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EXECUTIVE SUMMARY FINAL REPORT DERIVATION OF SITE-SPECIFIC SOIL GUIDELINES FOR THE FEED MATERIALS PRODUCTION CENTER DECEMBER 1, 1998

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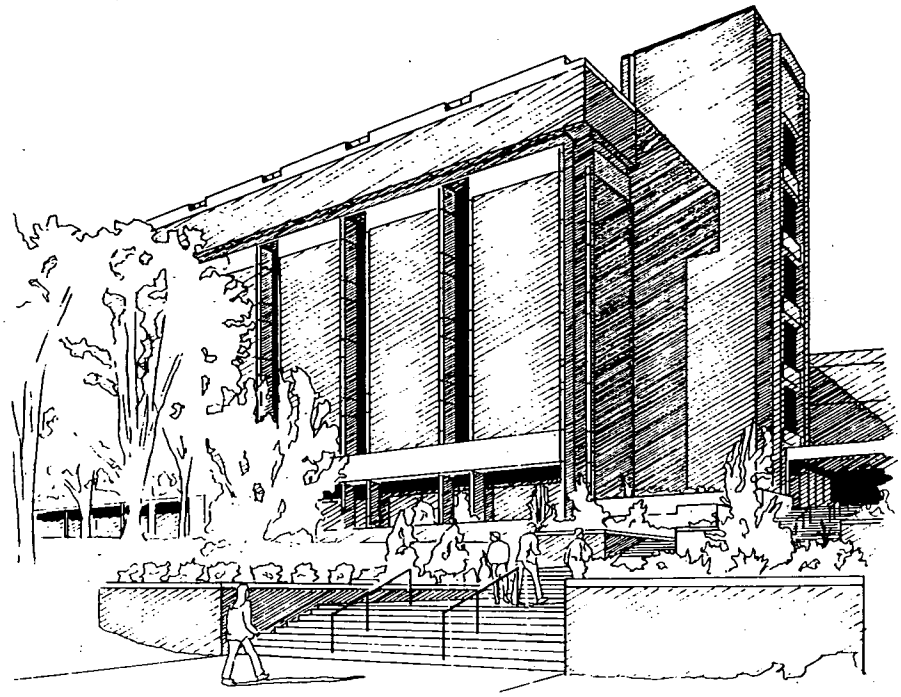

UNIVERSITY OF CINCINNATI
COLLEGE OF ENGINEERING

EXECUTIVE SUMMARY

FINAL REPORT

DERIVATION OF SITE-SPECIFIC SOIL GUIDELINES FOR THE FEED MATERIALS PRODUCTION CENTER

DECEMBER 1, 1988

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DR. ROY ECKART
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EXECUTIVE SUMMARY

This is a brief summary report of the final report entitled, "Derivation of Site-Specific Soil Guidelines for the Feed Materials Production Center". It is a concise version of the final report. The Executive Summary is intended to be utilized by WMCO management and technical staff to provide them with a brief review of the project. Background information and complete details of the analytical methods can be found in the final report. All table numbers and equation numbers are taken from the final report. The soil guidelines for the FMPC are shown in the Table of Results (next page) and the figure showing FMPC soil guidelines (following page).

Objective of the soil guideline study

The major objective of this study was to develop a set of site specific radionuclide soil guidelines for residual radioactivity at the Feed Materials Production Center (FMPC) site. These soil guidelines were derived for the decommissioning and decontamination of the site and its release by the DOE for unrestricted use by the general population. The preparation of this report does not imply any such action is currently contemplated by the DOE.

The DOE has issued a draft version of a manual containing guidelines, criteria and methodology for developing residual radioactivity soil guidelines at formerly utilized sites (FUSRAP program) and remote surplus facilities sites (SFMP program). The manual is entitled, "A Manual for Implementing Residual Radioactivity Guidelines" (Gilbert 1987). (Hereafter simply called the Manual).

One goal of this study was to determine if the general guidelines developed in this Manual were applicable to the FMPC site. If the Manual was found to be applicable, then utilize the guidelines, criteria and methodology

to develop a set of residual radioactivity soil guidelines for the FMPC. The soil guidelines developed for the Weldon-Springs vicinity properties were to be used as a prime example of an application of the Manual. The results were also verifed by comparison to an Idaho National Engineering Laboratory report, "Development of Criteria for Release of INEL Following Decontamination and Decommissioning" (EG&G 1986).

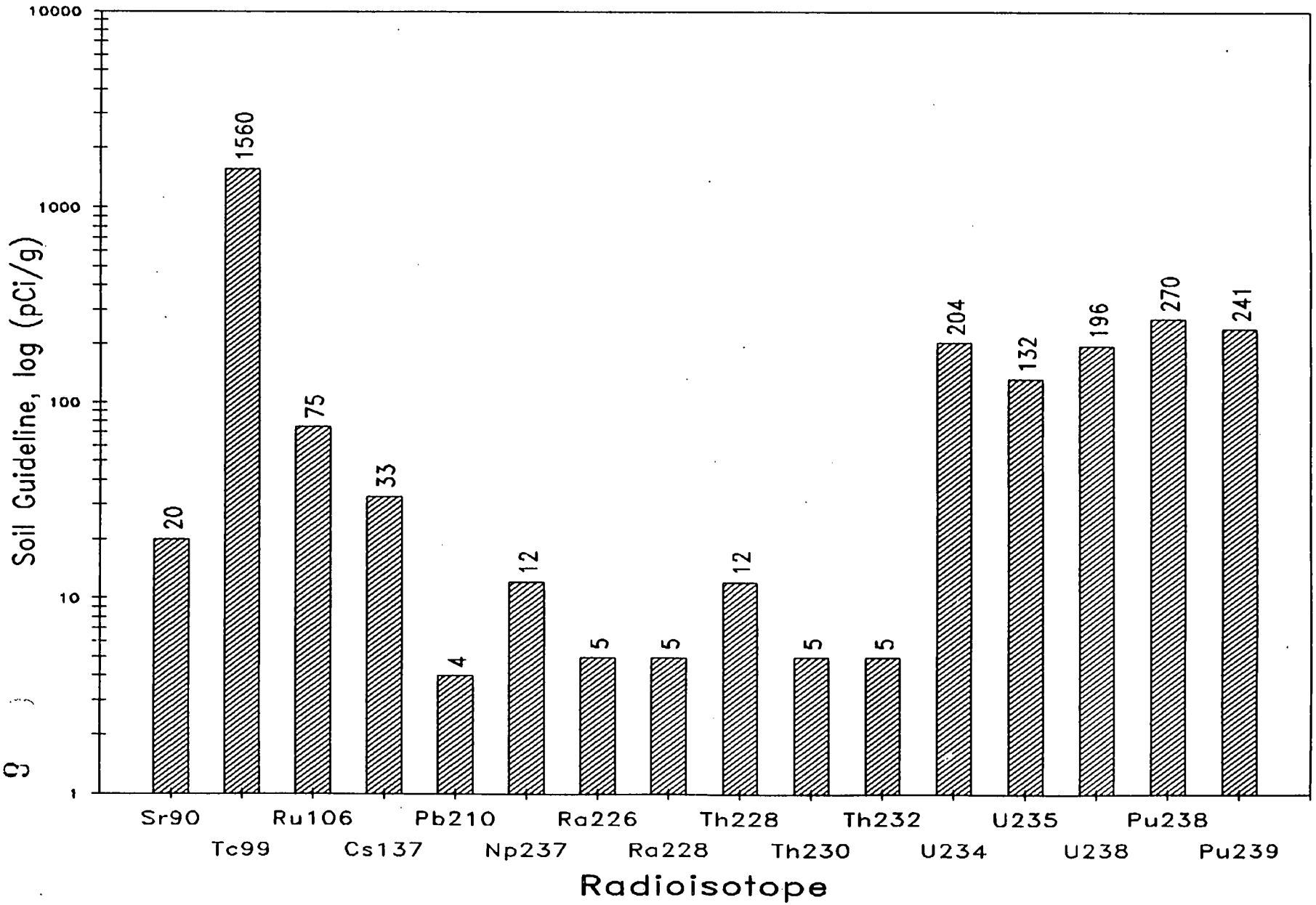
TABLE OF RESULTS

HOMOGENEOUS SINGLE RADIONUCLIDE SOIL CONCENTRATION GUIDELINES FOR THE FMPC

Radioisotope	Soil Guideline* (pCi/g)
	pCi/g
strontium 90	20
technetium 99	1560
ruthenium 106	75
cesium 137	33
lead 210	4
neptunium 237	12
radium 226	5
radium 228	5
thorium 228	12
thorium 230	5
thorium 232	5
uranium 234	204
uranium 235	132
uranium 238	196
plutonium 238	270
plutonium 239	241

*above background concentration

Results: Homogeneous Single Radionuclide Soil Concentration Guidelines for the FMPC



Environmental standards

The environmental standards investigation found the DOE limit (Gilbert 87) of 100 mrem per year committed effective dose equivalent to be one of the most widely cited standards. This standard is consistent with the NCRP standard for the general public (NCRP 87). The current NRC dose limit for an individual in the general population is 500 mrem per year. For a large number of people in the general population, the NRC dose limit is 170 mrem per year.

Since the most restrictive dose limit was the DOE limit, the soil guidelines for the FMPC were based on an annual limit of 100 mrem committed effective dose equivalent.

Review of investigations at other sites

A thorough review of remedial actions and soil guidelines work at other DOE sites, FUSRAP and SFMP sites was conducted. Special attention was given to reports on Weldon-Springs, since Weldon-Springs was also a uranium refinery operated by the DOE and decommissioned in 1966 (Gilbert 86). The feed material and product materials at Weldon-Springs were similar to the FMPC. A report prepared by EG&G for the decommissioning and decontamination of the Idaho National Engineering Laboratory (INEL) also provided excellent guidance in the execution of this work (EG&G 86). These studies provided useful information in the determination of the appropriate pathways to be considered and provided readily available comparisons for the analysis and results. Even though the circumstances of the FMPC study are significantly different in some areas, the methodologies employed are similar. The FMPC and INEL studies are unique situations because the sites are still operating with no date for decommissioning yet considered.

Soil Guidelines Analysis Method

The primary method of analysis was the method developed in the Manual for DOE sites. The analysis techniques and models in the Manual were adapted to the FMPC site. Two computer programs were also used to confirm the Manual analysis results and extend the analysis methods developed in the Manual. These are: ONSITE/MAXI (Napier 1984) and AIRDOS-EPA (Moore 1979). Both of these programs are described in detail in the final report.

Adapting the "Manual" to the FMPC site

A thorough and complete review was made of the "Manual for Implementing Residual Radioactivity Guidelines" to determine it's applicability to the FMPC site (Gilbert 87). The Manual methodology was determined to apply to the FMPC site soil guidelines project.

The Manual was adapted to the FMPC site by including detailed information on the site, the radionuclides present in the soil (source terms) and the chemical form of the radionuclide. An exposure scenario was developed along with a site-specific pathway analysis. Geologic and hydrogeologic information about the site were added along with site specific parameters such as: soil density, soil distribution coefficients, runoff coefficients, type of soil, annual precipitation, etc.

Limitations of the study

The methods used in this project to calculate residual radioactivity soil guidelines for the FMPC site can be used for any given set of radiological data. The study will be limited only by the availability of data needed for the analysis. The pathway analysis and methods could be modified to calculate dose to any present day scenario for remedial action.

Pathway models and exposure scenario

Environmental transport pathways describe the movement of radionuclides from the source in the soil through the biosphere to the human population. A large number of pathway models, described in the final report, were reviewed for this project. The actual pathways that lead to human exposure are determined by exposure scenarios. These are the patterns of human activity that can result in radiation dose linked to the residual radioactivity in the soil. These exposure scenarios are therefore very site-specific. Soil guidelines are based on the exposure to members of a critical population group. This is the person or group that would be expected to receive the highest effective dose equivalent. The maximally exposed individual should not receive a dose greater than the 100 mrem limit.

The Manual has defined the critical population group for a site that is being decommissioned, FUSRAP or SFMP site, as a family who takes up residence on the site after it has been released for unrestricted use. Exposure scenarios for this group are called resident scenarios. Since the FMPC site is over 1000 acres, the resident scenario has been shown to be the most critical scenario for this analysis. Because of the large area of the FMPC, the resident scenario becomes the "family farm" scenario. This scenario assumes that the resident family can produce all their food on site: grain, vegetables, beef and milk. A well on the site produces water for the family and irrigation water for the farm.

The scenario parameters established for the maximally exposed individual are listed in Table 3.1, shown on the next page. Using the scenario developed for the maximally exposed individual, the major pathways shown in Table 3.2 were identified for the FMPC site.

TABLE 3.1

SCENARIO PARAMETERS FOR THE MAXIMALLY EXPOSED INDIVIDUAL

Parameter	Value
Maximally exposed individual	member of resident family
Activity parameters	
Time spent indoors (50%)	
resting	2500 h/yr.
light activity	1800 h/yr.
Time spent outdoors (50%)	
onsite (25%)	2190 h/yr.
offsite (25%)	2190 h/yr.
Food consumption parameters	
Fraction of plant diet grown onsite	1.0
Fraction of drinking water from onsite well	1.0
Fraction of livestock food grown onsite	0.5
Fraction of meat and milk from onsite animals	1.0
Fraction of fish diet from farm pond	0.3
Housing parameters	
Dust quantity in house to outside air	0.5
Shielding factor for external gamma	0.7
Site general parameters	
Area of above background concentration of radionuclides	1050 acres
Initial thickness of protective soil cover	0 m
Erosion rate	0.05 mm/yr
Depth of contamination	15 cm

Major pathways for the FMPC

The major pathways to the maximally exposed individual who takes up residence at the released site are shown in Table 3.2.

TABLE 3.2

MAJOR PATHWAYS FOR THE FMPC SITE

1.0 External radiation

1.1 Ground
volume source
surface source

1.2 Air
resuspended dust

2.0 Internal Radiation

2.1 Inhalation
inhalation of resuspended dust

2.2 Ingestion-Foods
plant foods; vegetables, grains and fruits
meat
milk

2.3 Water Ingestion
deep well-drinking water
irrigation water

Near-term, non-aquatic pathways (initial release of the site, t=0 years)

When the FMPC is initially released for unrestricted use by the general public, the residual radionuclide contamination would be contained in the top layer of soil, called the contaminated zone. The aquifer zone is uncontaminated at t=0 years. The pathways shown in Table 3.2 are reduced for the non-aquatic pathway analysis to direct radiation from the soil, inhalation of resuspended dust and ingestion of radionuclides through foods such as fruit, vegetables, meat and milk. The family well is a deep well in the aquifer region, located directly below the site. The results of the radionuclide diffusion-migration model indicated that the aquifer region would not be contaminated at this initial time (t=0 years after release). Thus, the aquatic paths were deleted from the near-term pathway analysis. Table 3.3 lists the near-term pathways used to develop the soil guidelines.

TABLE 3.3

NEAR-TERM MAJOR PATHWAYS (0-100 YEARS)

1. External radiation from the ground

   1.1 Surface source
   1.2 Volume source

2. Internal radiation

   2.1 Inhalation
      inhalation of resuspended dust

   2.2 Ingestion by foods
      plant foods
      meat
      milk

Long-term, aquatic pathways

The radionuclide migration model developed for this project indicated that the radionuclides would migrate downward from the contaminated zone, through the unsaturated zone (vadose) to the saturated region (aquifer) in a few thousand years. The dose to the maximally exposed individual decreases as the radionuclide concentration in the contaminated zone decreases. This dose continues to decrease until the radionuclides begin to reach the saturated zone (aquifer). The long term scenario requires the aquifer well water be used for drinking and crop irrigation. The long-term pathways are dominated by the use of the aquifer water, which contains the fraction of the radionuclides that have migrated through the vadose zone to the aquifer region. The radionuclides are re-introduced to the surface through use of aquifer water containing low levels of contamination. The long-term aquatic pathways (1,000-10,000 years after release of the site) are listed below in Table 3.4. These pathways are based on the contamination being re-introduced into the surface soil through crop irrigation, as well as drinking water.

TABLE 3.4

LONG-TERM AQUATIC PATHWAYS (1000-10,000 YEARS)

1.0 External radiation from the ground (from contaminated irrigation water)
- volume source
- surface source

2.0 Internal radiation (contaminated well and irrigation water)

2.1 Inhalation
- inhalation of resuspended dust

2.2 Ingestion by foods
- plant foods
- meat
- milk

2.3 Ingestion by water pathways
- drinking water from deep well
- irrigation water from deep well

Radionuclide migration model

A radionuclide migration model was developed to evaluate the long term soil guidelines (1,000 years to 10,000 years after release of the site). The original draft of the Manual utilized a simple, overly conservative, ion-exchange model to calculate radionuclide migration from the surface to the aquifer region. In the ion-exchange model, the radionuclides quickly reach the aquifer region and are re-introduced back onto the surface soil through irrigation water. The drinking water from the deep well would also contain radionuclides. Because this occurs in a relatively short time interval, when the ion exchange model is used, the aquatic paths add to the original non-aquatic paths.

The model developed for the FMPC was much more realistic. It is based on the mass transport equation, simplified with actual FMPC hydrological and geological conditions. The mass transport model was formulated in two parts: (1) the unsaturated or vadose zone and (2) the saturated zone or aquifer region.

The general solution of the mass transport equation assuming local equilibrium and first order chemical reactions is:

$$R_d\,\Theta\,\frac{\partial C}{\partial t} - \bar{\nabla}\cdot(\Theta\,\bar{\bar{D}}\cdot\bar{\nabla}C) + \nabla\cdot(\bar{V}C) + [R_d\,\frac{\partial\Theta}{\partial t} + \lambda\Theta R_d]C=0 \qquad \text{(eq.3.1)}$$

where:

C= concentration of dissolved constituent (radionuclides), g/cm^3

$\bar{\bar{D}}$ = dispersion tensor, cm^2/s

$\bar{V}$ = fluid flux, cm/s

R_d = retardation coefficient, no units

λ = radiological decay constant, s^{-1}

Θ = volumetric water content of the medium

In the vadose region, a number of simplifying assumptions were made to reduce equation 3.1 to a form that could be solved. The assumptions are discussed in detail in the report (sections 3.5.2.1-3.5.2.3). These assumptions plus site specific information further simplified the equation.

The modified mass transport equation for the vadose region becomes:

$$R_d\Theta\,\frac{\partial C}{\partial t} = D_z\Theta\,\frac{\partial^2 C}{\partial z^2} - \bar{V}\,\frac{\partial C}{\partial z} - \lambda_R R_d C \qquad \text{(eq.3.4)}$$

The method used in the aquifer region to reduce the transport equation to a useful form was similar to the vadose region. (see section 3.5.2.3). The reduced form of this equation becomes:

$$\frac{\partial C}{\partial t} - \frac{D_x}{R_d}\frac{\partial^2 C}{\partial x^2} - \frac{D_y}{R_d}\frac{\partial^2 C}{\partial y^2} + \frac{\bar{V}}{R_d}\frac{\partial C}{\partial x} + \lambda C = 0 \qquad \text{(eq. 3.8)}$$

This is essentially a two-dimensional model for the aquifer region. It assumes constant aquifer depth.

Equations 3.4 and 3.8 were solved by the integral transform method, followed by a substitution for the error function and the compliment of the error function. The vadose solution becomes:

$$\frac{C(z)}{C_0} = \frac{1}{2}\operatorname{erfc}\left[\frac{z - \frac{V_z t}{R_d \theta}}{2\sqrt{\frac{D_z t}{R_d}}}\right]\exp(-\lambda_R t) + \frac{1}{2}\exp\left(\frac{z V_z}{\theta D_z}\right)\exp(-\lambda_R t)\operatorname{erfc}\left[\frac{z - \frac{V_z t}{R_d \theta}}{2\sqrt{\frac{D_z t}{R_d}}}\right] \qquad \text{(eq.3.9)}$$

The solution for equation 3.8 in the aquifer region is:

$$c_i = \frac{1}{n_e R_d} X_2 Y_2 Z_2, \qquad \text{(eq.3.10)}$$

where

$$X_2 = \frac{1}{2\ell}\left\{\operatorname{erf}\frac{\left(x+\frac{\ell}{2}\right) - \frac{ut}{R_d}}{\sqrt{4D_x t/R_d}} - \operatorname{erf}\frac{\left(x-\frac{\ell}{2}\right) - \frac{ut}{R_d}}{\sqrt{4D_x t/R_d}}\right\}\exp(-\lambda t)$$

$$Y_2 = \frac{1}{2w}\left\{\operatorname{erf}\frac{(w/2+y)}{\sqrt{4D_y t/R_d}} + \operatorname{erf}\frac{(w/2-y)}{\sqrt{4D_y t/R_d}}\right\}$$

$$Z_2 = \frac{1}{b}$$

A computer program was written to provide solutions to equations 3.4, 3.8, 3.9 and 3.10. Typical results are shown in figures 3.8, 3.14, 3.15, 3.18 and 3.27.

These figures represent the transport of material through the vadose and aquifer regions, as a function of time and position. The first three figures 3.8, 3.14, and 3.15, depict the concentrations of uranium 238, thorium 232, and radium 226 through the vadose zone. In each of these figures, there are five curves illustrating the concentration as a function of time at a particular depth within this zone. In all cases the 10 meter depth was considered to be the breakthough point. The concentration is normalized to the concentration at the surface at time zero. In the case of uranium 238 approximately 15% of the surface concentration has reached the aquifer in 10,000 years. Thorium 232 is much less than 1% at the 10 meter point in 10,000 years. Figures 3.18 and 3.27 illustrate the movement of material within the aquifer. Each of these figures represents the concentration as a function of time at a particular position in the aquifer. The positions in both cases are for zero in the 'y' direction and from 300 to 900 meters in the 'x' direction. These positions are with respect to the plane source at the top of the aquifer region. These figures for thorium and uranium illustrate the dilution that occurs within this region as well as the time for material to travel.

Results of the radionuclide migration analysis

The results of the radionuclide migration model showed that it required a few thousand years for the radionuclides to migrate from the contaminated zone to the aquifer region. The aquifer region provided a large dilution factor which reduced the concentration of the radionuclides in the drinking well and

Figure 3.8: Uranium 238 Migration in Vadose Zone
Distribution Coefficient = 270 (cc/gm)

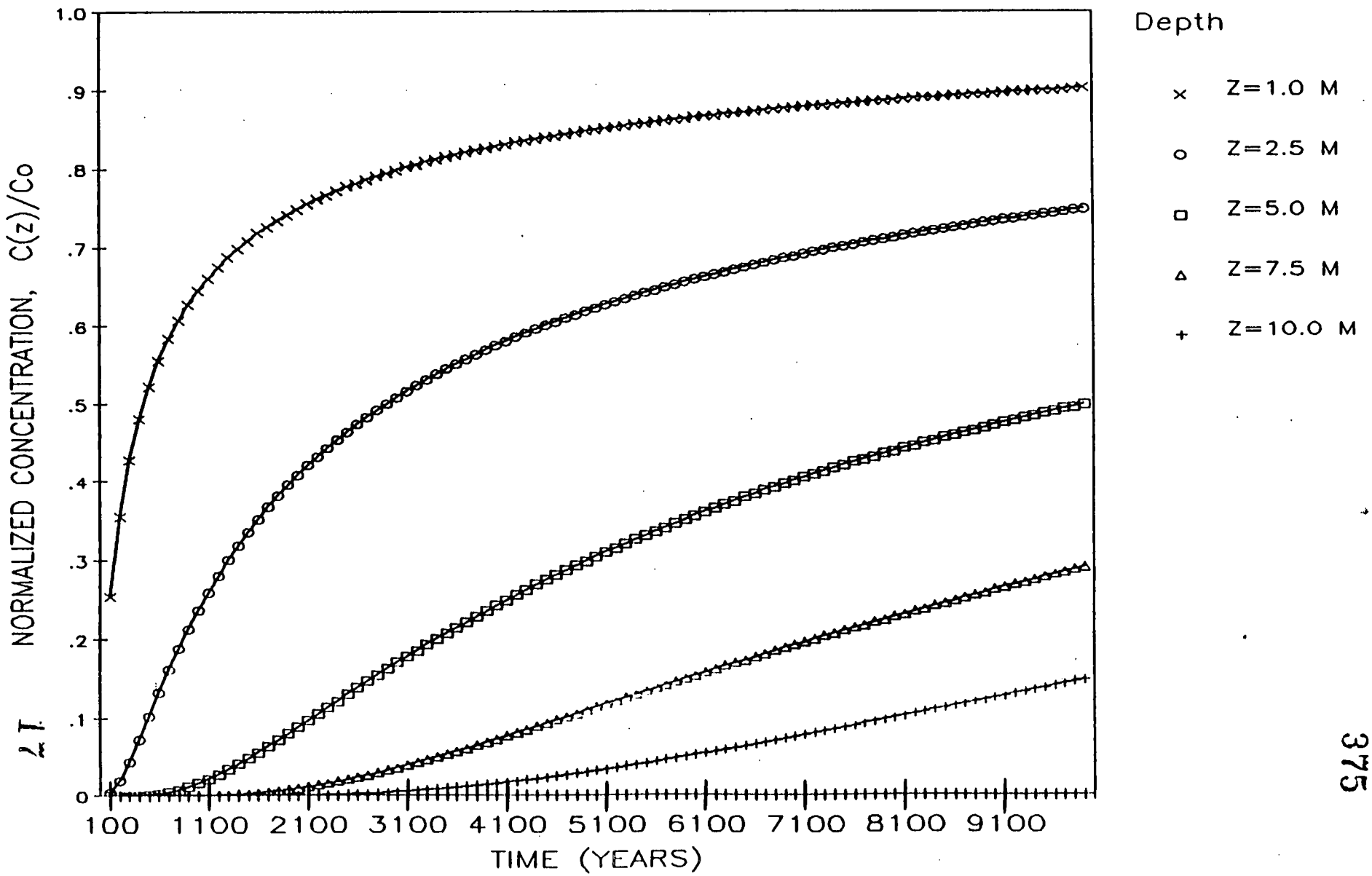


Figure 3.14: Thorium 232 Migration in Vadose Zone

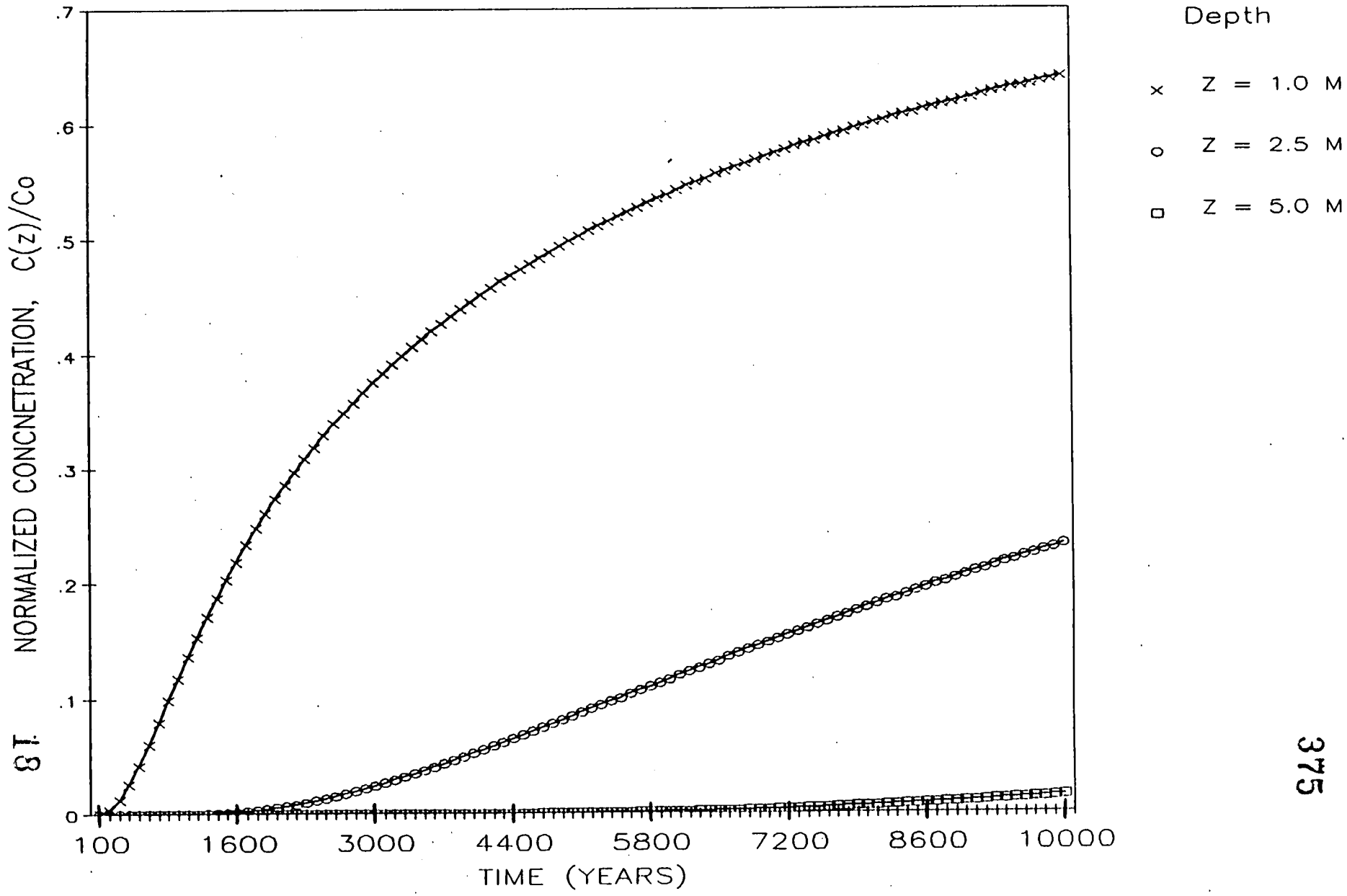


Figure 3.15: Radium 226 Migration in Vadose Zone

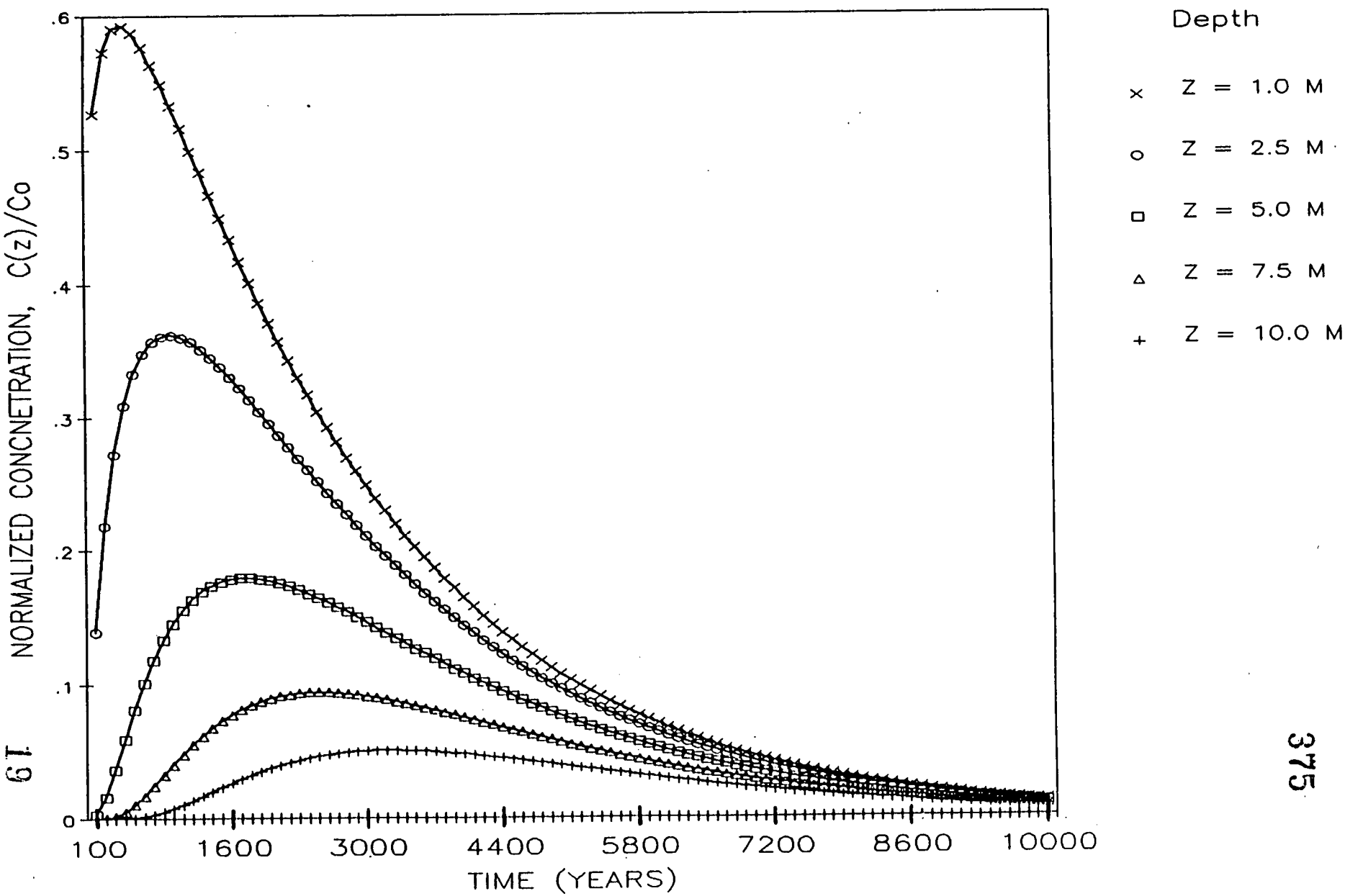


Figure 3.18: Thorium 232 Concentration in Groundwater

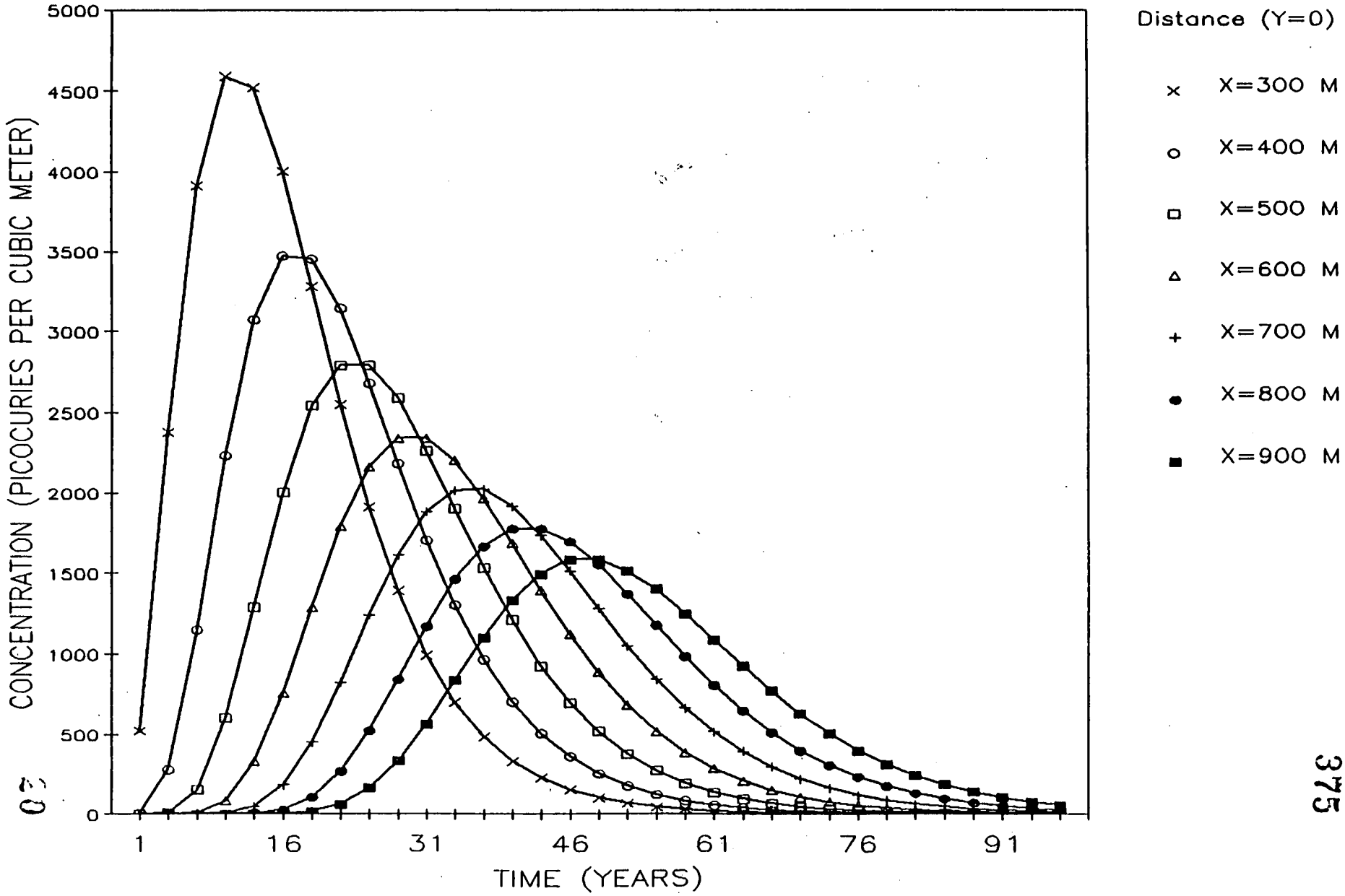
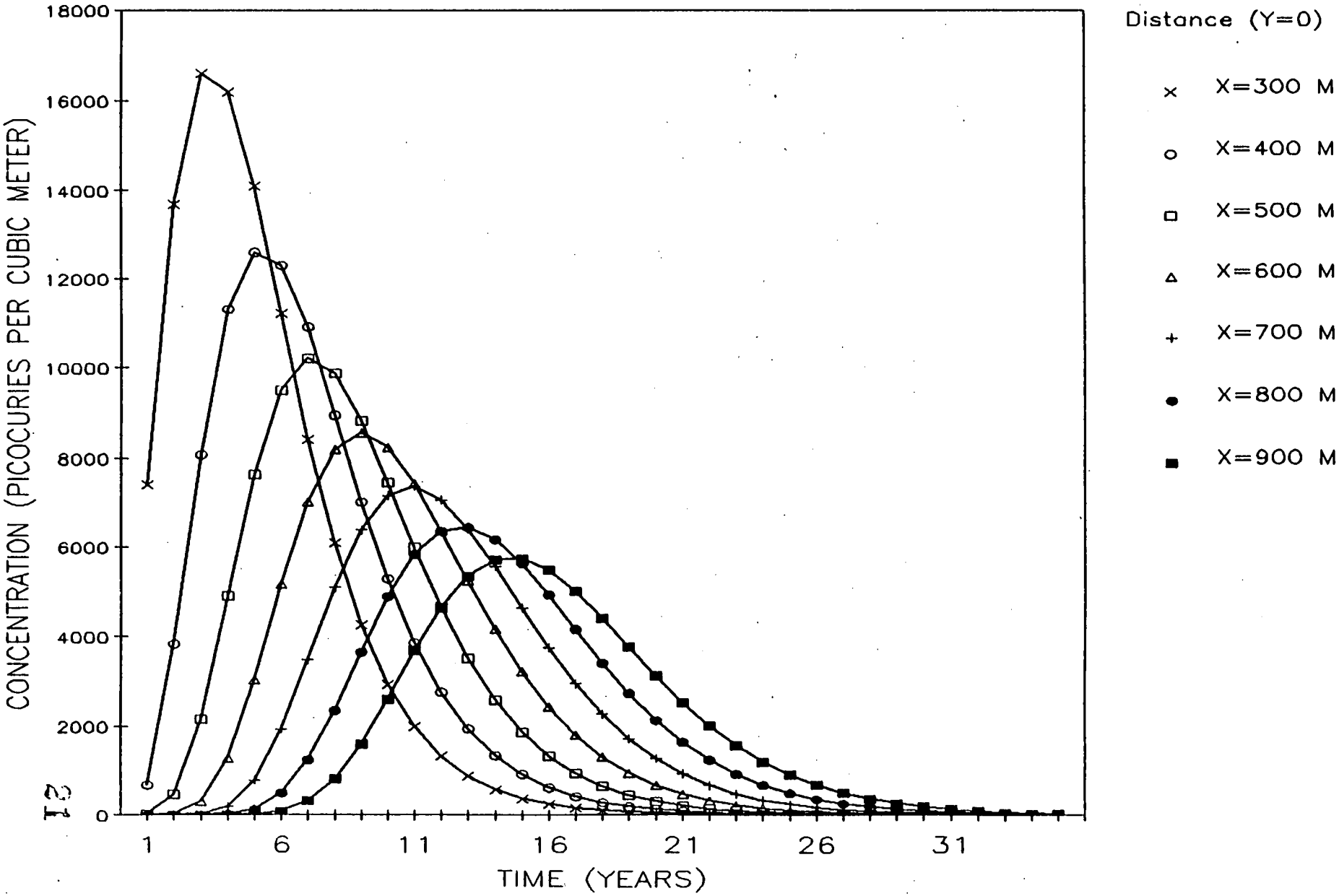


Figure 3.27: Uranium 238 Concentration in Groundwater



irrigation water. These results are shown in Tables 3.7 and 3.8. These results are fundamentally important to the pathway analysis and soil guidelines. By the time the radionuclides reach the aquifer, the concentration in the contaminated zone has been greatly reduced. Thus, the non-aquatic pathways that are important at the time the site is initially released , do not add to the aquatic pathways at the end of the planning horizon, 10,000 years.

Based on these results, the pathways analysis was divided into two major time periods; (1) initial release of the site, called the near-term non-aquatic paths (Table 3.3) and (2) the long-term aquatic paths (Table 3.4).

TABLE 3.7

FRACTION OF INITIAL CONCENTRATION CALCULATED AT 10 METERS DUE TO RADIONUCLIDE TRANSPORT IN THE VADOSE ZONE

NUCLIDE	HALF-LIFE (YEARS)	TIME (YEARS) 100	1000	5000	10000
Pu-239	2.41×10^{4}	5.5×10^{-17}	7.6×10^{-5}	5.8×10^{-2}	2.0×10^{-1}
Pu-238*	8.77×10^{1}	1.1×10^{-17}	2.6×10^{-8}	2.81×10^{-19}	$< 10^{-35}$
U-238	4.68×10^{9}	0	1.4×10^{-7}	1.5×10^{-2}	8.1×10^{-3}
U-235	7.04×10^{8}	0	1.4×10^{-7}	1.5×10^{-2}	8.1×10^{-2}
U-234	2.44×10^{4}	0	1.4×10^{-7}	1.5×10^{-2}	7.9×10^{-2}
Th-232	1.4×10^{10}	0	0	1.3×10^{-13}	1.4×10^{-7}
Th-230	7.7×10^{4}	0	0	1.2×10^{-13}	1.3×10^{-7}
Th-238**	1.91×10^{0}	0	0	0	0
Ra-226	1.60×10^{3}	2.1×10^{-16}	4.0×10^{-3}	2.3×10^{-2}	4.8×10^{-3}
Ra-228	5.75×10^{0}	0	0	0	0
Np-237	2.14×10^{6}	0	1.9×10^{-6}	2.8×10^{-2}	2.0×10^{-1}
Pb-210	2.23×10^{1}	0	3.6×10^{-17}	0	0
Cs-137	3.17×10^{1}	0	1.0×10^{-15}	0	0
Ru-106**	1.01×10^{0}	0	0	0	0
Tc-99	2.13×10^{5}	9.3×10^{-13}	1.2×10^{-3}	1.1×10^{1}	2.7×10^{1}
Sr-90	2.9×10^{1}	4.4×10^{-7}	5.4×10^{-12}	0	0

*Pu-238 decays to U-234
**completely decays away

TABLE 3.8

FRACTION OF INITIAL SURFACE CONCENTRATION IN AQUIFER REGION
(RATIO OF INITIAL SURFACE CONCENTRATION TO CONCENTRATION
PER LITER IN THE AQUIFER)

NUCLIDE	HALF-LIFE (YEARS)	TIME (YEARS)			
		100	1000	5000	10000
Pu-239	2.41×10^{4}	1.4×10^{-23}	9.7×10^{-12}	7.4×10^{-9}	1.8×10^{-8}
Pu-238*	8.77×10^{1}	8.7×10^{-25}	2.1×10^{-15}	2.24×10^{-25}	$< 10^{-35}$
U-238	4.68×10^{9}	2.8×10^{-21}	2.4×10^{-12}	2.7×10^{-7}	1.4×10^{-6}
U-235	7.04×10^{8}	2.8×10^{-21}	2.4×10^{-12}	2.7×10^{-7}	1.4×10^{-6}
U-234	2.44×10^{4}	2.8×10^{-21}	2.4×10^{-12}	2.6×10^{-12}	1.3×10^{-6}
Th-232	1.4×10^{10}	0	0	1.8×10^{-21}	2.0×10^{-15}
Th-230	7.7×10^{4}	0	0	1.8×10^{-21}	1.8×10^{-15}
Th-228	1.91×10^{0}	0	0	0	0
Ra-228	5.75×10^{0}	0	0	0	0
Ra-226	1.60×10^{3}	1.0×10^{-20}	1.9×10^{-7}	1.1×10^{-6}	2.2×10^{-7}
Np-237	14×10^{6}	2.9×10^{-20}	3.0×10^{-11}	4.4×10^{-7}	1.8×10^{-6}
Pb-210	2.23×10^{1}	9.0×10^{-18}	0	0	0
Cs-137	3.17×10^{1}	6.3×10^{-21}	0	0	0
Ru-106	1.01×10^{0}	0	0	0	0
Tc-99	2.13×10^{5}	3.2×10^{17}	4.0×10^{-8}	4.3×10^{-6}	1.0×10^{-5}
Sr-90	2.9×10^{1}	4.4×10^{-12}	0	0	0

* Pu-238 will increase U-234 concentration by a factor of 2

Pathway analysis methodology

Site specific soil guidelines are calculated by the formula:

$$S_{G,i} = D_L/(D/S)_i \qquad \text{(eq. 4.1)}$$

where:

$S_{G,i}$ = soil guideline for radionuclide i, pCi/g

$(D/S)_i$ = dose to source conversion factor for radionuclide, i mrem/y per pCi/g

D_L = annual committed effective dose equivalent, mrem

D_L = 100 mrem per year for DOE standards

The dose to source D/S ratios, are factored into two major components, a dose conversion factor, D/E and an environmental transport factor, E/S. The D/S ratio for radionuclide i and pathway p, $(D/S)_{i,p}$ can be be calculated from these two factors:

$$(D/S)_{i,p} = (D/E)_{i,p}\ (E/S)_{i,p} \qquad \text{(eq. 4.3)}$$

where:

$(D/E)_{i,p}$ = dose conversion factor for radionuclide i and pathway, p mrem/pCi

$(E/S)_{i,p}$ = environmental transport factor for radionuclide i and pathway, p in g/y or g/cm^3

The dose conversion factors, D/E, for internal radiation doses to organs and tissues of the body are estimated using factors representing the committed dose equivalent for a unit intake of a specific radionuclide via inhalation or ingestion. In the case of external irradiation, the dose rate to the body and organs depends on the concentration of the radionuclide in the environment. These factors are also dependent on the size of the dust particle inhaled and the chemical form of the radionuclide. A shortened version of Table 4.2 illustrates these data. (Refer to the final report for additional the D/E factors)

TABLE 4.2 (GILBERT 87)

D/E FACTOR FOR INTERNAL RADIATION FOR SELECTED RADIONUCLIDES

Principal Radionuclide	lung class	inhalation D/E (mrem/pCi)	ingestion D/E (mrem/pCi)
Th 232	W	1.64	2.73×10^{-3}
Th 232	Y	1.15	
U 238 + D	D	2.45×10^{-3}	2.55×10^{-4}
U 238 + D	W	7.06×10^{-3}	3.75×10^{-5}

In addition to inhalation or ingestion of a radionuclide, a person could receive a radiation dose directly from radionuclides on the surface of the soil (surface source) or from radionuclides within the soil (volume source). These dose rate factors are dependent on the depth of contamination of the radionuclides in the soil. Table 4.3 (again shortened) shows dose rate conversion factors for surface soil contamination and volume soil contamination.

TABLE 4.3 (GILBERT 87)

D/E FACTORS FOR EXTERNAL RADIATION FOR SELECTED RADIONUCLIDES

Principal Radionuclide	Surface Source	Volume Source (soil density 1.8 g/cm^3)
	$\frac{\text{mrem}}{\text{yr}}$ per $\frac{\text{pCi}}{\text{cm}^2}$	$\frac{\text{mrem}}{\text{yr}}$ per $\frac{\text{pCi}}{\text{cm}^3}$
Th 232	7.14×10^{-4}	6.04×10^{-4}
U 238 + D	1.33×10^{-1}	6.97×10^{-4}

The environmental transport factors, E/S, describe the means by which radionuclides are transported from the soil or water to inhalation or ingestion by humans. In a practical sense, these factors describe such radionuclide intakes as the quantities of radionuclides (pCi) that the maximally exposed individual would inhale from the resuspended dust or would ingest from the drinking water or through eating food products grown on site.

Each environmental transport factor is expressed as a product of pathway factors that include intake factors for the quantities of radionuclides inhaled or ingested, occupancy factors for the time spent in contaminated areas, transfer factors for the concentration ratios for the radionuclide concentrations in different media along a pathway, such as plant uptake factors and water to soil concentration ratios, and source factors for the area and depth of contamination and rate of release into the environment. The basic equations for selected environmental transport factors are included in Section 4 of the interim report. Extensive details of these factors can be found in the Manual. (Gilbert 87)

Derivation of dose to source ratios (D/S)

Dose to source ratios have been calculated for the near-term, non-aquatic pathways for selected radionuclides that may be present in above background concentration at the FMPC site. The Manual analysis technique was used to calculate D/S values for all the radionuclides identified as present at the site (WESTON 87). Section 5 of the final report contains the detailed analysis methodology of the Manual, AIRDOS and ONSITE/MAXI.

As an example of the details of the calculations, Table 5.1 lists the calculated D/S values for uranium 238 for near-term, non-aquatic pathways. The plant foods pathway is the most significant pathway.

TABLE 5.1

D/S VALUES FOR URANIUM 238 NEAR-TERM, NON-AQUATIC PATHS

Pathway	D/S
external radiation	0.0662
dust inhalation	0.0892
plant foods - root uptake	0.1122
plant foods - foliar deposition	0.0003
meat products - foliar deposition	0.0138
meat products - foliar deposition	0.0000
milk products - root uptake	0.0020
milk products - foliar deposition	0.0000
(D/S) Total	0.2837 $\frac{mrem}{yr}$ per $\frac{pCi}{yr}$

This value is in reasonable agreement with the calculated values in the Manual, Weldon-Springs and INEL reports. Since uranium 234 is in secular equilibrium with the uranium 238, the Manual includes these radionuclides together in an analysis. Table 5.2 shows the results of the dose to source analysis (D/S) for uranium 234 and uranium 238.

TABLE 5.2
D/S RATIOS FOR URANIUM 238 AND URANIUM 234 IN SECULAR EQUILIBRIUM FOR NEAR-TERM NON-AQUATIC PATHS (AT FMPC)

$\frac{D}{S}$ (mrem/yr)/(pCi/g)

Radionuclide	External Radiation	Dust Inhalation	Food			
			Plant	Meat	Milk	Total
U238 + D	0.0662	0.0892	0.1125	0.0138	0.0020	0.2839
U234	0.0006	0.0901	0.1167	0.0145	0.0025	0.2244
					Total	0.5083

The Table 5.9 below is taken directly from the work of Tom Gilbert for the Weldon-Springs vicinity properties soil guidelines (Gilbert 86).

TABLE 5.9

D/S RATIOS FOR WATER-INDEPENDENT, SHORT-TERM PATHWAYS (AT WELDON-SPRINGS) (GILBERT 85)

(all units are mrem/yr per pCi per gram)

Radionuclide	External Radiation	Dust Inhalation	Food			Total
			Plant	Meat	Milk	
U234	0.0008	0.11	0.038	0.005	0.0007	0.15
U238 + D	0.08	0.10	0.034	0.004	0.0006	0.22
Totals	0.08	0.21	0.072	0.009	0.0013	0.37

These results are consistent between FMPC and Weldon-Springs. The Weldon-Springs vicinity properties contained several smaller areas of contamination. This reduces the D/S ratios for food, since only a fraction of the resident family's food can be grown on site. The D/S ratio is higher at the FMPC due to an assumption that the entire diet can be obtained from the large site area.

The modified version of the AIRDOS-EPA computer program package was also used to calculate D/S ratios and the corresponding single radionuclide soil guidelines. The AIRDOS results are also consistent with the Manual. The other computer program that is being used in the analysis, ONSITE/MAXI (NAPIER 84) was obtained from Pacific Northwest Labs. A new version was received (April 23, 1987).

The AIRDOS results are obtained from the computer program for each radionculide considered individually, without the daughter products. For example, uranium 238 and uranium 234, Table 5.4 shows AIRDOS results to be consistent with the Manual analysis when allowance is made for the difference in the Manual type of analysis and the AIRDOS calculational sequence.

TABLE 5.4

D/S VALUES FROM THE AIRDOS PROGRAM FOR FMPC

Radionuclide	D/S Value
	mrem/yr per pCi/g
U 238	0.3086
U 234	0.3584
Total D/S	0.6670

Soil guidelines for the FMPC

The final report contains single radionuclide soil guidelines for selected radionuclides for the critical pathway, which is the near-term, non-aquatic pathway. These guidelines also assume homogeneous distribution of these radionuclides. When mixtures of radionuclides are present in above background levels of concentration, then the soil guideline values will be sharply reduced from the Table 6.1 values through the use of the mixture sum formula (discussed later).

The single radionuclide soil guidelines are calculated by dividing the annual dose limit of 100 mrem/year by the D/S value.

For uranium 238 in secular equilibrium with uranium 234,

$$S = \frac{100\ \text{mrem}}{\text{yr}} \frac{1}{0.5083} \frac{\frac{\text{pCi}}{\text{g}}}{\frac{\text{mrem}}{\text{yr}}} \doteq 96\ \frac{\text{pCi}}{\text{g}}$$

For the same pathways, Weldon-Springs shows a D/S total of 0.37, which leads to a single radionculide, water independent, near-term pathway soil guideline of 300 pCi/g. The FMPC result is lower because the site is much larger and the food pathway D/S values are correspondingly larger. Table 6.1 below, shows this comparison for uranium 238 and 234 in secular equilibrium and thorium 232.

TABLE 6.1

SINGLE RADIONUCLIDE SOIL GUIDELINES NEAR-TERM

	FMPC (pCi/g)	INEL (pCi/g)	Weldon-Springs (Gilbert 85) (pCi/g)
Uranium 238 + 234	196	200	300
Thorium 232 (generic)*	5/15	5/15	15

*(5 pCi/g in top 15 cm. of soil and 15 pCi/g below this distance)

Table 6.1 indicates that the methodology used to develop the FMPC soil guidelines is consistent with the Manual specifications. The lower guideline calculated for FMPC is due to the assumed larger area of contamination at the site. The remainder of the homogeneous single radionuclide soil guidelines have been calculated for each radionuclide identified in above background concentrations at the FMPC by the Weston Company (WESTON 87). These guidelines are listed in table 6.2 along with comparable values from the AIRDOS analysis results and the INEL study results.

TABLE 6.2

Homogeneous Single Radionuclide Soil
Concentration Guidelines — Non-Aquatic Pathways**

Radioisotope		"Manual" Analysis (Soil Guidelines)	AIRDOS Analysis	INEL + D & D
strontium	90	20		50
technetium	99	1560	1930	
ruthenium	106	75		60
cesium	137	33		10
lead	210	4	4	
neptunium	237	12	21	
radium	226	5*	153	
radium	228	5*	118	
thorium	228	12	156	
thorium	230	5*	41	
thorium	232	5*	328	
uranium	234	204	279	400
uranium	235	132		60
uranium	238	196		200
plutonium	238	270	150	300
plutonium	239	241		300

*generic guidelines, required by DOE; which include an aquatic pathway.

+EG&G, "Criteria For Release of Idaho National Engineering Lab Following Decontamination and Decommissioning", Aug. 86

**all units are pCi/gram

Soil guidelines when mixtures of radionuclides are present

If several radionuclides are present in the contaminated area, the soil guidelines criteria may be defined by an inequality:

$$\sum_i \frac{S_i}{S_{G,i}} < 1.0$$

where:

S_i = above background concentration of radioisotope, i, in the soil, pCi/g

$S_{G,i}$ = single radionuclide soil guideline for radioisotope, i, pCi/g

Using Table 6.2 data, if there were four radioisotopes present in the soil, uranium 238, uranium 234, strontium 90 and cesium 137, this would mean that the residual concentration of these radionuclides in the soil would have to satisfy the inequality:

$$\frac{C(U238)}{196} + \frac{C(U234)}{204} + \frac{C(Sr90)}{20} + \frac{C(Cs137)}{33} < 1.0$$

where:

C(U238) = conc. of uranium 238 in soil, pCi/g

C(U234) = conc. of uranium 234, in soil, pCi/g

C(Sr90) = conc. of strontium 90 in soil, pCi/g

C(Cs137) = conc. of cesium 137 in soil, pCi/g

MIXTURE SUM FORMULA FOR FMPC

Table 6.2 contains single radionuclide soil guidelines for all the radionuclides identified at the FMCP site. Thus, the soil guidelines for mixtures of these radionuclides would be defined by the rather long

inequality:

$$\frac{C(Sr90)}{20} + \frac{C(Tc99)}{1560} + \frac{C(Ru106)}{75} + \frac{C(Cs137)}{33} + \frac{C(Np237)}{12} + \frac{C(Ra226)}{9} + \frac{C(Pb210)}{4}$$

$$+ \frac{C(Ra228)}{17} + \frac{C(Th228)}{12} + \frac{C(Th230)}{142} + \frac{C(Th232)}{28} + \frac{C(U234)}{204} + \frac{C(U235)}{132} + \frac{C(U238)}{196}$$

$$+ \frac{C(Pu238)}{270} + \frac{C(Pu239)}{241} < 1.0$$

In each case, the C in the numerator would represent the residual above background concentration of that specific radionuclide in the soil (pCi/g). The denominator is the single radionuclide soil guideline for that specific radionuclide, (pCi/g). For the radioisotopes thorium 230, thorium 232, radium 226 and radium 228, the generic guidelines in the denometer have been replaced with the site specific derived guidelines. (see report for details). In each case, the 5 pCi/g limit would still apply to the individual radionuclide.

This inequality allows for a good deal of flexibility in the cleanup prior to release of the site. It is also obvious that the radionuclides with the low values for soil guidelines, such as lead, radium and thorium will need to be decontaminated to a level of about 1 or 2 picocuries above background.

The final report also contains the calculations for the soil guidelines for the long term (10,000 years after the site release). The long-term soil guidelines are established by the aquatic paths, the drinking water pathway and the irrigation water pathway. The radionuclides that are in the contaminated zone (top meter of soil) at the initial release of the site, migrate downward towards the aquifer. As this migration occurs, the dose to the maximally exposed individual from the non-aquatic paths begins to decrease. The individual's dose actually decreases until the radionuclides

begin to enter the aquifer system. This analysis is described in detail in section 3.5. The analysis indicated that the dose to the maximally exposed individual would reach a peak at the end of the planning horizon, 10,000 years. At this time, the concentration of the radionuclides has been greatly reduced. The dose to the individual is less than the dose due to the non-aquatic pathways at the initial release of the site. The aquatic pathways and calculations for the D/S ratios are presented in this section.

The initial aquatic pathways are the drinking water path and the irrigation water path. All the pathways shown in Table 3.2 were reviewed. The only significant pathways were the drinking water and the plant foods - irrigation water pathway (q=3). The meat and milk pathway was not significant at 10,000 years.

The external radiation pathway, p=1 was insignificant compared to the water pathways because the radionuclides have migrated downward from the original contaminated layer of soil. The dust inhalation pathway also proved to be very small compared to the aquatic paths.

The soil guidelines are also calculated using equation 4.1. The D/S ratios were calculated for the drinking water pathway, dust inhalation pathways, direct radiation from the soil and irrigation of plant and fodder crops. The results, given in the final report in section 5.3, show a significantly decreased value of the D/S ratios for the long-term aquatic paths compared to the short-term non-aquatic paths.

It was concluded that the soil guidelines for the FMPC are established by the soil contamination at the initial release of the site for unrestricted public use.

Health effects based on soil guidelines of 100 mrem/year

The report contains an extensive review of the health effects of ionizing radiation. The detailed calculation of the health effects of residual radioactivity was not part of this study. These effects have been included in case the question should arise. The DARTAB program performs these detailed calculations, using the widely accepted stochastic data of the BEIR report (NAS 1980) to predict cancer incidence per rem of absorbed dose. The individual risk of a person developing cancer in this country today is between .17 and .20, since most health estimates show that about 17% to 20% of the population are at risk from cancer during their lifetime. The BEIR data can be used to predict increased health risk due to exposure to residual radioactivity.

Assume the maximally exposed individual received the annual committed dose equivalent of 100 mrem for 50 years while residing on the former FMPC site and the risk per rem is 100×10^{-4}. The increased risk estimate is:

$$\text{increased risk} = (100\ \frac{\text{mrem}}{\text{yr}})(10^{-3}\ \frac{\text{rem}}{\text{mrem}})(50\ \text{yr})(100 \times 10^{-4})\ \frac{\text{risk}}{\text{rem}}$$

increased risk = 5×10^{-4} incidences of cancer

$$\text{percent increase in risk} = \frac{.17 + .000054 - .17}{.17}(100) = 0.30\%$$

Thus, the maximally exposed individual, living at the former FMPC site, would have an absolute risk of 20.30% of cancer incidence instead of the so-called normal incidence of 20%.

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