec \theta} \right] \\ + \frac{S_V}{2\mu_S} \left(\frac{A_2}{1+\alpha_2} \right) & \left[E_2(b_1) - \frac{E_2(b_1 \sec \theta)}{\sec \theta} - E_2[b_1 + (1+\alpha_2) \mu_S h] \right. \\ & \left. + \frac{E_2([b_1 + (1+\alpha_2) \mu_S h] \sec \theta)}{\sec \theta} \right] \end{aligned} \quad (51)$$

For the assumption $\mu_S h > 3$; that is, the depth of the contaminated spot is essentially infinite, the expression simplifies to

$$\begin{aligned} \Phi_P & \cong \frac{S_V}{2\mu_S} \left[\frac{A_1}{1+\alpha_1} + \frac{A_2}{1+\alpha_2} \right] \left[E_2(b_1) - \frac{E_2(b_1 \sec \theta)}{\sec \theta} \right] \\ & \cong \Phi_{P_{INF}} \left[E_2(b_1) - \frac{E_2(b_1 \sec \theta)}{\sec \theta} \right] \end{aligned} \quad (52)$$

Assuming a 1 MeV γ emitter, $\mu_S = 0.147 \text{ cm}^{-1}$, $\mu_{air} = 8.2 \times 10^{-5} \text{ cm}^{-1}$,

$\mu_{air} a = b_1 = 0.0082$ and $E_2(0.0082) = .96$, Φ_P becomes

$$\Phi_P \cong \Phi_{P_{INF}} \left[0.96 - \frac{E_2(0.0082 \sec \theta)}{\sec \theta} \right] \quad (53)$$

By substituting values for θ , the expression can be solved for the fraction of $\Phi_{P_{INF}}$ contributed by finite sources. A plot of this expression versus angle θ

is shown in Fig. 9. From the figure, when $\theta \sim 80^\circ$, $\Phi_P \sim 81\%$ of $\Phi_{P_{INF}}$ and the

source can be considered essentially infinite. For $\theta = 80^\circ$, $\tan 80^\circ =$

5.6 and r would be $\sim 5.6\text{m}$. For this radius,

$$\text{Area} = \pi r^2 = \pi (5.6)^2 = 31.4 \pi \text{ (m}^2\text{)} \sim 100 \text{ m}^2$$

If only 1% of the area is contaminated, then

$$\text{Area}_{\text{CONT.}} = 0.01 (31.4 \pi) = .31 \pi = \pi r_1^2 \text{ (m}^2\text{)}$$

$$r_1^2 = .31 \text{ m}^2$$

$$r_1 = 0.56\text{m}$$

For a contaminated spot of radius 0.56m, $\tan \theta = 0.56$ and $\theta = 29.2^\circ$. For this value of θ , Fig. 9 indicates that the fraction of the infinite flux density delivered from the finite source is ~ 0.1 . This is the basis of applying a correction factor of 0.1 in the case of external exposure computations. Since none of the contaminated spots at NBL had a depth of contamination which could be considered infinite, the factor appears to be properly conservative.

Fig. 9. Flux Density for a Finite Volume Source

5.0 Soil Cleanup Criteria

By combining the information in Tables 3 and 4, the factors in Table 7 were generated. For the inhalation pathway, the appropriate dose rate conversion factors for the specified organ were divided by I_{SAH} from Table 3 to arrive at the Table 7 Inhalation values. For the ingestion pathway, the dose rate conversion factors were divided by the sum of I_{SPH} , I_{SFAH} and I_{SWH} to get the Table 7 Ingestion values. Finally, the external dose conversion factors in Table 4 were divided by F_E in order to obtain the values listed under External Exposure in Table 7.

The factors in Table 7 give the soil concentration in the contaminated regions which would result in 1 mrem/yr to the stated organ for the particular pathway, if that were the only path which contributes to the dose rate. Since all three pathways contribute to the dose rate, the total dose equivalent rate, $\dot{H}_{WB}$, to the whole body for a given concentration C_g (pCi/g) in the contaminated region, was found from

$$\dot{H}_{WB} = \frac{C_g}{(\text{pCi/g/mrem/yr})_{INH}} + \frac{C_g}{(\text{pCi/g/mrem/yr})_{ING}} + \frac{C_g}{(\text{pCi/g/mrem/yr})_{EXT}} \quad (54)$$

Table 8 contains values for the soil concentration, C_g , of a given radionuclide in an isolated, contaminated region of the NBL site which would produce a composite annual dose equivalent rate of 10 or 170 mrem/yr to the total body. By referring to the Table 7 values, it can be seen that the dose equivalent rate contributed by external exposure exerts the greatest influence on the Table 8 values for natural U and natural Th.

TABLE 7

SOIL CONCENTRATION TO DOSE RATE CONVERSION FACTORS
pCi/g for 1 mrem/yr to the stated organ

	INHALATION			INGESTION			EXTERNAL EXPOSURE		
	Total Body	Lung	Bone Surface	Total Body	Lung	Bone Surface	Total Body	Lung	Bone Surface
^{239}Pu	408	114	38	3.41×10^4	2.84×10^{11}	2.51×10^3	1.08×10^7	4.23×10^7	1.59×10^6
^{241}Am	259	1.94×10^3	14	1.40×10^2	5.09×10^6	7.30	2.9×10^3	4.21×10^3	1.70×10^3
Normal U	505	61	1.57×10^4	1.40×10^4	2.20×10^6	4.50×10^3	404	442	330
Natural U*	122	15	1.12×10^3	3.92×10^3	4.68×10^5	317	4.2	4.4	3.7
Natural Th*	82	23	6	341	1.95×10^3	14.2	2.6	2	2.3

*Natural U and Natural Th are considered to be ^{238}U in equilibrium with all its daughter products and ^{232}Th in equilibrium with all its daughter products, respectively. Normal U is considered to be ^{238}U in equilibrium with its daughter products down to and including ^{234}U .

TABLE 8

SOIL CONCENTRATIONS FOR ANNUAL TOTAL BODY DOSE RATE

Nuclide	pCi/g of soil for: 10 mrem/yr	pCi/g of soil for: 170 mrem/yr
^{239}Pu	4032	6.85×10^4
^{241}Am	881	1.50×10^4
Normal U	2209	3.76×10^4
Natural U	41	690
Natural Th	25	425

The dose rate values were chosen as being representative of the ICRP recommendation of 500 mrem/yr for an individual in the population (ICRP 1977), assuming that the maximum exposure due to individual differences is not larger than a factor of 3, and a level (10 mrem/yr) which is approaching the practical de minimis level. The effective weighted whole body dose rate was chosen since this is a more acceptable measure of the index of harm with respect to stochastic effects.

Taking into account ALARA, as well as the cost effectiveness of time consuming sample analysis to achieve increased sensitivity, the soil concentration cleanup values for 10 mrem/yr were recommended with these exceptions: for ^{239}Pu , ^{241}Am and normal U, a value of 200 pCi/g was chosen. This choice seemingly represented a satisfactory compromise to those who felt that the numbers, as listed, "sounded" high and to those who were challenged to make timely measurements to allow the site D&D to proceed. In the application of the criteria, any contaminated region, or "hot" spot, which was encountered was essentially cleaned up so that the combined levels of the residual radioactive contamination met this criteria. In all cases, the residual levels as determined by laboratory analyses of relevant samples indicated that the site had been cleaned up to levels well below the criteria values. The cost difference to achieve this condition, compared to that of just meeting the criteria, was judged to be negligible for the specific conditions of this site.

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