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Date May 20, 1994

Radiation Dose Assessment for Plutonium Contamination at Area 13 of the Nevada Test Site using Nevada Applied Ecology Group Data and the RESRAD Code

A Thesis Presented for the

Master of Science Degree

University of Tennessee, Knoxville

Travis Shaw Kroodsma

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ABSTRACT

A radiation dose assessment is performed for plutonium contamination at Area 13 of the Nevada Test Site (NTS). Area 13 is one of five safety shot areas at NTS. Safety shots were experiments that tested the ability of nuclear weapons not to fission in the case of accident, storage, handling, and transport situations. As a result of the safety shots, plutonium, the majority of which is Pu-239, has contaminated surface soil of the five safety shot areas. This dose assessment determines approximate radiation doses that an industrial-worker or residential-farmer could receive at Area 13, and analyzes compliance of the potential doses with Department of Energy (DOE) standards.

The Nevada Applied Ecology Group (NAEG) determined that the ratio of plutonium ingestion to plutonium inhalation at NTS is approximately 100 for a residential-farmer. At this ratio, inhalation is responsible for approximately 100 % of the dose to the lungs and 95 % of the dose to the whole body and bone; lungs and bone were determined to be the critical organs. External dose was not considered by the NAEG. Because of results of the NAEG, this dose assessment only considers inhalation.

The RESRAD code is used to calculate radiation doses. RESRAD calculates dose by modeling environmental transport of radioactive contaminants from the source to a human receptor and using dose conversion factors (dose per unit intake of

radionuclide). The parameters used in the RESRAD code are subjected to sensitivity analysis to analyze variations in radiation dose that could occur from variations in the parameters. "Sensitive" parameters are the mass loading factor (mass of soil suspended per unit volume of air), inhalation rate, distribution coefficient (radionuclide adsorbed onto soil versus that in infiltrating water), contaminated zone thickness, evapotranspiration coefficient (percentage of precipitation that is lost by evaporation and transpiration), and soil mixing layer (depth to which surface soil undergoes mixing).

Values for committed effective dose equivalent (whole body dose from internal radiation) were calculated for a generic scenario (i.e., parameters were for normal weather conditions and/or were not specific to a given land-use scenario). The radiation doses reach a peak at 73.3 years, at which point the dose is 0.334 mrem/yr per pCi/g of initial plutonium contamination. Area 13 is divided into six contaminated strata, which range in plutonium activity from 14,000 pCi/g in stratum six to 36 pCi/g in stratum one. For year 73.3, the calculated doses would, therefore, be 4680 mrem/yr at stratum six and 12 mrem/yr at stratum one.

Results from the generic scenario were used to analyze compliance of the residential-farmer and industrial-worker scenarios with DOE standards. DOE Order 5400.5 states that the effective dose equivalent (whole body dose from internal and external radiation) to the public should not exceed 100 mrem/yr; this limit would apply to the residential-farmer. At year 73.3, the doses at four of the six Area 13

strata exceed this limit. The *DOE Radiological Control Manual* states that the effective dose equivalent to a worker should not exceed 5 rem/yr. At year 73.3 (or any other year), none of the doses calculated for Area 13 strata exceed this limit.

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ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ALARA	as low as reasonably achievable
Am	Americium
AMAD	Activity Median Aerodynamic Diameter
BECAMP	Basic Environmental Compliance and Monitoring Program
CFR	Code of Federal Regulations
Ci	Curie
DCF	Dose Conversion Factor
DOE	U.S. Department of Energy
EA	Environmental Assessment
EPA	U.S. Environmental Protection Agency
FUSRAP	Formerly Utilized Sites Remedial Action Program
GI	gastrointestinal
GMX	Gadgets, Mechanics, and Explosives
ICRP	International Commission on Radiological Protection
ID	Integrated Demonstration
MMAD	Mass Median Aerodynamic Diameter
NAEG	Nevada Applied Ecology Group
NAFR	Nellis Air Force Range
NAPCA	National Air Pollution Control Administration
NTIS	National Technical Information Service
NTS	Nevada Test Site
NV	DOE Nevada Field Office
NVO	DOE Nevada Operations
Pu	Plutonium
RD&D	Research, Development, and Demonstration
REECo	Reynolds Electrical & Engineering Company, Inc.
RESRAD	Computer Code for determining RESidual RADioactive material guidelines for soil
SFMP	Surplus Facilities Management Program
TRC	Test Range Complex
TTR	Tonopah Test Range
U	Uranium
US	United States
YMP	Yucca Mountain Project

1.0 Introduction

1.1 Nevada Test Site Background

1.1.1 Safety Shot Program

Safety shot tests were performed at the Nevada Test Site (NTS) as part of the United States (US) nuclear weapons program because of concerns by the Atomic Energy Commission and US military organizations about the safety of nuclear weapons in storage, handling, transport, and accident situations. The safety shots were performed by detonating a chemical explosive near arrangements of plutonium and/or uranium (Dunaway and White, 1974). The safety aspect was the prevention of accidental fission reactions. Benefits of the safety shot tests were seen in plane accidents at Palomares, Spain, and Thule Air Force Base, Greenland, which involved nuclear weapons and no significant fission reactions. As a consequence of these safety shots, the NTS and surrounding areas are contaminated and humans are exposed to potential health risks. Safety shots were performed aboveground from 1954 to 1963 (Bloom and Martin, 1978) before being moved underground.

Safety shots should be distinguished from the nuclear shots performed at NTS. Nuclear shots tested fission ability and other aspects of the weapons, while the safety shots tested the ability not to fission.

1.1.2 Nevada Applied Ecology Group

The Nevada Applied Ecology Group (NAEG) was formed in July 1970 with Planning Directive NVO-76 by the Department of Energy's (DOE's) Nevada Operations Office (NVO). The purpose of the NAEG was ". . . to coordinate the ecological, radiation monitoring and other environmental programs necessary to support continued nuclear testing activities; and to provide the mechanisms to effectively comply with requirements of the National Environmental Policy Act of 1969. . ." (Dunaway and White, 1974). The NAEG objectives were to identify areas of contamination, determine concentrations in the ecosystem, quantify rates of environmental transport, evaluate the radiological dangers associated with plutonium, identify areas that need to be remediated, and develop remediation technologies (Dunaway and White, 1974).

1.1.3 Problem Description

1.1.3.1 Radionuclides Present

The main radionuclides studied by the NAEG were plutonium (Pu) and americium (Am). Plutonium dispersed as a result of the safety shots consists of Pu-238, Pu-239, Pu-240, and Pu-241. Other radionuclides present are daughter products of the plutonium isotopes. Americium-241 is present in significant amounts because of decay of Pu-241, which has a half-life of 14.4 years. Uranium-235 is also present at some sites because of safety shots performed with uranium (U).

1.1.3.2 Safety Shot Sites

The safety shot sites studied by the NAEG are the Gadgets, Mechanics, and Explosives (GMX) site in Area 5 of NTS, Plutonium Valley in Area 11 of NTS, Project 57 in Area 13 of the Nellis Air Force Range (NAFR), and the Roller Coaster sites (Double Track and Clean Slate 1, 2, and 3) on the Tonopah Test Range (TTR). The location of the safety shot sites is shown in Figure 1-1 (Leavitt, 1974). The sites NTS, TTR, and NAFR are collectively known as the Test Range Complex (TRC); however, the term "NTS" is used in this study to refer to the general area of the safety shot sites on the TRC. Note the location of Las Vegas to the southeast of the TRC (see Figure 1-1).

Information is given in Table 1-1 on site areas, total inventories of plutonium, and number of shots performed at the sites (Martin and Bloom, 1980).

1.2 Land-Use Scenarios, Environmental and Exposure Pathways

1.2.1 Land-Use Scenarios

The scenario most likely for the present is the industrial-worker scenario, which involves possible exposure of a worker on the site. Activities presently conducted on the safety shot sites support DOE's plans to clean up the sites. DOE personnel at risk could be performing tasks such as surveying, sampling, and monitoring, or remediation activities such as removing surface soil and packaging the soil into containers. Another scenario currently possible is the intruder scenario; the intruder is someone that trespasses on the site.

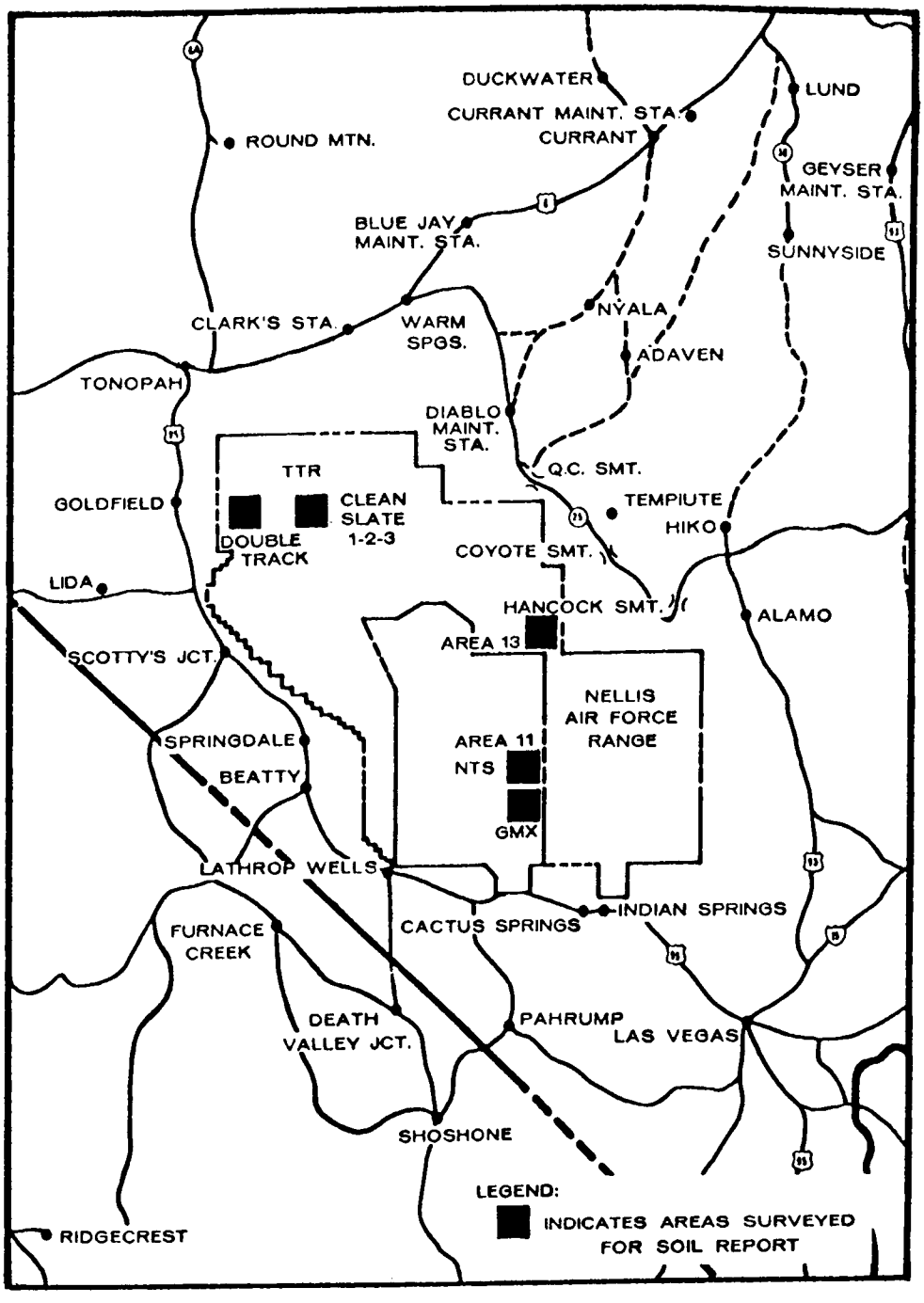


Figure 1-1: Location of the safety shot sites on the Test Range Complex

Source: Leavitt, V. D., 1974, Soil Surveys of Five Plutonium-Contaminated Areas on the Test Range Complex in Nevada, in *The Dynamics of Plutonium in Desert Environment*, P. B. Dunaway and M. G. White (Eds.), USAEC Report NVO-142, pp. 21-28, Nevada Operations Office, NTIS.

Table 1-1: **Safety shot site areas, plutonium inventories, and shots**

Site Location	Area (m^2)	Total Pu-239,240* (Ci)	No. of shots
Area 13	4,017,000	46 ± 9.0	1
Area 5 (GMX)	125,300	1.5 ± 0.19	22
Double Track	179,000	3.6 ± 0.95	1
Clean Slate 1	177,100	4.2 ± 1.2	1
Clean Slate 2	470,500	17 ± 3.7	1
Clean Slate 3	1,732,000	37 ± 5.4	1
Area 11	4,830,900	36 ± 4	4

* Mean ± standard error (SE); $SE = s/(n)^{1/2}$, where n is the number of samples

Source: Martin, W. E., and S. G. Bloom, 1980, Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man, in *Transuranic Elements in the Environment*, W. C. Hanson (Ed.), pp. 459-512, USDOE Report, DOE/TIC-22800.

A variety of land-use scenarios could occur in the future. An industrial-worker scenario, such as that previously mentioned, would still be possible. If NTS was released to the public, depending on the conditions of release, a recreational, residential, agricultural, industrial, or combination of these scenarios could occur. Recreational scenarios would include hiking, riding motorcycles, or driving four-wheel-drive vehicles. A residential scenario consists of someone living at the site. If a resident was growing crops or raising livestock, the residential scenario would be combined with an agricultural scenario (residential-farmer scenario). A strictly agricultural scenario would mean that only agriculture is taking place at the site, with no residence.

1.2.2 Environmental and Exposure Pathways

A diagram of the environmental and exposure pathways possible for a radioactively contaminated site is given in Figure 1-2 (Yu et al., February 1992). All of the pathways in Figure 1-2 are possible at NTS. Exposure to the human receptor can occur by external radiation or internal radiation. The two means of internal radiation are inhalation and ingestion. The probabilities of exposure by external radiation, inhalation, or ingestion are dependent on the land-use scenarios and environmental pathways likely for each land-use. Internal exposure by inhalation or external exposure can occur regardless of the scenario considered. Radionuclides present in the air because of resuspension can lead to internal exposure by inhalation and external exposure. Radionuclides on the ground surface also contribute to the external exposure. (next page)

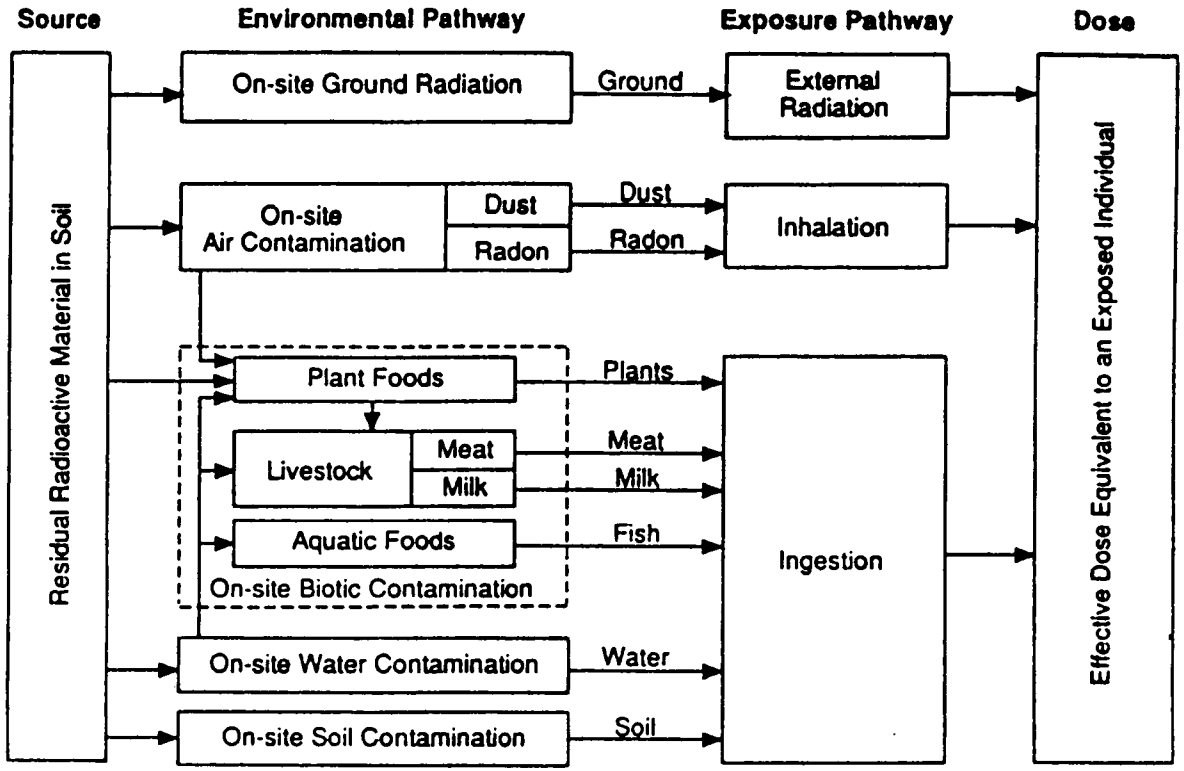


Figure 1-2: Environmental and exposure pathways for a radioactively contaminated site

Source: Yu, C., A. J. Zielen, J. J. Cheng, L. G. Jones, C. O. Loureiro, Y. C. Yuan, A. Wallo III, and W. A. Williams, February 1992, *Manual for Implementing Residual Radioactive Material Guidelines*, Department of Energy, Argonne National Laboratory.

Internal exposure by ingestion is possible for all scenarios, but it is most likely to occur in a residential scenario such as the residential-farmer scenario.

Possible items of ingestion for a residential-farmer are plants foods, meat and milk from livestock, drinking water, soil, and aquatic foods. Parts of NTS have fertile soil with the potential to support plant foods, and it is possible to graze livestock on the plants that grow naturally at NTS. Springs that could be a source of drinking water exist in the vicinity of the NTS. Ingestion of fish that live in the springs is possible but unlikely.

The most probable exposure pathways for the industrial-worker scenario are external exposure and internal exposure from inhalation.

1.3 Scope of Study

The RESRAD computer code, developed by Argonne National Laboratory for DOE, is used to calculate radiation doses from inhalation of plutonium at Area 13. RESRAD can calculate radiation doses to on-site residents, workers, and recreationists from RESidual RADioactive material. RESRAD calculates radiation dose by modeling environmental transport of the contaminant from the source to a receptor and using dose conversion factors (dose per unit intake of radionuclide).

The present land-use scenario considered in this study is the industrial-worker scenario. Various industrial-worker scenarios are very likely to occur because of

DOE plans to remediate the safety shot sites. The intruder scenario is also currently possible, but is not considered in this study.

The future land-use scenario considered in this study is the residential-farmer scenario. Depending on the conditions of release to the public, this scenario is not necessarily the most likely. The reason for consideration of this scenario is the potential to incur greater doses to the receptor than other scenarios; the residential-farmer scenario is usually considered the "worst case" scenario. In addition, Area 13 has potential for agriculture.

Because of results obtained by the NAEG Plutonium Transport and Dose Assessment Model, inhalation is the only mode of exposure considered in this paper. The NAEG Model was developed for determining dose to man in a typical ecosystem at NTS; it modeled environmental transport of plutonium and transport of plutonium within the human body. Studies by the authors of the NAEG model indicate that, for a residential-farmer scenario at NTS, inhalation accounts for approximately 100 % of the dose to lungs and approximately 95% of the dose to total body and bone (Martin and Bloom, 1980). For plutonium intake, lungs and bone are the critical organs. External dose was not considered in the NAEG model.

In the case of the industrial-worker, inhalation should account for even more than 95% of the dose to total body and bone; workers do not ingest agricultural products from the site.

The radiation doses calculated by RESRAD will be used to analyze the compliance of Area 13 with DOE standards. DOE Order 5400.5 (DOE, 1990) contains radiation standards for the public, and the *DOE Radiological Control Manual* (DOE, 1992) contains radiation standards for workers.

Based on a variety of factors, Area 13 was chosen as the site of study for this paper. These factors are briefly discussed in the following paragraphs.

The Roller Coaster sites Clean Slate 1, 2, and 3 and Area 13 are the safety shot areas which have potential for agriculture (Leavitt, 1974). The potential agricultural area of Clean Slate sites combined is about 5,000 acres, while that of Area 13 is about 2,560 acres. The 7,560 acres represent about two-thirds of the total area of the safety shot sites. Although ingestion is not considered in this study, the potential that an area has for agriculture makes it more likely to be used by a residential-farmer if released.

The highest concentration of plutonium is located in Area 11; it is 6,200 ± 2800 μCi/m^2. In comparison, the highest concentrations at Area 13 and the Roller Coaster Sites are 820 ± 340 and 2800 ± 1000 μCi/m^2, respectively. The

Clean Slate sites have the highest total plutonium inventory, followed by Area 13 and Area 11. Although Area 11 has no potential agricultural acres, it is a justifiable study area because of its high concentrations.

Area 13 was chosen for this study because of its high plutonium inventory, its potential for agriculture, and the abundance of data and knowledge that was made available by Dr. Tsuneo Tamura (Tamura, 1991-1994), member of the former NAEG, who did extensive studies on characteristics of plutonium at Area 13.

2.0 Area 13 Description

2.1 Area 13 Characterization

2.1.1 Stratum Areas and Activities

One safety shot (Project 57) was performed in Area 13; this shot was performed in 1957. Project 57 was a relatively large shot in comparison to safety shots at the other sites. 46 ± 9 Curies of Pu-239,240 activity existed over 6 strata of varying size as of November 1977 (Gilbert, 1977). A map of the main contaminated areas at Area 13 is given in Figure 2-1 (Tamura, 1975). An inner fence encloses about 250 acres and surrounds the 4 most highly contaminated strata (strata 3, 4, 5, and 6) in addition to parts of strata 1 and 2. An outer fence encloses about 1000 acres and surrounds the 6 strata analyzed by Gilbert (Gilbert et al., 1975, and Gilbert, 1977). Samples taken from the locations identified in Figure 2-1 are discussed in Section 2.1.4. Stratum areas and activity amounts are given in Table 2-1 (Gilbert et al., 1975, and Gilbert, 1977). The appearances of strata 1 and 2 in Figure 2-1 indicate that they would extend outside the outer fence; however, the areas analyzed by Gilbert for strata 1 and 2 were only those parts of the strata that were within the outer fence.

2.1.2 Site Environment

Leavitt (1974) performed a soil survey of the five safety shot areas at NTS. The surface soil at Area 13 is generally classified as gravelly sandy loam. Erosion by wind has removed the finer particles to create the gravelly surface known as desert

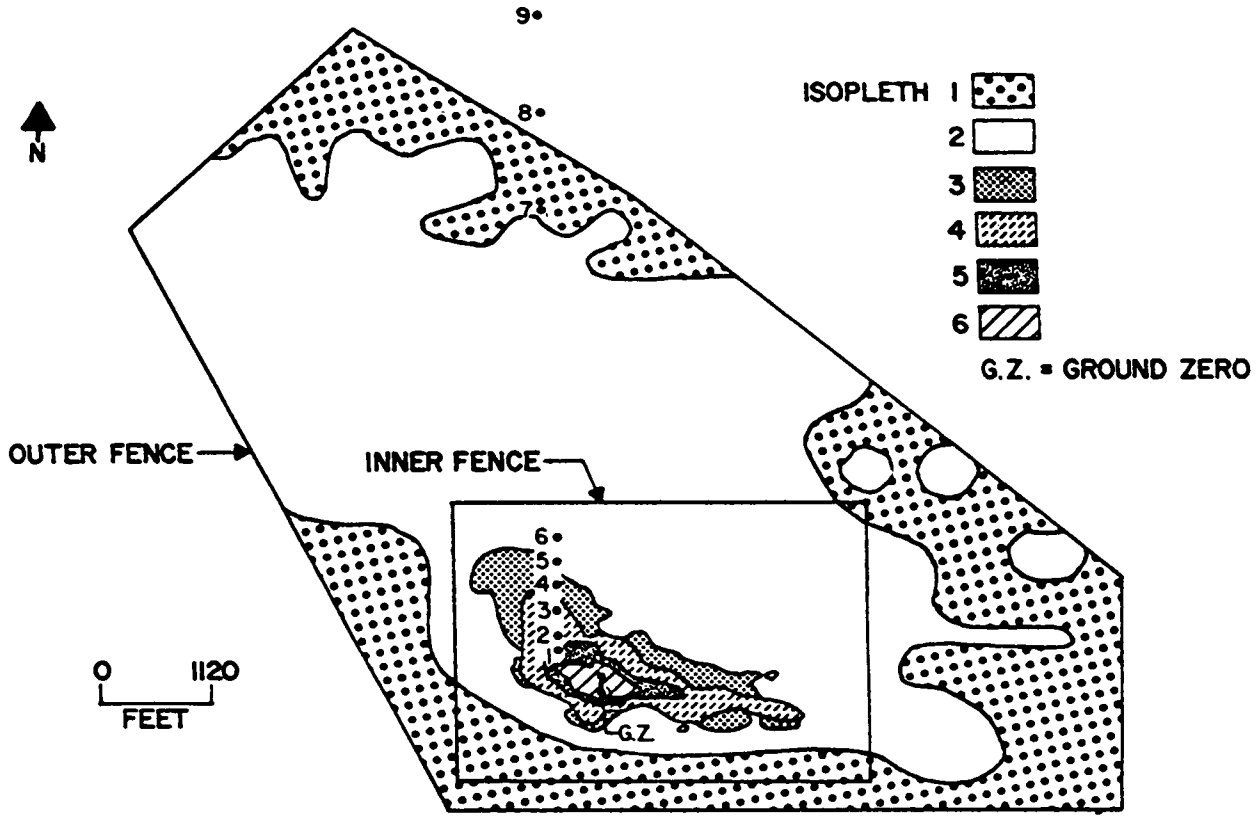


Figure 2-1: Area 13 stratum (isopleth) and sample locations

Source: Tamura, T., 1975, Characterization of Plutonium in Surface Soils from Area 13 of the Nevada Test Site, in *The Radioecology of Plutonium and other Transuranics in Desert Environments*, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-153, pp. 27-42, Nevada Operations Office, NTIS.

Table 2-1: Area 13 stratum areas and activities

Stratum	Stratum Areas		Pu-239,240*	Pu-239,240*	Estimated Inventory*	
	m^2	%	$\mu Ci/m^2$	nCi/g	Ci	%
1	1,245,000	31.0	1.9 ± 0.34	0.036 ± 0.0078	2.4 ± 0.42	5
2	2,547,000	63.4	5.8 ± 1.4	0.10 ± 0.025	15 ± 3.6	33
3	108,000	2.7	23 ± 4.3	0.40 ± 0.075	2.5 ± 0.46	5
4	74,000	1.8	54 ± 8.8	1.1 ± 0.15	4.0 ± 0.65	9
5	19,000	0.5	110 ± 19	2.4 ± 0.43	2.1 ± 0.36	5
6	24,000	0.6	820 ± 340	14 ± 6.4	20 ± 8.2	43

* Mean ± standard error (SE); SE = $s/(n)^{1/2}$, where n is the number of samples

Sources: 1) Gilbert, R. O., L. L. Eberhardt, E. B. Fowler, E. M. Romney, E. H. Essington, and J. E. Kinnear, 1975, Statistical Analysis of Pu-239,240 and Am-241 Contamination of Soil and Vegetation on NAEG Study Sites, in *The Radioecology of Plutonium and other Transuranics in Desert Environments*, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-153, pp. 207-216, Nevada Operations Office, NTIS.

2) Gilbert, R. O., 1977, Revised Total Amounts of $^{239,240}Pu$ in Surface Soil at Safety-Shot Sites, in *Transuranics in Desert Ecosystems*, M. G. White, P. B. Dunaway, and D. L. Wireman (Eds.), USDOE Report NVO-181, pp. 423-430, Nevada Operations Office, NTIS.

pavement. The desert pavement protects the surface from continual erosion. Area 13 contains approximately 2,560 potential agricultural acres; this value includes land area outside of the outer fence at Area 13. If water were available, this land could be cultivated for crops.

The plants at Area 13 consist of desert shrub at about 5–10 % plant density (Tamura, 1975). The dominant shrub is fourwing saltbush. The other dominant species of shrub at NTS are winterfat and galleta grass. Domestic livestock prefer these three types of plants to other species that exist at NTS. Area 13 has the potential to be used for grazing livestock (Leavitt, 1974).

Rainfall is approximately 4–8 inches per year (Tamura, 1975). Because most of this rain comes in short bursts, the majority is lost either by evapotranspiration or runoff versus permeation of the soil (DOE, Yucca Mountain Environmental Assessment (EA)). Springs exist in the vicinity of NTS that could be sources of drinking water.

2.1.3 Radionuclides Present

The plutonium isotopes present at Area 13 are Pu-238, Pu-239, Pu-240, and Pu-241. The majority of the plutonium is Pu-239; it is the main radionuclide of concern. Because of the nearly identical energies of the alpha particles emitted by Pu-239 and Pu-240, the activities of the two plutonium isotopes are generally reported as one number (Pu-239,240). Other radionuclides present are daughter products of the plutonium isotopes. U-234 is present from decay of Pu-238; U-235

is present from decay of Pu-239; U-236 is present from decay of Pu-240; and Am-241 is present from decay of Pu-241. Characteristics of the plutonium isotopes and their immediate daughter products are summarized in Table 2-2.

To comprehend the presence and relative amounts (amounts in terms of atoms or mass) of the plutonium isotopes, the method of production of plutonium can be examined. Because of the way plutonium is produced, in a given amount of plutonium, Pu-239 would account for the greatest amount, followed by Pu-240, and then Pu-241. Pu-239 and Pu-241 are the only fissionable types of plutonium. Plutonium can be formed in nuclear reactors or particle accelerators by bombarding natural uranium, U-238, with neutrons. U-239 is formed when U-238 absorbs a neutron. The new uranium isotope, U-239, undergoes beta decay and becomes Pu-239. U-239 has a half-life of 23.5 minutes. Pu-239 can then become Pu-240 or Pu-241 by absorbing one or two more neutrons, respectively. Another possible, but much less likely, way to produce Pu-240 is the phenomenon in which U-239 absorbs a neutron to become U-240, which undergoes beta decay to Pu-240.

The relative radioactivity of the plutonium isotopes can be determined from the initial, relative amounts (atoms or mass) of the isotopes and their respective half-lives. The relative radioactivity of Pu-239 and Pu-241 in a typical gram of plutonium is illustrated in Figure 2-2 (adapted from Fowler and Essington, 1974). The figure also illustrates the ingrowth of Am-241 activity because of decay of Pu-241. The original graph from Fowler and Essington did not explicitly include Pu-240. (next page)

Table 2-2: Characteristics of plutonium isotopes and daughter products

Radionuclide	Half-life (years)	Mode of Decay	Decay Energy (MeV)
Plutonium-238	87.7	Alpha	5.49
Plutonium-239	24,100	Alpha	5.15
Plutonium-240	6580	Alpha	5.16
Plutonium-241	14.4	Beta	0.02
Uranium-234 (from Pu-238)	2.46 E(5)	Alpha	4.77
Uranium-235 (from Pu-239)	7.04 E(8)	Alpha	4.40
Uranium-236 (from Pu-240)	2.39 E(7)	Alpha	4.48
Americium-241 (from Pu-241)	433	Alpha	5.48

Source: General Electric Company, 1989, *Nuclides and Isotopes*, 14th Edition, Nuclear Energy Operations, San Jose, California.

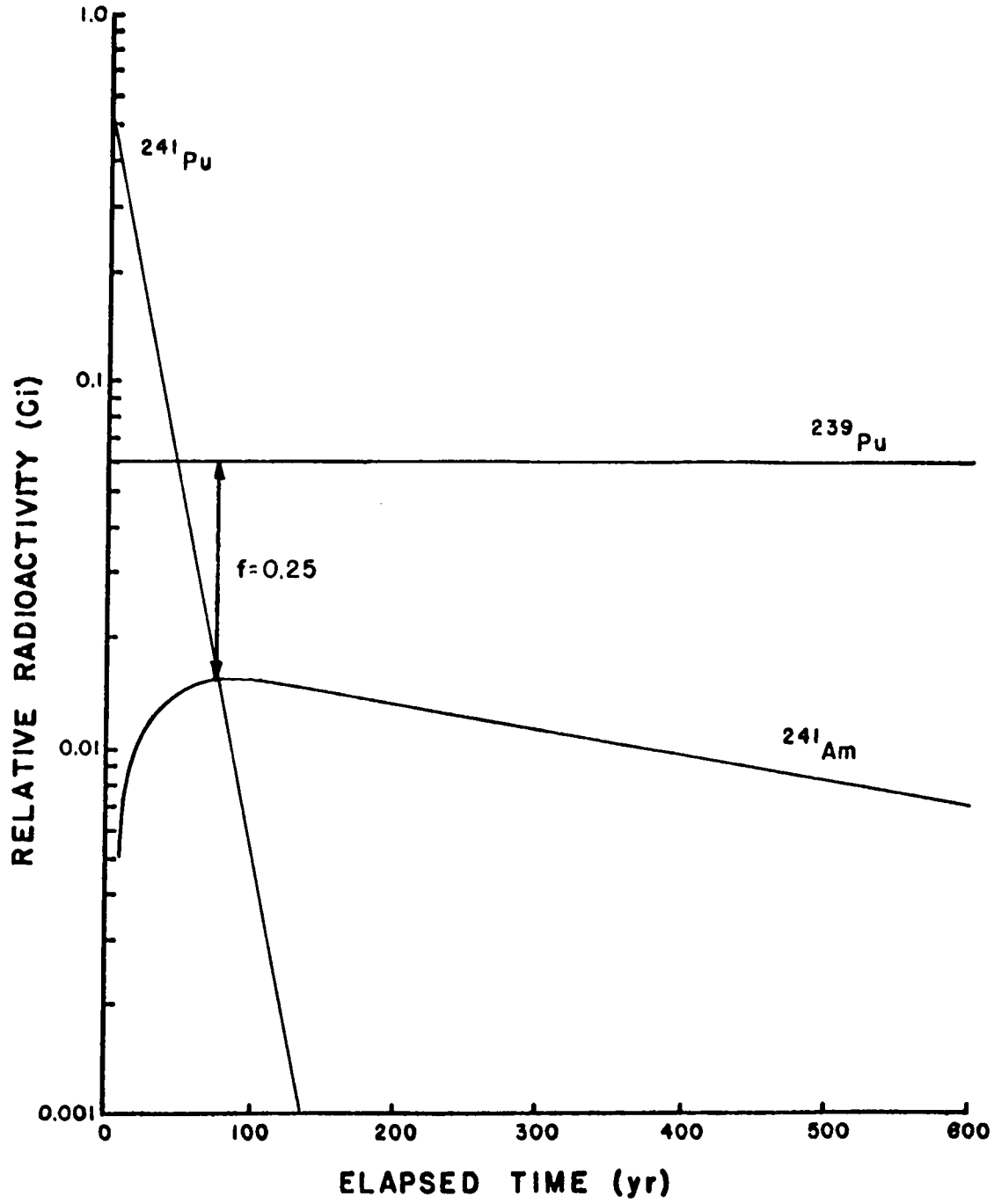


Figure 2-2: **Relative radioactivity of Pu-239, Pu-241, and Am-241 from plutonium**

Source: **Adapted from** Fowler, E. B., and E. H. Essington, 1974, Soils Element Activities for October, 1972 to September, 1973, in *The Dynamics of Plutonium in Desert Environment*, P. B. Dunaway and M. G. White (Eds.), USAEC Report NVO-142, pp. 7-16, Nevada Operations Office, NTIS.

Perhaps the Pu-240 activity in the original graph was included with the Pu-239 activity.

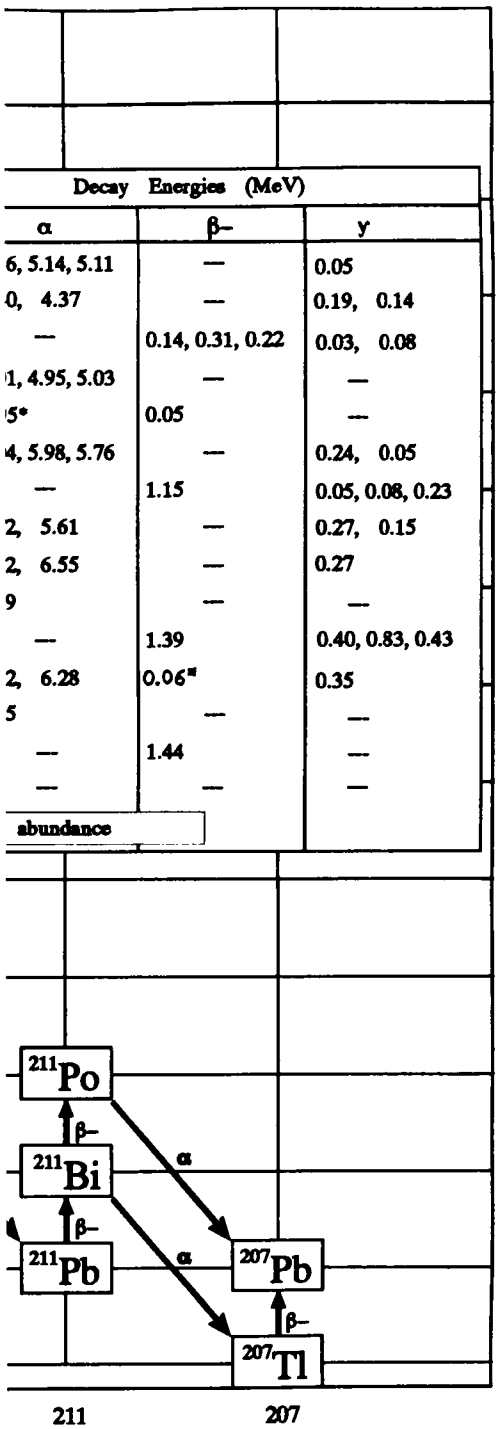
From Figure 2-2, the initial activity of Pu-241 is higher than that of Pu-239 by a factor of about 8.3. However, because the half-life of Pu-241 is only 14.4 years, its activity drops off rapidly while the activity of Pu-239 remains nearly constant. The activity of Am-241 increases as Pu-241 decays until the activity of Pu-241 equals the activity of Am-241, at which point a balance is reached between production of Am-241 from Pu-241 and decay of Am-241. At this point, which occurs at about 73.3 years, the activity of Am-241 reaches its peak activity, approximately 0.25 of Pu-239 activity.

The measured ratio of Pu-239 to Am-241 activity can vary according to site, sample, and depth. The average ratio at Area 13 computed from 154 soil samples was found to be 9.4 $\pm$ 0.14 (Gilbert et al., 1975). These soil samples were analyzed approximately 17 years after the safety shot at Area 13. The ratio of 9.4 is roughly consistent with the expected ratio for 17 elapsed years in Figure 2-2.

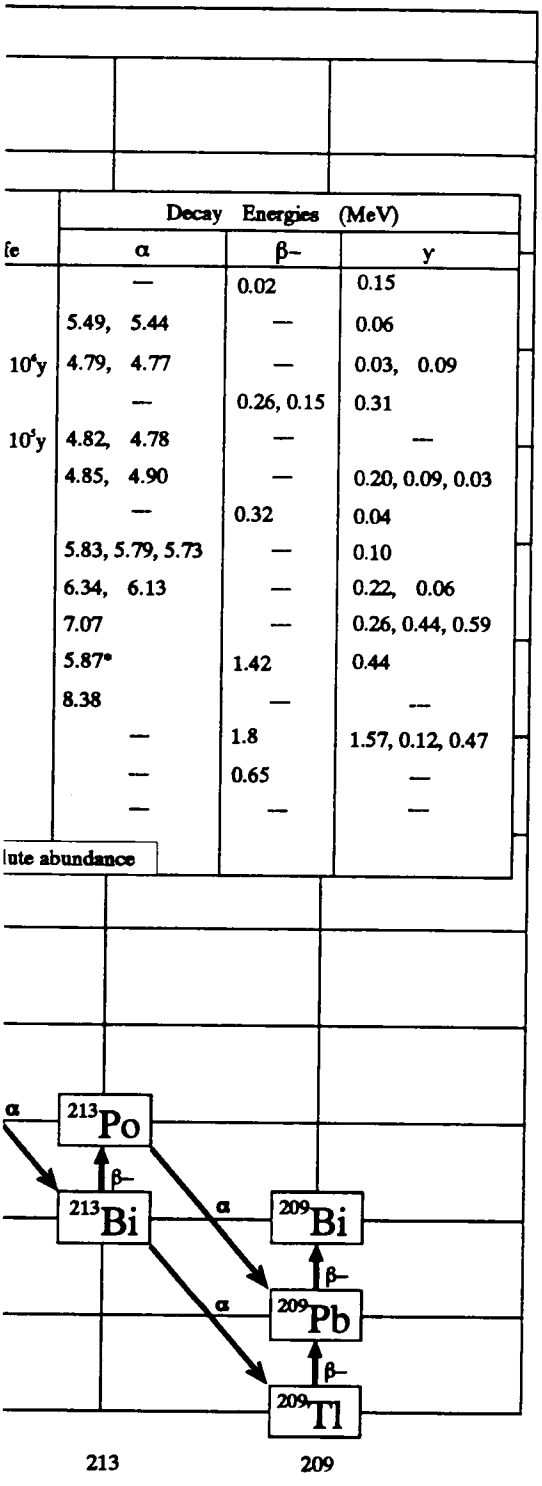
In this study, all Pu-240 activity is included with Pu-239 activity and is assumed to be Pu-239. Because the half-life of Pu-240 is less than Pu-239, assuming that the combined specific activity (activity/mass) of Pu-239 and Pu-240 is entirely Pu-239 specific activity appears to be a conservative assumption (i.e., including Pu-240 activity as Pu-239 activity assumes the total activity will remain for a longer period

of time). In addition, U-236, progeny of Pu-240, has a shorter half-life than U-235, progeny of Pu-239, while their alpha energies are nearly identical. Pu-241 and Am-241 activity is considered separately from Pu-239 and Pu-240 activity. It is also assumed that the initial activity of Pu-241 is 8.3 times the initial activity of both Pu-239 and Pu-240. This assumption is conservative because, according to Figure 2-2, the initial activity of Pu-241 is approximately 8.3 times the initial activity of only Pu-239 (assuming Pu-240 activity was not included with Pu-239 in Figure 2-2). Pu-238 is not considered in this study.

The full decay chains of Pu-239 and Pu-241 are given in Figure 2-3 and Figure 2-4, respectively (Kroodsma et al., 1993). The atomic number is plotted on the vertical axis and the mass number is plotted on the horizontal axis. Each decay chain illustrates all decays down to a stable element. Each radionuclide decays to another radionuclide by emitting an alpha or beta particle, and in the process may also emit gamma rays. The half-lives, decay modes, and decay energies are given for each radionuclide in the chain. Only decays that have intensities of approximately 10 % or more are listed; exceptions are noted with an asterisk (*). Data contained in Figure 2-3 and Figure 2-4 was obtained from the General Electric Company (1989), the Nucleon Lectern Associates, Inc. (1986), and the Chemical Rubber Company (CRC) Press (CRC, 1983).


Decay Energies (MeV)
α
β–
γ
6, 5.14, 5.11
—
0.05
0, 4.37
—
0.19, 0.14
—
0.14, 0.31, 0.22
0.03, 0.08
1, 4.95, 5.03
—
—
5*
0.05
—
4, 5.98, 5.76
—
0.24, 0.05
—
1.15
0.05, 0.08, 0.23
2, 5.61
—
0.27, 0.15
2, 6.55
—
0.27
9
—
—
—
1.39
0.40, 0.83, 0.43
2, 6.28
0.06#
0.35
5
—
—
—
1.44
—
—
—
abundance
211Po
β–
211Bi
β–
211Pb
α
α
207Pb
β–
207Tl
211
207

et al., 1993)



fe	Decay Energies (MeV) α	β−	γ
	—	0.02	0.15
	5.49, 5.44	—	0.06
10^4y	4.79, 4.77	—	0.03, 0.09
	—	0.26, 0.15	0.31
10^5y	4.82, 4.78	—	—
	4.85, 4.90	—	0.20, 0.09, 0.03
	—	0.32	0.04
	5.83, 5.79, 5.73	—	0.10
	6.34, 6.13	—	0.22, 0.06
	7.07	—	0.26, 0.44, 0.59
	5.87*	1.42	0.44
	8.38	—	—
	—	1.8	1.57, 0.12, 0.47
	—	0.65	—
	—	—	—

lute abundance

ə et al., 1993)

2.1.4 Plutonium Distribution in the Soil Particle Size Fractions

Gilbert et al. (1975) determined Pu-239,240 concentrations versus surface soil depth at the safety shot sites of NTS. For Area 13, approximately 17 years after deposition, about 93% of the Pu-239,240 resided in the top 5 cm of soil.

In an effort to further characterize the location of the plutonium, Tamura (1975) performed particle size separation and analysis for nine surface soil samples at Area 13. Each particle size fraction (or range) was analyzed for plutonium activity content (activity per gram of particles in that size fraction) and percentage of total soil plutonium activity. To calculate the percentage contribution to total soil plutonium, Tamura used the plutonium content of the particle size fractions and the weight contribution of the size fraction to soil. The reader is referred back to Figure 2-1 for the locations where the nine samples were obtained from Area 13.

Particle size distribution of the nine samples in percentage by weight is summarized in Table 2-3. The numbers show that the soils are high in sand content (2000 - 53 μm) and low in clay content (<2μm). More detail on particle size distribution in percentage by weight can be found in the original source by Tamura (1975).

The plutonium content of the particle size ranges and the contribution of these size ranges to the total plutonium activity is given in Table 2-4 for samples 1 through 7. The 20 - 5 μm medium silt size range has the highest plutonium concentration for

Table 2-3: Particle size distribution expressed in percentage by weight for nine surface soil samples from Area 13

Size Range (μm)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9
Gravel > 2000	1.60	6.80	10.35	7.04	10.08	8.50	3.51	3.55	3.47
Sand 2000 - 53	80.46	75.40	74.45	74.60	62.58	60.57	87.66	86.93	78.53
Silt 53 - 2	13.76	13.60	11.72	15.02	23.30	26.94	6.07	8.36	14.11
Clay < 2	3.74	3.10	1.89	3.28	3.34	4.53	2.72	1.30	3.90
TOTAL	99.56	98.90	98.41	99.94	99.30	100.54	99.96	100.14	100.01

Source: Tamura, T., 1975, Characterization of Plutonium in Surface Soils from Area 13 of the Nevada Test Site, in *The Radioecology of Plutonium and other Transuranics in Desert Environments*, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-153, pp. 27-42, Nevada Operations Office, NTIS.

Table 2-4: Plutonium content in the size fractions and contribution of the size fractions to total plutonium

Sample Number	Activity*	2000-840 µm	840-250 µm	250-125 µm	125-53 µm	53-20 µm	20-5 µm	5-2 µm	< 2 µm
1	A	123	114	606	7386	37,341	47,852	9052	2872
	B	4	30	116	1698	2864	1875	196	100
	C	0	0.4	2.4	24.5	41.3	27.0	2.8	1.4
2	A	52	26	306	2563	20,609	6859	1384	1360
	B	4	7	70	460	1447	284	34	42
	C	0.2	0.3	3.0	19.6	61.6	12.1	1.4	1.8
3	A	27	32	29	950	11,084	3968	992	896
	B	2	7	6	186	673	139	21	17
	C	0.2	0.7	0.6	17.7	64.0	13.2	2.0	1.6
4	A	22	24	12	14	5824	1672	256	144
	B	1	5	3	3	505	62	7	5
	C	0.2	0.9	0.4	0.5	85.4	10.5	1.2	0.8
5	A	56	2	2	85	3074	637	92	48
	B	4	1	0	14	268	61	5	2
	C	1.1	0.1	0	4.0	75.9	17.2	1.3	0.4
6	A	9	1	4	6	1936	408	44	536
	B	1	0	1	1	199	42	3	24
	C	0.2	0.1	0.2	0.4	73.4	15.6	1.0	9.0
7	A	0	2	3	2	328	512	24	10
	B	0	1	1	1	13	7	0	0
	C	0	2.4	4.0	1.8	58.6	30.8	0.9	1.3

* A = Plutonium Content (dpm/g) of Particles in Size Fraction
B = Activity Contribution (dpm/g) of Size Fraction to 1 Gram of Soil
C = Percentage Contribution of Activity in Size Fraction to Soil

Source: Tamura, T., 1975, Characterization of Plutonium in Surface Soils from Area 13 of the Nevada Test Site, in *The Radioecology of Plutonium and other Transuranics in Desert Environments*, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-153, pp. 27-42, Nevada Operations Office, NTIS.

samples 1 and 7. The 53 - 20 μm coarse silt size range has the highest concentration for all other samples. The 53 - 20 μm size range contributes the most to total plutonium in all samples. Even though its plutonium concentration is relatively lower for samples 1 and 7, the 53 - 20 μm size range contributes more to total plutonium than the 20 - 5 μm range because of its relatively higher weight percentage.

A possible explanation for the concentration of plutonium in the medium silt and coarse silt fractions lies in the surface area of the size fractions. As the particle sizes become smaller, the surface area of the particles per gram becomes larger. Because plutonium adsorbs to the surface of the soil particles, one would expect more surface area to be available to the plutonium for the smaller particles. This seems to be true to a point. As the particle sizes become very much smaller, as is the case with clay, the movement of the plutonium between soil particles is somewhat impeded. The medium and coarse silt sizes may have the optimum size to surface area ratio.

Sample 6 is unique with respect to its contribution to total plutonium by the clay size range and its clay weight percentage. The plutonium contribution in samples 1 through 5 and 7 ranges from 0.4 to 1.8 % while the contribution in sample 6 is 9.0 %. Sample 6 has the highest clay content of all the samples. (next page)

A possible explanation of this uniqueness could be that contaminated clay particles have been carried to the general area of sample 6 by water runoff and wind erosion of adjacent areas (Tamura, July 1992).

3.0 Plutonium Resuspension

Several methods that have been used to model resuspension at NTS are discussed in this chapter: the resuspension factor exponential formulas, the wind erosion power-laws, and the mass loading factor formula. The mass loading factor is used by both the NAEG Model and RESRAD.

3.1 Resuspension Factor

The resuspension factor approach is normally used only for modeling resuspension over fresh surface deposits of contamination. The resuspension factor, K, is equal to

$$K = \frac{Air\ concentration\ (Ci/m^3)}{Surface\ deposition\ (Ci/m^2)}$$

K has been measured in the approximate range of 1 E(-5) to 1 E(-11) m^{-1}. Martin and Bloom (1980) state that the resuspension factor varies with time and depends on such environmental conditions as wind speed and direction, rainfall, and any other conditions that would affect the aerodynamics of the soil surface. The resuspension factor is also dependent on the aerodynamics of the particles containing plutonium and their tendencies toward saltation, creep, and resuspension. Methods using this factor do not take into account the geometrical configuration of the source or the particle size distribution (Anspaugh, 1974).

The air concentration of a freshly deposited surface contaminant will decrease over

time largely because the mixing of the contaminant within the top layers of soil allow less of it to be available for resuspension. One way of modeling this decrease with time is the use of a single exponential function. Half-times ranging from 35 to 70 days have been used with this type of model (Langham, 1971, and Wilson et al., 1960). The problem with the single exponential function model is that it can be used with reasonable accuracy for only a short period of time following deposition.

The resuspension factor can be used to approximate resuspension over aged sources if the resuspension factor is measured over the aged source instead of when the source was fresh. Anspaugh (1974) used two types of measurements to come up with two different values for the resuspension factor at the GMX site of Area 5. One value was 3 E(-10) m^{-1} and the other was 2 E(-9) m^{-1}. These two different values demonstrate that use of this method can result in uncertainties. However, it can still serve as an order of magnitude estimation of resuspension over an aged source.

Another method used to model resuspension was developed by Anspaugh et al. (1975) in which the resuspension factor decreases as a function of time from 1 E(-4) to 1 E(-9)

$$K = 10^{-4} e^{-k(t)^{1/2}} + 10^{-9}$$

where k = 0.15 $day^{-1/2}$ and t = time from deposition in days. (next page)

This predictive model has been reasonably compared with measured values of K at NTS.

3.2 Wind Erosion Power-Law

Another type of model used for resuspension is the power-law formula

$$C_a = RU^n$$

where C_a is the air concentration (μCi/m^3), U is the wind velocity, and R and n are empirical constants derived from the data. Shinn and Anspaugh (1975) applied this model to NTS and derived n=2.1. Sehmel and Orgill (1973) derived n=2.1 for plutonium resuspension at Rocky Flats. Martin and Bloom (1980) found that n=2.1 for calcium molybdate resuspension at Hanford. A different result of n=6.4 was obtained by Shinn and Anspaugh (1975) for a plowed field in Texas. This suggests that a value of about 2 is appropriate for n as long the surface is undisturbed. The value of R is site-specific and must be found by taking at least one measurement of resuspension and wind speed.

3.3 Mass Loading Factor

The mass loading factor model is used in both the NAEG model and RESRAD. This model makes use of the mass loading factor, mass of soil per volume of air (its units are usually μg/m^3). The model is based on the assumption that the specific activity of dust particles in the air approximates the activity of the contaminated soil.

(next page)

To find the air concentration, the mass loading factor is multiplied by the soil concentration:

$$\textit{Air Concentration}(C i / m^3\ \textit{air}) = \textit{Mass Loading Factor}(g\ \textit{soil} / m^3\ \textit{air}) \times \textit{Soil Concentration}(C i / g\ \textit{soil})$$

3.3.1 Values for the Mass Loading Factor

1966 data by the National Air Pollution Control Administration (NAPCA) give mass loading factors for 217 urban and 30 nonurban stations. The annual arithmetic averages for the urban stations varied from 33 $\mu g/m^3$ for St. Petersburg, Florida to 254 $\mu g/m^3$ for Steubenville, Ohio. The mean arithmetic average for the urban stations was 102 $\mu g/m^3$. The averages for the nonurban stations varied from 9 $\mu g/m^3$ for White Pine County, Nevada, to 79 $\mu g/m^3$ for Curry County, Oregon. The mean arithmetic average for the nonurban stations was 38 $\mu g/m^3$.

Anspaugh (1974) has measured a mass loading factor of 70 $\mu g/m^3$ at the GMX site of Area 5. Anspaugh has suggested that a mass loading factor of 100 $\mu g/m^3$ be used for predictive purposes at NTS; this value is used in the NAEG model.

3.3.2 Application of the Mass Loading Model

The mass loading model is appropriate for aged sources such as the safety shot sites in which the contamination has been given time to mix with the surface soil. For a fresh deposit, the contaminant has not been given sufficient time to mix, and the specific activity in the air would not be a good estimate of the soil activity. This model should not be used for fresh deposits (Anspaugh, 1974).

The application of the mass loading factor to nuclear shot sites may not be appropriate. A study at Nuclear Site 201 found that disturbing the soil pavement surface by hand raking doubled the mass loading factor but increased the plutonium air concentration by a factor of 27 (Shinn and Homan, 1985). One explanation of this could be that the heat of the nuclear shot melted the sandy surface into a partially glass surface, stabilizing the concentration of plutonium. When the glassy surface is broken up by raking, this might not increase mass loading by much, but it could greatly increase the air plutonium concentration.

Situations exist where use of the mass loading factor could become difficult. Any activity on the soil such as agricultural cultivating or vehicular traffic could temporarily elevate the mass loading factor, complicating an effort to use the model.

The application of this model to safety shot sites at NTS would be difficult if the distribution of plutonium among the size fractions and the particle size distribution of the aerosol were taken into account. Measurements by Anspaugh (1974) at the GMX site of Area 5 taken with high-volume cascade impactors found an Activity Median Aerodynamic Diameter (AMAD) of 3.0 μm and a total Mass Median Aerodynamic Diameter (MMAD) of 1.7 μm. The AMAD is the diameter of a unit density sphere with the same terminal settling velocity in air as the aerosol particle whose activity is the median for the entire aerosol. For MMAD, the same definition applies, except for mass instead of activity. For several dry, sparsely vegetated

locations in the West, nearly all of the total mass concentration was contained in the range of 0.7 to 15 μm (Shinn and Anspaugh, 1975). The medium silt size (20 - 5 μm) at Area 13 has the highest activity per gram for particles in its size fraction for samples 1 and 7 (Tamura, 1975). For the remainder of samples, the coarse silt size (53 - 20 μm) has the highest activity per gram for particles in its size fraction; however, particles in the coarse silt size are not likely to be resuspended.

3.3.3 Soil Plutonium Index

To account for the different associations of plutonium with the particles sizes and the potential for resuspension of the size ranges, as well as lung deposition, Tamura (1977) defined the soil plutonium index. The soil plutonium index (SI) is defined as the product of the soil activity factor (SA), the lung depositional factor (LD), and the resuspendible activity factor (RA):

$$SI = SA \times LD \times RA$$

The soil activity factor is the ratio of the percent of total soil activity contained within a size range to the percent of total soil mass contained within that range; this ratio represents the activity in a gram of particles in that size range. The lung depositional factor is the percent of inhaled particles in a size range that are deposited in the pulmonary region of the lung. The resuspensible activity factor is the percentage of particles in a size range that have the potential to be suspended as aerosol. Table 3-1 lists data from Area 13 for these parameters and calculates a soil plutonium index.

Table 3-1: Parameter data for calculation of soil plutonium index

Size Range μm	Mass Fraction	Activity Fraction	Soil Activity Factor (SA)	Depositional Factor (LD)	SA x LD	Resuspendible Fraction	Soil Pu Index
<2	0.04	0.03	0.75	0.40	0.30	1	0.30
2 to 5	0.03	0.04	1.33	0.12	0.16	1	0.16
5 to 125	0.43	0.92	2.19	0.03	0.07	1	0.07
							Total - **0.53**

Source: Tamura, T., 1977, Plutonium Association in Soils, in *Transuranics in Natural Environments*, Symposium Proceedings, Gatlinburg, Tennessee, Oct. 5-7, 1976, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-178, pp. 97-114, Nevada Operations Office, NTIS.

Tamura also mentions the importance of other factors that would affect resuspension, but were not accounted for in the soil plutonium indices, such as soil erodiblity, plutonium solubility, and surface roughness.

3.3.4 EPA Enrichment Factor

The U.S. Environmental Protection Agency (EPA) (1977) suggests the use of an enrichment factor, which is the ratio of specific activity of aerosol (pCi/g) to the average activity of soil (pCi/g). The EPA method for calculating the enrichment factor involves the summation of the products of g_i and f; g_i is the ratio of the fraction of the total activity contained within the size increment i to the fraction of the total mass in the size, and f is the fraction of the airborne mass within each increment of particle size in the air.

Several basic similarities and differences exist between Tamura's method and the EPA method: (1) EPA's g_i has the same definition as Tamura's soil activity factor; (2) EPA considers the actual amount of suspension for each particle range instead of the resuspension ability; and (3) the EPA method does not account for lung deposition.

Tamura's method can be modified with the EPA method if f is substituted for Tamura's resuspendible fraction. Anspaugh (1974) measured a MMAD of 1.7 μm at the GMX site of NTS. Assuming the MMAD is similar for all NTS sites, this would provide us a rough estimate for size resuspension at Area 13. Referring to the size

ranges in Table 3-1, about 50 % of suspended mass would be in the <2 μm range and about 50 % of suspended mass would be in the combined 2 - 5 μm and 5 - 125 μm ranges. We will assume the 2 - 5 μm and 5 - 125 μm ranges each have 25 % of the mass.

An EPA enrichment factor and a "modified" soil plutonium index are calculated in Table 3-2. The derived enrichment factor, 1.3, means that for Area 13, the specific activity of aerosol could be approximately a factor of 1.3 greater than the average activity of soil. The modified soil plutonium index, 0.21, is approximately half of Tamura's soil plutonium index. Tamura's value is greater because of the relative conservatism of his resuspendible fraction when compared to EPA's factor f, resuspended fraction.

Values for the enrichment factor and the modified soil plutonium index can vary according to the data used. Another calculation was made using Tamura's particle size distribution and plutonium distribution data from NVO-153 (see Tamura, 1975). In addition, a particle size range of 5 to 20 μm is substituted for the 5 to 125 μm range because of observations of Shinn and Anspaugh (1975) that for several dry, sparsely vegetated locations in the West, including NTS, nearly all of the total mass concentration is contained in the range of 0.7 to 15 μm. The data and results for the calculation are given in Table 3-3. The enrichment factor for this calculation is 2.0. The modified soil plutonium index for this calculation, 0.22, is not significantly different than the previously calculated value of 0.21.

Table 3-2: Parameter data for calculation of EPA enrichment factor, *modified* soil plutonium index

Size μm	Mass Fraction	Activity Fraction	Soil Activity Factor or g_1	f: Suspension Fraction	SA(g_1) X f	Depositional Factor (LD)	SA(g_1) x f x LD
<2	0.04	0.03	0.75	0.50	0.38	0.40	0.15
2 to 5	0.03	0.04	1.33	0.25	0.33	0.12	0.04
5 to 125	0.43	0.92	2.19	0.25	0.55	0.03	0.02
					Total - **1.3**		Total - **0.21**

Source: Tamura, T., 1977, Plutonium Association in Soils, in *Transuranics in Natural Environments*, Symposium Proceedings, Gatlinburg, Tennessee, Oct. 5-7, 1976, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-178, pp. 97-114, Nevada Operations Office, NTIS.

Table 3-3: Parameter data for calculation of EPA enrichment factor, *modified* soil plutonium index

Size μm	Mass Fraction	Activity Fraction	Soil Activity Factor or g_1	f: Suspension Fraction	SA(g_1) X f	Depositional Factor (LD)	SA(g_1) x f x LD
<2	0.039	0.023	0.59	0.50	0.30	0.40	0.12
2 to 5	0.028	0.015	0.54	0.25	0.14	0.12	0.02
5 to 20	0.028	0.18	6.4	0.25	1.6	0.05	0.08
					Total - **2.0**		Total - **0.22**

Source: Tamura, T., 1975, Characterization of Plutonium in Surface Soils from Area 13 of the Nevada Test Site, in *The Radioecology of Plutonium and other Transuranics in Desert Environments*, M. G. White and P. B. Dunaway (Eds.), USERDA Report NVO-153, pp. 27-42, Nevada Operations Office, NTIS.

3.3.5 Application of the Modified Soil Plutonium Index and the Enrichment Factor to Dose Assessments

The modified soil plutonium index can be used to calculate the amount of plutonium retained in the pulmonary region of the lung for a given average soil concentration and mass loading factor. The necessary calculation is shown in the following equation:

Amount of Plutonium Retained in the Lung (Ci/(m^3 of air inhaled)) =

average soil concentration (Ci/g) × mass loading factor (g/m^3) × (modified soil plutonium index)

For example, if the average soil concentration is 1 pCi/g and the mass loading factor is 100 μg/m^3, then a modified soil plutonium index of 0.21 would mean that, for each m^3 of air inhaled, the plutonium retained in the lung is
(1 E(-12) Ci/g) X (100 E(-6) g/m^3) X 0.21 = 2.1 E(-17) Ci.

We can compare this calculation with one that makes no adjustment for the different associations of plutonium with the particle size ranges and the fraction suspended of the particles size ranges. We will assume for this calculation that the aerosol has an AMAD of 1 μm; pulmonary deposition of aerosol with an AMAD of 1 μm is 0.23 (ICRP-19, 1972). If the average soil concentration is 1 pCi/g and the mass loading factor is 100 μg/m^3 (similar to the previous calculation),
(1 E(-12) Ci/g) X (100 E(-6) g/m^3) X 0.23 = 2.3 E(-17) Ci are retained in the lung for each m^3 of inhaled air. (next page)

For this comparison, the values of 2.1 E(-17) Ci and 2.3 E(-17) Ci do not vary significantly.

The modified soil plutonium index calculates the amount of plutonium retained in the pulmonary region of the lung. The usefulness of calculations of plutonium retained in the pulmonary region of the lung to whole body dose calculations is limited because contaminants are transported to the body fluids from all three regions of the respiratory tract: nasopharyngeal, tracheobronchial, and pulmonary. It is possible that the modified soil plutonium index could be expanded to include deposition in the nasopharyngeal and tracheobronchial regions.

If only the enrichment factor was considered, then some consideration for particle size deposition in the respiratory tract would still have to be made. Eckerman (1992) created a computer program that can calculate doses to organs of the body and to the whole body from inhalation of aerosol with a given AMAD. The computer program can calculate whole body doses according to ICRP-26 (1977) or ICRP-60 methodology. Doses to individual organs are the same regardless of whether ICRP-26 or ICRP-60 methodology is used. ICRP-26 calculations are referenced below, because DOE standards are still based on ICRP-26 methodology.

The dose conversion factors used in RESRAD were calculated for an AMAD of 1 μm. The AMAD was measured as 3 μm at the GMX site of NTS by Anspaugh

(1974). According to Eckerman's code, inhalation of Pu-239 aerosol with an AMAD of 1 μm would lead to a whole body dose of 8.33 E(-3) rem/Bq. Inhalation of Pu-239 aerosol with an AMAD of 3 μm would lead to a whole body dose of 6.65 E(-3) rem/Bq. If the enrichment factor of 1.3 for Area 13 was used with the dose for an AMAD of 3μm, the "enriched" dose would be 1.3 X 6.65 E(-3) = 8.6 E(-3) rem/Bq. The ratio of the enriched dose to the dose for an AMAD of 1 μm is 8.6/8.33=1.04. This ratio can be interpreted as follows: for a given average soil concentration and mass loading factor, the dose for a 3 μm AMAD aerosol with an enrichment factor of 1.3 would lead to a whole body dose a factor of 1.04 greater than the whole body dose for an aerosol of 1 μm AMAD without an enrichment factor (enrichment factor = 1). If the enrichment factor of 2.0 was used with the dose for an AMAD of 3 μm, the enriched dose would be 1.3 E(-2) rem/Bq, and the ratio of the enriched dose to the dose for a 1 μm AMAD would be 1.6.

3.4 Comparison of Mass Loading Factor and Resuspension Factor Methods

The objective of resuspension modeling with respect to this dose assessment is to enable the modeler to determine the concentration of plutonium in the air. Two of the methods discussed thus far, the resuspension factor method and the mass loading factor method, can be compared according to this purpose.

Over an aged source, the resuspension factor is calculated by using measurements of air concentration (Ci/m^3) and soil concentration (pCi/m^2 or pCi/g). The resuspension factor is defined as the ratio of air concentration to soil concentration,

and has units of m^{-1}. In order to determine air concentrations from the resuspension factor, one could first measure resuspension factors at a site, and use an average of these values as a base for calculations. The average resuspension factor is then multiplied by the soil concentration at a certain point to determine the air concentration at that point.

Data obtained by Anspaugh (1974) will be used in a rough example. Anspaugh calculated two resuspension factors for the GMX site of Area 5 using measurements of soil concentration (dpm/g) and air concentration ($\mu Ci/cm^3$); these values are 3 E(-10) m^{-1} and 2 E(-9) m^{-1}. The average of these two values is 1.2 E(-9) m^{-1}. If this average is used to back-calculate the air concentration at the two points the resuspension factor was calculated, the result is an overestimation of about 280 % at the point where the factor 3 E(-10) m^{-1} was measured and an underestimation of about 21 % at the point where the factor 2 E(-9) m^{-1} was calculated. In either case, the estimates of air concentration are within an order of magnitude of the measured value. Resuspension factors varying from 9.1 E(-11) m^{-1} to 5.4 E(-9) m^{-1} were calculated at NTS by Romney et al. (1987); the geometric mean and arithmetic average of these calculations are 2.9 E(-10) m^{-1} and 6.8 E(-10) m^{-1}, respectively. If the average of 6.8 E(-10) m^{-1} is used to calculate the air concentration at the two points of measurement by Anspaugh, the result is an overestimation of about 120 % at the point where the factor 3 E(-10) m^{-1} was measured and an underestimation of about 55 % at the point where the factor 2 E(-9) m^{-1} was measured. (next page)

These estimates are also within an order of magnitude of the measured values.

To calculate the air concentration of plutonium using the mass loading factor, the mass loading factor ($\mu g/m^3$) is multiplied by the soil concentration (pCi/g). Using this method, similar to the resuspension factor method, one would have to assume an average mass loading factor. Anspaugh measured the mass loading factor at the GMX site as 70 $\mu g/m^3$. If this value for the mass loading factor is used along with the measured soil concentrations from the GMX site to calculate air concentrations, the result is an overestimation of about 270 % at the point where the factor 3 E(-10) m^{-1} was measured and an underestimation of about 24 % at the point where the factor 2 E(-9) m^{-1} was calculated. Similar to the resuspension factor, the mass loading factor can be used to obtain air concentrations within an order of magnitude of measured values.

4.0 NAEG Model

4.1 Background

The NAEG Model was developed for determining the dose to "standard man" in a typical ecosystem at NTS; it modeled environmental transport of plutonium and transport of plutonium within the human body. W. E. Martin and S. G. Bloom are the first to work extensively on the model. J. R. Kercher and L. R. Anspaugh are other NAEG members to do extensive work with the model. Anspaugh has continued to work on the model at the Basic Environmental Compliance and Monitoring Program (BECAMP). Numerous others have also contributed to this model. The original model is called the NAEG model; most recent versions of the model are called the BECAMP model. Versions referenced and/or consulted for this paper are NAEG versions and are listed in Table 4-1.

NAEG model results show that inhalation is far more significant than ingestion at NTS with respect to radiation dose. Section 4.2 summarizes these results. Methodology for the NAEG model is described following the summary of results, and is only that part of the methodology that affects either inhalation or both inhalation and ingestion. For information on the methodology used to determine ingestion doses, the reader is referred to one of the NAEG model reports listed in Table 4-1. External dose was not considered in the NAEG model.

Table 4-1: NAEG model reports referenced and/or consulted

NAEG Model Report Title	Authors	Source	Date
NAEG Plutonium Study Modeling Program: Plutonium Transport and Dose Estimation Model	Martin, W. E., S. G. Bloom, and R. J. Yorde, Jr.	*The Dynamics of Plutonium in Desert Environments* (NVO-142)	1974
Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man	Martin, W. E., and S. G. Bloom	*Transuranics in Natural Environments* (NVO-178)	1977
The Effect of Variations in Source Term and Parameter Values on Estimates of Radiation Dose to Man	Bloom, S. G., and W. E. Martin	*Selected Environmental Plutonium Research Reports of the NAEG* (NVO-192)	1978
Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man	Martin, W. E., and S. G. Bloom	*Transuranic Elements in the Environment*	1980
Analysis of the NAEG Model of Transuranic Radionuclide Transport and Dose	Kercher, J. R., and L. R. Anspaugh	*The Dynamic of Transuranics and other Radionuclides in Natural Environments* (NVO-272)	1985

4.2 NAEG Model Results

Martin and Bloom (1977) concluded that, for the residential-farmer scenario, inhalation is the principal exposure pathway to standard man for Pu-239 and the critical organs concerning radiation dose are the lungs and bone. Results of this analysis are shown in Figure 4-1. Cumulative doses from Pu-239 to various organs of standard man are graphed as a function of time. Lungs and bone, out of all organs for which radiation dose criteria have been set by the International Commission on Radiological Protection (ICRP), received the highest dose after 70 years (25,550 days). The lymph nodes received a higher dose, but criterion for these organs have not been established by the ICRP. The ICRP concluded that irradiation of the lung is likely to be a more limiting factor than irradiation of the lymph nodes for insoluble radioactive particles (ICRP-30, 1981).

The doses were calculated per unit soil concentration for constant intake rates. The constant intake rates, with units of pCi/day, for inhalation and ingestion are 0.002 C_s and 0.19 C_s, respectively, where C_s is the average soil concentration of plutonium. The ratio of the ingestion rate to the inhalation rate is 95.

Results from the NAEG model study indicate that inhalation is responsible for approximately 100 percent of the plutonium burden in the lungs and 95 percent of plutonium burden in bone, liver, and kidney. These results are based on the assumption that the ratio of plutonium input via ingestion to that via inhalation is approximately 100 for NTS in the case of the residential-farmer scenario.(next page)

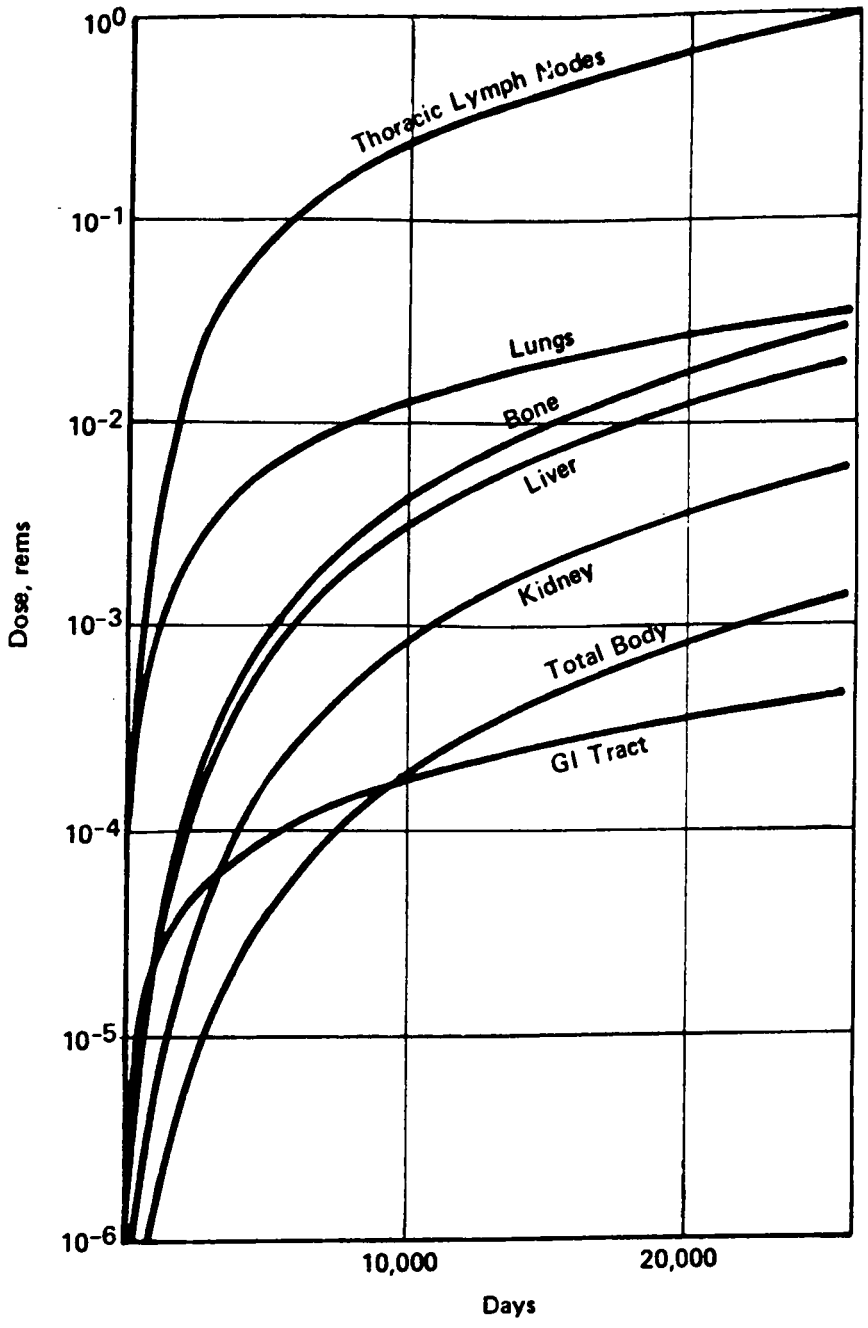


Figure 4-1: Predicted cumulative doses to organs of standard man from Pu-239

Source: Martin, W. E., and S. G. Bloom, 1977, Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man, in *Transuranics in Natural Environments*, M. G. White and P. B. Dunaway (Eds.), ERDA Report NVO-178, pp. 621-706, Nevada Operations Office, NTIS.

Fractions of plutonium organ burden in the bone, liver, and kidney because of chronic ingestion and inhalation are given in Table 4-2 (Martin and Bloom, 1977).

4.3 Mass Loading Model

To model resuspension of plutonium-contaminated soil and determine inhalation intake, the NAEG model uses the mass loading model. Martin and Bloom (1980) state the amount of plutonium inhalation as

$$A_m = B_m L_a C_s = 0.002\ C_s$$

where

A_m = plutonium inhalation rate for man (pCi/day)

B_m = respiration rate (20 m^3/day)

L_a = mass loading factor (100 $\mu g/m^3$ = 1 E(-4) g/m^3), and

C_s = average concentration of plutonium (pCi/g) in soil of the contaminated area.

Several assumptions are made in the use of the mass loading model. Environmental conditions are assumed to be at steady-state (i.e., the mass loading factor does not change with time). Uncertainty in this assumption would arise for conditions such as high velocity winds, vehicular traffic, and agricultural plowing which could temporarily increase the mass loading factor. A value of 100 $\mu g/m^3$ is assumed for the mass loading factor, which is the value suggested by Anspaugh (1974) for modeling purposes. The respiration rate is assumed to be 20 m^3/day. The different association of plutonium with the particle sizes and the suspended

Table 4-2: Fractions of Pu-239 in bone, liver, and kidney because of chronic ingestion and inhalation for a period of 50 years*

Ratio of Ingestion/Inhalation	Fraction from Ingestion	Fraction from Inhalation
1	0.0005	0.9995
10	0.0053	0.9947
100	0.0506	0.9494
200	0.0964	0.9036
400	0.1758	0.8242
1000	0.3478	0.6522

*Estimated burdens based on ICRP Publications 2 and 19 (1959; 1972)

Source: Martin, W. E., and S. G. Bloom, 1977, Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man, in *Transuranics in Natural Environments*, M. G. White and P. B. Dunaway (Eds.), ERDA Report NVO-178, pp. 621-706, Nevada Operations Office, NTIS.

fractions of the particle sizes are not accounted for in the model. The AMAD of the aerosol particles is assumed to 0.5 μm, and the plutonium particles are considered to be in the yearly translocation class.

4.4 Dose Assessment

The following procedure for calculating radiation dose to a reference organ is from Martin and Bloom (1980).

$$\frac{dD}{dt} = \frac{E}{m} y$$

where

t = time (days)

D = dose to the reference organ (rem)

E = 51.2159ϵ, a dose-rate factor ((g·rem)/(μCi·day))

ϵ = effective energy absorbed in the reference organ per disintegration of radionuclide (MeV/dis)

y = plutonium burden in the organ (μCi), and

m = mass of the organ (g).

The dose accumulated in the organ during a given exposure period of time T_D is

$$D = \frac{E}{m} \int_0^{T_D} y \, dt$$

If ingestion and inhalation to plutonium were terminated at time T_D, the individual would accumulate an additional dose from the radionuclide present in the body at

time T_D. The dose commitment is the sum of the dose accumulated to T_D plus the additional dose.

$$D_c = D + D_a$$

where

D_c = dose commitment (rem), and

D_a = additional dose (rem).

Lung burdens are calculated using the ICRP Task Group on Lung Dynamics Model; a diagram of the lung model is given in Figure 4-2 (Houston et al., 1975). For information on the differential equations that govern this model, the reader can consult ICRP-30 (1981), or Martin and Bloom (1980).

Values for the parameters of the ICRP Task Group on Lung Dynamics Model are given in Table 4-3. Deposition in the nasopharyngeal, tracheobronchial, and pulmonary regions (values D_3, D_4, and D_5 from Figure 4-2) as a function of particle size is given in Table 4-3, Part A (Martin and Bloom, 1980). As particle size gets larger, more of the particles are retained in the nasopharyngeal region and less are deposited in the pulmonary region. Deposition in the tracheobronchial region is constant regardless of particle size. Fractions of plutonium (f) cleared by the compartments as a function of compartment and translocation class are given in Table 4-3, Part B (Martin and Bloom, 1980). Compartments a, c, and e transport contaminants to the body fluids, while compartments b, d, f, and g transport contaminants to the gastrointestinal (GI) tract.

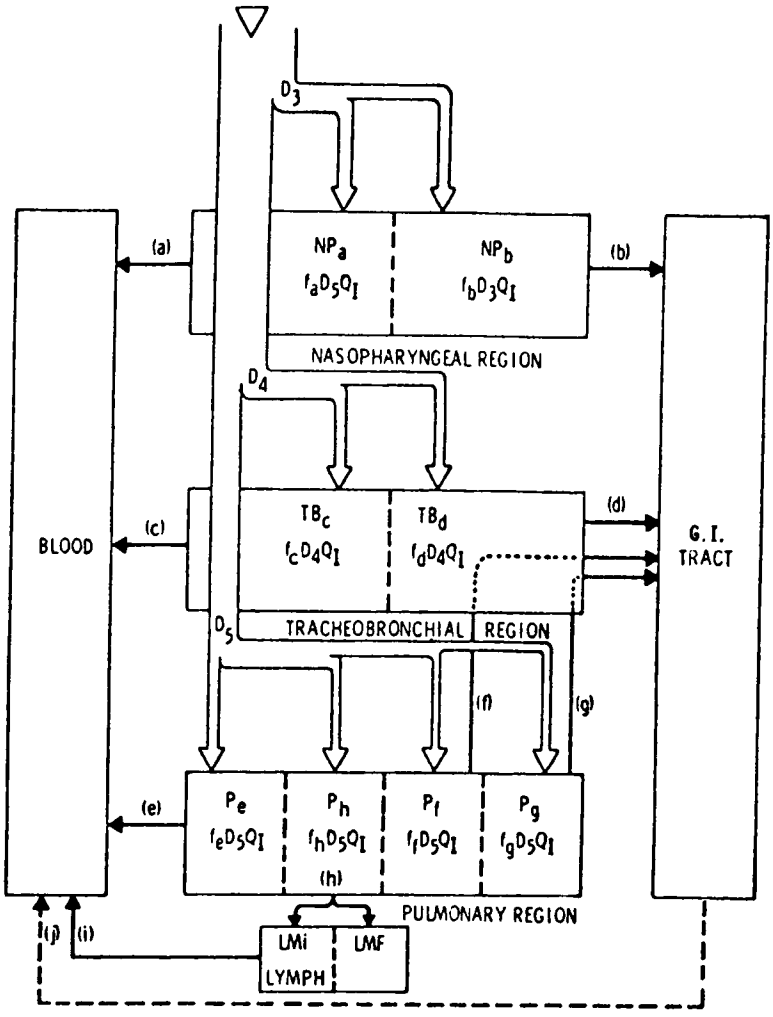


Figure 4-2: ICRP Task Group on Lung Dynamics Model

where

f is the fraction of plutonium transferred from one location to another in the lung model; subscripts refer to the compartments

D_3, D_4, D_5 are the fractions of inhaled material that are deposited in the nasopharyngeal, tracheobronchial, and pulmonary regions, respectively, of the respiratory tract

and Q_I is the plutonium inhalation rate

Source: Houston, J. R., Strenge, D. L., and Watson, E. C., 1975, *DACRIN - A Computer Program for Calculating Organ Dose from Acute or Chronic Radionuclide Inhalation*, USAEC Report BNWL-B-389, Battelle, Pacific Northwest Laboratories, NTIS.

Table 4-3: ICRP Task Group on Lung Dynamics parameter values (Parts A & B)

Part A

Fraction of Inhaled Particles Deposited in the Respiratory System vs. Particle Diameter[1]			
	Fraction of inhaled quantity retained		
Particle size (AMAD), μm	Nasopharyngeal region (D_3)	Tracheobronchial region (D_4)	Pulmonary region (D_5)
0.05	0.001	0.08	0.59
0.1	0.008	0.08	0.50
0.3	0.063	0.08	0.36
0.5	0.13	0.08	0.31
1.0	0.29	0.08	0.23
2.0	0.50	0.08	0.17
5.0	0.77	0.08	0.11

Part B

Clearance Parameter Values[2]							
		Translocation Class					
		Daily		Weekly		Yearly	
Compartment	k*	$T^b(k)$**	f(k)***	$T^b(k)$**	f(k)***	$T^b(k)$**	f(k)***
NP	a	0.01	0.50	0.01	0.10	0.01	0.01
	b	0.01	0.50	0.40	0.90	0.40	0.99
TB	c	0.01	0.95	0.01	0.50	0.01	0.01
	d	0.20	0.05	0.20	0.50	0.20	0.99
P	e	0.50	0.80	50	0.15	500	0.05
	f	NA	NA	1	0.40	1	0.40
	g	NA	NA	50	0.40	500	0.40
	h	0.50	0.20	50	0.05	500	0.15
LM	i	0.50	1.00	50	1.00	1000	0.90

1 estimated from data of Morrow et al. (1966)
2 as amended by ICRP-19 (1972)
* clearance pathway
** biological half-time of clearance in days for pathway k
*** fraction cleared by pathway k

Source: Martin, W. E., and S. G. Bloom, 1980, Nevada Applied Ecology Group Model for Estimating Plutonium Transport and Dose to Man, in *Transuranic Elements in the Environment*, W. C. Hanson (Ed.), pp. 459-512, USDOE Report, DOE/TIC-22800.

Characterization of the translocation class of aerosol particles is very important. Particles in the yearly class (relatively insoluble, immobile particles) can cause a pulmonary lung burden 600 to 700 times greater than particles in the daily class (relatively soluble, mobile particles) (Bloom and Martin, 1978). This difference in lung burden because of translocation class is evident in the data for biological half-times in Table 4-3, Part B. Particles in the yearly class have greater biological half-times than particles in the daily and weekly classes. The plutonium particles at NTS are generally considered to be in the yearly translocation class.

5.0 RESRAD Model Methodology

RESRAD is a computer program developed by Argonne National Laboratory for DOE's Formerly Utilized Sites Remedial Action Program (FUSRAP) and Surplus Facilities Management Program (SFMP). RESRAD was developed to calculate radiation dose to on-site residents from RESidual RADioactive material and determine soil guidelines according to the limits specified in DOE Order 5400.5 (DOE, 1990).

Although RESRAD was produced for FUSRAP, SFMP, and the residential scenario, the procedure for determining dose and soil guidelines is general and use of the code is being encouraged for all DOE sites and various land-use scenarios.

The RESRAD code models environmental transport only. RESRAD uses dose conversion factors for inhalation, ingestion, and external radiation to determine dose; it does not model transport of radionuclides within the body.

The source for RESRAD information referenced in this section is Yu et al. (February 1992). RESRAD is a relatively new code and is currently undergoing revisions and additions.

RESRAD is used in this study to calculate inhalation dose only. The methodology described in the following sections for environmental transport and dose

assessment is only that part of the RESRAD methodology that is relevant to inhalation. Only the dose calculation option of RESRAD is used in this study; soil guidelines were not calculated.

5.1 Environmental Transport

5.1.1 Atmospheric Transport

Similar to the NAEG model, RESRAD uses the mass loading factor to determine resuspension of radionuclides in surface soil to the atmosphere. To calculate the annual intake E(t) (Ci/yr) of the radionuclide by dust inhalation, an environmental transport factor ETF(t) (g/yr) is multiplied by the concentration S(t) (Ci/g) of the radionuclide in the soil. The ETF is expressed as

$$ETF(t) = ASR \times FA \times FCD(t) \times FO \times FI$$

where

ETF(t) = environmental transport factor at time t for dust inhalation of radionuclide (g/yr)

ASR = average mass loading of airborne contaminated soil particles (g soil/m^3 air)

FA = area factor (dimensionless)

FCD(t) = cover and depth factor (dimensionless)

FO = occupancy factor (dimensionless), and

FI = annual intake of air (m^3/yr).

For determining on-site exposure, an estimate of dilution of resuspended

contaminated aerosol by uncontaminated aerosol blown in from off-site is made with a simple mixing model. The model assumes perfect mixing within a volume defined by a mixing height and the area of the exposed contaminated zone. The alternative to this model is the Gaussian plume model, which uses an area distribution of point sources with zero release height. The Gaussian plume model is usually applied to distances from one hundred to several thousand meters and has not been validated for on-site exposure immediately above the source. Uncertainties in the Gaussian plume model for immediate area exposures and large computational requirements are the reasons that the simple mixing model is used. The RESRAD mixing model defines the area factor (FA) as

$$FA = \frac{A^{\frac{1}{2}}}{A^{\frac{1}{2}} + DL}$$

where

A = area of contaminated zone (m^2), and

DL = dilution length (m).

This equation illustrates that the dilution length and area factor become less important for larger areas. The dilution length depends on wind speed, mixing height, resuspension rate, and thickness of the resuspendible dust layer.

The cover and depth factor (FCD) is the fraction of resuspendible soil particles at the ground surface that are contaminated. It is calculated using the assumption that mixing of the soil will occur within a layer of thickness d_m at the surface:

$$
\begin{aligned}
FCD(t) &= 1 && C_d(t) = 0,\ T(t) \geq d_m \\
&= T(t)/d_m && C_d(t) + T(t) < d_m \\
&= 1 - C_d(t)/d_m && C_d(t) < d_m\ C_d(t) + T(t) \geq d_m \\
&= 0 && C_d(t) \geq d_m
\end{aligned}
$$

where

d_m = depth of soil mixing layer (m)

$C_d(t)$ = cover depth at time t (m), and

$T(t)$ = thickness of contaminated zone at time t (m).

The occupancy factor, FO, is the percentage of time the person spends in the contaminated area.

5.1.2 Leaching Model

The decrease in the radionuclide soil concentration because of leaching by infiltrating rainwater can be estimated with RESRAD's leaching model. RESRAD uses a sorption-desorption, ion-exchange leaching model. The radionuclide release rate, $\dot{R}(t)$ (Ci/yr), is

$$\dot{R}(t) = L\ \rho_b^{(\alpha)}\ A\ T(t)\ S(t)$$

(next page)

where

L = leach rate (yr^{-1})

$\rho_b^{(cz)}$ = bulk density of the contaminated zone (g/m^3)

A = area of the contaminated zone (m^2)

T(t) = thickness of the contaminated zone at time t (m), and

S(t) = average concentration of radionuclide in the contaminated zone available for leaching at time t (pCi/g).

The equation for the leach rate constant, L(t), is

$$L(t) = \frac{I}{\theta^{cz}\ T(t)\ R_d^{(cz)}}$$

where

I = infiltration rate (m/yr)

$\theta^{(cz)}$ = volumetric water content of the contaminated zone, and

$R_d^{(cz)}$ = retardation factor in the contaminated zone.

The infiltration rate is

$$I = (1-C_e)[(1-C_r)P_r+I_m]$$

(next page)

where

C_e = evapotranspiration coefficient

C_r = runoff coefficient

P_r = precipitation rate (m/yr), and

I_{rr} = irrigation rate (m/yr).

The evapotranspiration coefficient is used instead of the evapotranspiration rate because the rate value does not account for the correlation between precipitation and evapotranspiration. The evapotranspiration coefficient is related to the evapotranspiration rate by the formula

$$C_e = \frac{E_t}{(1-C_r)P_r+I_{rr}}$$

where E_t is the evapotranspiration rate (m/yr).

Runoff coefficients account for the precipitation lost by runoff and vary with the type of environment.

The equation for the volumetric water content of the contaminated zone is

$$\theta^{cz} = R_s\theta^{cz}_{sat}$$

where

θ^{cz}_{sat} = saturated water content of the contaminated zone, and

R_s = saturation ratio.

This is a general definition that can apply to all zones, not just the contaminated

zone. R_s equals unity when the medium is saturated.

The saturation ratio can be estimated with the following formula

$$R_s = (I/K_{sat})^{\frac{1}{2b+3}}$$

where

I = infiltration rate (m/yr)

K_{sat} = saturated hydraulic conductivity (m/yr), and

b = soil-specific exponential parameter.

The hydraulic conductivity of soil is the ability to allow movement of water through the soil medium when subjected to a hydraulic gradient, or pressure. Saturated hydraulic conductivity is the hydraulic conductivity when the medium is saturated. Hydraulic conductivity is also referred to as permeability.

The last parameter in the leaching model equation is the retardation factor. The retardation factor is the ratio of average pore water velocity to radionuclide transport velocity. If the adsorption-desorption process is assumed to approximate a linear Freundlich isotherm, the formula for the retardation factor is

$$R_d = 1 + \frac{\rho_b K_d}{\theta}$$

(next page)

where

ρ_b = bulk soil density (g/cm^3)

K_d = distribution coefficient (cm^3/g), and

θ = volumetric water content.

The distribution coefficient is the equilibrium concentration of the adsorbed radionuclide in soil to the desorbed radionuclide in water.

5.2 Dose Assessment

RESRAD uses Dose Conversion Factors (DCFs) to determine dose; it does not model transport of radionuclides within the body. The DCFs in RESRAD for inhalation dose are committed effective dose equivalent received per unit intake of radionuclide:

$$DCF = \frac{H_E}{E}$$

where

H_E = committed effective dose equivalent, and

E = exposure to unit quantity of radionuclide.

Committed effective dose equivalent can then be determined by multiplying the dose conversion factor by the exposure to a given quantity of radionuclide. DCFs used in RESRAD were taken from a DOE Report (1988). DCF values similar to those in the DOE Report were calculated by Eckerman et al. (1988) for an EPA report.

Committed effective dose equivalent is the sum of the committed doses equivalent to individual organs, H_T, multiplied by their respective weights, W_T (Killough and Eckerman, 1983):

$$H_E = \sum_T W_T H_T \quad (rem)$$

Weighting factors are derived from values for organ-specific risk per unit dose equivalent to the organ. The risk is that of stochastic fatal health effects, which are assumed to be a function of dose and without threshold. Examples are malignant disease such as cancer and genetic disorders. Nonstochastic effects are related to a threshold value after which acute radiation effects appear such as cataracts and skin burns (Killough and Eckerman, 1983). Table 5-1 provides the organs considered in the effective dose equivalent and their corresponding values of risk and weighting factor (ICRP-26, 1977). A weighting factor of 0.06 is applied to the five organs or tissues not given specific weighting factors that receive the greatest dose equivalent (0.30/5=0.06).

The committed dose equivalent is the total dose equivalent that an organ would receive over a 50-year period following exposure. Fifty years represents a general working lifetime. Dose equivalent, H, to an organ is calculated with the following formula from Killough and Eckerman (1983):

$$H = \frac{1}{M} \int_R [H(P)\ \rho(P)\ dV(P)]$$

(next page)

Table 5-1: Stochastic risk and weighting factors for organs considered in the effective dose equivalent

Organ/tissue (T)	Risk (rem^{-1})	Weight (W_T)
Gonads	4.0 E-5	0.25
Breast	2.5 E-5	0.15
Red marrow	2.0 E-5	0.12
Lung	2.0 E-5	0.12
Thyroid	5.0 E-6	0.03
Bone surfaces	5.0 E-6	0.03
Remainder	5.0 E-5	0.30
Total	1.65 E-4	1.00

Source: International Commission on Radiological Protection, 1977, ICRP Publication 26, Pergamon Press, Inc., Oxford.

where

M = mass of the organ

R = region of space that the organ occupies

$H(P)$ = dose equivalent at point P

$\rho(P)$ = local mass density, and

$dV(P)$ = local volume element.

The integral is taken over all points within the region R that the organ occupies.

6.0 RESRAD Results

6.1 Parameters for the Generic Scenario and Ranges for Sensitivity Analysis

The RESRAD dose assessment is performed with an initial Pu-239 soil concentration of 1 pCi/g. The activity of Pu-240 is included with that of Pu-239, and concentrations of other radionuclides are relative to the 1 pCi/g initial concentration for Pu-239,240. The purpose is to obtain a total, normalized dose (committed effective dose equivalent for all radionuclides per pCi/g of initial Pu-239,240 activity) that can be scaled to actual stratum contamination values for Pu-239,240 at Area 13.

The values used for the parameters in the dose assessment are approximate. The importance of the various parameters is judged using RESRAD's sensitivity analysis, and important parameters are subjected to additional research to form a reasonable bound on the parameter range. The parameters used in the dose assessment are for a generic scenario (i.e., they are generally for undisturbed land and/or are not specific to a given land-use scenario). After the initial dose assessment and sensitivity analysis, the effects that the residential-farmer and industrial-worker scenarios could have on the sensitive parameters is considered and, if possible, quantified.

Sensitivities of the parameters are judged with respect to their effect on the dose from Pu-239. All parameters for which RESRAD sensitivity analysis can be applied

and that affect Pu-239 dose are considered in the sensitivity analysis conducted for this study. A parameter is varied for sensitivity analysis by RESRAD using the factor F. This factor is derived using the percent variation of the range, R, with the following formula: $F = 1 + 0.01 \times R$. Therefore, a range (R) of 300% would convert to a factor (F) of 4. The value of the parameter is multiplied by F to obtain the upper value and divided by F to obtain the lower value. Sensitivity of the parameter is judged by viewing a graph of three plotted values: the lower value, the base value, and the upper value.

The approximate range for each parameter is derived by either judgement of data, or if sufficient data were not found, then the range is chosen arbitrarily. The parameter ranges do not necessarily correspond with the generic scenario (i.e., some of the ranges take into account the variations that could occur with land-use scenarios).

Values for the RESRAD model parameters used in the dose assessment and descriptions of the values are given in Table 6-1 parts "A" through "G" (titles for each part are given in the next paragraph). If the parameter was subjected to sensitivity analysis, immediately below the parameter value is its approximate range. If the range was chosen from judgement of data, then specific values are given for the range. If the range was chosen arbitrarily, then the percent variation of the range is given. Discussion of the parameter ranges used in the sensitivity analysis is also included in the parameter descriptions in Table 6-1.

The RESRAD computer model requires the user to input data for the inhalation pathway in seven different screens (sections). Data provided in Table 6-1 for the model are organized according to these divisions: Contaminated zone parameters are in Part A; Initial soil concentrations are in Part B; Cover and contaminated zone hydrological data are in Part C; Distribution coefficients and leach rates are in Part D; External gamma and dust inhalation parameters are in Part E; Ingestion pathway data and nondietary parameters are in Part F; and Inhalation dose conversion factors are in Part G.

6.2 RESRAD Results for Generic Parameter Set

6.2.1 Pu-239 and U-235

RESRAD results for the generic parameter set and radionuclides Pu-239 and U-235 are given in Figures 6-1 and 6-3, respectively. Figures 6-2 and 6-4 concern non-leaching scenarios for the radionuclides. The graphs are semi-logarithmic (the x-axis is logarithmic scale) with the committed effective dose equivalent in mrem accumulated per year plotted as a function of year after initial time (year after material placement) up to 100,000 years. Year 1, the beginning time in the graph, would be 1 year after initial time. Therefore, since the test at Area 13 was conducted in 1957, Year 1 represents 1958.

In Figure 6-1, the curve begins at approximately 0.24 mrem/yr at 1 year and drops off gradually to about 0.01 mrem/yr at 100,000 years. The drop in the curve is because of a combination of radioactive decay and leaching by infiltrating

Table 6-1: RESRAD model parameter values and descriptions

Part A: Contaminated zone parameters

Parameter	Value	Description
Contaminated Zone Area	4,000,000 m^2 (100%)	The approximate area of the contaminated zone at Area 13 is 4,000,000 m^2 (Tamura, 1975). Although the area should not vary much in size from estimated values, we will arbitrarily vary it at 100%.
Contaminated Zone Thickness	0.05 m (100%)	Seventeen years after deposition, approximately 93 % of the plutonium contamination at Area 13 was mixed within the top 5 cm of soil (Gilbert et al., 1975). Most of the plutonium will likely stay in this 5 cm layer unless disturbed. A situation that would distribute the plutonium among a greater depth would be plowing or tilling by a residential-farmer. We will arbitrarily vary the thickness by 100%.

Part B: Initial soil concentrations

Parameter	Value	Description
Initial Plutonium-239 Concentration	1 pCi/g	The RESRAD dose assessment is done with a initial soil concentration of 1 pCi/g. The result can be translated as dose per pCi/g, and will later be scaled to actual Area 13 stratum contamination values. Pu-240 is assumed to be a part of the Pu-239.
Initial Plutonium-241 Concentration	8.3 pCi/g	From Figure 2-2 of Chapter 2, the initial activity of Pu-241 is approximately 8.3 times that of Pu-239 in a typical gram of plutonium.

Table 6-1 (continued)

Part C: Cover and contaminated zone hydrological data

Parameter	Value	Description
Cover Depth	0 m	Because the safety shots were done on the surface, the contamination consists of a surface layer with no significant cover. Vegetation is not considered by RESRAD as part of the cover depth.
Contaminated Zone Density	1.50 g/cm^3 (1.25 to 1.99)	The value of 1.5 g/cm^3 for bulk density, p_b, was back-calculated from the formula for total porosity, $n_t = 1 - p_b/p_s$. Total porosity is 0.40 (explained below). The particle density, p_s, has a generally accepted value of 2.65 g/cm^3 for soil. Using the range for total porosity (see below), the range for bulk density is calculated as 1.25 to 1.99 g/cm^3.
Contaminated Zone Erosion Rate	1 E(-8) m/yr (1 E(-9) to 1 E(-7))	The approximate value of 1 E(-8) m/yr was chosen from judgement of miscellaneous information. From the RESRAD manual (Yu et al., 1992, p. 148), the lowest range of values for the erosion rate were given for humid sites east of the Mississippi River; these values are 8 E(-7) to 3 E(-6) m/yr for 2% slope and natural succession vegetation. Erosion rates are generally less for arid sites. Area 13 is about 10 – 15 % vegetation and has a slope of 0 to 2% (Leavitt, 1974). A range of 1 E(-9) to 1 E(-7) m/yr was chosen for the sensitivity analysis.

Table 6-1 (continued)

Part C (continued)

Parameter	Value	Description
Contaminated Zone Total Porosity	0.40 (0.25 to 0.53)	At Area 13, the soil is generally classified as gravelly sandy loam (Leavitt, 1974). Tamura (1975) analyzed the particle size distribution. Sands (2000-53 μm) are responsible for approximately 60 to 80 % of the soil weight. The majority of the sand weight is located in the very fine sand range (125-53 μm), the fine sand range (250-125 μm), and the medium sand range (840-250 μm). Silts (53-2 μm) are responsible for 6 to 26 % of the soil weight. From the RESRAD manual (Yu et al., 1992, p. 250), the range for fine sand is 0.25 to 0.53, for coarse sand, 0.31 to 0.46, for fine gravel, 0.25 to 0.38, and for silt, 0.34 to 0.51. The average of the means of these ranges is 0.40. A range was chosen for the sensitivity analysis as 0.25 to 0.53.
Contaminated Zone Effective Porosity	0.29 (0.16 to 0.46)	From the RESRAD manual (Yu et al., 1992, p. 250), the range for fine sand is 0.01 to 0.46, for medium sand, 0.16 to 0.46, for coarse sand, 0.18 to 0.43, for fine gravel, 0.13 to 0.40, and for silt, 0.01 to 0.39. The average of the means of these ranges is 0.29. A range was chosen for the sensitivity analysis as 0.16 to 0.46.
Contaminated Zone Hydraulic Conductivity	178 m/yr (178 to 556)	The water permeability (hydraulic conductivity) for Area 13 is moderate (0.8 to 2.5 in/hr) (Leavitt, 1974). These values can be converted into 178 to 556 m/yr, which is the range used in the sensitivity analysis. For conservative purposes (i.e., less plutonium is leached from the contaminated zone, 178 m/yr is used in the generic scenario).

Table 6-1 (continued)

Part C (continued)

Parameter	Value	Description
Contaminated Zone B Parameter	4.40 (4.05 to 5.39)	The surface soil at Area 13 is generally classified as gravelly sandy loam (Leavitt, 1974). From the RESRAD manual (Yu et al., 1992, p. 234), the b parameter for sandy loam is 4.9, for sand, 4.05, for loamy sand, 4.38, for silty loam, 5.30, and for loam, 5.39. A value of 4.4 was chosen for the generic scenario. A range of 4.05 to 5.39 was chosen for the sensitivity analysis.
Evapotrans-piration Coefficient	0.994 (0.75 to 1.00)	An evapotranspiration coefficient can be calculated from the formula $I = (1 - C_e)[(1 - C_r)P_r]$ (Yu et al., 1992, p. 230), where I is the infiltration rate, C_e is the evapotranspiration coefficient, C_r is the runoff coefficient, 0.2 (see below), and P_r is the precipitation rate, 4 in/yr (see below). For the vicinity of Yucca Mountain (Yucca Mountain is on the western border of NTS), the water recharge rate is 0.02 in/yr (DOE, Yucca Mountain EA). If equilibrium is assumed, the infiltration rate can be approximated with the recharge rate, 0.02 in/yr. C_e calculated from this formula is 0.994. This is a relatively high evapotranspiration coefficient when compared to less arid and humid sites. Precipitation at the NTS averages about 20% of potential evapotranspiration (DOE, Yucca Mountain EA). Most of the rainfall in southern Nevada comes in short bursts. At Yucca Mountain, the annual precipitation is about 5.7 in, the monthly maximum is 4.0 in, and the daily maximum is 2.1 in. Because of the short bursts of rain, most of the water is lost to runoff or evapotranspiration versus permeation of the soil (DOE, Yucca Mountain EA). A range was not found for this parameter, so a range of 0.75 to 1.00 was chosen arbitrarily.

Table 6-1 (continued)

Part C (continued)

Parameter	Value	Description
Precipitation	0.15 m/yr (0.15 to 0.20)	The annual precipitation at Area 13 is 4 to 8 in. This is equivalent to 0.15 to 0.20 m/yr, which is the range used in the sensitivity analysis. For conservatism (i.e., less plutonium is leached from the contaminated zone), the value of 0.15 is used in the generic scenario.
Runoff Coefficient	0.2 (0.2 to 0.4)	The RESRAD manual (Yu et al., 1992, p. 231) gives runoff coefficients for urban and agricultural environments. The runoff coefficient for an agricultural environment is $C_r = 1 - C_1 - C_2 - C_3$. C_1 is 0.3 for flat land, C_2 is 0.4 for open sandy loam, and C_3 is 0.1 for cultivated lands. These values lead to a C_r of 0.2, which is used in the generic scenario. If a C_2 of 0.2 for intermediate combinations of clay and loam is used, then C_r is 0.4. A range of 0.2 to 0.4 is used in the sensitivity analysis.

Table 6-1 (continued)

Part D: Distribution coefficients and leach rates

Parameter	Value	Description
Distribution Coefficient for Pu-239	2000 cm^3/g (200 to 8500)	Values for the distribution coefficient, K_d, of plutonium were taken from the RESRAD manual (Yu et al., 1992, p. 235, 239). For soils and clays, K_d = 2000 cm^3/g, for sand, K_d = 200 cm^3/g, for pH = 7, K_d = 8500 cm^3/g, and for pH = 11, K_d = 1000 cm^3/g. The pH at Area 13 ranges from 7.8 to 8.4 (Leavitt, 1974). An approximate K_d of 2000 was chosen from judgement of this information. Higher values are more conservative because less contamination is being leached from the contaminated zone. A range of 200 to 8500 cm^3/g was chosen for the sensitivity analysis.
Distribution Coefficient for U-235	50 cm^3/g	Because the activity of uranium is very small relative to the activity of plutonium (importance is minimal), we simply use the RESRAD default, which is 50 cm^3/g. However, the K_d of uranium can vary widely. The RESRAD manual gives a K_d of 23,000 cm^3/g for pH = 7.7 and a K_d of 100 for pH = 8. The pH at Area 13 ranges from 7.8 to 8.4.
Distribution Coefficient for Pu-241	2000 cm^3/g	Distribution coefficients for an element do not vary significantly according to the isotope of the element. The distribution coefficient for Pu-241 at Area 13 should therefore be the similar to that for Pu-239. We will use 2000 cm^3/g.
Distribution Coefficient for Am-241	2000 cm^3/g	It has been noted that the adsorption of americium to soil is as great or greater than the adsorption of plutonium to soil (Glover et al., 1976). The RESRAD default for K_d of Am-241 is 20 cm^3/g. The value used for plutonium is 2000 cm^3/g. We will use 2000 cm^3/g.

Table 6-1 (continued)

Part E: External gamma and dust inhalation parameters

Parameter	Value	Description
Inhalation Rate	7300 m^3/yr (6350 to 8400)	The value of 7300 m^3/yr is used in the NAEG model (Martin and Bloom, 1980). It is recommended in ICRP-2 (1959) for reference man. The default value of RESRAD is 8400 m^3/yr, which is recommended in ICRP-23 (1975) for reference man. The value of 8400 m^3/yr accounts for different levels of activity and breathing; per day, levels of breathing correspond with eight hours of "light activity" working, eight hours of nonoccupational activity, and eight hours of resting. A range of 6350 to 8400 is used in the sensitivity analysis.
Mass Loading Factor	100 $\mu g/m^3$ (50 to 200)	Anspaugh (1974) provides justification for 100 $\mu g/m^3$ as an reasonably conservative estimate for normal weather conditions at NTS. He measured a value of 70 $\mu g/m^3$ at the GMX site of Area 5. The RESRAD default is 200 $\mu g/m^3$. A range of 50 to 200 is used in the sensitivity analysis.
Dilution Length for Airborne Dust	3 m (300%)	For very large areas such as Area 13, the dilution length becomes negligible. Therefore we use the RESRAD default of 3 m for the generic scenario. A range of 300% was chosen arbitrarily for the sensitivity analysis.
Occupancy Factor	1	For conservatism, this value can be set at 1.

Table 6-1 (continued)

Part F: Ingestion pathway data and nondietary parameters

Parameter	Value	Description
Depth of Soil Mixing Layer	0.05 m (100%)	Seventeen years after deposition, approximately 93 % of the plutonium contamination at Area 13 was mixed within the top 5 cm of soil (Gilbert et al., 1975). Most of the plutonium will likely stay in this 5 cm layer unless disturbed. An activity such as plowing by a residential-farmer would increase the thickness of the contaminated zone, and by loosening the upper layers of soil, increase the soil mixing layer. Planting of crops would then stabilize the layer. The uncertainty in the soil mixing layer would be large for the residential-farmer. A range of 100% was chosen for the sensitivity analysis.

Table 6-1 (continued)

Part G: Inhalation dose conversion factors

Parameter	Value	Description
Inhalation Dose Conversion Factor for Pu-239	0.33 mrem/pCi	This value is a dose conversion factor for Pu-239 particles of yearly translocation class. Plutonium in soil at NTS is generally in the form of oxides or hydroxides, which ICRP-30 (1981) classify as yearly.
Inhalation Dose Conversion Factor for U-235	0.12 mrem/pCi	We assume that much of the uranium from decay of plutonium will be in oxide form. Uranium oxides are highly insoluble in the lung, and are classified as yearly.
Inhalation Dose Conversion Factor for Pu-241	5.7 E(-3) mrem/pCi	Similar to the value for Pu-239, this value is also a yearly dose conversion factor. Plutonium at NTS is generally considered to be in the yearly translocation class.
Inhalation Dose Conversion Factor for Am-241	0.52 mrem/pCi	Americium has been noted to have greater mobility in the lung than plutonium, especially in oxide form, and for this reason is assigned to the weekly translocation class. Americium from decay of plutonium oxides will be likely to exist in oxide form.
Aerosol Particle Size	1 μm	The inhalation dose conversion factors that RESRAD uses were calculated for particles with AMAD of 1 μm.

(RETURN TO PAGE 68)

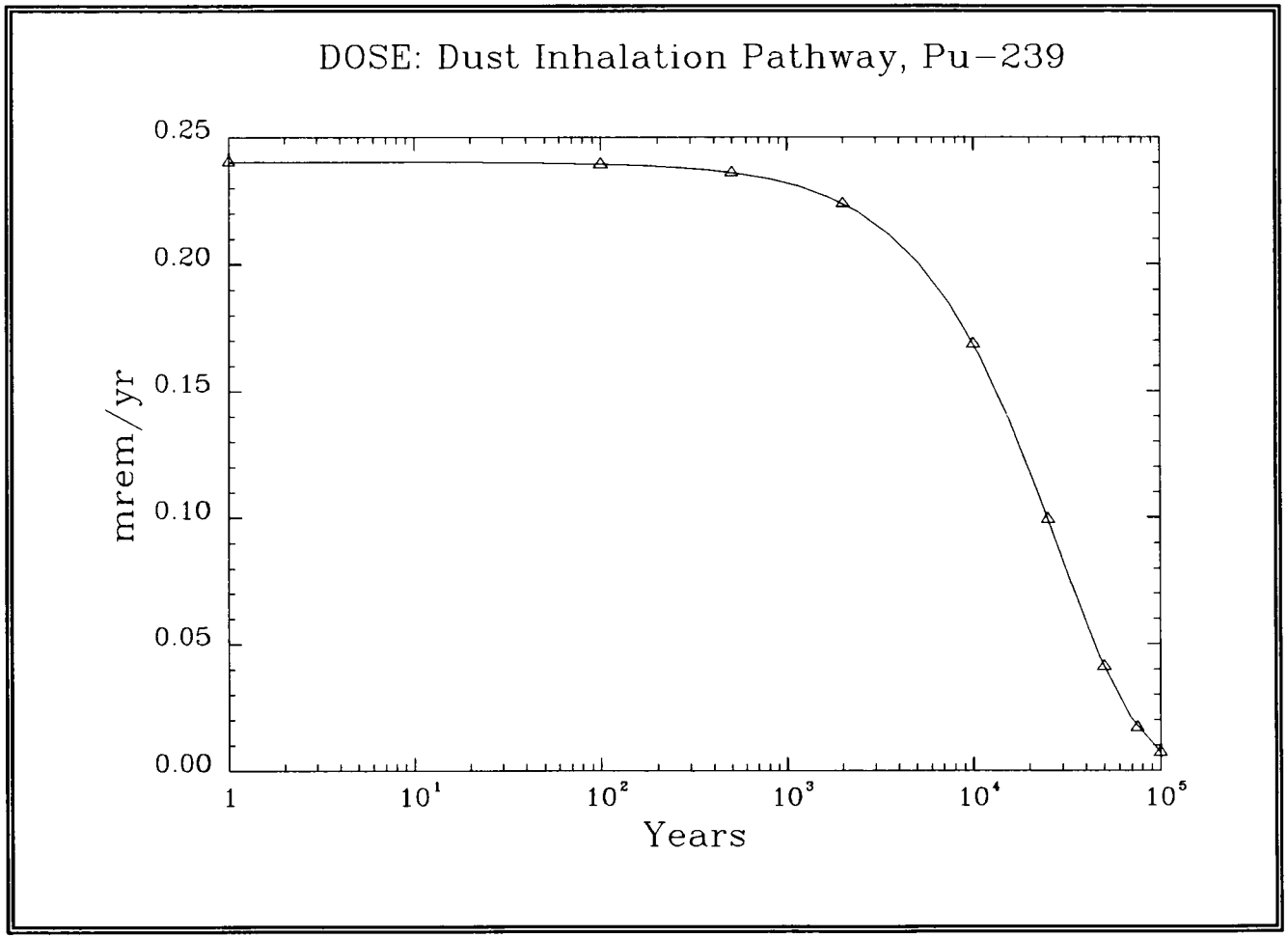


Figure 6-1: Committed effective dose equivalent accumulated per year as a function of year after initial time for Pu-239 and the generic parameter set

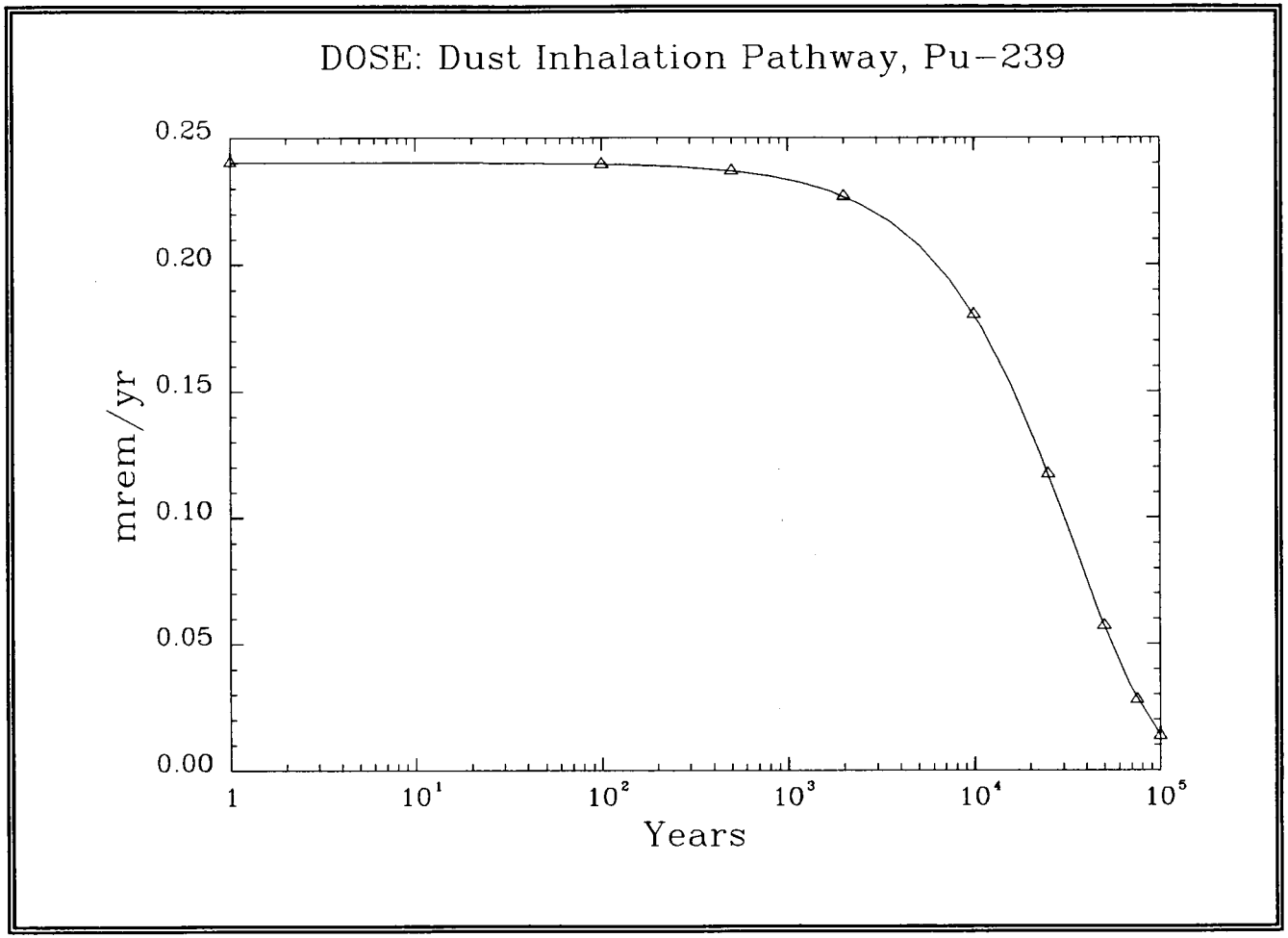


Figure 6-2: Committed effective dose equivalent accumulated per year as a function of year after initial time for Pu-239; radioactive decay only

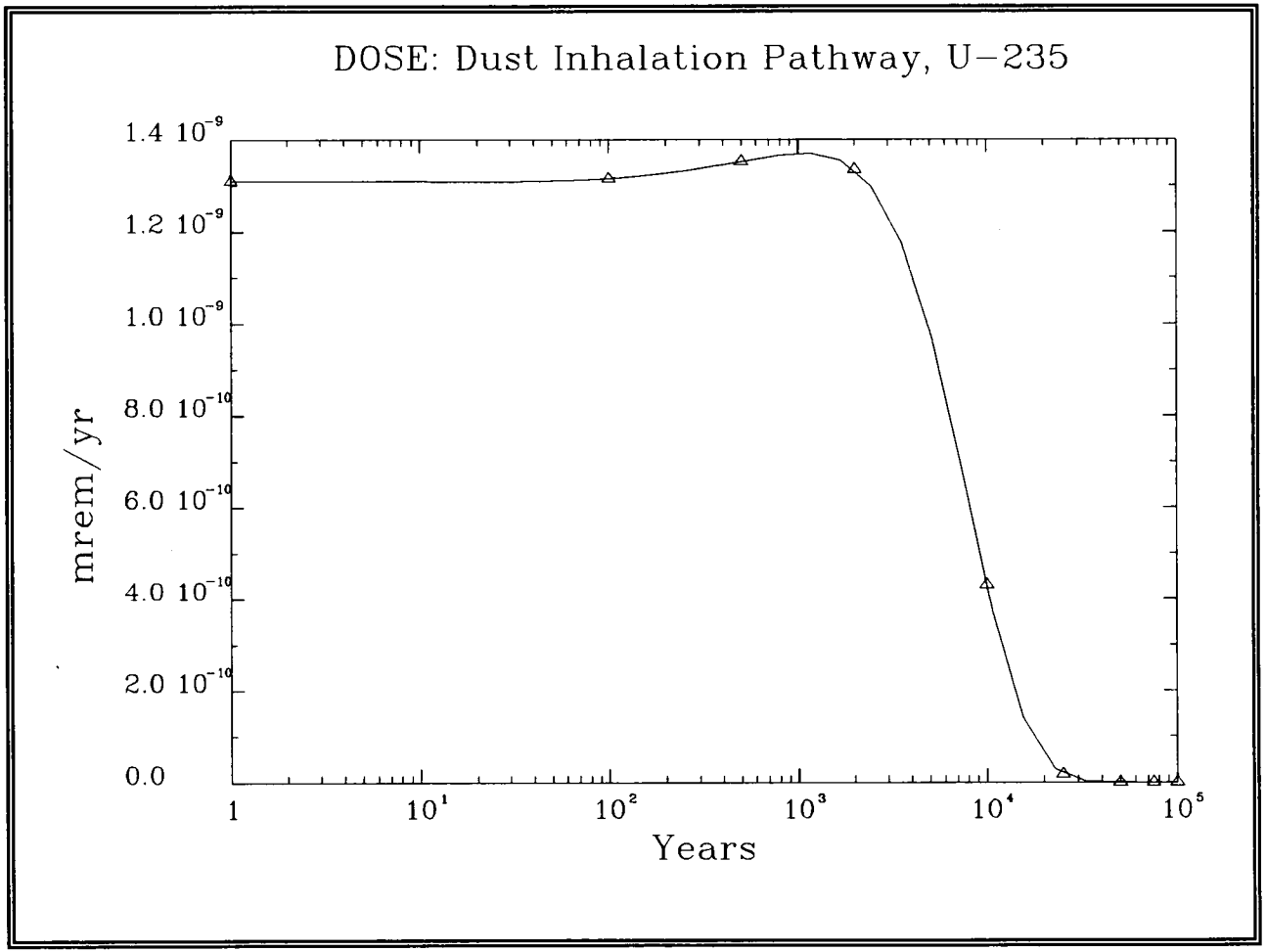


Figure 6-3: Committed effective dose equivalent accumulated per year as a function of year after initial time for U-235 and the generic parameter set

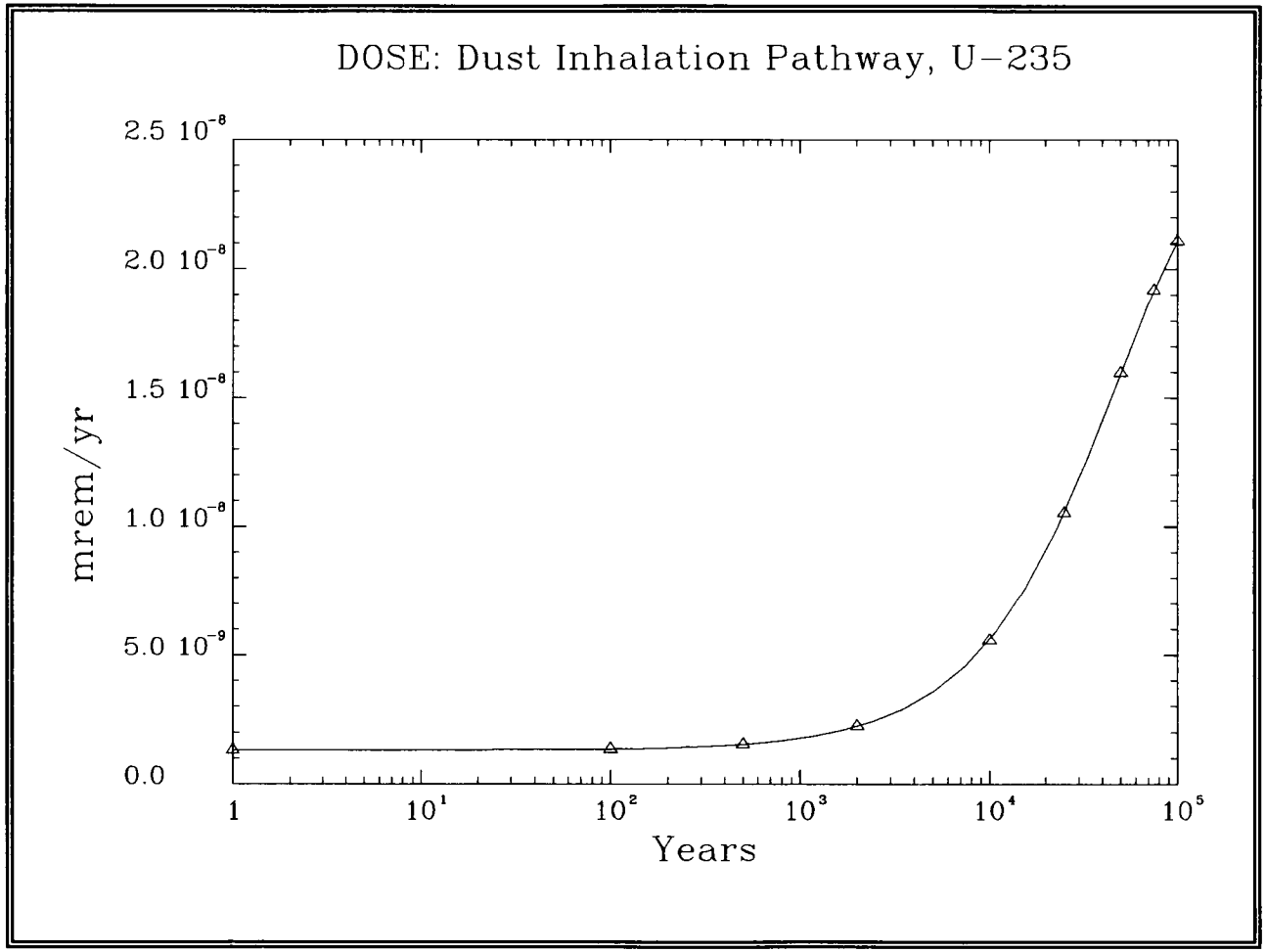


Figure 6-4: Committed effective dose equivalent accumulated per year as a function of year after initial time for U-235; radioactive decay only

rainwater. The majority of the drop is because of radioactive decay; the effect of leaching is relatively small when compared to radioactive decay. To demonstrate the dominance of radioactive decay in this instance, Figure 6-2 graphs the dose per year for the plutonium source being depleted by radioactive decay only. A visual comparison of Figures 6-1 and 6-2 will reveal that the graphs are nearly identical.

Several factors cause the small effect that leaching has on the depletion of plutonium. The first factor is the magnitude of the distribution coefficient of plutonium. The distribution coefficient is the ratio of the mass of radionuclide adsorbed or precipitated onto unit mass of soil versus the solute concentration. The higher the distribution coefficient, the lower the concentration of the radionuclide in infiltrating water. In addition, the amount of infiltrating rainwater is low because of the small amount of yearly rainwater and high evapotranspiration and runoff at NTS.

The curve for U-235 in Figure 6-3 begins at about 1.3 E(-9) mrem/yr at 1 year, rises gradually to the time of about 1600 years, and then drops off to zero dose at approximately 30,000 years. The gradual rise is because of ingrowth of uranium from decay of plutonium. Because of the relatively low distribution coefficient of 50 cm^3/g used for uranium, the drop in Figure 6-3 is mainly due to leaching. The half-life of U-235 is 7.04 E(8) years. Figure 6-4 shows what the dose accumulated per year for uranium would be if no leaching of the source occurred. If the K_d of U-235 at Area 13 is closer to 23,000 cm^3/g versus 50 cm^3/g (see Table 6-1d),

Figure 6-4 would depict the actual case better than Figure 6-3. Figure 6-4 shows that, in the time frame of 100,000 years, uranium is produced from plutonium faster than it can decay, so the graph is continually increasing. Regardless of the uncertainties involved in determining the dose from U-235, its dose is so small that it can be neglected for practical purposes.

6.2.2 Pu-241 and Am-241

The RESRAD results for the generic parameter set and the radionuclides Pu-241 and Am-241 are given in Figure 6-5. RESRAD calculations combine the dose for the two radionuclides. The graph is semi-logarithmic (the x-axis is logarithmic scale) with the committed effective dose equivalent in mrem accumulated per year plotted as a function of year after initial time up to 100,000 years.

The graph rises because of ingrowth of Am-241 from the decay of Pu-241, and then begins to fall as decay of Am-241 is more dominant than its production. At zero years (not on graph), all of the dose is due to Pu-241. At 73.3 years, where the peak occurs, most of the dose (about 99%) is due to Am-241. Similarly to the Pu-239 case described in Section 6.2.1, the decrease in dose over time is mainly because of radioactive decay versus leaching.

The relative contributions from Pu-241 and Am-241 to the dose in Figure 6-5 are calculated from an analysis of Figure 2-2, which is repeated here as Figure 6-6. From Figure 6-6, the period of time after initial time that appears to be the highest

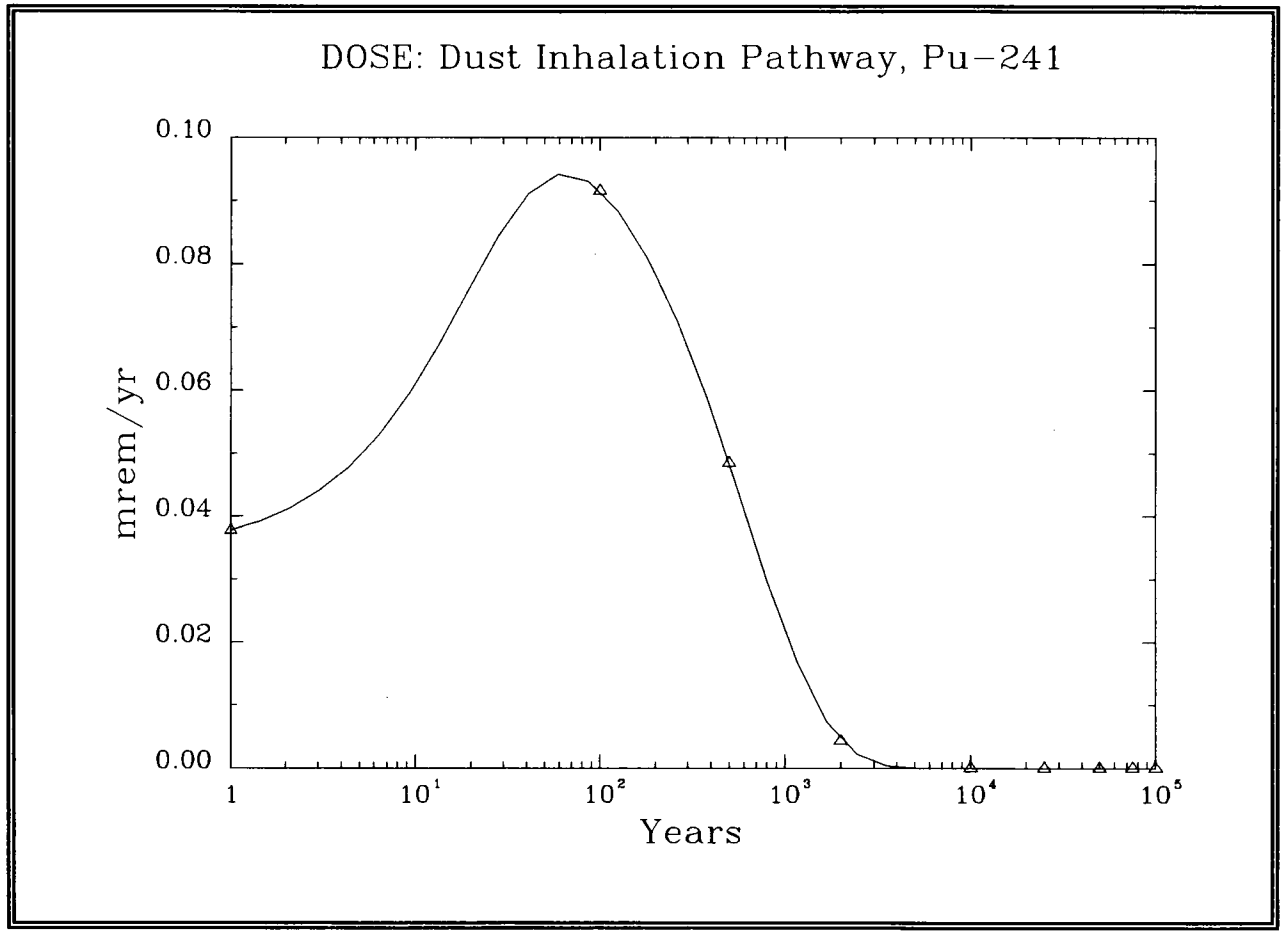


Figure 6-5: Committed effective dose equivalent accumulated per year as a function of year after initial time for Pu-241 and Am-241 and the generic parameter set

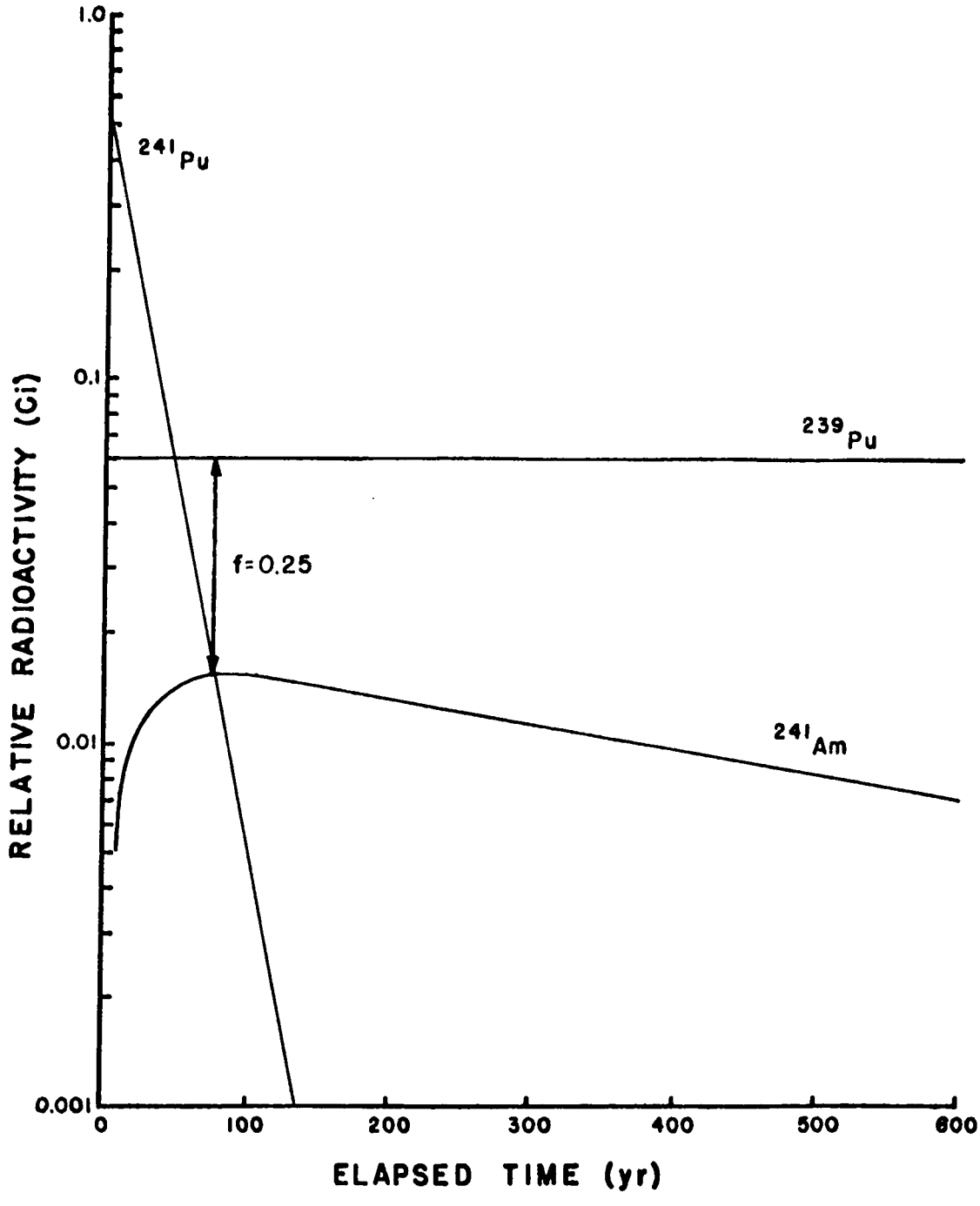


Figure 6-6: Relative radioactivity of Pu-239, Pu-241, and Am-241 from plutonium

Source: **Adapted from** Fowler, E. B., and E. H. Essington, 1974, Soils Element Activities for October, 1972 to September, 1973, in *The Dynamics of Plutonium in Desert Environment*, P. B. Dunaway and M. G. White (Eds.), USAEC Report NVO-142, pp. 7-16, Nevada Operations Office, NTIS.

in activity is the period between 0 and 75 years. At zero years, Pu-241 activity is at its maximum. At about 50 years, Pu-241 activity is equal to that of Pu-239, and Am-241 activity is nearly at its maximum. At 73.3 years, Am-241 reaches its peak, and the activity of Pu-241 is equal to that of Am-241.

The dose incurred by each radionuclide is a function of both its activity and its potential to inflict bodily harm; the latter is represented in the dose conversion factor. Doses from Pu-241 are small relative to its activity because of its low dose conversion factor. The low dose conversion factor of Pu-241 is because of the relatively less harmful effect of inhaling a low-energy beta particle when compared to inhaling a high-energy alpha particle from Pu-239 or Am-241. Table 6-2 contains the data needed to calculate the relative dose contributions (the table also contains data for Pu-239). The two calculations outlined in Table 6-2 are made for 0 years and 73.3 years. If Figure 6-5 is extrapolated to year zero, 100% of the dose would be from Pu-241 since no Am-241 has formed. The contribution of Pu-241 to total dose is approximately 13% at year zero. At year 73.3, about 99% of the dose in Figure 6-5 is because of Am-241. Am-241 represents approximately 28% of the total dose at year 73.3.

6.2.3 Total Dose

Calculation of percent contribution to total dose from radionuclides Pu-239, Pu-241, and Am-241 for years 0 and 73.3 after initial time is outlined in Table 6-2. These calculations are based on Figure 6-6. At year zero, Pu-239 and Pu-241 contribute

Table 6-2: Dose contributions from Pu-239, Pu-241, and Am-241 as a function of year after initial time

Radionuclides at Year 0	Translocation Class	Inhalation Dose Conversion Factor (DCF) (mrem/pCi)	Activity Relative to 1 pCi Pu-239 (pCi)	Relative Dose (mrem)	Contribution to Total Dose (%)
Pu-239	Yearly	3.3 E(-1)	1	0.33	87
Pu-241	Yearly	5.7 E(-3)	8.3	0.05	13
Radionuclides at Year 73.3					
Pu-239	Yearly	3.3 E(-1)	1	0.33	72
Pu-241	Yearly	5.7 E(-3)	0.25	0.0014	~0
Am-241	Weekly	5.2 E(-1)	0.25	0.13	28

87% and 13%, respectively. At year 73.3, Pu-239 and Am-241 contribute 72% and 28%, respectively.

Table 6-3 illustrates addition of the dose curves in Figures 6-1 and 6-5 for the radionuclides Pu-239, Pu-241, and Am-241. Because the dose for Pu-241 and Am-241 was calculated relative to 1 pCi/g of initial Pu-239 activity, the total dose is also relative to 1 pCi/g of initial Pu-239 activity. Recall that the activity of Pu-240 will be included with that of the Pu-239. Including Pu-240 activity with Pu-239 activity is conservative because it will increase the relative amount of Pu-241, Am-241 dose; this is under the assumption that Pu-240 activity was not included with Pu-239 activity in Figures 2-2 and 6-6. The result of the addition in Table 6-3 is therefore a total, normalized dose (committed effective dose equivalent, mrem/yr, for all radionuclides per pCi/g of initial Pu-239,240 activity). The doses are added for various points in the two curves to produce the total dose. Note that the total dose in Table 6-3 is greatest at year 73.3, followed by year 400. Year one is third in magnitude.

6.3 Sensitivity Analysis Results

The parameters subjected to sensitivity analysis are summarized in Table 6-4. The table contains the nominal parameter values, the upper and lower values of the ranges, the percent variation of the ranges, the range types, and the figures that display the RESRAD-generated sensitivity graphs.

Table 6-3: Calculation of total dose accumulated per year as a function of year after initial time

Time (years)	Pu-239 Dose (mrem/yr per pCi/g of initial Pu-239/240), % of Total Dose	Pu-241, Am-241 Dose (mrem/yr per pCi/g of initial Pu-239/240), % of Total Dose	Total Dose (mrem/yr per pCi/g of initial Pu-239/240)
1	0.24 (87%)	0.038 (13%)	0.278
73.3	0.24 (72%)	0.094 (28%)	0.334
400	0.238 (80%)	0.06 (20%)	0.298
1000	0.234 (91%)	0.022 (9%)	0.256
10000	0.17 (100%)	0	0.17
30000	0.083 (100%)	0	0.083
100000	0.01 (100%)	0	0.01

Table 6-4: Parameter ranges for sensitivity analysis

Parameter (units)	Lower Value	Nominal Value	Upper Value	Approx. %	Range Type	Figure
Contaminated Area (m^2)	—	4,000,000	—	100	Arbitrary	6-7
Contaminated Zone Thickness (m)	—	0.05	—	100	Arbitrary	6-8
Bulk Density (g/cm^3)	1.25	1.50	1.99	30	Judgement of Data	6-9
Erosion Rate (m/yr)	1 E-9	1 E-8	1 E-7	900	Judgement of Data	6-10
Total Porosity	0.25	0.35	0.53	65	Judgement of Data	6-11
Effective Porosity	0.16	0.25	0.46	100	Judgement of Data	6-12
Hydraulic Conductivity (m/yr)	178	275	556	100	Judgement of Data	6-13
B-parameter	4.05	4.50	5.39	20	Judgement of Data	6-14

Table 6-4 (continued)

Parameter (units)	Lower Value	Nominal Value	Upper Value	Approx. %	Range Type	Figure
Evapotranspiration Coefficient	0.75	0.975	—	30	Arbitrary	6-15
Precipitation (m/yr)	0.15	0.17	0.20	25	Judgement of Data	6-16
Runoff Coefficient	0.20	0.27	0.40	50	Judgement of Data	6-17
Pu-239 Distribution Coefficient (cm^3/g)	200	1,300	8,500	600	Judgement of Data	6-18
Inhalation Rate (m^3/year)	6350	7300	8400	15	Judgement of Data	6-19
Mass Loading Factor (g/m^3)	50	100	200	100	Judgement of Data	6-20
Dilution Length (m)	—	3	—	300	Arbitrary	6-21
Soil Mixing Layer (m)	—	0.05	—	100	Arbitrary	6-22

If the parameter's range was chosen from judgement of data, the upper and lower values of its range are given along with the corresponding percent variation. If the range was chosen arbitrarily, then only the percent variation is given. The nominal values listed in the table are used as a base for RESRAD percentage variation. If the range is arbitrary, then the nominal values are identical with the values used in the generic scenario. If the range is from judgement of data, the nominal values are, in most cases, different from the values used in the generic scenario. Due to the method of percent variation, the nominal values need to be closer to the lower value of the range (they are not the half-way point in the range).

Sensitivities of the parameters are judged using a visual inspection of the graphs generated by the RESRAD sensitivity analysis option. By comparing the graphs, one can also see the relative sensitivities of the parameters. The sensitivity of each parameter is because of a combination of two factors: (1) the percentage variation of the parameter range, and (2) the function of the parameter in the equations of the RESRAD model.

Sensitivities of the parameters are judged with respect to their effect on the dose from Pu-239. Therefore, the appearance of the RESRAD-generated sensitivity graphs is similar to Figure 6-1. For the parameters that have nominal values different than the values in the generic scenario, the corresponding curve for the nominal parameter in the sensitivity graph will be slightly different from the curve in Figure 6-1.

Sensitivity analysis graphs are provided in Figures 6-7 through 6-22. Three lines total are plotted in the graphs: the lower value, nominal value, and upper value. Because of the low sensitivity of some of the parameters, the upper and lower value lines are not completely visible on all the graphs.

The most sensitive parameters (in order of occurrence in Table 6-4) are the contaminated zone thickness, evapotranspiration coefficient, Pu-239 distribution coefficient, inhalation rate, mass loading factor, and soil mixing layer. The potential sensitivities of these parameters are discussed in Section 6.4.

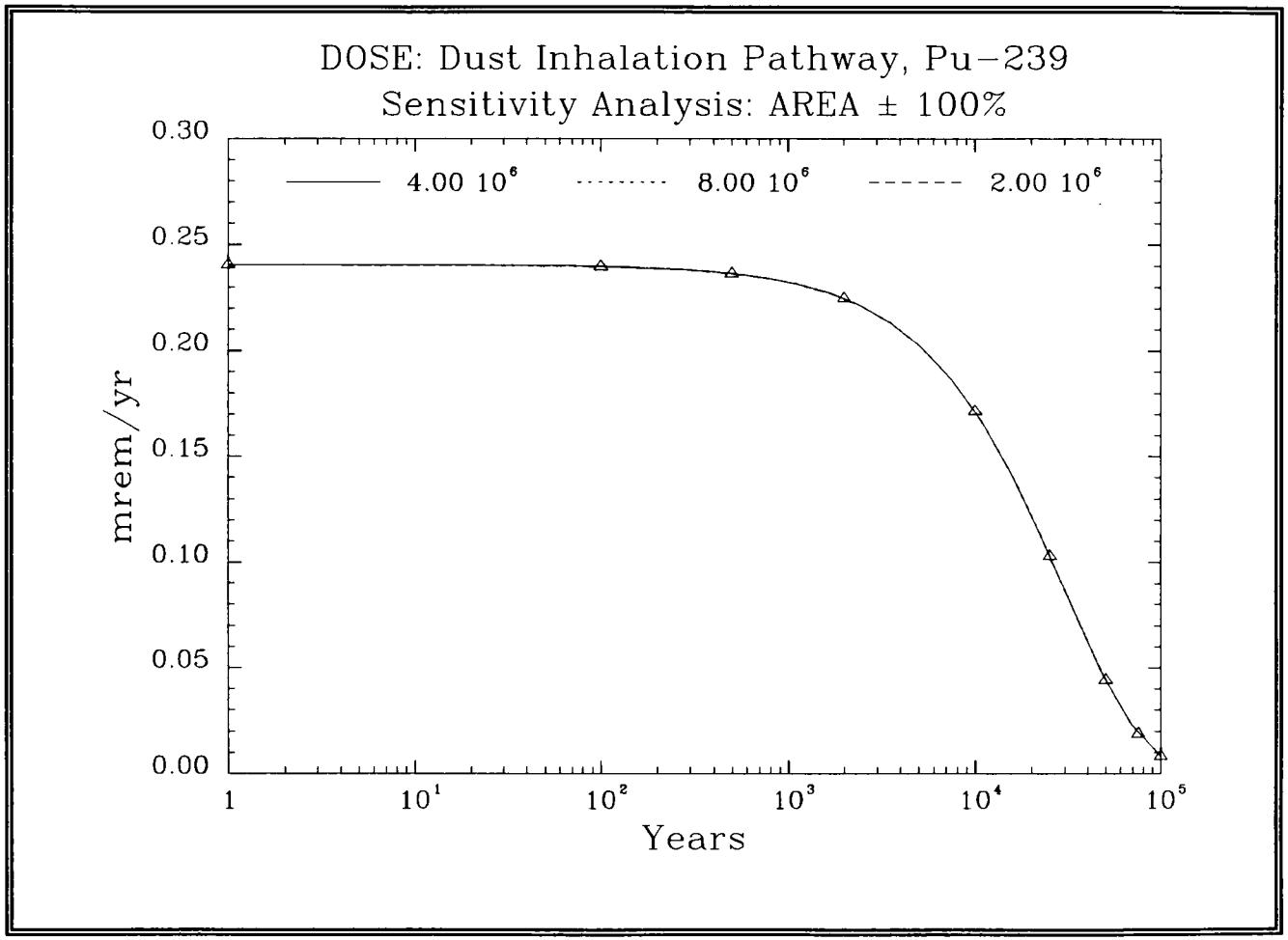


Figure 6-7: Contaminated area sensitivity

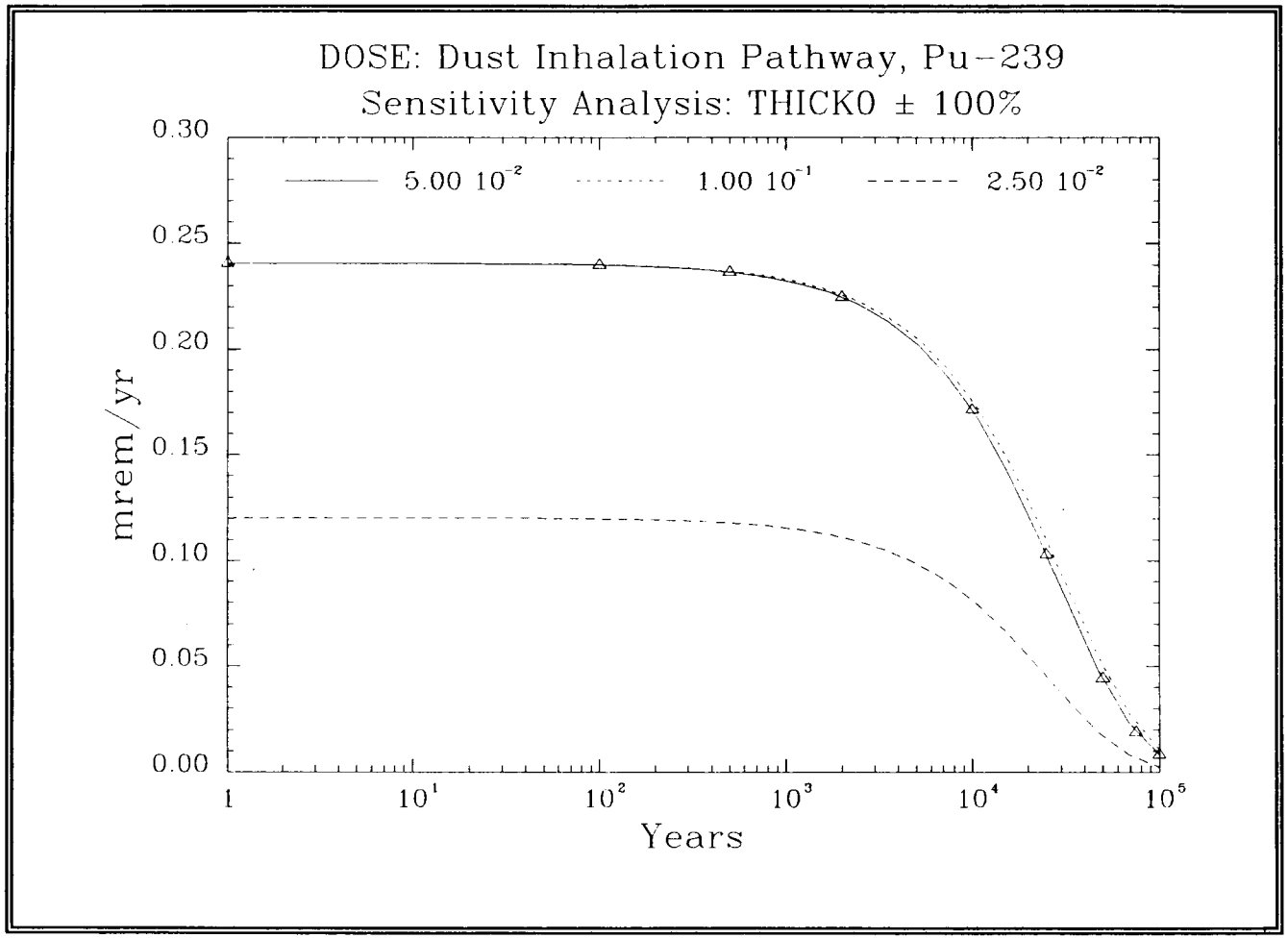


Figure 6-8: Contaminated zone thickness sensitivity

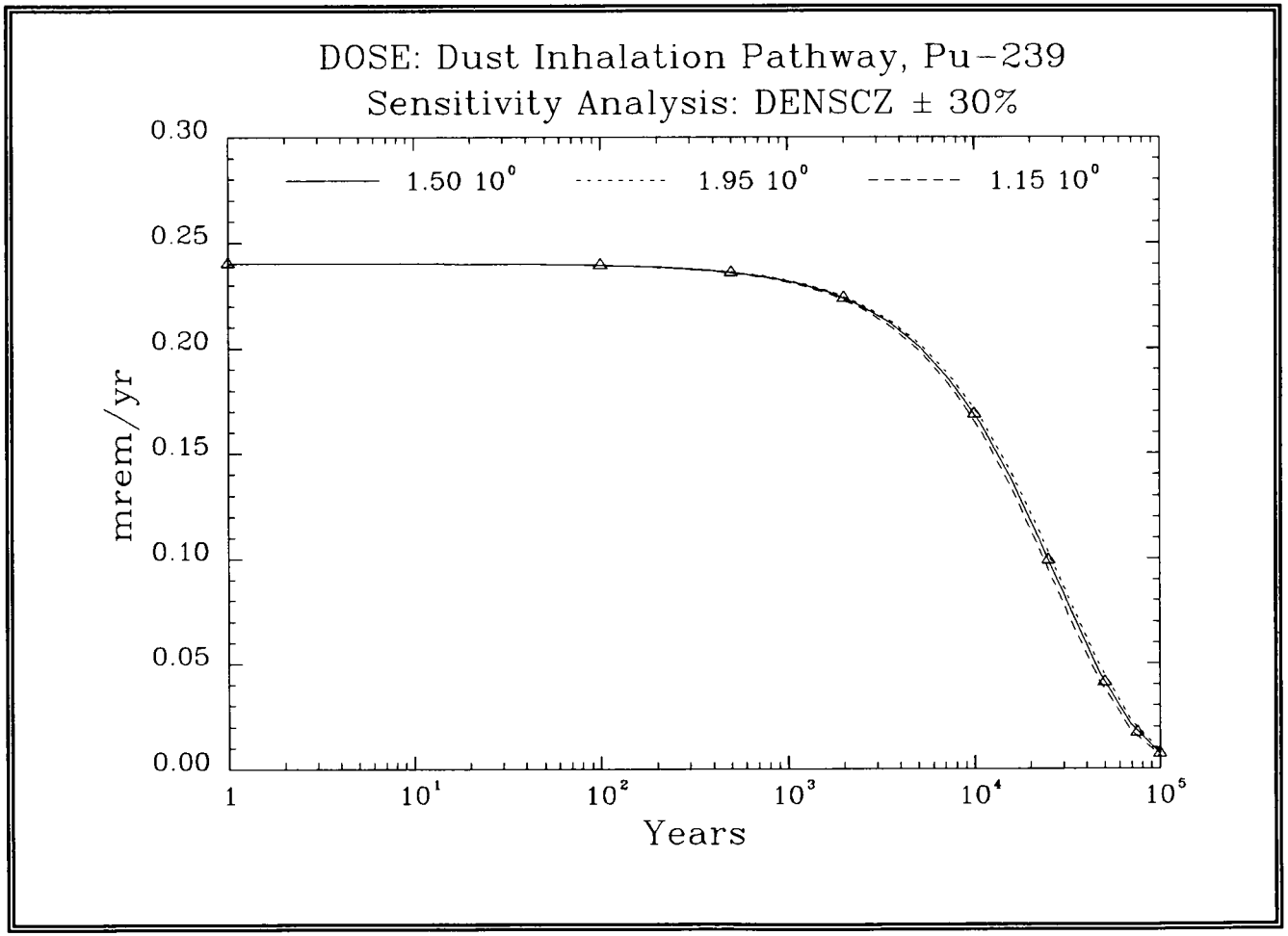


Figure 6-9: Bulk density sensitivity

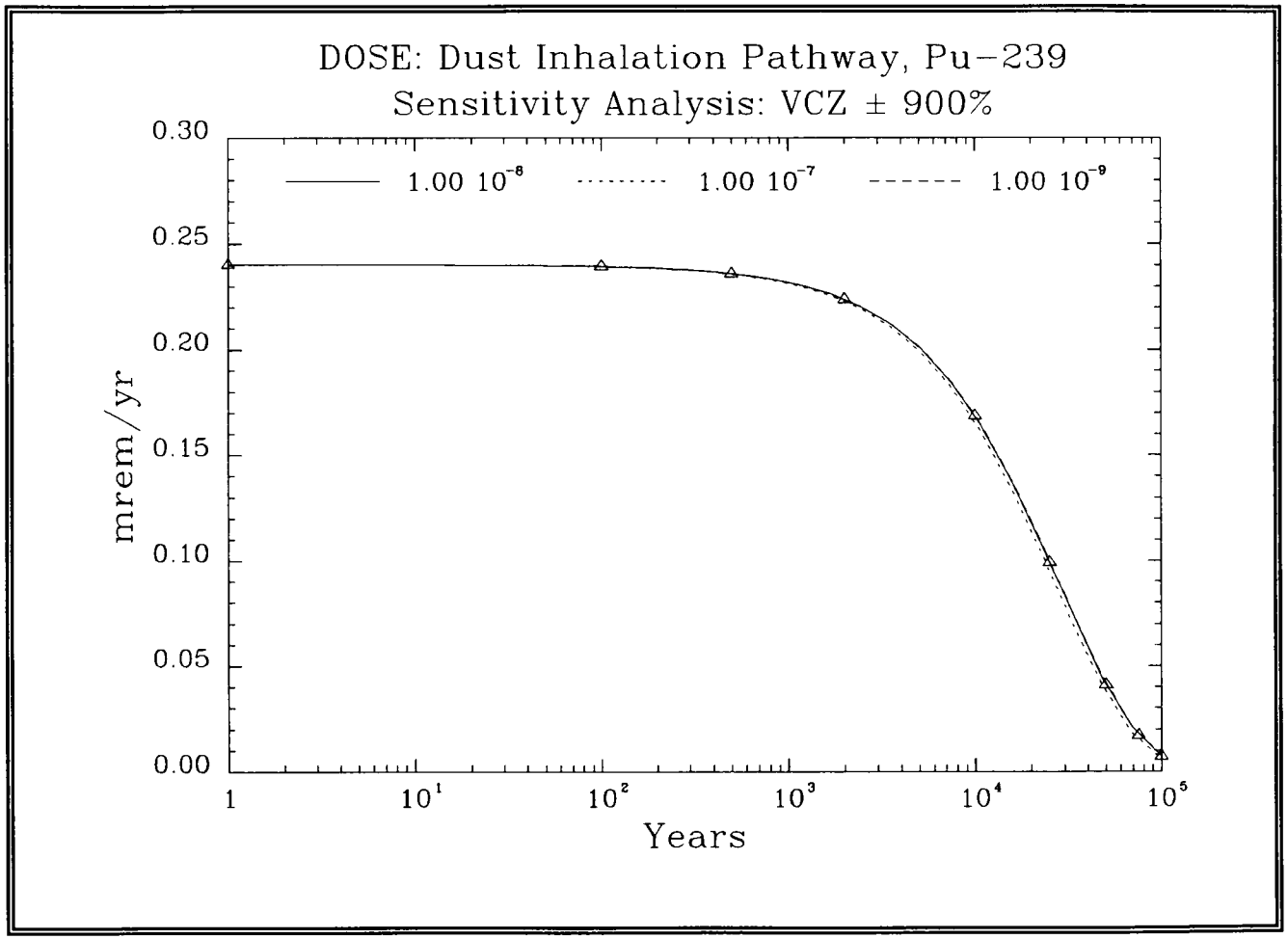


Figure 6-10: Erosion rate sensitivity

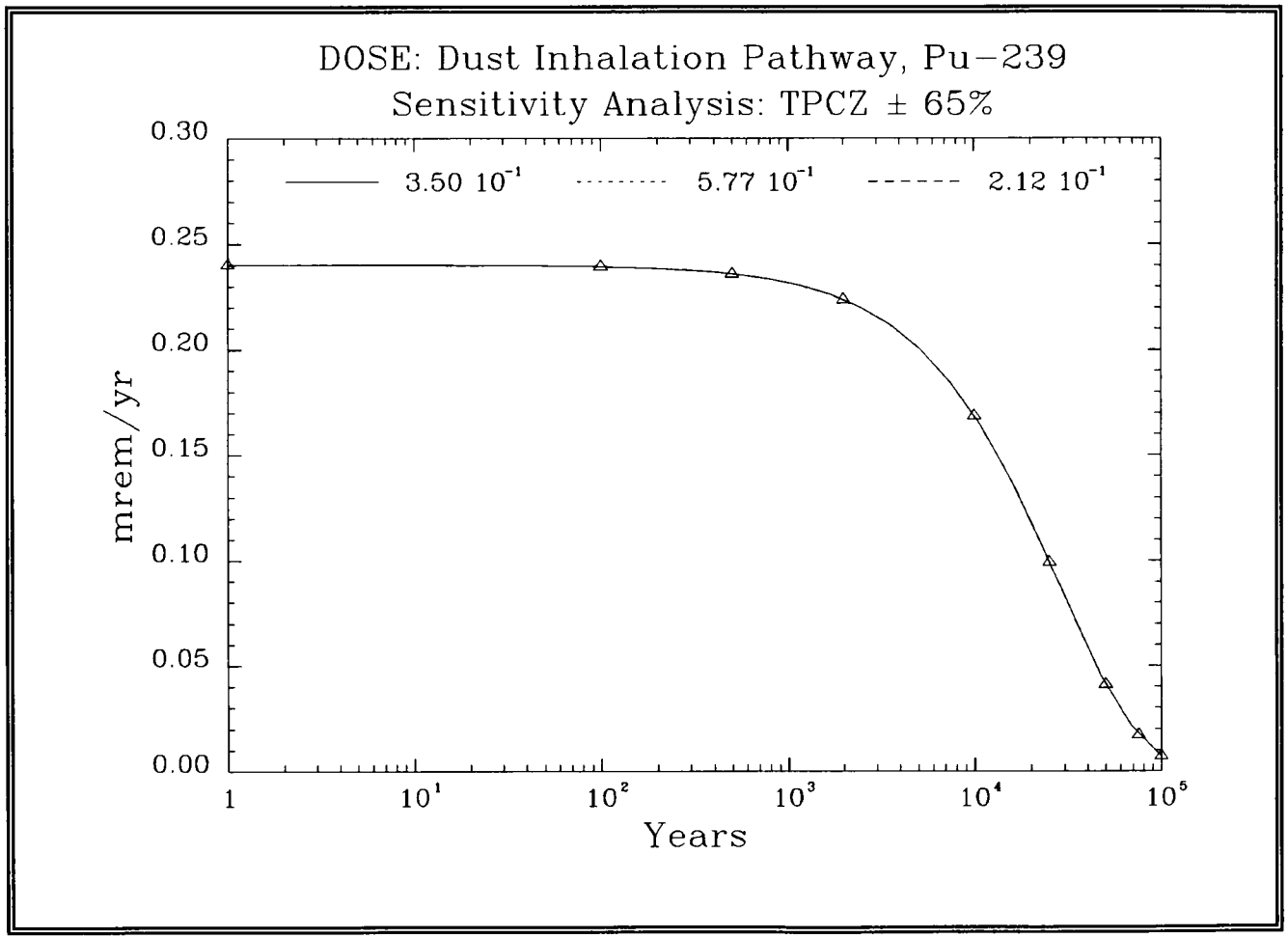


Figure 6-11: Total porosity sensitivity

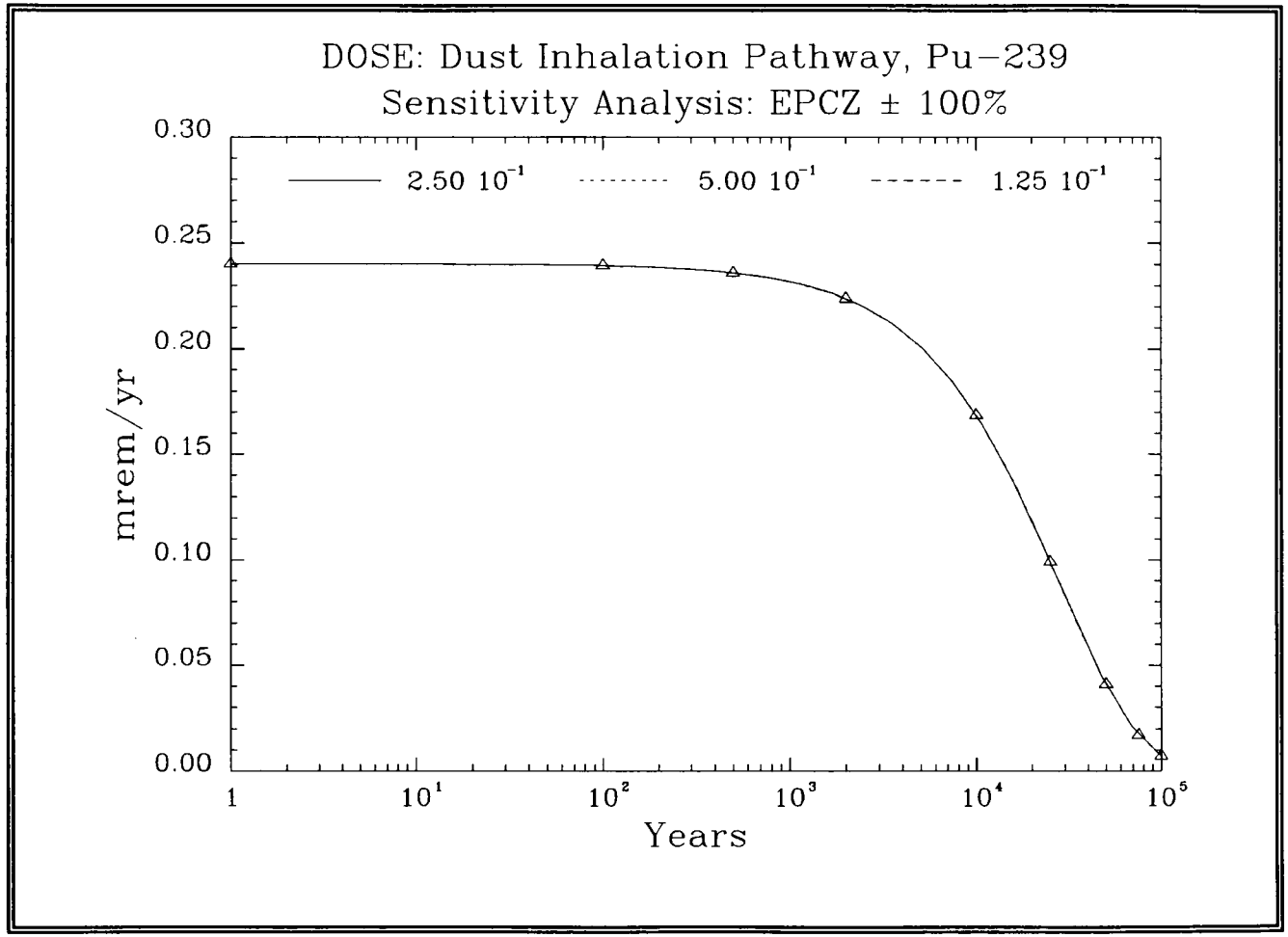


Figure 6-12: Effective porosity sensitivity

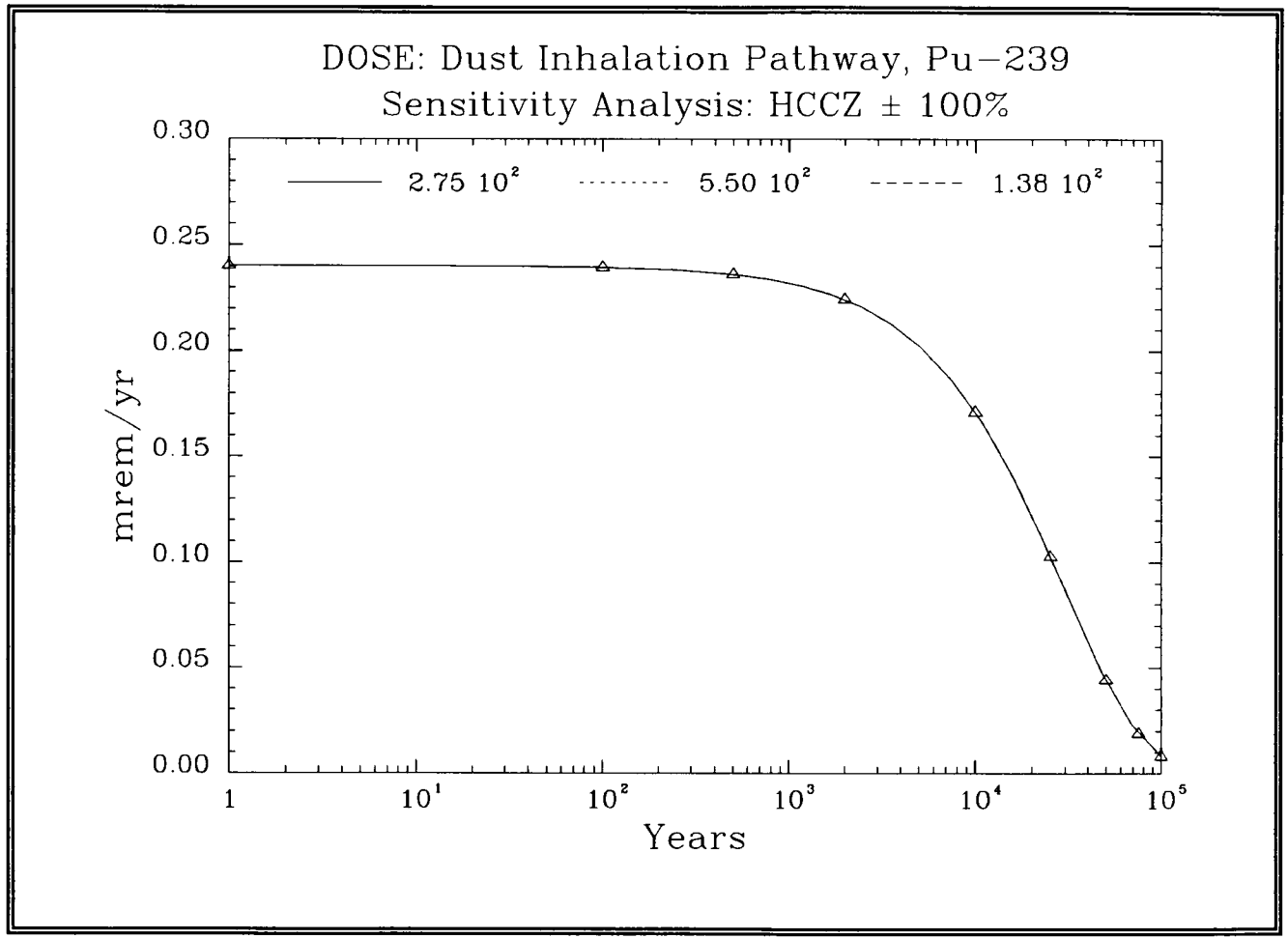


Figure 6-13: Hydraulic conductivity sensitivity

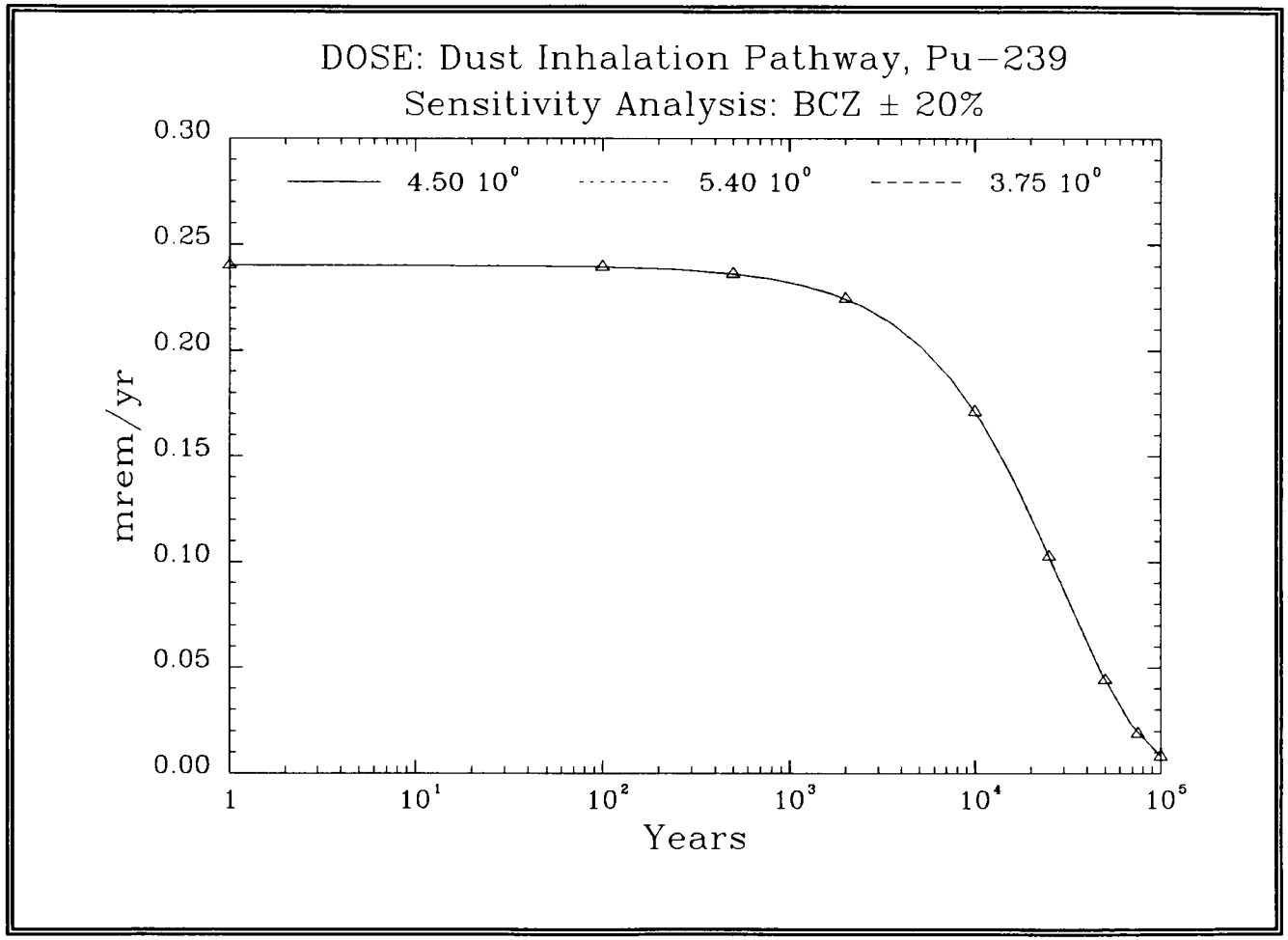


Figure 6-14: B-parameter sensitivity

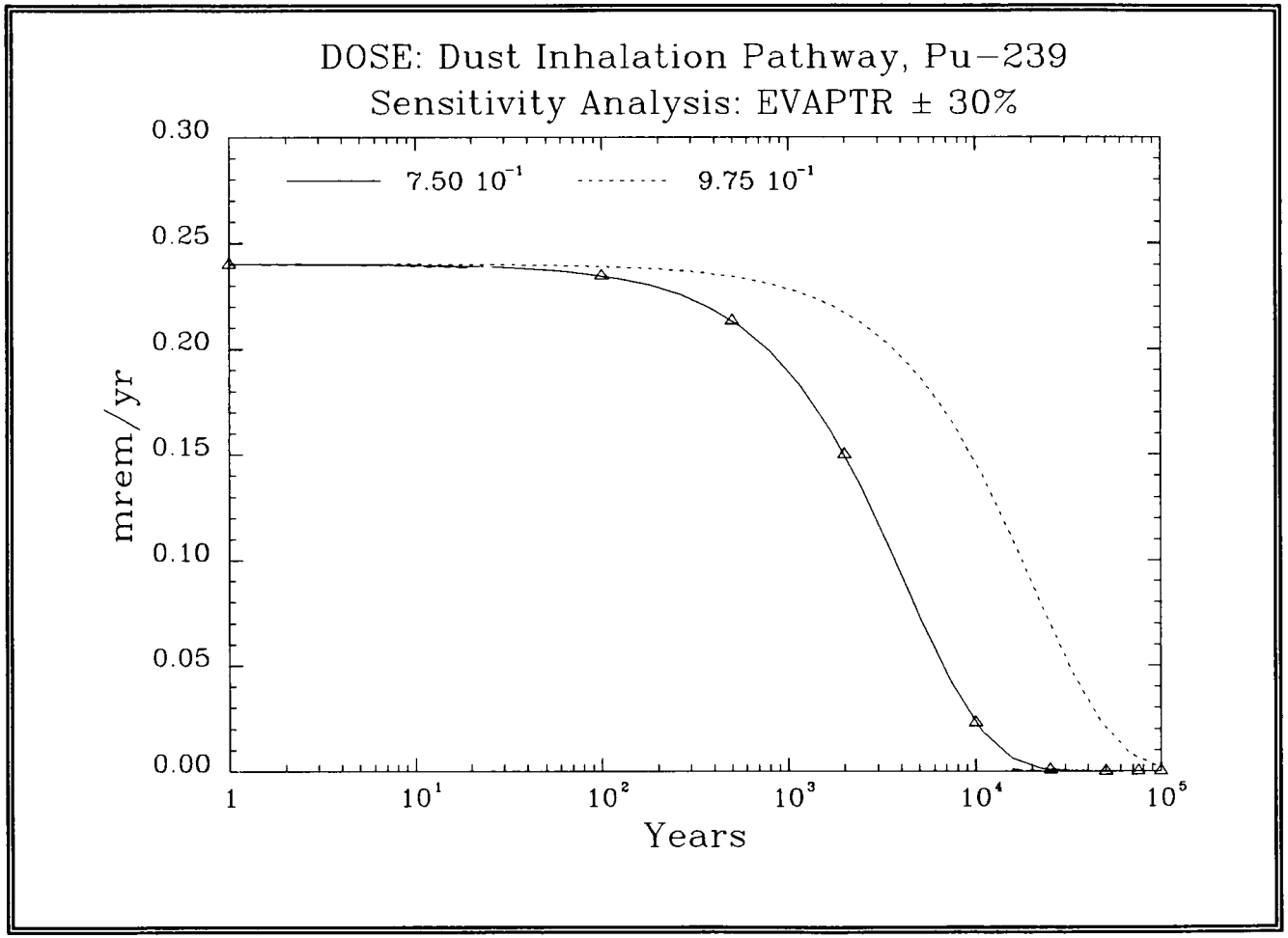


Figure 6-15: Evapotranspiration coefficient sensitivity

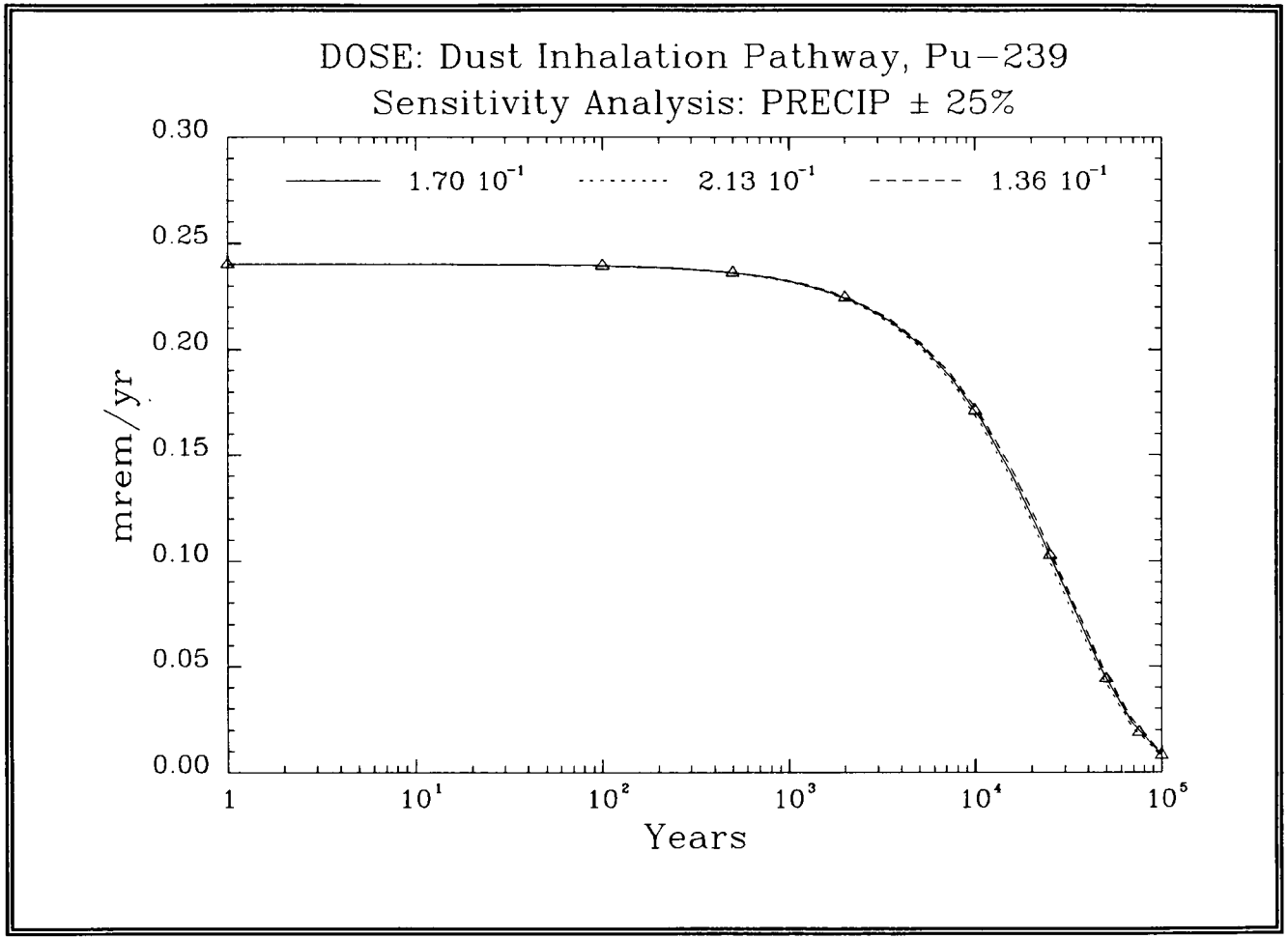


Figure 6-16: Precipitation sensitivity

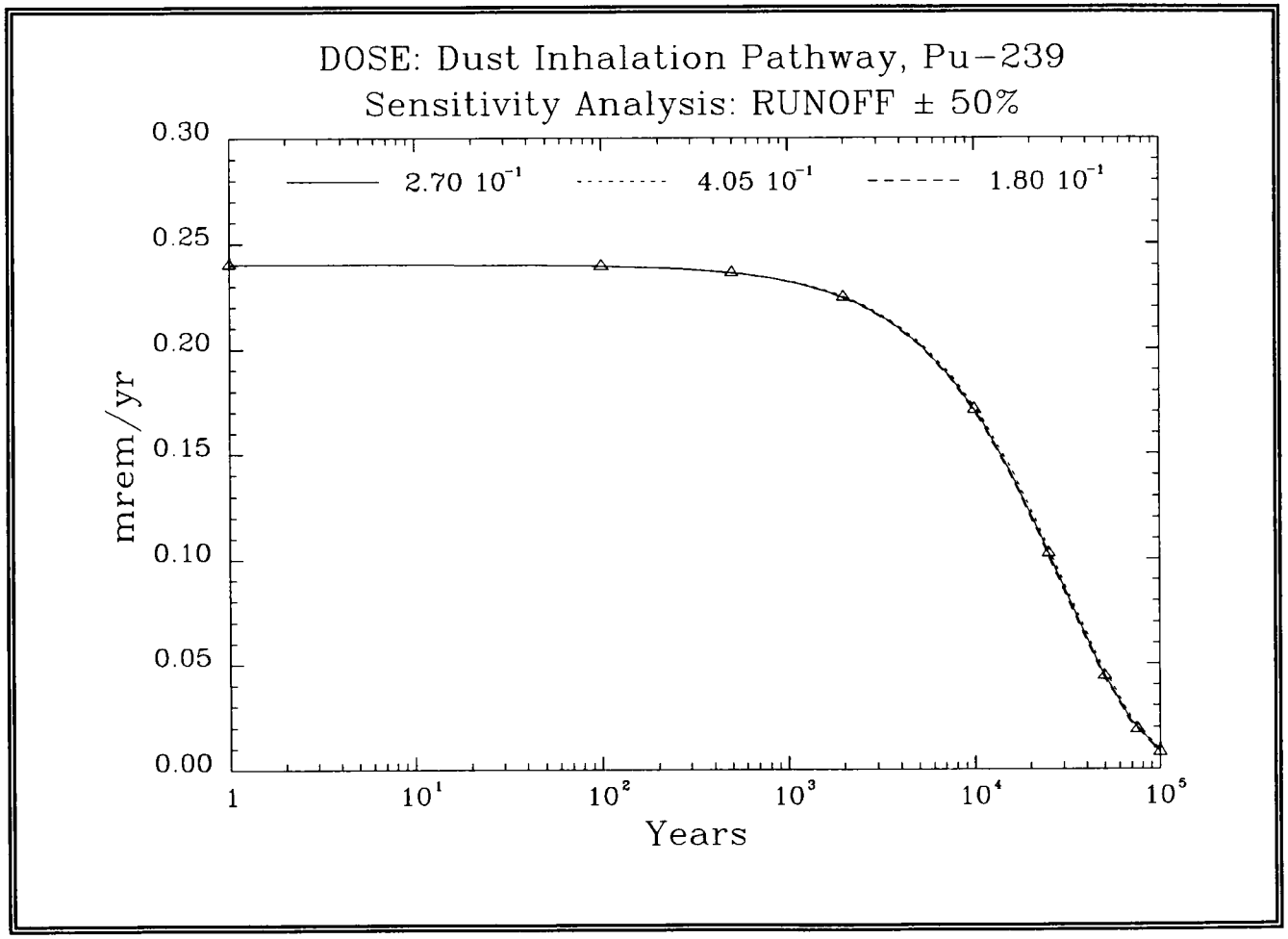


Figure 6-17: Runoff coefficient sensitivity

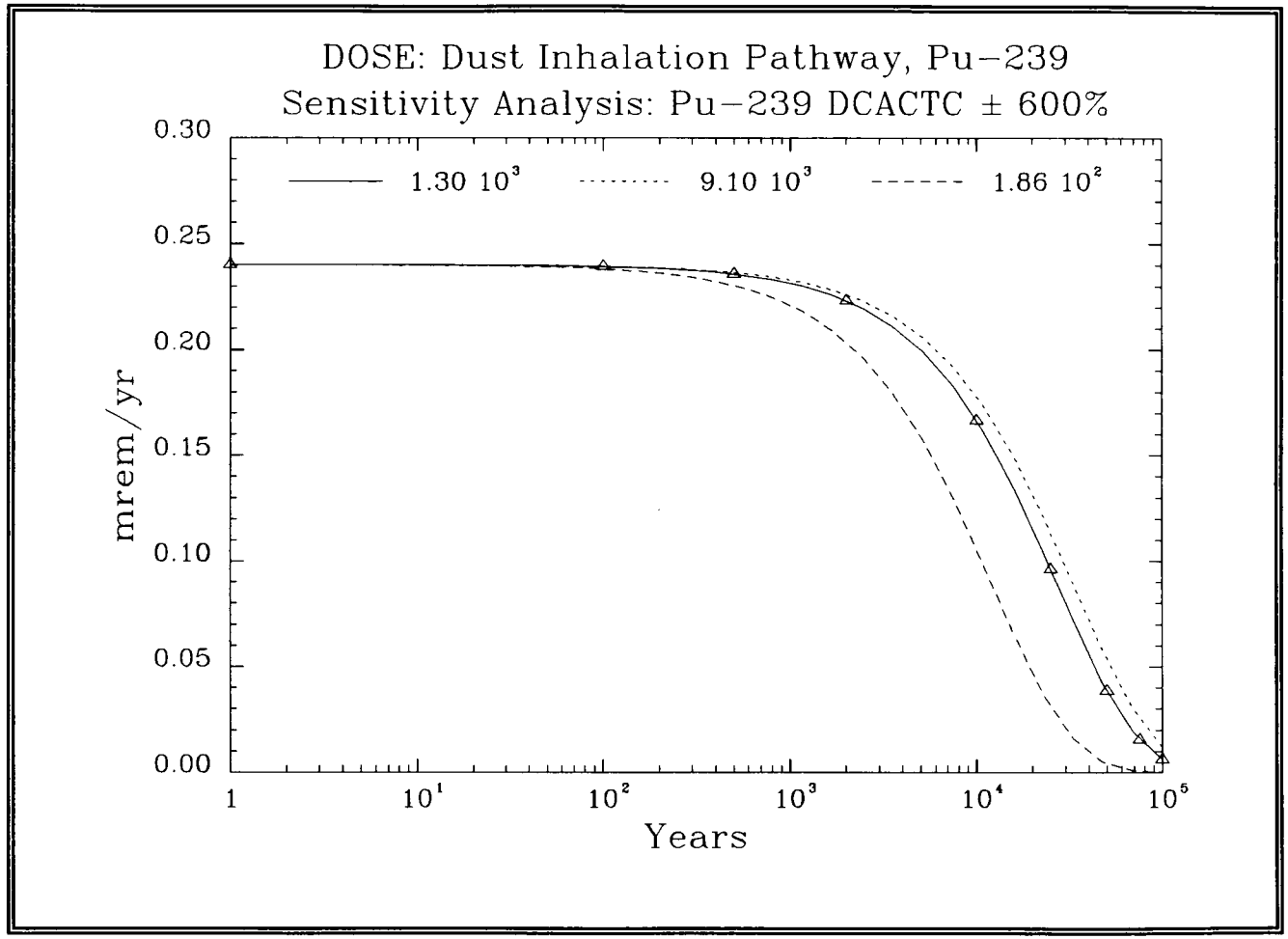


Figure 6-18: Pu-239 distribution coefficient sensitivity

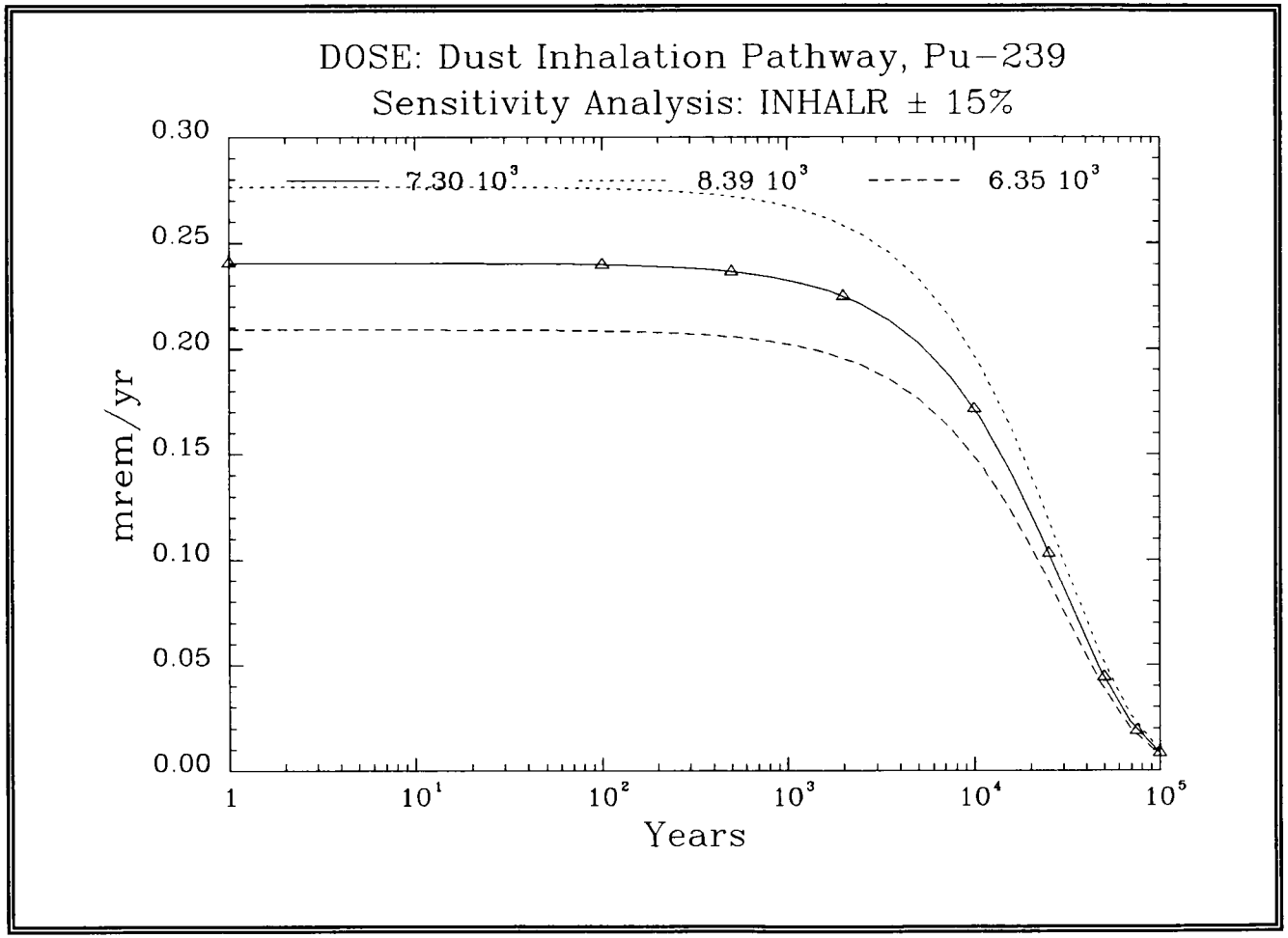


Figure 6-19: Inhalation rate sensitivity

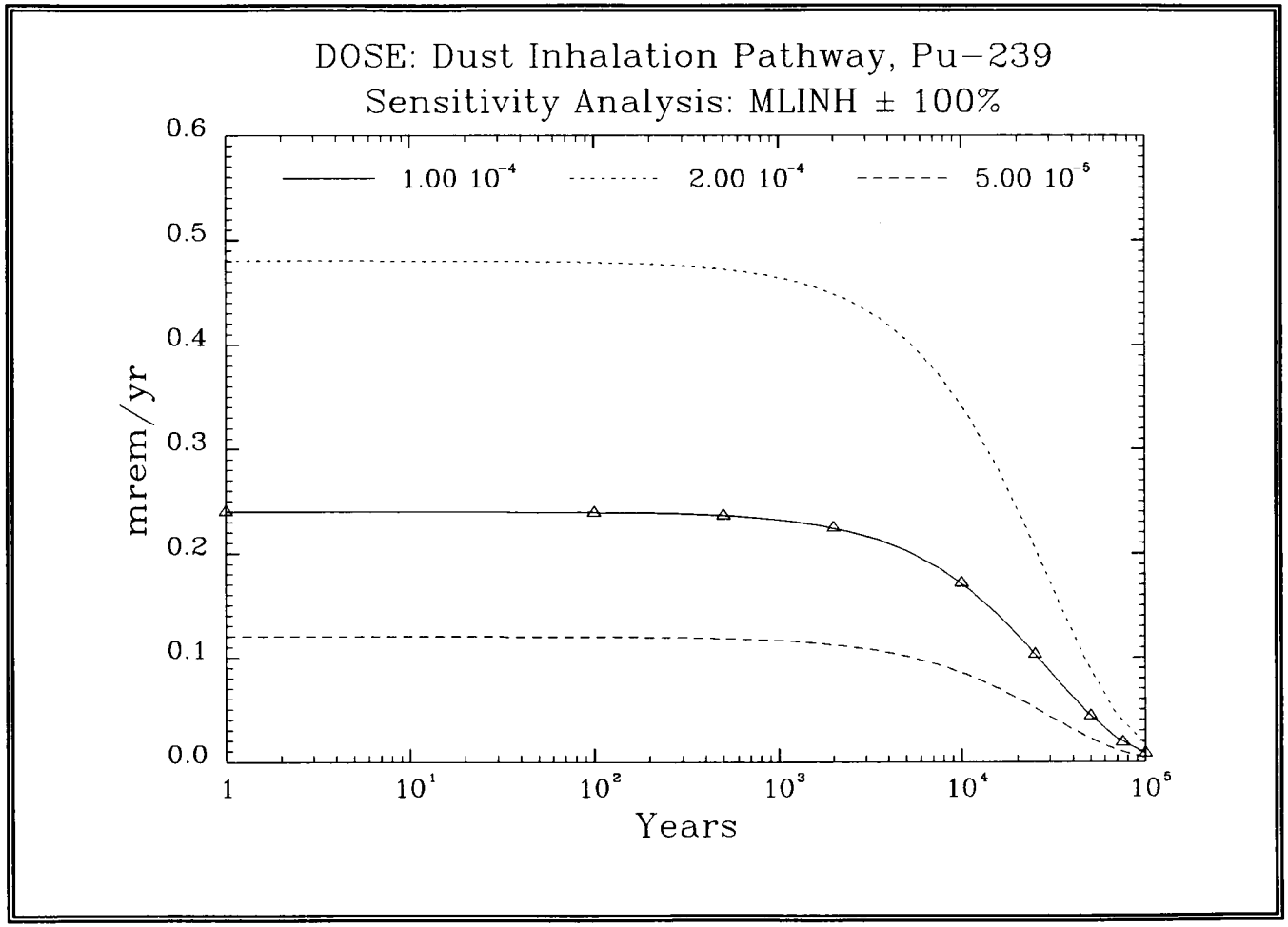


Figure 6-20: Mass loading factor sensitivity

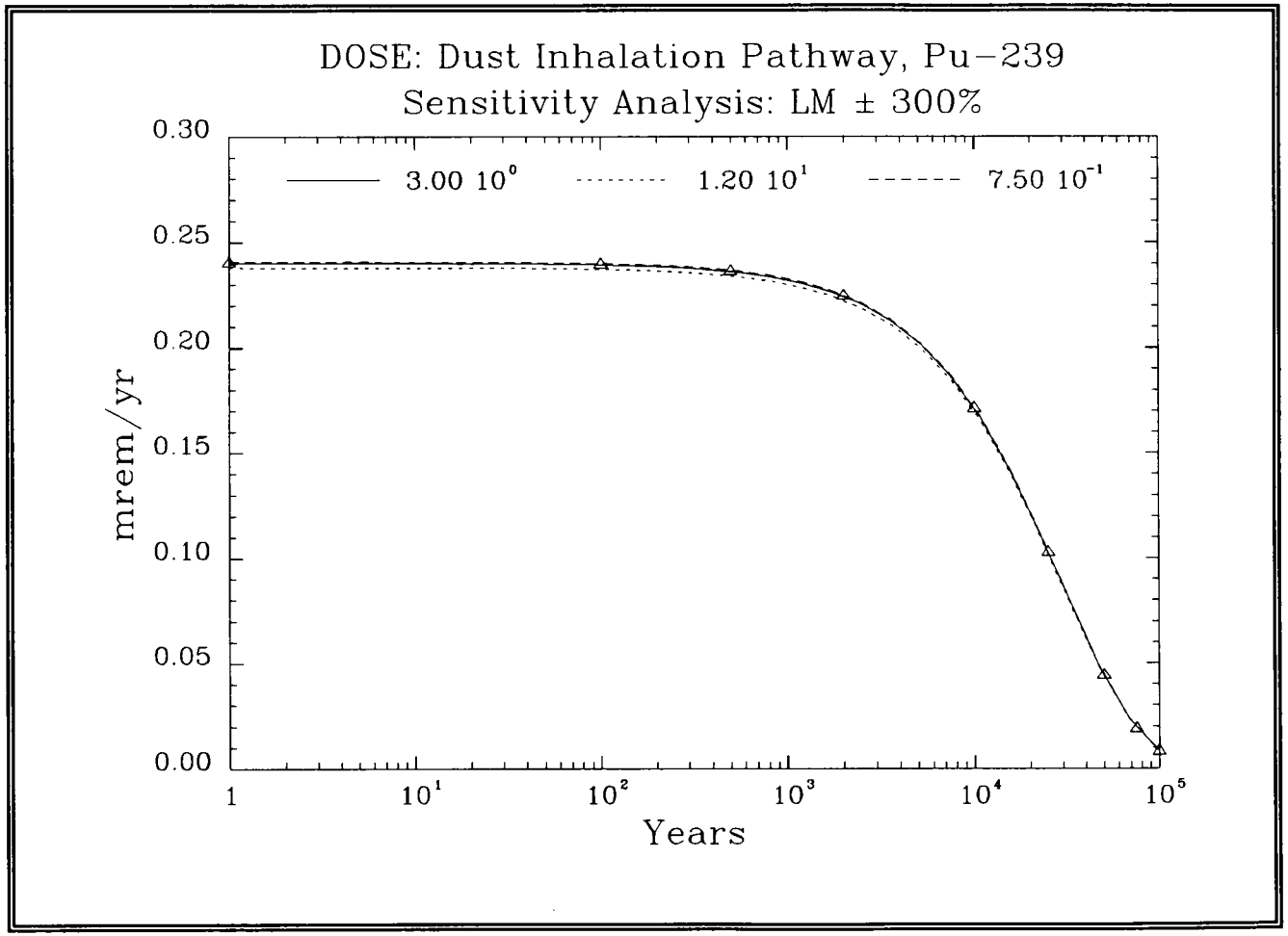


Figure 6-21: Dilution length sensitivity

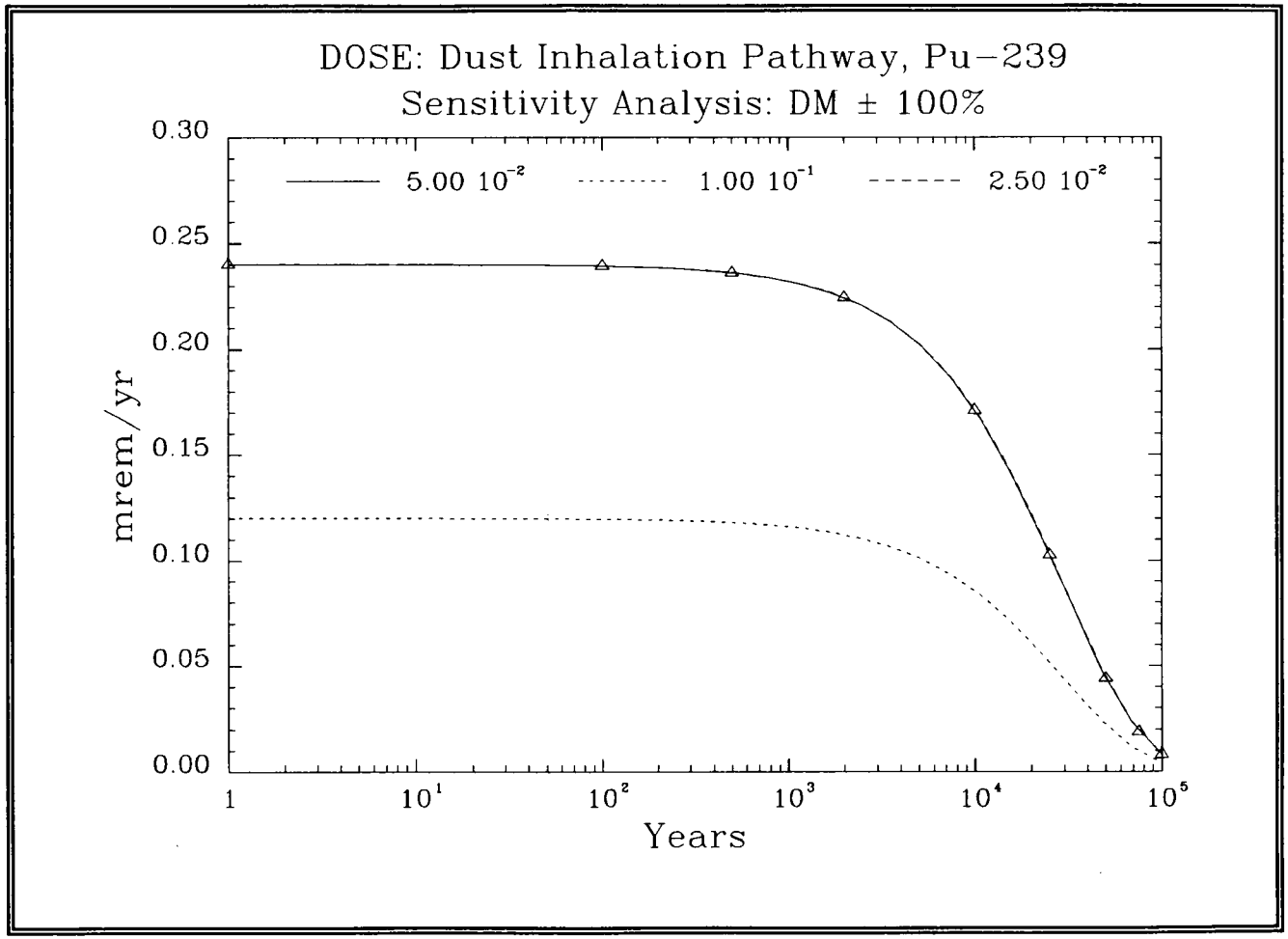


Figure 6-22: Soil mixing layer sensitivity

6.4 Sensitivity Analysis Results Discussion, Discussion of the Sensitive Parameters

The most sensitive parameters (in order of occurrence in Table 6-4) are the contaminated zone thickness, evapotranspiration coefficient, Pu-239 distribution coefficient, inhalation rate, mass loading factor, and soil mixing layer. The results of the RESRAD sensitivity analysis and the potential sensitivities of these parameters are discussed in Sections 6.4.1 through 6.4.6.

6.4.1 Contaminated Zone Thickness (Figure 6-8)

The RESRAD sensitivity analysis of the contaminated zone thickness does not appear to be useful for this study. RESRAD sensitivity of the thickness seems to be based on uncertainties in the initial estimate of the thickness. The type of sensitivity of contaminated zone thickness that would be useful for an Area 13 study is the changes in dose that would occur if changes in the thickness occurred over time. The thickness at Area 13 is fairly well quantified. Seventeen years after deposition, approximately 93 % of the Plutonium contamination at Area 13 was mixed within the top 5 cm of soil (Gilbert et al., 1975). Most of the plutonium will likely stay in the 5 cm layer unless disturbed.

For the case of Area 13, we are concerned with changes that could occur to the thickness over time instead of uncertainty in the initial estimate. The most likely change in the thickness over time would be an increase. A situation that would increase the thickness, thereby distributing the plutonium among a greater depth, would be plowing or tilling by a residential-farmer. (next page)

In this case, if the contamination is evenly spread over a 10 cm layer (twice the original thickness), the concentration and subsequent dose would be cut in half.

When RESRAD's sensitivity analysis analyzes the effect on the dose if the thickness is greater by a factor of 2 (10 cm), RESRAD assumes that the initial thickness is 10 cm; RESRAD does not consider that the increase in size occurred after initial time. Because RESRAD considers the uncertainty to be in the initial estimate of thickness, the soil concentration is considered to be the same and the net amount of contamination is greater by a factor of two. Because the concentration and mass loading factor are still the same, the amount of radionuclide being suspended in the air is still the same regardless of thickness, and the dose remains the same.

6.4.2 **Evapotranspiration Coefficient** (Figure 6-15)

Figure 6-15 shows that the lower the evapotranspiration coefficient, the lower the dose (i.e., more water infiltrates the contaminated zone to carry away contaminants). Using a value of 0.994 in the generic scenario is conservative and seems to be the upper bound on the realistic range.

6.4.3 **Distribution Coefficient** (Figure 6-18)

The distribution coefficient is the ratio of the mass of radionuclide adsorbed or precipitated onto unit mass of soil versus the solute, or leachate concentration. Therefore, the higher the distribution coefficient, the lower the concentration of the radionuclide in infiltrating water. When considering dust inhalation as the primary

source of dose, a high K_d is conservative. More plutonium is retained in the surface soil for resuspension. A lower K_d allows the plutonium to leach out of the surface soil at a faster rate.

Values for the distribution coefficient, K_d, were taken from the RESRAD manual (Yu et al., 1992, p. 235, 239). For soils and clays, K_d = 2000 cm^3/g, for sand, K_d = 200 cm^3/g, for pH = 7, K_d = 8500 cm^3/g, and for pH = 11, K_d = 1000 cm^3/g. The pH at Area 13 ranges from 7.8 to 8.4 (Leavitt, 1974).

Bondietti and Tamura (1980) state that determining the K_d at NTS is a complex problem. The plutonium exists in mixed-oxidation-state species; the majority of the plutonium is in oxidation state Pu(IV). Because the soil at NTS consists of different components (sand, silt, and clay), the interplay between these components and the stability of the various Pu oxidation states further complicates the problem.

The majority of the soil at NTS is sand. Samples taken by Tamura (1975) ranged from approximately 60 to 80 % sand by weight. The reason that K_d for sands (53 - 2000 μm) is less than K_d for clay (<2 μm) could be a combination of factors. As the size of a soil particle increases, the surface area to volume ratio decreases (i.e., less surface area per unit of mass of soil is available for particles to adsorb). In addition, effective porosities for sand are greater than effective porosities for clay (i.e., more pore space is available in sand for infiltrating rainwater).

Tamura (August 1992) believes the pH of a soil has more effect on K_d than the soil type. Figure 6-23 illustrates the relationship between K_d and pH for different soil to solution ratios and Pu oxidation states.

Using Figure 6-23 and the range of pH at Area 13 of 7.8 to 8.4, one can approximate K_d at Area 13 as 2,000 to 30,000 cm^3/g. This range is on the upper side of the nominal value in Figure 6-18. As can be seen in Figure 6-18, increases in K_d from the nominal value do not affect the dose as much as decreases from the nominal value. If we assume the K_d at Area 13 to be 2000 cm^3/g or higher, the changes in the dose would not be significant.

6.4.4 **Inhalation Rate** (Figure 6-19)

The inhalation rate has a one-to-one proportionality with dose. In Figure 6-19, when the inhalation rate is increased 15% (8400/7300=1.15), the dose is also increased by 15% (0.276/0.240=1.15).

Martin and Bloom use a value of 7300 m^3/yr in the NAEG model (1980). This value is recommended in ICRP-2 (1959). The default value of RESRAD is 8400 m^3/yr, which is recommended in ICRP-23 (1975). Both of these values were recommended for "reference man." Reference man (ICRP-23, 1975) is defined as being a Caucasian male 20-30 years of age, 170 cm in height and weighing 70 kg. Reference man is assumed to spend, per day, 8 hours working at a "light activity" pace, 8 hours doing nonoccupational activity, and 8 hours resting. Any differences

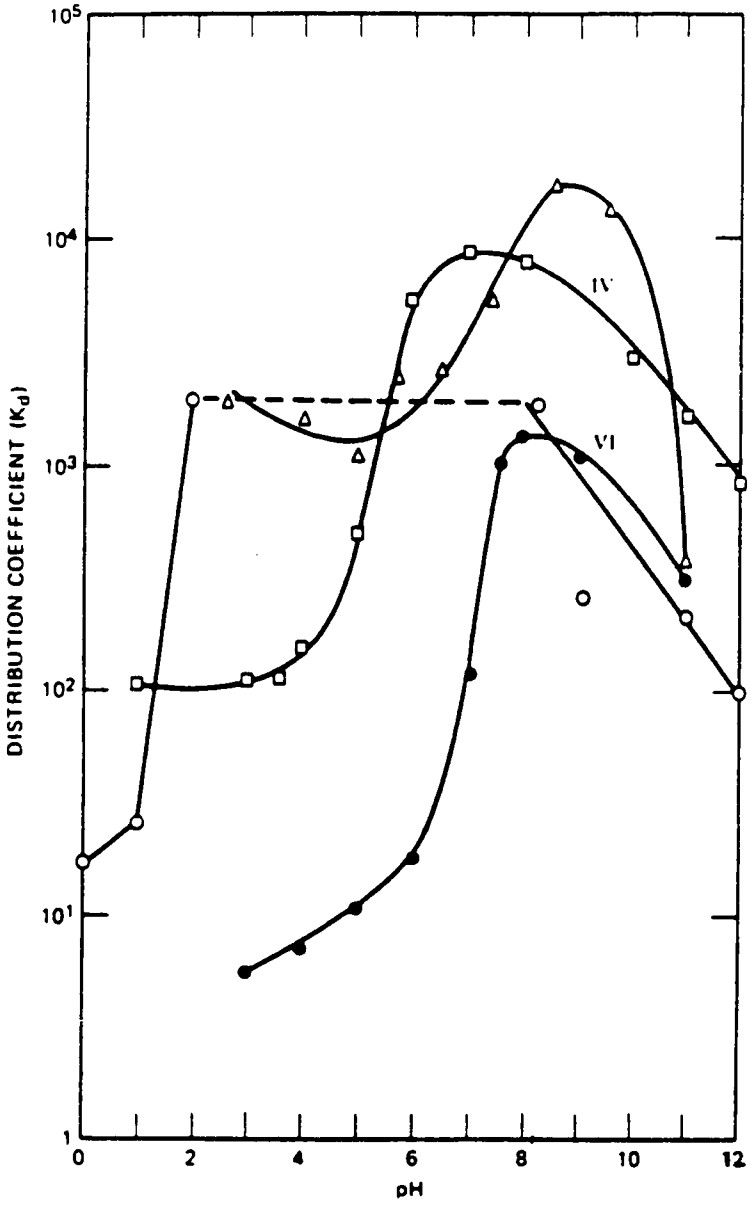


Figure 6-23: Effect of pH on plutonium sorption to soils

△: soil/solution ratio, 1/12.5 (Nishita, 1976)
●: soil/solution ratio, 1/10, Pu(VI) (Prout, 1958)
□: soil/solution ratio, 1/10, Pu(IV) (Prout, 1958)
○: soil/solution ratio, 1/20 (Rhodes, 1957)

Source: Bondietti, E. A., and T. Tamura, 1980, Physicochemical Associations of Plutonium and Other Actinides in Soils, in *Transuranic Elements in the Environment*, W. C. Hanson (Ed.), pp. 145-164, USDOE Report, DOE/TIC-22800.

in an individual from these reference man statistics will likely mean a difference in the inhalation rate as well. An individual could have any combination of the descriptive factors such as age, sex, race, height, weight, and activity. The inhalation rate varies more with certain differences than with others. Differences in weight and activity will probably have more effect on the inhalation rate than differences in age, sex, or race.

For purposes of conservatism, the value of 8400 m^3/yr could be used instead of 7300 m^3/yr.

Although not considered in the sensitivity analysis, a factor that will influence the inhalation rate *of contaminated dust* is the occupancy factor, or fraction of time the receptor spends in the contaminated area. For conservatism, the occupancy factor in the RESRAD model was set at 1. An occupancy factor of 1 means that the receptor is exposed to contamination 24 hours a day, 7 days a week, for a total of 168 hours a week. This factor will change according to land-use scenarios. A resident on the site would have the highest occupancy factor. If the resident was living at the center of the site, the occupancy factor could be very close to 1. A worker on the site, if working 40 hours a week, would have an occupancy factor of about 0.24.

6.4.5 **Mass Loading Factor** (Figure 6-20)

The mass loading factor appears to have the most potential for sensitivity because a combination of its one-to-one proportionality with dose and its potential for variability.

Anspaugh (1974) has suggested that a mass loading factor of 100 $\mu g/m^3$ is a reasonably conservative estimate for normal weather conditions at NTS and can be used for predictive purposes. This value is used in the NAEG model. The mass loading factor observed during the cascade impactor run at the GMX site of NTS was measured as 70 $\mu g/m^3$. The RESRAD default for the mass loading factor is 200 $\mu g/m^3$.

The mass loading factor can be approximated using the resuspension factor, which is the ratio of air concentration (curies per cubic meter) to surface soil concentration (curies per square meter). Resuspension factors varying from 9.1 E(-11) m^{-1} to 5.4 E(-9) m^{-1} (Romney et al., 1987) were calculated at NTS from measurements of surface soil and air concentrations. The geometric mean and arithmetic average of these calculations are 2.9 E(-10) m^{-1} and 6.8 E(-10) m^{-1}, respectively. If it is assumed that the radioactivity of one square meter is associated with 50 kg of soil (5 cm depth x E(4) cm^2/m^2 x E(-3) kg/cm^3 soil), a resuspension factor of 1 E(-10) m^{-1} is equivalent to a mass loading factor of 5 $\mu g/m^3$ (1 E(-10) m^{-1} X 50,000 g/m^2 = 5 E(-6) g/m^3). Using this conversion technique, the range of 9.1 E(-11) m^{-1} to 5.4 E(-9) m^{-1} converts to 4.55 $\mu g/m^3$ to 270 $\mu g/m^3$,

respectively. The geometric mean and arithmetic average of 2.9 E(-10) m^{-1} and 6.8 E(-10) m^{-1} convert to 14.5 $\mu g/m^3$ and 34 $\mu g/m^3$, respectively. The geometric mean and arithmetic average of the range, after conversion to mass loading factor units, are lower than both the measured value of 70 $\mu g/m^3$ and the suggested modeling value of 100 $\mu g/m^3$. However, the extreme of the range, 270 $\mu g/m^3$, is higher than both 70 and 100 $\mu g/m^3$.

Data from 1966 by the NAPCA gives mass loading factors for 217 urban and 30 non-urban stations. The annual arithmetic averages for the urban stations varied from 33 $\mu g/m^3$ for St. Petersburg, Florida to 254 $\mu g/m^3$ for Steubenville, Ohio. The mean arithmetic average for the urban stations was 102 $\mu g/m^3$. The averages for the non-urban stations varied from 9 $\mu g/m^3$ for White Pine County, Nevada to 79 $\mu g/m^3$ for Curry County, Oregon. The mean arithmetic average for the non-urban stations was 38 $\mu g/m^3$. The measured extremes of this variable for various U.S. localities are approximately 5 E(-7) to 0.5 grams/m^3 (0.5 to 5 E(-5) $\mu g/m^3$, respectively).

The mass loading factor can vary significantly according to weather phenomena. "Dust devils" commonly occur at NTS and could temporarily increase the mass loading factor. "Dust devils" are similar to tornados except less powerful in magnitude.

In addition to possible variations according to the weather, the mass loading factor

can also vary significantly according to land-use scenarios. Any activity that disturbs the surface soil could raise the mass loading factor above its value for ambient conditions. A residential-farmer could raise the mass loading factor in any number of ways such as agricultural plowing, tilling, and cultivating, or using transport vehicles. If the farmer was involved in ranching activities, his/her cattle or dairy herd could increase the mass loading factor by roaming and grazing. An estimated mass loading factor for agriculture-generated dust is 300 $\mu g/m^3$ (Oztunali et al., 1981). Mass loading factors as high as 1.3 g/m^3 (1.3 E(6) $\mu g/m^3$) have been measured for instantaneous mass loading during tilling (Yu et al., December 1992).

Removing soil, such as removal for sampling or cleanup, would be an example of a way a worker at the site could raise the mass loading factor. Wetting of the soil prior to removal would reduce resuspension.

6.4.6 **Soil Mixing Layer** (Figure 6-22)

Seventeen years after deposition, approximately 93 % of the plutonium contamination at Area 13 was mixed within the top 5 cm of soil (Gilbert et al., 1975). From this observation, one can approximate the soil mixing layer as 5 cm. Unless the surface soil is disturbed, most of the plutonium will likely stay in the 5 cm layer.

At Area 13, a realistic scenario for the future would be an increase in the soil mixing layer. This increase in the soil mixing layer would be because of a disturbance of

the surface soil, and the subsequent increase in the contaminated zone thickness to the size of the soil mixing layer could be simultaneous or gradual. If plowing by a residential-farmer was performed on the surface soil, the soil mixing layer and contaminated zone thickness would increase simultaneously. If a large vehicle were to travel over the surface soil, the upper layers of soil could be loosened, increasing the soil mixing layer, and promoting a gradual change in the contaminated zone thickness.

An increase in the size of soil mixing layer and thickness would spread the contamination over a greater depth, reducing concentration and subsequent dose. In Figure 6-20, when the soil mixing layer is greater by a factor of two, the dose is less by a factor of two.

6.5 Normalized Dose Results Scaled to Area 13 Stratum Contamination Values

In Section 6.2.3, Table 6-3, Normalized Dose results (committed effective dose equivalent, mrem/yr per pCi/g of Pu-239,240) as a function of year after initial time were calculated for the radionuclides Pu-239, Pu-240, Pu-241, and Am-241. The purpose of Section 6.5 is to scale the normalized dose results to the activity of the six different strata at Area 13. The results of Table 6-3 are summarized in Table 6-5.

Table 6-6 performs the scaling of the total, normalized doses in Table 6-5. The initial activity of Pu-239,240 for each stratum is multiplied by the total doses for the various years after initial time in Table 6-5. The result is a matrix of doses as a

Table 6-5: Total, normalized dose (mrem/yr per pCi/g of initial Pu-239,240) as a function of year after initial time

Year 1	Year 73.3	Year 400	Year 1000	Year 10000	Year 30000	Year 1 E(5)
0.278	0.334	0.298	0.256	0.17	0.083	0.01

Table 6-6: Total doses for Area 13 strata and radionuclides Pu-239, Pu-240, Pu-241, and Am-241

Area 13 Stratum	Initial Pu-239/240 pCi/g	Dose at Year 1	Dose at Year 73.3	Dose at Year 400	Dose at Year 1000	Dose at Year 10000	Dose at Year 30000	Dose at Year 1 E(5)
1	36	10.0	12.0	10.7	9.22	6.12	2.99	0.36
2	100	27.8	33.4	29.8	25.6	17.0	8.30	1.00
3	400	111	134	119	102	68.0	33.2	4.00
4	1100	306	367	328	282	187	91.3	11.0
5	2400	667	802	715	614	408	199	24.0
6	14000	3890	4680	4170	3580	2380	1160	140

function of stratum and time. For example, for Year 1 and stratum 1, the dose is 10 mrem/yr ((36 pCi/g of initial Pu-239,240 activity) X (0.278 mrem/yr per pCi/g of initial Pu-239,240 activity) = 10.0 mrem/yr).

The numbers for initial Pu-239,240 activity in Table 6-6 were actually measured approximately 17 years after the initial time of 1957 (Gilbert et al., 1977). However, because the half-life of Pu-239 is 24,100 years, these numbers differ from the activities at initial time by only a factor of about 0.0005 (0.05%).

The results in Table 6-6 are illustrated graphically in Figure 6-23. The dose (mrem/yr) for each stratum is plotted as a function of year after initial time.

6.6 Compliance with Department of Energy Standards

6.6.1 DOE Order 5400.5: 100 mrem/yr to Public

The current DOE standards for protection of the public and the environment are contained in DOE Order 5400.5, issued by DOE in February 1990. The DOE is now proposing to promulgate the standards to law in *10 Code of Federal Regulations* (CFR) *Part 834*. The proposed rule was published for comment in March 1993, and differs from DOE Order 5400.5 in format rather than substance.

The primary dose limit to members of the general public is 100 mrem/yr effective dose equivalent for a combination of external and internal exposures. This limit was recommended in ICRP-26 (1977) and is based on the prevention of stochastic

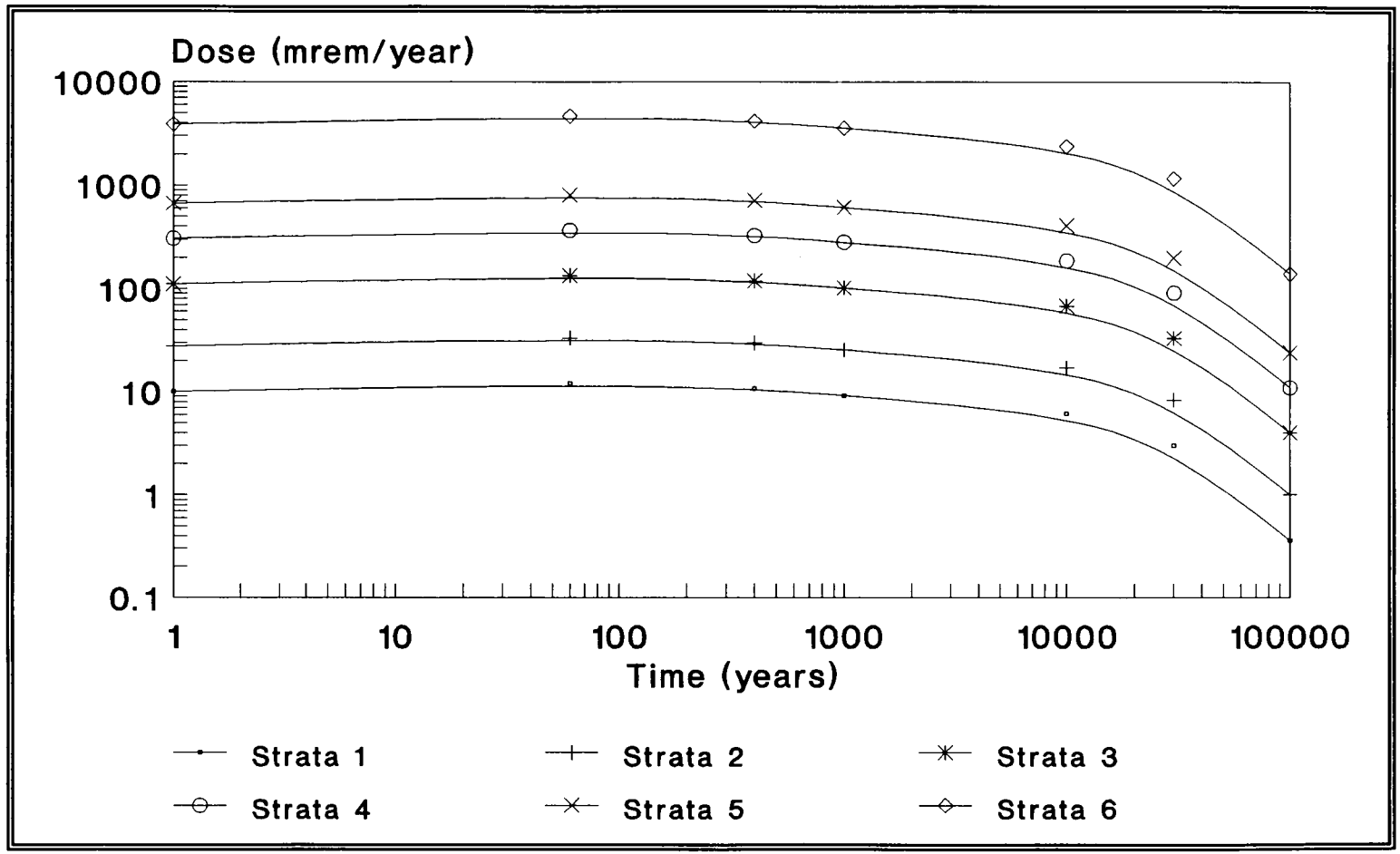


Figure 6-24: Dose accumulated per year as a function of year after initial time and Area 13 strata

(probabilistic) radiation effects. The ICRP concluded that risks relating to the limit of 100 mrem/yr are consistent with the public's general "level of acceptance" for risks, which is the range of 1 E(-6) to 1 E(-5) per year. DOE did not set limits for non-stochastic (deterministic) effects because the limit for protection against stochastic effects is well below the threshold for non-stochastic effects. Non-stochastic effects occur only after a threshold dose is exceeded. Examples of such effects are cataracts and skin burns. Radiation-induced cancer is an example of a stochastic effect. The DOE assumes that stochastic effects can occur without a threshold (i.e., it is assumed that any exposure, even a low exposure, can cause adverse health effects); therefore, DOE requires that the As Low As Reasonably Achievable (ALARA) concept be implemented in addition to the primary dose limit.

In the case of residual radioactive material, such as the plutonium at Area 13, Argonne National Laboratory, through the support of DOE, developed the RESRAD computer code for calculating doses and RESidual RADioactive Material Guidelines. RESRAD was developed to aid in implementing the limits and applying the ALARA process required by DOE Order 5400.5.

For analyzing Area 13's compliance with the 100 mrem/yr primary limit of DOE Order 5400.5, we examine the dose values given in Table 6-6. Up to the year 1000, doses calculated for strata three through six exceed the limit. At year 10000, values in strata four through six exceed the limit. (next page)

At year 30000, values in strata five and six exceed the limit, and at year 1 E(5), only the value in stratum six exceeds the limit.

DOE Order 5400.5 states that site-specific soil activity concentrations should be achieved that yield doses below the specified limits and that satisfy ALARA. For scenarios that have a fairly high probability of occurring within the first 50 years after release of the property, the activity limits selected should ensure that doses to individuals on the property are well below the primary dose limit and are ideally on the order of a few mrem in a year. For scenarios that have a low probability of occurring immediately after release or over the long term, a large fraction of the 100 mrem/yr dose limit is acceptable.

A future land-use probability investigation for Area 13 was not performed in this study. The probability of a residential-farmer at Area 13 would have to be considered along with probabilities of other possible future land-uses to determine appropriate land-release criteria. In addition, special consideration must be given to Area 13 due to its location on NAFR. As long as national security is a concern, NAFR will probably be needed by the Air Force. Therefore, Area 13 probably will never be released.

6.6.2 *DOE Radiological Control Manual*: 5 rem/yr to Workers

The *DOE Radiological Control Manual* was developed to protect occupational workers from overexposure to radiation. A fundamental principle of the manual

taken from the Radiation Protection Guidance to the Federal Agencies for Occupational Exposure (signed by President Reagan in January 1987) is

> There should not be any occupational exposure of workers to ionizing radiation without the expectation of an overall benefit from the activity causing the exposure.

The Reynolds Electrical & Engineering Company, Inc. (REECo), site contractor for DOE Nevada Operations, has prepared a site specific manual, the *Nevada Field Office / Yucca Mountain Project (NV/YMP) Radiological Control Manual* (DOE, 1992), to implement the limits and procedures outlined in the *DOE Radiological Control Manual*.

The *DOE Radiological Control Manual* sets dose limits for the whole body and individual organs. The whole body dose limit is 5 rem (effective dose equivalent). This whole body dose is for a combination of internal and external exposures. The dose limit for any organ or tissue and skin is 50 rem (dose equivalent), except for the lens of the eye, which has a limit of 15 rem. These limits were suggested in ICRP-30 (1981). In addition to setting dose limits, the manual states that exposures should be as low as reasonably achievable (ALARA).

None of the doses calculated for the Area 13 strata exceed the 5 rem/yr (5000 mrem/yr) whole body limit.

The next step is to analyze compliance with the 50 rem organ or tissue limit. Weighting factors are defined in ICRP-30 (1981) to convert dose equivalents, H_Ts, for the various organs and tissues to a whole body effective dose equivalent, H_E. If the doses to the organs and tissues and the whole body are calculated for a 50-year period following internal exposure, then the dose is a committed dose. The committed effective dose equivalent is

$$H_{50,E} = \sum_T w_T H_{50,T}$$

Killough and Eckerman (1983) have calculated committed doses equivalent to organs and tissues of the body from a unit intake by inhalation or ingestion of various radionuclides and have summed these doses using the above equation to yield committed effective doses equivalent (whole body doses). The results of calculations by Killough and Eckerman (1983) for inhalation of a unit intake of Pu-239 (1 Bq or 1 disintegration/second) are given in column 2 of Table 6-7; committed doses equivalent are listed for various organs and tissues. All organs given weighting factors by the ICRP are listed in the table. The remainder organs are considered to be the five highest irradiated tissues for which specific weighting factors were not assigned. In addition to listing the calculations of Killough and Eckerman, Table 6-7 lists the relative committed doses equivalent that would be received by the various organs and tissues in order for a worker to receive 5 rem

Table 6-7: Committed doses equivalent to various organs and tissues from inhalation of Pu-239

Organ or Tissue	Dose, H_T (rem/Bq)	Relative Dose, H_T (rem)	Weighting Factor, w_T	Contribution to H_E ($H_T w_T$), (rem)
(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)
Gonads	1.20 E(-3)	0.7	0.25	0.17
Breast	2.79 E(-9)	~0	0.15	~0
Red Bone Marrow	7.60 E(-3)	4.1	0.12	0.49
Lungs	3.23 E(-2)	18.1	0.12	2.17
Thyroid	2.34 E(-10)	~0	0.03	~0
Endosteal Bone Surfaces	9.50 E(-2)	51.7	0.03	1.55
Remainder	4.16 E(-3)	2.3	0.30	0.69
Whole Body	H_E = 9.19 E(-3)	H_E = 5	Σw_T = 1	H_E = 5

Source: Killough, G. G., and K. F. Eckerman, 1983, Internal Dosimetry, in *Radiological Assessment: A Textbook on Environmental Dose Analysis*, J. E. Till and H. R. Meyer (Eds.), Report NUREG/CR-3332, Chapter 7, Oak Ridge National Laboratory, Oak Ridge, TN, NTIS

committed effective dose equivalent. The committed effective dose equivalent for a 1 Bq intake of Pu-239 is 9.19 E(-3) rem. To receive a committed effective dose equivalent of 5 rem by inhalation, the relative committed doses equivalent that would be received by the various organs and tissues are listed in column three. These numbers were calculated using the numbers in column two. For the lungs, 3.23 E(-2)/9.19 E(-3) = x/5, x = 18.1. The committed doses equivalent in column three were multiplied by weighting factors in column four to obtain the numbers in column five, which add up to the 5 rem committed effective dose equivalent.

On the assumption that 100 % of the whole body dose is because of inhalation, if the whole body dose is 5 rem, only the dose for endosteal bone surfaces of 51.7 rem exceeds the 50 rem organ or tissue limit set in the manual. Generally, it seems reasonable for Area 13 that if a worker is in compliance with the 5 rem whole body limit, then the worker is most likely also in compliance with the 50 rem organ or tissue limit.

Various scenarios are possible for worker exposure. DOE Nevada Operations and site contractor REECo are planning cleanup for Area 13. In preparation for cleanup, workers obtain soil samples for laboratory analysis. Exposure to the contamination during sampling is low. The workers are only on the site a short period of time to obtain samples, and the soil is wetted to reduce suspension of soil particles.

A worker scenario that has much greater potential for exposure is that of the remediation worker. Contaminated surface soil will be removed from the site and cleaned at an off-site area. The proposed method for removing the surface soil is a rotomill pavement trimmer. The crucial factor to consider in determining exposure potential is the mass loading factor. The act of removing soil could highly elevate the mass loading factor above its value for ambient conditions. A precaution to reduce the greater risk of a higher mass loading factor is the wetting of the soil prior to removal. Another precaution that will likely be taken during soil removal is the wearing of special breathing apparatuses by the workers.

For conservatism, the doses in Table 6-6 were calculated for an occupancy factor of 1. An occupancy factor of 1 means that the receptor is exposed to contamination 24 hours a day, 7 days a week, for a total of 168 hours a week. A worker on the site, if working 40 hours a week, would have an occupancy factor of about 0.24. A worker with an occupancy factor of 0.24 would receive 0.24 of the dose that a worker with an occupancy factor of 1 would receive.

7.0 Discussion of Results

The objective of this study is to analyze the potential hazard of plutonium at Area 13 for current and future human land-use scenarios. The generic dose assessment produced results in terms of normalized doses (mrem/yr per initial pCi/g) as a function of year after initial time; these doses were scaled to the concentrations of the Area 13 strata. The stratum doses were used to analyze compliance of the land-use scenarios at Area 13 with DOE standards. Each step taken in the study adds more uncertainty to the study and its results. To understand the accuracy and appropriateness of this application of RESRAD and its results, we will briefly analyze the assumptions used to obtain the results, the subsequent uncertainties in the results from these assumptions, and uncertainties in applying the results.

To address the assumptions and uncertainties in this study, we attempt to answer the following questions. What assumptions were made to obtain values for the RESRAD model parameters? What assumptions were made in using the equations of the RESRAD model (i.e., how accurate are the equations in modeling natural phenomena)? What assumptions were made in applying the RESRAD results to the strata of Area 13? In what ways do these assumptions create uncertainties in the results? What assumptions were made in applying the dose results to analyze compliance of land-use scenarios at Area 13 with DOE standards?

The discussion of assumptions used to obtain the results, subsequent uncertainties in the results, and uncertainty in applying the results to analyze compliance with DOE standards will be used to lead into a discussion about the usefulness of this study, especially in light of DOE plans to clean up the safety shot areas. This discussion will include mention of efforts by DOE to plan and conduct cleanup at the TRC, applicability of the study results to administrative and regulatory decision making, and applicability of RESRAD to modeling environmental transport and determining dose at Area 13. An outline of the contents of this chapter is given in Figure 7-1.

7.1 Assumptions and Uncertainties in RESRAD Model Parameters

For the generic dose assessment, values used for the parameters were approximate values. These approximate values were determined using a literature search for data and a subsequent analysis of this data. For most of the parameters, determining these approximate values required judgement and assumptions. Every approximate value used will create some uncertainty in the results. The purpose of the sensitivity analysis was to lead us to parameters for which the variations might have a significant effect on the results (i.e., "sensitive parameters"). From this sensitivity analysis, six parameters were found to be potentially sensitive. These values are the contaminated zone thickness, evapotranspiration coefficient, Pu-239 distribution coefficient, inhalation rate, mass loading factor, and soil mixing layer. These parameters, therefore, have the potential to add more uncertainty to the results than the other parameters. (next page)

7.1 Assumptions and Uncertainties in RESRAD Model Parameters

7.2 Accuracy of the RESRAD Model Equations
- 7.2.1 Atmospheric Modeling
- 7.2.2 Leaching Model

7.3 Other Assumptions
- 7.3.1 Radionuclide Concentrations in Soil
- 7.3.2 Radionuclide Contribution to Dose
- 7.3.3 Modes of Exposure

7.4 Assumptions in Scaling Results to Area 13 Strata

7.5 Uncertainty in Applying Results to DOE Standards
- 7.5.1 DOE Order 5400.5, Residential-Farmer
- 7.5.2 *DOE Radiological Control Manual*, Industrial-Worker

7.6 Applicability of Results to Decision Making
- 7.6.1 DOE Plans to Clean Up Plutonium-Contaminated Soil on the TRC
- 7.6.2 Key Decisions in Cleanup Operations
- 7.6.3 Effect of Cleanup on Applicability of Results
- 7.6.4 Standards

7.7 Applicability of RESRAD to Determining Potential Doses at NTS

7.8 Applicability of RESRAD Sensitivity Analysis

Figure 7-1: Outline of discussion sections

Variations in these parameters that could occur according to activities of human land-users are discussed in Sections 7.5.1 and 7.5.2.

An analysis of model uncertainty from parameter uncertainty is not within the scope of this study; however, a brief discussion is appropriate. From Chapter 6, to obtain the annual intake, E(t) (Ci/yr), of radionuclide by dust inhalation, an environmental transport factor ETF(t) (g/yr) is multiplied by the concentration, S(t), of the radionuclide in the soil (Ci/g). The ETF is expressed as

$$ETF(t) = ASR \times FA \times FCD(t) \times FO \times FI$$

where

ETF(t) = environmental transport factor at time t for dust inhalation of radionuclide (g/yr)

ASR = average mass loading of airborne contaminated soil particles (g soil/m^3 air)

FA = area factor (dimensionless)

FCD(t) = cover and depth factor (dimensionless)

FO = occupancy factor (dimensionless), and

FI = annual intake of air (m^3/yr).

Because of the multiplicative nature of RESRAD's inhalation model, uncertainties in each parameter of the above equation multiply, and hence uncertainties in the annual intake, E(t), accrue multiplicatively. The leaching model creates uncertainty in the annual intake because of its effect on uncertainty of the soil concentration,

S(t). For a detailed description on procedures for conducting uncertainty analysis, one can refer to Hoffman and Gardner (1983).

7.2 Uncertainties in the RESRAD Model Equations

In addition to uncertainties in the parameters, uncertainties in the accuracy of the RESRAD model equations can lead to uncertainties in the results. The equations are approximations of natural phenomena. Under the hypothetical situation that all model parameters were highly accurate, how well would the equations model the actual situations in nature?

The two categories of equations from the RESRAD model used in this study, atmospheric modeling with the mass loading factor and the leaching model, are described in the next two sections.

7.2.1 Atmospheric Modeling

The atmospheric model of RESRAD uses the mass loading factor to model resuspension. Numerous uncertainties can arise in the use of this model. The model assumes that the specific activity of aerosol (pCi/g) will approximate the specific activity of soil (pCi/g). Use of Tamura's soil plutonium index and EPA's enrichment factor in Chapter 3 analyzed the accuracy of this assumption. These measures accounted for the distribution of plutonium among the particle sizes and the particle size distribution of the aerosol. Using these parameters, it was found that, at Area 13, the specific activity of aerosol could be 1.3 to 2.0 times greater

than the specific activity of soil. These calculations did not account for mixing of the aerosol with aerosol from surrounding strata or for dilution of the aerosol by uncontaminated dust blown in from uncontaminated areas. No adjustment was made in this study to account for the potential difference between specific activity of soil and specific activity of aerosol.

The RESRAD model attempts to account for dilution of contaminated aerosol by uncontaminated aerosol with the parameter dilution length. The dilution length depends on wind speed, mixing height, resuspension rate, and thickness of the resuspendible dust layer (Gilbert et al., 1983). Sensitivity of the dilution length with respect to its possible effect on results becomes less important for larger areas such as Area 13.

7.2.2 Leaching Model

For this study of inhalation dose at Area 13, the leaching model in RESRAD is used to model the decrease in activity of the contaminated zone because of leaching by infiltrating rainwater. RESRAD's leaching model is also designed to model the movement of contaminants to groundwater; this type of modeling would be useful in a study of possible ingestion dose.

For this study, the results of RESRAD indicate that leaching is not a crucial issue (i.e., the decreases in the activity of the contaminated zone because of leaching do not significantly affect inhalation dose). This is because of a combination of several

factors. Area 13 has a relatively low amount of precipitation and relatively high evapotranspiration coefficient, which means that not much water is infiltrating the soil. Of the water that does enter the soil, not much of this water is able to carry away contaminants because of the high distribution coefficient of plutonium (plutonium is strongly adsorbed to the soil) and the particulate nature of the element.

Decreases in the doses calculated by RESRAD for Pu-239, Pu-241, and Am-241 (see Figure 6-1 and Figure 6-5) were mainly because of radioactive decay. Decreases in the activity of the contaminated zone were calculated by RESRAD for leaching and radioactive decay only. Several other factors that could deplete the contaminated zone were not accounted for by RESRAD. Depletion by runoff (rainwater washing contaminated soil off-site) and erosion was not accounted for by RESRAD. The runoff coefficient used in RESRAD was only used to approximate the amount of rainwater that penetrates the surface. Resuspended contaminants in aerosol can be transported off-site by wind (this is a type of erosion). Although RESRAD does model dilution of contaminated aerosol by uncontaminated aerosol blown in from off-site, it does not model the amount of contaminated aerosol blown off-site.

7.3 Other Assumptions

7.3.1 Plutonium Concentrations in Soil

Variations occur in the concentrations of Pu-239,240 in soil at the safety shot areas. Values were reported by Gilbert et al. (1975, 1977) in terms of a range; mean ± standard error (SE) ($SE = s/(n)^{1/2}$ where n is the number of samples). The mean of the range for each stratum at Area 13 was used to scale the normalized doses. Variations in the concentrations of Pu-239,240 at Area 13 have a significant effect on potential doses. The concentration of the source term has a direct effect on dose; an increase in the concentration of the source term by 100 % would also increase dose by 100 % (assuming all other factors remained constant).

In addition, uncertainties exist in the relative quantities of the plutonium isotopes (Pu-239, Pu-240, and Pu-241) assumed for this study. Pu-240 specific activity is assumed to be Pu-239 specific activity, which appears to be a conservative assumption because the half-life of Pu-240 is less than that of Pu-239. The initial ratio of Pu-241 activity to Pu-239 activity is assumed to be 8.3, and ingrowth of Am-241 from decay of Pu-241 is modeled based on this ratio.

7.3.2 Radionuclide Contribution to Dose

Pu-239,240, Pu-241, and Am-241 at Area 13 were considered in this dose assessment. Pu-238 was not considered. Eckart et al. (1993) determined doses for Pu-238, Pu-239,240 and Am-241 for various land-use scenarios at the safety shot sites of the TRC. At Area 13, the doses calculated for Pu-238, as a

percentage of total dose, are 0.176 % for the Inner Zone and 1.35 % for Overall. The Inner Zone refers to the most contaminated stratum, stratum 6, and Overall refers to area at Area 13 within the outermost fence.

7.3.3 Modes of Exposure

Inhalation was the only mode of exposure considered in this study. Nevertheless, exposure can still occur from ingestion and external radiation. The likelihood of each exposure mode depends on the land-use scenario. Authors of the NAEG model concluded that doses received from ingestion are insignificant when compared to the doses received by inhalation for the residential-farmer, who would have the largest ingestion dose of any land-use scenario receptor.

External dose was not considered in the NAEG model, nor was it considered in this study. Eckart et al. (1993) calculated a rough external dose for the Inner Zone of the Double Track safety shot site. Pu-238, Pu-239,240, and Am-241 combined activity in nCi/m^2 yielded a conservative estimate for external dose that is 0.01 % of the total dose. The total dose combined the doses from the exposure modes of inhalation, soil ingestion, dermal contact, and external exposure.

7.4 Assumptions in Scaling Results to Area 13 Strata

In Chapter 6, the normalized doses calculated in the generic scenario were scaled to the soil activity levels at each of the six strata of Area 13. The result of this scaling is a matrix of doses as a function of strata and year after initial time (see

Table 6-6). In calculating doses for each individual stratum, a key assumption is made. The human receptor is breathing aerosol containing contaminated soil from only one stratum at Area 13. Two assumptions are inherent in the key assumption: the aerosol from the stratum in question does not contain contaminated aerosol from the surrounding strata, and the receptor stays in only the stratum in question.

The human receptor, depending on the scenario, could be active at Area 13 over an area larger that one stratum. The residential-farmer, depending on the scale of his/her agriculture (i.e., whether for personal or for business purposes), could be active over more than one stratum of Area 13. In the scenario of soil removal for cleanup, the industrial-worker could also be active over more than one stratum. In addition, the aerosol at any point in Area 13 could contain a mix of soil from the stratum containing that point and other surrounding strata. However, because of the large size of Area 13, the majority of aerosol at any stratum will likely be from only that stratum. The largest stratum at Area 13, stratum two, is approximately 629 acres in size, and the smallest stratum, stratum five, is about 4.7 acres.

If a modeler wanted to determine the doses that receptors could receive as a result of land-use activities occurring over more than one stratum of Area 13, or mixing of contaminated aerosol from the various strata of Area 13, then the modeler could perform mathematical weighting of the doses in Table 6-6. To weight the doses in Table 6-6, additional research would need to be performed. To model the effect on doses as a result of land-use over more than one stratum, assumptions would have

to be made regarding activities by potential receptors. To model the effect on doses as a result of aerosol mixing, wind behavior would have to be analyzed.

7.5 Uncertainty in Applying Results to DOE Standards

To debate the appropriateness of applying the results to an analysis of compliance of human land-use scenarios with DOE standards, we examine the ways the human receptor could affect the accuracy of this application.

7.5.1 Compliance of Residential-Farmer Scenario with DOE Order 5400.5

The first application of the doses calculated for Area 13 is an analysis of compliance with DOE Order 5400.5 for the residential-farmer scenario. DOE Order 5400.5 states that the effective dose equivalent (whole body dose from internal and external radiation) to the public cannot exceed 100 mrem/yr (DOE, 1990). At year 73.3, the calculated doses reach a maximum, and doses at four of the six Area 13 strata exceed this limit.

One might ask, "How could the residential-farmer affect the model parameters?" Many of the parameters in the model could be affected by the farmer. Perhaps more importantly, how could the residential-farmer affect the sensitive parameters? Of the sensitive parameters, several seem very likely to be affected by the residential-farmer: the contaminated zone thickness, the mass loading factor, the inhalation rate, and the soil mixing layer.

The contaminated zone thickness and soil mixing layer, depth to which soil undergoes mixing, are interrelated terms. The soil mixing layer is important in its effect on the contaminated zone thickness. Over a period of time, the values for these two parameters should be equal. A realistic change in the values for these parameters would be an increase from their current values of 0.05 m. Agricultural activities such as plowing or tilling are examples of activities that could increase these parameters. An increase in size of the contaminated zone thickness would reduce the specific activity of the soil and hence decrease dose.

The same activities that increase the contaminated zone thickness could also increase the mass loading factor. Examples of activities that could increase the mass loading factor are plowing, tilling, harvesting, cattle roaming and grazing, and vehicular traffic. Variations in the mass loading factor could also occur because of weather phenomena, such as an increase because of the high winds of a dust devil. Most of the events that increase the mass loading factor increase it temporarily and, in the long run, would increase the average mass loading factor. The mass loading factor used in the generic scenario is 100 $\mu g/m^3$.

Increases in the contaminated zone thickness and mass loading factor would have offsetting effects on the results. (next page)

If both of these parameters doubled in magnitude, the model results would still be the same; doubling the contaminated zone thickness would decrease the dose by a factor of two (assuming a homogenous activity in the soil), and doubling the average mass loading factor would increase the dose by a factor of two.

The activities of the farmer could lead to a faster decrease in the activity of the contaminated zone than the decrease which is predicted by the RESRAD model. The evapotranspiration coefficient is important because it determines how much water enters the contaminated zone (i.e., how much water is available to leach out contaminants). The high evapotranspiration coefficient at Area 13 ensures that contaminants will be around for a longer period of time. If irrigation is used by the farmer, the evapotranspiration coefficient would probably be a less crucial parameter. Irrigation would mean more water enters the contaminated zone to potentially leach out contaminants. However, this additional water might be taken up by plant crops instead of carrying away contaminants. In addition, because plant crops draw contaminants out of the soil, each harvest would further decrease the contaminated zone activity.

It is possible that agitation of the soil by the farmer's activities, such as tilling and plowing, could loosen the plutonium that has adsorbed to the soil, decreasing the distribution coefficient and increasing subsequent leaching.

Strenuous activity by the residential-farmer over the course of a year could raise

his/her yearly inhalation rate. The inhalation rate recommended by ICRP-23, 8400 m^3/yr (ICRP, 1975), accounts for different levels of activity and breathing in determining its value; per day, levels of breathing correspond with eight hours of "light activity" working, eight hours of nonoccupational activity, and eight hours of resting. It is very likely that the farmer could be involved in eight or more hours of "high activity" working that could raise his/her inhalation rate over the ICRP-recommended value.

The residential-farmer's activities on Area 13 could not only change model parameters, but could possibly also affect the accuracy of the RESRAD model equations. By significantly changing the surface characteristics of Area 13, the farmer could especially affect the accuracy of the leaching model.

The activities of the residential-farmer could affect the reliability of the assumptions used to scale the dose results to the strata of Area 13. The farmer, depending on the scale of his/her agriculture (i.e., whether for personal or for business purposes), could be active over more than one stratum of Area 13.

An additional uncertainty is the time when the residential-farmer is most likely to reside on Area 13. At 73.3 years after initial time, year 2030, the dose results reach a maximum. However, it is not likely that the land will be released for public use by this time. (next page)

It is more likely that a farmer could use the land 400 years after initial time, when the dose is about 11% less than the maximum, or at 1000 years after initial time, when the dose is about 23% less than the maximum.

7.5.2 Compliance of the Industrial-Worker Scenario with the *DOE Radiological Control Manual*

The second application of the doses calculated for Area 13 is an analysis of compliance with the *DOE Radiological Control Manual* (DOE, 1992) for the industrial-worker scenario. The manual states that the effective dose equivalent to a worker cannot exceed 5 rem/yr. None of the doses calculated for Area 13 strata exceed this limit.

Similar to the residential-farmer, the worker has the ability to change model parameters. The worker scenario that has the most potential to change model parameters is the scenario of soil removal for cleanup (cleanup scenario). Model parameters would not have as much potential to be affected by the worker in non-cleanup scenarios.

In non-cleanup scenarios at Area 13, the industrial-worker would probably not have a significant impact on the contaminated zone thickness or the soil mixing layer. In addition, effects that an industrial-worker could have on the evapotranspiration coefficient and distribution coefficient appear to be minimal for non-cleanup scenarios.

Both future workers and site residents such as farmers could be affected by changes in Area 13 that occur because of cleanup. If cleanup of the site is conducted, numerous characteristics of the site could change significantly. Soil that is returned to the site after its removal and cleanup would have a lower activity. The thickness of the contaminated zone and soil mixing layer would be different from their current values. The values for these parameters would probably be equivalent, and be equal to thickness of the layer of soil that is returned to the site. The distribution coefficient would probably be different, perhaps higher, because the plutonium that remains in the soil might be more tightly adsorbed than the plutonium that was removed. The evapotranspiration coefficient might be changed slightly because of the different physical nature of the cleaned soil. Depending on the stabilization techniques used after the soil is returned to the site and the physical nature of the cleaned soil, the mass loading factor could also be different.

Any activity by the worker that disturbs the ground surface has the potential to raise the mass loading factor significantly above its value for ambient conditions. The magnitude of the increase depends on the activity and precautions taken by the workers to reduce resuspension. During soil removal, for example, a precaution would be wetting of the soil. In addition, the worker would likely be wearing protective respiratory gear while performing an activity that has potential to raise the mass loading factor.

As with the farmer, "high activity" working over the course of a year by the industrial-worker could raise his/her inhalation rate over the ICRP-recommended value of 8400 m^3/yr (ICRP, 1975).

Workers spend less time on the site than the residential-farmer. RESRAD results were calculated for an occupancy factor of 1. The worker's occupancy factor would be based on the percentage of a seven-day week that the worker spent on site, which would be about 0.24 for a 40-hour work-week.

Similar to the residential-farmer, the application of single stratum doses would be difficult for the industrial-worker. In the scenario of soil removal for cleanup, the industrial-worker could be active over more than one stratum at Area 13.

It is very possible that workers could be active on Area 13 at the time the calculated doses reach a maximum, 73.3 years after initial time, or about year 2030. However, the degree to which NTS soils will be cleaned by DOE at that time is uncertain (i.e., which areas will be cleaned and to what level of activity).

Similar to the agricultural activities of the residential-farmer, cleanup operations by an industrial-worker at Area 13 could not only change model parameters, but could possibly also affect the accuracy of the RESRAD model equations. By significantly changing the surface characteristic of Area 13, the worker could affect the accuracy of the leaching model.

7.6 Applicability of Results to Decision Making

Because of the previously discussed uncertainties in the results and uncertainties in applying the results to possible land-use scenarios and DOE standards, caution should be exercised when attempting to make administrative and/or regulatory decisions based on this study or other similar studies.

If cleanup is performed as planned by DOE at Area 13 and other areas on the TRC, this cleanup operation will have an impact on the way this study can be applied.

7.6.1 DOE Plans to Clean Up Plutonium-Contaminated Soil on the TRC

An effort to prepare for cleanup of plutonium-contaminated safety shot areas at the TRC began several years ago. DOE's Nevada Operations Office, Technology Development Division, described the three-year Research, Development, and Demonstration (RD&D) project to cleanup the plutonium at sites on NTS, TTR, and NAFR (May 2, 1991). Plutonium problems at other DOE sites were also under study as part of an integrated demonstration (ID). All aspects of cleanup were to be investigated in the project. These aspects are "soil and vegetation removal, volume reduction through separation of plutonium from soil and vegetation, transportation and disposal options, site restoration including stabilization and revegetation, and radiation detection systems to characterize sites and to monitor, guide and certify the cleanup."

The Technology Development Division of Nevada Operations Office describes a

more current effort at NTS in its June 1, 1993, report. Some of the activities described in the May 2, 1991 report are still under investigation. Bench-scale systems are being tested to determine the optimum method for separating plutonium from the most contaminated particle sizes, and radiation monitoring equipment are being developed "to guide excavations of contaminated soil, verify that the area excavated is clean, and measure the activity of processed soil. . ." In addition, the report describes risk assessment research conducted by the University of Cincinnati (Eckart et al., 1993).

7.6.2 Key Decisions in Cleanup Operations

In conducting cleanup of the safety shot areas at the TRC, numerous decisions will have to be made. Perhaps the most important decision is, "What is the target level of activity for soil at the TRC safety shot areas?" (i.e., "What will be the acceptable level of activity for soil that is not removed for cleanup, and for the soil that is removed, to what level of activity will it be cleaned before it can be returned to the site?"). This study or the risk assessment performed by the University of Cincinnati (Eckart et al., 1993) could be used to aid in making decisions such as these. However, before decisions are made, uncertainties in the results of the studies and uncertainties in applying the results must be considered.

One method in determining acceptable residual levels of activity in soil is to predict the most likely use of the land, and clean soil to a level of activity that is acceptable for that land-use. This level of cleanup is performed instead of a more thorough

cleanup that could be performed in preparation for a worst case land-use scenario such as the residential-farmer. Cleanup by DOE for the most probable use scenarios instead of the worst case scenarios would save DOE, and hence the public, much money in cleanup expenses.

Possibilities for release of the land are unlimited public use, such as being made available for purchase for private or business purposes, or for limited use such as a recreational area for the public. To determine the probable and/or desired uses for the land, public involvement can be solicited through community meetings attended by government personnel.

7.6.3 Effect of Cleanup on Applicability of Results

This study was performed on the condition that no cleanup of the soils at Area 13 has been conducted. If cleanup is performed, how useful will this study be to decision making?

If cleanup is performed, model parameters used in this study could change significantly. The methodology used in this study to analyze potential doses to workers and residents could still apply to the changed site. An analysis would be necessary to determine new values for the parameters, especially the sensitive parameters. Changes in the sensitive parameters that could occur because of cleanup is briefly discussed in Section 7.5.2.

This study calculated individual stratum doses for Area 13. If soil from much of Area 13 is removed, cleaned, and returned to the site, the new soil activity levels at the site could be more uniform with respect to area. This would simplify dose assessments performed for the changed site.

7.6.4 Standards

Government standards for limiting radiation dose to the public and workers may be used both as motivator and guide for cleanup actions. This study considered compliance of Area 13 with DOE standards. The limit of 100 mrem/yr to the public is a standard in DOE Order 5400.5; this limit was suggested in ICRP-26 (1977). The limit of 5 rem/yr to workers is a standard in the *DOE Radiological Control Manual*; this limit was suggested in ICRP-30 (1981). These standards are currently not required by law. DOE has proposed to promulgate the standards in DOE Order 5400.5 to law in 10 CFR Part 834. In addition to DOE, the EPA and Nuclear Regulatory Commission have also adopted ICRP recommendations in creating standards for radiation dose.

7.7 Applicability of RESRAD to Determining Potential Doses at NTS

The RESRAD code makes use of general environmental transport models, and its use is being encouraged by DOE for all sites that contain residual radioactive material in the environment. It is valid to question the usefulness of this application of RESRAD to modeling the dose at NTS. The purpose of a general model such as RESRAD should be for use as a screening tool (i.e., to point out issues that are

important and require further investigation). The ability of RESRAD to model natural phenomena is discussed in Section 7.2.

The atmospheric models of both RESRAD and the NAEG model use the mass loading factor. Studies by Anspaugh (1974) have helped improve the general understanding of the mass loading factor. In addition, the mass loading factor has been suggested for use in generic modeling situations by Healy (1980).

Depletion in the activity of the contaminated zone was calculated by RESRAD for leaching and radioactive decay only. Depletion by rainwater runoff and erosion was not accounted for by RESRAD. Although the leaching model of RESRAD is a general and simplified set of equations to model natural phenomena, it is a good tool that the dose assessor can use to understand the factors that are involved in stability of contaminants in soil. One must keep in mind the simplified nature of the leaching model when attempting to analyze or use its results. Leaching of contaminants by rainwater was not considered in the NAEG model.

RESRAD uses dose conversion factors to calculate dose; it does not model transport of contaminants within the human body. The dose conversion factors used in RESRAD were taken from a DOE report (DOE, 1988), and similar values obtained by K. F. Eckerman can be found in an EPA report (Eckerman et al., 1988). Very detailed analyses of transport of plutonium within the human body were performed in the NAEG model. (next page)

The methods used by Eckerman to calculate dose conversion factors employed ICRP-recommended models and were similar to the methods used in the NAEG model to model internal transport of plutonium.

7.8 Applicability of RESRAD Sensitivity Analysis

Sensitivity of a parameter, as calculated by RESRAD, is a combination of two factors: the function the parameter has in the RESRAD equations, and the magnitude of the parameter's range. Therefore, the accuracy of the RESRAD sensitivity analysis is based on the ability of the RESRAD equations to model natural phenomena, and the ability of the modeler to gather sufficient information to obtain parameter ranges. The ability of RESRAD to model natural phenomena is discussed in Section 7.2.

The parameter ranges used in this study were obtained in the same way parameter values were obtained; a literature search for data and a subsequent analysis of available data. The types of parameter ranges varied. For most of the parameters, the ranges were determined from judgement of data (e.g., to determine the range for total porosity at Area 13, ranges of total porosity for various soil types were analyzed). For other parameters, such as the evapotranspiration rate, sufficient data were not obtained, and a range was chosen arbitrarily.

8.0 Conclusion

This study used the RESRAD code to calculate values for committed effective dose equivalent (whole body dose from internal radiation) because of inhalation of plutonium at Area 13. NAEG data were used to guide the study and provide model information. Normalized doses (mrem/yr per initial pCi/g) were calculated for a "generic scenario" (i.e., parameters were for normal weather conditions and/or were not specific to a given land-use scenario). The normalized doses were scaled to the concentrations of Area 13 strata to form a matrix of doses as a function of strata and year after initial time. The dose results of the generic scenario were used to analyze compliance of the residential-farmer and the industrial-worker scenarios at Area 13 with DOE standards.

The normalized radiation doses calculated in the generic scenario reach a peak at 73.3 years, at which point the dose is 0.334 mrem/yr per pCi/g of initial plutonium contamination. When this value is multiplied by the initial concentrations of the strata at Area 13, the results range from a high of 4680 mrem/yr at stratum six to a low of 12 mrem/yr at stratum one. DOE Order 5400.5 states that the effective dose equivalent (whole body dose from internal and external radiation) to the public cannot exceed 100 mrem/yr; this limit would apply to the farmer. At year 73.3, the doses at four of the six Area 13 strata exceed this limit. The *DOE Radiological Control Manual* states that the effective dose equivalent to a worker cannot exceed 5 rem/yr. (next page)

At year 73.3 (or any other year), none of the doses calculated for Area 13 strata exceed this limit.

Parameters used in the generic scenario were subjected to sensitivity analysis to analyze variations in radiation dose that could occur from variations in the parameters. Parameters indicated to be sensitive are the contaminated zone thickness, evapotranspiration coefficient, Pu-239 distribution coefficient, inhalation rate, mass loading factor, and soil mixing layer. Several parameters appear to be especially important. The mass loading factor is important because of its potential for variation according to land-use activities and weather and its direct proportionality with dose. The activities of the residential-farmer could significantly affect the thickness of the contaminated zone; the contaminated zone thickness has an inverse proportionality with dose. Although not included in the RESRAD sensitivity analysis, the concentrations of the source term are also very important; they have a direct proportionality with dose.

To determine more accurate doses for the residential-farmer and the industrial-worker land-use scenarios than those calculated in the generic scenario, one would have to determine model parameters that are specific to the land-use scenario under consideration instead of a "generic scenario." Perhaps a more important step would be to analyze the effects that the land-user would have on the sensitive parameters, and then analyze the subsequent effects that could occur to the doses calculated in the "generic scenario." In addition, if one wanted to determine the

doses that a residential-farmer or industrial-worker could receive as a result of land-use activities occurring over more than one stratum of Area 13, then mathematical weighting could be performed on the individual stratum doses calculated for the six Area 13 strata.

This study analyzed the doses that could occur at Area 13 on the condition that no cleanup of soil has been performed at the site. Any use of the results of this study would have to consider the plans by DOE to clean up the safety shot areas at the TRC. Although many of the model parameters may change after cleanup, the methodology used to determine doses would still be the same.

Future consideration should be given to the model parameters determined to be sensitive, especially if cleanup is performed. Any changes or differences from the values used in this study should be noted. Values for other parameters should also be noted, in case parameter(s) turn out to be more sensitive than indicated in this study.

Although dose limitations to the public and workers are set by DOE using ICRP-recommended limits, debates still occur concerning, "what is a safe level of dose?". Therefore, the ALARA principle should be exercised for any activity that occurs at the safety shot sites in addition to guiding the cleanup efforts.

It is the author's desire that this study will be of benefit to the scientific and

regulatory community. This study could benefit those wishing to understand the factors that are involved in determining possible doses that a human receptor could receive from plutonium in soils such as those found at Area 13, and could be used *cautiously* to aid in making decisions concerning aspects of cleanup, including decisions regarding an acceptable level of activity in soil. If decisions are made based on a study such as this, the decision maker should consider the uncertainties involved, and optimally, determine which uncertainties are most crucial and act based on those uncertainties. Uncertainties in this study arise from approximate parameter values and ranges, accuracy of the RESRAD model equations, accuracy of the RESRAD sensitivity analysis, calculation of individual stratum doses, human activities occurring in the land-use scenarios, and application of the doses to analyze compliance with DOE standards.

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