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DERIVATION OF SITE-SPECIFIC SOIL GUIDELINES FOR THE FEED MATERIALS PRODUCTION CENTER AT FERNALD, OHIO DECEMBER 15, 1988

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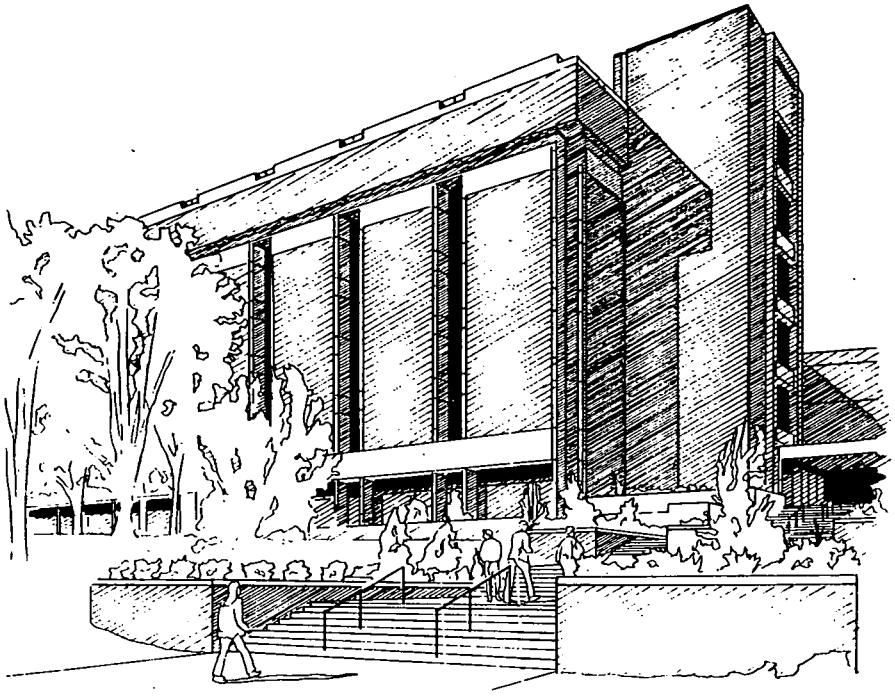

UNIVERSITY OF CINCINNATI
COLLEGE OF ENGINEERING

FINAL REPORT

DERIVATION OF SITE-SPECIFIC SOIL GUIDELINES FOR THE FEED MATERIALS PRODUCTION CENTER At Fernald, Ohio

DECEMBER 15, 1988

by

Dr. Roy Eckart
Mr. Randy Janke

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APPENDIX SECTION

1.0 INTRODUCTION

1.1 Purpose and Objective of Soil Guideline Study

The Department of Energy (DOE), has prepared a draft document, "A Manual for Implementing Residual Radioactivity Guidelines", (Gilbert, 1985). A revision to this document (still in draft form) was issued in 1987 (Gilbert, 1987). A "Final Draft" was issued in January of 1988 (Gilbert 1988). This document (which shall be referred to as "the Manual") presents procedures and data for implementing DOE decontamination guidelines at sites identified as Formerly Utilized Sites Remedial Action Program (FUSRAP) and remote sites identified as the Surplus Facilities Management Program (SFMP). The DOE guidelines provide criteria for certifying a site for release for unrestricted use. These criteria are expressed as guidelines for unrestricted use. Site specific soil guidelines are derived from a basic dose limit for the annual average radiation dose to a critical population group. One of the objectives of this study is to identify that population group and define the pathways that exist for that group from the radionuclide sources in the soil for exposure, by inhalation or ingestion of the radionuclides. The DOE annual committed effective dose equivalent limit of 100 mrem was also to be evaluated as a suitable dose criteria for unrestricted release of the site.

Utilizing the Manual and other derived guideline reports, the main objective of this study was to develop a set of site-specific residual radioactivity soil guidelines for the Feed Materials Production Center (FMPC) located in Fernald, Ohio. The facility is operated by the Westinghouse Materials Company of Ohio (WMCO).

The quantitative determination of the concentrations and types of radionuclides at the FMPC facility are still being determined. The Weston Company (WESTON 87) has completed a radiological analysis of the waste pits.

A number of radionuclides have been identified in the waste pit areas. Soil guidelines have been prepared for each radionuclide identified as present in the waste pits. Radiological data on the remainder of the site has been acquired in a less formal and less extensive manner. The soil guidelines have been calculated by a method that will allow the guidelines to be easily re-evaluated as new radiological data become available. This was accomplished by an adaptation of the mixture sum formula that will allow a great deal of flexibility in the site cleanup.

1.2 Environmental Standards Investigation

The recommendation of the DOE (KOCHER 87) and the NCRP (NCRP 87) are that the annual effective dose equivalent to the maximally exposed individual be limited to 100 mrem. This would include the dose equivalent from external radiation plus the effective dose equivalent from internal radiation. It is believed that the 100 mrem standard will soon be the industry standard for unrestricted release of decommissioned facilities and will replace the wide variety of standards cited in the discussion which follows. The soil guidelines for the FMPC are based on 100 mrem per year.

The environmental standards investigation was performed to determine the source and the reasoning for the derived limits of exposure and to compare these limits with those from various agencies. The agencies considered were the Nuclear Regulatory Commission (NRC), the Environmental Protection Agency (EPA), the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurement (NCRP), and the Department of Energy (DOE). With the exception of the ICRP, all of the above are organizations within the United States. When one considers the evolution of these organizations the flow of rules and guidelines is apparent. The ICRP

establishes the general philosophy and makes recommendations. The NCRP then follows the lead of the ICRP and delineates specific criteria for applications in the United States. The NRC adopts the recommendations of these organizations and establishes the regulations that will govern the commercial uses of radioactive sources. The regulations put forth by the NRC are contained in the Code of Federal Regulations (CFR), Title 10 covering energy. The chapter covering the limits of exposure to workers and the public is 10 CFR 20. This chapter refers the reader to 40 CFR 190 for additional regulations governing the uranium fuel cycle. The dose limits expressed in 10 CFR 20.105 which apply to an individual in the general public are summarized as follows: (a) dose to the whole body shall be less than 0.5 rem in any one one year and (b) when continuously present the dose shall be less than 2 mrem in any one hour period, or less than 100 mrem in any 7 consecutive days. As a comparison the dose limits delineated in 40 CFR 190 are (1) .025 rem to the whole body, (2) .075 rem to the thyroid, and (3) .025 rem to any other organ. As one can immediately see, the doses to the public from the fuel cycle (40 CFR 190) and from other commerical nuclear facilities (10 CFR 20) are not in agreement. The EPA limits are the more stringent in terms of total annual dose but there is no stipulation on the time span in which the exposure can occur. The NRC clearly delineates the limit one can be exposed to on a continuous basis. The most stringent committed effective dose equivalent limit is set by the DOE guidelines. The limit in this case is 100 mrem in a year from all sources. The major difference is in the committed dose. This stipulates that the quantity of radioactive material that is retained in the body is considered as a source for an individual's life. As an example, consider an individual who happens to ingest a small quantity of radioactive material. The individual's dose limit is now based on the dose that the

person receives each year from the ingested quantity which is retained in the body, plus any new dose for that year.

1.3 Review of Investigations Performed at Other Sites

The most relevant work related to this soil guidelines project was the work done for the Weldon-Springs vicinity properties. Several reports pertaining to the Weldon Springs site were obtained and used as guidance in the preparation of the FMPC soil guidelines. In addition to the Weldon-Springs work, the reports listed in Table 1.1 show the variety of radiological assessment type work that has been done. These studies covered many of the areas of concern in the FMPC soil guideline study. Some of these reports include the health assessment due to various sources, soil and air analysis, and the remedial action required to limit the dose to the public. When considering any of these areas one must investigate the pathways by which radionuclides end up as sources of exposure to the public. The assumptions needed to model the pathways are generally similar. Some of the more important assumptions to note are that secular equilibrium exists for elements below Ra-226 and Th-232 in their respective series decay chains, migration of elements does not change between isotopes, and source terms are generally considered homogeneous. Internal exposures are by the inhalation and ingestion pathways.

These studies provided useful information in the determination of the appropriate pathways to be considered and provided readily available comparisons for the analysis. Even though the circumstances of the FMPC study are significantly different in some areas, the methodologies employed are similar. The FMPC study is a unique situation because the site is still operating with no date established for decommissioning.

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Soil Guidelines Study Background Information

Company	Investigators	Site	Type of Study	Methodology/ Analysis	Time of Report
Camp Dresser & McKee Inc. Chicago, IL DE86003069	J.Y. Yang J. Wang	Weldon Springs Raffinate Pits	Environmental Assessment Remedial Action Study	Interim Stabilization Methods	1985
Argonne Natl. Lab, IL DE85004021	J. Wang J. Yang	Wayne New Jersey	Radioactive Releases from Thoriom Contiminated Site Pre-Remedial Act Study	Interim Stabilization Methods Two possibilities 1. No action 2. improved containment.	1985
Argonne Natl. Lab DE83014548	R.A. Wynveen W.H. Smith C.B. Mayes A.L. Justus	Chemicals Group Olin Corp. Joliet, IL	Remedial Action Radiological Survey	Instrument and smear surveys soil and air analysis and health assessment	1983
Bechtel Natl. DE85000629		Los Alamos New Mexico	Remedial Action Acid/Pueblo Canyon Site	Health assessment and removal of top soil	Oct. 1984
Bechtel Natl. DE86001223		Weldon Spring Quarry	Radiological Survey	Instrument and smear surveys soil and air analysis and health assessment	1985
Bechtel Natl. DE84015853		Weldon Spring Raffinate Pits	Radiological Survey	Instrument and smear surveys soil and air analysis and health assessment	1984

TABLE 1.1

Soil Guidelines Study Background Information

Company	Investigators	Sites	Type of Study	Methodology/ Analysis	Time of Report
Argonne Natl. Lab DE84017227	S.Y. Tsai J.M. Peterson	Weldon Spring Raffinate Pits	Analysis of groundwater contamination Weldon Spring	Analyze confinement capabilities of Raffinate Pits	1984
Argonne Natl. Lab DE84011431	R.A. Wynveen W.H. Smith C.M. Sholeen A.L. Justus K.F. Flynn	Watertown, MA Arsenal	Remedial Action Program FUSRAP	Radiological Survey Dose and Health hazard estimate of contamination	Oct. 1983
Bechtel Natl. DE86009331		Maywood, NJ	Onsite/offsite dispersal concepts	Eng. evaluation disposal of waste from Remedial Actions around Maywood, NJ	1986
Bechtel Natl. DE86009332		Colonie, NJ	Onsite/offsite dispersal concepts	Eng. evaluation disposal of waste from Remedial Actions around Maywood, NJ	1986
Bechtel Natl. Inc. DE85017437		Weldon Spring	Environmental/ Report	Health effects evaluation	July 1985

TABLE 1.1

1.4 The Use of Computer Programs for Analysis

The use of computer codes can greatly increase the number of radionuclides to be considered and assist in calculating the dose to the public. The codes utilized in this study were the AIRDOS-EPA(Moore 1979), and ONSITE/MAXI(Napier 1984).

AIRDOS was used in this study to calculate the dose equivalent to the maximally exposed individual following decommissioning of the site and the near term release of the site for unrestricted use. FMPC area site specific data were used in the code for such parameters as the population distribution, agricultural information, and the local meterological conditions. Details concerning the collection and evaluation of these data will be covered in the section 2. The air concentrations, surface, and ground deposition rates were also input to the code directly. This enabled the determination of doses from unit quantities of radionuclides mixed homogeneously in the environment. The pathways utilized within the AIRDOS code were: (1) external dose due to immersion in an infinite cloud, (2) external dose due to the exposure from surface contamination, (3) internal dose from inhalation of the airborne particulates, and (4) the internal dose due to the ingestion of meat, milk, water, and vegetables produced or grown within the contaminated zone.

The AIRDOS computer code was modified to incorporate the addition of a continuous contamination of the soil. The air concentrations were determined by estimating a value for the resuspension of soil in the zone of interest. The code was then used to calculate the dose from uranium 238. This value was compared to dose calculations performed using the methods in the Manual and hand calculations. The results of this comparison illustrated two facets not previously considered. The first of these was that the dose conversion factors used in the AIRDOS code were different from those used in the

Manual. The second facet was that great care must be taken when calculating the dose from a particular radionuclide. The dose conversion factors given in the Manual are for principal radionuclides. These are radionuclides with half lives of one year or more and members of decay chains. The dose conversion factors take into account the decay products up to a point where the daughter has a significantly long half life (one year or longer). The conversion factors used in AIRDOS only consider the individual radionuclide. In order to calculate the total dose contribution from uranium 238, an appropriate model of the uranium decay chain must be input into the code. At first glance this may appear to be a liability. However, this is actually an advantage, especially in the FMPC study. In nature the decay products will usually be in secular equilibrium with the parent. At a facility that processes uranium and slightly enriched uranium, seldom are all the daughters in secular equilibrium with the parent. Since the AIRDOS code makes no assumption regarding secular equilibrium, the resulting doses can be easily determined from any radionuclide concentration on an individual radionuclide basis. This was accomplished in this study by utilizing a value of 1 picocurie per gram of soil for selected radionuclides as the basis of dose calculations using AIRDOS. Additional details concerning the AIRDOS models, the modifications, and the results will be covered in Section 5.

1.5 The ONSITE/MAXI Computer Program

Mr. Bruce Napier and his co-workers at Pacific Northwest Laboratories (PNL) developed the ONSITE/MAXI computer program (Napier 1984) for the NRC. The objective of this program was to allow the NRC Waste Management Division staff to conduct human-intrusion, dose pathway analysis for onsite burial of low level radioactive wastes.

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Specific human intrusion scenarios were developed for various combinations of direct exposure to radiation, inhalation of airborne radionuclides, ingestion of agricultural products raised in contaminated soil and ingestion of water containing radionuclides. These scenarios will be described in more detail later in this section.

The ONSITE/MAXI software package contains four computer programs. ONSITE is an interactive computer program that allows the user to construct exposure scenarios for a wide variety of contaminated site soil parameters. MAXI 1 utilizes this scenario and site information to calculate the maximum annual dose to an individual at the site for the selected pathways. The MAXI 2 program generates intermediate dose conversion factors for food pathways. The dose conversion factors are stored in a file. The MAXI 3 computer program calculates similar dose conversion factors for aquatic pathways. Figure 1.1 depicts the flow chart for the ONSITE/MAXI computer program.

The MAXI 1 program contains data files with dose conversion factors for inhalation of air containing radionuclides and external dose conversion factors. The dose conversion factors for inhalation are based on the lung model developed by International Commission on Radiological Protection. (ICRP) ICRP 30 (1978a) describes this model in great detail. It is the most widely used lung model in the world for calculation of inhalation dose. For ingestion pathways, food products or drinking water, the MAXI 2 and MAXI 3 computer programs utilize the dosimetry model called the GI tract model, developed by ICRP in reports 23 and 30.

For external exposure, dose conversion factors are utilized which convert the radionuclide source strength to the dose rate in tissue at a height of 1 meter above the surface. This is also a widely used procedure to calculate the dose to an individual from a contaminated surface or volume soil source.

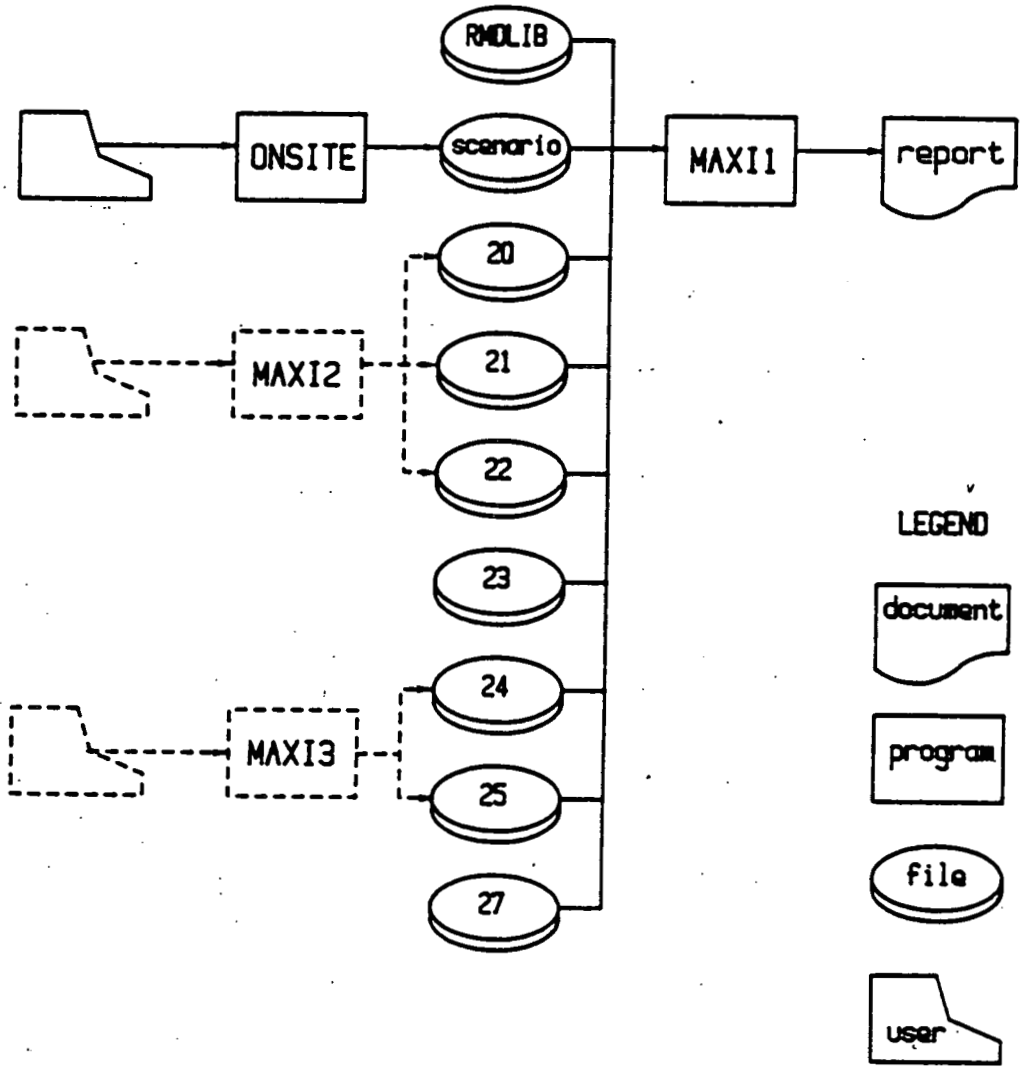

FIGURE 1.1 ONSITE/MAXI SOFTWARE PROCESS FLOW CHART (NAPIER 84)

MAXI 2 generates dose conversion factors associated with the food chain pathways. MAXI 2 accounts for radionculides in the soil that are taken up by the roots of garden or farm crops. It also accounts for deposition of radionuclides on soil or crops.

The MAXI 3 computer program is used to evaluate the drinking water and aquatic food pathway. MAXI 3 generates dose conversion factors for contaminated drinking water and aquatic food harvested from contaminated water. There are four standard scenarios that can be accessed interactively with the ONSITE program and one scenario that can be completely defined by the user. These scenarios are briefly described below:

(1) External Exposure Scenario. An individual is assumed to work for 2000 hr/yr in a 1 hectare (ha) area previously used for onsite disposal. External exposure factor files are supplied to consider surface-soil contamination, buried wastes at depths of 0.5 m or 1.0 m, or entry into a room (or vault) that is used for waste storage or disposal. For soil contamination, the inventory may be modified by a factor of 0.2 to account for dilution. Only whole-body dose is calculated. The user selects the location of the waste (e.g., surface, buried, or stored) and supplies the waste inventory. The user may modify the amount of radioactive decay before exposure, the dilution of the waste, the reference site size, and the duration of exposure.

(2) External Exposure Plus Inhalation Scenario. An individual is assumed to work for 2000 hr/yr in a 1 hectare area with surface-soil contamination resulting from a waste exhumation event. Air concentrations of radionuclides are calculated using a resuspension equation by Anspaugh (1975). For the resuspension equation, the age of the contamination at the beginning of the scenario is assumed to be zero and the top 1.0

centimeter of the contaminated surface soil is assumed to be available for resuspension. Doses to the total body, bone, lungs, thyroid, and the lower large intestine (LLI) of the GI tract are calculated. The dilution factor for the inventory is 0.2 unless changed by the analysis. The user provides the waste inventory. The user may modify the amount of radioactive decay before exposure, the duration of the exposure and the reference site size. The user may also optionally select a mass-loading equation, and specify fewer organs. This scenario is similar to the intruder-construction scenario described in the Draft Environmental Impact Statement (DEIS) for 10 CFR Part 61 (U.S. NRC 1981).

(3) Agricultural Scenario. An individual is assumed to raise his entire diet in 1 hectare of soil contaminated by the onsite disposal of radioactive wastes. The individual is assumed to be exposed 2000 hr/yr by external exposure and by inhalation of resuspended radionuclides in soil. Again, the air concentration resulting from resuspension is calculated using the equation by Anspaugh (1975), with parameters presented for Scenario 2. Doses to total body, bone, lungs, thyroid and LLI are calculated. The user furnishes the waste inventory to which a dilution factor of 0.2 is applied. Modifications can be made to the amount of radioactive decay before exposure, the duration of the exposure, the fraction of the total diet grown on the site, the reference site size, and the dilution of the waste. As in the previous scenarios, the user may substitute the mass-loading dust model and specify fewer organs. This scenario is similar to the intruder agriculture scenario described in the DEIS for 10 CFR Part 61 (U.S. NRC 1981).

(4) Irrigation/Drinking-Water Scenario. An individual is assumed to use a water supply contaminated by radionculides from an onsite disposal site for irrigation and/or drinking. The user is required to input the concentration of each radionuclide in the water supply. The exposed individual is assumed to irrigate his field at a rate of 150 $L/m^2/mo$ during a six month growing season. The site is assumed to be irrigated with contaminated water for 10 years prior to the beginning of the scenario. The individual obtains his entire diet (or a fraction of it) from a 1 hectacre irrigated field, and drinks 1.2 L of water per day from a contaminated water source. In addition, he is assumed to be subjected to 2000 hr/yr of external exposure and inhalation of resuspended radionuclides that are deposited on the surface of the soil by the irrigation water. Doses to total body, bone, lungs, thyroid and LLI are considered. Irrigation and drinking water may be from the same or separate water supplies. When providing the inventory, the user is asked for radionuclide concentration in drinking and irrigation water separately. Irrigation or drinking water can be individually simulated by entering zero concentrations for the other pathway. The user may modify the irrigation rate, the length of the irrigation season, the time of irrigation prior to the scenario, the fraction of diet grown with contaminated irrigation water, the consumption of drinking water, the times of exposure, the resuspension equation selection, the reference site size, and the organ selection.

(5) User-Defined Scenario. The user may construct his own scenario by selecting exposure pathways and defining conditions associated each pathway.

1.6 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. The Manual, as it will be referred to, was determined to apply to the FMPC situation. Assuming the FMPC plant is decommissioned at some future date, the Manual can be used to develop soil guidelines for the unrestricted release of the site. The pathways and soil guidelines may also be used to assist in the remedial action program.

The major task in adapting the Manual to the FMPC situation was development of a site specific analysis. This required information on the size and shape of the contaminated areas, the radionuclides present in the soil, (source terms), the chemical form of the radionuclide, an exposure scenario, a site-specific pathway analysis, geologic and hydrogeologic information about the site and dozens of site specific parameters such as: soil density, soil distribution coefficients, runoff coefficients, type of soil, annual precipitation, etc.

1.7 Goals of this Study

The major goal of this study was to develop a set of site specific radionuclide soil guidelines for residual radioactivity at the FMPC. The project used DOE guidelines and the Manual to develop a set of criteria for certifying the site for unrestricted use following decommission. The residual radioactive soil guidelines were developed to limit the committed effective dose equivalent of the maximally exposed individual to 100 mrem per year or less (US DOE 1985a,b).

1.8 Limitations of This Study

The major limitations of this study were the lack of availability of site specific data; especially information on the extent of the radionuclide contamination at the site. The soil guidelines are dependent on knowledge of the specific radionuclides that are present on the site in above background concentrations. The analysis is also very dependent on the chemical form of these radionuclides and the size and shape of the contaminated area (local hot spots vs. large areas). The depth of the contaminated area is also an important factor. The Weston report (Weston 87) provided good information on radionuclides in the waste pit areas. There was also some limited information provided on uranium 238 and thorium 232 in other areas of the site. There was no information provided on the K65 silo contents. Thus, the project focused on guidelines for radionuclides that were identified in the waste pit areas. The soil guidelines for single radionuclides and the mixture sum formula apply to large areas such as the waste pit areas. If smaller areas of contamination exist at other locations (small hot spots) the results will not directly apply to these small hot spots. Simple modifications would be required.

And finally, it will also be obvious to the reader of this report, that many of the assumptions and data used throughout the Manual and this analysis are the best engineering assumptions and data that are available today. Some of these techniques may be improved as better data and better analytical techniques are developed. The Manual requires a very conservative analysis, thereby insuring the health and safety of the general population, when the FMPC site is released for unrestricted use.

2.0 SITE SPECIFIC INFORMATION

2.1 Non-Radiological Data Acquisition

2.1.1 Description of the FMPC site and nearby properties

The Feed Materials Production Center (FMPC) located at Fernald, Ohio is operated by Westinghouse Materials Company of Ohio (WMCO) for the U.S. Department of Energy (DOE). It is the only uranium refinery operated by the DOE. The plant chemically purifies various forms of uranium to an extremely high purity uranium metal. The facility is located approximately 20 miles northwest of Cincinnati, Ohio, with operations covering about 136 acres in the center of a 1025 acre site. Several rural communities lie within a 1-5 mile radius of the plant, as shown in Figure 2.1. The FMPC site is predominantly level and is located 3/4 mile west of the big bend area of the Great Miami River. Paddy's Run Creek runs along the west side of the complex. The site layout is illustrated in Figure 2.2.

On-site vegetation is typical of that occuring elsewhere in the region under similar land use practices. The on-site areas north and west of the production area are moderately wooded with a variety of deciduous hardwoods. To the immediate north of the production area and to the Southwest White and Austrian Pines were planted in 1973. The remainder of the site is covered with a variety of pasture grasses typical of the area. Most of the pasture grasses are leased to local dairy producers for grazing purposes. There are several small industries nearby. The major economic activities in the area are farming, dairy farms, and raising beef cattle. Major farm crops are sweet and field corn, soybeans and wheat. Gravel and ground water are also important products sold commercially. A water company just 2 km upstream of the FMPC outfall pumps nearly 20 million gallons of water per day. Many gravel pit operations are found in the Miami Valley both near the river and

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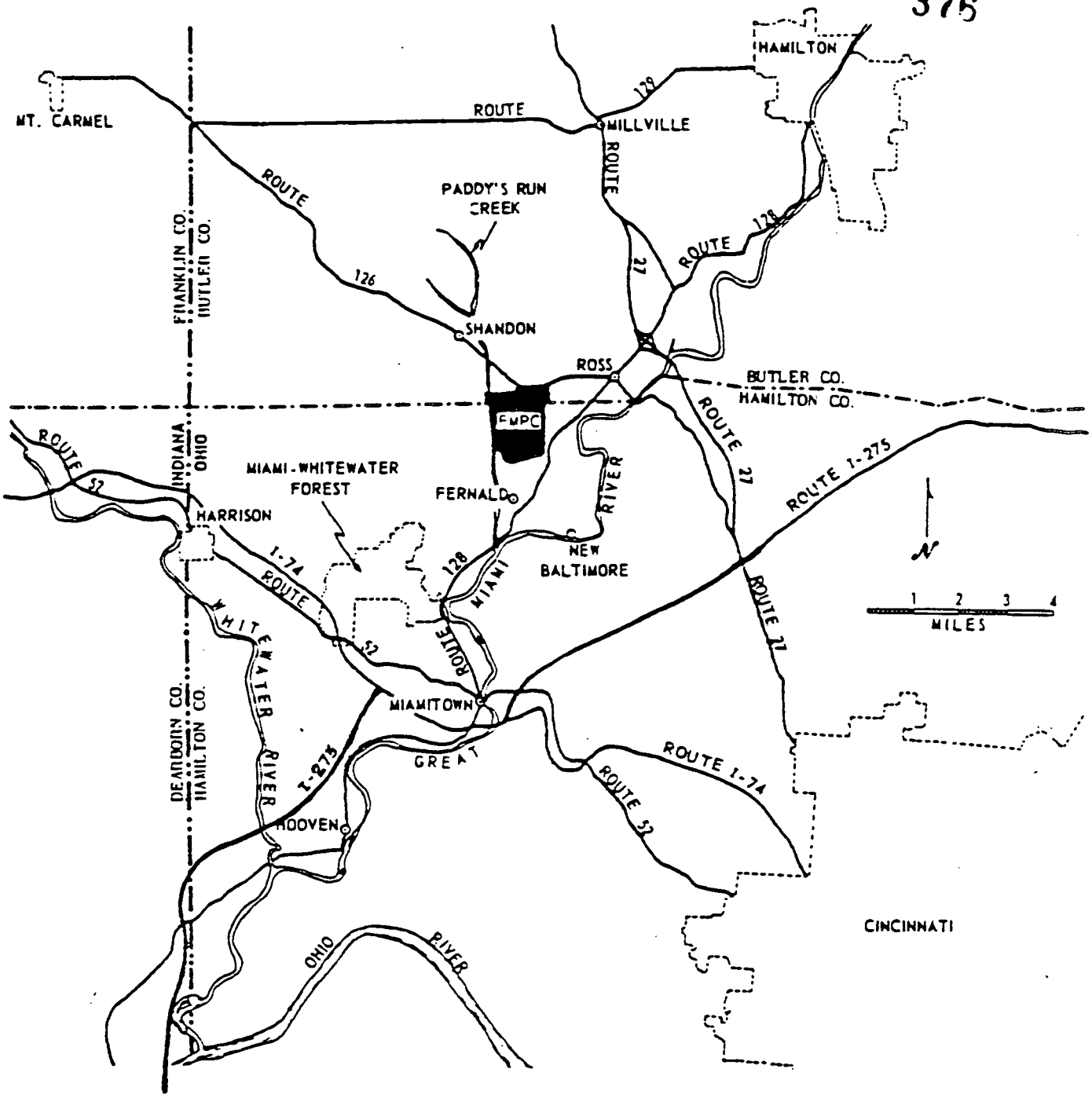

FIGURE 2.1 FMPC AREA MAP (TAKEN FROM FMPC ENVIRONMENTAL MONITORING REPORT FOR 1984, NLO)

FIGURE 2.2 GENERALIZED LAYOUT OF THE FMPC SITE

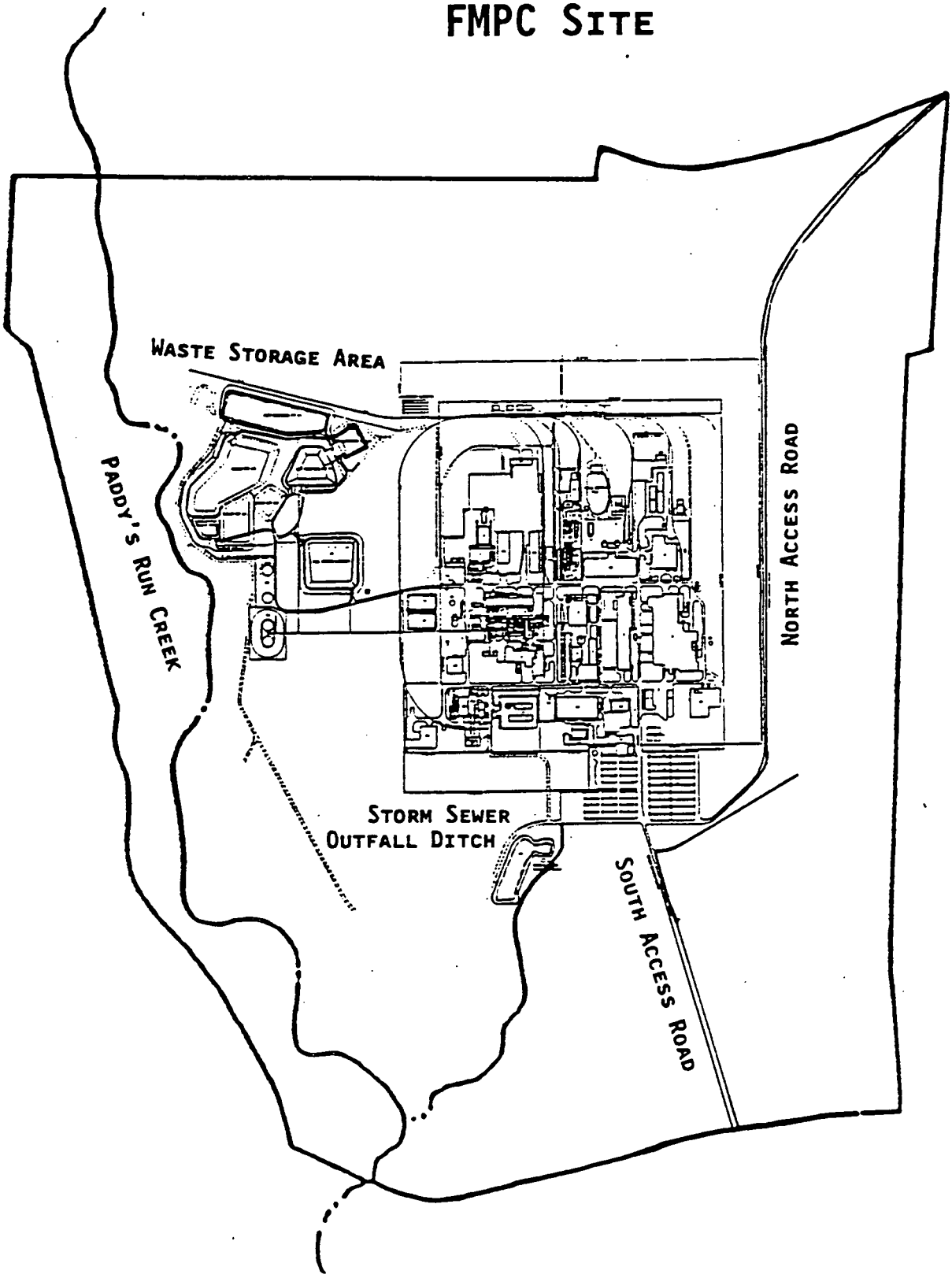

Figure is a composite based on material made available by Westinghouse Materials Company of Ohio (WMCO).

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inland in the flood plains.

The area around the FMPC is sparsely populated with approximately 40 percent of the people within 5 miles occupying the areas East, North East and South East of the site. The remaining people are spread evenly in all directions. Additional details on population density will be given in Section 2.1.4.

2.1.2 Agricultural base

The present agricultural base around the FMPC site provides a good indication of the possible use of the site if it were released for unrestricted use. We have therefore catalogued the present agricultural use.

The agricultural base for the area surrounding the FMPC consists primarily of farms producing corn, hay, and wheat and dairy forms located in Hamilton and Butler countries.

The FMPC resides in an area of Ohio that is both rural and developed, consisting of large farms and cities within close proximity to the plant. For this reason a large area was used for considering the population dose and to support the farmer scenario. An area with a 30 mile radius from the FMPC was then selected as the assessment area for considering the agricultural base. The assessment area occupies nearly all of both Hamilton and Butler counties. Using this basis, a crop and farm animal distribution was determined for the FMPC study. Information was obtained from the Hamilton County Extension of the Department of Agriculture. The data was a list of the crop and livestock production in the State of Ohio. From this data it is immediately apparent that the four major crops are (1) corn - with Butler County producing just about 11 times more bushels than Hamilton County, (2) soybeans with the ratio of about 5 to 1, (3) wheat - with Hamilton County

producing fewer than 1000 acres in 1985, and (4) hay with the ratio of about 4 to 1. This information reinforces the concept that a large portion of Hamilton County is dedicated to urban and city living. This fact has important consequences on the pathway analysis of people in the assessment area. Since a majority of the public live to the Southwest of the FMPC site and the majority of the food is grown in the North and Northwest, careful consideration must be given to the quantity of food that will be grown in the assessment area. A significant quantity of food is grown within 5 miles of the facility. The agricultural data also contains the total number of beef and milk cattle as well as the number of hogs and sheep.

The total number of animals and crops were reduced to density distributions based on the 30 mile radius around the plant. This was accomplished using scale maps of the two counties and estimating the land available for agriculture. Since the population density was known to a distance of 50 miles from the site, a reasonable estimation for the farming could be made. Table 2.0 is a summary of the population and agricultural distribution within 5 miles of the site.

TABLE 2.0

SUMMARY OF AREA (5 mile radium) SURROUNDING THE FMPC

Area	Meat Animals	Milk Cattle	Food Crops (Square Meters)	Population
N	311	47	0.500E+07	403
NNE	311	47	0.500E+07	200
NE	311	47	0.500E+07	443
ENE	142	28	0.853E+07	2255
E	142	28	0.853E+07	464
ESE	142	28	0.853E+07	646
SE	142	28	0.853E+07	1455
SSE	142	28	0.853E+07	892
S	142	28	0.853E+07	606
SSW	142	28	0.853E+07	353
SW	142	28	0.853E+07	167
WSW	142	28	0.853E+07	398
W	142	28	0.853E+07	470
WNW	311	47	0.500E+07	142
NW	311	47	0.500E+07	463
NNW	311	47	0.500E+07	470

2.1.4 Population density distribution

Population density distribution data was based from a "Report of Findings, Population Studies for DOE Feed Materials Production Center, near Fernald, Ohio, for NLO, Inc.", May 1981. This data, although established for a radius of 80 km, was easily condensed to meet the needs of this study. This was accomplished by using an averaging technique and taking a ratio of the data for the greater distances to the smaller sectors used in the study. The original data and the condensed data are presented in Appendix A. This information is then input to the AIRDOS computer code so that population exposure and risk assessments can be determined.

2.1.5 Area geological features

Glacial action during the Illinoian and Wisconsin Glaciation periods left the area in much the same geological form as it is today. In the immediate

area, outwash from retreating glaciers filled the remains of an ancient river valley. The Great Miami River, which runs in a southerly direction about 1 km east of the FMPC, cut its present course through this fill.

To understand what the area is like today, one must know something of the underlying structure. The most prominent feature to note is a valley, approximately 2 miles wide and 200-300 feet deep. This valley represents the remnants of a preglacial drainage system. The average gradient of this buried valley, from West Carrollton to the Ohio River, is approximately 2 feet per mile. Just south of Hamilton, near Fairfield, the gradient flattens to approximately 1.3 feet per mile. This gradient remains nearly constant across the area being studied.

The configuration of the bedrock surface, upon which the valley-fill aquifer material rests, can be described as a flat-bottomed trough with steeped walled sides [GeoTrans, 1985]. The trough is inclined slightly (about 2 feet per mile) toward the southwest. The aquifer is assumed horizontal over the limited area around and near the FMPC site. There is a bedrock island to the east of the FMPC. It acts as a barrier to flow and diverts ground water around it towards the towns of New Baltimore and Fernald.

The valley-fill aquifer was deposited within this bedrock valley system by repeated ice advances in combination with fluvial sediment transport processes during interglacial periods. The aquifer has three types of unconsolidated material: (1) ice contact outwash, (2) proglacial outwash, and (3) till. The internal structure of these materials depends on the proximity of the continental ice sheet at the time the material was deposited. The proglacial drift and the ice contact are highly stratified where the till, being directly deposited by the ice, is not stratified.

Till can be either of two types, lodgment or ablation, with each having

different water transmitting properties. Lodgment is more compact than ablation and, therefore less permeable. Ablation, being less compact is associated with surficial moraine deposits. In general till units are rich in clay and act to retard water movement. The clay enriched layers contain silt and sand in their textural makeup. At the FMPC site, lodgment and ablation till restrict both recharge from precipitation and the hydraulic connection between the upper and lower portions of the aquifer system. The valley-fill aquifer of the Great Miami River is an agglomeration of the aforementioned types of unconsolidated sediments. These drift materials have been integrated into a single, regional aquifer system. Most of this information in this section was obtained from the FMPC Environmental Monitoring Annual Report for 1985, and from a GeoTrans, Inc. report prepared for the Ohio Environmental Protection Agency entitled, "Preliminary Characterization of the Groundwater Flow System, near the Feed Materials Production Center, Great Miami River Valley-Fill Aquifer, Fernald, Ohio". The full references are given at the end of this report.

2.1.6 Hydrogeology of the area

Section 2.1.5 contained information indicating that the valley-fill is composed of three types of unconsolidated sediments. These drift materials have been integrated into a single, regional aquifer system. A close look at the internal character of this aquifer and its associated hydraulic properties suggests extreme heterogeneity on a local scale. Individual units or strata do not possess extensive lateral or vertical continuity (tens to hundreds of feet). The fluid transmission properties of the media are therefore anisotropic with respect to direction. The magnitude of directional hydraulic conductivity varies naturally with the lithology of the sediments and the

scale (the ratio of the depth to length of the region) at which the aquifer property is measured.

The aquifer systems in this vicinity can be characterized as follows: (1) the main valley-fill aquifer unit (type I-A-1 and I-A-2) and (2) a secondary aquifer (type III). The main valley-fill aquifer is located in the vicinity of the Great Miami River and is predominantly sand and gravel with minor clay lenses. The horizontal conductivity of this main aquifer is approximately 350 feet per day and the vertical conductivity is 35 feet per day with a recharge of 15 inches per day.

The second aquifer unit extends further westward of the river. It is divided into two vertical subunits by a laterally extensive clay layer located about 440 feet above mean sea level. The horizontal hydraulic conductivity of these subunits is 250 feet per day with a vertical conductivity of 25 feet per day and a recharge of 6 inches per year. The conductivity of the intervening clay is 0.025 feet per day. The ground water velocity in the Fernald FMPC area is estimated to be 2.2 feet per day.

The aquifer near the FMPC site is characterized by extreme variability and hence the flow or containment of water is dependent on the local variations. The area in general has the capability of retaining large quantities of water. It was previously mentioned that this gives rise to a significant economic incentive for the supply of water to industry. The water extracted from the aquifer is used in and around the area.

2.1.7 Soil data

The flow and storage of water, the movement of air, and the ability of the soil to supply nutrients to plants are properties determined by the size and arrangement of the soil particles. The soil is composed of two types of particulate matter; organic and inorganic. The inorganic materials occupy about one half of the total volume of surface soils. The percentages of sand, silt and clay determine the texture of the soil.

The soil is broken into three vertical layers which are: (1) the surface soil, which is from 30 to 60 cm deep; (2) the subsoil, which extends to about 1 meter; and (3) third layer, which extends to 1.5 meters deep and is composed of loose and partly decayed rock. These layers are generally designated as the A, B and C horizons. The exact composition of these layers will determine which types of plants can grow and how much nutrients are available for their growth.

The soils in the vicinity of the FMPC vary slightly with location. In general, the soils have fairly high percentages of clay and silt. Some deviation from this is found in the soils nearer to the gravel pits, where slightly higher concentrations of sand are found. For the most part, the soils are classified as loam or clay loam. Further details on the contaminants of the soils are given in the next section covering the radiological data aquisition.

2.2 Natural Background Data

Data were collected to determine the natural level of radionuclides in soil, water and food products. The Manual defines a contaminated area as an area with above background concentrations of a radionuclide if the inequality

$$S_i > S_{B,i} + \delta S_{B,i} + \delta S_i$$

is satisfied.

where:

S_i = concentration of radionuclide i in soil, pCi/g

$S_{B,i}$ = natural background of radionuclide, i, pCi/g

$\delta S_{B,i}$ = twice the standard deviation in the measured background concentration, pCi/g

δS_i = twice the standard deviation of the counting statistics, pCi/g

This section contains a compilation of data related to normal levels of radioactivity in soil, water and foods.

Table 2.1 consists of Ra-226, Th-232, U-238 and K-40 concentrations in soil stated in units of pCi per gram of soil. The values are given for Ohio and for the lowest and highest state values in the United States. The values for Ohio can be compared to the lows and highs, and observe that for Ra-226, Ohio is equal to the high value, for Th-232 Ohio is at the U.S. average, and for U-238 Ohio is a little below the high value. Only one piece of data was found for K-40 and is presented at a U.S. average.

TABLE 2.1

MEAN RADIONUCLIDE CONCENTRATIONS IN SOIL (Myrich 1983)

State		^{226}RA (pCi/g)	^{232}TH (pCi/g)	^{238}U (pCi/g)	^{40}K (pCi/g)
Ohio		1.50	1.00	1.40	
LOW	Alaska	0.65			
	Florida		0.24		
	Louisiana			0.58	
HIGH	Kentucky	1.50		1.60	
	Nevada		1.50		
U.S. Mean		1.10	0.98	1.00	12.00

Measurements were performed by the University of Cincinnati on local sand and gravel samples for the WMCO In-Vivo Monitoring Facility. Samples were taken from local concrete supplies and analyzed for uranium 238, radium 226, thorium 232 and potassium 40. The results of these radiological measurements are shown below in table 2.2. Although these are not soil measurements, the results of the sand analysis are likely to be an indication of the background content of these radionuclides in local soils.

TABLE 2.2 (Eckart, et.al. 1987)

NATURAL RADIONUCLIDES IN SAND*

Concrete Vendor	^{226}Ra pCi/g	^{238}U pCi/g	^{232}Th pCi/g	^{40}K pCi/g
Ernst	0.464	0.985	0.239	6.26
Harrison	0.428	0.402	0.208	7.19
Hilltop	0.367	0.753	0.217	6.28
Miami Valley	0.438	0.920	0.214	7.35
Plainville	0.437	1.910	0.211	7.12
Roth	0.476	1.010	0.249	7.22

*maximum reported concentrations

Table 2.3 consists of concentrations of uranium isotopes in drinking water given in units of pCi per liter of water. Values are given for Cincinnati, specifically, and for the high and low cities in the United States. A U.S. average is also tabulated. It can be seen in this table that all isotopic concentrations given for Cincinnati are at or close to the lowest values found in the country.

TABLE 2.3

AVERAGE URANIUM CONCENTRATIONS IN DRINKING WATER (Cothern 1983)

City	^{234}U (pCi/L)	^{235}U (pCi/L)	^{238}U (pCi/L)
Cincinnati	0.035	0.002	0.029
HIGH: Las Vegas	3.150	0.111	2.080
LOW: Portland	0.015	0.002	0.011
AVERAGE: U.S.	0.364	0.018	0.277

Table 2.4 consists of concentrations of the isotopes of Plutonium in drinking water given in units of pCi per liter of water. The data given is for the City of Columbus and again for high and low city values in the United States. The findings of this search showed no values for Cincinnati. The values for Columbus were cited, since it is the closest city in which drinking water samples were analyzed. The Table 2.4 indicates that the concentrations found in Columbus are at or near the lowest found in the U.S.

TABLE 2.4

AVERAGE PLUTONIUM CONCENTRATIONS IN DRINKING WATER(EPA 1985)

Location	^{238}Pu (pCi/l)	^{239}PU (pCi/l)
OH: Columbus	0.005	0.000
HIGH: SC: Jenkinsville	0.067	0.053
LOW: MS: Port Gibson	0.003	0.000
AVERAGE: U.S.	0.035	0.026

Table 2.5 consists of concentrations for Radon-222 in municipal water supplies. The values are given in units of pCi per liter of water. Values

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were not found for the State of Ohio, therefore the state values found are presented and an average is computed for these states.

TABLE 2.5 A

MEAN RADON-222 CONCENTRATIONS IN MUNICIPAL WATER (Prichard 1983)

STATE	^{222}Rn In Well Water (pCi/L)
Arkansas	135.00
Indiana	151.00
Iowa	175.00
Louisiana	151.00
Minnesota	252.00
Nebraska	262.00
New Mexico	287.00
Oklahoma	117.00
AVERAGE	191.25

Radon values for Ohio ranged from a few procuries per liter to a high of 685 picocuries per liter in Huber Heights (EPA 85).

TABLE 2.5 B

URANIUM 238 CONENTRATION IN DRINKING WATER (Cothern 1983)

CITY		Concentration of Uranium 238 (pCi/L)
Cincinnati	OH	0.028
Montgomery	AL	0.014
Berkeley	CA	0.018
Los Angeles	CA	1.400
Denver	CO	0.974
Miami	FL	0.083
Chicago	IL	0.182
Las Vegas	NV	2.080
Knoxville	TN	0.025
Columbia	SC	0.009

Table 2.6 presents concentration values for Ra-226 in milk and meat, given in units of pCi per kg of milk or meat. The values are given for locations in the United States and are then averaged.

TABLE 2.6

Radium-226 CONCENTRATIONS IN MILK AND MEAT

Site	Milk (pCi/kg)	Meat pCi/kg)	Reference
Chicago	0.23	0.55	Hallden 83
New York State	0.13	0.00	Stroube 85
New York City	0.25	0.02	Fisenne 70
	0.25	0.46	Hallden 83
San Francisco	0.09	0.02	Fisenne 70
	0.25	0.46	Hallden 83
Tennessee	0.27		Stroube 85
Wisconsin	0.23		Stroube 85
AVERAGE	0.21	0.25	

Table 2.7 is a compilation of data found for different radionuclides in foods. These concentration values are given in units of pCi per kg of food. The main types of food in which values were sought for were milk, meat, potatoes, corn, wheat and soybeans, since these are the major crops and foods raised in the Cincinnati area. Upon locating data for a particular radionuclide, concentrations may be presented for some foods and not others. Therefore not all of the radionuclides presented here were determined for all of the food types in which we are interested. In some cases, data was found for general food groups instead of the particular type of food. For example, for Sr-90, Th-228, and uranium, values were found for "dairy foods" in general, but not for "milk". Therefore we can assume the value of milk to be that found for dairy foods. The values presented for Ra-226 are averaged over data found for the cities of New York, San Francisco, and Chicago, and the values for Sr-90 are averaged over data found for New York and San Francisco.

TABLE 2.7

RADIONUCLIDE CONCENTRATIONS IN FOODS

Food Type	^{90}Sr(a) (pCi/kg)	^{226}Ra(b) (pCi/kg)	^{137}Cs(c) (pCi/kg)
Dairy Foods	4.624		
Milk		0.210	
Meat	1.097	0.250	2.400
Cereals	3.317		3.500
Wheat Flour		2.733	
Leafy Vegetables	4.881	1.312	5.200
Root Vegetables	5.000	2.417	2.100
Potatoes	3.637	1.612	
Dried Beans		4.200	

Food Type	^{40}K(d) (pCi/kg)	^{228}Th(e) (pCi/kg)	Uranium (f,g) (pCi/kg)
Dairy Foods	4.624		
Milk		0.210	
Meat	1.097	0.250	2.400
Cereals	3.317		3.500
Wheat Flour		2.733	
Leafy Vegetables	4.881	1.312	5.200
Root Vegetables	5.000	2.417	2.100
Potatoes	3.637	1.612	
Dried Beans		4.200	

References Cited:

a. Stroube 85
b. Halladen 83
c. Hardy 82
d. Klement 64
e. Turner 58
f. Tracyb 83
g. Welford 67

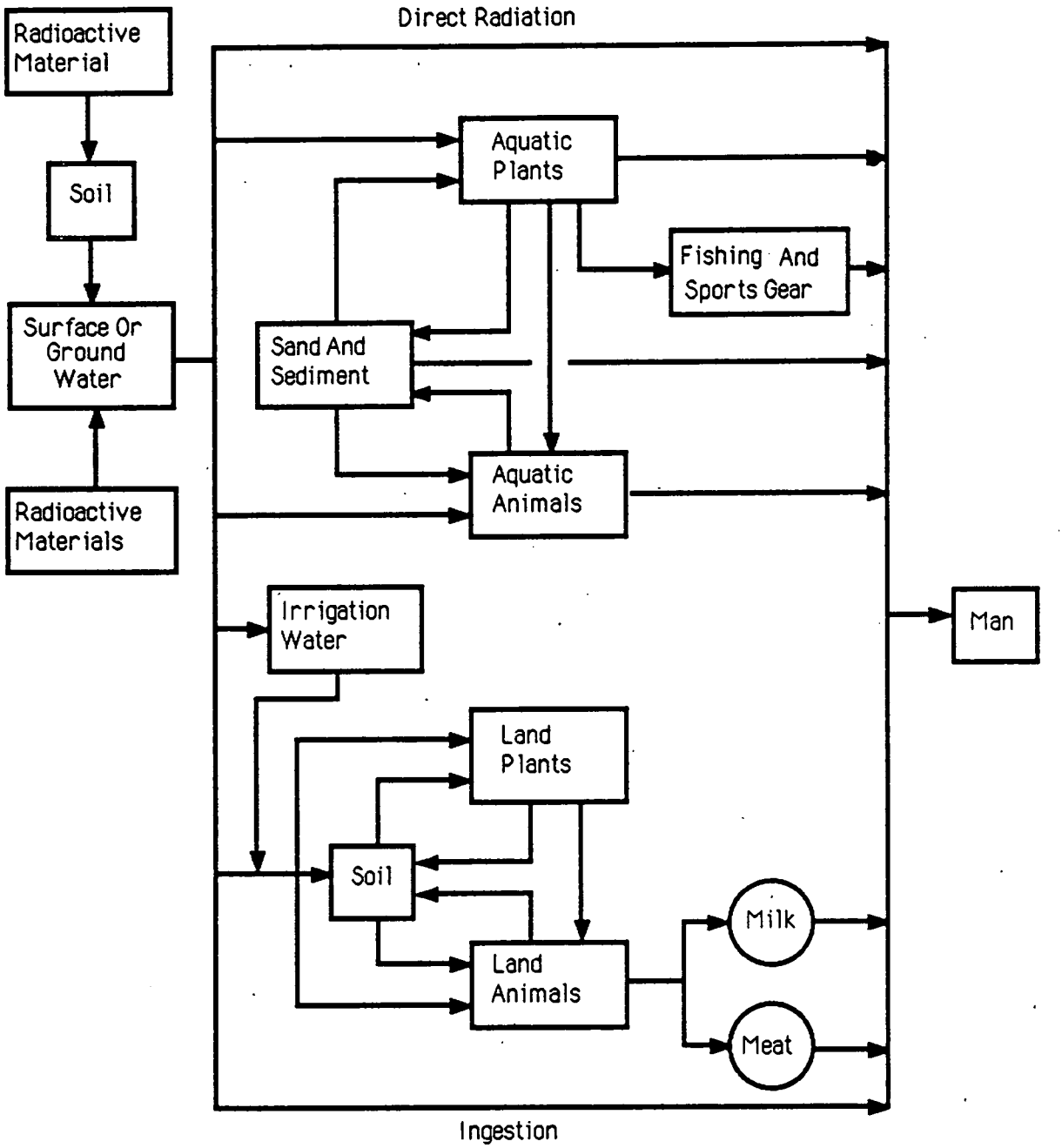
3.0 PATHWAY MODELS AND ANALYSIS FOR ENVIRONMENTAL TRANSPORT OF RADIONUCLIDES

3.1 Generalized Pathway Analysis

Environmental transport pathways describe the movement of radionuclides from the source of emission through the biosphere to the human population. These pathways are considered to be of prime importance in evaluating the impact of radionuclides on human health and the environment. Various pathway models were reviewed as part of this work. Figures 3.1 and 3.2 illustrate typical pathway models. There are two major generalized pathways: the liquid pathway shown in Figure 3.1 and the gaseous pathway shown in Figure 3.2.

The liquid pathway, shown in Figure 3.1, is usually called the aquatic pathway. Radioactive material escapes or is released from some source and ends up in surface water or ground water. Radionuclides usually originate in this pathway as liquids or by fallout or washout of airborne radionuclides. Each of the heavy lines shown in Figure 3.1 represent a means by which the radionuclide can be transported by surface or ground water from the source to human populations. These radionuclide transport routes are called pathways. In this figure, there are a large number of possible pathways. Direct radiation, shown at the top of the diagram, would be the dose an individual would receive from swimming or boating in water (lake or stream) containing above normal concentrations of radionuclides. The pathway at the lower end of the diagram, labeled "ingestion" would represent the dose an individual would receive from drinking water containing small quantities of radionuclides. An example of a rather lengthy pathway shown on this figure would be the use of water containing radionuclides to irrigate crops. This contaminated irrigation water introduces radionuclides into the soil. The radionuclides

Figure 3.1 Generalized Liquid Pathways to Man.



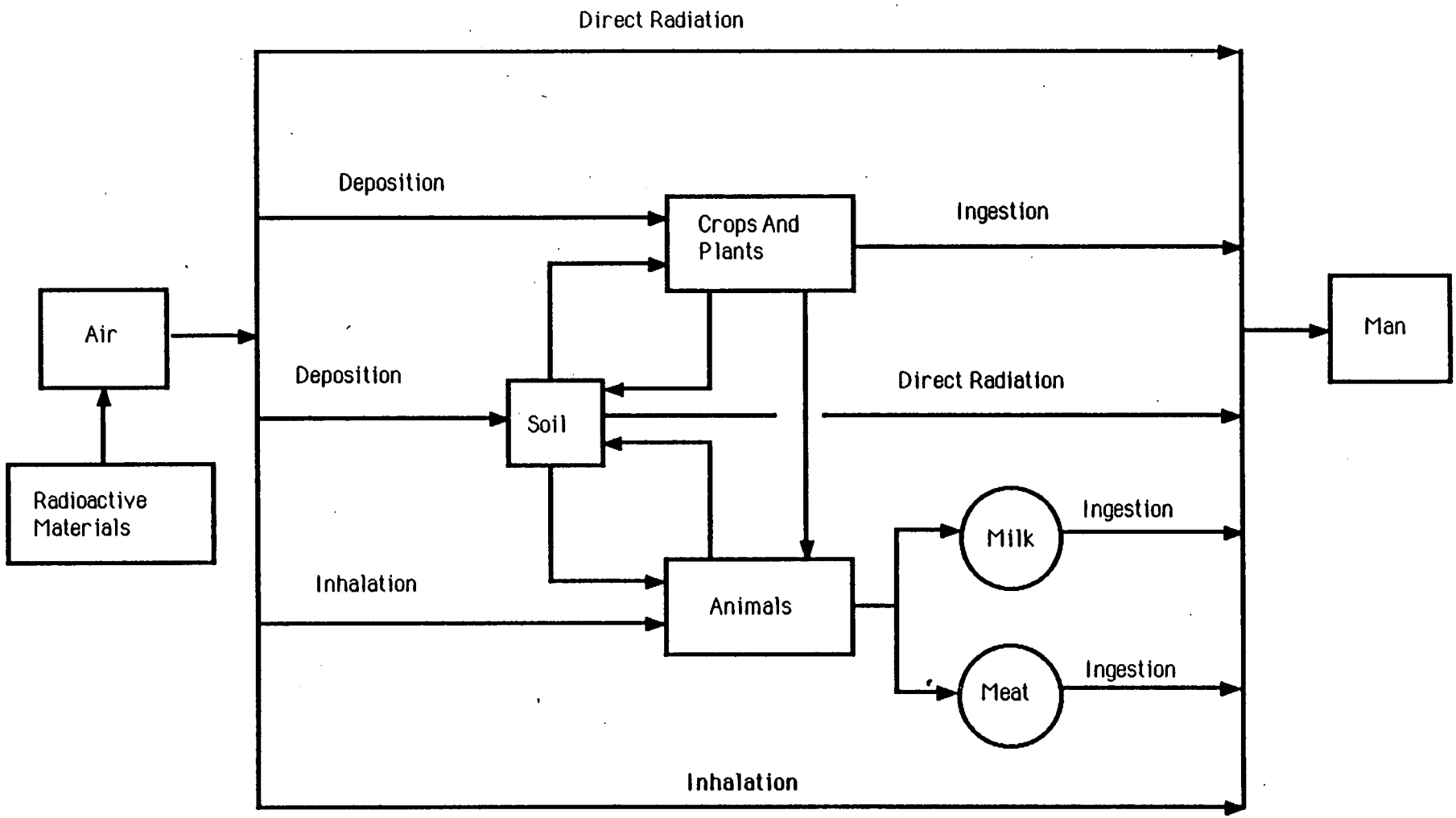


Figure 3.2 Generalized Gaseous Pathways to Man

are absorbed by the plants and are transported to the edible portion of the plant. Farm animals eat the plants, such as corn or grass and a small fraction of the radionuclides from the plants is transferred to the meat or milk. When humans eat the meat or drink the milk, a small fraction of the radionuclide content of the meat or milk is transferred to the individual. The individual receives a dose from eating or drinking this food. This would be called an indirect pathway.

The gaseous pathways shown in Figure 3.2 can be explained in much the same fashion. Radioactive material from a source is released or escapes into the atmosphere in the form of particulates, vapors or gases. The upper pathway, labeled "direct radiation" would represent the dose to an individual if the individual were surrounded by air containing small quantities of the radionuclides. For example, the person may be down wind of a stack release in the form of a plume. The individual could receive a skin surface dose or whole body dose from the external radiation emitted by the radionuclides in the plume. The individual might also inhale some of this air and receive an internal dose from inhalation of radionuclides in this air. This simple, but important pathway, is shown at the bottom of figure 3.2 and is labeled, "inhalation". A more complex gaseous pathway would be the deposition of the radionuclide from the air to the soil. Here again, the roots of the plant uptake the radionuclide, then the farm animals eat the plant and humans eat the animals and drink the milk. As with the similar liquid pathway previously described, fractions of the original quantity of the radionuclide are transferred at each step in the pathway until finally ingested by the human population.

3.2 Exposure Scenarios

The actual pathway that leads to human exposure is 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 will also be site specific. Soil guidelines are based on the exposure to members of an critical population group. This is the group that would be expected to receive the highest effective dose equivalent.

The Manual has defined the critical population group for a 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 Fernald FMPC site is over 1000 acres, the resident scenario has been shown to be the most critical scenario for this analysis.

In the standard residential scenario, the family is unaware that the soil contains above background levels of radioactivity. The family is assumed to move onto the site, build a home and raise crops for family consumption. At the FMPC, the large size of the site leads to the conservative assumption that all of the family's food could be grown on the site. It is further assumed that all the meat and milk products consumed by the family are produced from onsite animals. The members of the family would receive a dose from eating these foods grown on the site (called ingestion). The family members would also receive a radiation dose from exposure of direct radiation from radionuclides in the soil and by inhalation of resuspended dust. For a large site, the Manual requires the conservative assumption that an on-site well supplies the family drinking water and crop irrigation water.

Other scenarios have been investigated as part of this project. Using the data base collected and discussed in Section 2 of this report, offsite resident scenarios were considered around the FMPC site. The external

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radiation dose from the soil was found to decrease rapidly with distance from the FMPC site due to the lower radionuclide concentrations at these distances. The dose to an offsite individual from the inhalation pathway also decreases for the same reason. The food ingestion pathway also decreases with decreasing concentration of radionuclides in the soil. The dose from the drinking water pathway to an offsite family cannot be easily dismissed as less than the dose to an onsite family. The contribution from the groundwater pathway will be largest for drinking water obtained from a well at the boundary of the contaminated region on the southeast corner of the site that draws water from the unconfined aquifer. This contribution to individual dose could be the same at the boundary for onsite and offsite residents, but will decrease for wells at greater distances from the boundary.

The Manual requires that exposure scenarios used for establishing soil guidelines should be conservative and correspond to actions, events and processes that will result in the largest exposure to members of the resident family. In discussions with members of the Westinghouse technical staff, it was pointed out that the silty clay soil at the site could contain enough water to support a shallow family well for drinking water. This conservative scenario has been incorporated into the site-specific scenario for the resident family. Table 3.1 summarizes that most significant site-specific exposure scenarios developed for the unrestricted release of the FMPC.

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 gammas	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	1.0 m

These parameters help to establish the annual exposure to radiation and ingestion of radionuclides to the maximally exposed individuals living on the site. The activity parameter values and the housing parameter values were adopted directly from the Manual. The food and water consumption parameters were suggested values from the Manual for large sites.

3.3 Pathway Analysis For DOE Facilities

The derivation of radionuclide soil concentration guidelines is based on the concentration of the radionuclide in the soil at the site and the consequent radiation dose received by the maximally exposed individuals. A site specific pathway analysis must be conducted to determine and evaluate this dose.

Various pathway models have been proposed for residual radioactivity guidelines at formerly utilized DOE sites. These programs are referred to as the "Formery Utilized Sites Remedial Action Program" or FUSRAP and remote sites identified by the "Surplus Facilities Management Program" or SFMP.

Gilbert has constructed a general pathway diagram (Gilbert 87) showing all the pathways that lead from FUSRAP waste to human exposure at the FUSRAP site. The release mechanisms and pathways shown in Figure 3.3 are adapted from the generic FUSRAP site for the FMPC. Figure 3.3 is simply a starting point for pathway analysis for all possible FMPC exposure scenarios.

3.4 Important Pathways for the FMPC

As discussed previously, after careful pathway and scenario analysis, we have identified the maximally exposed individual as the member of a family who takes up residence at the site and essentially eats foods produced at the site and drinks water from wells at the site. Based on this scenario, the major pathways to the maximally exposed individual are listed in Table 3.2. All of these pathways were investigated as part of this study. Sensitivity calculations were conducted for each pathway shown in Figure 3.3, in order to identify the most important or critical pathways for the FMPC site.
The inhalation of resuspended dust at the site resulted in a dose on the order of 2 mrem per year per picocurie of uranium per gram of soil. Using

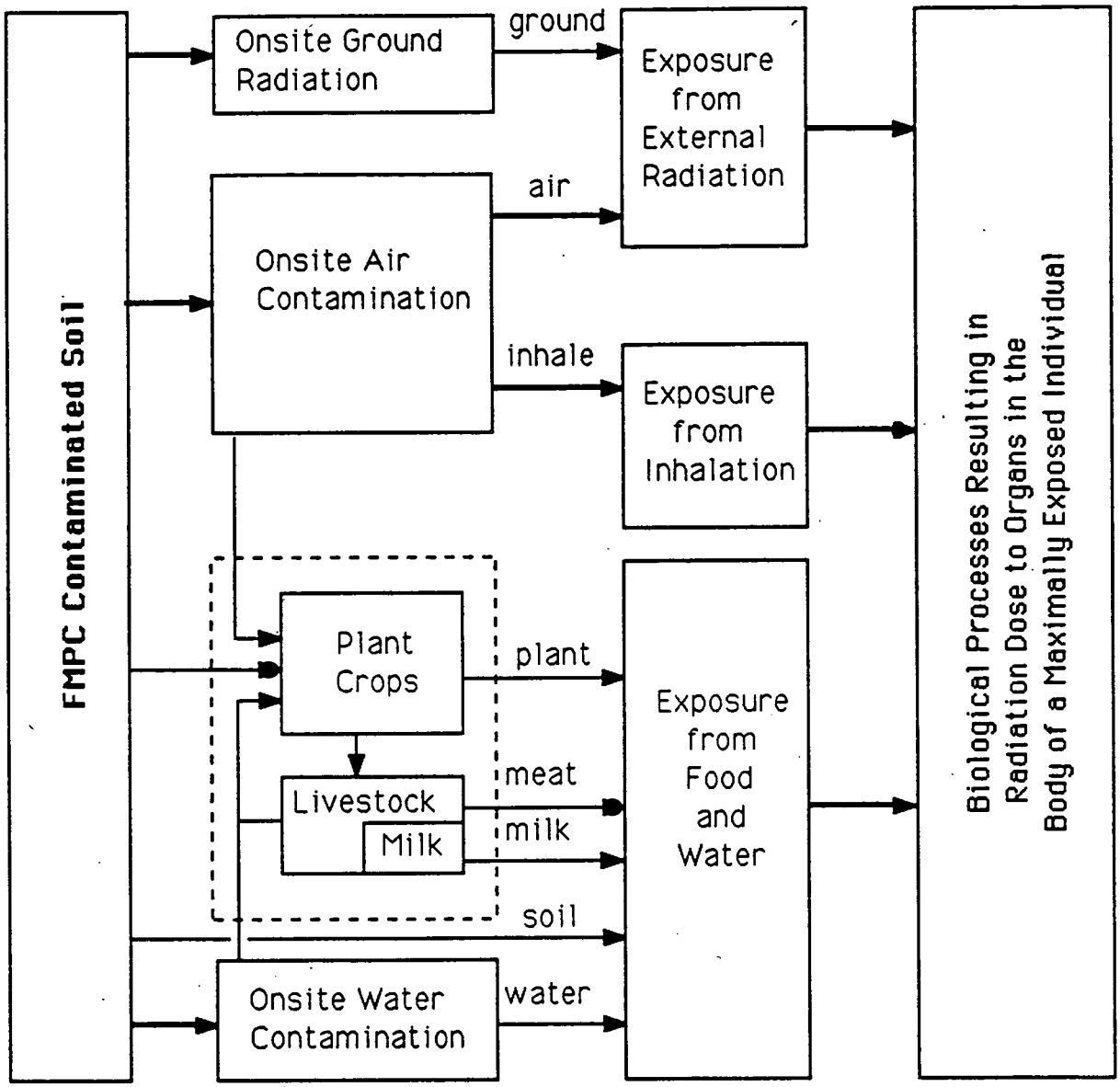

Figure 3.3 Simplified Diagram Showing Major Pathways to the Maximally Exposed Individual.

sensitivity studies, such as this, the most important pathways were identified for the FMPC site for the resident family scenario.

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

The external radiation dose from radon and the radon daughters and the resuspended dust is small and was deleted from the final pathway analysis. Only inhalation dose is included in the pathway analysis. Calculations show the external dose from radon and resuspended dust is almost a factor of 100 less than the inhalation dose from this dust.

Because of the unusual soil and hydrogeologic characteristics of the FMPC site, the pathway analysis has been further divided into a near-term pathway analysis (0-100 years) and a long-term pathway analysis (1000-10,000 years). DOE requires a planning horizon of 10,000 years. Figure 3.4 is a generalized hydrogeologic cross section of the local area. This figure and other similar

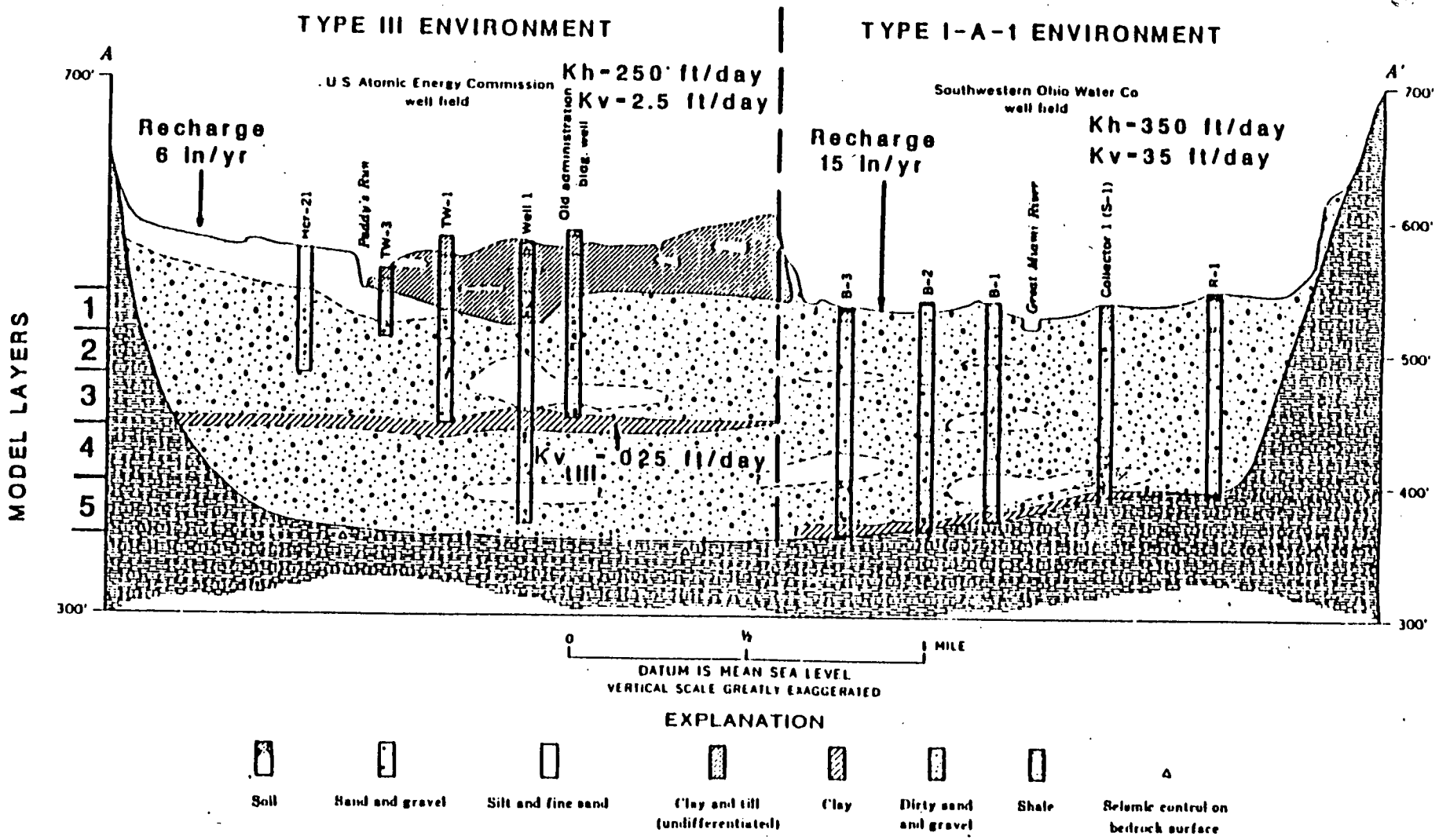

FIGURE 3.4 GENERALIZED HYDROGEOLOGICAL CROSSECTION OF THE AREA NEAR THE FMPC

figures show a bed of clay or silty clay soil immediately under the FMPC site. Below this, lies an unconfined sand and gravel aquifer. Initially, it was assumed that this silty clay could support a shallow family well that could be used for drinking water, but not sufficient water for crop irrigation. Subsequent discussions with members of the WMCO technical staff resulted in this assumption being challenged. The WMCO staff did not believe that the silty clay could support even a family well. This pathway was deleted from the final analysis. Crop irrigation would be from the deep well only. The deep well is assumed to draw water from the sand and gravel aquifer shown in Figure 3.4.

For near term, unrestricted release, the critical pathways are shown in Table 3.3, and the long term critical pathways are listed in Table 3.4. These pathways were determined by an analysis (presented later) of the time required for radionuclide migration through the soil.

TABLE 3.3

NEAR-TERM CRITICAL 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

TABLE 3.4

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

1.0 External radiation from the ground
volume source

2.0 Internal radiation

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

These pathways results are based on uranium contamination in the top layer (few meters) of soil upon release of the site for unrestricted use. Initially, the land may be used to support a family who takes up residence on the site. The uranium has not yet migrated downward into the aquifer to contaminate the deep well water. Thus, initially the critical pathways are the non-water pathways: external surface and volume radiation from the ground, inhalation of resuspended dust, and a variety of food chain pathways.

In the mid-term time interval, 100 to 1000 years, the radionuclides migrate downward toward the aquifer. Eventually, after a few thousand years, the radioactivity begins to enter the saturated zone of the aquifer and contaminates the well water. During the long term interval, the radioactivity in the well water becomes the dominant transport pathway for radioactivity to humans: drinking water and crop irrigation water. Most of the uranium contamination in the long term time interval has migrated from the top few meters of soil to the aquifer. Section 3.5 contains the analysis for the radionuclide migration.

These time intervals, 0-100 years and 1000-10,000 years, define the time frame for the application of the critical pathways for the determination of the site specific soil guidelines. The soil guidelines for the critical pathways for each of these time intervals were calculated to determine the most restrictive guidelines.

3.5 Transport of radionuclides from the surface soil to the aquifer

Groundwater contamination from radionuclides released to the soil can affect the long term soil guidelines significantly. The analysis of the groundwater pathway can be divided into several time increments: long, short, and intermediate. For this reason the groundwater path is important in that the radioactive material can affect people both in the present and in the future. Radioactive material in the groundwater has the potential for moving far from the release point. This movement can result in contamination of fairly large areas both near and far from the original source. This movement can be a slow process, taking sometimes as many as one thousand years or more to move only a few meters, in unsaturated clay regions. In other instances however, the transport time can be only a few years or months for material in saturated regions or in surface waters. The situation to be modeled at the FMPC site requires only the consideration of groundwater in the saturated and the vadose zones, since there are no significant surface water sources on site. The bed of Paddy's Run Creek is commonly dry and is composed primarily of sand and silt. The sand lens in this region can permit radionuclides to migrate much faster than in till or clay regions. This effect will be discussed more fully in section 3.5.5.1

3.5.1 The Problem

This model concentrates on the transport of radionuclides in two zones lying beneath the ground surface. These zones are commonly referred to as the vadose and the saturated regions. The vadose region usually contains much less moisture or water than the saturated area and is sometimes referred to as the unsaturated zone. The scenario considered here is depicted in figure 3.5 which shows a cross section of the aquifer and vadose regions in the Great Miami River Valley near the FMPC. The objective of this model is to calculate the time of transport and concentration of radionuclides moving through these zones. This calculation is based on the analytical solutions of the generalized transport equation in one and two dimensions. Some assumptions and simplifications had to be made in order to build and solve the models discussed here. The details of these models including the physical data aquisition and geologic investigation conducted will follow in the next sections.

3.5.1.1 The Assessment Area

The area under primary consideration for this model is the waste pits in the Northwest corner of the FMPC site. This area was chosen as a representative portion of the FMPC site due to the large size of the area and the data available on the geology, as well as the radionuclide contamination. Several geologic investigations were performed for the FMPC site by the U.S. Geological Service, GeoTrans Inc., and The International Technologies Corporation (IT). The site geological and hydrological features were presented in sections 2.1.5 and 2.1.6.

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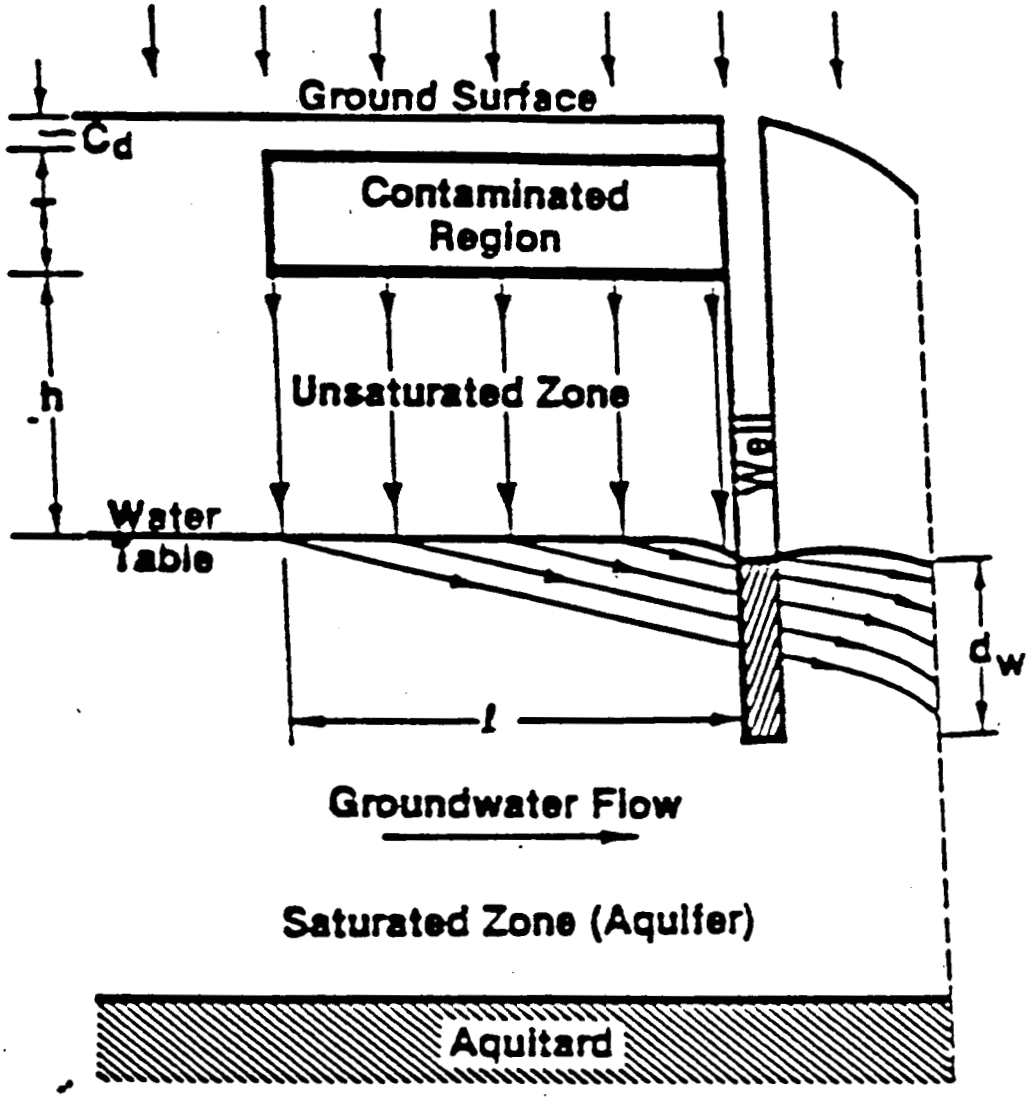


FIGURE 3.5 CONCEPTUAL MODEL FOR THE RADIONUCLIDE TRANSPORT ANALYSIS

3.5.2 Modeling the Problem

3.5.2.1 The Generalized Transport Equation

The task at hand is to devise an analytical method for determining the concentration as a function of time and position in the vadose and aquifer regions. This model must necessarily rely on basic assumptions to enable both an analytical solution and a accurate approximation to the problem. The first step was to identify the regions in question and determine the physical situation as close as practical. The next step was to approximate the physical situation. This was accomplished as shown in figures 3.4 through 3.7. The depth of the aquifer was taken as an average 125 feet and an average hydraulic gradient of 2 feet per mile. The vadose zone was handled in a similar manner with the average depth of about 10 meters. To assess the transport of contaminants in these regions a generalized transport equation was considered (Till 83).

$$R_d\,\theta\,\frac{\partial C}{\partial t} - \nabla\cdot(\theta\bar{\bar{D}}\cdot\nabla C) + \nabla\cdot(\bar{V}C) + [R_d\,\frac{d\theta}{dt} + \lambda\theta R_d]C=0 \qquad [3.1]$$

where:

C = the concentration of dissolved constituent $(\frac{g}{cc})$

$\bar{\bar{D}}$ = the dispersion tensor $(\frac{cm^2}{sec})$

$\bar{v}$ = the fluid flux $(\frac{cm}{s})$

λ = Radiological decay constant $(\frac{1}{s})$

This is the most general form of the mass transport equation governing movement of contaminants in the saturated-unsaturated media when the water is in a single phase. If local equilibrium of mass transfer and first order chemical reactions are assumed, sorption can be represented as a linear relationship and the retardation coefficient can then be represented as:

FIGURE 3.6: CONCEPTUAL MODEL FOR THE VADOSE REGION

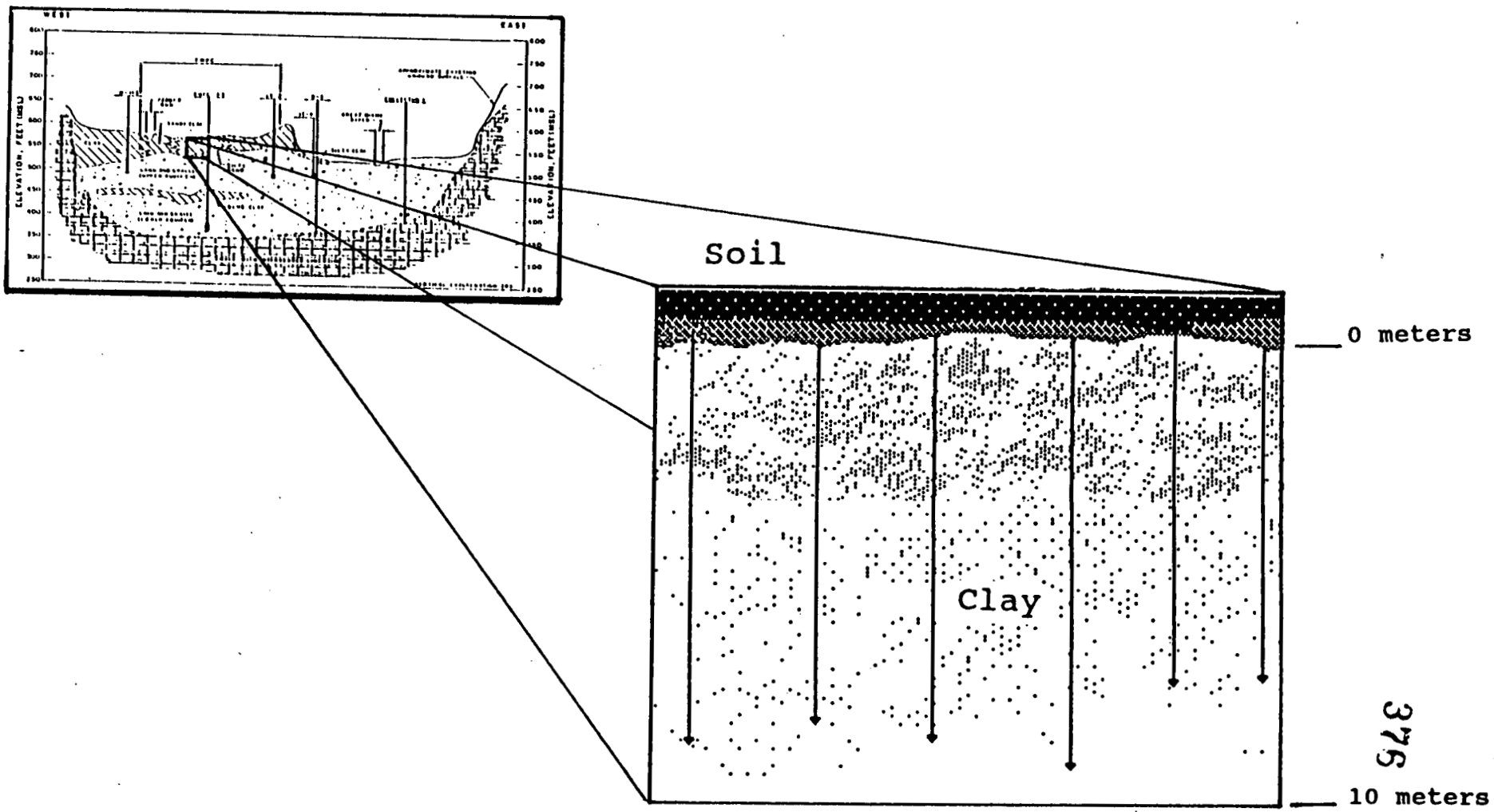
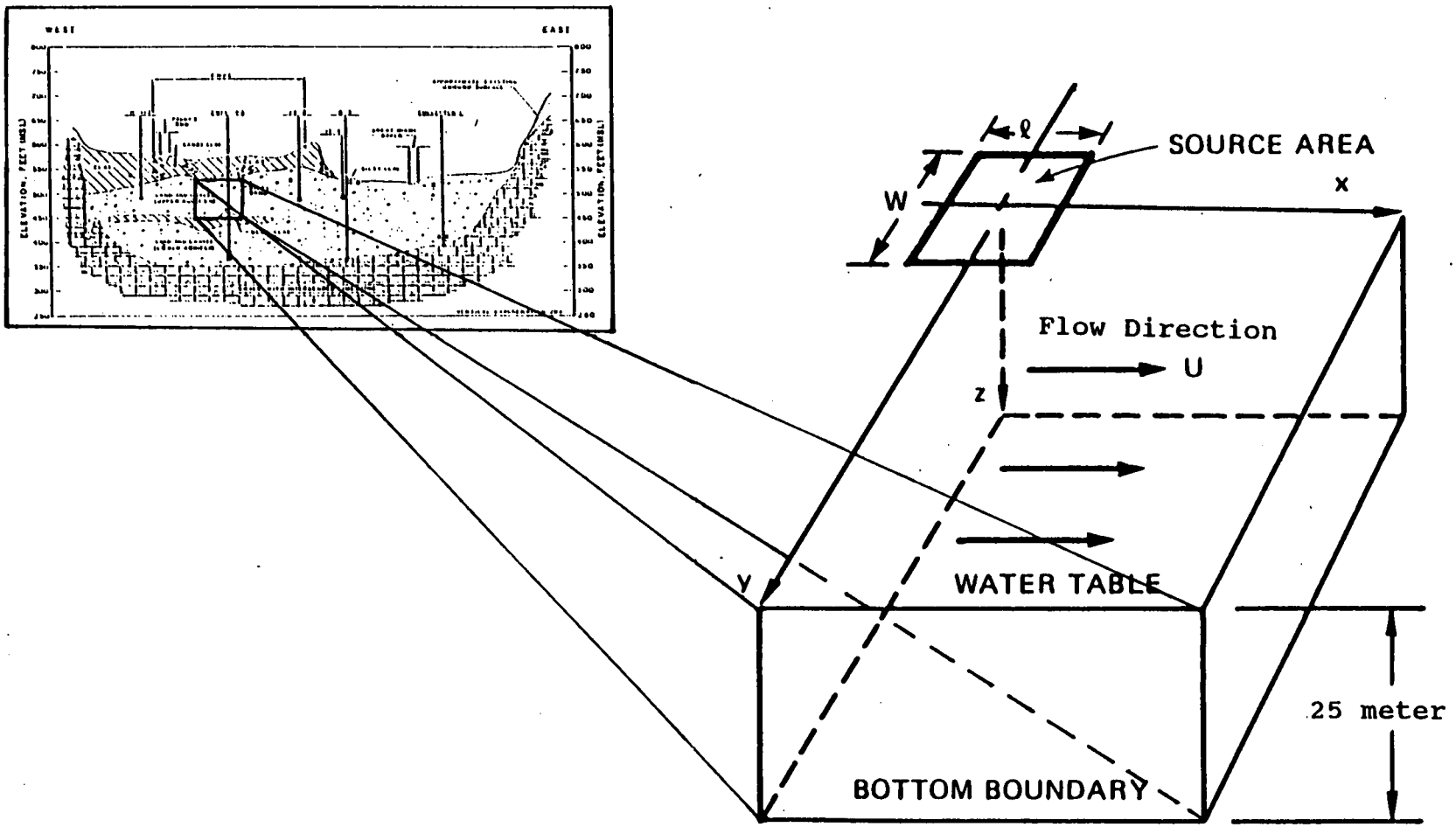


FIGURE 3.7: CONCEPTUAL MODEL FOR THE AQUIFER REGION



$$R_d = \frac{n}{n_e} + \frac{P_b}{n_e} K_d \qquad [3.2]$$

where

n = porosity

n_e = effective porosity

P_b = bulk density $(\frac{g}{cc})$

K_d = Distribution coefficient $(\frac{cc}{g})$

This form of the transport equation does not lend itself to analytical solutions for two reasons: 1) the equation is nonlinear in θ., and 2) the dispersion tensor requires more data than is typically available to evaluate the nine terms. The dispersion tensor and the flux vector account for the heterogeneity of the environment. This of course requries detailed knowledge of the aquifer on a local scale. The nonlinearity precludes solutions by any means other than numerical methods. Due to these constraints some type of modification had to be made to the equation. These modifications are detailed in the next section.

3.5.2.2 The modified Equation for the Vadose Zone

In order to solve equation 3.1 for this region several assumptions were made. These assumptions are: 1) the vadose region consists predominately of clay and has an average depth of 10 meters below the ground surface, 2) the volumetric water content, θ, is considered to be averaged over time and is therefore only a function of depth, 3) the source is considered an infinite plane and is homogeneous with horizontal diffusion being zero, and 4) the clay-silt medium is approximated as isotropic and homogeneous and therefore

the dispersion tensor is assumed to be given by:

$$\theta D_{ij} = \alpha_T V \delta_{ij} + (\alpha_L - \alpha_T)\, V_i V_j / V \qquad [3.3]$$

Where: α_L = longitudinal dispersivity

α_T = transverse dispersivity

V = magnitude of the flux

V_i, V_j = components of the flux

δ_{ij} = kronecker delta function

The modified vadose equation is then given by:

$$R_d\, \theta \frac{dC}{dt} = D_Z \theta \frac{d^2C}{dZ^2} - \bar{V} \frac{dC}{dZ} - \lambda_R R_d C \qquad [3.4]$$

where:

D_Z = 1-dimensional dispersion element

The use of models based on uniform and isotropic medium is quite prevelent in performing generalized assessments of contaminant transport. Several reasons for these assumptions are 1.) The models can typically be solved with analytical techniques, 2.) the specific data required is significantly reduced and can often use average values, and 3.) the time and cost of the overall analysis is reduced. The rationale presented here is typically not sufficient to justify the simplifying assumptions alone. The results of the analysis must be reasonable and sufficiently accurate for justification. The results can be campared to actual physical measurements

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taking into account long time intervals of the processes. 376

The simplified models can be evaluated at less cost and within short time periods in order to provide flexibility for comparing with actual measurements as well as performing sensitivity analysis for obtaining best and worst cases.

The assumption of an infinite planar source allows for the one dimensional treatment. This is justified in the sense that, as the contaminants migrate downward in the 'z' direction, any diffusion in the 'x' or 'y' direction is balanced. This of course is not the case at the boundaries, however they are assummed to be sufficiently far removed so as to not detract from the solution.

The volumetric water content was determined from curve fitting data collected from the site and a relationship for the infiltration from rain and runoff. The infiltration relation was determined using information from the U.S. Department of Energy Manual for estimating Residual Radioactive Soil Guidelines (U.S.DOE, 1985a), and a text on groundwater hydrology (Bouwer, 1978). The relation for θ is as follows:

$$\theta = A_4 Z^4 + A_3 Z^3 + A_2 Z^2 + A_1 Z_1 + A_0 \qquad [3.5]$$

$A_4 = 0.024332$

$A_3 = -0.15863$

$A_2 = 0.26760$

$A_1 = 0.094508$

$A_0 = 0.10012$

and the infiltration relation is:

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$$In = (1-C_e)\ [(1-C_r)P_r + I_{rr}] \qquad [3.6]$$

C_e = evapotranspiration

C_r = runoff coefficient

P_r = precipitation rate $(\frac{m}{yr})$

I_{rr} = irrigation rate $(\frac{m}{yr})$

3.5.2.3 The Modified Equation for the Aquifer

The method used for the Aquifer for reducing the generalized transport equation to a usable form is similar to that used in the vadose zone. There are some differences. The first and most notable difference is the water content of the saturated region. The water content in the vadose zone was found to vary sharply with distance, whereas the water in the aquifer is uniform, has a prominent direction, and velocity component. In this region one can assume completely saturated conditions exist. This immediately reduces the generalized equation to:

$$R_d \frac{\partial C}{\partial t} - \nabla\cdot(\bar{\bar{D}}\cdot\nabla C) + \nabla\cdot[\frac{\bar{V}C}{n}] + \lambda R_d C = 0 \qquad [3.7]$$

Furthermore it was found that the fluid movement is consistent in this aquifer and the velocity is assumed to be parallel to the 'x-axis' as illustrated in figure 3.7. If the aquifer is assumed to be isotropic and homogeneous, then the equation further reduces to:

$$\frac{\partial C}{\partial t} - \frac{Dx\ \partial^2 C}{R_d\ \partial x^2} - \frac{Dy\partial^2 C}{R_d \partial y^2} + \frac{U}{R_d}\frac{\partial C}{\partial x} + \lambda C = 0 \qquad [3.8]$$

One other significant difference between this model and the model for the vadose zone is the size of the source. Due to the type of source assumed in

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the vadose zone, the source for the aquifer was determined to be a plane with finite area and is appropriately considered to be an instantaneous release. This can be assumed due to the significant variation in travel times for the radionuclides in the two regions. The migration time in the vadose zone can be on the order of a thousand years to travel several meters while that in the aquifer is on the order of a few years to travel this same distance. Once the transported material reaches the aquifer after having emerged from the vadose zone, by comparison the contaminant is taken away almost instantaneously.

All of the assumptions made in this assessment are substantiated by the site characteristics or the physical relationships except for the isotropic and homogeneous approximations. Even with the existence of stratified gravel and sand layers and the local anisotropic conditions in the vadose or till regions, the homogeneous assumption works satisfactorily when considering large planar sources. The scale of the source areas are as follows:

Surface Source ———— 600 m x 300 m

Aquifer Source ———— 200 m x 70 m

These models and assumptions agree with various sources in industry practice. (Codell et al, 1983), (DeWiest, 1969). The next section sets forth the solutions for these two models.

3.5.3 Solutions of the Modified Equations

The solutions to the equations developed for both regions were obtained using the integral transform method and then substituting for the Error Function and it's compliment. Tables of the Error Functions are available for hand calculation, however the use of a microcomputer and numerical integration of the Error Function provides for faster and more efficient data aquisition. The solution to the vadose zone is given first followed by the

aquifer solution.

3.5.3.1 The Vadose solution

The function given below is the solution to the modified second order partial differential equation governing the vadose zone in one spatial dimension and time. The initial condition and boundary conditions for this model are as follows: 1) the concentration for the entire region is 0 at time t=0, 2) the concentration for all time at z=0 is a constant C_o, 3) the concentration at an extrapolated boundary (assumed to be infinite) is 0 for all time. This solution is in terms of a normalized and continuous source $C(z)/C_o$.

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

(eq.3.9)

3.5.3.2 The Aquifer Solution

The function arrived at for the aquifer region is based on an instantaneous 1 Curie release to the aquifer of average depth. This solution is then the concentration as a function of time and two spatial directions

'x', and 'y' as given below.

$$c_i = \frac{1}{n_e R_d} X_2 Y_2 Z_2, \qquad [3.10]$$

where

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

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

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

3.5.4 Results

3.5.4.1 Radionuclides in Vadose Zone

Figures 3.8 through 3.17 depict the concentration of radionuclides in the vadose zone as a function of time and of the depth in the region. These figures illustrate the vertical dispersion and holdup of material moving through this zone. Each figure depicts the concentration as a function of time for several positions within this region which are 1, 2.5, 5, 7.5, and 10 meter depths. The breakthrough point was taken as 10 meters which is an average depth of the vadose region at the FMPC site. Figures 3.8, 3.9, and 3.10 are for uranium 238 utilizing different values of the distribution coefficient (K_d).

Since site-specific values of the distribution coefficient were not available for all the radionuclide in this study, a range of values were utilized. The most conservative (shortest migration times) results were used in the analysis of the soil guidelines. Figures 3.8 through 3.10 illustrate the effect the distribution coefficient has on the concentration and transport time of uranium in the vadose zone. These figures illustrate that a factor of three increase in the distribution coefficient decreases the concentration, at a ten meter depth after 10000 years, by a factor of fifteen. The transport time is similarily increased by a factor of three. The range of K_d values tested was as low as 270 cc/g and as high as 1000 cc/g. The values for the distribution coefficient are for clay soil which is the predominant material within the vadose zone at the FMPC site [Till 83] [Geotrans 85]. These figures illustrate the dependence of the transport time on this coefficient. Figure 3.11, 3.12, and 3.13 illustrate the effect of the dispersivities on the transport time for uranium. The increase in the dispersivity of the medium has the opposite effect of the distribution coefficient on the concentration

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

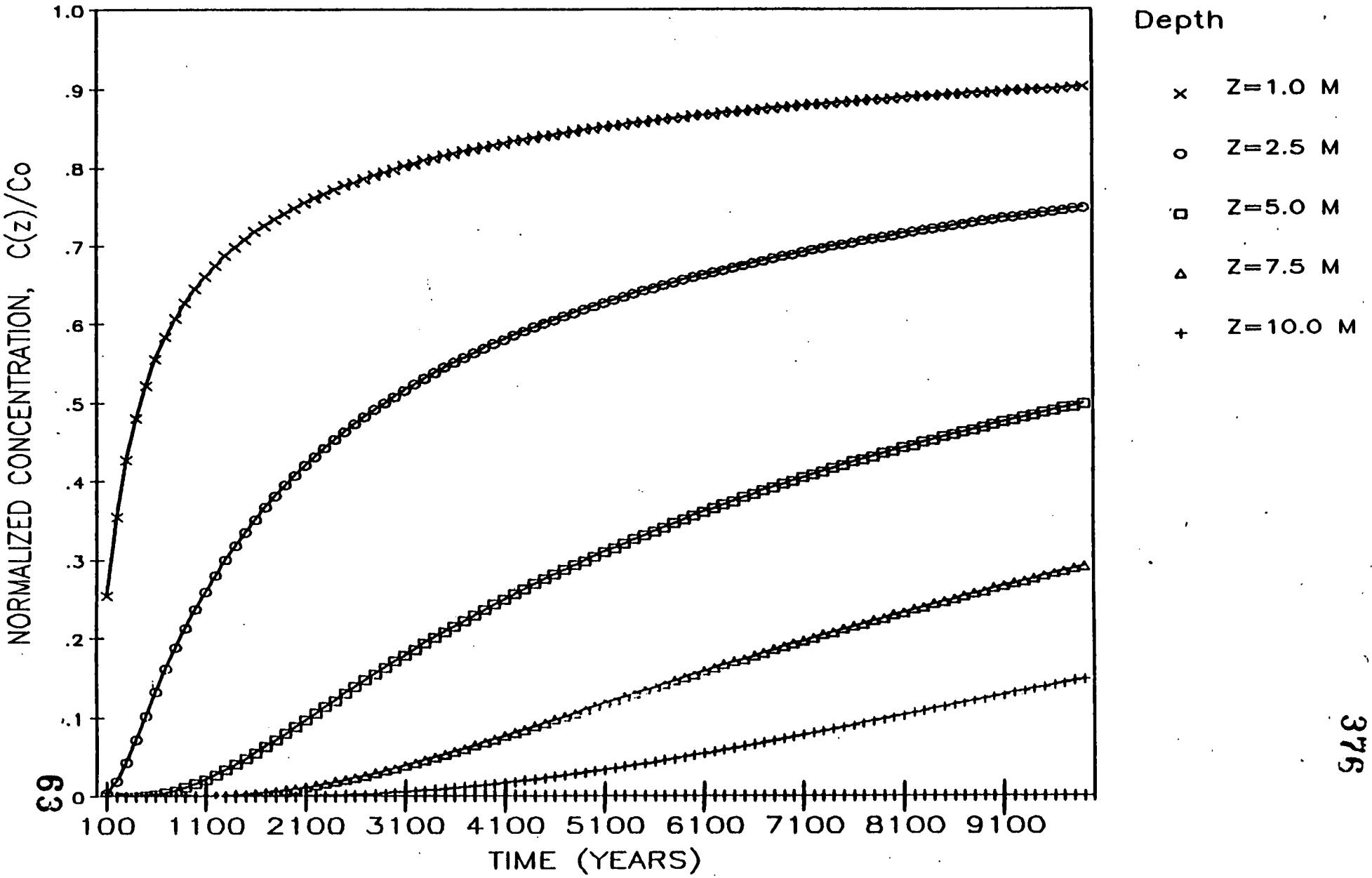


Figure 3.9: Uranium 238 Migration in Vadose Zone
Distribution Coefficient = 400 (cc/gm)

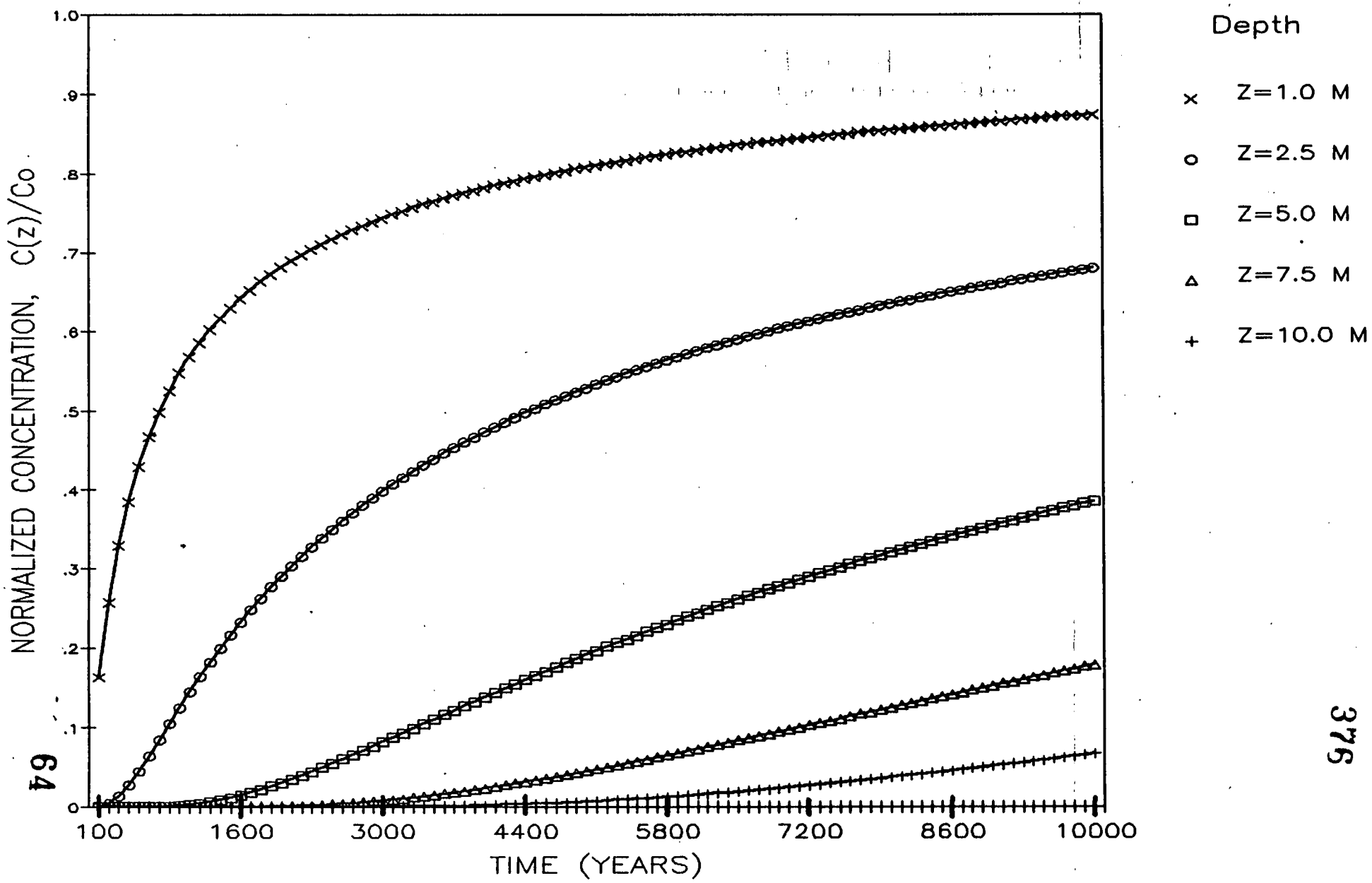


Figure 3.10: Uranium 238 Migration in Vadose Zone
Distribution Coefficient = 800 (cc/gm)

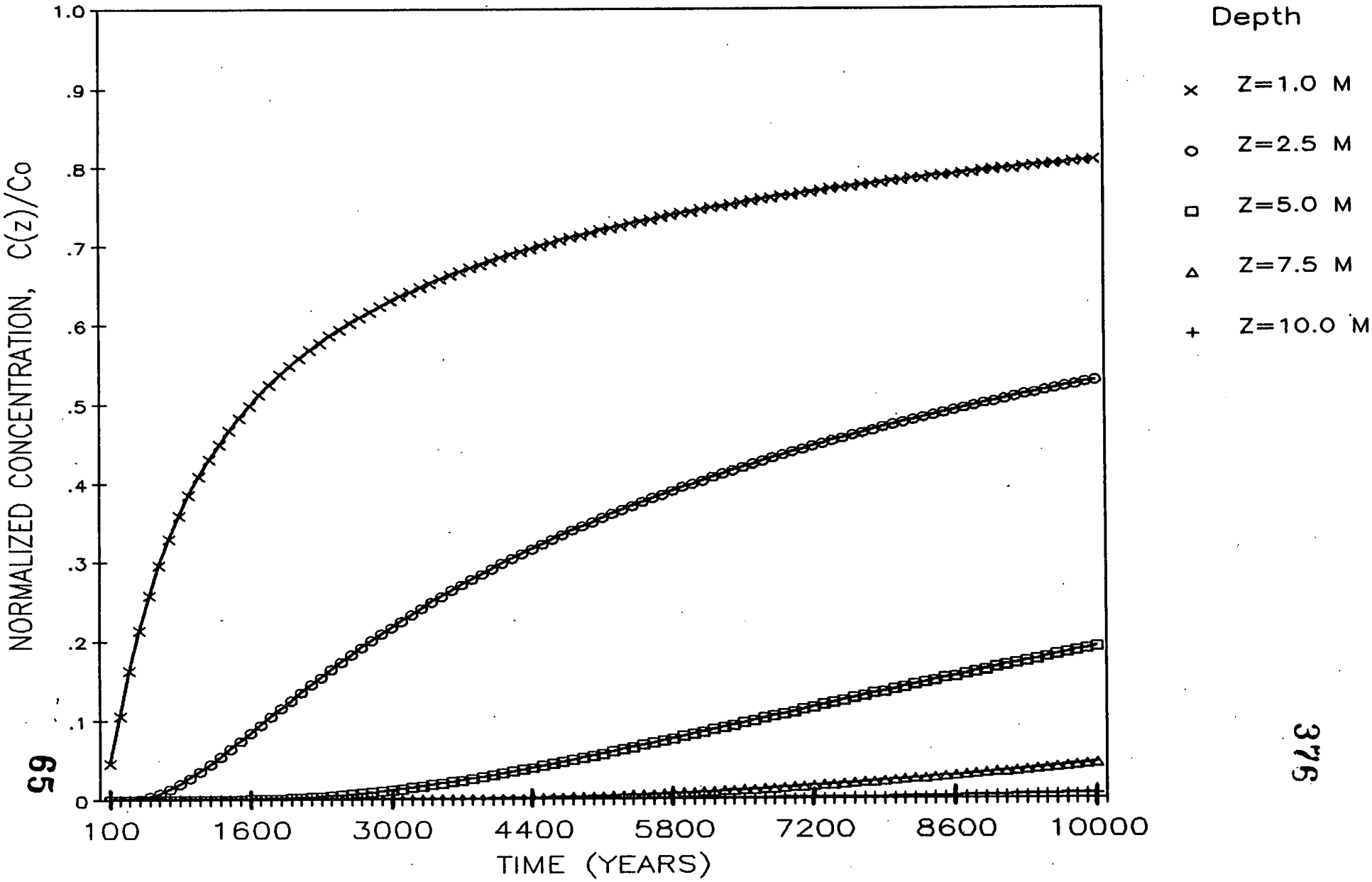


Figure 3.11: Uranium 238 Migration in Vadose Zone
Vertical Disspersivity = 5 Meters

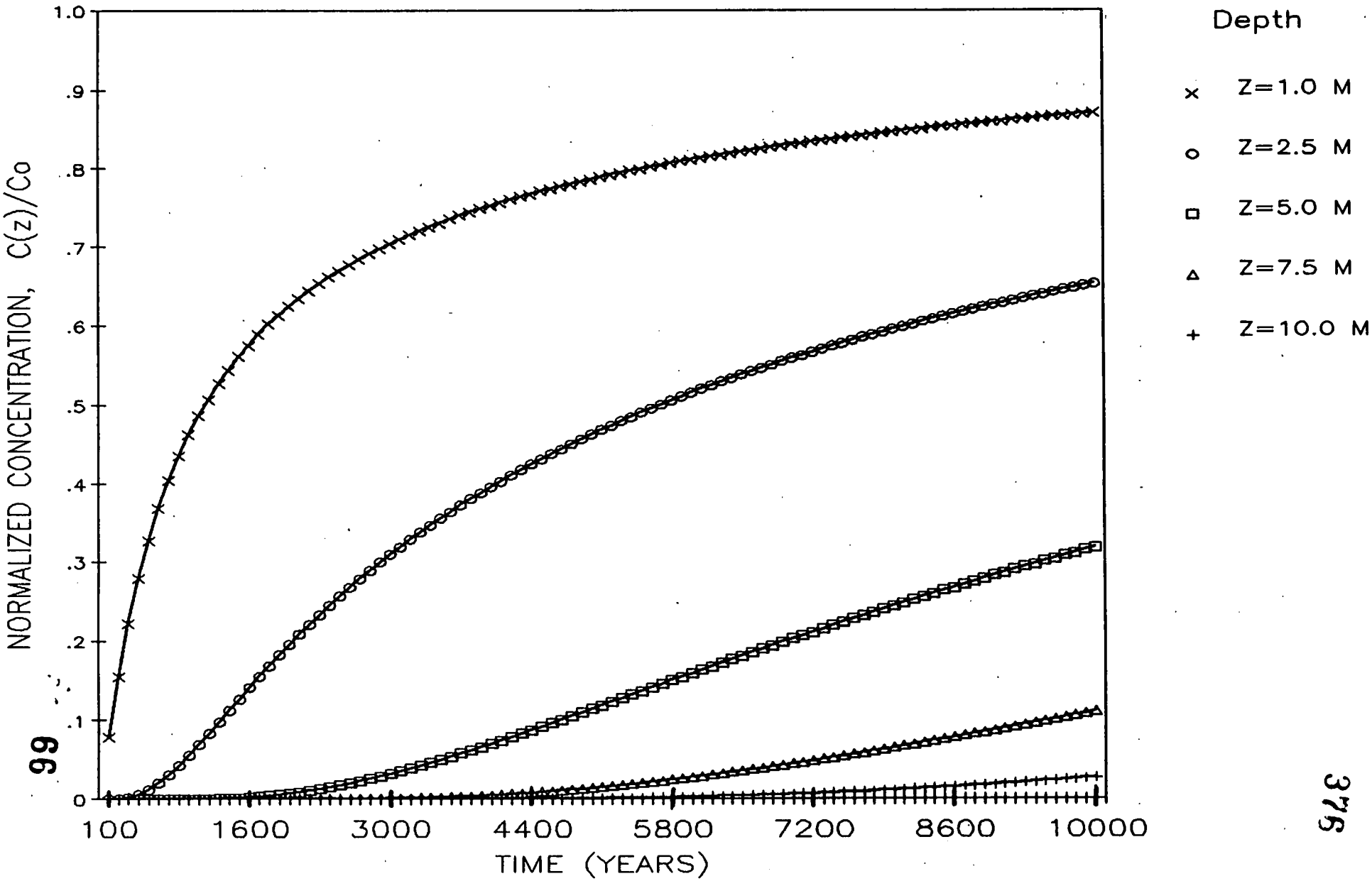


Figure 3.12: Uranium 238 Migration in Vadose Zone
Vertical Disspersivity = 10 Meters

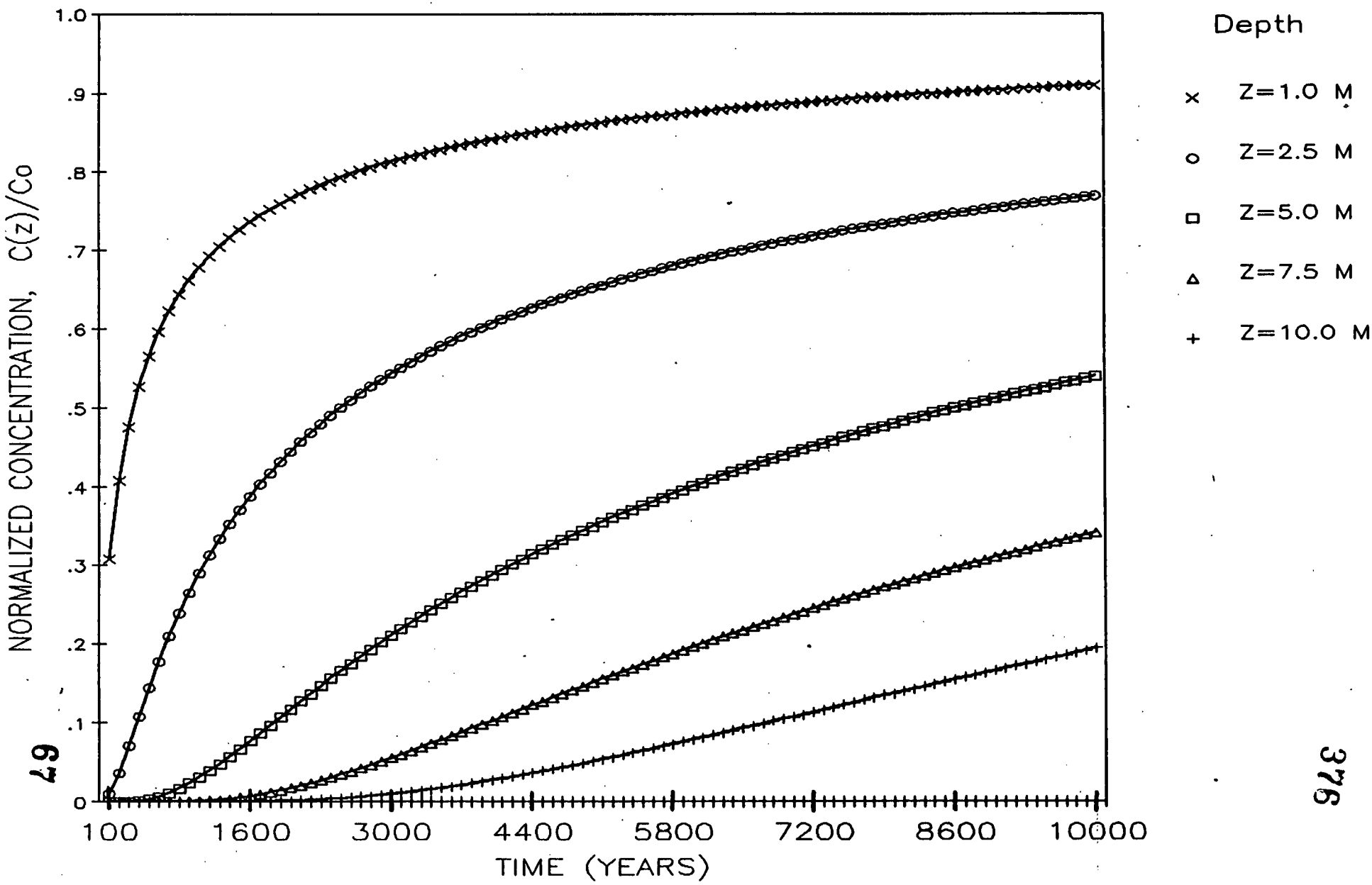
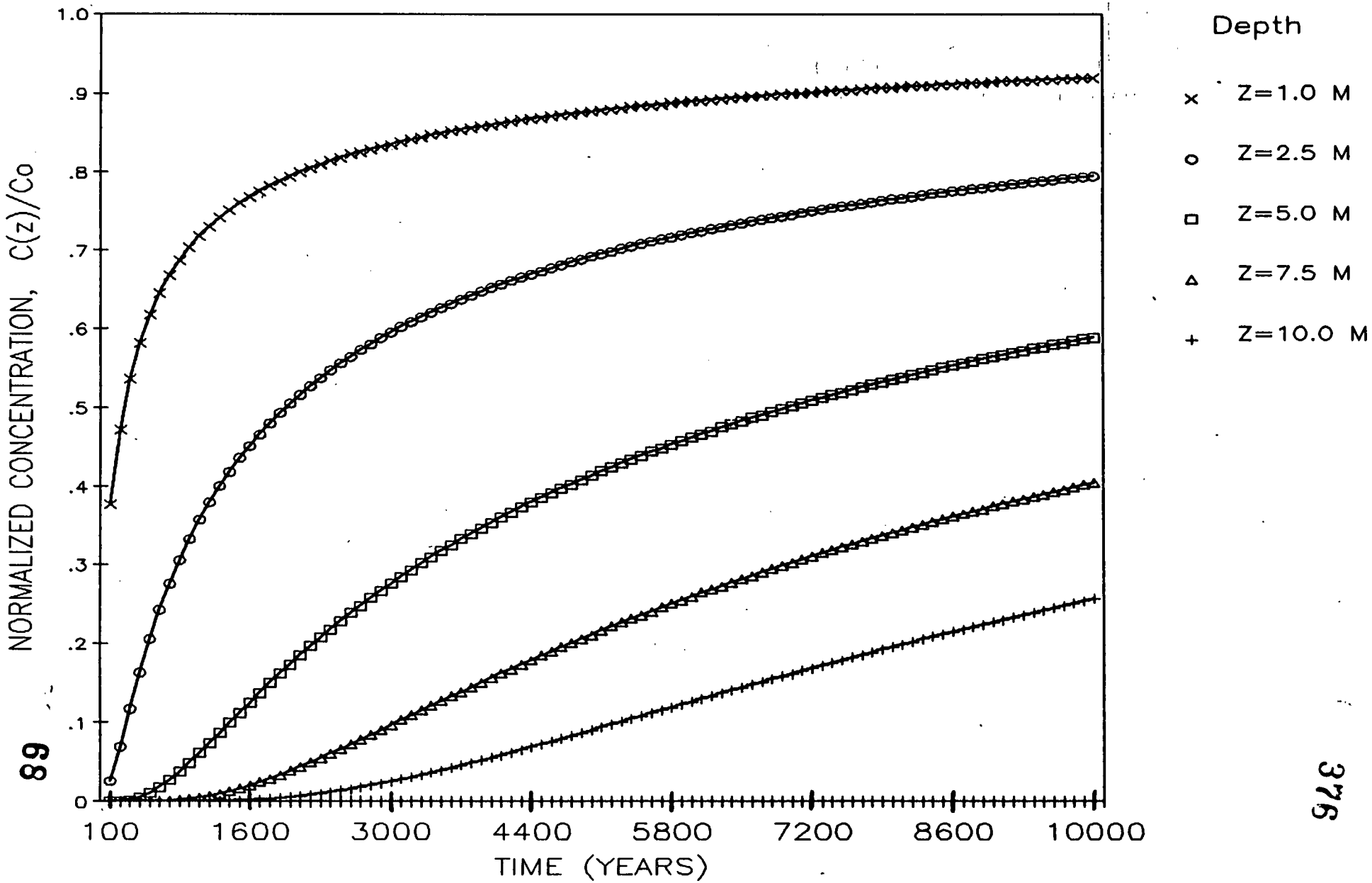


Figure 3.13: Uranium 238 Migration in Vadose Zone
Vertical Disspersivity = 15 Meters



and transport time. In this case a three fold increase in the dispersivity results in a factor of fifteen increase in the concentration ratio at the saturated zone and similarily a factor of three decrease in the transport time. Values for these coefficients were selected to yield conservative results. When actual data for the various input parameters was not available values that yielded the most conservative results were used. Figures 3.14 through 3.17 depict the results of the following isotopes thorium-232, radium-226, strontium-90, and plutonium-239. An interesting result is that the transport time, for elemental therium to reach the saturated zone, was calculated and found to be longer than 10000 years. For this reason, Figure 3.14 contains only these depths where measurable concentrations would appear. Tables 3.5, and 3.6 list the range of the input parameters used for the analysis of the identified radionuclides.

3.5.4.2 Model Development for Radionuclides in the Aquifer

The radionuclide transport in the aquifer has been modeled to include horizontal dispersion in the x-y plane. As a result of the horizontal and vertical dispersion significant dilution occurs when material enters the aquifer. The results of the transport of thorium in the aquifer are illustrated in two types of graphs. The first type shows the concentration as a function of time for a particular 'x', 'y' coordinate and these are designated as figures 3.18 and 3.19. The second style of data display illustrates the same information, however, instead of graphing the function, values of the concentration are superimposed on a plan view of the assessment area for each 'x' and 'y' coordinate pair at a particular time. In this way the reader can become aquainted with the plume movement by seeing the concentration of the dissolved constituent in the aquifer. These figures 3.20

Figure 3.14: Thorium 232 Migration in Vadose Zone

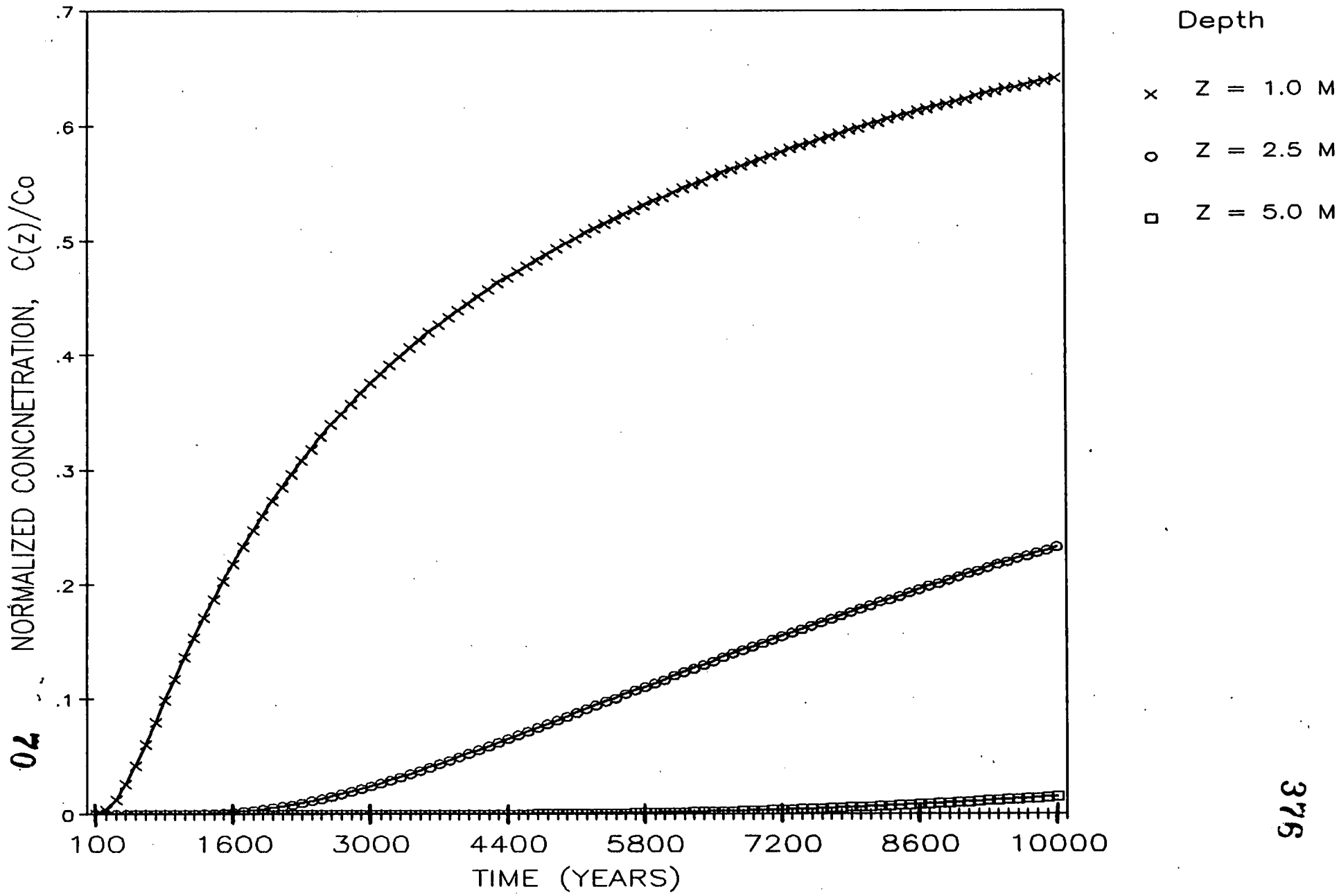


Figure 3.15: Radium 226 Migration in Vadose Zone

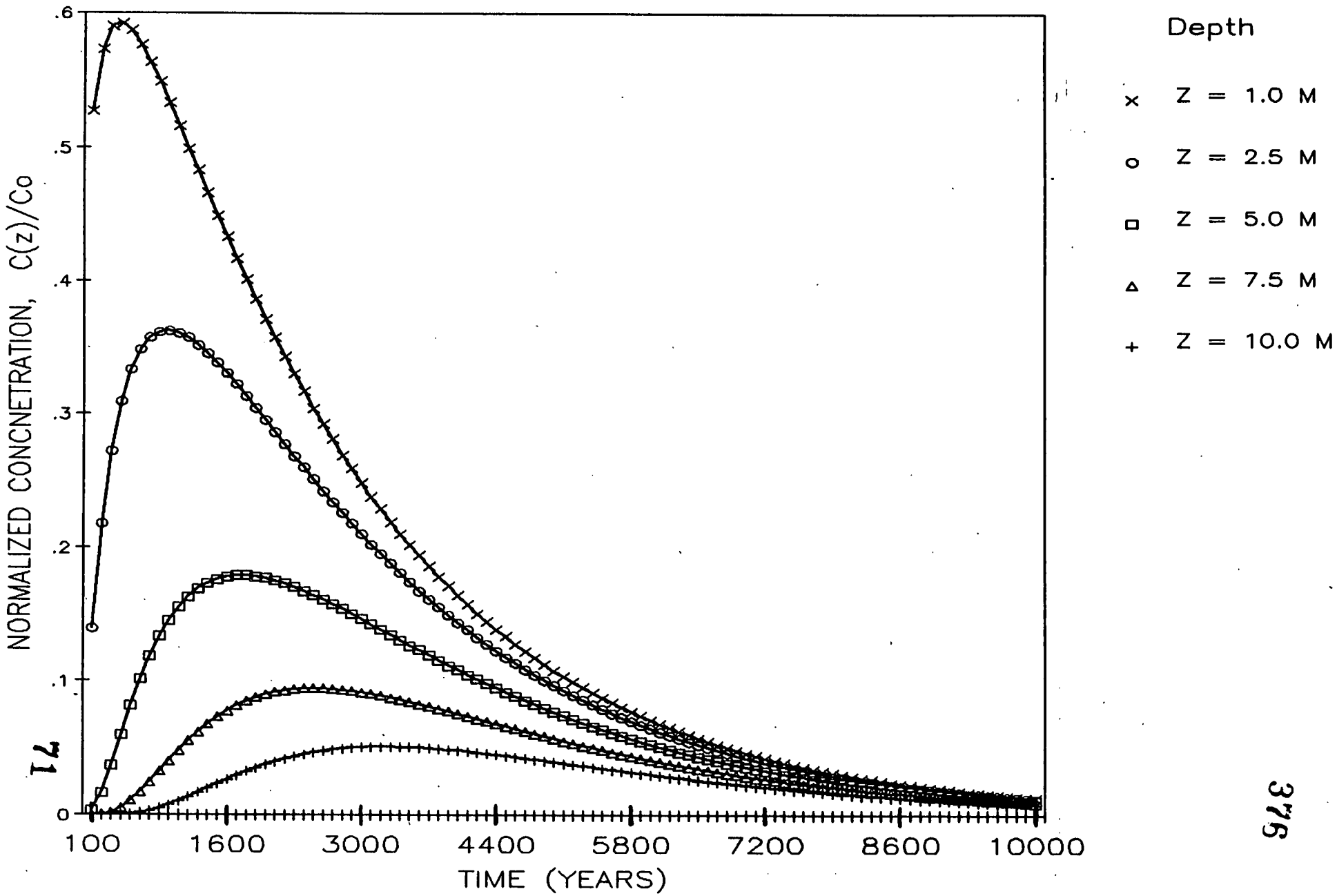


Figure 3.16: Plutonium 239 Migration in Vadose Zone

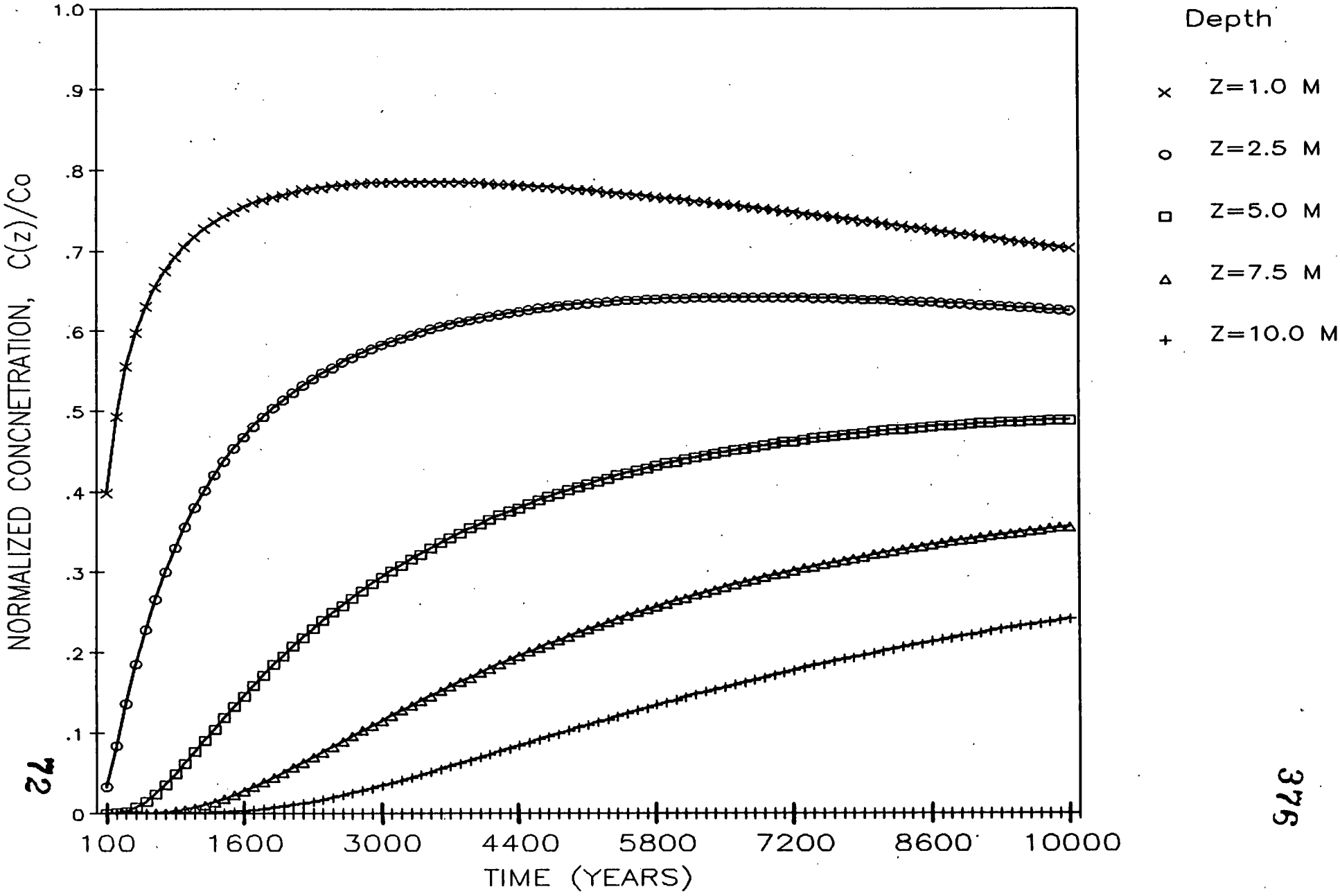


Figure 3.17: Neptunium 237 Migration in Vadose Zone

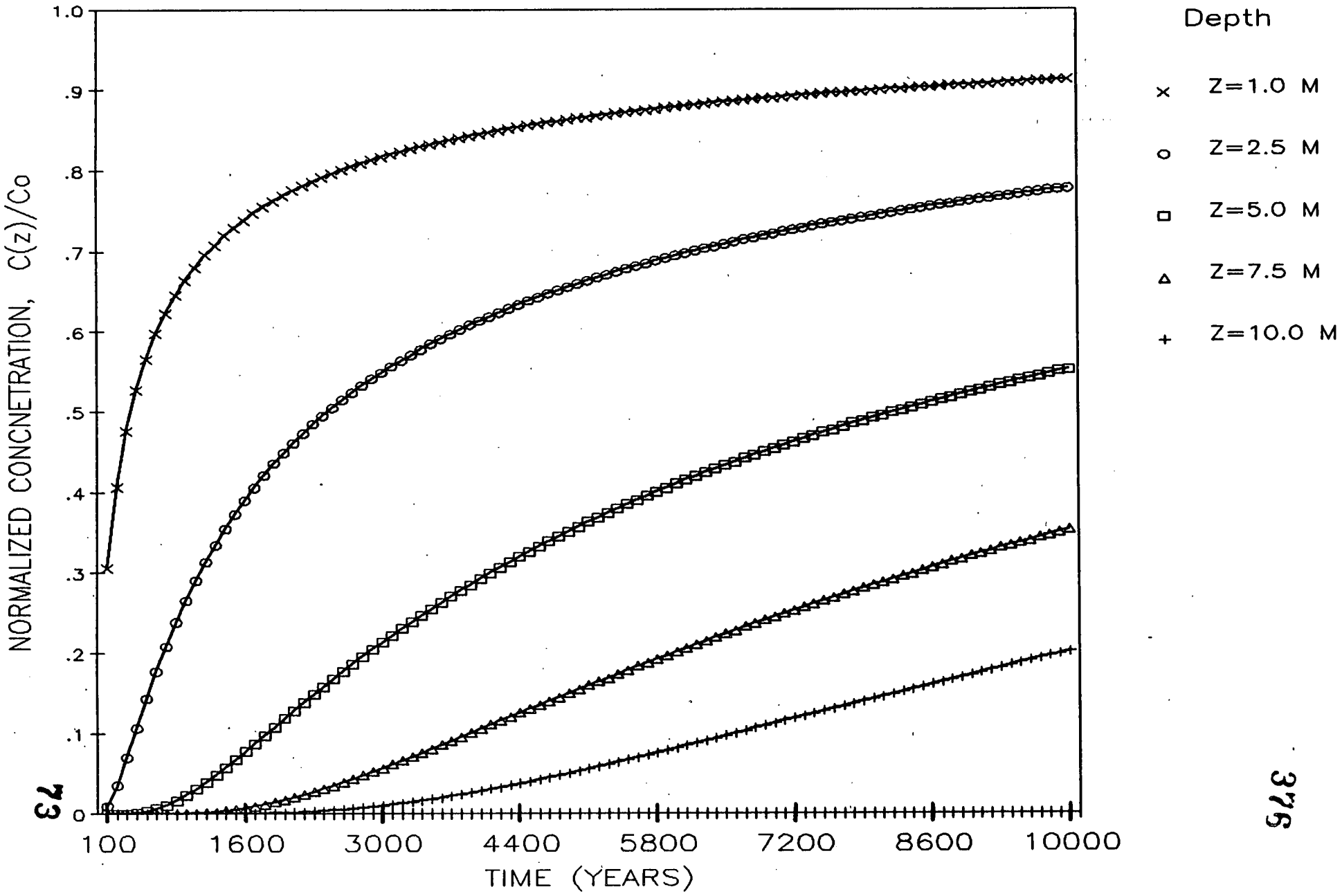


TABLE 3.5 HYDROGEOLOGICAL DATA

	Aquifer (sand/gravel)	Vadose (clay)
(a,b) Bulk Density	1.3 - 1.6 (g/cc)	1.8 (g/cc)
(a,c) Effective Porosity	0.28 - 0.38	0.11 - 0.03
(a,c) Total Porosity	0.42 - 0.46	0.52 - 0.56
(c) Dispersivity: Longitudinal	21.0 - 32.0 (m)	------
Transverse	5.0 - 15.0 (m)	5.0 - 15.0 (m)
(a,b) Hydraulic Gradient	0.001 - 0.005 (ft/ft)	0.006 - 0.008 (ft/ft)
(a,b) Hydraulic Conductivity	150 - 250 (ft/day)	0.2 - 2.5 (ft/day)

a - U.S. DOE Manual for Implementing Residual Radioactive Soil Guidelines (Gilbert, 1987)
b - Site specific data obtained from WMCo as a result of on and off site monitoring wells.
c - Radiological Assessment, NUREG 0868 (Till and Meyer, 1982)

Table 3.6 Radioisotope Dependent Data

Nuclide	Half-Life (years)	Distribution Coefficient (Kd) ** Aquifer (ml/g)	Vadose (ml/g)
239 plutonium	2.4E4	100 - 200	150 - 2000
238 plutonium	87.7	100 - 200	150 - 2000
238 uranium	4.5E9	10 - 100	270 - 4400
235 uranium	7.0E8	10 - 100	270 - 4400
234 uranium	2.4E5	10 - 100	270 - 4400
232 thorium	1.4E10	40 - 130	270 - 10000
230 thorium	7.7E4	40 - 130	270 - 10000
228 thorium	1.9	40 - 130	270 - 10000
228 radium	5.75	7 - 50	70 - 2400
226 radium	1600	7 - 50	70 - 2400
* 237 neptunium	2.1E6	20 - 170	220 - 3400
210 lead	22.3	10 - 100	100 - 10000
137 cesium	30.2	10 - 100	189 - 1053
* 106 ruthenium	1.0	30	100
* 99 technetium	2.1E5	10 - 40	120
90 strontium	29	1 - 43	19 - 282

* Values estimated based on oxidation states and ionization potentials

** - U.S. DOE Manual for Implementing Residual Radioactive Soil Guidelines (Gilbert, 1987)

ml/g - milliliters per gram.

through 3.25 show a stop time effect on the concentration for thorium. The next set of graphs, figures 3.26, 3.27 and 3.28 depicts the transport of radium and uranium in the aquifer. The obvious difference between the thorium and the uranium in the aquifer is the peak concentration for uranium is greater than that for the thorium. This is due primarily to the K_d values for each element. Tables 3.7 and 3.8 illustrate the remainder of the nuclides considered in this study. These values were taken close to the release point and at the plume centerline. The final results are then tabulated for the various time frames considered between 100 and 10,000 years.

3.5.5 Conclusions and Recommendations

This model attempts to investigate the transport of radionuclides in the ground (both the aquifer and the vadose regions). To remain conservative in the model the distribution coefficients used were always near the lower limit for the element and medium resulting in faster transport times and higher concentrations.

The recommendation that can be put forth as a result of this study is that additional situations involving the transport of radionuclides be investigated using this present model. Modifications to the model for the boundaries at the saturated zone and other interfaces can be made. An example is the change to a time dependant source for the vadose zone, and possibly the addition of diffusion in the horizontal direction. The model performed as expected for a first approximation considering nearly ideal conditions. This model is considered an improvement on the typical ion-exchange model due to the consideration of the dispersion terms (molecular diffusion and mechanical dispersion) and the convection terms not normally considered. The result of considering the dispersivity was to balance the effect from the distribution

Figure 3.18: Thorium 232 Concentration in Groundwater

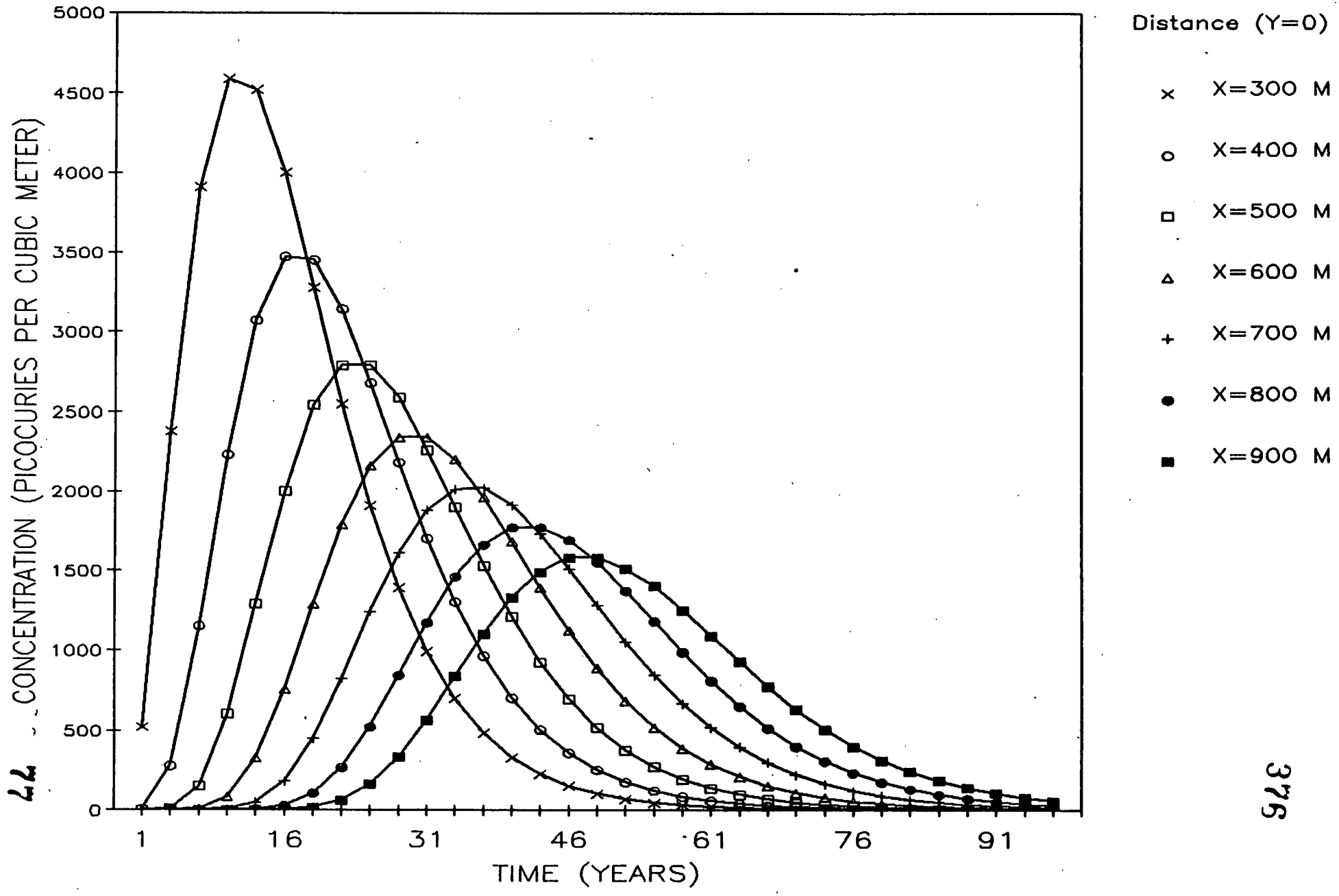


Figure 3.19: Thorium 232 Concentration in Groundwater

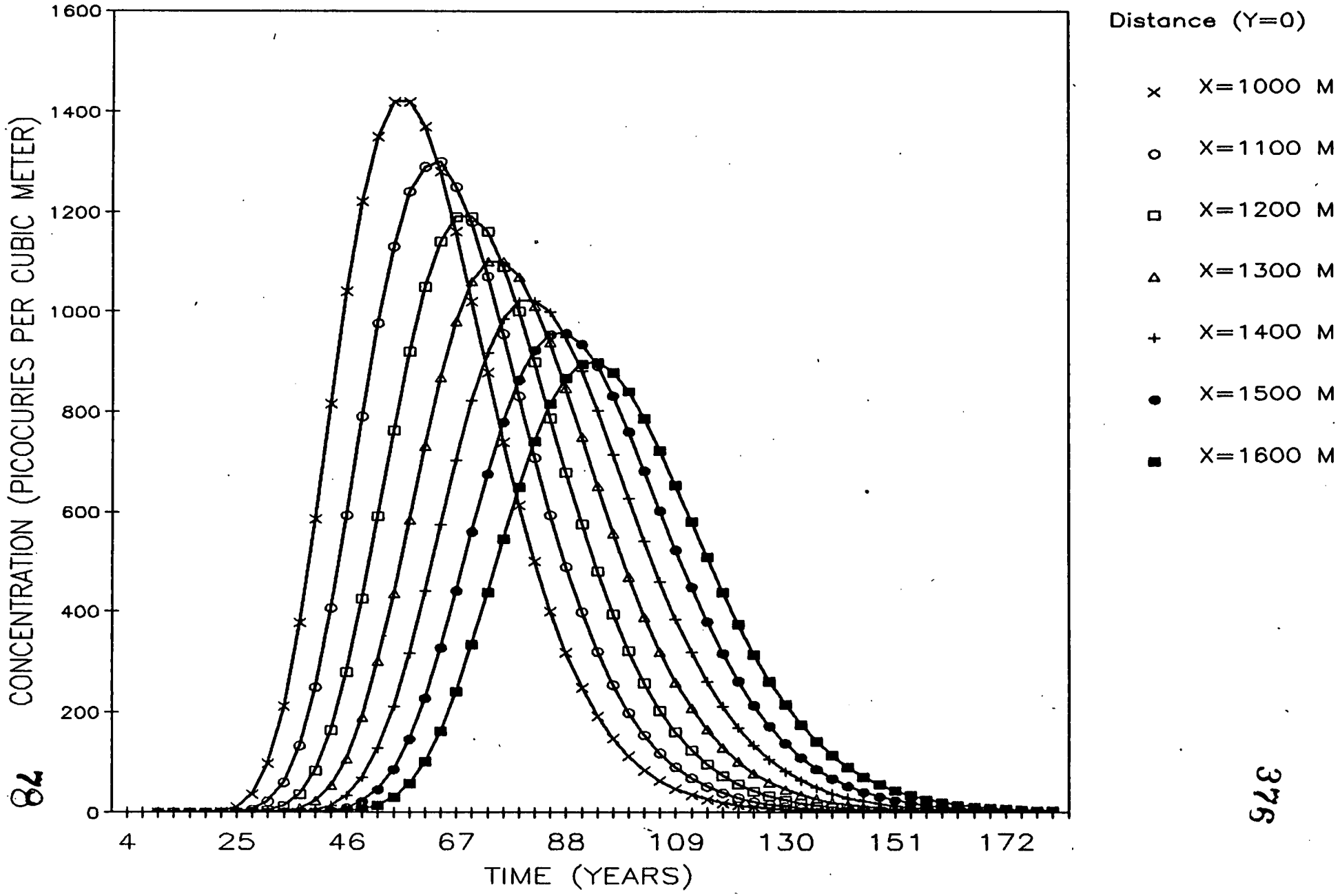


Figure 3.20: Concentration in the Aquifer After 11 Years (pCi/m3)

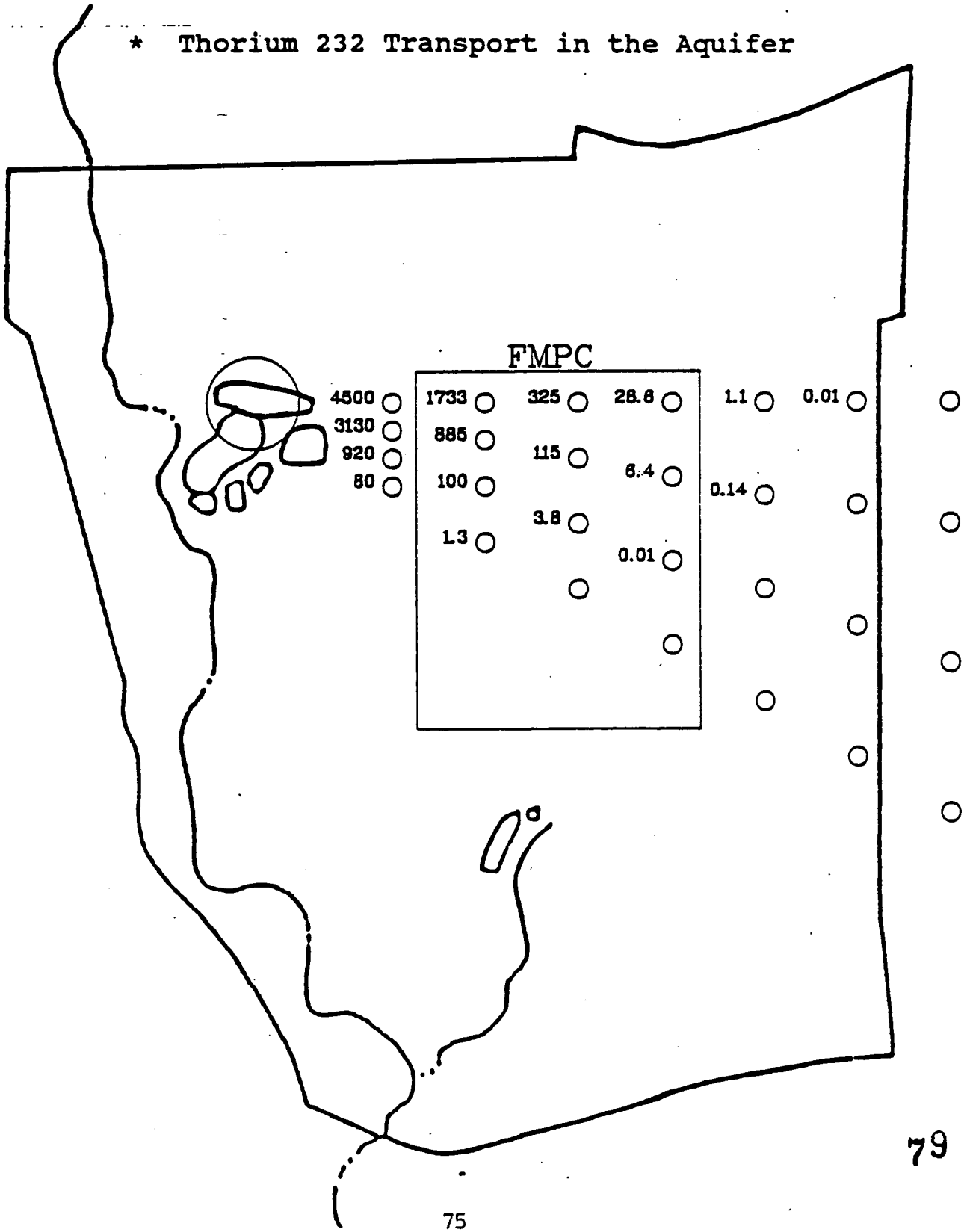


Figure 3.21: Concentration in the Aquifer After 21 Years (pCi/m3)

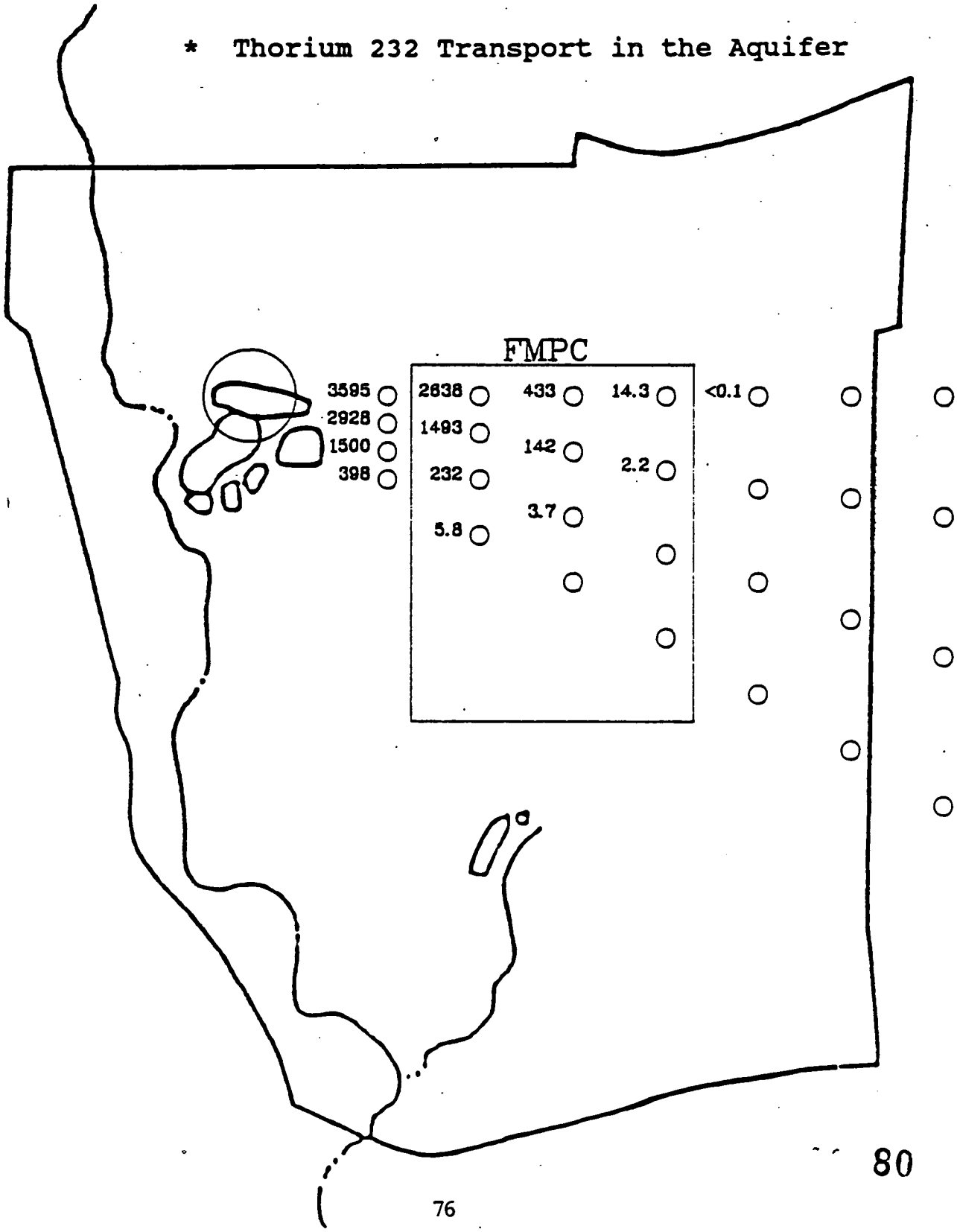


Figure 3.22: Concentration in the Aquifer After 31 Years (pCi/m3)

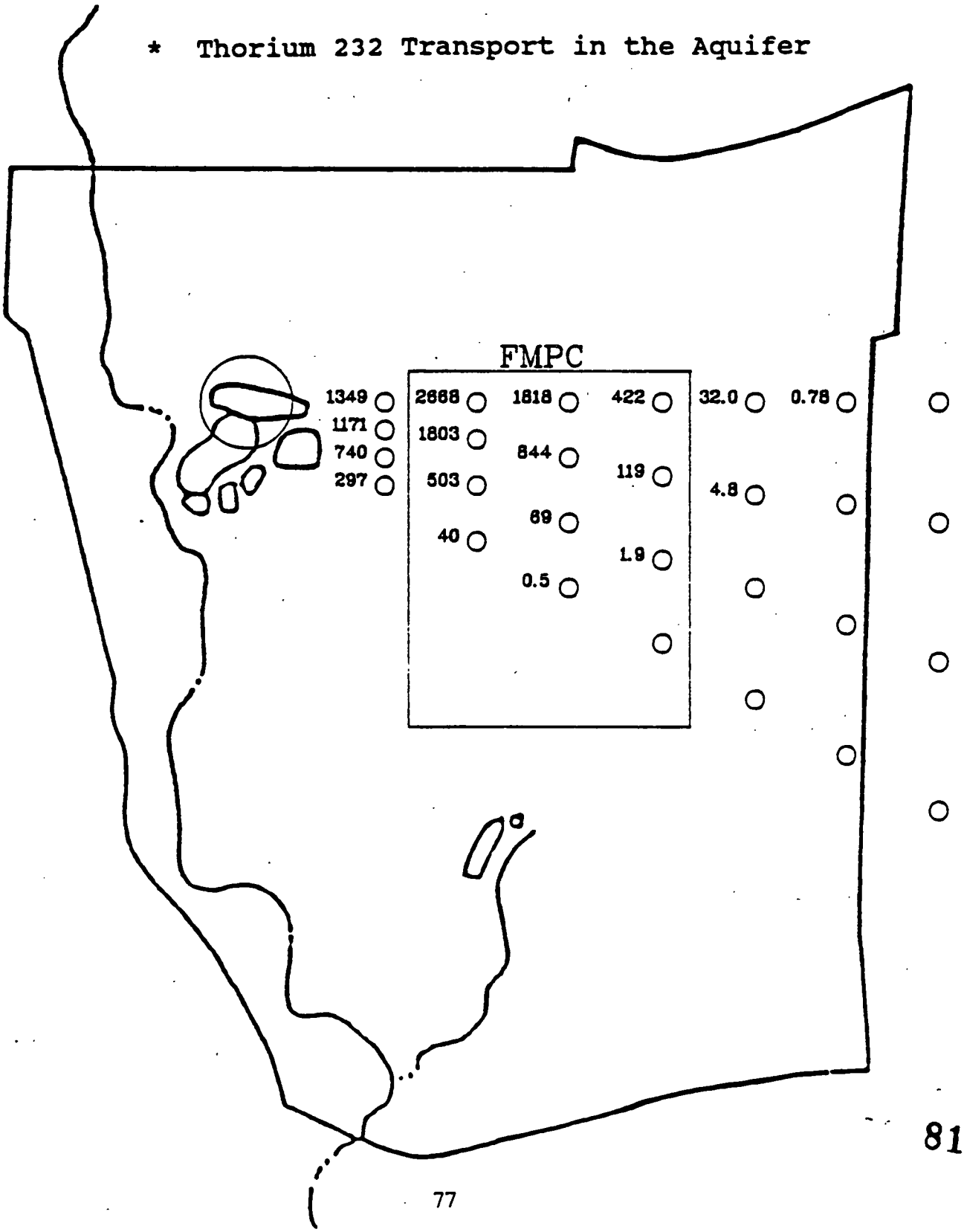


Figure 3.23: Concentration in the Aquifer After 41 Years (pCi/m3)

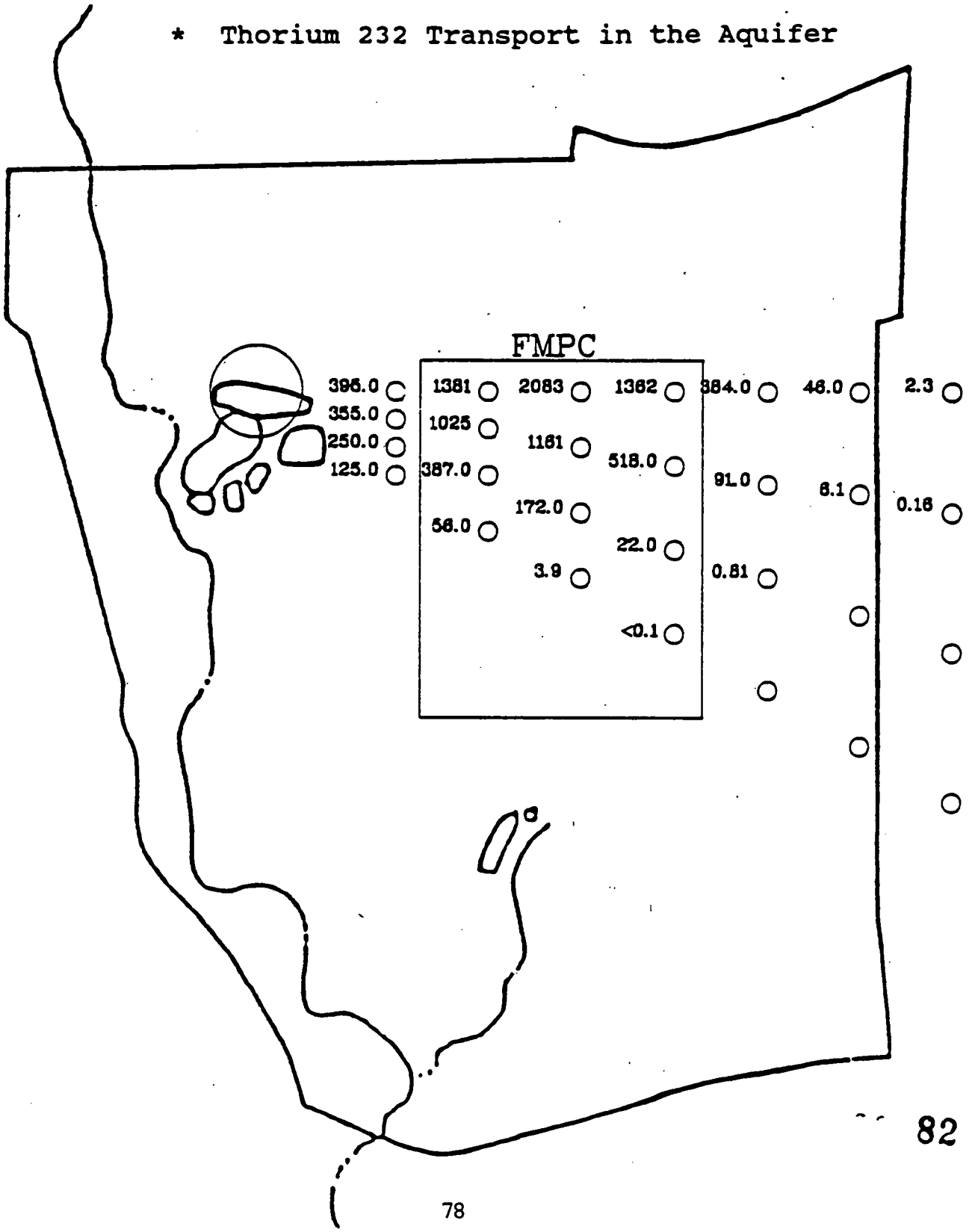


Figure 3.24: Concentration in the Aquifer After 51 Years (pCi/m3)

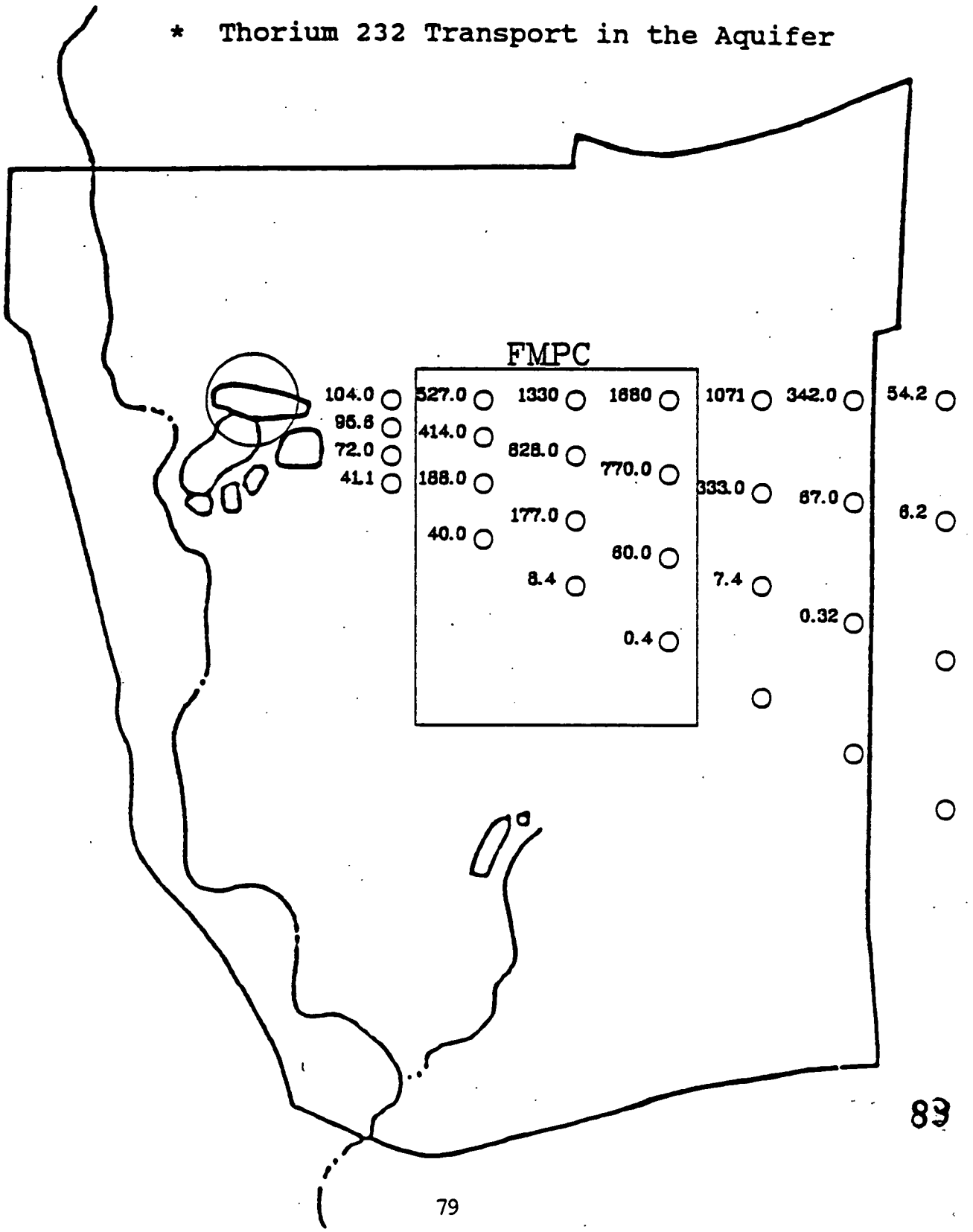


Figure 3.25: Concentration in the Aquifer After 61 Years (pCi/m3)

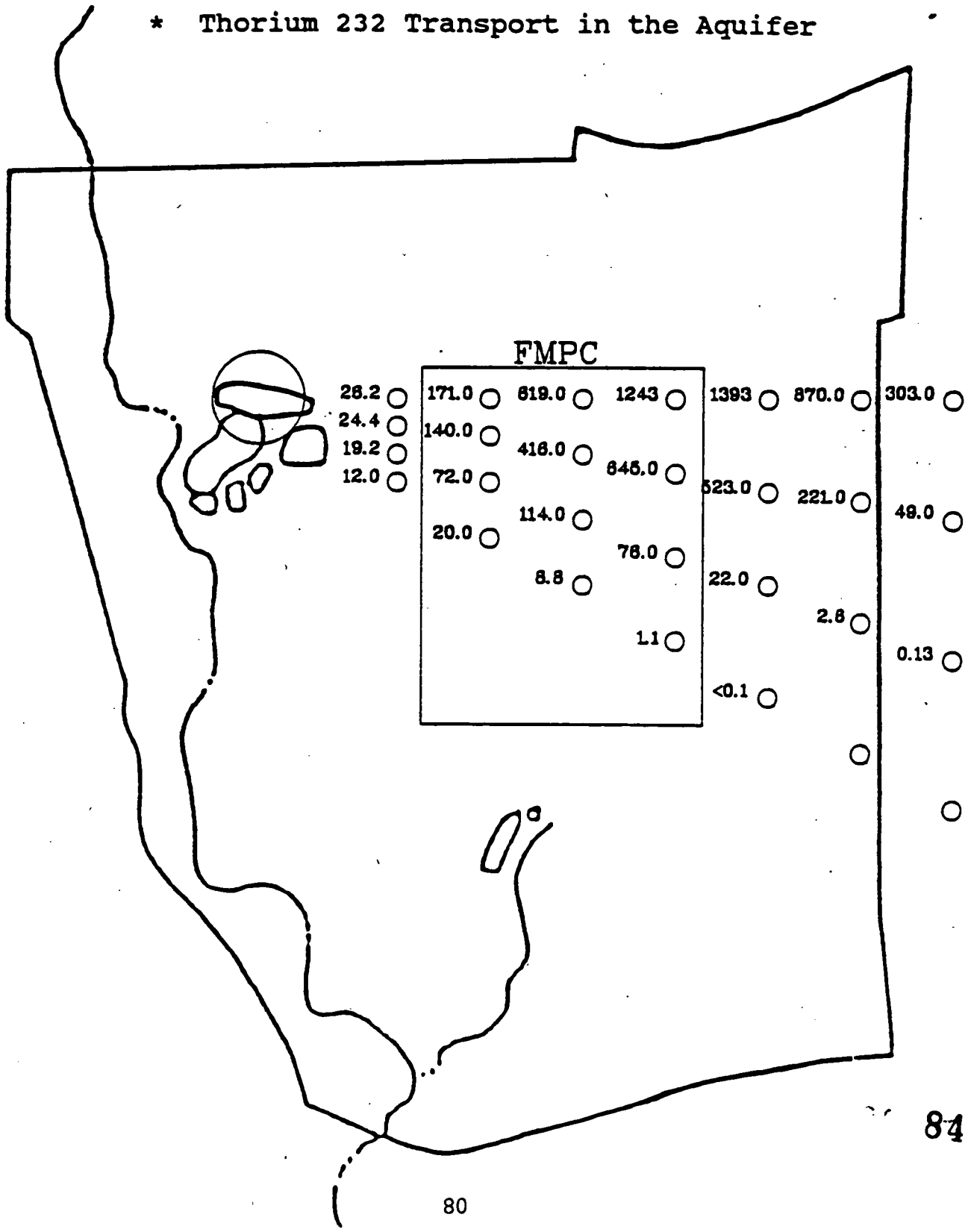


Figure 3.26: Radium 226 Concentration in Groundwater

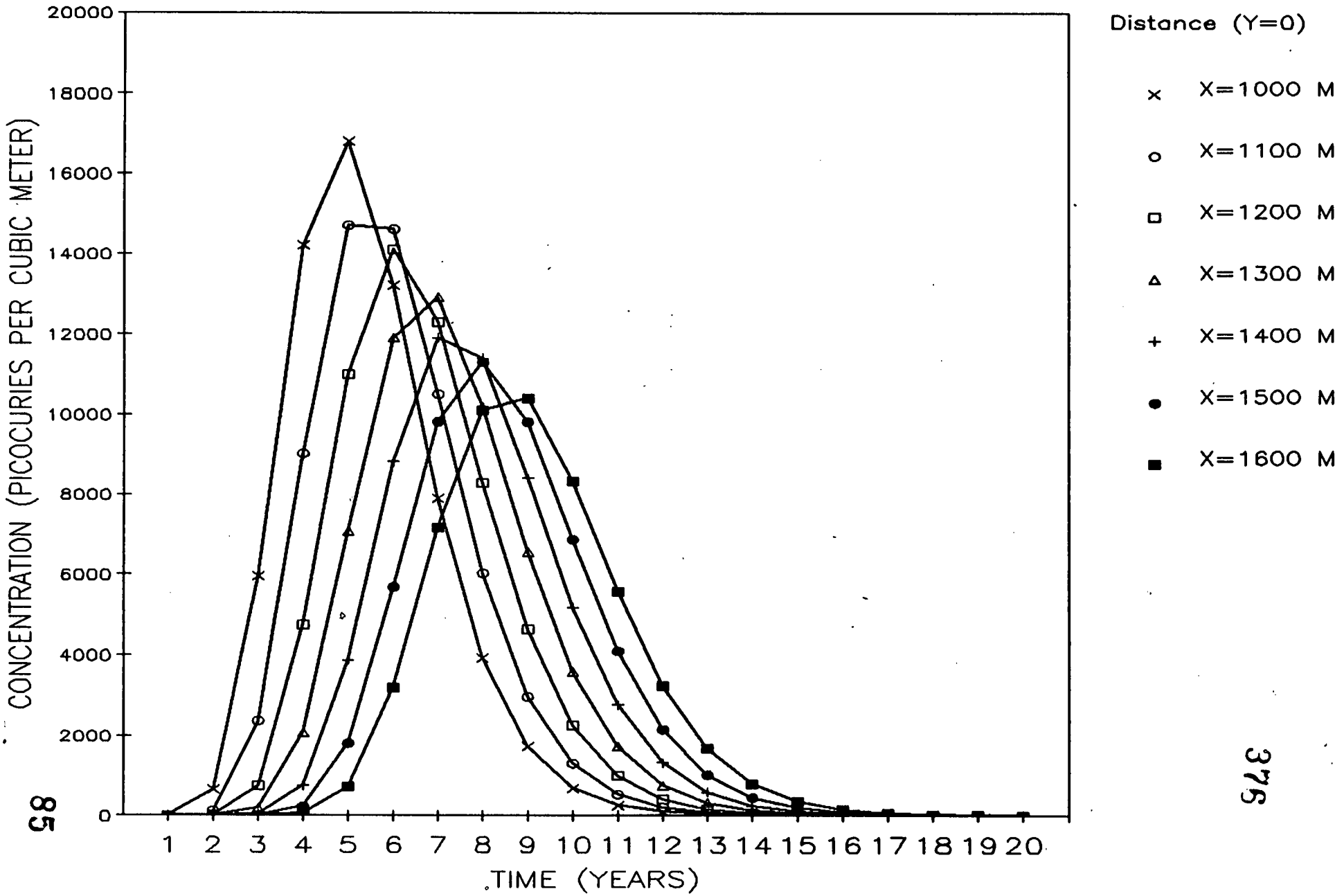


Figure 3.27: Uranium 238 Concentration In Groundwater

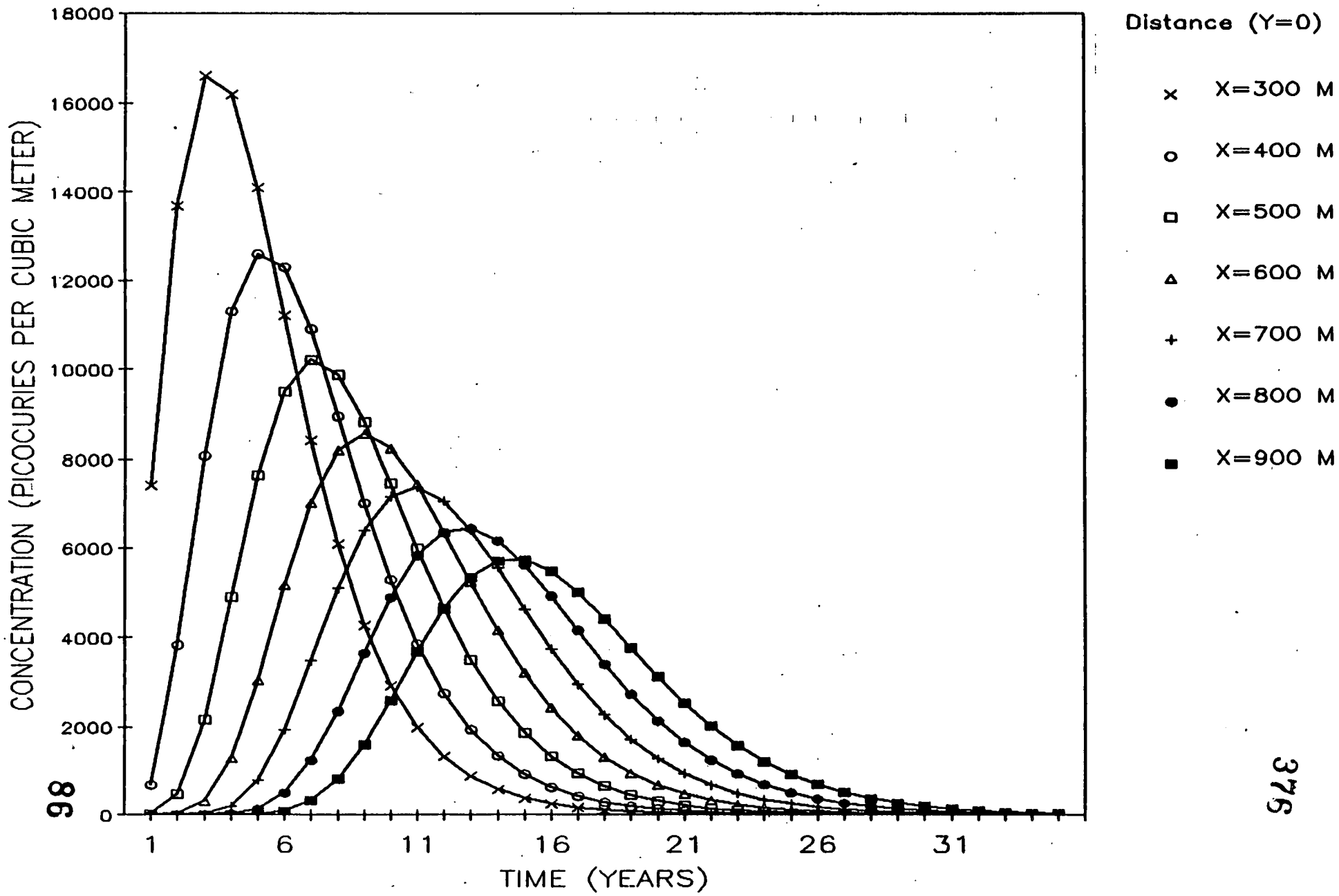


Figure 3.28: Uranium 238 Concentration In Groundwater

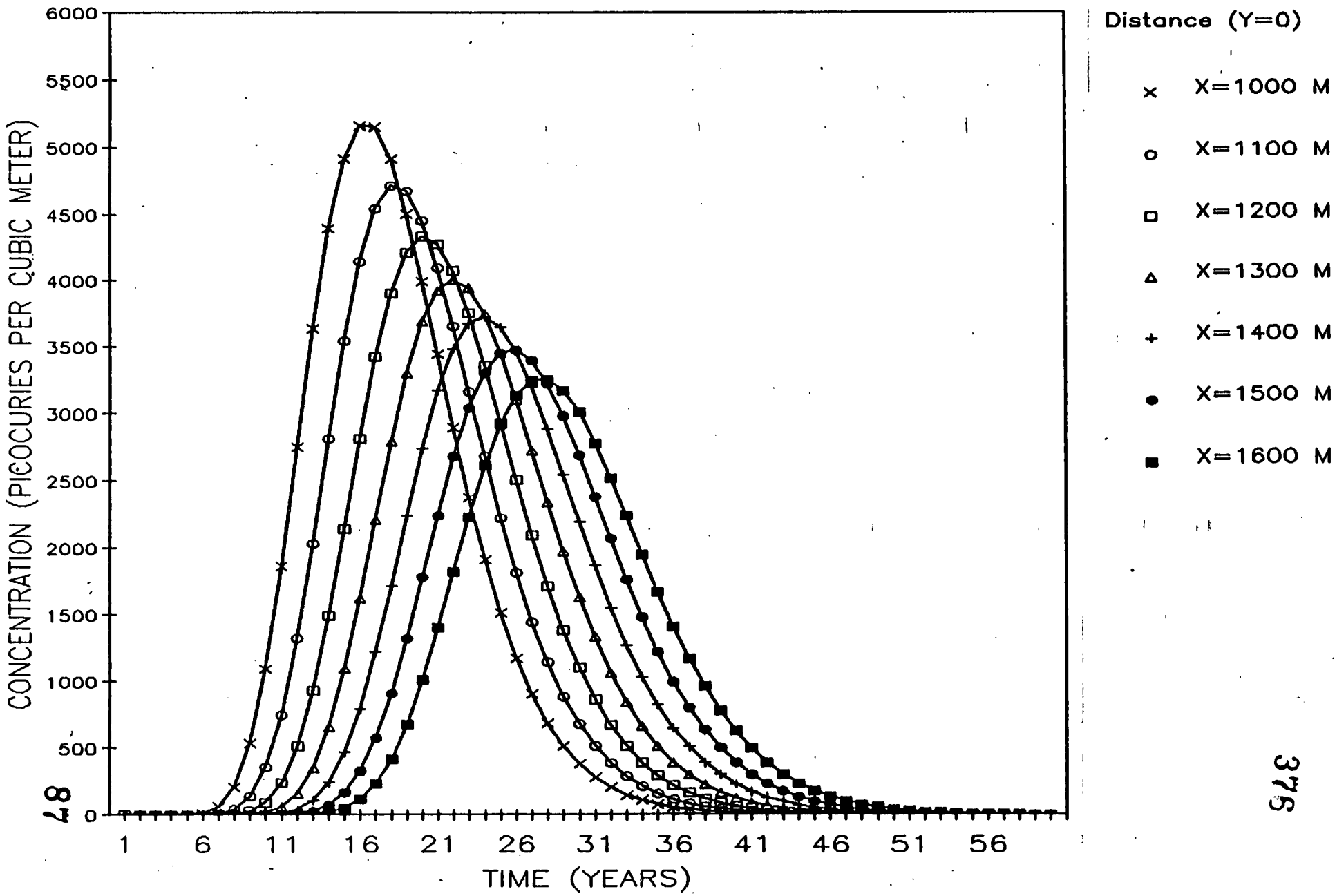


TABLE 3.7

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

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coefficient and thus obtain both realistic and conservative results.

3.5.5.1 The Limitations of the Model

A few of the limitations have been noted, such as taking the medium as homogeneous and isotropic. This section will focus on the basis of the model and the range of applicability.

The basis for this model stems from a scenario in which FMPC site has been returned to public use at some time in the future. The actual time figure for this situation can not be determined given present information. The assumption then was made that this site would be reclaimed to some degree and that the residual radioactive material would contribute a dose of 100 mrem or less per year to an individual in the general public. The remedial action was thought to occur in a time frame that would permit any contamination in the aquifer to be reduced to background levels. Additionally the residual radioactive material in the soil was limited to the first 15 cm to 1 meter of depth from the surface. The migration model is then used to represent a clean environment other that at the surface.

The model presented here applies to this scenario and is used to predict a break through time and concentration for various radionuclides moving from the surface soil to the saturated region. Once the radioactive material reaches the saturated region the model is used to estimate the movement and dilution within this region. This estimate provides the concentration of contaminant per liter of water for use in the dose to source ratios. This analysis did not consider the region near paddy's runs creek due to a groundwater divide predicted by GeoTrans 1985. Contaminants reaching the aquifer in this region would be expected to move south towards the Great Miami River. The family farm was assumed to lie within the FMPC and to the east of

Paddy's Run near the waste site area or within the area now occupied by the production facilities. Additionally the transport times for contaminants moving through sand and silt are typically orders of magnitude shorter than for regions of clay. This would enable small concentrations of contaminants to appear in the drinking water within the 0-100 year time frame. This time frame of 0-100 years is dominated by the inhalation and ingestion pathways and preliminary analysis indicated that the contribution from the drinking water was negligable. After the initial 100 years the near term inhalation and ingestion dominated paths are reduced by leaching and weathering processes. At this point the sand and silt regions would have had all but background material leached out and once again would not contribute to the water pathway. The intermediate and longterm analysis of the soil guidelines will consider the transport of the contaminants through the vadose regions.

3.5.5.2 Comparison to The Manual

The Department of Energy's manual for implementing residual radioactivity guidelines was in review draft when this contract began and now the Manual is in final draft form. Significant changes in the water pathways have taken place in the updated versions of the Manual. Due to data availability some of the proposed models are still not incorporated in the current version of the RESRAD code, particularily the diffusion-controlled leaching model. In almost all cases and for sufficiently long transport times the dominant factor will be diffusion. [U.S. DOE, 85] In the 1985 version of the Manual three models were proposed to estimate the concentration of radionuclides in water that has percolated through the contaminated regions. These models were: 1) the solubility model, 2) the ion-exchange model, and 3) the diffusion model. These three models were revised and are now considered as the 1) dissolution-

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controlled, 2) desorption-controlled, and 3) diffusion-controlled leaching models. The model developed for this study utilizes both the desorption and diffusion mechanisms to estimate the concentration as a function of time and distance. Tables 3.9 shows results of the breakthrough time for uranium using the original ion-exchange model (Gilbert 85). The ion-exchange model is expected to over estimate the concentration of the radionuclides that will migrate through the unsaturated zone and transport times can differ significantly due to linear dependence on the distribution coefficient and hydraulic conductivity. The results shown here illustrate the over dependence on the hydraulic conductivities.

The greater the hydraulic conductivity the shorter the transport time. This approach assumes a uniform saturation across the medium. The Manual does not incorporate the diffusion-controlled model into the RESRAD code due to difficulty in determining the diffusion coefficients for the medium and the radionuclides. The model used in this study utilizes the measured dispersivities for material similiar to that at the FMPC. In this way both the mechanical dispersion and the molecular diffusion can be approximated.[Till, 83] The error due to this approximation is on the order of that due to using measured values of distribution coefficients from other sources. The increased transport time due to the ion-exchange coupled with the more rapid migration due to diffusion combine to give a better approximation of the physical situation. To ensure that the actual situation is being represented one should measure site specific dispersivities as well as distribution coefficients for the vadose and saturated regions.

Table 3.9 Transport Time for Uranium Based on Ion Exchange Model

Distribution Coefficient (ml/g)	Hydraulic Conductivity (m/yr)	Transport Time (yr)
150	22.25	1210
270	22.25	2185
400	22.25	3237
800	22.25	6473
1000	22.25	8090
5000	22.25	40500
270	111.25	437
270	191.45	254
270	278.35	180

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4.0 PATHWAY ANALYSIS METHODOLOGY

4.1 Development of Analysis Methods

The allowable levels of residual radioactivity in the ground are specified in terms of single radionuclide soil concentration guidelines, called simply, "soil guidelines". These soil guidelines are developed for the principal radionuclides, which have a half life of one year or longer.

The Department of Energy has several projects underway to develop analytical techniques and computer programs to calculate residual radioactivity soil guidelines for formerly intilized sites such as FUSRAP and SMFP sites. A manual was developed to assist in calculating soil guidelines. This manual is called "A Manual for Implementing Residual Radioactivity Guidelines. It was distributed as a draft copy in 1985 (Gilbert 85) and a revised draft copy was distributed in 1987. (Gilbert 87) A Final Draft copy was released in January of 1988. (Gilbert 88). In this project, we are adapting the generic Manual analysis to a site-specific analysis for the FMPC. We are essentially adapting a generic soil guidelines analysis methodology developed for FUSRAP sites, to the FMPC plant.

A computer program developed at Pacific Northwest Laboratories (Napier 84) was also obtained to help develop soil guidelines. This program, called ONSITE/MAXI was developed by the DOE to perform pathway analysis for the onsite disposal of radioactive waste. ONSITE/MAXI is another method of calculating soil guidelines. The details of the analysis by ONSITE/MAXI are given in Section 5.4 of this report. A new computer program, called RESRAD, is also being developed to compute soil guidelines. It is not yet available for use.

A third method that was used to evaluate the effect of residual soil radioactivity on human populations was a computer program called AIRDOS-EPA. This program is actually a package of computer programs. One of the programs,

called DARTAB, is a program for calculating health effects due to ingestion or inhalation of radiation. Section 5.3 contains the details of the AIRDOS analysis.

This three-pronged attack provides a wide variety of analytical methods to calculate the soil guidelines. Each method provides additional insight into the problem. Most importantly, having three independent methods provides an excellent cross check for results. Hand calculations by traditional formulas were also used to check the computer results.

Each of the three methods utilize some very common and very fundamental concepts related to how humans receive a dose from residual radiation in the soil. This section will present a very brief, but hopefully understandable, review of these common analytical methods.

Site specific soil guidelines are calculated by the formula:

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

where:

$S_{G,i}$ = single radionuclide 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/yr. per US DOE standards

The D/S ratio for each radionuclide may be given as the pathway sum:

$$(D/S)_i = \sum_{paths} (D/S)_{i,paths} \qquad \text{(eq. 4.2(a))}$$

or

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$$(D/S)_i = \sum_p (D/S)_{i,p} \qquad \text{(eq. 4.2(b))}$$

The index, p, is a pathway index label. Thus, the total dose to an individual from residual radioactivity in the soil, would be the sum of each dose received through all the pathways. The derivation of soil guidelines requires a detailed evaluation of site values for each of the $D/S_{i,p}$ terms.

The 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 can be calculated from these two factors:

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

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, g/y or L/y

The next section will describe these two factors and discuss methods of obtaining the D/E and E/S parameters.

4.2 Dose Conversion Factors for Internal Radiation, D/E

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 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 relationships are referred to as "dose conversion factors".

Internal radiation dose to organs and tissues of the body is evaluated by models and analysis methods developed by the International Commission on Radiological Protection (ICRP). These methods are widely used in predicting the dose to humans from ingestion or inhalation of radionuclides.

Calculation of dose equivalents in organs or tissues of the body requires the use of these models to (1) describe the entrance of materials into the body (respiratory and gastrointestinal tract) and the deposition and subsequent retention of the radionuclides in body organs (referred to as metabolic models), and (2) estimate the energy deposition in tissues of the body. In applying the results of these calculations, some insight into the details of models for the lung and gastrointestinal tract is required because these models define the interface between man and the environment.

Inhalation of radionuclides attached to airborne particles is a potential route for intake of radionuclides into the body. The ICRP model of the respiratory tract divides the tract into a nasopharyngeal region, a tracheobronchial region, and a pulmonary region. These regions are interconnected with one another as well as with body fluids and the gastrointestinal tract. The fraction of inhaled activity deposited in these regions is a function of the size of the airborne particles. The activity median aerodynamic diameter (AMAD) is the measure most widely used to characterize the aerosol. It is basically the "size" of the particle in microns.

The rate at which the deposited material is removed from the above described compartments is considered to be independent of particle size. The removal rate is related to the chemical form of the particles. Chemical compounds are assigned to one of three classes to characterize their removal rate from the lung. The lung classes are denoted as D, W, and Y - corresponding to clearance or removal times from the pulmonary region of the

lung on the order of days, weeks, or years, respectively. The specific classes assigned to uranium compounds are listed in Table 4.1.

TABLE 4.1

SOLUBILITY CLASSIFICATION OF SELECTED URANIUM COMPOUNDS

Class D - Soluble (transported) compounds - solubility half-life (time for half of the compound to be dissolved in lung fluids) of 1 to 10 days.

Ammonium diuranate (ADU)	$(NH_4)_2U_2O_7$
Uranium hexafluoride	UF_6
Uranium trioxide	UO_3
Uranyl acetate	$UO_2(C_2H_3O_2)_2$
Uranyl chloride	UO_2Cl_2
Uranyl fluoride	UO_2F_2
Uranyl nitrate	$UO_2(NO_3)_2$
Uranyl sulfate	UO_2SO_4

Class W - moderately soluble (slowly-transportable) compounds-estimated solubility half-life of 10 to 100 days inclusive.

Uranium dioxide	UO_2
Uranium tetroxide	UO_4

Class Y - relatively insoluble (very slowly-transportable) compounds estimated solubility half-life of greater than 100 days.

Uranium aluminide	UAl_x
Uranium carbide	UC_2
Uranium dioxide (high-fired)	UO_2
Uranium oxide	U_3O_8
Uranium tetrafluoride	UF_4
Uranium-zirconium alloy	UZr

A portion of the material initially deposited in the lung enters the gastrointestinal (GI) tract. Ingested radionuclides can also enter the GI tract directly. The ICRP model of the GI tract divides the tract into four compartments: stomach, small intestine, upper large intestine, and lower large intestine. This model is also described in more detail in the Appendix. In the GI tract, absorption of materials into body fluids is generally considered to occur within the small intestine. The fraction of the ingested material absorbed into blood from the tract is denoted as f_1. The numerical value of f_1 is dependent on the chemical form of the ingested

material.

Radionuclides that enter body fluids either from the lung or through the GI tract may be deposited within the various organs of the body. Metabolic processes and radioactive decay reduce the radioactivity in the body. These removal processes are modeled in a rather simple manner in which the organs are represented by a number of mathematical compartments from which the removal rate is directly proportional to the amount of radionuclide present. This approach leads to functions involving a sum of exponentials to describe the rate of change of radioactivity with time in the body tissues and compartments.

The respiratory tract model and the GI tract model are used to calculate the committed dose equivalent to humans that inhale or ingest radiation. Since the internal dose is always directly proportional to the quantity of radioactive material inhaled or ingested, the calculations are performed for a unit intake of the radionuclide. When one drinks a liter of water containing one picocurie (pCi) of uranium 238 in the chemical form uranyl chloride (UO_2Cl_2), the dose to the various body organs and tissues can be calculated. Since the results for ingestion of 1 pCi of UO_2Cl_2 are always the same, they can be easily tabulated for future use. If a person ingests 10 pCi of the same compound, the dose to each organ is exactly ten times the dose due to ingestion of 1 pCi. The same is true for inhalation, if a worker breathes air containing 10 pCi/m^3 of uranium hexafluoride, UF, the dose to the lungs of this worker would be exactly ten times the dose from 1 pCi/m^3.

4.3 Dose Factors for Inhalation and Ingestion

Factors representing the effective committed dose equivalent per unit intake for selected radionuclides via inhalation and ingestion are given in Table 4.2. These values were taken directly from the Manual. In many instances, several chemical forms have been considered: that is, more than one clearance class (inhalation) or f_1 (ingestion) value is given for the radionuclide. If the user of the Manual has information indicating the chemical forms expected in the particular environment being considered then the appropriate value should be selected after consulting ICRP Publication 30 (ICRP 1979). If no information on the relevant chemical forms is available, then the most conservative value (i.e., the highest estimate of dose) should be used. Table 4.1 listed this clearance class for uranium compounds. Based on these ICRP models, dose conversion factors for selected radionuclides of interest to the FMPC soil guidelines study are listed in Table 4.2.

TABLE 4.2

D/E FACTOR FOR INTERNAL RADIATION FOR SELECTED RADIONUCLIDES (Gilbert 87)

Principal Radionuclide	lung class	f_i	inhalation D/E mrem/pCi	f_i	ingestion D/E mrem/pCi
Tc99	D	$8x10^{-1}$	$1.02x10^{-6}$	$8x10^{-1}$	$1.46x10^{-6}$
Tc99	W	$8x10^{-1}$	$8.33x10^{-6}$	$8x10^{-1}$	$1.46x10^{-6}$
Ra 226+D	W	$2x10^{-1}$	$8.59x10^{-3}$	$2x10^{-1}$	$1.32x10^{-3}$
Ra 228+D	W	$2x10^{-1}$	$4.86x10^{-3}$	$2x10^{-1}$	$1.44x10^{-3}$
Th 230	W	$2x10^{-4}$	$3.26x10^{-1}$	$2x10^{-4}$	$5.48x10^{-4}$
Th 230	Y	$2x10^{-4}$	$3.26x10^{-1}$	$2x10^{-4}$	$5.48x10^{-4}$
Th 232	W	$2x10^{-4}$	$1.64x10^{0}$	$2x10^{-4}$	$2.73x10^{-3}$
Th 232	Y	$2x10^{-4}$	$1.15x10^{0}$	$2x10^{-4}$	$2.73x10^{-3}$
U 235+D	D	$5x10^{-2}$	$2.53x10^{-3}$	$5x10^{-2}$	$2.66x10^{-4}$
U 235+D	W	$5x10^{-2}$	$7.29x10^{-3}$	$2x10^{-3}$	$2.81x10^{-5}$
U 235+D	Y	$2x10^{-3}$	$1.23x10^{-1}$	$2x10^{-3}$	$2.81x10^{-5}$
U 238+D	D	$5x10^{-2}$	$2.45x10^{-3}$	$5x10^{-2}$	$2.55x10^{-4}$
U 238+D	W	$5x10^{-2}$	$7.06x10^{-3}$	$2x10^{-3}$	$3.75x10^{-5}$
U 238+D	Y	$2x10^{-3}$	$1.18x10^{-1}$	$2x10^{-3}$	$3.75x10^{-5}$
Pu 238	W	$1x10^{-4}$	$4.63x10^{-1}$	$1x10^{-4}$	$3.96x10^{-4}$
Pu 238	Y	$1x10^{-5}$	$3.15x10^{-1}$	$1x10^{-5}$	$5.55x10^{-5}$
Pu 239	W	$1x10^{-4}$	$5.18x10^{-1}$	$1x10^{-4}$	$4.40x10^{-4}$
Pu 239	Y	$1x10^{-5}$	$3.40x10^{-1}$	$1x10^{-5}$	$5.88x10^{-5}$
Pu 240	W	$1x10^{-4}$	$5.18x10^{-1}$	$1x10^{-4}$	$4.40x10^{-4}$
Pu 240	Y	$1x10^{-5}$	$3.40x10^{-1}$	$1x10^{-5}$	$5.92x10^{-5}$

Dose conversion factors identified with "+D" in Table 4.2 are the sums of dose conversion factors for a principal radionuclide (a radionuclide with a half-life greater than 1 year) and its associated decay chain (all short-lived decay products of a principal radionuclide down to, but not including, the next principal radionuclide or the final nonradioacitve nuclide in the chain). These aggregated dose conversion factors correspond to ingestion or inhalation of the principal radionuclide together with its associated decay product radionuclides, which are assumed to be in secular equilibrium at the time of intake.

4.4 Dose Conversion Factors for External Radiation (D/E)

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 or from radionuclides within the soil. The body tissue and organs can be irradiated from this external source if the radionuclides are gamma emitters. This photon radiation can be extremely penetrating; it will irradiate the entire body, including the body organs. There is some shielding afforded the body organs by the body tissue itself. If the tissue or muscle dose is 1.0 mrem, the dose to some organs (lungs, liver, etc.) may be as low as 0.6 mrem due to this shielding.

The effective dose equivalent concept includes a weighting factor W_t, for each body organ. This weighting factor is designed to make the health risk due to irradiation of an individual body organ statistically equivalent to irradiation of the entire body. For example, the weighting factor for the thyroid is $W_t = 0.03$. A dose of 100 mrem to the thyroid would be equivalent to a risk of fatal cancer incidence from a dose to the whole body of 3 mrem as shown below.

$D_{wb} = W_t D$ thyroid $\qquad W_t = .03$ (thyroid)

$D_{WB} = .03\ (100) = 3$ mrem

Kocher (Kocher 1983) prepared extensive tables of dose rate factors for radionuclides in air, water and on the ground surface. Kocher later derived dose rate factors for radionuclides uniformly distributed in the soil volume. These are essentially the D/E values used in the Manual and computer programs.

Dose conversion factors for external radiation from airborne radionuclides have not been included because the dose from this source is

small compared with the dose from inhalation of airborne radionuclides. Dose conversion factors for water immersion have not been included because this contribution will also be negligible compared with other pathways due to the low concentration of radionuclides in surface water (compared with the concentration in the ground and in drinking water from a well) and the small fraction of time that an individual would be exposed to external radiation from surface water.

The dose conversion factors for ground contamination are for exposure at a point 1 meter above ground. The surface contamination is assumed to be a uniform layer of infinitesimal thickness and infinite lateral extent; the volume contamination is assumed to be uniformly distributed to infinite depth and infinite lateral extent. Contributions from all associated radionuclides, which are assumed to be in secular equilibrium with the parent principal radionuclide, are included in the dose conversion factors for principal radionuclides.

These dose conversion factors assume a field of infinite extent. Corrections must be made in the analysis for small contaminated areas or "hot spots". The Manual describes these corrections.

Dose conversion factors for radionuclides distributed in the ground volume will depend on the bulk density of the soil (ρ_b) Factors for $\rho_b = 1.0$ g/cm^3 and $\rho_b = 1.8$ g/cm^3 are listed in Table 4.3. Values for other soil densities may be obtained by interpolation. Linear interpolation of D/E can be used, although linear interpolation of ln(D/E) gives slightly more accurate results.

Table 4.3 lists some D/E factors for external radiation from contaminated ground; surface soil or volume sources.

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)
	$\frac{mrem}{yr}$ per $\frac{pCi}{cm^2}$	$\frac{mrem}{yr}$ per $\frac{pCi}{cm^3}$
Tc 99	6.33×10^{-7}	9.32×10^{-7}
Ra 226+D	1.70×10^{0}	8.56×10^{0}
Ra 228+D	9.62×10^{-1}	4.51×10^{-0}
Th 230	9.58×10^{-4}	1.03×10^{-3}
Th 232	7.14×10^{-4}	6.04×10^{-4}
U2235+D	1.93×10^{-1}	4.90×10^{-1}
U238+D	1.33×10^{-1}	6.97×10^{-4}
Pu 238	9.29×10^{-4}	6.65×10^{-4}
Pu 239	4.07×10^{-4}	3.76×10^{-4}
Pu 240	8.92×10^{-4}	6.35×10^{-4}

4.5 Environmental Transport Factor, E/S

The environmental transport factors describe the means by which the radionuclides are transported from the source term in the soil to exposure, inhalation or ingestion by humans. One example of an environmental transport factor would be the simple act of drinking water from a contaminated well on the site. The environmental transport factor would be expressed as:

$$(E/S)_i = (E/W)(W/S)_i \qquad \text{(eq. 4.4)}$$

E/W = drinking water intake factor, L/d

$(E/S)_i$ = environmental transport factor for radionuclide, i, $\frac{pCi}{d}$

$(W/S)_i$ = concentration of radionuclide, i, in the drinking water, pCi/L

If the well water contains 10 pCi/L and a person drinks 500 ml/d, then the environmental transport factor is

$$E/S = .500 \text{ L/d} \times 10 \text{ pCi/L} = 5 \text{ pCi/d}$$

The environmental transport factors are the mechanism by which the radionuclide is transported from the source to the point at which it represents an exposure to humans or is ingested by people in food or water.

Environmental transport factors can become very complex, especially for the aquatic paths and the food chain paths. Fortunately, these environmental transport factors have also been evaluated for a large number of radioisotopes and a selected number of important food chain pathways (see Tables 4.4-4.6). Only a brief description will be given for environmental transport factors in this section. For additional information, consult the Manual, or the documents entitled, "Models and Parameters for Environmental Radiological Assessments" (Miller 84) and "Radiological Assessment" (Till 83).

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 summarized below. Details can be found in the Manual.

<u>Transport Factor for External Volume Source</u> (no units)

$$\frac{E}{S} = (FO)\ (FA)\ (FD) \qquad \text{(eq. 4.5)}$$

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where:

E/S = environmental transport factor for external volume source

FO = occupancy factor, related to time spent on site

FA = area factor, related to size of contaminated area

FD = depth factor, related to depth of contaminated area

Transport Factor for Dust Inhalation (g/yr)

$$\frac{E}{S} = \left(\frac{E}{A}\right) (FO) (FA) (FD) \left(\frac{A}{S}\right) \qquad \text{(eq. 4.6)}$$

where:

$\frac{E}{S}$ = environmental transport factor for dust inhalation, g/yr

$\frac{E}{A}$ = annual air intake, m^3/yr.

$\frac{A}{S}$ = mass loading of airborne dust, g/m^3 of air

Transport Factor for Water and Foods, g/yr

The environmental transport factor for plant foods is the sum of each of the three transport processes listed below: root uptake, foliar deposition and irrigation water. For root uptake, the transport factors are:

$$\frac{E}{S} = \left(\frac{E}{C}\right) (FA) (FD) \left(\frac{C}{S}\right) \qquad \text{(eq. 4.7)}$$

where:

$\frac{E}{S}$ = environmental transport factor for root uptake, Kg/y

$\frac{E}{C}$ = annual intake of food, Kg/yr.

$\frac{C}{S}$ = radionuclide transfer factor, soil to plants

The environmental transport factor for radionuclides deposited from the dust in the air to the plant foliage is:

$$\frac{E}{S} = \left(\frac{E}{C}\right) (FA) \left(\frac{C}{A}\right) \left(\frac{A}{S}\right) \qquad \text{(eq. 4.8)}$$

where: $\frac{C}{A}$ = radionuclide transfer factor from foliar deposition

$\frac{A}{S}$ = mass loading of airborne dust, g/m^3

The third contribution to the transport factor for food and water is a result of irrigating the farm crops grown on site with contaminated water from a well on site or nearby pond. This factor can be calculated from:

$$\frac{E}{S} = \left(\frac{E}{C}\right) (FA) \left(\frac{C}{W}\right) \left(\frac{W}{S}\right) \qquad \text{(eq. 4.9)}$$

where: $\frac{C}{W}$ = radionuclide transfer factor from water to food, $\frac{L}{g}$

$\frac{W}{S}$ = water to soil concentration ratio, g/L

Table 4.6 shows the value of the environmental transport factors for selected radionuclides.

TABLE 4.6

ENVIRONMENTAL TRANSPORT FACTORS FOR FOODS (E/S)
(CONTAMINATED IRRIGATION WATER COMPONENT)

Principal Radionuclide	Plant Foods	Meat	Milk
Tc 99	1.1×10^3	2.4×10^1	1.1×10^3
Ra 226, 228	7.7×10^2	1.6×10^1	1.6×10^1
Th 230, 232	7.7×10^2	7.9×10^1	2.0×10^1
U 235, 238	7.7×10^2	7.8×10^1	4.8×10^1
Pu 238, 239, 240	7.7×10^2	7.8×10^1	2.0×10^{-3}

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These environmental transport factors are for a full diet of foods which are grown entirely on a formerly utilized site. The factors must be modified in the analysis to account for the fraction of the foods grown on the family's farm and the fraction of the foods grown on the family farm that are grown in formerly contaminated areas. (area factor). For large contaminated areas, two hectares or more, these factors become 1.0.

The environmental transport factor for meat and milk is also the sum of three component parts related to the meat or milk animals eating feed or fodder that has picked up some of the radionuclides from the soil by root uptake, foliar deposition or irrigation water. For root uptake and foliar deposition;

$$\frac{E}{S} = \left(\frac{E}{C}\right) (FA) \left(\frac{C}{Q}\right) \left(\frac{Q}{F}\right) \left(\frac{F}{S}\right) \qquad \text{(eq. 4.10)}$$

while for fodder irrigation and livestock water,

$$\frac{E}{S} = \left(\frac{E}{C}\right) (FA) \left(\frac{C}{Q}\right) \left[\left(\frac{Q}{F}\right) \left(\frac{F}{W}\right) + \frac{Q}{W}\right] \frac{W}{S} \qquad \text{(eq. 4.11)}$$

where: $\frac{C}{Q}$ = radionuclide transfer factor from forage, fodder, or water to meat or milk as appropriate.

$\frac{Q}{F}$ = annual livestock feed intake, Kg/yr.

$\frac{Q}{W}$ = annual livestock water intake, L/yr.

Typical values of the environmental transport factor, $\frac{E}{S}$, for the previously described processes are given in the Manual for standard scenarios. Tables 4.4 - 4.7 list $\frac{E}{S}$ values for selected radionuclides.

As these tables for environmental transport factors show, the food related transport factors are dependent on the elemental form of the radioisotope. Uranium behaves the indentical way in plants regardless if its uranium 235 or uranium 238.

TABLE 4.4

ENVIRONMENTAL TRANSPORT FACTORS FOR FOODS

(ROOT UPTAKE COMPONENT)

Principal Radionuclide	Plant Foods	Meat	Milk
Tc 99	4.4×10^{4}	1.1×10^{3}	1.5×10^{4}
Ra 226, 228	2.4×10^{2}	6.0×10^{0}	1.4×10^{0}
Th 230, 232	7.4×10^{2}	9.0×10^{1}	5.4×10^{-2}
U 235, 238	4.4×10^{2}	5.4×10^{1}	7.7×10^{0}
Pu 238, 239, 240	4.1×10^{1}	5.4×10^{0}	3.2×10^{-5}

TABLE 4.5

ENVIRONMENTAL TRANSPORT FACTORS FOR FOODS

(FOLIAR DUST DEPOSITION COMPONENT)

Principal Radionuclide	Plant Foods	Meat	Milk
Tc 99	1.8×10^{0}	3.3×10^{-2}	1.7×10^{0}
Ra 226, 228	1.2×10^{0}	2.0×10^{-2}	2.3×10^{-2}
Th 230, 232	1.2×10^{0}	9.8×10^{-2}	2.9×10^{-4}
U 234, 238	1.2×10^{0}	9.8×10^{-2}	6.9×10^{-2}
Pu 238, 239, 240	1.2×10^{0}	9.8×10^{-2}	2.9×10^{-6}

5.0 DERIVATION OF DOSE TO SOURCE RATIOS (D/S)

5.1 Sources Identified at the FMPC Site

The Westinghouse Materials Company of Ohio was responsible for collecting source data. The basic source data provided for this study consisted of the annual "Environmental Reports" (WMCO 87) and the Weston study. (WESTON 87)

5.2 Derivation of D/S Ratios for Uranium 238 as a Principal Radionuclide Using the Manual Analysis for Near Term Pathways.

An example of the method used to calculate soil guidelines will be presented in this section using uranium 238 as the example radionuclide.

As shown previously in section 4.0, site specific soil guidelines ($S_{G,i}$) are calculated by the formula

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

Where $(D/S)_i$ is the calculated value of the dose to source conversion factor for radionuclide, i. The D_L term is the annual committed effective dose equivalent limit established by the DOE at 100 mrem/yr.

This section will derive the D/S ratio for uranium 238 for the near-term, non-aquatic pathways identified as critical to the unrestricted release of the FMPC site. A detailed analysis will be performed in this section. A similar analysis was performed for each radionuclide identified in above background concentrations at the FMPC site. These are single radionuclide soil guidelines. The mixture sum formula must be used if a number of radionuclide are present in above background concentrations.

5.2.1 External radiation pathway, p=1

The D/S ratio for the external radiation pathway is:

$$\left(\frac{D}{S}\right)_1 = \left(\frac{D}{E}\right)_1 \rho_b \, (FO)_1 \, (FA)_1 \, (FD)_1 \qquad \text{(eq. 5.1)}$$

where:

$\left(\frac{D}{S}\right)_1$ = dose conversion factor for external radiation from contaminated ground, mrem/yr per pCi/cm^3.

ρ_b = soil density, g/cm^3

FO = occupancy factor, no units

FA = area factor, no units

FD = contaminated soil depth factor, no units

The D/E factor was discussed in section 4. Table 4.3 listed D/E factors for selected prinicpal radionuclides. For uranium 238 in a soil volume source of silty clay;

$$\left(\frac{D}{E}\right)_1 = 6.97 \times 10^{-2} \frac{\text{mrem}}{\text{yr}} \text{ per } \frac{\text{pCi}}{\text{cm}^3}$$

The soil density of the FMPC site was obtained from information supplied by the WMCO technical staff and a soil analysis performed by a contractor (IT 85). Based on these data, the density for a silty clay till was selected for this study.

$$\rho_b = 1.82 \text{ g/cm}^3$$

The occupancy factor, FO, was calculated using the assumptions recommended in the Manual. The occupancy factor is a unitless factor that

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gives the average fraction of time that an individual is exposed to the source of radiation. It is determined by the exposure scenario described in Section 3 and for values listed in Table 3.1. From Table 3.1 the scenario is defined by the following time allocation:

time spent outdoors = 25%

time spent indoors = 50%

time spent offsite = 25%

Based on this scenario and assuming the house reduces the radiation by 30% (Manual assumption), the occupancy factor is found to be:

$$FO_1 = 0.25 + .50\ (1.0 - 0.3) + .25\ (0) = 0.6$$

The area factor, FA, is tabulated in the Manual (pages 4-7) as a function of the size of the contaminated area. For external radiation from a contaminated ground area larger than 1200 m^2, FA = 1.0. Since the FMPC site is $4.25 \times 10^6 m^2$ and there is above background concentrations of uranium 238 over much of the site,

$$FA_1 = 1.0$$

It should be noted that even the waste pit areas are larger than $1200M^2$, except for pit number 6.

The depth factor, FD, is the ratio of the external exposure for a contaminated layer of thickness, T, and cover depth, C_d, to the exposure for a contaminated layer of infinite thickness and no cover. The equations used to calculate FD are:

$$FD_1 = \exp(-k\,\rho_b C_d)\,[1 - \exp k\rho_b T] \qquad \text{(eq. 5.2)}$$

In this equation, k is an empirical constant defined by:

$$k = -\ln\,[1 - FD\,(1.0,\ \rho_b)]/1.0\ \rho_b \qquad \text{(eq. 5.3)}$$

The empirical parameter FD (1.0 ρ_b) is tabulated in the Manual, Table 4.2 (pages 4-10). For ρ_b= 1.82 and a contaminated depth of 1 meter (used throughout this study), the depth factor is:

$$FD\,(1.0,\ 1.8) = 8.8 \times 10^{-1}$$

Substituting this value into eq. 5.3,

$$k = \frac{-\ln\,(1 - .88)}{1.0\ (1.8)}$$

$$k = 7.85$$

Using this value of k in eq. 5.2, and with C_d = 0; (This assumes the contaminated zone is from the surface of the soil to a depth of one meter.)

$$FD_1 = \exp\,(0)\ [1 - \exp\,(-7.85)\ (1.8)\ (1.0)]$$

$$FD_1 = 0.88$$

Substituting these values for the parameters in eq 5.1, the D/S value is obtained.

$$\left(\frac{D}{S}\right)_1 = 6.97 \times 10^{-2}\ (1.8)\ (0.6)\ (1.0)\ (0.88)$$

$$\left(\frac{D}{S}\right)_1 = 0.06624\ \frac{\text{mrem}}{\text{yr}}\ \text{per}\ \frac{\text{pCi}}{\text{gr}}$$

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For the external radiation pathway, (D/S) = 0.0662

5.2.2 Dust inhalation pathway, p=2

The D/S ratio for the dust inhalation pathway is calculated from the equation below, where all terms now relate to dust inhalation pathway parameters. (p = 2)

$$\left(\frac{D}{S}\right)_2 = \left(\frac{D}{E}\right)_2 \left(\frac{E}{A}\right)_2 (FO)_2 \, (FS)_2 \left(\frac{A}{S}\right)_2 \qquad \text{(eq. 5.4)}$$

where:

$\left(\frac{D}{E}\right)_2$ = dose conversion factor for dust inhalation; $\frac{mrem}{pCi}$

$\left(\frac{E}{A}\right)_2$ = annual air intake, m^3/yr.

FO_2 = occupancy factor, no units

FS_2 = source factor, no units

$\left(\frac{A}{S}\right)_2$ = quantity of dust in the air, g/m^3

As discussed in the methodology section, the D/E factor for dust inhalation depends on the chemical form of the uranium compound. If this information is not available, the most conservative value for D/E must be used. From Table 4.2, for uranium 238, class y,

$$\left(\frac{D}{E}\right)_2 = 1.18 \times 10^{-1} \frac{mrem}{pCi}$$

The annual air intake is based on the ICRP data for standard man (ICRP 1977), which defines the daily air intake as 23 m^3/d. The value for E/A is:

$$\left(\frac{E}{A}\right)_2 = 23 \frac{m^3}{d} \times 365 \frac{d}{yr} = 8395 \frac{m^3}{yr}$$

The occupancy factor for path 2 is calculated based on the assumption that 50% of the resident's time is spent indoors, where the dust level is 40% of the outdoor level (Manual assumption), 25% of the resident time is spent outdoors at the site and 25% of the time is spent away from the site.

$$(FO)_2 = (.5)(.4) + .25(1.0) = 0.45$$

The FS_2 is a source factor related to the location of the contaminated soil and whether it would be available for re-suspension in the air to be inhaled. This essentially allows for a dilution of the radionuclide content in the air. If the surface of the soil is contaminated as well as the volume of soil directly below the surface, the manual recommends FS=1.0.

$$FS_2 = 1.0$$

The final term in this equation relates to the dust loading in the air. The Manual recommends using a conservative value of 200 ug/m^3 unless data are available to provide a better estimate. Equations are also available to allow the dilution of this value from offsite dust. Due to the size of the FMPC site, no credit was taken for dilution.

$$(\frac{A}{S})_2 = 2.0 \times 10^{-4}\ g/m^3$$

Substituting all the values obtained, the $(D/S)_2$ value can be calculated

$$(\frac{D}{S})_2 = (1.18 \times 10^{-1})(8395)(0.45)(1.0)(2.0 \times 10^{-4})$$

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$$\left(\frac{D}{S}\right)_2 = 0.0892 \frac{\text{mrem}}{\text{yr}} \text{ per } \frac{\text{pCi}}{\text{g}}$$

For the external dust inhalation pathway, $\left(\frac{D}{S}\right)_2 = .0892$

5.2.3 Drinking water pathway (near term) p=3

The onsite well used by the resident family is assumed to be in the aquifer below the FMPC. The aquifer does not contain any above background concentration of radionuclides during the near term release of the FMPC site for unrestricted use. This pathway does not enter into the calculation of the near term soil guidelines.

5.2.4 Food pathways, plants (p=4), meat (p=5) and milk (p=6).

The food pathways are each analyzed for root uptake (q=1), foliar deposition (q=2) and irrigation and livestock water (q=3). Consistent with the discussion in Section 5.2.3, the q=3 path will not be a factor in the near term soil guidelines.

The D/S ratio for the food paths is given by the general expression:

$$\left(\frac{D}{S}\right)_p^q = \left(\frac{D}{E}\right)_p \left(\frac{E}{S}\right)_p^q (FA)_p \, (FD)_p^q \qquad \text{(eq. 5.5)}$$

In evaluating these D/S ratios, the above notation would be interpreted as: (typical examples)

$\left(\frac{D}{S}\right)_4^1$ = D/S ratio from ingestion of plant foods containing radioactivity absorbed by the plants from the roots in the contaminated soil.

$\left(\frac{D}{S}\right)_6^2$ = D/S ratio from drinking milk containing radioactivity due to cows

eating feed which has absorbed radioactivity through the foliage. The radioactivity is deposited on the foliage from dust containing resuspended radioactivity.

The (D/E) values are obtained for the ingestion path from Table 4.2. For uranium 238, the most conservate values of D/E for ingestion are the most soluble forms, class D. Thus, for p = 4, 5 and 6

$$\left(\frac{D}{E}\right)^{q}_{4,5,6} = 2.55 \times 10^{-4} \frac{\text{mrem}}{\text{pCi}}$$

The environmental transport factors, E/S, for these paths were discussed in detail in Section 4. Values for these transport factors for uranium are given in Table 4.4 and 4.5.

$$\left(\frac{E}{S}\right)^{1}_{4} = 4.4 \times 10^{2}$$

$$\left(\frac{E}{S}\right)^{2}_{4} = 1.2 \times 10^{0}$$

$$\left(\frac{E}{S}\right)^{1}_{5} = 5.4 \times 10^{1}$$

$$\left(\frac{E}{S}\right)^{2}_{5} = 9.8 \times 10^{-2}$$

$$\left(\frac{E}{S}\right)^{1}_{6} = 7.7 \times 10^{0}$$

$$\left(\frac{E}{S}\right)^{2}_{6} = 6.9 \times 10^{-2}$$

The area factor, FA, for these paths is related to the size of the site. For an area greater than 2 hectares, the Manual requires FA = 1.0 the area factor is:

FA = 1.0

The depth factor, FD, is related to the root uptake fraction in the plant foods and animal feed.

$$FD = 1 - e^{-0.92T} \qquad \text{(eq. 5.6)}$$

where:

T ≡ contaminated depth, m

Since contaminated depths are presently unknown, the value of FD will be set at 1.0, consistent with the recommendation in the Manual.

FD = 1.0

All the parameters have been defined for the D/S calculation for the feed pathways. For plant foods, root uptake component of D/S:

$$\left(\frac{D}{S}\right)_4^1 = (2.55 \times 10^{-4})(4.4 \times 10^{2})(1)(1) = \underline{0.1122}$$

The plant foods, foliar deposition component:

$$\left(\frac{D}{S}\right)_4^2 = (2.55 \times 10^{-4})(1.2 \times 10^{0})(1)(1) = \underline{0.003}$$

For meat foods, root uptake by feed, fodder:

$$\left(\frac{D}{S}\right)_5^1 = (2.55 \times 10^{-4})(5.4 \times 10^{1})(1)(1) = \underline{0.0138}$$

For meat foods, foliar deposition on feed, fodder:

$$\left(\frac{D}{S}\right)_5^2 = (2.55 \times 10^{-4})(9.8 \times 10^{-2})(1)(1) = \underline{0.0000}$$

For milk products, root uptake to feed, fodder:

$$\left(\frac{D}{S}\right)_6^1 = (2.55 \times 10^{-4})(7.7 \times 10^{0})(1)(1) = \underline{0.0020}$$

For milk products, foliar deposition on feed, fodder:

$$(\frac{D}{S})^2 = (2.55 \times 10^{-4})(6.9 \times 10^{-2})(1)(1) = 0.0000$$

The $\frac{D}{S}$ value for near term, non aquatic paths is summarized in Table 5.1.

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 sum	0.2837 ($\frac{mrem}{yr}$ per $\frac{pCi}{gr}$)

This value is in reasonable agreement with the calculated values in the Manual and Weldon Springs 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 D/S analysis of uranium 234 along with uranium 238.

TABLE 5.2

D/S RATIOS FOR URANIUM 238 AND URANIUM 234 IN SECULAR EQUILIBRIUM FOR NEAR-TERM NON AQUATIC PATHS.

	$\frac{D}{S}$ (mrem/yr.)/(pCi/g)					
			Food			
Radionuclide	External Radiation	Dust Inhalation	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 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,

$$S = \frac{100 \text{ mrem}}{\text{yr.}} \frac{1}{0.5083} \frac{\frac{\text{pCi}}{\text{g}}}{\frac{\text{mrem}}{\text{yr.}}} = 196 \frac{\text{pCi}}{\text{g}}$$

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The uranium 238 results are consistent with Weldon Springs results. For the same pathways, Weldon-Springs shows a D/S total of 0.37, which leads to a single radionuclide, water independent near term pathway soil guideline of 300 pCi/g. The FMPC soil guidelines are lower because the site is much larger and the food pathway D/S values are correspondingly larger. Most of the contaminated areas at the Weldon Springs vicinity properties were small local hot spots with an area less than 1000 m^2.

5.3 DERIVATION OF D/S RATIOS USING THE MANUAL ANALYSIS, FOR LONG-TERM PATHWAYS

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 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 Figure 3.3 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 were calculated using equation 4.1, namely

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

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The area factor, FA, and the occupancy factor, FO remain unchanged. 376

The drinking water pathway, p=3, is an important pathway for the long term guidelines. The D/S value for radionuclide, i, in drinking water is given by the equation:

$$\left(\frac{D}{S}\right)_i = \left(\frac{D}{E}\right)_i \left(\frac{E}{W}\right) \left(\frac{W}{S}\right) \qquad \text{(eq. 5.7)}$$

where:

$\left(\frac{D}{S}\right)_i$ = dose to source ratio for radionuclide, i, in units of

$\frac{\text{mrem}}{\text{yr}}$ per $\frac{\text{pCi}}{\text{g}}$

$\left(\frac{D}{E}\right)$ = dose rate conversion factor, mrem/pCi

$\left(\frac{E}{W}\right)$ = annual consumption of drinking water, L/y

= 410 L/y per the "Manual"

$\left(\frac{W}{S}\right)$ = ratio of the concentration of the radionuclide in the water to that in the contaminated zone.

For the long-term analysis,

$$\left(\frac{W}{S}\right)_i = \left(\frac{W_o}{S}\right)_i \times DF \qquad \text{(eq.5.8)}$$

Where:

W_o = concentration of the radionuclide in the water of the contaminated

zone, pCi/L

S = initial concentration of the radionuclide in the soil, pCi/g

$$\left(\frac{W_o}{S}\right) = [g/L]$$

DF = dilution factor calculated by the migration model (section 3.5).

The Manual suggests that the (W_o/S) term can be estimated by using the distribution coefficient, K_d;

$$\frac{W_o}{S} = \frac{1000}{K_d} \qquad \text{(eq. 5.9)}$$

The D/S ratios for the long term drinking water pathway can be calculated using the above equations. A typical example calculation for uranium 238 at t=10,000 years is shown below.

$$\frac{D}{S} = \frac{D}{E} \times \frac{E}{W} \times \frac{1000}{K_d} \times DF$$

$$\frac{D}{E} = 2.55 \times 10^{-4} \text{mrem/pCi}$$

$$\frac{E}{W} = 410 \text{ L}$$

$$k_d = 50 \text{ cm}^3/\text{g}$$

$$DF = 8.1 \times 10^{-3} \text{ (maximum value)}$$

$$\frac{D}{S} = 2.55 \times 10^{-4} (410) \left(\frac{1000}{50}\right) 8.1 \times 10^{-3} = .017$$

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$$\frac{D}{S} = 0.017 \frac{mrem}{y} \text{ per } \frac{pCi}{g}$$

For the food pathways, using the contaminated irrigation water, the $(D/S)_i$ ratio for uranium 238 can be calculated by the same methods used for the non-aquatic food pathways with the $(E/S)_i$ values multiplied by the $(W/S)_i$ ratio calculated from the long term diffusion-migration model.

$$\left(\frac{D}{S}\right)^3_{p = 3,4,5} = \left(\frac{D}{E}\right)^3_i \left(\frac{E}{W}\right)^3_i (FA)(FD) \times \left(\frac{1000}{K_d}\right) DF \qquad \text{(eq. 5.10)}$$

where:

$\left(\frac{E}{W}\right)_i$ = environmental transport factor for food grown using contaminated irrigation water, g/y

$(DF)_i$ = dilution factor in the aquifer region for radionuclide, i

The other symbols have been previously defined. The uranium 238 calculation is shown below. The environmental transport factor is found in the Manual for the radionuclide of interest. For uranium 238, with DF = 8.1 x 10^{-3}

$$\frac{E}{S} = 7.7 \times 10^2 \text{ (plant foods, } p = 3)$$

$$\frac{E}{S} = 7.8 \times 10^1 \text{ (meat, } p = 4)$$

$$\frac{E}{S} = 4.8 \times 10^1 \text{ (milk, } p = 5)$$

$$\frac{D}{S} = 2.55 \times 10^{-4} \; (7.7 \times 10^2)(1)(1) \; 8.1 \times 10^{-3} \; \left(\frac{1000}{50}\right) = 0.032$$

$$\frac{D}{S} = 0.032 \frac{mrem}{yr} \text{ per } \frac{pCi}{g} \text{ (plant foods)}$$

$$\frac{D}{S} = 0.0031 \frac{mrem}{yr} \text{ per } \frac{pCi}{g} \text{ (meat)}$$

$$\frac{D}{S} = 0.0020 \frac{mrem}{yr} \text{ per } \frac{pCi}{g} \text{ (milk)}$$

These D/S ratios for the aquatic pathways are much lower than the corresponding D/S ratios for the non-aquatic pathways.

The total D/S ratio for uranium 238 for the aquatic long term pathway is

$$\frac{D}{S} = 0.0371 \frac{mrem}{g} \text{ per } \frac{pCi}{g}$$

on this basis, the soil guideline for uranium 238 would be:

$$S_G = \frac{100}{D/S} = \frac{100}{.0371} = 2995 \frac{pCi}{g}$$

with uranium 234 in secular equilibrium the value of S_G becomes

$$S_G = 1325 \frac{pCi}{g}$$

When the long term soil guidelines for uranium are compared with the short term soil guidelines, the short term soil guidelines establish the FMPC site soil guidelines. The short term guidelines were 194 pCi/g compared to the above result of 1325 pCi/g. Calculations for the other radionuclides yield similar results.

5.4 ANALYSIS USING THE AIRDOS-EPA COMPUTER PROGRAM PACKAGE

5.4.1 AIRDOS-EPA Code Packages

The AIRDOS computer package actually consists of three codes. These codes work together to assess the dose to either an individual or a population and to determine the associated risks due to the release of radioactive contaminants to the environment. The three codes in AIRDOS are: 1) PREPAR, which is a preprocessor type program; 2) AIRDOS, which estimates the radiation dose caused by the radionuclides released; and 3) DARTAB, which combines exposure data with dosimetric and health effects. The PREPAR program is designed to allow for easy data input to the AIRDOS code. This code also provides default values for all variables, so the user needs only to enter data for the variables that need to be changed. PREPAR is used to input data to, read files for, and write files concerning the AIRDOS program.

The AIRDOS code uses meteorological, and agricultural data to estimate both the transport and concentrations of radionuclides in the environment. Both point sources and uniform area sources of atmospheric releases of radionuclides can be evaluated by AIRDOS. AIRDOS estimates: 1) concentrations of radionuclides in air, 2) rates of deposition on ground surfaces, 3) ground surface concentrations, 4) intake rates by humans via food ingestion and air inhalation, and 5) radiation doses received by man. The radiation doses to humans are estimated for total body, red marrow, lungs, endosteal cells, stomach wall, lower large intestine wall, thyroid, liver, kidneys, testes, and ovaries. These doses are calculated for each of five separate exposure modes or pathways.

The DARTAB code is designed to combine radionuclide environmental exposure data with dosimetric and health effects data to generate tabulations of the predicted impact of radioactive airborne effluents. DARTAB is

independent of the environmental transport code used to generate the environmental exposure data and the codes used to produce the dosimetric and health effects data. The DARTAB code allows the user to select specific tabulations such as cancer site, or exposure pathway to facilitate the characterization of the human health impacts.

5.4.2 Adapting the AIRDOS package to the FMPC study

The AIRDOS package permits the user flexibility in using these codes. The AIRDOS code was originally developed to be used with an operating facility and a continuous or puff release from a stack to the environment. This study utilizes a direct input option, that allows for the determination of dose from a uniform distributed source.

The assessment area was segregated into sectors and a uniform ground deposition rate, air concentration, and surface concentration of radionuclides was input to AIRDOS. This allows for the exact quantity of radionuclides in the soil to be known. The unit quantity of 1 picocurie per gram of soil was used for each of the radionuclides considered for the study. The AIRDOS code requires the input to be in the form of picocuries per square centimeter on the surface, and in picocuries per cubic centimeter in the air. Using soil density values for the Fernald area and typical values for the dust loading factors, determination of air concentration and surface concentrations were made. Once the air concentration was determined the ground deposition rate was calculated.

The pathway analysis used in AIRDOS conforms very closely to the Manual. Some modification to the calculations in AIRDOS were required to determine the dose due to the surface exposure and ingestion terms. The pathways considered were: 1) submersion or immersion in air (dose from an

infinite cloud), 2) surface exposure from contaminated soil, 3) inhalation of radionuclides suspended in air, and 4) the ingestion of contaminated food (vegetation, milk, and beef). This section briefly describes the equations that were utilized in the code and the modifications made to these equations. For additional details and information, the reader is referred to the AIRDOS-EPA manual (Moore 1977).

Air immersion dose pathway

The air immersion dose is calculated by equation 5.7 shown below. The symbols correspond to the symbols used in the AIRDOS manual.

$$d_{imm} = 8.760 \times 10^{-3}\ \chi C_{imm} \qquad \text{(eq. 5.7)}$$

where:

d_{imm} = dose in rem/year

χ = ground level concentration of the radionuclide in air, pCi/cm^3

C_{imm} = dose conversion factor for immersion, $\frac{rem}{hr}$ per $\frac{\mu Ci}{cm^3}$

Surface exposure dose pathway

The dose to an individual from radionuclides on the surface of the soil is computed by equation 5.8.

$$D_{surf} = 8.760 \times 10^{-3} \left[R_t \frac{(1-e^{-\lambda_T t})(86400)}{\lambda_T}\right] C_{surf} + S_C K_1 (e^{-\lambda_T t}) \qquad \text{(eq. 5.8)}$$

where:

R_t = ground deposition rate

S_c = surface concentration

$\lambda_T = \lambda_R + \lambda_W$

t = time for radionuclide buildup in plants and on ground

C_{surf} = dose conversion factor for surface contamination

$K = 8.76 \times 10^{-3} C_{surf}$

Inhalation dose pathway

The dose due to inhalation of radionuclides in the air is calculated by the equations shown below.

$$D_{inh} = 8.760 \times 10^{-3} \chi B_r C_{inh} \qquad \text{(eq. 5.9)}$$

where:

χ = concentration of the radionuclide in air, pCi/cm^3

B_r = breathing rate, cm^3/hr

C_{inh} = dose conversion factor (rem/μCi)

Ingestion dose

The ingestion dose is obtained by a series of equations related to the quantity of radionuclides ingested in vegetables, milk and meat. The ICRP GI tract model is used to calculate the dose to specific organs. The ingestion dose equations, which are quite lengthy, will not be listed in this report. The reader is referred to the AIRDOS manual for these equations (Moore 1977).

The above equations are used in the AIRDOS code to calculate the dose to a person from a specific pathway. Equation 5.7 is the dose due to immersion in an infinite cloud with a certain concentration of radionuclides. In this analysis the air concentration was input directly and was due entirely to resuspension of contaminated soil. Equation 5.8 is used to calculate the

external dose due to contaminated soil. This equation was modified to account for soil that was previously contaminated. Originally the AIRDOS code contained only two direct input arrays. These were for air concentration (ACON), and ground deposition rate (GCON). A third array was added (SCON) surface concentration. With this addition a surface exposure dose can be calculated without having radionuclides deposited from the air. Equation 5.9 calculates the dose due to the inhalation of air containing radionuclides. Again, the concentration of radionuclides in the air was assumed to be caused by the resuspension of the soil. The ingestion equations utilized by The AIRDOS package are used to calculate the dose from ingesting contaminated food. The equations have five parts with each part accounting for a specific facet of the ingestion pathway. The exposure due to the submersion in water was not considered in this study. The AIRDOS calculations follow closely those utilized in the Manual.

The assessment area used in this study was a circular area with a radius of approximately seven miles from the FMPC plant. This area has a uniform concentration on the surface and in the air. Using this area and the quantity of one picocurie per gram of soil, the dose in rem per year to a maximally exposed individual is determined by the code.

Non-radiological input data used in AIRDOS were consistent with values found in the Manual and the Weldon Springs soil guidelines study (Gilbert, 1986). Quantities of radionuclides in foods take into consideration the concentration factors for uptake of beef, milk, and vegetation (crops and pasture grasses); fraction of nuclide ingested by animals to that appearing in milk and meat; and various agricultural quantities such as how much feed cattle eat and the amount of time per year the animals graze. All of the values are listed in Appendix A with additional AIRDOS input and output

values. Some values used in the code are user defined and were determined by comparison with previous studies. The fraction of food consumed that is grown onsite in contaminated soil is 0.5 which is the value suggested in the Manual for a credible scenario. Typical values for the quantitiy of radionuclides remaining on vegetables after washing were used.

Radiological data and dose factors used in the code were obtained from a data base incorporated in the AIRDOS code. This data base was compiled from work done by the U.S.NRC and based on ICRP guides (Dunning, 1981). The data base contains dose conversion factors for eleven target organs. The dose conversion factors are dependent on solubility class and particle size. In this study the particle size used was 1.0 AMAD and generally the solubility class used was years (Y). The data base also contains the radiological decay constants for the isotope considered. This data is also contained in Appendix D for the nuclides considered.

5.4.3 Analytical model used

The model used in this study was outlined in Section 5.3.2. This section contains explanation of the calculational methods used for the resuspension parameters, the surface contaminations and deposition rate.

Surface concentration was determined by using the soil density and an average depth factor. The volume source was converted to a real density factor which was then input into the array for surface concentation of pico curies per square centimeter. The soil density used as 1.8 g/cm^3 and the depth factor was 15 cm. (Till & Meyer 1985). The dust loading factor used in this study was based on typical values presented in the Manual which was 2 x 10^{-4} grams of dust per cm^3 of air. This leads to a resuspension value that is the same order of magnitude as experimental values listed in Table 5.3.1 (Till & Meyer 1981). The deposition rates for each nuclide were obtained from

values presented in the Manual for each nuclide. 376

The values used in the data arrays are listed in Appendix A.

5.4.4 Results

The AIRDOS code was used to evaluate the dose in millirem per year as a result of uniform ground contamination, at 1 pCi/gram of soil, from selected radionuclides. These radionuclides were: uranium 238, uranium 234, plutonium 239, thorium 232, radium 226, technitium 99, and potassium 40. Table 5.3 shows the dose to source ratios (D/S) in millirem per year for each picocurie per gram of soil (mrem/yr)/(pCi/g). The corresponding near term (0-100 year) water independent soil guideline values for these nuclides are given in Table 5.4. The values resulting from the AIRDOSE analysis will be compared with the soil guidelines developed by the Manual in Section 6. Some important factors to note in the analysis using the AIRDOS-EPA code are: (1) The soil guidelines were based on unit quantities of the radionuclides presented; and (2) The dose conversion factors developed for these radionuclides are based only on the radionuclide in question and not on the entire decay chain. It is for these reasons that the dose from thorium 232 is only slightly hilgher than for uranium 238. When the entire decay chain of the respective isotopes is considered and secular equilibrium is assumed the dose from thorium is a factor of 10 high than uranium. Additional dose information corresponding to various organs and pathways is listed in Appendix D. The results from the risk assessment from the unit quantities of nuclides is given in Section 7.

TABLE 5.3.3

AIRDOS (D/S) DOSE TO SOURCE RATIOS (mrem/yr)/(pCi/gr)

	Pathway				
				Ingestion*	
Radionuclide(**)	External	Inhalation	Plant	Meat	Milk
U-238	0.029	0.277	0.002	0.001	0.0002
			0.004	0.001	0.0002
Pu-239	0.023	0.610	0.008	~0	~0
			0.016	0.007	~0
Th 232	0.051	0.423	0.050	0.003	~0
			0.100	0.005	~0
K 40	3.822	~0	0.170	0.020	0.0113
			0.340	0.020	0.0102
U-234	0.041	0.313	0.002	0.001	0.0001
			0.004	0.001	0.0001
Ra 226	0.230	0.321	0.100	0.001	0.0002
			0.200	0.001	0.0002
Tc 99	~0	~0	0.050	0.000	0.0051
			0.980	0.000	0.0062

**No daughter radionuclides
* Two calculations made: (1) 50% of food grown in contaminated zone (2) 100% grown in contaminated soil

TABLE 5.4

SOIL GUIDELINES BASED ON AIRDOS-EPA RESULTS (near term)

Radionuclide	Near Term Soil Guideline pCi/g
U-238	324
U-234	279
Pu-239	159
Th-232	198
Ra-226	153
Tc-99	1930

5.5 Analysis using the ONSITE/MAXI computer program

Background Information

There are a number of research projects in progress at the DOE National Laboratories (Argonne, Pacific Northwest and Oak Ridge) related to the onsite disposal of low level radioactive waste and residual radioactivity in the soil at formerly utilized nuclear sites.

The initial draft of the Manual, dated September 30, 1985, made reference to a computer program called "ONSITE/MAXI1" (Napier 1984). The Manual reference states, "Calculation of the pathway factors is the central and critical part of the derivation of site-specific soil guidelines. The models used for these calculations are adaptations of models used in the ONSITE/MAXI code developed for an intruder dose pathway analysis for onsite disposal of radioactive waste." The ONSITE/MAXI computer program was obtained along with two volumes of documentation.

The ONSITE/MAXI program has subsequently been revised twice by Bruce Napier and Becky Peloquin (both from PNL). These revisions have been largely based on suggestions and observations made by the University of Cincinnati. The original versions of the program could not be verified by simple analytical calculations. ONSITE/MAXI is a useful program to perform pathway analysis and develop soil guidelines.

The second draft of the Manual, (Gilbert 87), dated August 1987, contained no reference to the ONSITE/MAXI program. A new computer program, RESRAD, was introduced in the second draft version of the manual. It is apparent that RESRAD is intended to be the computer program that one would use to calculate the residual radioactivity soil guidelines.

The ONSITE/MAXI Computer Program

The ONSITE/MAXI computer program was developed by PNL for the U.S. Nuclear Regulatory Commission (NRC). The current policy of the NRC is to review all requests for proposed onsite burial of radioactive wastes on a case by case basis. The intent is to minimize the health risk to human populations. The technical assessment of proposed onsite waste disposal requires modeling of the potential pathways to humans and projecting the magnitude of potential radiation dose commitments. Specific human-intrusion scenarios were developed for various potential combinations of direct exposure to penetrating radiation, inhalation of airborne radionuclides, ingestion of agricultural products raised in contaminated soil and ingestion of radionuclides in drinking water.

The ONSITE/MAXI software package allows for five human exposure scenarios.

1. External exposure scenario

An individual is assumed to work in an area where the soil contains residual radioactive material. Only external exposure to radiation is evaluated.

2. External exposure plus inhalation scenario

An individual is assumed to work in an area where the soil contains residual radioactivity. External radiation exposure is again calculated and a second exposure term, inhalation of resuspended radionuclides from surface soil also considered.

3. Agricultural scenario

External exposure, inhalation of resuspended radionuclides from surface soil and food grown in contaminated soil are evaluated for the dose to the maximally exposed individual.

4. Irrigation and drinking water scenario

The maximally exposed individual is assumed to irrigate the food crops and/or drink water from a supply contaminated by radionuclides from an onsite well. This scenario also evaluates external exposure and inhalation dose from soil surfaces contaminated with this radioactive irrigation water.

5. User-defined scenario

This option gives the user the ability to construct a scenario by selecting exposure pathways.

Mathematical Models Used in ONSITE/MAXI

The general expression shown in Eq. 5.10 is used to calculate radiation dose to the maximally exposed individual: (notation here is the notation from ONSITE/MAXI)

$$R_{ipr} = C_{ip} U_p D_{ipr} \qquad \text{(eq. 5.10)}$$

where:

R_{ipr} = the radiation dose equivalent or committed radiation dose equivalent from radionuclide i via exposure pathway p to organ r (rem)

C_{ip} = concentration of radionuclide i in the media of exposure pathway p; for calculations involving airborne radionuclides, C_{ip} is replaced with the term χ_1, which represents the average airborne concentration of radionuclide i (pCi/m^3, pCi/L, or pCi/kg)

U_p = usage parameter (exposure rate or intake rate) associated with exposure pathway p (L/hr, or kg/yr)

D_{ipr} = radiation dose equivalent factor or the committed dose equivalent factor for radionuclide i exposure pathway p and organ r to convert the concentration and usage parameters to the radiation dose equivalent or to the committed radiation dose equivalent (mrem/pCi)

This equation, 5.10, compares very favorably with the Manual analysis equations. Comparison with the Manual will show that:

C = S (concentration of radionuclide in soil or water)

U = E/S environmental transport factor

D = D/E dose conversion factor

An analysis of radiation doses from separate exposure pathways requires a determination of the radionuclide concentrations and exposure rate or intake rate associated with each exposure pathway. For external exposure, the concentration of radionuclides and the duration of exposure must be quantified. For ingestion of farm products grown on a contaminated site, the radionuclide concentration in separate food products must be determined by accounting for root transfer from soil, dry deposition from air on leaves, or animal consumption of contaminated forage or feed. The annual diet for the maximally exposed individual, and the holdup time between harvest and consumption must also be determined.

For inhalation, the airborne concentration of resuspended radionuclides can be determined directly from the ground concentration using a mass-loading factor, resuspension factor, or resuspension rate analysis (Anspaugh 1975). Site-specific parameters can be used to determine the exposure pathways and the radionuclide mixture, pathway concentrations, and exposure or intake rates.

The annual dose to any organ is computed in MAXI by calculating the dose to that organ for the current year and adding the dose to that organ from radionuclides deposited in the body during previous years. The summation of these doses to the whole body or any organ of interest over 50 years represents the committed dose equivalent.

The annual dose to the organ of reference is calculated for each year, with the year parameter t, varying from year 1 to year 50. The maximum annual dose in any year during this interval is determined by the program.

Experience with this method to date indicates 50 years to be a suitable 376 maximum value of t; however, higher maximum values are not precluded. The radiation dose equivalent terms are determined using existing radiation dose computer programs for pertinent radiation-exposure pathways. Details about the methods of calculating the radionuclide concentrations in various media, C_{ip} from equation 5.10 can be found in the program documentation (Napier 86). The mathematical models used to calculate the dose are basically the same as used in the Manual, but cast into different form for use in the computer. There are a number of predetermined default values in the program.

For analysis of dust inhalation to evaluate the dose from resuspended soil, the dust particle size is taken as 1 AMAD. This is consistent with the Manual and AIRDOS.

For direct deposition from the air, Equation 5.11 is used to describe the deposition of airborne particulate radionuclides directly onto food products and onto the ground.

$$d_i = 86{,}400\ \chi_1 V_{di} \qquad \text{(eq. 5.11)}$$

where:

d_i = deposition rate or flux of radionuclide i, pCi/(m^2-day)

χ_1 = average air concentration of radionuclide i is estimated using either the mass-loading or resuspension factor as pCi/m^3

V_{di} = deposition velocity of radionuclide i, m/second, is assumed in MAXI to be 1×10^{-3} m/sec for all particles

The MAXI computer program permits selection of two methods for calculating the average air concentration. These methods are mass-loading and resuspension analysis. The mass-loading method uses the product of the surface soil radionuclide concentration and the average mass-loading of dust

or particulate material in the atmosphere. In the absence of data for a particular site, a value of $1x10^{-4}$ g/m^3 has been suggested for predictive purposes (EPA 1977; Anspaugh 1975).

For suspension, the average airborne concentration is the product of a resuspension factor and the surface contamination level as shown in Equation 5.12.

$$\chi = S_f S_A \qquad \text{(eq. 5.12)}$$

where:

S_f = resuspension factor, m^{-1}
S_A = surface radioactivity, pCi/m^2

The MAXI1 computer program permits the use of a time-dependent resuspension factor (S_f) as given by Anspaugh et.al. (1975).

$$S_f = 1x10^{-4} e^{-\lambda\sqrt{t}} + 1x10^{-9} \qquad \text{(eq. 5.13)}$$

where:

10^{-4} = resuspension factor at time t = 0, m^{-1}

λ = effective decay constant controlling the availability of material for resuspension, 0.15 day$^{-1/2}$

t = time after deposition (days)

$1x10^{-9}$ = resuspension factor after 17 years, m^{-1}

The concentration of radioactivity in food (vegetables, milk and meat) is calculated by a complex set of equations that require many empirical parameters. The methods are well developed, but lengthy. For details, the

reader is referred to the references listed: Napier 86, Till 83 or Miller 84.

The data libraries for the ONSITE/MAXI1 computer program are based on a minimum site area of 1 ha. To account for the limited exposure potential from smaller disposal areas, site area correction factors are required. For example, the amount of agricultural products raised on a site depends upon the intensity of the farming and the types of crops raised. A small site may produce a large fraction of the seasonal fruit and vegetable diet with intensive farming, but be unable to provide enough forage and grain to support a milk cow or other animals. Thus, while a large fraction of the seasonal fruit and vegetable diet may be raised on a small site, the total quantity raised may only equal a small fraction of the total annual diet.

For the ingestion and inhalation pathway, the correction factors are in the form of a step function. This function assumes five steps of potential exposure versus site area, ranging from small to large sites. The steps of total exposure are: (1) 10% for sites with areas less than 50 m^2, (2) 25% for sites with areas between 50 and 200 m^2, (3) 50% for sites with areas between 200 and 1,000 m^2 (4) 75% for sites with areas between 1,000 and 10,000 m^2 and (5) 100% for sites larger than 10,000 m^2 (or 1 ha).

A step function is used rather than a continuous curve because of the inherent uncertainty in predicting the future actions of individuals. The step function allows consideration of small areas without forcing extreme conservatism on larger areas. That is, it implies that the small areas may be intensely farmed for vegetables, whereas the larger areas may be less efficiently used (i.e., in raising cattle).

A standard ingestion model analysis is used to calculate the dose to the individual from drinking water (ICRP 1978a). Dose conversion factors for ingestion of drinking water used in MAXI1 are calculated using the MAXI3

computer program. The dose, R_{wr}, in mrem, from ingestion of water containing radionuclides, is calculated from Equation 5.14.

$$R_{wr} = U_w \sum_{i=1}^{i=n} C_{idw} \exp(-\lambda_i t_h) D_{ir} \qquad \text{(eq. 5.14)}$$

where:

R_{wr} = dose in mrem

U_w = annual consumption of contaminated drinking water, L

C_{idw} = the concentration of radionuclide i in the drinking water, pCi/L

λ_i = radiological decay constant for radionuclide i, $days^{-1}$

t_h = transit time required for radionuclide, days

D_{ir} = radiation dose equivalent factor for ingestion, mrem/pCi

The inhalation dose is calculated based on the volume of air the individual breathes (ICRP 1977), the radionuclide content of the air and the previously described dose conversion factor. The equation is:

$$R_{hr} = V\ T\ t_m \sum_{i=1}^{i=n} (\chi_i A_C^I) D_{ir} \qquad \text{(eq. 5.15)}$$

where:

V = breathing rate of exposed individual, m^3/s

T = duration of exposure, s

t_m = modification factor applied to T to adjust time if exposure or breathing rate differs from 230 cc/sec (ICRP 1975)

D_{ir} = radiation dose equivalent factor for inhalation, mrem/pCi

A_C^I = the area correction factor (Fig. 5.4)

Dose from external radiation due to a surface source or volume source of radionuclide is calculated by the computer program in the same manner as the

Manual technique described in Section 5.2.

$$R_{er} = U_p \sum_{i=1}^{i=n} D_{ir} A_C^E D_{ip} \qquad \text{(eq. 5.16)}$$

where:

R_{er} = dose from external exposure, mrem

A_C^E = the area correction factor for external exposure, and where U_p, D_{ir} and C_{ip} are for external exposure and have been previously defined

Corrections are made in the program for site size, i.e. sites greater than 2 ha, $A_c^E = 1.0$. Corrections are also made for the various types of radiation and particle energy of different nuclides. There will be considerable attenuation of beta particles and low energy gammas.

6.0 SOIL GUIDELINES FOR THE FMPC

Background Information

This report contains single radionuclide soil guidelines for all the radionuclides identified as present on the FMPC site. Soil guidelines were calculated for the near-term non-aquatic pathways and for the long term aquatic pathways. A mixture sum formula was developed that could be used to determine the residual radioactivity guidelines for areas where a number of radionuclides are present in above background concentrations.

The results of the analysis show that the soil guidelines are established by the near-term non-aquatic pathways.

6.1 Single Radionuclide Soil Guidelines for the FMPC Non-Aquatic Pathways

The homogeneous single radionuclide soil concentration guidelines for the FMPC site are shown in Figure 6.1 and Table 6.1. These guidelines are based on a dose to the maximally exposed individual of 100 mrem annual effective dose equivalent and on the near-term, non-aquatic pathways (0 to 100 years after unrestricted release of the site). The long-term aquatic pathways were shown in Section 5 to result in soil guidelines that were a factor of 10 higher than the near term guide lines. Soil guidelines were calculated for each radionuclide known to be present in above background levels at the FMPC. The radionuclides listed in Figure 6.1 and Table 6.1 were identified by the Roy F. Weston Company as present in the waste storage pit area (Weston 87).

The soil guidelines were calculated for two conditions identified as limiting:

(1) the near-term release of the FMPC site for unrestricted use by the general public (generally 0-100 years after site release)

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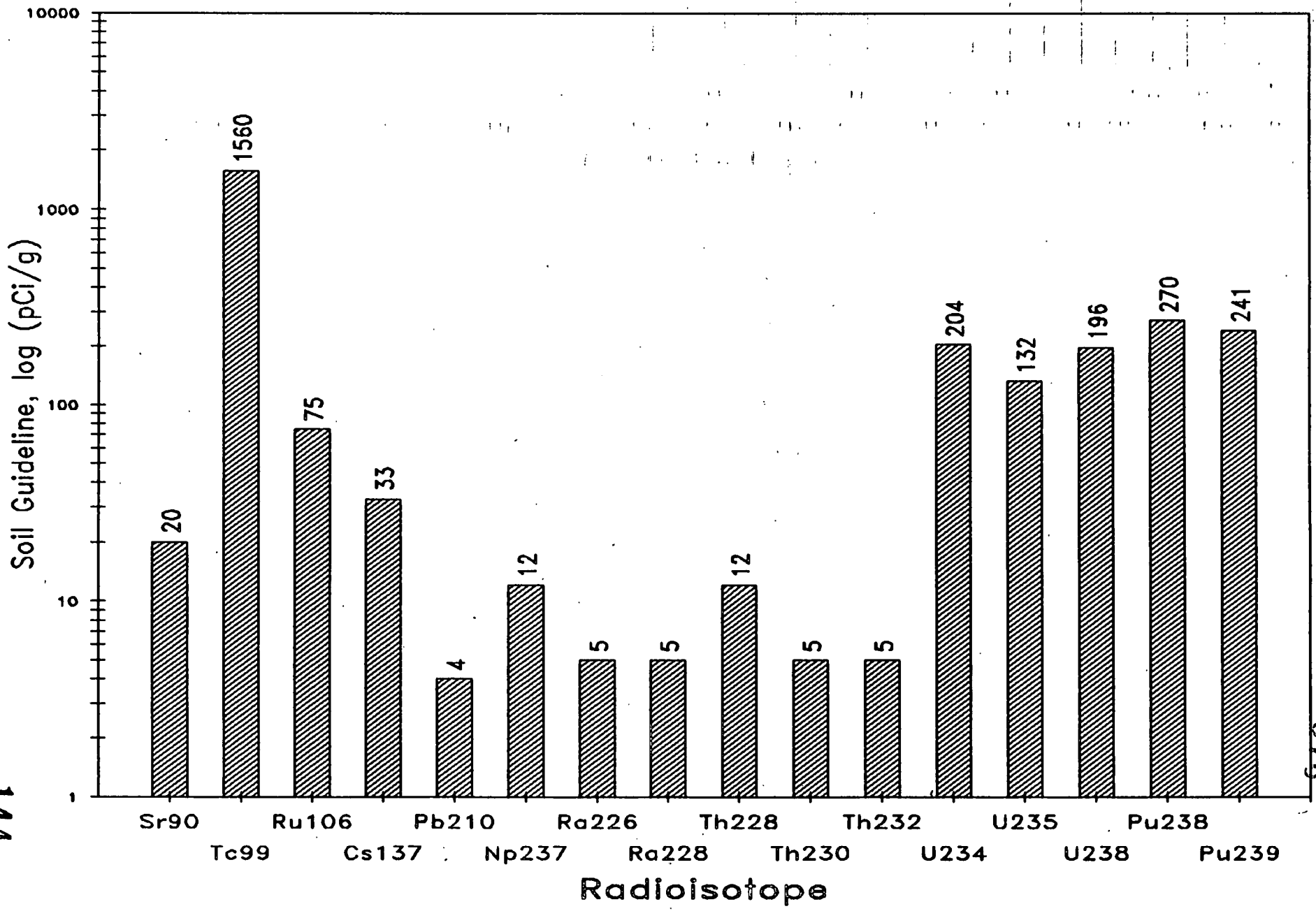
Figure 6.1 Homogeneous Single Radionuclide Soil Concentration Guidelines for the FMPC



(2) the long-term release of the site, based on a 10,000 year planning horizon

TABLE 6.1
HOMOGENEOUS SINGLE RADIONUCLIDE SOIL CONCENTRATION GUIDELINES FOR THE FMPC

Radioisotope	Soil Guideline (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

*generic guidelines developed by the DOE

The analysis methodology used in determining the soil guidelines for the FMPC was presented in detail in Section 5 of this report. Sample calculations were made for uranium 238 and uranium 234. This same methodology was also used to calculate the near-term and long-term soil guidelines for each radionuclide listed in Table 6.1. In order to evaluate the accuracy of our work, we compared the uranium 238 and uranium 234 guidelines with the Weldon-Springs results reported by Gilbert (Gilbert 85b) for uranium 238 and uranium 234. These were the only soil guidelines available for Weldon-Springs). The soil guidelines for the other radionuclides were compared with the soil guidelines developed by EG&G for the Idaho National Engineering Laboratory

(INEL). Both of these comparisons will be presented and discussed in this section. These comparisons gave us a great deal of confidence in the soil guidelines developed for the FMPC.

The two limiting conditions selected for the soil guidelines calculations were the near-term release (0-100 years) and the long-term release (1000-10,000 years). The near-term release is selected because the radionuclides are concentrated in the upper 15 centimeters of soil depth. The concentration of radioactivity in the surface layer of soil results in a number of significant exposure pathways: inhalation of airborne radionuclides in re-suspended dust, direct radiation from the soil, a number of food chain pathways and possibly a drinking water and irrigation water pathway. The near term release soil guidelines are always calculated in a soil guidelines study. (Gilbert 85, EG&G 87).

A number of years after the initial release of the site for unrestricted use, the radionuclides begin to migrate downward through the unsaturated layer of soil (vadose) to the saturated layer, the aquifer. The effect of this migration is to reduce the dose to the maximally exposed individual from such pathways as the inhalation of re-suspended dust, direct radiation from the soil and the food chain pathways. The radionuclides eventually enter the saturated region and begin to increase the dose due to radionuclides in deep well water and irrigation water. This phenomenon reaches a maximum during the time period of 1,000 to 10,000 years. Thus, the second set of detailed calculations was made at the end of the 10,000 year time interval. As a precaution, some soil guideline calculations were made at 1000 years after release of the site. In this time period, most of the radionuclides had either decayed or migrated downward from the upper 15 centimeters of soil, but had not yet reached the aquifer. The results confirmed our assumption that

either the initial release time (t = 0) or the end of the planning horizon (t = 10,000 years) would establish the soil guidelines for the FMPC.

The results of the radionuclide migration analysis show clearly that the most restrictive soil guidelines for the FMPC are for the near-term release of the site. The critical pathways are the direct radiation from the soil, the inhalation of resuspended dust and ingestion of food products (fruits and vegetables) grown in contaminated soil. (root uptake). By the time the radionuclides migrate through the unsaturated zone to the saturated region, (aquifer) a significant, orders of magnitude reduction in the concentration of the radionuclides has occurred. The concentration of the radionculides in the aquifer water is very dilute. Table 6.2 shows the relative concentration of the radionuclides in the aquifer region compared to the initial surface concentration.

TABLE 6.2

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

NUCLIDE	T1/2	100	1000	5000	10000
239 Pu	2.411×10^{4}Y	1.4×10^{-23}	9.7×10^{-12}	7.38×10^{-9}	1.8×10^{-8}
238 Pu	87.74Y	8.7×10^{-25}	2.1×10^{-15}	2.24×10^{-25}	$<10^{-35}$*
238 U	4.468×10^{9}Y	2.8×10^{-21}	2.4×10^{12}	2.7×10^{-7}	1.4×10^{-6}
235 U	7.04×10^{8}Y	2.8×10^{-21}	2.4×10^{-12}	2.7×10^{-7}	1.4×10^{-6}
234 U	2.44×10^{5}Y	2.8×10^{-21}	2.4×10^{-12}	2.6×10^{-7}	1.3×10^{-6}
232 Th	1.4×10^{10}Y	0	0	1.8×10^{-21}	2.0×10^{-15}
230 Th	7.7×10^{4}Y	0	0	1.8×10^{-21}	1.8×10^{-15}
228 Th	1.913Y	0	0	0	0
228 Ra	5.75Y	0	0	0	0
226 Ra	1600Y	1×10^{-20}	1.9×10^{-7}	1.1×10^{-6}	2.2×10^{-7}
237 Np	2.14×10^{6}Y	2.9×10^{-20}	$3 \times 10x^{-11}$	4.4×10^{-7}	1.8×10^{-6}
210 Pb	22.3Y	9×10^{-18}	0	0	0
137 CS	30.17Y	6.3×10^{-21}	0	0	0
106 Ru	368d	0	0	0	0
99 Tc	2.13×10^{5}Y	3.2×10^{-17}	4×10^{-8}	4.3×10^{-6}	1×10^{-5}
90 Sr	29Y	4.4×10^{-12}	0	0	0

*Pu238 will increase U234 conc. x 2

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As shown in Section 5 of this report, the soil guidelines for t = 10,000 years using the data of Table 6.2 would be considerably higher than the most restrictive case at t = 0.

Thus, the soil guidelines for the FMPC are established by the initial concentration of radionuclides present in the soil when the site is released for general use.

In order to verify the analysis methods used in developing the FMPC guidelines, we compared our results with the only available data published in the open literature. This was a soil guidelines study performed by Gilbert for Weldon-Springs vicinity properties (Gilbert 85b) and the soil guidelines study performed by EG&G for INEL. (EG&G 87).

Gilbert performed the Weldon-Springs study to provide an example of the use of the "Manual". Gilbert calculated soil guidelines for the near-term and long-term release cases. The generic soil guidelines are developed for a model site described in the Manual. The model site is basically a FUSRAP site that contains a large contaminated area, homogeneous distribution of the radionuclide in the upper 15 centimeters of soil. A fraction of the intruder residence family's food is grown onsite. The Weldon-Springs study provides a model which allows an order of magnitude check on site-specific results. The Weldon-Springs results are compared with the FMPC results in Table 6.3.

Table 6.3 indicates that the methodology used to develop the FMPC soil guidelines is consistent with the Manual specifications. The lower guideline calculated for the FMPC is due to the assumed larger area of contamination at the site. The area is large enough to justify the the conservative assumptions that the entire diet of the maximally exposed individual can be produced at the former site. The increase in uranium intake through food ingestion is the primary reason for the lower soil guidelines for the near-term, non-aquatic pathway. Table 6.3 shows the detailed dose to source, D/S, values for the food pathways. (A higher D/S value means a lower soil guideline since for single soil guideline, S = 100/(D/S).

TABLE 6.3*

DOSE TO SOURCE D/S PATHWAY COMPARISON FOR THE FMPC AND WELDON-SPRINGS FOR URANIUM 238 AND URANIUM 234

	Pathway				
Radionuclide	external radiation	dust inhalation	food plant	meat	milk
Uranium 238	D/S	D/S	D/S	D/S	D/S
FMPC	0.0662	0.0892	0.1125	0.0138	0.0020
Weldon Spring	0.0800	0.1000	0.0340	0.0040	0.0006
Uranium 234					
FMPC	0.0006	0.0901	0.1167	0.0145	0.0025
Weldon Spring	0.0008	0.1100	0.0380	0.0050	0.0007

*units for D/S are mrem/y per pCi/g

The difference in external radiation and dust inhalation is due to the depth factor, FD, used in the analysis. The FMPC analysis assumed a uniform contaminated soil depth of 15 centimeters. The Weldon-Springs analysis used 1 meter or greater for the contaminated depth. This results in more contaminated soil available for resuspension and hence a greater dose due to inhalation of this contaminated soil. This additional dose is reflected by a

higher D/S value for dust inhalation for the Weldon-Springs pathway. Also, the greater depth of contaminated soil also means a higher dose from external radiation to someone working or living on the site. Thus, the D/S value for external radiaton path is higher for Weldon-Springs than the FMPC. If at some future time, results of a radiological survey at the FMPC indicate a greater depth of contamination than 15 centimeters, the results can be re-evaluated. The D/S values for these two pathways, dust inhalation and external radiation would then approach the Weldon-Springs values. This is not a significant change.

The results shown in Table 6.3 clearly show the importance of the food chain pathways for large contaminated areas. The big difference between the results of the Weldon-Springs work and the FMPC analysis can be attributed to the total diet for the resident family at FMPC being produced onsite.

The EG&G performed a study almost identical to this contract to develop a set of soil guidelines for the decommissioning and decontamination of the Idaho National Engineering Laboratory (INEL) site. Many of the radionuclides considered in the INEL study were different than those considered for the FMPC study. However, there were eight radionuclides common to each study. As in the FMPC case, the near-term, non-aquatic pathways established the soil guidelines for INEL.

The INEL soil guidelines are shown in Table 6.3 along with the FMPC soil guidelines. The comparison provides good agreement between the two studies.

TABLE 6.4

HOMOGENEOUS SINGLE RADIONUCLIDE SOIL CONCENTRATION GUIDELINES - NON-AQUATIC PATHWAYS
(ALL Units are pCi/g)

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*	198	
uranium	234	204	279	400
uranium	235	132		60
uranium	238	196	324	200
plutonium	238	270	150	300
plutonium	239	241	159	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

6.2 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 6.1 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 6.1 contains single radionuclide soil guidelines for all the radionuclides identified at the FMPC site. For the mixture sum formula, the generic guidelines for thorium and radium shown in Table 6.1 are replaced with the site specific derived values of the soil guidelines. The derived site specific homogeneous single radionuclide soil guidelines for these radionuclides are given in Table 6.5

TABLE 6.5

DERIVED SOIL GUIDELINES FOR THORIUM AND RADIUM

Radioisotope	Site-Specific Soil Guideline pCi/g
radium 226	9
radium 228	17
thorium 230	142
thorium 232	28

Using these values from Table 6.5 above and the remainder of the homogeneous single radionuclide soil guideline values from Table 6.1 the mixture sum formula is defined by the inequality:

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

$$+ \frac{C(Ra228)}{17} + \frac{C(Th228)}{12} + \frac{C(Th230)}{142} + \frac{C(Th232)}{9} + \frac{C(U234)}{204} + \frac{C(U235)}{132} + \frac{C(U238)}{196}$$

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

In each case, the C in the numerator would represent the residual concentration of that specific radionuclide in the soil (pCi/g). The denominator is the single radionuclide soil guideline for that specific radionuclide, (pCi/g).

This inequality allows for a good deal of flexability 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.

6.3 Comparison With AIRDOS Results

The inhalation and external exposure dose pathways in AIRDOS compare most favorably with the single soil guidelines developed for FMPC, from the Manual, and the Weldon-Springs analysis (Gilbert 1986). A significant difference is in the ingestion pathway. This is due to different dose conversion factors used within the AIRDOS code which are based only on the radionuclide being considered and not on the daughter radionuclides. For example AIRDOS considers only uranium 238 decay. The Manual considers uranium 238 and two of its short half life daughters, thorium 234 and protactinium 234, a reasonable calculation since these daughters are in secular equilibrium with the uranium in a matter of days. AIRDOS was very useful to compare results for any radionuclide with the "Manual".

7.0 HEALTH EFFECTS BASED ON SOIL GUIDELINES

7.1 Background Information on Health Effects of Ionizing Radiation

All human activities involve some degree of risk. In this section, some brief background information will be presented on the risk associated with radiation exposure. This risk will then be quantified using the best available data in the computer program DARTAB. (Part of the AIRDOS - EPA computer package).

As a result of exposure to radiation, energy may be deposited in the human body; biological tissue, organs, bone, etc. Many scientists, but not all, believe that even small amounts of radiation exposure produce some degree of risk to the health of exposed individuals. The regulatory guides are based on a linear, no threshold assumption of risk for any exposure to ionizing radiation. The DARTAB analysis is based on these risk estimates.

Health effects which show up in the exposed individual are called somatic. Health effects which may affect future generations are called genetic effects. The principal somatic effect of long-term, low-level exposure to radiation is the induction of cancer in various organs or tissues. Other somatic effects are manifest at high levels of radiation. For this study, only the low level effect of cancer incidence need be considered.

Genetic effects involve chromosomal alterations in the exposed individuals, resulting in possible disorders manifested in descendent generations. Genetic effects have been observed in laboratory tests on insects and animals. These effects occur at higher dose levels, usually 200-250 rem. Genetic effects have not been observed in humans and are not considered in the assignment of health risk, especially at low dose levels.

The somatic effects of radiation are also classified as stochastic or non-stochastic (ICRP 77). For stochastic effects, the probability of

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occurrence of the effect, rather than the severity, is a function of the dose. Cancer induction is considered a stochastic effect. Non-stochastic effects are those health effects for which the severity of the effect is directly proportional to the dose or at least a function of the absorbed dose. Cell death, blood cell changes, cataracts and non-malignant skin damage are examples of non-stochastic, somatic effects.

At low levels of radiation exposure, such as would be encountered with residual radioactivity in the soil, the principal health detriment is the induction of stochastic effects, especially cancer, such as solid tumors or leukemia. Three major groups of scientists have studied the stochastic effects of ionizing radiation: 1) International Commission on Radiological Protection (ICRP), 2) National Academy of Sciences (NAS 1980) and 3) United Nations Scientific Committee on the Effects of Atomic Radiation. Although the data and results differ slightly, all three major groups establish the risk of cancer incidence by a linear, no-threshold extrapolation of the data from high dose to zero effect. Table 7.1 shows the risk estimates cited by these groups.

TABLE 7.1

STOCHASTIC EFFECTS OF RADIATION RISK PER 10^6 PERSON-REM

	BEIR	ICRP	UNSCEAR
Leukemia	25	20	15-25
Lung	39	20	25-50
Breast (female)	90	25	60
Bone	6	5	2-5
G-I tract	30	-	25
Thyroid	-	5	5-15
Other	30	50	25
	180	100	120

BEIR (male) = 90×10^{-6}/rem

BEIR (female) = 180×10^{-6}rem

Using data such as this, with the linear, no-threshold hypothesis, it is always possible to estimate health effects even from the most minute levels of exposure. Most scientists believe that these models greatly overpredict the health effects of radiation at low dose levels, such as encountered in this study. However, this study will use these models to make the predictions.

Using the BEIR data from Table 7.1, the absolute risk of cancer induction is 180 cases per million person rem for women and 90 incidences per million person rem for men. If for example, 10,000 women were exposed to 1 rem each, the exposure would be 10,000 person-rem (pr).

$$\text{extra cancers} = 10{,}000 \text{ pr} \times 180 \times 10^{-6} \frac{\text{cancers}}{\text{pr}}$$
$$= 1.8 \text{ extra cancer incidences}$$

In the same group of people, about 20% would be expected to develop cancer from "normal" causes. Thus, in this group, the increased risk from 1 rem would be

$$\text{increased risk} = \frac{(2000 + 1.8)}{2000} (100) = 0.09\%$$

7.2 Health Effects Based on DOE Soil Guidelines

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 the lifetime.

Assume the maximally exposed individual received the annual committed dose equivalent of 100 mrem for 50 years while residing on the former FMPC site. The increased risk estimate is:

$$\text{increased risk} = (100\ \frac{\text{mrem}}{\text{yr}})(10^{-3}\ \frac{\text{rem}}{\text{mrem}})(50\ \text{yr})(180 \times 10^{-6})\ \frac{\text{risk}}{\text{rem}}$$ 376

increased risk = .0009 incidences of cancer

$$\text{percent increase in risk} = \frac{.17 + .0009 - .17}{.17}(100) = 0.53\%$$

7.3 Cancer Risk Estimated By the AIRDOS-EPA Computer Code Package

The AIRDOS-EPA package was reviewed in Section 5.3. The DARTAB code described previously, estimates the risk that a fatal cancer incidence will develop as a result of radiation exposure. In this study the dose resulting from the uniform concentration of one picocurie of a specific radionuclide in the soil was the basis for determining the cancer risk occurring in an exposed individuals lifetime. Table 7.2 shows the results of the DARTAB code calculations. This data indicates the relationship between the low dose equivalent received and the resultant risk of cancer. For the case of uranium 238, the dose equivalent to the exposed individual is 0.288 mrem per year and the associated lifetime cancer risk is 2.27×10^{-6}. Uranium 234 with a dose equivalent of 0.325 mrem per year results in a lifetime cancer risk of 2.56×10^{-6}. The lifetime basis used in the DARTAB code is 50 years. These values correspond closely to a risk factor near 180×10^{-6} risk per rem as in the BEIR case for women. The values used in DARTAB depend not only on gender but also the nuclide to separate the high and low linear energy transfer factor (LET) associated with the specific decay. This also enables the code to consider the higher probability of some nuclides to affect specific organs. The values listed in Table 7.2 are the weighted totals based on eleven target organs associated with the radiation dose equivalent. As one can readily see the lifetime risk due to the pico curie quantitites of radionuclides in the soil are on the order of 1.3×10^{-7}% increased risk over that normally expected in nature. 159

TABLE 7.2

RISK OF CANCER INCIDENCE AS A FUNCTION OF RADIONUCLIDE AND DOSE EQUIVALENT

Dose Rates: Weighted Sums of Organ Dose Rates Nuclides:	U-234	PU-239	U-238	TC-99	RA-226	TH-232	Total
Low Let (mrad/y)	9.25E-03	4.34E-03	2.13E+00	5.18E-02	1.04E-01	8.20E-03	2.32E+00
High Let (mrad/y)	1.58E-02	3.24E-02	1.39E-02	0.00E+00	2.21E-02	2.72E-02	1.46E-01
Dose Equivalent (mrem/y)	3.25E-01	6.52E-01	2.88E-01	5.18E-02	5.45E-01	5.52E-01	5.24E+00

*** Selected Individual ***

Lifetime Fatal Cancer Risk: Nuclides:	U-234	PU-239	U-238	TC-99	RA-226	TH-232	Total
Low Let	1.84E-07	8.59E-08	1.80E-07	1.03E-06	2.05E-06	1.61E-07	4.61E-05
High Let	2.37E-06	3.55E-06	2.09E-06	0.00E+00	3.14E-06	3.39E-06	1.84E-05
Total	2.56E-06	3.64E-06	2.27E-06	1.03E-06	5.19E-06	3.55E-06	6.45E-05

*All dose calculations based on 1 pCi per gram of each radionuclide the soil

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Appendix A - AIRDOS Data and Input Values

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AIRDOS Input File used in the FMPC Soil Guidelines Study

```
OPTION
 &OPTI OPTION=2,1,,2,,,,,,,LIPO=1,NSTB=2,NTTB=1,TSUBB=0.0,
  GSFAC=0.5 &END
GRID
 &GRID NOL=1,NOU=16,NRL=1,NRU=4,IDIST=7250,14500,21750,
  29000 &END
PLUME RISE
 &PLUM PR=1*10. &END
METEOROLOGICAL DATA
 &METE LID=10.0,RR=0.0,TA=21.13 &END
PHYSICAL STACK DATA
1
 &PHYS PH=15.2,DIA=.15,VEL=0 &END
WIND FREQUENCY DATA
STAR
DEFAULT
RADIONUCLIDE DATA
1
 &RADI NUC='U-238',VD=1.0,SC=.2  &END
MODIFICATIONS OF NUCLIDE DATA
2
 &MODI LAMSUR=5.48E-5,SC=1E-5,VG=0 &END
 &MODI ISOL='*',LAMSUR=4.53E-2,SC=0 &END
AG DATA
 &AGDT FV=7.6,0,92.4,FB=0.8,0,99.2,FM=0,0,100 &END
AG ARRAYS
FILE 23
SKIP  5
USER
(16I5)
(8F10.0)
POPULATION ARRAY
FILE 24
FREE
CONCENTRATION
FILE 35
SKIP 1
FREE
COMMENTS
****** THIS IS A TEST RUN WITH FMPC SITE SPECIFIC DATA ******
```

Table A.1

Wind Frequency Data for use in AIRDOS

		Stability Class A	B	C	D	E	F
N	A	0.00016	0.00027	0.00000	0.00000	0.00000	0.00000
NNE	A	0.00000	0.00007	0.00000	0.00000	0.00000	0.00000
NE	A	0.00002	0.00034	0.00000	0.00000	0.00000	0.00000
ENE	A	0.00001	0.00027	0.00000	0.00000	0.00000	0.00000
E	A	0.00001	0.00027	0.00000	0.00000	0.00000	0.00000
ESE	A	0.00000	0.00007	0.00000	0.00000	0.00000	0.00000
SE	A	0.00002	0.00041	0.00000	0.00000	0.00000	0.00000
SSE	A	0.00008	0.00014	0.00000	0.00000	0.00000	0.00000
S	A	0.00016	0.00021	0.00000	0.00000	0.00000	0.00000
SSW	A	0.00017	0.00041	0.00000	0.00000	0.00000	0.00000
SW	A	0.00009	0.00041	0.00000	0.00000	0.00000	0.00000
WSW	A	0.00015	0.00007	0.00000	0.00000	0.00000	0.00000
W	A	0.00025	0.00055	0.00000	0.00000	0.00000	0.00000
WNW	A	0.00008	0.00021	0.00000	0.00000	0.00000	0.00000
NW	A	0.00015	0.00014	0.00000	0.00000	0.00000	0.00000
NNW	A	0.00001	0.00027	0.00000	0.00000	0.00000	0.00000
N	B	0.00045	0.00151	0.00082	0.00000	0.00000	0.00000
NNE	B	0.00066	0.00137	0.00062	0.00000	0.00000	0.00000
NE	B	0.00066	0.00151	0.00062	0.00000	0.00000	0.00000
ENE	B	0.00038	0.00123	0.00110	0.00000	0.00000	0.00000
E	B	0.00075	0.00226	0.00082	0.00000	0.00000	0.00000
ESE	B	0.00058	0.00110	0.00075	0.00000	0.00000	0.00000
SE	B	0.00082	0.00226	0.00062	0.00000	0.00000	0.00000
SSE	B	0.00073	0.00130	0.00055	0.00000	0.00000	0.00000
S	B	0.00077	0.00322	0.00226	0.00000	0.00000	0.00000
SSW	B	0.00094	0.00151	0.00158	0.00000	0.00000	0.00000
SW	B	0.00067	0.00185	0.00219	0.00000	0.00000	0.00000
WSW	B	0.00102	0.00192	0.00199	0.00000	0.00000	0.00000
W	B	0.00124	0.00226	0.00178	0.00000	0.00000	0.00000
WNW	B	0.00046	0.00164	0.00062	0.00000	0.00000	0.00000
NW	B	0.00052	0.00130	0.00082	0.00000	0.00000	0.00000
NNW	B	0.00051	0.00089	0.00075	0.00000	0.00000	0.00000
N	C	0.00053	0.00205	0.00260	0.00048	0.00000	0.00000
NNE	C	0.00020	0.00110	0.00219	0.00041	0.00000	0.00000
NE	C	0.00039	0.00205	0.00205	0.00000	0.00000	0.00000
ENE	C	0.00044	0.00164	0.00260	0.00041	0.00000	0.00000
E	C	0.00045	0.00192	0.00377	0.00021	0.00000	0.00000
ESE	C	0.00020	0.00123	0.00233	0.00007	0.00000	0.00000
SE	C	0.00031	0.00192	0.00267	0.00014	0.00000	0.00000
SSE	C	0.00038	0.00192	0.00151	0.00000	0.00000	0.00000
S	C	0.00107	0.00288	0.00575	0.00048	0.00000	0.00000
SSW	C	0.00109	0.00336	0.00562	0.00096	0.00014	0.00000
SW	C	0.00110	0.00342	0.00603	0.00068	0.00007	0.00007
WSW	C	0.00028	0.00144	0.00555	0.00116	0.00014	0.00000
W	C	0.00050	0.00288	0.00390	0.00116	0.00014	0.00000
WNW	C	0.00027	0.00110	0.00267	0.00027	0.00000	0.00000
NW	C	0.00011	0.00082	0.00274	0.00021	0.00007	0.00000
NNW	C	0.00009	0.00034	0.00144	0.00021	0.00000	0.00000

Table A.1 (cont.)

		Stability Class A	B	C	D	E	F
N	D	0.00002	0.00267	0.00664	0.00342	0.00034	0.00000
NNE	D	0.00015	0.00199	0.00377	0.00253	0.00021	0.00000
NE	D	0.00015	0.00260	0.00418	0.00178	0.00021	0.00000
ENE	D	0.00036	0.00253	0.00411	0.00212	0.00000	0.00000
E	D	0.00023	0.00342	0.00651	0.00205	0.00000	0.00000
ESE	D	0.00029	0.00212	0.00397	0.00144	0.00007	0.00000
SE	D	0.00030	0.00342	0.00514	0.00185	0.00007	0.00000
SSE	D	0.00023	0.00397	0.00397	0.00247	0.00000	0.00000
S	D	0.00081	0.00842	0.01014	0.00918	0.00123	0.00014
SSW	D	0.00009	0.00377	0.00993	0.01493	0.00274	0.00041
SW	D	0.00031	0.00486	0.01068	0.01336	0.00260	0.00034
WSW	D	0.00029	0.00267	0.00897	0.01048	0.00212	0.00021
W	D	0.00051	0.00500	0.01048	0.01445	0.00377	0.00062
WNW	D	0.00029	0.00226	0.00678	0.00856	0.00199	0.00027
NW	D	0.00008	0.00178	0.00486	0.00486	0.00055	0.00014
NNW	D	0.00008	0.00116	0.00390	0.00315	0.00041	0.00000
N	E	0.00049	0.00233	0.00877	0.00521	0.00027	0.00005
NNE	E	0.00041	0.00178	0.00534	0.00240	0.00021	0.00000
NE	E	0.00029	0.00274	0.00671	0.00233	0.00034	0.00007
ENE	E	0.00050	0.00253	0.00541	0.00260	0.00007	0.00000
E	E	0.00074	0.00363	0.01041	0.00274	0.00021	0.00000
ESE	E	0.00063	0.00205	0.00521	0.00116	0.00007	0.00000
SE	E	0.00029	0.00267	0.00692	0.00253	0.00007	0.00000
SSE	E	0.00024	0.00322	0.00658	0.00158	0.00007	0.00000
S	E	0.00129	0.00534	0.01610	0.00712	0.00082	0.00014
SSW	E	0.00119	0.00432	0.01253	0.00890	0.00123	0.00007
SW	E	0.00128	0.00274	0.00856	0.00836	0.00089	0.00048
WSW	E	0.00072	0.00274	0.00658	0.00575	0.00096	0.00007
W	E	0.00127	0.00459	0.00973	0.01007	0.00253	0.00041
WNW	E	0.00056	0.00226	0.00705	0.00795	0.00130	0.00007
NW	E	0.00007	0.00219	0.00685	0.00534	0.00068	0.00007
NNW	E	0.00012	0.00151	0.00322	0.00329	0.00027	0.00000
N	F	0.00196	0.00877	0.00486	0.00000	0.00000	0.00000
NNE	F	0.00333	0.00747	0.00233	0.00000	0.00000	0.00000
NE	F	0.00290	0.00842	0.00233	0.00000	0.00000	0.00000
ENE	F	0.00319	0.00897	0.00356	0.00000	0.00000	0.00000
E	F	0.00561	0.01342	0.00377	0.00000	0.00000	0.00000
ESE	F	0.00416	0.00959	0.00103	0.00000	0.00000	0.00000
SE	F	0.00344	0.00849	0.00144	0.00000	0.00000	0.00000
SSE	F	0.00389	0.00842	0.00103	0.00000	0.00000	0.00000
S	F	0.01266	0.02473	0.00589	0.00000	0.00000	0.00000
SSW	F	0.01356	0.02541	0.00685	0.00000	0.00000	0.00000
SW	F	0.00920	0.01459	0.00404	0.00000	0.00000	0.00000
WSW	F	0.00441	0.00842	0.00322	0.00000	0.00000	0.00000
W	F	0.00267	0.00692	0.00404	0.00000	0.00000	0.00000
WNW	F	0.00106	0.00514	0.00349	0.00000	0.00000	0.00000
NW	F	0.00103	0.00486	0.00322	0.00000	0.00000	0.00000
NNW	F	0.00056	0.00253	0.00171	0.00000	0.00000	0.00000

Table A.2 Agricultural Data for use in AIRDOS

1		16		2		16									
333		662		904		1267		1762		2533		3524		4519	
6615		9037		12667		17619		25333		35238		45185		66154	

Part I Milk Cattle in Hamilton and Butler Counties

0		0		0		0									
311	934	1557	2178	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	311	934	778	544	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	311	700	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	142	340	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
142	214	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	142	320	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	142	427	356	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	142	427	284	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
142	427	306	249	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	142	320	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	142	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	142	107	0	249
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
142	680	1557	1634	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	311	467	1557	2178	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	311	308	250	2178	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	311	934	1557	2178
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.2 (Cont.)

Part II Beef Cattle in Hamilton and Butler Counties

47	142	236	331	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	47	142	118	83	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	47	107	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	28	57	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	28	64	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	28	85	71	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	28	85	57	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	85	61	50	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	28	64	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	28	21	0	50
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	114	236	248	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	47	71	236	331	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	47	47	38	331	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	47	142	236	331
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.2 (Cont.)

Part III Vegetable Crops in Hamilton and Butler Counties

5.000E+06	1.500E+07	2.500E+07	3.500E+07	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	5.000E+06	1.500E+07	1.250E+07	8.740E+06
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.000E+06	1.130E+07	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	8.530E+06	1.010E+07	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.530E+06	1.280E+07	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	8.530E+06	1.920E+07	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.530E+06	2.560E+07	2.130E+07	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	8.530E+06	2.560E+07	1.700E+07	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.530E+06	2.560E+07	1.830E+07	1.500E+07	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	8.530E+06	1.920E+07	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.530E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	8.530E+06	6.390E+06	0.0	1.500E+07
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.530E+06	2.030E+07	2.500E+07	8.740E+06	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	5.000E+06	7.500E+06	2.500E+07	3.500E+07
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.000E+06	4.950E+06	4.050E+06	3.500E+07	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	5.000E+06	1.500E+07	2.500E+07	3.500E+07
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

FROM EPA 520/7-79-006.

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TABLE A.3 POPULATION DATA USED IN THE AIRDOS PROGRAM

Population Distribution *

	0 - 8 km	8 - 16 km	16 - 32 km	total
N	445	3395	6743	10583
NNE	221	18959	12805	31985
NE	489	32001	36705	69195
ENE	2489	25760	29830	58079
E	512	40770	70762	112044
ESE	713	54533	150630	205876
SE	1606	36467	247846	285919
SSE	985	28923	207202	237119
S	669	19214	53673	73556
SSW	390	4217	10614	15221
SW	185	2957	13066	16208
WSW	440	4961	3930	9331
W	519	1765	3292	5576
WNW	157	1361	5211	6729
NW	511	1433	1802	3746
NNW	519	1134	21042	22695
total	10850	277859	875153	1163862

Percentage

	0 - 8 km	8 - 16 km	16 - 32 km	total
N	4.20	32.08	63.72	100
NNE	0.69	59.27	40.04	100
NE	0.70	46.25	53.05	100
ENE	4.29	44.35	51.36	100
E	0.45	36.39	63.16	100
ESE	0.34	26.49	73.17	100
SE	0.57	12.75	86.68	100
SSE	0.42	12.20	87.38	100
S	0.91	26.12	72.97	100
SSW	2.56	27.71	69.73	100
SW	1.15	18.24	80.61	100
WSW	4.71	53.17	42.12	100
W	9.31	31.65	59.04	100
WNW	2.33	20.23	77.44	100
NW	13.65	38.25	48.10	100
NNW	2.28	5.00	92.72	100
	0.93	23.87	75.20	100

* Based on "Report of Findings, Population Studies for DOE Feed Materials Production Center, Near Fernald, Ohio, for NLO, Inc.", May 18, 1981.

TABLE A.3 (cont.) POPULATION DATA USED IN THE AIRDOS PROGRAM

Population Distribution (modified for AIRDOS model)

	0 - 7.25 km	7.25 - 14.5 km	14.5 - 21.75 km	21.75 - 32	total
N	403.3	2800.2	3059.8	4319.7	10583
NNE	200.3	15424.9	8156.6	8203.2	31985
NE	443.2	26046.7	19191.0	23514.1	69195
ENE	2255.7	21163.3	15550.2	19109.8	58079
E	464.0	33173.6	33074.5	45331.9	112044
ESE	646.2	44374.9	64357.6	96497.3	205876
SE	1455.4	29780.0	95907.2	158776.3	285919
SSE	892.7	23599.6	79888.0	132738.8	237119
S	606.3	15674.1	22891.4	34384.3	73556
SSW	353.4	3462.9	4605.1	6799.6	15221
SW	167.7	2419.9	5250.0	8370.4	16208
WSW	398.8	4072.1	2342.5	2517.7	9331
W	470.3	1482.7	1514.0	2108.9	5576
WNW	142.3	1120.5	2127.9	3338.3	6729
NW	463.1	1212.2	916.3	1154.4	3746
NNW	470.3	970.0	7774.6	13480.0	22695
total	9832.8	226777.6	366606.7	560644.9	1163862

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TABLE A.4 LIST OF INPUT VALUES FOR RADIONUCLIDE-INDEPENDENT VARIABLES USED IN AIRDOS

TIME DELAY--INGESTION OF PASTURE GRASS BY ANIMALS (HR)	.000E+0 *
TIME DELAY--INGESTION OF STORED FEED BY ANIMALS (HR)	.216E+4
TIME DELAY--INGESTION OF LEAFY VEGETABLES BY MAN (HR)	.336E+3
TIME DELAY--INGESTION OF PRODUCE BY MAN (HR)	.336E+3
REMOVAL RATE CONSTANT FOR PHYSICAL LOSS BY WEATHERING (PER HOUR)	.290E-2
PERIOD OF EXPOSURE DURING GROWING SEASON--PASTURE GRASS (HR)	.720E+3
PERIOD OF EXPOSURE DURING GROWING SEASON--CROPS OR LEAFY VEGETABLES (HR)	.144E+4
AGRICULTURAL PRODUCTIVITY BY UNIT AREA (GRASS-COW-MILK-MAN PATHWAY (KG/SQ. METER))	.280E+0
AGRICULTURAL PRODUCTIVITY BY UNIT AREA (PRODUCE OR LEAFY VEG INGESTED BY MAN (KG/SQ. METER))	.716E+0
FRACTION OF YEAR ANIMALS GRAZE ON PASTURE	
FRACTION OF DAILY FEED THAT IS PASTURE GRASS WHEN ANIMAL GRAZES ON PASTURE	.430E+0
CONSUMPTION RATE OF CONTAMINATED FEED OR FORAGE BY AN ANIMAL IN KG/DAY (DRY WEIGHT)	.156E+2
TRANSPORT TIME FROM ANIMAL FEED-MILK-MAN (DAY)	.200E+1
RATE OF INGESTION OF PRODUCE BY MAN (KG/YR)	.176E+3
RATE OF INGESTION OF MILK BY MAN (LITERS/YR)	.112E+3
RATE OF INGESTION OF MEAT BY MAN (KG/YR)	.850E+2
RATE OF INGESTION OF LEAFY VEGETABLES BY MAN (KG/YR)	.180E+2
AVERAGE TIME FROM SLAUGHTER OF MEAT ANIMAL TO CONSUMPTION (DAY)	.200E+2
FRACTION OF PRODUCE INGESTED GROWN IN GARDEN OF INTEREST	.100E+1
FRACTION OF LEAFY VEGETABLES GROWN IN GARDEN OF INTEREST	.100E+1
PERIOD OF LONG-TERM BUILDUP FOR ACTIVITY IN SOIL (YEARS)	.100E+3
EFFECTIVE SURFACE DENSITY OF SOIL (KG/SQ. M, DRY WEIGHT) (ASSUMES 15 CM PLOW LAYER)	.215E+3
VEGETABLE INGESTION RATIO-IMMEDIATE SURROUNDING AREA/TOTAL WITHIN AREA	.100E+1
MEAT INGESTION RATIO-IMMEDIATE SURROUNDING AREA/TOTAL WITHIN AREA	.100E+1
MILK INGESTION RATIO-IMMEDIATE SURROUNDING AREA/TOTAL WITHIN AREA	.100E+1
INHALATION RATE OF MAN (CUBIC CENTIMETERS/HR)	.916E+6
BUILDUP TIME FOR RADIONUCLIDES DEPOSITED ON GROUND AND WATER (DAYS)	.365E+5
DILUTION FACTOR FOR WATER FOR SWIMMING (CM)	.100E+1
FRACTION OF TIME SPENT SWIMMING	.000E+0
MUSCLE MASS OF ANIMAL AT SLAUGHTER (KG)	.200E+3
FRACTION OF ANIMAL HERD SLAUGHTERED PER DAY	.380E-2
MILK PRODUCTION OF COW (LITERS/DAY)	.110E+2
FALLOUT INTERCEPTION FRACTION-VEGETABLES	.200E+0
FALLOUT INTERCEPTION FRACTION-PASTURE	.570E+0
FRACTION OF RADIOACTIVITY RETAINED ON LEAFY VEGETABLES AND PRODUCE AFTER WASHING	.500E+0

* E with + or - indicates 10 to the power delineated

Table A.6 Dose Conversion Factors Used in AIRDOS

This data was taken from the data file 'ALLRAD.DAT' The file is set up such that the dose conversion factors can be obtained for each isotope as well as for the manner in which the radionuclides are taken into the body.

The first set of numbers in scientific notation indicates the correction factors for immersion in air and water as well as surface exposure, and the decay constant. These are followed by the 11 organs dose conversion factors.

The data preceeded by either a 'D', 'W', or a 'Y' are the corresponding inhalation dose conversion factors associated with that lung class and the specific particle size. All the factors are in Rems per micro-Curie.

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SR-90    66     1     1 0.000E+00 0.000E+00 0.000E+00 6.635E-05 6.635E-05
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    2
 1.000E-02 5.621E-03 2.170E-02 4.925E-02 1.776E-04 1.776E-04 1.776E-04
 9.653E-04 4.793E-02 1.904E-04 1.776E-04 1.776E-04
 3.000E-01 1.118E-01 6.511E-01 1.478E+00 5.329E-03 5.329E-03 5.329E-03
 3.555E-03 3.672E-02 5.710E-03 5.329E-03 5.329E-03
    2
D          1.000E+00 3.000E-01 1.958E-01 1.146E+00 2.600E+00 9.433E-03
 9.433E-03 1.497E-02 4.884E-03 1.020E-02 1.071E-02 9.433E-03 9.433E-03
Y          1.000E+00 1.000E-02 1.685E+00 1.112E-01 2.510E-01 9.808E-04
 9.809E-04 7.922E+00 3.002E-02 5.298E-01 1.839E-03 9.808E-04 9.808E-04

TC-99    68     1     2 4.769E-04 1.110E-06 1.127E-07 8.914E-09 8.914E-09
 5.089E-01 3.662E-01 8.721E-01 7.332E-01 8.659E-01 4.997E-01 4.352E-01
 4.214E-01 4.511E-01 3.343E-01 4.617E-01
    1
 8.000E-01 1.916E-03 2.312E-04 2.312E-04 5.976E-03 2.312E-04 2.312E-04
 1.255E-02 2.203E-03 3.035E-04 2.312E-04 2.312E-04
    2
D          1.000E+00 8.000E-01 1.722E-03 1.755E-04 1.755E-04 4.536E-03
 1.755E-04 1.805E-03 9.266E-03 4.198E-04 2.304E-04 1.755E-04 1.755E-04
W          1.000E+00 8.000E-01 2.181E-02 1.548E-04 1.548E-04 4.000E-03
 1.548E-04 9.920E-02 8.333E-03 1.160E-03 2.032E-04 1.548E-04 1.548E-04
TC-99M   68     1     2 1.190E+02 2.684E-01 2.760E-02 2.763E+00 2.763E+00
 5.326E-01 4.714E-01 8.082E-01 7.089E-01 8.082E-01 5.140E-01 4.643E-01
 4.572E-01 4.679E-01 3.864E-01 4.750E-01
    1
 8.000E-01 7.457E-05 2.328E-05 9.436E-06 3.183E-04 1.482E-05 1.293E-05
 2.637E-04 1.056E-04 1.687E-05 3.890E-05 1.965E-05
    2
D          1.000E+00 8.000E-01 6.408E-05 1.283E-05 6.667E-06 1.923E-04
 9.161E-06 1.322E-04 1.096E-04 1.997E-05 1.186E-05 1.871E-05 9.582E-06
W          1.000E+00 8.000E-01 5.729E-05 1.179E-05 7.529E-06 8.159E-05
 8.032E-06 1.757E-04 5.968E-05 1.636E-05 1.281E-05 1.724E-05 7.169E-06
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RU-106  59     1     3 0.000E+00 0.000E+00 0.000E+00 1.883E-03 1.883E-03
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    1
 5.000E-02 1.123E-02 5.635E-03 5.407E-03 5.530E-03 5.597E-03 5.468E-03
 9.109E-03 1.431E-01 5.573E-03 5.548E-03 5.654E-03
    3
D          1.000E+00 5.000E-02 5.609E-02 5.348E-02 5.225E-02 5.394E-02
 5.372E-02 7.623E-02 2.931E-02 4.959E-02 5.372E-02 5.324E-02 5.420E-02
W          1.000E+00 5.000E-02 2.745E-01 1.577E-02 1.527E-02 1.582E-02
 1.583E-02 1.252E+00 1.193E-02 7.882E-02 1.621E-02 1.619E-02 1.586E-02
Y          1.000E+00 5.000E-02 1.231E+00 6.734E-03 6.097E-03 6.653E-03
 6.873E-03 5.889E+00 9.061E-03 7.665E-02 8.774E-03 9.285E-03 6.357E-03

CS-137  19     1     1 0.000E+00 0.000E+00 0.000E+00 6.288E-05 6.288E-05
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    1
 9.500E-01 4.446E-02 4.365E-02 3.052E-02 5.080E-02 4.799E-02 4.438E-02
 3.568E-02 2.928E-02 4.786E-02 4.440E-02 5.055E-02
    1
D          1.000E+00 9.500E-01 3.039E-02 2.901E-02 2.029E-02 3.378E-02
 3.190E-02 3.394E-02 2.311E-02 1.871E-02 3.184E-02 2.952E-02 3.359E-02


PB-210  48     1     2 3.904E+00 9.875E-03 6.541E-03 8.526E-05 8.526E-05
 1.386E-01 5.618E-02 2.280E-01 2.128E-01 3.609E-01 1.232E-01 9.767E-02
 9.002E-02 1.102E-01 6.310E-02 1.469E-01
    1
 2.000E-01 3.835E+00 5.953E+00 8.375E+01 4.973E-01 4.974E-01 4.974E-01
 4.941E-01 5.028E-01 2.331E+01 4.974E-01 1.081E+01
    9
D          3.000E-01 2.000E-01 1.078E+01 1.673E+01 2.353E+02 1.398E+00
 1.398E+00 1.401E+00 1.388E+00 1.389E+00 6.552E+01 1.398E+00 3.040E+01
D          1.000E+00 2.000E-01 9.817E+00 1.524E+01 2.144E+02 1.273E+00
 1.273E+00 1.275E+00 1.265E+00 1.266E+00 5.968E+01 1.274E+00 2.769E+01
D          3.000E+00 2.000E-01 1.098E+01 1.705E+01 2.399E+02 1.424E+00
 1.425E+00 1.426E+00 1.415E+00 1.418E+00 6.676E+01 1.425E+00 3.098E+01
W          3.000E-01 2.000E-01 1.367E+01 6.837E+00 9.606E+01 5.890E-01
 5.890E-01 4.484E+01 5.856E-01 5.981E-01 2.755E+01 5.890E-01 1.278E+01
W          1.000E+00 2.000E-01 9.660E+00 6.707E+00 9.428E+01 5.706E-01
 5.707E-01 2.606E+01 5.671E-01 5.770E-01 2.671E+01 5.707E-01 1.239E+01
W          3.000E+00 2.000E-01 7.841E+00 7.926E+00 1.115E+02 6.676E-01
 6.676E-01 1.372E+01 6.633E-01 6.729E-01 3.127E+01 6.676E-01 1.451E+01
Y          3.000E-01 2.000E-01 2.802E+02 5.261E+00 7.371E+01 4.844E-01
 4.848E-01 1.333E+03 4.824E-01 5.020E-01 2.256E+01 4.847E-01 1.047E+01
Y          1.000E+00 2.000E-01 1.626E+02 4.847E+00 6.802E+01 4.309E-01
 4.311E-01 7.683E+02 4.288E-01 4.431E-01 2.011E+01 4.311E-01 9.332E+00
Y          3.000E+00 2.000E-01 8.523E+01 5.543E+00 7.789E+01 4.765E-01
 4.766E-01 3.937E+02 4.738E-01 4.863E-01 2.229E+01 4.766E-01 1.034E+01
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NP-237  44     1     1 2.967E+01 7.132E-02 2.338E-02 8.872E-10 8.872E-10
 3.535E-01 2.573E-01 5.758E-01 4.962E-01 6.383E-01 3.383E-01 2.943E-01
 2.863E-01 3.042E-01 2.303E-01 3.213E-01
    1
 1.000E-03 3.146E+00 7.510E+00 9.278E+01 1.158E-01 1.160E-01 1.162E-01
 1.196E-01 2.216E-01 1.836E+01 1.164E-01 1.163E-01
    2
W          1.000E+00 1.000E-03 4.007E+02 9.102E+02 1.125E+04 1.404E+01
 1.406E+01 1.094E+02 1.396E+01 1.402E+01 2.227E+03 1.410E+01 1.409E+01
Y          1.000E+00 1.000E-03 3.475E+02 3.606E+02 4.454E+03 5.569E+00
 5.582E+00 9.475E+02 5.549E+00 5.617E+00 8.962E+02 5.610E+00 5.592E+00


RA-228  54     1     2 3.549E-06 8.904E-09 7.385E-09 3.301E-04 3.301E-04
 7.800E-03 1.913E-04 9.484E-04 3.696E-04 5.788E-02 5.847E-04 1.509E-04
 1.222E-04 7.190E-06 4.314E-04 8.866E-07
    1
 2.000E-01 4.714E-01 9.784E-01 9.611E+00 3.319E-01 3.326E-01 3.320E-01
 3.294E-01 3.693E-01 3.946E-01 3.323E-01 3.379E-01
    6
W          3.000E-01 2.000E-01 6.661E+00 1.520E+00 1.510E+01 5.100E-01
 5.112E-01 2.888E+01 5.156E-01 5.624E-01 1.146E+00 5.145E-01 5.257E-01
W          1.000E+00 2.000E-01 4.058E+00 1.332E+00 1.319E+01 4.487E-01
 4.496E-01 1.679E+01 4.509E-01 4.885E-01 8.587E-01 4.514E-01 4.604E-01
W          3.000E+00 2.000E-01 2.437E+00 1.423E+00 1.404E+01 4.811E-01
 4.820E-01 8.851E+00 4.806E-01 5.182E-01 7.625E-01 4.828E-01 4.915E-01
Y          3.000E-01 2.000E-01 3.054E+02 3.850E+00 3.769E+01 1.399E+00
 1.409E+00 1.462E+03 1.546E+00 2.448E+00 5.518E+00 1.463E+00 1.823E+00
Y          1.000E+00 2.000E-01 1.761E+02 2.517E+00 2.465E+01 9.071E-01
 9.135E-01 8.424E+02 9.917E-01 1.524E+00 3.301E+00 9.443E-01 1.153E+00
Y          3.000E+00 2.000E-01 9.041E+01 1.792E+00 1.757E+01 6.353E-01
 6.389E-01 4.316E+02 6.780E-01 9.714E-01 1.896E+00 6.546E-01 7.644E-01


RA-226  54     1     2 6.414E+00 1.431E-02 1.612E-03 1.187E-06 1.187E-06
 5.183E-01 4.820E-01 7.365E-01 6.708E-01 7.563E-01 5.005E-01 4.518E-01
 4.469E-01 4.584E-01 3.860E-01 4.709E-01
    1
 2.000E-01 7.391E-01 2.311E+00 2.723E+01 3.325E-01 3.333E-01 3.329E-01
 3.348E-01 4.973E-01 3.237E-01 3.331E-01 3.327E-01
    6
W          3.000E-01 2.000E-01 3.553E+01 2.912E+00 3.111E+01 7.837E-01
 7.844E-01 1.662E+02 7.817E-01 8.624E-01 4.796E-01 7.843E-01 1.101E+00
W          1.000E+00 2.000E-01 2.081E+01 2.754E+00 3.058E+01 6.088E-01
 6.096E-01 9.593E+01 6.078E-01 6.951E-01 4.275E-01 6.095E-01 7.936E-01
W          3.000E+00 2.000E-01 1.122E+01 3.157E+00 3.620E+01 5.674E-01
 5.683E-01 4.939E+01 5.672E-01 6.818E-01 4.644E-01 5.682E-01 6.659E-01
Y          3.000E-01 2.000E-01 3.472E+02 7.859E+00 2.586E+01 3.724E+00
 8.722E+00 1.643E+03 8.675E+00 8.759E+00 2.591E+00 8.723E+00 1.532E+01
Y          1.000E+00 2.000E-01 2.003E+02 5.235E+00 2.321E+01 5.130E+00
 5.130E+00 9.464E+02 5.103E+00 5.198E+00 1.592E+00 5.130E+00 8.933E+00
Y          3.000E+00 2.000E-01 1.030E+02 3.872E+00 2.588E+01 2.804E+00
 2.804E+00 4.848E+02 2.791E+00 2.919E+00 9.834E-01 2.804E+00 4.755E+00
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TH-228  70     1     5 2.777E+00 6.625E-03 3.055E-03 9.919E-04 9.919E-04
 3.337E-01 2.673E-01 5.179E-01 4.526E-01 5.635E-01 3.205E-01 2.825E-01
 2.755E-01 2.916E-01 2.278E-01 2.992E-01
    1
 2.000E-04 7.716E-02 2.970E-01 3.635E+00 7.788E-03 7.873E-03 7.801E-03
 1.265E-02 2.423E-01 3.429E-02 7.841E-03 9.547E-03
    6
W          3.000E-01 2.000E-04 1.850E+02 1.760E+02 2.173E+03 2.412E+00
 2.416E+00 7.093E+02 2.441E+00 3.007E+00 1.897E+01 2.420E+00 2.577E+00
W          1.000E+00 2.000E-04 1.193E+02 1.600E+02 1.976E+03 2.145E+00
 2.148E+00 4.094E+02 2.158E+00 2.550E+00 1.719E+01 2.150E+00 2.235E+00
W          3.000E+00 2.000E-04 8.039E+01 1.709E+02 2.111E+03 2.244E+00
 2.247E+00 2.108E+02 2.247E+00 2.560E+00 1.830E+01 2.248E+00 2.284E+00
Y          3.000E-01 2.000E-04 9.547E+02 4.304E+01 5.253E+02 1.311E+00
 1.321E+00 4.554E+03 1.560E+00 4.295E+00 5.618E+00 1.346E+00 2.296E+00
Y          1.000E+00 2.000E-04 5.509E+02 2.890E+01 3.533E+02 8.122E-01
 8.178E-01 2.624E+03 9.572E-01 2.609E+00 3.678E+00 8.319E-01 1.381E+00
Y          3.000E+00 2.000E-04 2.836E+02 2.172E+01 2.664E+02 5.115E-01
 5.146E-01 1.344E+03 5.886E-01 1.564E+00 2.628E+00 5.218E-01 8.066E-01

TH-230  70     1     5 1.224E+00 3.064E-03 2.418E-03 2.464E-08 2.464E-08
 1.444E-01 9.477E-02 2.243E-01 1.930E-01 3.143E-01 1.316E-01 1.127E-01
 1.077E-01 1.182E-01 8.650E-02 1.237E-01
    1
 2.000E-04 2.362E-01 1.150E+00 1.433E+01 2.581E-03 2.581E-03 2.581E-03
 6.614E-03 9.994E-02 2.183E-02 2.581E-03 2.581E-03
    6
W          3.000E-01 2.000E-04 1.905E+02 7.780E+02 9.690E+03 1.747E+00
 1.747E+00 1.635E+02 1.739E+00 1.783E+00 1.477E+01 1.747E+00 1.747E+00
W          1.000E+00 2.000E-04 1.596E+02 6.952E+02 8.659E+03 1.561E+00
 1.561E+00 9.474E+01 1.554E+00 1.603E+00 1.320E+01 1.561E+00 1.561E+00
W          3.000E+00 2.000E-04 1.573E+02 7.306E+02 9.100E+03 1.640E+00
 1.640E+00 4.936E+01 1.634E+00 1.699E+00 1.387E+01 1.640E+00 1.640E+00
Y          3.000E-01 2.000E-04 4.245E+02 4.603E+02 5.733E+03 1.055E+00
 1.056E+00 1.599E+03 1.052E+00 1.100E+00 8.925E+00 1.056E+00 1.055E+00
Y          1.000E+00 2.000E-04 2.480E+02 2.824E+02 3.517E+03 6.466E-01
 6.468E-01 9.214E+02 6.457E-01 7.003E-01 5.468E+00 6.467E-01 6.466E-01
Y          3.000E+00 2.000E-04 1.329E+02 1.736E+02 2.162E+03 3.962E-01
 3.963E-01 4.719E+02 3.973E-01 4.710E-01 3.350E+00 3.962E-01 3.962E-01

TH-232  70     1     5 1.034E+00 2.612E-03 2.363E-03 1.350E-13 1.350E-13
 7.933E-02 4.324E-02 1.150E-01 9.831E-02 2.207E-01 6.568E-02 5.507E-02
 5.197E-02 5.793E-02 4.120E-02 6.201E-02
    1
 2.000E-04 2.152E-01 1.049E+00 1.310E+01 2.288E-03 2.291E-03 2.290E-03
 5.726E-03 8.533E-02 1.900E-02 2.290E-03 2.262E-03
    6
W          3.000E-01 2.000E-04 1.719E+02 7.092E+02 8.857E+03 1.540E+00
 1.542E+00 1.405E+02 1.534E+00 1.573E+00 1.286E+01 1.542E+00 1.522E+00
W          1.000E+00 2.000E-04 1.445E+02 6.337E+02 7.914E+03 1.374E+00
 1.376E+00 8.145E+01 1.369E+00 1.412E+00 1.148E+01 1.375E+00 1.358E+00
W          3.000E+00 2.000E-04 1.428E+02 6.658E+02 8.315E+03 1.441E+00
 1.443E+00 4.245E+01 1.436E+00 1.493E+00 1.206E+01 1.443E+00 1.424E+00
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Table A.6 (cont.)

(thorium-232 cont.)

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Y           3.000E-01 2.000E-04 4.244E+02 4.742E+02 5.909E+03 2.179E+00
 2.187E+00 1.580E+03 2.212E+00 2.335E+00 1.349E+01 2.223E+00 2.222E+00
Y           1.000E+00 2.000E-04 2.476E+02 2.889E+02 3.600E+03 1.289E+00
 1.294E+00 9.105E+02 1.309E+00 1.403E+00 8.053E+00 1.315E+00 1.314E+00
Y           3.000E+00 2.000E-04 1.322E+02 1.744E+02 2.174E+03 7.173E-01
 7.199E-01 4.664E+02 7.289E-01 8.160E-01 4.603E+00 7.306E-01 7.292E-01


U-234   72    1   14 1.270E+00 3.233E-03 3.009E-03 7.763E-09 7.763E-09
 5.217E-02 2.478E-02 6.377E-02 5.447E-02 1.837E-01 3.687E-02 3.026E-02
 2.861E-02 3.102E-02 2.375E-02 3.354E-02
    3
 2.000E-03 8.436E-03 1.084E-02 1.712E-01 3.851E-04 3.854E-04 3.851E-04
 4.501E-03 9.916E-02 3.851E-04 3.852E-04 6.619E-02
 5.000E-02 1.098E-01 2.709E-01 4.279E+00 9.626E-03 9.627E-03 9.627E-03
 1.369E-02 1.036E-01 9.626E-03 9.627E-03 1.655E+00
 2.000E-01 4.267E-01 1.084E+00 1.712E+01 3.851E-02 3.851E-02 3.851E-02
 4.242E-02 1.175E-01 3.851E-02 3.851E-02 6.619E+00
   15
D           3.000E-01 5.000E-02 1.737E+00 3.006E+00 4.747E+01 1.068E-01
 1.068E-01 2.817E+00 1.064E-01 1.107E-01 1.068E-01 1.068E-01 1.836E+01
D           3.000E-01 2.000E-01 1.752E+00 3.045E+00 4.809E+01 1.082E-01
 1.082E-01 2.819E+00 1.078E-01 1.114E-01 1.082E-01 1.082E-01 1.860E+01
D           1.000E+00 5.000E-02 1.358E+00 2.645E+00 4.177E+01 9.397E-02
 9.398E-02 1.656E+00 9.413E-02 1.084E-01 9.397E-02 9.397E-02 1.615E+01
D           1.000E+00 2.000E-01 1.408E+00 2.774E+00 4.381E+01 9.856E-02
 9.857E-02 1.660E+00 9.870E-02 1.106E-01 9.856E-02 9.857E-02 1.694E+01
D           3.000E+00 5.000E-02 1.281E+00 2.851E+00 4.503E+01 1.013E-01
 1.013E-01 9.010E-01 1.020E-01 1.300E-01 1.013E-01 1.013E-01 1.741E+01
D           3.000E+00 2.000E-01 1.379E+00 3.104E+00 4.902E+01 1.103E-01
 1.103E-01 9.100E-01 1.110E-01 1.343E-01 1.103E-01 1.103E-01 1.896E+01
W           3.000E-01 5.000E-02 3.453E+01 8.588E-01 1.356E+01 3.052E-02
 3.053E-02 1.648E+02 3.228E-02 7.407E-02 3.052E-02 3.052E-02 5.246E+00
W           3.000E-01 2.000E-01 3.468E+01 1.237E+00 1.953E+01 4.394E-02
 4.396E-02 1.648E+02 4.563E-02 8.053E-02 4.395E-02 4.395E-02 7.554E+00
W           1.000E+00 5.000E-02 2.001E+01 7.951E-01 1.256E+01 2.825E-02
 2.826E-02 9.497E+01 3.024E-02 7.684E-02 2.826E-02 2.825E-02 4.857E+00
W           1.000E+00 2.000E-01 2.017E+01 1.216E+00 1.921E+01 4.322E-02
 4.323E-02 9.499E+01 4.513E-02 8.403E-02 4.322E-02 4.322E-02 7.430E+00
W           3.000E+00 5.000E-02 1.043E+01 8.759E-01 1.383E+01 3.112E-02
 3.113E-02 4.865E+01 3.382E-02 9.628E-02 3.113E-02 3.113E-02 5.350E+00
W           3.000E+00 2.000E-01 1.065E+01 1.441E+00 2.275E+01 5.119E-02
 5.119E-02 4.867E+01 5.378E-02 1.059E-01 5.119E-02 5.119E-02 8.799E+00
Y           3.000E-01 2.000E-03 3.380E+02 4.444E-01 7.016E+00 1.593E-02
 1.619E-02 1.629E+03 1.802E-02 6.641E-02 1.607E-02 1.596E-02 2.737E+00
Y           1.000E+00 2.000E-03 1.948E+02 2.751E-01 4.343E+00 9.855E-03
 1.001E-02 9.382E+02 1.225E-02 6.762E-02 9.933E-03 9.872E-03 1.693E+00
Y           3.000E+00 2.000E-03 9.975E+01 1.730E-01 2.731E+00 6.187E-03
 6.265E-03 4.805E+02 9.423E-03 8.410E-02 6.227E-03 6.196E-03 1.063E+00
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U-235    72     1     5 1.443E+02 3.233E-01 3.988E-02 2.697E-12 2.697E-12
 5.166E-01 4.794E-01 7.395E-01 6.723E-01 7.542E-01 4.998E-01 4.502E-01
 4.461E-01 4.560E-01 3.829E-01 4.677E-01
    3
 2.000E-03 8.600E-03 1.087E-02 1.656E-01 3.767E-04 4.626E-04 3.870E-04
 4.545E-03 1.061E-01 3.722E-04 4.683E-04 6.136E-02
 5.000E-02 1.056E-01 2.664E-01 4.139E+00 9.399E-03 9.527E-03 9.439E-03
 1.344E-02 1.100E-01 7.847E-03 9.536E-03 1.532E+00
 2.000E-01 4.087E-01 1.065E+00 1.656E+01 3.759E-02 3.785E-02 3.773E-02
 4.124E-02 1.222E-01 3.121E-02 3.787E-02 6.127E+00
    5
D          1.000E+00 5.000E-02 1.288E+00 2.599E+00 4.041E+01 9.175E-02
 9.224E-02 1.536E+00 9.120E-02 1.072E-01 7.609E-02 9.227E-02 1.495E+01
D          1.000E+00 2.000E-01 1.337E+00 2.726E+00 4.238E+01 9.624E-02
 9.675E-02 1.540E+00 9.562E-02 1.092E-01 7.980E-02 9.678E-02 1.568E+01
W          1.000E+00 5.000E-02 1.853E+01 7.821E-01 1.215E+01 2.790E-02
 2.832E-02 8.789E+01 3.108E-02 9.108E-02 2.386E-02 2.873E-02 4.495E+00
D          1.000E+00 2.000E-01 1.869E+01 1.196E+00 1.858E+01 4.252E-02
 4.301E-02 8.791E+01 4.549E-02 9.739E-02 3.596E-02 4.342E-02 6.877E+00
Y          1.000E+00 2.000E-03 1.803E+02 2.844E-01 4.213E+00 1.623E-02
 2.131E-02 8.682E+02 3.557E-02 1.744E-01 2.788E-02 2.950E-02 1.574E+00
U-238    72     1    14 1.038E+00 2.654E-03 2.519E-03 4.247E-13 4.247E-13
 4.245E-02 1.552E-02 4.958E-02 4.145E-02 1.703E-01 2.751E-02 2.182E-02
 2.006E-02 2.267E-02 1.634E-02 2.406E-02
    3
 2.000E-03 7.905E-03 1.147E-02 1.486E-01 3.461E-04 3.537E-04 3.473E-04
 3.984E-03 9.141E-02 2.980E-04 3.521E-04 5.915E-02
 5.000E-02 1.047E-01 2.864E-01 3.714E+00 8.652E-03 8.678E-03 8.664E-03
 1.221E-02 9.527E-02 7.361E-03 8.666E-03 1.478E+00
 2.000E-01 4.071E-01 1.146E+00 1.486E+01 3.461E-02 3.469E-02 3.465E-02
 3.791E-02 1.073E-01 2.943E-02 3.465E-02 5.914E+00
   15
D          3.000E-01 5.000E-02 1.617E+00 3.179E+00 4.121E+01 9.606E-02
 9.628E-02 2.488E+00 9.528E-02 9.936E-02 8.198E-02 9.615E-02 1.640E+01
D          3.000E-01 2.000E-01 1.631E+00 3.220E+00 4.174E+01 9.730E-02
 9.753E-02 2.489E+00 9.651E-02 9.994E-02 8.304E-02 9.740E-02 1.662E+01
D          1.000E+00 5.000E-02 1.272E+00 2.797E+00 3.626E+01 8.450E-02
 8.470E-02 1.463E+00 8.425E-02 9.755E-02 7.203E-02 8.458E-02 1.443E+01
D          1.000E+00 2.000E-01 1.320E+00 2.933E+00 3.803E+01 8.863E-02
 8.883E-02 1.467E+00 8.833E-02 9.947E-02 7.554E-02 8.871E-02 1.514E+01
D          3.000E+00 5.000E-02 1.210E+00 3.014E+00 3.908E+01 9.107E-02
 9.128E-02 7.969E-01 9.131E-02 1.173E-01 7.753E-02 9.116E-02 1.556E+01
D          3.000E+00 2.000E-01 1.304E+00 3.281E+00 4.255E+01 9.914E-02
 9.937E-02 8.049E-01 9.931E-02 1.210E-01 8.440E-02 9.924E-02 1.694E+01
W          3.000E-01 5.000E-02 3.062E+01 9.160E-01 1.179E+01 2.781E-02
 2.793E-02 1.461E+02 3.025E-02 9.235E-02 2.495E-02 2.793E-02 4.687E+00
W          3.000E-01 2.000E-01 3.076E+01 1.315E+00 1.696E+01 3.987E-02
 4.003E-02 1.461E+02 4.220E-02 9.796E-02 3.521E-02 4.001E-02 6.749E+00
W          1.000E+00 5.000E-02 1.775E+01 8.453E-01 1.091E+01 2.561E-02
 2.571E-02 8.415E+01 2.785E-02 8.473E-02 2.254E-02 2.570E-02 4.339E+00
W          1.000E+00 2.000E-01 1.791E+01 1.291E+00 1.668E+01 3.907E-02
 3.919E-02 8.416E+01 4.118E-02 9.099E-02 3.398E-02 3.916E-02 6.638E+00
W          3.000E+00 5.000E-02 9.268E+00 9.285E-01 1.201E+01 2.809E-02
 2.818E-02 4.311E+01 3.068E-02 9.599E-02 2.430E-02 2.815E-02 4.780E+00
W          3.000E+00 2.000E-01 9.478E+00 1.525E+00 1.975E+01 4.612E-02
 4.625E-02 4.313E+01 4.854E-02 1.044E-01 3.963E-02 4.620E-02 7.862E+00
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Table A.6 (cont.)

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    (uranium-238 cont.)
Y           3.000E-01 2.000E-03 3.001E+02 5.030E-01 6.143E+00 1.755E-02
 1.904E-02 1.445E+03 2.947E-02 2.503E-01 2.166E-02 2.033E-02 2.449E+00
Y           1.000E+00 2.000E-03 1.729E+02 3.099E-01 3.800E+00 1.072E-02
 1.158E-02 8.327E+02 1.866E-02 1.716E-01 1.300E-02 1.232E-02 1.515E+00
Y           3.000E+00 2.000E-03 8.855E+01 1.927E-01 2.386E+00 6.515E-03
 6.964E-03 4.265E+02 1.238E-02 1.341E-01 7.533E-03 7.341E-03 9.508E-01

PU-238  53     1     2 1.372E+00 3.511E-03 3.304E-03 2.163E-05 2.163E-05
 2.606E-02 4.396E-03 1.737E-02 1.420E-02 1.500E-01 9.776E-03 6.518E-03
 5.546E-03 5.933E-03 5.626E-03 6.671E-03
    1
 1.000E-03 2.883E+00 6.765E+00 8.342E+01 1.038E-01 1.038E-01 1.038E-01
 1.081E-01 2.169E-01 1.712E+01 1.038E-01 1.038E-01
    2
W           1.000E+00 1.000E-03 3.714E+02 8.196E+02 1.011E+04 1.258E+01
 1.258E+01 1.219E+02 1.253E+01 1.258E+01 2.074E+03 1.258E+01 1.258E+01
Y           1.000E+00 1.000E-03 3.572E+02 3.183E+02 3.925E+03 4.886E+00
 4.886E+00 1.070E+03 4.867E+00 4.930E+00 8.155E+02 4.886E+00 4.886E+00


PU-239  53     1     2 5.655E-01 1.431E-03 1.270E-03 7.860E-08 7.860E-08
 6.506E-02 3.931E-02 8.056E-02 6.825E-02 2.014E-01 4.878E-02 4.177E-02
 4.068E-02 4.132E-02 3.491E-02 4.199E-02
    2
 1.000E-04 3.431E-01 8.091E-01 9.964E+00 1.240E-02 1.240E-02 1.240E-02
 1.676E-02 1.189E-01 1.981E+00 1.240E-02 1.240E-02
 1.000E-03 3.390E+00 8.091E+00 9.964E+01 1.240E-01 1.240E-01 1.240E-01
 1.279E-01 2.299E-01 1.981E+01 1.240E-01 1.240E-01
    2
W           1.000E+00 1.000E-03 4.318E+02 9.807E+02 1.208E+04 1.503E+01
 1.503E+01 1.178E+02 1.496E+01 1.502E+01 2.403E+03 1.503E+01 1.503E+01
Y           1.000E+00 1.000E-04 3.728E+02 3.842E+02 4.731E+03 5.889E+00
 5.889E+00 1.021E+03 5.864E+00 5.924E+00 9.565E+02 5.889E+00 5.889E+00
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