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FINAL REPORT

Task 1: Cleanup Levels at Other Sites

Radionuclide Soil Action Level Oversight Panel

April 1999

Submitted to the Radionuclide Soil Action Level Oversight Panel
in Partial Fulfillment of Contract between RAC and the Rocky Flats Citizen's Advisory Board

Risk Assessment Corporation

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INTRODUCTION

Soil action levels are calculated to identify the concentration of one or more radionuclides in the soil above which action should be taken to prevent people from receiving unacceptable radiation doses. The soil action levels for radionuclides calculated for the Rocky Flats Environmental Technology Site (RFETS) by the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), and the Colorado Department of Public Health and Environment (CDPHE) have come under scrutiny because of lack of public involvement throughout their development. As a result of public concern, DOE provided funds for the Radionuclide Soil Action Level Oversight Panel (RSALOP) and to hire a contractor to conduct an independent assessment and calculate soil action levels for Rocky Flats. *Risk Assessment Corporation (RAC)* was hired to perform the study. The Rocky Flats Citizen's Advisory Board is administering a grant for the review.

The first task of the study (Task 1: *Cleanup Levels at Other Sites*) was designed to provide the RSALOP with a clear and unbiased evaluation and comparison of previously developed soil action levels for the RFETS and other facilities. This report documents the findings of Task 1.

SOIL ACTION LEVELS AND CONCENTRATIONS AT OTHER SITES

A number of national and international sites have established soil action levels, cleanup criteria, or soil concentrations that are either calculated or measured. These soil action levels have been determined to be protective of human health based on a reasonable land use scenario and predetermined dose criteria. This section briefly summarizes each site in terms of the dose, scenario, and pathways used to calculate the cited soil action level. A later section of the report describes the details of each calculation, including important parameter values, and provides equitable comparisons, where possible.

The one constant across all the sites is that the soil action level was calculated or soil concentration determined for ^{239,240}Pu. This concentration is provided for each site. Where ^{241}Am soil concentrations are available, they are also given.

The sites evaluated in this analysis are

- Rocky Flats Environmental Technology Site
- Hanford, Washington
- Nevada Test Site
- U.S. Nuclear Regulatory Commission (NRC) codes for remediation
- Johnston Atoll, Marshall Islands
- Enewetak Atoll, Marshall Islands
- Maralinga, Australia
- Semipalatinsk Nuclear Range, Kazakhstan
- Thule, Greenland
- Palomares, Spain.

Rocky Flats Environmental Technology Site

Soil action levels were calculated for the RFETS and documented in a 1996 report (DOE 1996). The RESRAD computer code (Yu et al. 1993) was used to calculate these action levels for three different land use scenarios at two different dose levels.

The three scenarios used in the Rocky Flats calculations were (1) an open space exposure scenario, (2) an office worker exposure scenario, and (3) a hypothetical future resident scenario. Action levels were calculated for ^{241}Am, ^{238}Pu, ^{239,240}Pu, ^{241}Pu, ^{242}Pu, ^{234}U, ^{235}U, and ^{238}U. Soil action levels for the open space and office worker scenarios were calculated for the annual effective dose equivalent limit of 15 mrem, and the hypothetical future resident scenario soil action levels were calculated for both the 15 mrem and 85 mrem annual effective dose limits, as selected by the DOE (1996).

The open space exposure scenario assumed that an individual visited the area a limited number of times during the year for recreation (DOE 1996). This recreation might include hiking, biking, or wading in creeks. For this exposure scenario, soil ingestion, soil inhalation, and external gamma exposure were the pathways considered. The remaining pathways available in RESRAD (plant ingestion, meat ingestion, milk ingestion, aquatic food ingestion, ground and surface water ingestion, and radon exposure) were not considered (DOE 1996).

The office worker exposure scenario assumed an individual worked mainly indoors, in a building surrounded by paved areas or landscaping. Exposure pathways considered were soil ingestion, soil inhalation, and external gamma exposure (DOE 1996).

The hypothetical future resident scenario assumed that a person resided at Rocky Flats all year and ate produce grown in contaminated soil. Pathways included in this analysis were soil ingestion, plant ingestion, soil inhalation, and external gamma exposure. The pathways removed from consideration were either inconsistent with the site conceptual model or not significant dosimetrically (DOE 1996). For instance, the groundwater and surface water ingestion pathway was removed from the analysis because it was assumed that the water found on the Rocky Flats site would not be sufficient to support domestic use (DOE 1996).

In Table 1, action levels for each scenario (in units of picocuries per gram) are given for each dose level for the radionuclides ^{239,240}Pu and ^{241}Am.

Table 1. Soil Action Levels for Each Scenario and Dose at the RFETS (pCi g^{-1})

	Scenario used for soil action level calculation			
Radionuclide	Open Space Exposure Scenario (15 mrem y^{-1})	Office Worker Scenario (15 mrem y^{-1})	Hypothetical Future Resident (15 mrem y^{-1})	Hypothetical Future Resident (85 mrem y^{-1})
^{239,240}Pu	9906	1088	252	1429
^{241}Am	1283	209	38	215

These action levels are for single radionuclides. That is, each action level is calculated assuming that the radionuclide of interest is the only radionuclide found on site.

Hanford, Washington

Calculations of soil action levels at Hanford were also done using the RESRAD code, and details of these analyses were published in a 1997 document (WDOH 1997). The two scenarios considered in this study were (1) rural residential exposure and (2) commercial/industrial exposure. These two scenarios are somewhat parallel to the hypothetical resident and office worker Rocky Flats scenarios.

The rural residential scenario assumed a person lived full-time on the Hanford facility. This individual was exposed chronically, indoors and outdoors, to radionuclides in soil, via ingestion, inhalation, and external exposure. The rural residential scenario assumed that the individual worked primarily offsite and engaged in light farming and recreational activities onsite. A portion of the produce, meat, milk, and fish consumed were assumed to come from the site, and drinking water was from an onsite well (WDOH 1997).

The commercial/industrial scenario assumed a person worked onsite, primarily inside a building, although outdoor exposures were also assumed to occur. This scenario assumed that the office worker lived offsite. No ingestion of homegrown food was included in this scenario. Pathways included were limited to external gamma, inhalation of soil, and ingestion of soil (WDOH 1997).

Table 2 shows soil action levels for the two Hanford scenarios, calculated for an annual effective dose limit of 15 mrem.

Table 2. Soil Action Levels for each Scenario and Dose at Hanford (pCi g^{-1})

	Scenario used for soil action level calculation	
Radionuclide	Rural Residential Scenario (15 mrem y^{-1})	Commercial/Industrial Scenario (15 mrem y^{-1})
$^{239,240}Pu$	34	245
^{241}Am	31	210

Nevada Test Site

Calculations of soil action levels were done for the Nevada Test Site by the DOE Nevada Operations Office (DOE-NV 1997). These calculations were performed to show that, subsequent to remediation, the doses received by individuals who may occupy the Tonopah Test Range at the Nevada Test Site would not exceed the dose limits established by the DOE of 100 mrem y^{-1}.

Calculations were done assuming that all areas of the Tonopah Test Range Clean Slate Sites where radiation levels due to $^{239,240}Pu$ exceeded 200 pCi g^{-1} would be remediated to 200 pCi g^{-1} or lower. The RESRAD code was used to calculate dose from the assumed radiation levels in soil.

Four scenarios were used in the dose calculation: a residential rancher, a residential farmer, a rural residence (nonfarming), and a person who worked in light commercial industry. In addition to these adult scenarios, a scenario involving a child who participated in the rancher exposure scenario was included. The rural resident scenario was exposed to external radiation; inhalation of contaminated soil and radon gas and daughter products; and ingestion of soil, drinking water, homegrown produce, meat, and milk. This person was, however, assumed to work offsite and spend only limited time gardening and recreating onsite.

The rancher and farmer scenarios are the closest comparisons to the Rocky Flats rural resident because these scenarios include a significant fraction of time during the year spent onsite. These two scenarios both included exposure pathways of external exposure, inhalation of soil and radon gas and daughter products, and ingestion of soil and drinking water. The rancher scenario included the additional pathways of ingestion of meat and milk, and the farmer scenario included ingestion of homegrown produce. The child scenario implemented the same pathways as the rancher scenario, but it included breathing rates and diet parameters consistent with those of a child.

The industrial worker scenario at the Nevada Test Site is somewhat comparable to the office worker scenario calculated for Rocky Flats. The industrial worker was exposed to external radiation, inhalation of soil and radon, and ingestion of soil and groundwater. This scenario included an 8-hour work day involving both indoor and outdoor work.

Doses for the five scenarios (four adults and one child) were calculated for an achievable $^{239,240}Pu$ soil concentration, determined by the site, of 162 pCi g^{-1}. A soil concentration of 13.2 pCi g^{-1} was presumed for ^{241}Am. Table 3 shows the doses resulting from this soil concentration for both ^{241}Am and $^{239,240}Pu$.

Table 3. Doses for each Scenario for Soil Concentrations Shown at the Nevada Test Site (mrem)

	Scenario used for dose calculation for given soil concentration				
Radionuclide	Rural Residential Scenario	Rancher Scenario	Farmer Scenario	Industrial Worker Scenario	Child Rancher Scenario
^{241}Am (13.2 pCi g^{-1})	1.00	3.56	1.84	0.42	1.61
$^{239,240}Pu$ (162 pCi g^{-1})	10.7	42.6	20.1	3.97	16.7

U.S. Nuclear Regulatory Commission DandD Code Scenarios

The Decontamination and Decommissioning software (DandD) was written for use by NRC licensees to assist them in making screening calculations for cleanup of contaminated facilities. The residential farmer scenario outlined in the DandD code was for a full-time resident of the facility of interest, allowing for some time offsite, as did the Rocky Flats residential calculation. This resident grew as much food as reasonably possible on the facility of interest. The pathways included in the analysis were external gamma exposure; inhalation of soil; and ingestion of soil, water, plants, meat, milk, fish, and poultry. The calculation also included a pathway for irrigation of crops and livestock fodder with contaminated water.

On the whole, the pathway calculations in DandD are highly conservative. We encountered a great deal of difficulty in comparing DandD and RESRAD results because the design of this code is still in preliminary stages and the documentation describing the pathways is not complete or publicly available.

Using default parameters for the DandD residential scenario (Beyeler et al. 1998) (which were selected by the NRC as screening level values), for a soil concentration of 1 pCi g^{-1}, the calculated maximum dose for $^{239,240}Pu$ is shown in Table 4.

Table 4. Dose for Given Soil Concentration in the U.S. NRC DandD Code (mrem)

Radionuclide	Residential Farmer Scenario
$^{239,240}Pu$ (1 pCi g^{-1})	288

Johnston Atoll, Marshall Islands

The dose assessment done for Johnston Atoll in the Marshall Islands was completed after the cleanup efforts were finished. Soil was cleaned to approximately 15 pCi g^{-1} using mining techniques, and this cleanup was verified by Oak Ridge National Laboratory (Wilson-Nichols et al. 1997).

A permissible soil concentration at Johnston Atoll was calculated for a full-time resident exposed to radioactive material through inhalation of contaminated soil. This was the only pathway considered in this dose assessment, and concentrations were calculated for a dose limit of 20 mrem y^{-1}. Because only the inhalation pathway was considered, establishing a detailed scenario was not necessary. Because occupation of the site by the exposed individual is year-around, the Rocky Flats hypothetical future resident scenario exposure traits are the most comparable.

For the Johnston Atoll residential scenario, the dose was calculated for generic compounds of plutonium or americium. The soil concentration was defined as that for $^{239,240}Pu$.

Table 5. Soil Concentration for the Residential Scenario at Johnston Atoll (pCi g^{-1})

Radionuclide	Residential Scenario (20 mrem y^{-1})
$^{239,240}Pu$	17.0

Enewetak Atoll, Marshall Islands

The soil concentrations established for use at Enewetak Atoll have not been discovered to be correlated to a dose assessment. Three different categories of land use were selected, and these categories are shown in Table 6 with their soil concentration limits. Although attempts have been made, the dose calculations associated with these soil concentrations have not been found in the literature.

Table 6. Soil Concentrations Established for Different Land Uses at Enewetak Atoll (pCi g^{-1})

Land use		
Food gathering	Agricultural	Residential
160	80	40

Maralinga, Australia

At the Maralinga Range in Australia, soil concentrations were calculated for a population of semi-traditional aboriginal people permanently residing in the area. Soil concentrations were calculated for a publicly accepted dose limit of 500 mrem. The only pathway considered in this analysis was exposure via inhalation of contaminated soil. The scenario from the Rocky Flats analysis most comparable to the Maralinga soil concentrations is the hypothetical future resident.

Soil concentrations calculated at 500 mrem for this residential aboriginal population are shown in Table 7.

Table 7. Soil Concentration Calculated for the Residential Scenario at Maralinga (pCi g^{-1})

Radionuclide	Residential Scenario (500 mrem y^{-1})
$^{239,240}Pu$	280

Semipalatinsk Nuclear Range, Kazakhstan

This facility in Kazakhstan was the site of many Russian nuclear tests. The dose and soil concentration information from this facility included no summary of the calculational method used to obtain the dose information. It was not apparent from reading through the available documentation whether the doses and deposited activities were associated with each other in any way. Deposited activities were converted to soil concentrations, assuming normal soil density and depth of contamination. The dose and soil concentration information is shown in Table 8.

Table 8. Activity and Population Dose at Principal Settlements in Semipalatinsk

$^{239,240}Pu$ Deposited Activity (pCi g^{-1})	Individual Dose to Population (mrem)
1.32	Up to 1.5×10^5

Thule, Greenland

The nuclear accident at Thule, Greenland, resulted in concentrations in sediments and not in soils. Because these concentrations are not comparable to Rocky Flats, we do not relate them to Rocky Flats concentrations in this section.

Palomares, Spain

Following a nuclear accident, soil contamination at Palomares, Spain, was immediately cleaned. A dose assessment was completed later by Iranzo et al (1987). For a residential receptor, the pathway of concern was the inhalation of contaminated soil. For this pathway, the acceptable air concentration was calculated based on an annual acceptable dose of 100 mrem. The soil concentration is shown for $^{239,240}Pu$ in Table 9.

Table 9. Soil Concentration for the Residential Scenario at Palomares (pCi g^{-1})

Radionuclide	Residential Scenario (100 mrem y^{-1})
$^{239,240}Pu$	1230

Summary of Available Site Information

Across the mentioned sites, soil concentrations and associated doses vary greatly. The following table is a summary of the soil concentrations measured or calculated at the sites reviewed for this study. Only the scenarios that are comparable to Rocky Flats scenarios are shown. In the next section, we compare all calculations from the different facilities possible to the Rocky Flats in an effort to identify the differences.

Table 10. Soil Concentrations and Associated Doses for ^{241}Am and ^{239,240}Pu Across Sites

Site	Scenario	Soil Concentration (pCi g^{-1})		Dose (mrem y^{-1})	
		^{241}Am	^{239,240}Pu	^{241}Am	^{239,240}Pu
Rocky Flats	Hypothetical future resident	215	1429	85	85
	Office worker	209	1088	15	15
Hanford	Rural resident	31	34	15	15
	Occupational/Industrial worker	210	245	15	15
Nevada Test Site	Rancher	13.2	162	3.56	42.6
	Industrial worker	13.2	162	0.42	3.97
U.S. NRC Codes	Residential farmer	NA	1.0	NA	288
Johnston Atoll	Residential (inhalation)	NA	17.0	NA	20
Enewetak Atoll	Residential	NA	40	NA	unavailable
Maralinga	Residential (inhalation)	NA	280	NA	500
Semipalatinsk	Settlements	NA	1.32	NA	150000
Palomares	Residential (inhalation)	NA	1230	NA	100

SENSITIVITY ANALYSIS

Initial sensitivity analyses of the RESRAD code and parameters used for the Rocky Flats hypothetical future resident scenario at the 85 mrem y^{-1} dose level show that a few parameters dominate the outcome of the action level calculation. These parameters were identified using a single-parameter sensitivity analysis (that is, only one parameter was altered at a time to explore the sensitivity of the RFETS calculation to changes in the parameter). This sensitivity analysis helped identify those parameters that controlled the Rocky Flats soil action level calculation for the Task 1 study. For example, when an action level at another site was significantly different from the RFETS value, we could identify what was likely controlling the difference. Two parameters at the RFETS emerged from the sensitivity analysis as most important and most sensitive to change: mass loading factor and dose conversion factor. The mass loading factor for the RFETS calculations was 0.000026 g m^{-3}. The dose conversion factor for ingestion was 0.000052 mrem pCi^{-1} and for inhalation was 0.308 mrem pCi^{-1}. These dose conversion factors are consistent with Class Y (insoluble) plutonium with a particle size of 1 μm activity median aerodynamic diameter (AMAD). These parameters will be explored in more detail in Tasks 2 and 3, but their importance affects the Task 1 study.

METHOD OF COMPARISON

Action and cleanup levels are often determined independently of dose levels or are based on a dose other than the 15 or 85 mrem y^{-1} used in the RFETS scenario calculations. These varying dose levels made direct comparison more difficult; therefore, we mathematically compared different soil action levels among sites by normalizing the action level to annual dose. In the remainder of this report, annual dose is understood, and dose is represented in units of millirem (mrem). Normalization means that a ratio was calculated for soil action level or concentration to dose level, representing the action level for a unit dose, or 1 mrem. This equitable comparison allows for straightforward identification of pathway, scenario, and parameter differences that affect the ratio. If these differences can be identified among the RFETS and other sites, the ratios between sites should be comparable.

Each ratio is identified in two ways:

1. Dose to soil action level (millirem per picocurie per gram) (mrem [pCi $g^{-1}]^{-1}$) and
2. Soil action level to dose (picocurie per gram per millirem) ([pCi g^{-1}] $mrem^{-1}$).

These ratios are reciprocals. They each have their merits and many different readers find one of the two easier to understand. For a true normalization to dose, the focus should be on the soil action level to dose ratio, which identifies the action level per unit dose, or the soil concentration for each site consistent with a 1 mrem effective dose level. Therefore, if the soil action level to dose ratio is higher for the RFETS than it is for another site, then the allowable soil concentration is greater for the same dose. The opposite situation may also be true. In all cases, this report identifies possible sources for the difference in ratios and calculates the effect of each difference on the ratio to identify the contrast between the ratios.

Because the primary goal of this task was to understand why Rocky Flats soil action levels are consistently greater than those at other sites, we limited out calculations to gaining an understanding of the parameters that drive the action levels to such high levels. Identifying and comparing critical parameters for the RFETS with each site was the endpoint of each investigation. Precisely equating the soil action level to dose ratio between other sites and the RFETS was not our goal. Instead, it was important for us to identify the parameters controlling the action level and show their impact, thereby, making the RFETS action level calculation more transparent.

In some cases, cleanup at a site was conducted independent of dose, and a dose calculation could not be found in the available literature. In these cases, we described the cleanup level along with the soil concentration, but we did not make an effective or meaningful comparison. Without a ratio and some indication of how the calculation was completed, it was impossible to identify the differences among the sites in a way that is meaningful for this study.

COMPARISONS OF ROCKY FLATS SOIL ACTION LEVEL TO SOIL ACTION LEVELS AT OTHER SITES

Several of the previously discussed sites employed alternate action level calculations that lent themselves to comparisons to the Rocky Flats soil action levels for the Task 1 report. These included:

- Hanford, Washington
- Nevada Test Site
- Johnston Atoll, Marshall Islands
- Maralinga, Australia
- Palomares, Spain.

Additionally, the following sections discuss the events that resulted in soil concentrations at Enewetak Atoll, Marshall Islands; Semipalatinsk Nuclear Range, Kazakhstan; and Thule, Greenland. Because no information about dose calculations was available for these facilities, however, our discussion is limited to the facts and does not analyze the calculation or make a comparison of a ratio for these facilities to Rocky Flats. We also describe the U.S. NRC calculations and codes in more detail, but no comparisons of ratios are made to Rocky Flats because of the lack of documentation on the DandD code and the time frame and scope of this project.

Table 11 identifies the dose to soil action level and soil action level to dose ratios for each site where information was available. All ratios shown are for $^{239,240}Pu$, and additional ratios for ^{241}Am are shown when the data were available. The scenarios identified in Table 10 are shown for each site. Ratios and scenarios are described in more detail in the following sections.

Table 11. Ratios for Comparison among Different Sites[a]

Site	Scenario	Soil action level to dose ratio ([pCi g^{-1}] mrem^{-1})		Dose to soil action level ratio (mrem [pCi g^{-1}]$^{-1}$)	
		$^{239,240}Pu$	^{241}Am	$^{239,240}Pu$	^{241}Am
Rocky Flats, Colorado	Rural Residential	17	2.5	0.06	0.39
	Office Worker	73	14	0.01	0.07
Hanford, Washington	Rural Residential	2.3	2.1	0.44	0.48
	Industrial Worker	16.3	14	0.06	0.07
Nevada Test Site[b]	Rancher	3.8	3.7	0.26	0.27
	Industrial Worker	41	31	0.02	0.03
Johnston Atoll[c]	Residential (inhalation)	0.85	NA	1.2	NA
Maralinga, Australia	Residential (inhalation)	0.56	NA	1.8	NA
Palomares, Spain	Residential (inhalation)	12.3	NA	0.08	NA

[a] References identified in appropriate section of text.
[b] Ratios from Clean Slate Site 1.
[c] Dose from all alpha particles, soil action level for $^{239,240}Pu$.

It is clear that the values are not the same for all sites. In fact, the soil action level to dose ratio is less than 1 in some cases. For similar scenarios, the Rocky Flats soil action level to dose ratio for $^{239,240}Pu$ is always larger than the ratio at another facility. The following paragraphs provide a site-by-site analysis of each $^{239,240}Pu$ ratio for each scenario and why it differs from the ratio for the RFETS residential or office worker scenario.

Because the ^{241}Am soil action level to dose ratio was either the same for similar scenarios between Rocky Flats and another facility or larger at the other facility, we did not examine ^{241}Am

further. For this task, we were interested primarily in why Rocky Flats ratios exceeded those at other facilities. This condition did not apply to ^{241}Am.

Hanford, Washington

The Hanford Site in Washington was part of the nuclear weapons production complex and it still operates as a DOE laboratory. Dose reconstruction and cleanup efforts are underway at the facility. As a part the clean up, soil action levels were calculated for the facility using parameter evaluation techniques similar to those undertaken at the RFETS. The Hanford calculation is described in detail in a document issued by the State of Washington (WDOH 1997). All parameter values for Hanford cited and used in this section come from WDOH (1997).

For the residential scenarios at Hanford and RFETS, the soil action level to dose ratio for ^{239,240}Pu at Hanford is 2.3 (pCi g^{-1}) $mrem^{-1}$, compared to 17 (pCi g^{-1}) $mrem^{-1}$ at Rocky Flats. At Hanford, this scenario represented a person who lived on the current Hanford site all year, eating crops and livestock grown onsite, drinking from site streams, inhaling air, and ingesting soil. The Rocky Flats ratio for plutonium was significantly higher than that at Hanford, so an investigation was warranted.

To compare the Hanford and Rocky Flats ratios, we identified differences in significant parameters and observed how making these parameters the same affected the outcome of the ratio comparison.

The most obvious difference between the Rocky Flats residential scenario and the Hanford residential scenario was the active exposure pathways. The Hanford residential scenario included all exposure pathways allowed in RESRAD except the radon pathway. Compared to Rocky Flats, Hanford included four additional pathways: ingestion of drinking water, ingestion of meat from animals raised on contaminated land, ingestion of milk from animals raised on contaminated land, and ingestion of locally caught fish containing radionuclides.

Holding all other parameters in the Hanford calculation constant, removing these pathways made very little difference to the calculation's outcome. The ratio of soil action level to dose for ^{239,240}Pu changed indistinguishably. It is interesting to note that the ingestion pathways (milk, meat, fish, and drinking water) had almost no effect on the ratio for ^{239,240}Pu. The largest change in soil action level to dose occurred for ^{137}Cs and ^{90}Sr because the transport of these radionuclides is primarily through such food chains. These radionuclides were not of concern for the RFETS, so we focused primarily on changes in the ^{239,240}Pu calculation.

The two parameters identified in the RFETS sensitivity calculation (mass loading factor and dose conversion factor) differed between the RFETS and Hanford calculations. We examined these parameters to see how changes affect the Hanford and RFETS calculations.

A major difference between the Hanford and RFETS calculations was values for dose conversion factors. In the Hanford calculation, dose conversion factors for soluble plutonium were used, which are larger, or more conservative, than those for insoluble plutonium. In the RFETS calculation, plutonium was assumed to be insoluble, and smaller dose conversion factors for both inhalation and ingestion were used. Maintaining our previous pathway modification and using the dose conversion factors for insoluble plutonium in the Hanford calculation, the soil action level to dose ratio for ^{239,240}Pu changed from 2.3 to 9.9 (pCi g^{-1}) $mrem^{-1}$. This ratio was much closer to the RFETS ratio of 17 (pCi g^{-1}) $mrem^{-1}$, indicating that the form of plutonium identified in the environment plays a significant role in the difference between these two calculations.

The mass loading factor used in the Hanford calculation was 0.0001 g m^{-3}, compared to the value used in the RFETS calculation of 0.000026 g m^{-3}. Maintaining all previous modifications to the Hanford calculation and altering the mass loading factor to match the RFETS value, the soil action level to dose ratio for $^{239,240}Pu$ changed from 9.9 to 34 (pCi g^{-1}) $mrem^{-1}$. This large increase in the ratio occurred for two reasons. First, assuming the plutonium was in an insoluble form made inhalation the dominant pathway for dose. Second, decreasing the mass loading factor decreased the amount of plutonium in the air, making less plutonium available for inhalation. The combination of these two changes increased the allowable concentration of plutonium in soil, and correspondingly increased the soil action level for a unit dose.

When the Hanford calculations using RESRAD were run implementing the RFETS pathways and parameter values for mass loading and dose conversion factor, the soil action level to dose ratio for Hanford exceeded that for the RFETS. Table 12 shows the incremental change in the soil action level to dose ratio when the parameters in the Hanford calculation were altered.

For the office worker scenario at Rocky Flats and the industrial worker scenario at Hanford, the pathways analyzed were identical: external gamma exposure, inhalation of soil, and ingestion of soil. The soil action level to dose ratios for $^{239,240}Pu$ for Hanford and RFETS, respectively, were 73 and 16.3 (pCi g^{-1}) $mrem^{-1}$.

We assumed that the same parameter changes that controlled the residential scenario calculation, dose conversion factor and mass loading, would have significant control over this calculation. In fact, this proved to be true. When dose conversion factors were changed to conform to the insoluble form of plutonium, the soil action level to dose ratio for Hanford went from 16.3 to 44. Maintaining this change and changing mass loading from 0.0001 g m^{-3} to 0.000026 g m^{-3}, the soil action level to dose ratio for the Hanford calculation went from 44 to 159 (pCi g^{-1}) $mrem^{-1}$, exceeding the Rocky Flats ratio of 73 (pCi g^{-1}) $mrem^{-1}$. In the case of both residential and worker scenarios, the same parameters controlled the soil action level calculation for $^{239,240}Pu$. Table 12 also shows the changes in parameters that controlled the outcome of the industrial worker scenario.

Table 12. Changes in the Soil Action Level to Dose Ratio with Parameter Value Changes for ^{239,240}Pu in the Hanford and RFETS Calculations

Site and Scenario	Parameter change	Soil action level to dose ratio ([pCi g^{-1}] mrem^{-1})	Dose to soil action level ratio (mrem [pCi g^{-1}]$^{-1}$)
Rocky Flats residential	Original calculation	17	0.06
Hanford residential	Original calculation	2.3	0.44
	Remove meat, milk, fish, drinking water	2.3	0.44
	+ change dose conversion factor	9.9	0.10
	+ change mass loading	34	0.03
Rocky Flats office worker	Original calculation	73	0.01
Hanford industrial worker	Original calculation	16.3	0.06
	Change dose conversion factor	44	0.02
	+ change mass loading	159	0.006

Nevada Test Site

The Nevada Test Site was the location of numerous nuclear weapons tests in the 1940s, 1950s, and 1960s during the buildup and testing of the nation's nuclear arsenal. Two documents reported dose calculations for individuals who might live or work onsite after cleanup of the site. One of the dose assessments assumed very realistic scenarios for future site uses and calculations were performed for scenarios including an industrial worker, bomb detonation, removal of safe munitions, aircraft crew flying overhead, ground troops being deployed onsite, explosive ordinance demolition, and a construction worker. In short, these scenarios were designed assuming that the site will be under military control in the future. Ratios associated with these scenarios are large; they are not discussed here because they do not relate to the Rocky Flats scenarios (DOE 1998).

In the second document, doses were assessed for presumed cleanup levels given scenarios similar to those we looked at for the RFETS (DOE-NV 1997). This assessment was performed with RESRAD but reported dose from a given soil concentration, instead of soil action level.

The 100 mrem y^{-1} public dose standard is presumed to be the primary standard for protection of the public based on the DOE Order 5400.5 (DOE-NV 1997). DOE-NV (1997) cited a number of studies detailing soil action levels that resulted in doses similar to or less than this standard. Based upon this information, this dose assessment assumed that the soil needed to be cleaned to a level not exceeding 200 pCi g^{-1} of ^{239,240}Pu. Given existing concentrations in soils, hypothetical concentrations after remediation were identified, and dose calculations using RESRAD were completed to assess the dose resulting from both the unremediated and remediated soils. If these doses were less than the 100 mrem y^{-1} public limit, the remediation was termed adequate, or even unnecessary, if the precleanup levels met the dose requirement.

Two scenarios from the Nevada Test Site evaluation related most closely to the Rocky Flats scenarios: the rancher scenario and the industrial worker scenario. In the rancher scenario, a person lived on and farmed the land for personal livelihood, eating many of the crops and livestock produced. Pathways included external radiation; inhalation of soil and radon; and ingestion of soil, drinking water, meat, and milk. The same scenario at Rocky Flats did not include radon inhalation, or ingestion of drinking water, milk, or meat. The cited post-remediation soil concentration level for $^{239,240}Pu$ of 162 pCi g^{-1} and dose of 38.9 mrem y^{-1} yielded a soil action level to dose ratio of 3.8 (pCi g^{-1}) $mrem^{-1}$. The ratio for a similar scenario at the RFETS was 17 (pCi g^{-1}) $mrem^{-1}$. Because the plutonium ratio at Rocky Flats was larger than the ratio at Nevada Test Site, this ratio was worthy of examination for this task.

The industrial worker scenario included exposure pathways for external gamma radiation, inhalation of soil, inhalation of radon, ingestion of soil, and ingestion of drinking water. This scenario included two pathways not used in the Rocky Flats calculation: inhalation of radon and ingestion of drinking water. The soil action level to dose ratio for the industrial worker Nevada Test Site calculation for $^{239,240}Pu$ was 41 (pCi g^{-1}) $mrem^{-1}$, compared to the RFETS ratio of 73 (pCi g^{-1}) $mrem^{-1}$. Again, the plutonium ratio was significantly larger.

The primary difference between the RESRAD calculations for the Nevada Test Site and the RFETS was the assumed solubility class of plutonium. The Nevada Test Site calculation used the RESRAD default value for plutonium dose conversion factor, which corresponded to Class W (soluble) plutonium. For purposes of simplicity, changes were made to the readily available RFETS calculation. When dose conversion factors for soluble plutonium were used in the Rocky Flats residential calculation, which originally used Class Y (insoluble) plutonium dose conversion factors, the RFETS soil action level decreased from 1429 to 242 pCi g^{-1}, and the soil action level to dose ratio decreased from 17 to 2.8 (pCi g^{-1}) $mrem^{-1}$.

When this same change was made in the Rocky Flats office worker calculation, the soil action level to dose ratio decreased from 73 to 16 (pCi g^{-1}) $mrem^{-1}$. This single parameter accounts for the difference between these two calculations. Table 13 summarizes the differences between the ratios and the parameter changes employed.

Table 13. Changes in the Soil Action Level to Dose Ratio with Parameter Value Changes for $^{239,240}Pu$ in the Nevada Test Site and RFETS Calculations

Site and scenario	Parameter change	Soil action level to dose ratio ([pCi g^{-1}] $mrem^{-1}$)	Dose to soil action level ratio (mrem [pCi g^{-1}]$^{-1}$)
Rocky Flats residential	Original calculation	17	0.06
	Change dose conversion factor	2.8	0.36
Nevada Test Site residential	Original calculation	4.1	0.24
Rocky Flats office worker	Original calculation	73	0.01
	Change dose conversion factor	16	0.06
Nevada Test Site industrial worker	Original calculation	41	0.02

U.S. Nuclear Regulatory Commission DandD Code Scenarios

The NRC produced its own computer code using models similar to those in RESRAD. This code, called DandD, was designed for use by NRC agencies as a guideline for cleanup and remediation of contaminated sites. Two sets of scenarios were developed for generic use with DandD: (1) scenarios for the release of buildings and (2) scenarios for the release of contaminated land. Only the contaminated land scenarios are comparable to the RFETS calculations. Of the land use scenarios, the residential use, or surface soil, scenario is the most directly comparable to the situation at Rocky Flats.

This scenario assumes residential farming of land with limited gardening activities. The pathways considered are inhalation of soil; ingestion of soil, water, milk, meat, poultry, and fish grown/raised and irrigated by contaminated water; and external gamma exposure. Indoor radon is not considered.

The total effective dose equivalent for the residential scenario for ^{239,240}Pu, assuming surface soil activity of 1 pCi g^{-1}, is 288 mrem. This yields a soil action level to dose ratio of 0.003 (pCi g^{-1}) $mrem^{-1}$, much smaller than the Rocky Flats ratio.

The differences between these two calculations are numerous, and are not, in all cases, completely transparent without the benefit of the code documentation. Upon running the DandD code, the most noticeable difference is that the primary contributors to the dose are the aquatic pathway (66%), the irrigation pathway (21%), and the drinking water pathway (13%). This results from the use of dose conversion factors that correspond to a soluble class of plutonium, as well as very conservative pathway assumptions relating to concentration factors in fish and plants.

The pathways used in DandD appear to be quite different from those in RESRAD, making it very difficult to compare results from the two without extensive documentation. Representatives from the NRC have indicated to *RAC* that DandD was written for a purpose very different than the calculation of soil action levels, and they did not recommend that actual scenario dose calculations be made with this code; rather, the code is intended to be used for screening level, conservative calculations only.

The differences between the RESRAD and DandD codes are so extensive that a comparison of Rocky Flats residential calculations with RESRAD and the DandD residential farmer scenario is not instructive or possible given the limited time and scope of this project. DandD is reviewed somewhat more extensively in the Task 2 report.

Johnston Atoll, Marshall Islands

Plutonium contamination in the environment at the Johnston Atoll in the Marshall Islands resulted from three accidents in 1962: the destruction of two off-course rockets at high altitude and one explosion on the rocket launching pad (Spreng 1999). Using mining techniques, the soil was cleaned to about 15 pCi g^{-1} (Bramlitt 1988). An independent verification of the cleanup was performed by Oak Ridge National Laboratory (Wilson-Nichols et al. 1997). Currently, a company called GeoCenters is reviewing the cleanup levels and revising the calculations using more realistic receptors. A draft report of this work was due in March 1999 (Spreng 1999).

The scenario used in the Johnston Atoll calculations was a residential scenario using only the inhalation pathway. This resident differed from the Rocky Flats resident in that residence was assumed 24 hours a day, 365 days per year. Using existing information, the soil action level to dose ratio for a Johnston Atoll resident was calculated to be 0.85 (pCi g^{-1}) $mrem^{-1}$ (Wilson-Nichols et al. 1997). The soil concentration was calculated for doses only from inhaled alpha emitters. The soil screening limit, *SSL*, (or soil action level) was calculated using Equation (1).

$$SSL = \frac{C_{air,acceptable}}{ML ? EF} \quad (1)$$

where

$C_{air, acceptable}$ = acceptable air concentration (pCi m^{-3})
ML = mass loading (g m^{-3})
EF = enrichment factor (unitless).

The acceptable air concentration is calculated for the accepted annual committed dose. For the Johnston Atoll calculation, the annual committed dose limit was 20 mrem y^{-1}, which corresponds to an air concentration of 2.6 _ 10^{-3} pCi m^{-3} for the alpha emitters, plutonium or americium compounds, assuming a quality factor of 20 (Wilson-Nichols et al. 1997). This air concentration was calculated for Class Y (insoluble) compounds of plutonium that are retained in the lung for years. The committed dose applies to the pulmonary region of the lung.

It is important to note that this calculation was performed based upon a significantly older version of the International Commission on Radiological Protection (ICRP) lung model than that currently in use. The lung model was described in ICRP Publication 19 (ICRP 1972) when recommendations from ICRP 2 (ICRP 1959) were outdated, but ICRP 30 (ICRP 1978) had not yet been published. The ICRP 19 (ICRP 1972) document was prepared by a task group and described an updated version of the lung model. However, ICRP 19 did not yet include calculation of total body dose; the emphasis at this time was still on organ-specific dose. As a result, acceptable air concentrations for the Johnston Atoll were calculated based only on doses to the pulmonary region of the lung. In contrast, the RFETS calculation, which was founded on later ICRP recommendations, describes dose to the entire body. Therefore, the ratios should be compared with caution.

The mass loading factor selected for this calculation was 0.0001 g m^{-3}, as defined by the EPA for developing a soil screening limit (EPA 1977). Even during cleanup and soil disturbance activities at the Johnston Atoll site, mass loading factors were smaller than this value, so the 0.0001 g m^{-3} value was assumed to be a conservatively high (Wilson-Nichols et al. 1997).

The enrichment factor considers how the ^{239,240}Pu concentration in the respirable fraction of the soil compares to plutonium concentrations in soil of all particle sizes. An EPA study that looked at five sites in the U.S., including the RFETS, listed enrichment factors for each site (EPA 1977). According to this study, Rocky Flats had the largest enrichment factor of the sites studied across the U.S.. To be conservative, the Johnston Atoll study used an average of the Rocky Flats data to develop an enrichment factor of 1.5.

Using this information and Equation (1), the soil screening limit for the Johnston Atoll was calculated to be 17 pCi g^{-1} for a committed dose equivalent of 20 mrem y^{-1}, giving the ratios cited above. Using Rocky Flats data in this equation helps clarify the differences between the ratios for Johnston Atoll and the ratios for the RFETS.

The first step was to determine the difference between dose conversion factors for the two sites. To extract the Johnston Atoll dose conversion factor from the existing information, we used an equation for effective dose from inhaled material. Equation (2) calculates dose (in units of millirem) from inhaled material.

$$Dose = V_{inhaled} \, ?C_{air} \, ?DCF \qquad (2)$$

where
$V_{inhaled}$ = volume inhaled (m^3 y^{-1})
C_{air} = concentration in air (pCi m^{-3})
DCF = dose conversion factor (mrem pCi^{-1}).

The volume inhaled in the Johnston Atoll calculation was 8395 m^3 y^{-1}, based on the ICRP reference man (ICRP 1975) for full-time occupation. The concentration in air was 2.6 _ 10^{-3} pCi m^{-3} for a 20 mrem dose. The dose conversion factor that results from inputting these values and rearranging Equation (2) is 0.91 mrem pCi^{-1}. This contrasts with the RFETS dose conversion factor for insoluble plutonium of 0.308 mrem pCi^{-1}. It is important to remember that the RFETS dose conversion factor is for total body dose, and the Johnston Atoll dose conversion factor is only for dose to the pulmonary region of the lung.

Equation (2) can be used to calculate an acceptable air concentration for Johnston Atoll using RFETS parameters. For a Johnston Atoll limit of 20 mrem effective dose limit, RFETS volume inhaled of 7000 m^3 y^{-1} and RFETS dose conversion factor identified above, the concentration in air is equal to 9.27 _ 10^{-3} pCi m^{-3}.

Equation (1) is used to calculate the Johnston Atoll soil screening limit using Rocky Flats values. The Rocky Flats value for mass loading was 0.000026 g m^{-3}. The air concentration was calculated above, and in the RFETS calculation, no enrichment factor was employed. The soil screening limit for Johnston Atoll using RFETS parameter values is 356 pCi g^{-1}, which gives a soil action level to dose ratio of 17.8 (pCi g^{-1}) $mrem^{-1}$ and matches that of the RFETS. Table 14 summarizes the results of this analysis.

Table 14. Soil Action Level to Dose Ratio for $^{239,240}Pu$ Changes with Parameter Alteration for Johnston Atoll and RFETS Calculations

Location	Parameter change	Soil action level to dose ratio ([pCi g^{-1}] $mrem^{-1}$)	Dose to soil action level ratio (mrem [pCi g^{-1}]$^{-1}$)
Rocky Flats	Original calculation	17	0.06
Johnston Atoll	Original calculation	0.85	1.2
	Calculate concentration in air using RFETS dose conversion factor and volume inhaled	3.1	0.32
	+ change to RFETS mass loading	11.9	0.08
	+ change to RFETS enrichment factor	17.8	0.056

Enewetak Atoll, Marshall Islands

The cleanup levels established for the Enewetak Atoll are very different in scope and intent than those discussed previously. This cleanup was driven more by time, money, and military concerns than an identified limit for concentrations in soil.

The Defense Nuclear Agency published a book describing the cleanup of Enewetak Atoll after numerous U.S. nuclear tests took place there in the 1950s and 1960s (DNA 1981). This book primarily documents the cleanup efforts and decisions made throughout the process; it does not provide a clear assessment of doses and accepted cleanup levels for the islands.

The cleanup of the Marshall Islands was one of the first efforts of its magnitude. Although accidents had occurred at other facilities, guidance was just beginning to be developed for nuclear material soil standards, particularly for transuranics. The EPA guidance on transuranic elements in the environment had not yet been released, and ICRP models for dose were still limited at the time of cleanup.

As a result of limited guidance, decisions about soil cleanup came slowly and only after considerable discussion, disagreement, and finally consensus. As many as three committees produced recommendations for the Enewetak Atoll cleanup, and all committees agreed on some levels and disagreed on others.

The first remediation goal, established by the Environmental Research and Development Agency (ERDA) in conjunction with the U.S. Army Support Command, was to reduce plutonium concentrations in soil to levels below 40 pCi g^{-1}. This concentration level would qualify the land for residential and agricultural use (DNA 1981).

At a workshop held to discuss ERDA plans for the Marshall Islands, doubts and objections to this cleanup strategy were raised, questioning whether the guidelines for soil removal were supportable. As a result of these questions, ERDA convened a panel of scientists, known as the Bair Committee, to review Atomic Energy Commission (AEC) recommendations. An Atomic Energy Commission task group that suggested 400 pCi g^{-1} as an acceptable limit in soil because it was conservatively equivalent to the maximum permissible concentration in air for radiologically unrestricted areas. The task group then introduced a safety margin of a factor of 10, recommending that no cleanup was required below 40 pCi g^{-1}. The areas with soil concentrations between 40 and 400 pCi g^{-1} would be assessed on a case-by-case basis depending on the use of the land. Finally, this task group suggested that after cleanup was initiated, soil levels should be reduced to the lowest possible level (DNA 1981).

Following the AEC recommendations, ERDA established an Operating Plan recognizing that cleanup of all areas to below 40 pCi g^{-1} would require removing large quantities of soil for no appreciable benefit. The Operating Plan suggested conditions for soil use. Condition A specified that an island could be used for food gathering if surface plutonium did not exceed 400 pCi g^{-1}. Condition B allowed agricultural use of land if surface plutonium did not exceed 100 pCi g^{-1}. Residential use, outlined by Condition C, required cleanup to levels below 40 pCi g^{-1}. The final condition involved using the land for all three purposes if the surface conditions met the appropriate requirements and subsurface plutonium concentrations did not exceed 400 pCi g^{-1}.

The Bair Committee approved of the ERDA Operating Plan cleanup criteria and suggested that more specific guidance be established for the soil concentrations between 40 and 400 pCi g^{-1}. When the 1977 EPA guidance on transuranics was released, the Bair Committee adapted its recommendations for agricultural land soil concentrations to 80 pCi g^{-1} and food gathering land soil concentrations to 160 pCi g^{-1}. These values were apparently based on a dose assessment study performed by Lawrence Livermore National Laboratory. A first study done by Lawrence Livermore National Laboratory was based on the original soil cleanup criteria, but the results were deemed incorrect because of a mathematical error. The Laboratory performed a new dose assessment. Results from this new dose assessment influenced the Bair Committee's decisions concerning action levels for different soil uses.

We could not locate the Lawrence Livermore National Laboratory study in the literature. The Defense Nuclear Agency document lists the radiation doses from this study only unit of millirad; however, these values cannot be converted to effective doses without knowing more about the dose model used to make the calculations. We can assume that Lawrence Livermore National Laboratory scientists used the same model as that used in the Johnston Atoll study, with a large dose conversion factor. However, we would need to have access to the Lawrence Livermore National Laboratory study to make comparisons to RFETS values. We contacted Dr. William Bair, Chair of the Bair Committee, in an attempt to locate documentation. He no longer had copies of the pertinent information, but referred us to Bill Robison at Lawrence Livermore National Laboratory. He has been contacted, and we await a response from him concerning the Lawrence Livermore National Laboratory dose assessment documentation.

Maralinga, Australia

Nuclear weapons trials conducted between 1953 and 1963 by the United Kingdom contaminated the Maralinga site in Australia. This land was the home of semi-traditional Aboriginal tribes, and it became necessary to restore it for their use. A rehabilitation project was undertaken in 1996 because of the extensive $^{239,240}Pu$ contamination in the area. This facility is more difficult to compare to Rocky Flats because RESRAD calculations were not performed. However, a dose evaluation was performed and cleanup criteria were established, so we did have some mechanism to compare the facilities. Doses for the Maralinga facility were calculated for a resident living in a semi-traditional Aboriginal life style, but they focused only on doses from inhalation. This resident lived at the site 24 hours a day, 365 days per year.

In the context of the Maralinga site, the term soil action level is used loosely because cleanup criteria is a more appropriate term. However, we use the term soil action level here for consistency.

The soil action level to dose ratio for the Maralinga site is 0.56 (pCi g^{-1}) $mrem^{-1}$. This ratio was calculated by rearranging the equation used at the Maralinga site to calculate dose. Equation (3) shows the dose calculation used at the Maralinga facility.

$$Dose\,(mrem\;y^{-1}) = C_{air}\ ?BR\ ?DCF \qquad (3)$$

where
C_{air} = concentration in air (pCi m^{-3})
BR = breathing rate (m^3 y^{-1})
DCF = dose conversion factor (mrem pCi^{-1})
and

$$C_{air} = C_{soil}\ ?ML \qquad (4)$$

where
C_{soil} = soil concentration (pCi g^{-1})
ML = mass loading (g m^{-3}).

Combining and rearranging Equations (3) and (4) yields Equation (5), which gives a direct calculation of the dose to soil action level ratio. The reciprocal of Equation (5) is the soil action level to dose ratio.

$$\frac{Dose\,(mrem)}{C_{soil}\ (pCi\ g^{-1})} = ML\ ?BR\ ?DCF \qquad (5)$$

where all quantities are as previously defined.

The values used in Equation (5) for the Maralinga calculation and the information about the site were extracted from two sources: the journal of *Health Physics* (Johnston et al. 1992) and the Australian Radiation Laboratory (ARL 1998).

Mass loading for the site was determined by simulating some Aboriginal dust raising activities. These data were the only data available to the Australian Radiation Laboratory group, and a value of 0.001 g m^{-3} was used for adults. Breathing rates were taken by the Australian Radiation Laboratory from Haywood (1987). For adults, an annual breathing rate of 8400 m^3 y^{-1} was used. The dose conversion factors were extracted from ICRP 56 (ICRP 1989), but they were corrected for 5 μm AMAD particles because a study indicated this particle size best represented the respirable fraction at the Maralinga site. The dose conversion factor for $^{239,240}Pu$ was calculated assuming the worst case scenario translocation rate for the Australian test sites would be represented by 25% of the plutonium being Class W (soluble) and 75% being Class Y (insoluble). This series of conversions results in a dose conversion factor for $^{239,240}Pu$ of 0.215 mrem pCi^{-1}.

The three parameter values used in Equation (5) lead to a dose to soil action level ratio of 1.8 mrem (pCi $g^{-1})^{-1}$ and a soil action level to dose ratio of 0.56 (pCi g^{-1}) $mrem^{-1}$ for the Maralinga site.

To compare the ratio for the Maralinga site to the Rocky Flats ratio, we inserted RFETS parameter values into the Maralinga calculation. Using the Rocky Flats values for mass loading (0.000026 g m^{-3}), breathing rate (7000 m^3 y^{-1}), and $^{239,240}Pu$ inhalation dose conversion factor (0.308 mrem pCi^{-1}) in Equation (5), yields a dose to soil action level ratio of 0.056 mrem (pCi $g^{-1})^{-1}$ and a soil action level to dose ratio of 17.8 (pCi g^{-1}) $mrem^{-1}$.

Using the Rocky Flats values in Equation (5) accounts for the difference in the two ratios. Table 15 summarizes the changes in the ratios between Maralinga and the RFETS by altering the parameter values used in the calculation.

Table 15. Soil Action Level to Dose Ratio for ^{239,240}Pu Changes with Parameter Alteration for Maralinga and RFETS Calculations

Location	Parameter change	Soil action level to dose ratio [(pCi g^{-1}) mrem^{-1}]	Dose to soil action level ratio [mrem (pCi g^{-1})$^{-1}$]
Rocky Flats	Original calculation	17	0.06
Maralinga	Original calculation	0.56	1.8
	Change to RFETS breathing rate	0.67	1.5
	+ change to RFETS mass loading	26	0.039
	+ change to RFETS dose conversion factor	17.8	0.056

Semipalatinsk Nuclear Range, Kazakhstan

At this location in the former Soviet Union, 124 atmospheric nuclear tests were carried out between 1949 and 1962 (Zeevaert et al. 1997). These tests resulted in environmental contamination and radiation exposure. The contamination was extensively documented and radiation dose rates measured. The results from this work do not yield a soil cleanup level, but they do document existing surface contamination and resulting doses.

It is important to point out that the values given in the literature document either a range of surface radiation levels associated with a single dose or a range of doses associated with a single radiation level. It is very difficult to correlate dose to corresponding soil concentration, not only because surface radiation levels are only tenuously converted to concentrations but also because the surface levels are not related directly to an inhalation dose. Zeevaert et al. (1997) should be carefully reviewed if more information is desired.

For settlements at the Semipalatinsk site, maximum soil activity was given as 11 kBq m^{-2}, corresponding to a soil concentration of 1.32 pCi g^{-1}. We assumed a depth of contamination of 15 cm and a soil density of 1.5 g cm^{-3} to enable us to make this conversion because these factors were not given in Zeevaert et al. (1997). The individual dose to the population resulting from this concentration is identified as 1.5 Sv, or 150,000 mrem. It is not clear from the documentation what this individual dose represents, how it was calculated, or if it correlates in any way to the defined surface soil activity.

The resulting soil concentration to dose ratio is 8.8 _ 10^{-6} (pCi g^{-1}) mrem^{-1}. This ratio is fraught with uncertainties, both in measurement techniques and capabilities and difficulty correlating dose to soil concentration in the literature. While this is smaller than the Rocky Flats ratio, it is impossible to account for the differences because the Semipalatinsk soil concentration was measured in the environment, not calculated. Furthermore, Zeevaert et al. (1997) does not describe the dose calculation techniques. We present the ratio only in the interests of completeness, and do not compare it to Rocky Flats.

Another territory affected by the Semipalatinsk tests was Ouglovski, with soil concentrations of 0.66 pCi g^{-1}. The doses cited for this region are external doses, however, and cannot be applied to obtain a ratio.

Thule, Greenland

Near the Air Force Base at Thule, Greenland, on January 21, 1968, a military plane carrying four nuclear weapons crashed and burned. Plutonium contamination was spread about the crash site on the ice, with a maximum contamination level of 14.8 kBq m^{-2}. This site had to be cleaned up before the ice melted in the spring, dictating the time frame of the project. As a result, the only data we have from this crash site are concentrations of plutonium in sediments and estimated dose data from ingestion of sea mussels. Comparisons between this site and the RFETS are impossible because of lack of appropriate data and dissimilar pathway analyses. We report the dose and concentration data in this report for completeness.

After cleanup, the maximum concentration of ^{239}Pu in sediments under the crash site was 1.85 Bq g^{-1}, or 50 pCi g^{-1}. Inhalation is not an appropriate pathway because plutonium is contained in sediments, not dry soil; therefore, the pathway of interest is consumption of mussels. In 1974 (6 years after the accident), the average concentration of plutonium in the edible part of mussels was 0.74 Bg g^{-1} (20 pCi g^{-1}). With a consumption rate of 100 g d^{-1} of mussels for 70 years, the annual committed dose rate to the bone was calculated to be 0.75 mGy (75 mrad) (Church 1998).

Palomares, Spain

Another nuclear accident occurred in Palomares, Spain, on January 17, 1966, when a U.S. Air Force bomber collided with its tanker and exploded above the town. Two of the bomber's four nuclear weapons impacted very near the town and released plutonium. Plutonium oxide contaminated about a 225-hectare (560-acre) area of brushland, farmland, and urban area.

The contamination of this area was so great that immediate cleanup was warranted. Soil concentrations measured just after the accident indicated areas of ^{239,240}Pu contamination ranging from 212 μCi g^{-1} (2.12 _ 10^{8} pCi g^{-1}) down to 2.12 μCi g^{-1} (2.12 _ 10^{6} pCi g^{-1}) (Iranzo et al. 1987). Cleanup was immediately undertaken, with the soil layer at the highest contamination level removed (10 cm deep) and disposed of as radioactive waste. The remainder of the soil was irrigated thoroughly, plowed to a depth of about 30 cm, and homogenized to move contaminated soils to lower levels. At lower levels, the soil would not be available for resuspension to become a potential source of inhalation and dose to residents (Iranzo et al. 1987).

At the time, a dose assessment based on these contamination levels was not performed. The contamination was so widespread that cleanup was the issue at hand. After the cleanup was complete, a monitoring program was established, which included air sampling, soil sampling, crop sampling, and urine and lung counting of the residents.

Air concentrations measured in the environment were compared to (a) annual limits on intake and (b) derived air concentrations from these limits as recommended by the ICRP for radiation workers (ICRP 1978). Because values for acceptable air concentrations for the public were not provided in ICRP 30 (1978), the radiation worker values were multiplied by the ratio of dose limits recommended for the public to those recommended for radiation workers (0.1). This concentration was again reduced to account for ICRP recommendations that effective dose equivalent throughout the life of a member of the exposed population does not exceed the value resulting from a 1 mSv (100 mrem) annual effective dose equivalent. Therefore, acceptable concentration values for members of the public were set at 1.2 mBq m^{-3} (3.2 _ 10^{-2} pCi m^{-3}) for

Class Y (insoluble) compounds of plutonium and 0.5 mBq m^{-3} (1.35 _ 10^{-2} pCi m^{-3}) for Class W (soluble) compounds of plutonium. In the context of the RFETS parameter values, with insoluble Class Y plutonium and a mass loading factor of 0.000026 g m^{-3}, this air concentration corresponds to a soil concentration of 1230 pCi g^{-1}.

Using these values to establish a soil concentration to dose ratio (for the 100 mrem dose for which the air concentration was calculated) results in a ratio for ^{239,240}Pu of 12.3 (pCi g^{-1}) $mrem^{-1}$. This ratio is only for inhaled plutonium, and it is based upon the ICRP reference man, who breathes at a rate of 23 m^3 d^{-1} (ICRP 1975). For an exposure time of 8760 h y^{-1} (a full-time resident), this corresponds to an annual breathing rate of 8395 m^3 y^{-1}, which contrasts with the RFETS breathing rate of 7000 m^3 y^{-1}.

Placing the breathing rate of 8395 m^3 y^{-1} into the RFETS calculation yields a soil action level of 1202 pCi g^{-1} and a soil action level to dose ratio of 14.1 (pCi g^{-1}) $mrem^{-1}$. We were unable to discover the reason for the remaining difference between these two ratios during this assessment.

Table 16 summarizes the changes made to the RFETS calculation and ratio.

Table 16. Soil Action Level to Dose Ratio for $^{239.240}$Pu Changes with Parameter Alteration for Palomares and RFETS Calculations

Location	Parameter change	Soil action limit to dose ratio ([pCi g^{-1}] $mrem^{-1}$)	Dose to soil action level ratio (mrem [pCi g^{-1}]$^{-1}$)
Rocky Flats	Original calculation	17	0.06
	Change breathing rate	14.1	0.07
Palomares	Original calculation	12.3	0.08

It is important to note that at the Palomares site, the air concentrations measured in the environment after cleanup were almost always below the acceptable limits, with the exception of four 10-day periods during 1966–1969. During these periods, the increases in contaminated air above the acceptable level could be attributed to cultivation activities, which were hypothesized to raise contaminated soil to the surface and make it available for resuspension (Iranzo et al. 1987).

CONCLUSIONS

The soil action levels at the RFETS are significantly higher than action or cleanup levels at other facilities, even when normalized to dose. However, we understand the reasons for these elevated levels. The outcome of the RESRAD calculation is strongly controlled by a few parameters, and almost without exception, it is these parameters that affect the differences in the soil action levels for a unit dose between sites. The parameters are

- Dose conversion factor (solubility class of plutonium),
- Mass loading (resuspension), and to a lesser degree
- Breathing rate.

Breathing rate is less significant because the range of possible values is limited to within reasonable boundaries. The dose conversion factor varies depending on the assumed solubility of plutonium. For soluble Class W plutonium, the inhalation dose conversion factor is

0.429 mrem pCi^{-1} and the ingestion dose conversion factor is 0.0035 mrem pCi^{-1}. For insoluble Class Y plutonium, the inhalation dose conversion factor is 0.308 mrem pCi^{-1} and the ingestion dose conversion factor is 0.000052 mrem pCi^{-1} (ICRP 1978). When soluble plutonium is assumed, the ingestion pathway becomes a more dominant contributor to the dose, and the dose per unit intake is considerably greater. For the RFETS, we can determine the appropriate assumption based upon the oxidation state of the plutonium found in the soil at Rocky Flats.

The mass loading parameter can vary over orders of magnitude depending on assumed environmental conditions. Mass loading and similar resuspension parameters have been extensively measured at Rocky Flats under a variety of conditions, and it will be important to use this information to establish a plausible range of values for this parameter. If insoluble plutonium is assumed, inhalation will dominate dose, and mass loading will become a critical parameter.

We reviewed the soil action level to dose ratios for the other sites studied during Task 1 in terms of the calculations, models, and parameters used to calculate soil concentrations and/or dose. In almost every case, differences between sites could be explained by the different assumptions made for one or more of the key parameters identified above (see Table 17).

With Task 1, we identified the input model parameters that are of primary importance in determining the soil action levels so we can carefully review them when completing the Task 3 report, Inputs and Assumptions.

Table 17. Summary of Comparisons between RFETS Calculations and Those for Other Facilities

Location	Parameter change	Soil action limit to dose ratio ([pCi g^{-1}] $mrem^{-1}$)	Dose to soil action limit ratio (mrem [pCi g^{-1}}$^{-1}$)
Rocky Flats residential	Original calculation	17	0.06
Hanford residential	Original calculation	2.3	0.44
	Remove meat, milk, fish, and drinking water pathways and change to RFETS dose conversion factor and mass loading	34	0.03
Rocky Flats office worker	Original calculation	73	0.01
Hanford industrial worker	Original calculation	16.3	0.06
	Change dose conversion factor and mass loading	159	0.006
Rocky Flats residential	Original calculation	17	0.06
	Change to Nevada Test Site dose conversion factor	2.8	0.36
Nevada Test Site residential	Original calculation	4.1	0.24
Rocky Flats office worker	Original calculation	73	0.01
	Change dose conversion factor	16	0.06
Nevada Test Site industrial worker	Original calculation	41	0.02
Rocky Flats	Original calculation	17	0.06
Johnston Atoll	Original calculation	0.85	1.2
	Change to RFETS mass loading, enrichment factor, and calculate air concentration using RFETS dose conversion factor and breathing rate	17.8	0.056
Rocky Flats	Original calculation	17	0.06
Maralinga	Original calculation	0.56	1.8
	Change to RFETS mass loading, breathing rate, dose conversion factor	17.8	0.056
Rocky Flats	Original calculation	17	0.06
	Change to Palomares breathing rate	14.1	0.07
Palomares	Original calculation	12.3	0.08

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