FINAL REPORT

Technical Project Summary

Radionuclide Soil Action Level Oversight Panel

February 2000

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

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Risk Assessment Corporation

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EXECUTIVE SUMMARY

The primary objective of this project has been to review radionuclide soil action levels (RSALs) adopted by the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the Colorado Department of Health and Environment in 1996 for cleanup at the Rocky Flats Environmental Technology Site. Another objective has been to recommend a technical method for independently deriving RSALs for the site. As a result of public concern about the soil action levels established in 1996, the Radionuclide Soil Action Level Oversight Panel, a group of community members with considerable experience in Rocky Flats issues, was formed. In 1998, DOE provided funds for the Radionuclide Soil Action Level Oversight Panel to select a contractor to conduct an assessment of the interim RSALs and to independently calculate RSALs for the RFETS. Through a competitive bidding process and evaluation, *Risk Assessment Corporation* (*RAC*) was selected by the Radionuclide Soil Action Level Oversight Panel to carry out the study.

RAC's methodology for determining RSALs applicable to the Rocky Flats site was based on several extensions of an earlier approach proposed by DOE/EPA/CDPHE that used the RESRAD computer program. The contract required that the work consider maximum annual dose limits of 15 and 85 mrem in any year over the next 1000 years. *RAC* adopted the 15 mrem y^{-1} limit for a technically based RSAL because it was more protective of the public. Although several computer codes were considered for use as the basis of *RAC*'s analysis, the RESRAD code was adopted because it was the most practical choice and was required to be used in addition to any other code that may have been selected. *RAC* designed extensions to RESRAD to include (1) considering the heterogeneity of radionuclide concentrations in soil around the site, (2) quantifying uncertainty in predictions of dose, (3) considering additional exposure scenarios, and (4) treating the possible occurrence of a large grass fire. The exposure pathways considered were inhalation, soil and food ingestion, and external irradiation. In addition, groundwater use for both irrigation and drinking water was assumed for some scenarios.

The RSAL values include estimates of the uncertainties and are designed to ensure that the permitted annual dose limit for the targeted individual is exceeded only with low probability. For each scenario, curves were presented that representing the probability of exceeding the radiation dose limit as a function of $^{239+240}Pu$ or uranium concentrations in the soil. Each probability level corresponds to a distinct concentration of $^{239+240}Pu$ or uranium in soil.

RAC applied this methodology to the Rocky Flats data using the most restrictive exposure scenarios approved by the Rocky Flats Soil Action Level Oversight Panel and assuming a 10% probability that the 15 mrem y^{-1} dose limit will be exceeded (i.e. a 90% probability that the dose limit will <u>not</u> be exceeded). Using this approach, the technically derived RSAL for $^{239+240}Pu$ in soil at Rocky Flats would be 35 pCi g^{-1}. This calculation was corroborated by an alternate method calculation that also resulted in an RSAL at the 10% level of about 37 pCi g^{-1}, suggesting 35 pCi g^{-1} as a technically based RSAL for the Rocky Flats site. The results as presented are a reasonable indication of RSAL magnitudes based on purely scientific considerations if the prescribed dose is not to be exceeded.

The calculation of uranium RSALs was done somewhat differently than those for plutonium because of significant differences in the nature and extent of contamination and the mobility of

uranium in the subsurface. For each uranium scenario, consideration was given to whether groundwater was a viable pathway. A viable groundwater pathway assumed that the surficial aquifer underlying the site would provide enough water for human consumption and irrigation. The impacts of a probabilistic fire were also evaluated but inclusion of this process in our calculations made little difference in the resulting RSALs. Assuming the groundwater pathway was viable and a 10% probability, the technically derived ^{238}U RSAL for the most restrictive scenario (child of rancher) was 10 pCi g^{-1}.

We believe the general approaches presented in this report and these results are sound and we recommend their adoption. Data limitations impose uncertainties on estimates of doses, and we have been careful to indicate these uncertainties in our analysis. The project's time and budget goals precluded a more in-depth investigation of several important areas of research that, if addressed in the future, could strengthen this analysis. We have presented these recommendations for further research and recognize that they could change these results somewhat and improve them as a basis for decision making.

Public involvement was particularly important in this study because of the impact the cleanup may have on the local communities surrounding the site. *RAC*, along with the Rocky Flats Soil Action Level Oversight Panel, were committed to ensuring that there was public involvement and interaction during the entire review process through open technical work sessions and general public meetings.

A sound technical foundation and credible scientific methodology are the most important elements in setting soil action levels for Rocky Flats site. However, the final decision on setting the RSALs ultimately lies in the hands of the stakeholders, U.S. Department of Energy, State and federal authorities, and the community working together to arrive at a cleanup level that provides long term protection of the public. *RAC* believes that additional research in specific areas could reduce some of the uncertainties and help to develop more well-defined methods in the approach.

CONTENTS

TECHNICAL SUMMARY

INTRODUCTION

The Rocky Flats Environmental Technology Site (RFETS) is owned by the U.S. Department of Energy (DOE) and is currently operated by Kaiser-Hill Company. The RFETS is located 5–6 mi (8–10 km) from the cities of Arvada, Westminster, and Broomfield, Colorado, and 16 mi (26 km) northwest of downtown Denver, Colorado (Figure 1). For most of its history, the Dow Chemical Company operated the Rocky Flats Plant as a nuclear weapons research, development, and production complex. For almost 40 years the site manufactured components for nuclear weapons, and, in the process, released contaminants to the environment. In 1989 Rocky Flats stopped weapons parts production and, in 1992, began the process of cleaning up contamination at the site. The soil on the Rocky Flats site is contaminated with plutonium and uranium from routine and accidental releases of radionuclides during operations, and from leaking barrels of contaminated oils and solvents that were stored at the 903 Area, an outdoor area directly east of the main buildings at the Rocky Flats plant.

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Figure 1. Aerial photograph of the Rocky Flats Plant looking northwest. The highest levels of plutonium in the soil are found in the vicinity of the 903 Area, which is marked on the photograph.

The focus of the current project was to develop a methodology for determining radionuclide soil action levels (RSALs) and to calculate RSALs for Rocky Flats by applying this methodology. RSALs are certain levels or concentrations of one or more radionuclides in soil above which remedial action should be considered so that people do not receive radiation doses above permitted levels. In October 1996 DOE, the U.S. Environmental Protection Agency (EPA), and the Colorado Department of Public Health and Environment (CDPHE) adopted radionuclide soil action levels to be used in the cleanup of the Rocky Flats site (DOE/EPA/CDPHE 1996).

In response to public concern about the interim soil action levels proposed in 1996, DOE provided funding for an independent assessment and calculation of soil action levels for the Rocky Flats cleanup work.

As a result of public concern about the soil action levels established in 1996, the Radionuclide Soil Action Level Oversight Panel (RSALOP) was formed. The RSALOP is a group of community members with considerable experience in Rocky Flats issues (see Appendix E). In 1998, DOE provided funds for the RSALOP to select a contractor to conduct an assessment of the interim RSALs and to independently calculate RSALs for the RFETS. Through a competitive bidding process and evaluation, *Risk Assessment Corporation* (*RAC*) was selected by the RSALOP to carry out the study. Work began in October 1998 and was completed in March 2000.

This final report summarizes *RAC*'s work on the soil action level project. It provides an overview of the project and includes as attachments the full set of technical reports issued as a part of this project. This report outlines the background to the project and scope of work. It describes the methodology that we developed for determining RSALs, and identifies the results we obtained for each scenario. This report also describes the individual project tasks and how they contributed to the project as a whole. Finally, we provide technically derived RSALs for $^{239+240}$Pu and uranium in soil at Rocky Flats and discuss our conclusions concerning the methodology and its application to soil cleanup at RFETS.

OBJECTIVES AND DESIGN OF THE STUDY

The objective of this current study was to conduct an independent assessment of the interim RSALs adopted by DOE/EPA/CDPHE in October 1996 (DOE/EPA/CDPHE 1996) and to develop and apply a methodology for determining RSALs applicable to RFETS.

The scope of work dictated a number of design objectives for the methodology:

1. To base the soil action level on a dose limit, rather than a level of risk.
2. To consider two dose limits: 15 mrem in a year (15 mrem y^{-1}) for unrestricted use of the site, and 85 mrem in a year (85 mrem y^{-1}) for unrestricted use after failure of land use controls at the site These dose limits are those chosen for the 1996 assessment (DOE/EPA/CDPHE 1996) and are based on Draft Title 40 CFR 196. *RAC* developed technically based RSALs using the 15 mrem y^{-1} dose limit for two reasons: it is more protective of the public and our evaluation of risk associated with this dose better corresponds to the target level of risk associated with federal guidance.
3. To consider any realistic scenarios of exposure for the future, without being restricted to previously proposed scenarios.
4. To include uncertainties in the calculation to the greatest extent possible.
5. To incorporate site-specific data into the calculation where they are available.

6. To evaluate different computer codes available for calculating RSALs and select one that is the most appropriate for the situation at Rocky Flats. The RESRAD environmental transport computer code (Yu et al. 1993) was used in the previous assessment as specified by DOE Order 5400.5.
7. To use a documented and reviewed computer code, though the code could be modified to improve the quality of the calculation.
8. To evaluate all input parameters to the RESRAD computer code and suggest alternatives if values are not appropriate for the Rocky Flats site.
9. To complete the work within the time constraints given and interact with the RSALOP and the public at monthly availability sessions and formal meetings.

The dose limits for the project, 15 mrem y^{-1} and 85 mrem y^{-1}, are based on draft EPA guidance and are the dose limits used in the previous DOE/EPA/CDPHE assessment in 1996. The 15 mrem dose limit applies to a site that is open to the public and is the more important limit for this project.

The work was broken into eight project tasks that we describe in detail below. First we outline a number of other factors that influenced the *RAC* methodology. *RAC* recognized that the goal of soil action levels is to protect people who may, in the near or distant future, come into contact with a site where the soil is contaminated with radionuclides at levels above background. Therefore, setting soil action levels must consider how:

- Particular radioactive materials are transported in the environment to people (transport pathways)
- People might be exposed to the radioactive materials (exposure scenarios)
- Radiation dose to a person is assessed (radiation dosimetry)
- Radiation protection guidelines are applied (annual dose limits).

Because of these considerations, *RAC* concentrated on several processes important in the transport of radioactive materials in air and water in an area like Rocky Flats and developed exposure scenarios for the project. In designing the scenarios, *RAC* followed the principle that if the person living onsite full-time is protected, then the person living offsite will be protected. It was also important to understand the behavior of radionuclides in the soil and how soil can be disturbed or resuspended, because inhalation can be one of the important exposure pathways for those living on or near the site. The potential significance of the complex groundwater pathway was considered during the project. *RAC* did not assess the groundwater pathway in detail in the RSAL project because too little is now known. Extensive ongoing research by the Actinide Migration Evaluation (AME) team is expected to provide data not currently available. Although the groundwater pathway was ruled out in the previous analysis (DOE/EPA/CDPHE 1996), *RAC* included the pathway in our analysis for three scenarios to

Radionuclide soil action levels can be calculated for individual radionuclides in the soil. In reality, the soil contains a mix of radionuclides that can contribute to radiation dose; therefore, a mathematical method, called the sum-of-ratios, was used.

provide a likely-conservative calculation because the groundwater pathway could not clearly be ruled out as a possible exposure pathway for the future. We recognized and pointed out, however, that our assessment of the groundwater pathway was limited by the complexity of the pathway and a lack of available information.

RSALs can be calculated for an individual radionuclide, as though it were the only one present in the soil. Realistically though, the soil contains a mix of radionuclides that collectively contribute to dose. A mathematical approach, called sum-of-ratios, was used to combine the individual RSALs and assess the mixture of the contaminants in the soil. The concentration of each radionuclide is divided by its RSAL, and these ratios are added. The dose limit is exceeded if this sum-of-ratios is greater than 1. Conversely, the dose limit is not exceeded if the sum-of-ratios is less than or equal to 1

Each soil action level can be calculated in two ways: deterministically or stochastically (where uncertainties are considered). When calculated deterministically, the soil action level represents a single number, without indication of uncertainty in the value. In this case, when the ratios of radionuclide levels divided by soil action levels are summed and compared with 1, the sum-of-ratios is itself a deterministic quantity; that is, a single number, with typically no indication of uncertainty. This is the approach used in the interim soil action level calculations (DOE/EPA/CDPHE 1996).

A deterministic calculation yields a single number because the input values are single numbers with the result or output from the calculation being a single number. In contrast, a stochastic calculation takes into account the uncertainties of the input parameters, and it results in a distribution of possible results. We adopted the stochastic approach in this study.

However, the movement of each radionuclide through environmental media and into possible contact with people is an uncertain process, and mathematical models are used to simplify these processes.

In a stochastic calculation, the natural variability and lack of complete knowledge about the parameters can be treated as parameters with probability (or uncertainty) distributions. In this case, the soil action levels and sum-of-ratios that result from the model calculations, reflect the uncertainty of the input parameters. The data and input parameters are presented as probability distributions, using probability theory and Monte Carlo computational methods to propagate uncertainty to the results. Many simulations are carried out using random sampling to select values from the distributions of model parameters. This simulation yields a range of values that are used to construct uncertainty distributions for the results.

When uncertainties in soil action levels are considered, the decision about the extent of cleanup is not as straight-forward as in the deterministic case, where the sum-of-ratios is a single number that is to be compared to 1. When uncertainties are considered in the calculation, the sum-of-ratios is a distribution of values, which provides an estimate of how probable it is that the sum-of-ratios exceeds 1. If that probability is small, then a decision may be made that no action is required, even though there is some possibility that the annual dose limit could be exceeded.

Based on *RAC*'s methodology, input parameters, and exposure scenarios, we provided a technically derived RSAL for $^{239+240}$Pu and uranium in soil at Rocky Flats. The RSAL values include estimates of the uncertainties and are designed to make it unlikely that a scenario subject would receive more than a 15 mrem y^{-1} dose. By protecting the most conservative individuals described by the scenarios, the RSALs should protect others as well. The technically derived RSAL values selected from this methodology are those calculated to ensure that the permitted annual dose limit for the targeted individual is exceeded only with low probability.

PREVIOUS CALCULATIONS OF INTERIM SOIL ACTION LEVELS

Table 1 presents the interim soil action levels adopted in 1996 (DOE/EPA/CDPHE 1996) for individual radionuclides, assuming the presence of no other radionuclides. To represent RSALs based on a mix of radionuclides in the environment, the sum-of-ratios calculation, described earlier, must be completed. DOE/EPA/CDPHE completed an example of this type of calculation in their 1996 report, using a fixed ratio of $^{239,240}Pu$ and ^{241}Am. Table 2 shows the results of these calculations. *RAC*'s calculations inherently include the sum-of-ratios assumption of shared residence of contaminants in soil.

Table 1. Individual Radionuclide Soil Action Levels (in pCi g^{-1}) Adopted by DOE/EPA/CDPHE in October 1996 [a]

	Resident		Office worker	Open space user
Radionuclide	15 mrem[b]	85 mrem[b]	15 mrem[b]	15 mrem[b]
Americium-241	38	215	209	1283
Plutonium-239	252	1429	1088	9906
Plutonium-240	253	1432	1089	9919
Uranium-234	307	1738	1627	11500
Uranium 235	24	135	113	1314
Uranium-238	103	586	506	5079

[a] Taken from Table 5-1, DOE/EPA/CDPHE (1996). These RSALs were calculated using a different methodology than the RSAL values that *RAC* calculated and presents in this report. Thus, comparing the results of the two methods is misleading.

.[b] Annual dose limits from EPA draft 40 CFR 196 (EPA 1996) that were used in the previous assessment (DOE/EPA/CDPHE 1996).

Table 2. Example of the DOE/EPA/CDPHE Radionuclide Soil Action Levels (in pCi g^{-1}) Based on the Sum-of-Ratios [a]

	Resident		Office Worker
Radionuclide	15 mrem [b]	85 mrem [b]	15 mrem [b]
Plutonium-239,240	115	651	562
Americium-241	21	117	101

[a] Taken from Table 5-2, DOE/EPA/CDPHE (1996), which states that "this example assumes that the $^{241}Am/^{239}Pu$ activity ratio equals 0.18 and that only ^{239}Pu and ^{241}Am are present." These RSALs were calculated using a different methodology than those *RAC* calculated and presents in this report. Thus, comparing the results of the two methods is misleading.

.[b] Annual dose limits from EPA draft 40 CFR 196 (EPA 1996) that were used in the previous assessment (DOE/EPA/CDPHE 1996).

RAC's approach to calculating RSALs and the approach employed in the previous DOE/EPA/CDPHE (1996) assessment cannot be readily compared because the two assessments used quite different assumptions. The two sets of calculations were performed with different dose conversion factors and different soil resuspension models and data. Additionally, in the DOE/EPA/CDPHE (1996) calculation, the principal pathway contributing to a person's dose was inhalation; in the corresponding *RAC* estimate, ingestion played a much more significant role. Finally, the DOE/EPA/CDPHE calculation was deterministic, whereas *RAC*'s was stochastic; the RSALs provided by *RAC* represent the 90th percentile of a stochastic simulation. *RAC* also included the effects of a prairie grass fire in the calculation of soil action levels for each scenario, considering the probability of a fire occurring in the area (see *Task 4: Methodology for Determining Soil Action Levels* section). Evaluating similarities or differences between *RAC's* RSAL values and those reported in the DOE/EPA/CDPHE (1996) is inappropriate because of the numerous differences between the methodologies used.

PROJECT TASKS

To calculate soil action levels for the RFETS, the current project was designed to follow a careful and systematic course. The selected approach proceeded after selecting a computer code to analyze exposure pathways and sensitive parameters affecting the final results. This project was laid out in eight tasks. Five of the tasks (Tasks 1, 2, 3, 5, and 6) resulted in written reports; one task was completed as a presentation (Task 4); and two tasks (Tasks 7 and 8) were ongoing throughout the project. Table 3 summarizes the project tasks.

Each task listed in Table 3 was an important step in the process of this work. The following pages explain each task in detail. Our discussion begins with Task 8, and is followed by Task 7, because these two tasks involved interaction throughout the project.

Table 3. Project Tasks and Reports

Task	Reference	Location in current report[a]
1: Cleanup Levels at Other Sites	Weber and Till, 1999	Attachment A
2: Review Computer Models to Calculate Soil Action Levels	Killough et al. 1999	Attachment B
3: Inputs and Assumptions	Aanenson et al. 1999	Attachment B
4: Methodology for Determining Soil Action Levels	Presented at November 1998 RSALOP meeting; described in Killough et al. 2000	Attachment B
5: Independent Calculation of RSALs	Killough et al. 2000	Attachment B
6: Soil Sampling Protocol	Thorne and Rood 1999	Attachment C
7: Interaction with Actinide Migration Evaluation team	No report required[b]	Attachment D
8: Public Interaction	No report required	

[a] The layout of the final summary report was specified in the project contract; this required that the reports for Task 2, 3, and 5 be grouped into Attachment B.
[b] Attachment D contains written summaries of the quarterly AME meetings.

TASK 8: PUBLIC INTERACTION

Public involvement was particularly relevant in this study because of the impact the cleanup levels may have on the local communities surrounding the site. With any study that involves members of the public as stakeholders, it is important to involve the public in new and creative ways in the decision-making process. *RAC*, along with the RSALOP, focused on this end throughout the project by scheduling and conducting public meetings and making written materials available. Advanced Integrated Management Services, Inc. (AIMSI) provided management support to the RSALOP for the project. The Citizens' Advisory Board managed the DOE grant for the work, made their web site available for the dissemination of project information, and provided technical assistance throughout the project.

It was important to keep the public and local stakeholders informed about the scientific review of the interim RSALs and calculations undertaken by *RAC*. The RSALOP, as well as *RAC*, were committed to ensuring that there was public involvement and interaction during the entire review process. Monthly meetings were scheduled to update the RSALOP on the progress of the project. The monthly RSALOP meetings were important forums for interaction with the RSALOP, the agencies, and the public. During these meetings, *RAC* received guidance from RSALOP members regarding the direction of the project and input parameter values. Ideas and insights coming from discussions at these meetings would have been lost had this interaction not existed.

The RSALOP and *RAC* agreed to hold informal public technical sessions immediately before the regular monthly meetings to make sure all questions could be addressed and all issues discussed fully. These technical work sessions gave anyone interested in attending a chance to ask more specific questions and to discuss the technical details of the work. These sessions served as round-table discussions and much was accomplished by explaining our methodology, clarifying issues, and presenting examples of our work to the attendees.

Three general public meetings took place during the course of the project. The public meetings were geared toward a general audience to update them on the work being done and to respond to their questions and comments.

A special workshop on risks from exposure to radioactive materials was held on February 11, 1999, in response to panel concerns about radiation risk estimates and how they are derived. This workshop, led by Mr. Charles Meinhold, President of the National Council on Radiation Protection and Measurements, was open to the public and helped inform the RSALOP about current practices in risk protection and management.

Five peer reviewers from around the country, contracted by the RSALOP and paid from community funds, reviewed and provided written comments on each of our five draft technical reports. We also received review comments from RSALOP members, DOE personnel, and others attending the monthly meetings. This review process helped identify areas of concern not already considered and allowed us to address many of the concerns within the context of our work. We responded to all comments in writing, and these responses were reviewed and accepted by the RSALOP. The final reports reflected changes made in response to all review comments. The process of public interaction and review took place throughout the entire project and provided a valuable means for identifying issues that were critical for the public.

TASK 7: ACTINIDE MIGRATION EVALUATION AT ROCKY FLATS

The Actinide Migration Studies group was established by DOE in 1996 to investigate and model $^{239,240}Pu$, ^{241}Am, and uranium transport in the site environment. (The project was later renamed the Actinide Migration Evaluation [AME]). Periodic technical and public meetings have enabled the scientists involved in the study of actinide movement in the Rocky Flats environment to report on the progress of their work. Their input into our project was valuable , and Attachment D contains summaries of meetings held during the course of the project.

Quarterly AME working meetings were held throughout the duration of the RSAL project, and *RAC* attended the meetings to gather information that might be helpful for our studies. Research on actinide migration processes at Rocky Flats is relevant to the current soil project because the studies may help characterize the chemical and physical form of plutonium at the Rocky Flats site and help define the potentially significant pathways of exposure. To date the research into the movement of actinides in the Rocky Flats environment has not provided any new models of groundwater movement, but it did provide *RAC* some information to make our calculations more site-specific. For example, surface water discharge and actinide activity data from site monitoring programs during the 1990s were compiled to compute actinide loads on a storm-specific and annual basis. Other studies report $^{239,240}Pu$ and ^{241}Am activity in surface soil sampled in the Walnut and Woman Creek watersheds. These types of data can be used to calibrate the models that estimate soil erosion and associated actinide transport. Other work is underway to characterize plutonium in samples from the 903 Area using state-of-the-art analytical techniques. This work has so far concluded what many have assumed all along¾ that plutonium in the soil at Rocky Flats is insoluble PuO_2. While results from some of the AME studies indicated that this insoluble form of plutonium might not enter groundwater, *RAC* used a conservative approach to address the question of whether or not the groundwater exposure pathway could be ruled out of the current analysis. We understood the importance of groundwater and surface water pathways in the long term and we included the groundwater pathway in one of our scenarios. We did recognize, however, that our assessment of the groundwater pathway was limited by the complexity of the pathway and, therefore, we used broad ranges of values for the soil-water equilibrium distribution coefficients.

Findings from the Actinide Migration Evaluation studies were incorporated into our calculations and results. Studies verified that (1) plutonium is in an insoluble form in the soil in the 903 Area, an outdoor storage area that is heavily contaminated and that (2) actinides move through the Rocky Flats environment quite slowly toward the aquifer, if they move at all.

The AME work provided two key pieces of information to the current study. First, the AME research provided a qualitative picture of movements of actinides through the Rocky Flats environment; that they move quite slowly toward the shallow aquifer underlying the site if they move at all. Continuing research will hopefully solidify understanding of these processes and perhaps produce a more complete model for actinide movement in the Rocky Flats environment. Second, some of the AME's research was adapted for use in our independent calculations of soil action levels. We used the work of Honeyman and Santschi (1997) to provide upper bounds on our distributions of the soil-water equilibrium distribution coefficient. This quantity, in a simple dissolved-phase transport model, dictates the rate of actinide movement. It is possible that future AME work might have an impact on *RAC*'s results.

TASK 1: CLEANUP LEVELS AT OTHER SITES

This task was designed to provide the RSALOP with a clear and unbiased comparison between soil action levels previously developed at other sites and those adopted for Rocky Flats in October 1996 (Weber and Till, 1999). Because of the varied analytical methodologies, cleanup criteria, exposure pathways, and input parameters for calculating dose and contamination levels in soil, this task was challenging, but it provided an important comparison and perspective on the magnitude of the interim soil concentration criteria at Rocky Flats. The Task 1 report, which is included as Attachment A in the current report, describes information for each site in terms of the dose, scenario, and potential exposure pathways used to calculate the cited soil action level or cleanup target. The study evaluated ^{239,240}Pu soil action levels that were reported to be protective of human health based on reasonable land use scenarios and predetermined dose criteria. Soil concentrations of ^{241}Am were also provided when available for these sites or facilities.

To compare cleanup levels or soil action levels, at other sites with those at Rocky Flats, RAC normalized the levels to the radiation dose that would result from being exposed to each soil concentration.

The sites methods included in the Task 1 analysis were

- Rocky Flats Environmental Technology Site, Colorado
- Hanford, Washington
- Nevada Test Site, Nevada
- 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.

Dose is a general term denoting the quantity of radiation or energy that is absorbed by the body. Effective dose provides a measure of the dose to the whole body, taking into account the dose absorbed by each of the target organs and the sensitivity of those organs to radiation.

To provide an equitable comparison among the sites, the reported soil action levels or cleanup criteria were normalized to the targeted effective radiation dose after cleanup was completed. This procedure resulted in a ratio for each site, calculated by dividing the reported soil action levels or cleanup criteria by the radiation dose. In the report, we refer to this ratio as the soil action level to dose ratio. A lower soil action level to dose ratio indicates a lower proposed or calculated cleanup level. This ratio enabled us to identify the factors or parameters that affected the outcome of the calculation to the greatest extent and that accounted for the differences among soil action levels at the different facilities. Table 4 summarizes the results of our analysis, and appears as a summary table in the report (Attachment A, Weber and Till 1999).

Table 4. Summary of Comparisons between Rocky Flats Environmental Technology Site Calculations and Those for Other Facilities [a]

Location	Parameter change	Ratio of the soil action limit to dose ([pCi g^{-1}] $mrem^{-1}$)	Ratio of the dose to soil action limit (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 pathways; change to RFETS dose conversion factor[b] 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[b] and mass loading	159	0.006
Rocky Flats residential	Original calculation	17	0.06
	Change to Nevada Test Site dose conversion factor[b]	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

[a] From Weber and Till (1999); see Attachment A.
[b] Dose conversion factor is the committed effective dose per unit intake of radioactivity through exposure pathways like inhalation or ingestion; the impact of the dose conversion factor on the calculations is explained more fully in the *Task 5: Independent Calculation* section.

Our evaluation showed that the interim soil action levels at the RFETS (DOE/EPA/CDPHE 1996) are higher than action or cleanup levels at other facilities, even when normalized to dose. Our comparison was done using the RESRAD Model Version 5.61, which was used to set the interim RSALs in October 1996. We reviewed the soil action level to dose ratios for the other sites in terms of the calculations, models, and parameters used to calculate soil concentrations and/or dose. The outcome of the RESRAD calculation was strongly controlled by a few parameters, and, almost without exception, it was these parameters that affected the differences in the soil action levels for a unit dose between sites. If the same or similar assumptions were made for each site, similar ratios resulted. The parameters that affected the determination of soil action levels or clean-up criteria to the greatest extent were the

- **Dose conversion factor (solubility class of plutonium):** The dose conversion factor represents the committed effective dose per unit intake of radioactivity through exposure pathways like inhalation or ingestion. For plutonium, the dose conversion factor depends, to a considerable extent, on the assumed solubility of the plutonium. For example, soluble plutonium has a dose conversion factor for inhalation that is about 1.4 times greater than for insoluble plutonium; more importantly, for ingestion, the dose conversion factor for soluble plutonium is over 65 times higher than for insoluble plutonium.[1] These differences mean that the form of the plutonium in the soil assumed for each site (i.e., soluble or insoluble) greatly impacted the level of cleanup that was done or required. The difference in the chemical form of the plutonium in the soil accounted for the difference in the cleanup standards at several of the sites with lower cleanup standards than at the RFETS. For example, the plutonium in the soil at the Hanford site was assumed to be soluble while the plutonium at the RFETS site was assumed to be in an insoluble form. When we did a calculation based on the assumption of soluble plutonium for the RFETS, the ingestion pathway became a more dominant contributor to the dose, and the dose per unit intake was considerably greater.

- **Mass loading (resuspension)**: The mass loading parameter, a measure of the resuspension of material transferred from the soil surface to the atmosphere, can vary over orders of magnitude depending on the assumed environmental conditions. Mass loading and similar resuspension parameters have been extensively measured at Rocky Flats under a variety of conditions.
- **Breathing rate**: The breathing rate of the exposed individuals has a less pronounced effect on the cleanup or soil action levels than the previous two parameters because the range of possible values is limited to within reasonable physiological boundaries.

A more complete evaluation of the primary model input parameters and assumptions is described and summarized in the full report for Task 3, *Inputs and Assumptions* (Attachment A; see also Aanenson et al. 1999).

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[1] The dose conversion factors referred to here are the ICRP 30 dose conversion factors that were used in the different analyses reviewed for Task 1. The newer ICRP 67 and 71 dose conversion factors are used by *RAC* in the current analysis.

TASK 2: REVIEW AND SELECTION OF COMPUTER MODELS

Task 2 focused on reviewing the RESRAD computer model used to calculate the interim soil action levels adopted for Rocky Flats. It also reviewed four other computer-based models that could potentially be used for making calculations of soil action levels for the RFETS (Killough et al 1999). The objective was to select the most suitable one for our analysis.

The models reviewed were RESRAD, MEPAS, GENII, MMSOILS, and DandD. DOE calculated the 1996 Rocky Flats soil action levels with the RESRAD program (Version 5.61), and part of the scope of this project was to review their calculations for choice of the parameter values used in RESRAD. *RAC* selected programs that were generally comparable to RESRAD and that are widely used. All five programs examined were developed under sponsorship of one or more federal agencies. The results of this discussion and comparison of models are contained in Killough et al (1999), Attachment B to this report.

RAC selected the programs using the following criteria:

1. Correctness of the mathematical models. How well does the model account for exposure pathways and site features, and how consistent is the program with site-specific data?.
2. Validation of the programs. Has the program been checked or confirmed with data that are well documented?
3. Source code. How available is the entire computer code to *RAC*, and has the program been documented?
4. Platform (i.e., computer and operating system) and programming language.
5. Flexibility of operating features. Is it possible to bypass the graphic user interface to directly specify input and output files from the operating system level?

A further consideration in selecting computer programs for the study was our desire to use state-of-the-art methods for carrying out our work, particularly by incorporating uncertainty estimates into the process of calculating RSALs. The term uncertainty usually implies lack of full or precise knowledge about the value of a model parameter or the accuracy of a model prediction. *RAC* represented these uncertainties as probability distributions. Because inputs to the selected code were in the form of probability distributions, *RAC* carefully considered the suitability of the various computer programs for providing a distribution of results for dose, or soil action levels.

Five environmental assessment computer codes (RESRAD, MEPAS, GENII, MMSOILS, and DandD) were evaluated for their applicability to calculating radionuclide soil action levels for the rocky Flats site. We concluded that either RESRAD or GENII could be adapted for the purposes of the project. We selected RESRAD.

All five of the programs selected for evaluation could be installed and executed under some version of the Microsoft Windows operating system and, as a result, all of the programs were accessible. The following paragraphs summarize our evaluation of each of these computer programs.

RESRAD (RESidual RADioactivity) was developed by DOE and Argonne National Laboratory to evaluate the cleanup and remediation of radionuclide-contaminated soils at DOE facilities. *RAC* used the most recent version of RESRAD (Version 5.82), which differs in some ways from older versions that are still in use. In general, the newer version is a windows-based application of earlier versions of RESRAD. The primary technical difference in the newer version, however, is how the program treats the resuspension of soil. *RAC* bypassed this portion of the code and developed resuspension factors based on site-specific data from Rocky Flats (Aanenson et al. 1999; Killough et al. 2000).

The Multimedia Environmental Pollutant Assessment System (MEPAS), which was developed at Battelle's Pacific Northwest Laboratories (PNL) and commercially marketed, was applicable to radioactive and nonradioactive pollutants in many environmental media. Because Battelle Memorial Institute declined our request for permission to examine portions of the MEPAS source code, we were not able to consider the MEPAS program for application to the Rocky Flats site. GENII, also developed at PNL, provided internal and external dose estimates for exposure through all pathways that were ordinarily considered in environmental radiological assessments. GENII had been under development for more than a decade and was unlikely to be modified further by its developers. Two resuspension models are available in GENII, including a mass loading approach that is similar to the one in RESRAD. GENII also has available a scenario of an offsite subject who has been exposed to radioactivity that has been released from the site. The RESRAD code in its traditional format cannot address such an offsite scenario. GENII also considers an onsite groundwater pathway similar to RESRAD's implementation.

MMSOILS, developed for the EPA, was a large multimedia environmental transport program that was designed for screening assessments of chemical contamination. Although it did not treat radioactivity and decay chains, it was included in our review because with some modification, it could consider radionuclides in soils. *RAC* ruled out its use in developing soil action levels for the Rocky Flats site, given the time constraints of this project.

The *Decontamination and Decommissioning* (DandD) computer program was designed by the NRC as a screening-level analysis program to provide a simplified estimate of the dose to an average member of a screening group of people. We decided against DandD because it was still in its first version and had not been used extensively and did not have published documentation. Moreover, the source code had not been released at the time our project began.

Based on our evaluation of the available computer codes, *RAC* concluded that either RESRAD or GENII could be adapted for the purposes of the project. *RAC* used the most recent version of RESRAD (Version 5.82) for this project. Attachment B contains the full Task 2 report for further details on the models.

TASK 3: INPUTS AND ASSUMPTIONS TO THE MODEL

Following the evaluation of computer codes, *RAC* identified and developed probability distributions for the input parameters to the soil action level calculation that had the most significant impact on dose. The selection of these values and distributions is the subject of the report for Task 3, *Inputs and Assumptions* (Aanenson et al. 1999, see also Attachment B). We also developed exposure scenarios, that is, hypothetical individuals who might be exposed to radioactive contamination at Rocky Flats in the future. These scenarios specify the individuals for whom doses and soil action levels were calculated.

To calculate RSALs, *RAC* used the most recent version of RESRAD (Version 5.82)) to calculate the soil action levels for this project. To run the code for this project, numerous input values and assumptions needed to be selected to determine the soil action levels for cleanup at the RFETS so that the permitted annual dose of 15 mrem (in some cases 85 mrem) would not be exceeded. We performed a sensitivity analysis using RESRAD to identify those parameters that have the greatest impact on the outcome of the soil action level calculation. For the parameters that were the most important to the final outcome, *RAC* developed site-specific values if data were available or created uncertainty distributions of values from published literature sources if site-specific data were not available. The probability distributions described the uncertainty in the values that arose from natural variability or from incomplete knowledge about a particular parameter. Attachment B of this report includes our assessment of the inputs and assumptions (Aanenson et al. 1999).

The sensitivity analysis was a single-parameter analysis, where a range of values for one parameter at a time was evaluated. Of over 50 parameters assessed for their influence on the final result, four parameters were found to impact the final result to the greatest extent. These parameters were:

- soil-water equilibrium distribution coefficient
- area of contamination
- mass loading factor
- mean annual wind speed.

Six parameters were found to affect the outcome of the calculation only slightly: (1) cover depth (depth of soil that must be removed to reveal the contaminated soil), (2) fraction of the total outside air contamination that is available indoors (indoor dust filtration), (3) soil-to-plant transfer factors, (4) depth of soil mixing layer (depth of uniform contamination), (5) fraction of irrigation water contaminated by groundwater, and (6) thickness of contaminated zone (non-uniformly distributed). The results showed little sensitivity to more than 40 other parameters required to run the RESRAD code, and therefore additional effort was not given to changing or revising the values from the ones used in the previous RSAL assessment., *RAC* made minor changes for some parameters, either in the value previously used or in the method of calculating the parameter value, to ensure a consistent approach.

Parameter Evaluations

Most of our efforts focused on providing parameter values or uncertainty distributions for the four most important parameters, based on site-specific data or on literature values (Aanenson et al. 1999, Attachment B). Table 5 summarizes the differences in parameter values or approach between the previous DOE/EPA/CDPHE assessment (DOE/EPA/CDPHE 1996) and our approach (Aanenson et al. 1999; Killough et al. 2000).

The *distribution coefficient* is important in the soil action level assessment because it defines the relationship of the concentration of the contaminant in the soil to the concentration of the contaminant in water, and it can influence calculations involving contaminants in the groundwater. *RAC* included groundwater as a source of water in the *RAC* rancher scenario. The distribution coefficient can extend over a very wide range even for a single type of soil; therefore, it was important to incorporate as much data as possible in our assessment. We created a wide distribution of values for distribution coefficients of uranium, plutonium, and americium, based on an extensive review of the published literature (Honeyman and Santschi 1997; Sheppard and Thibault 1990; Dames and Moore 1984; Till and Meyer 1983). In our assessment, the distribution for each radionuclide was defined by the geometric standard deviation, which gives an estimate of the uncertainty there is about the midpoint (geometric mean or median).

The *area of contaminated zone* is a parameter required in the RESRAD code that defines a specified area in which the contamination is uniformly distributed. Unfortunately, for much of the area around Rocky Flats, especially east of the 903 Area, the plutonium concentrations can vary by factors of more than 100. This large heterogeneity contradicts the uniformity that the RESRAD soil model assumes. To address this issue, *RAC* compiled historic soil monitoring data from the Rocky Flats area to create contours of contamination at and surrounding the 903 Area. These contours approximate the actual contamination in soil and were used in RESRAD to help calculate soil action levels.

Table 5. Values for the Four Most Sensitive Parameters for the Independent Calculation and Comparison with Those from the Previous Assessment[a]

Parameter	DOE/EPA/CDPHE value	*RAC* value
Distribution coefficient	Deterministic Pu = 218 cm^3 g^{-1} Am = 76 cm^3 g^{-1} U = 50 cm^3 g^{-1}	Treated stochastically based on Rocky Flats measurements and literature values; median values (GSD[a]) of Pu = 2300 cm^3 g^{-1} (5.6) Am = 1800 cm^3 g^{-1} (8.1) U = 2.3 cm^3 g^{-1} (5.4)
Area of Contaminated Zone	40,000 m^2	Defined based on historic soil concentration measurements at Rocky Flats (see report text)
Mass loading	0.000026 g m^{-3}	Model will be calibrated based on results of soil and airborne concentration (see report text)
Mean annual wind speed	Not required for RESRAD Version 5.61	Will use 5-year annual average STAR data set collected at Rocky Flats meteorological station

[a] From Aanenson et al. (1999); see also Attachment A.
[b] GSD = geometric standard deviation, which is a measure of the extent of the distribution

The *mass loading* parameter is a measure of resuspension of soil from the ground. Resuspension is a complex process that is affected by many environmental factors that have not been well documented. The current version of RESRAD uses a mass loading factor to define resuspension but even the developers of RESRAD stressed its inadequacy at representing actual conditions at a given site. As a result, *RAC* used historic air monitoring data as the best measure of resuspension. *RAC* considered the location of each scenario onsite where the hypothetical person resides and/or works and used actual air monitoring data in combination with the soil contamination data to estimate a relationship between concentrations in air and soil that was used to estimate resuspension. This process bypasses the calculation in RESRAD and defines resuspension based on actual air monitoring data from the site.

The *mean annual wind speed*, not required in the previous version of RESRAD, is important in estimating resuspension in the current RESRAD Version 5.82. However, *RAC*'s method bypasses the RESRAD calculation of resuspension. Because we estimated resuspension based on site-specific air monitoring data, it also was important to use site-specific meteorological data. *RAC* used 5-year average frequency information from the onsite Rocky Flats meteorological station for wind speed, wind direction, and atmospheric stability class. The effect of high wind events on moving contamination from the 903 Area before it was covered with an asphalt pad was evaluated in the Historical Public Exposure Studies on Rocky Flats (Weber et al. 1999). Because high wind results in lower air concentrations than would be expected if the same material was dispersed over a longer period of time during average wind speed conditions, we did not evaluate high wind events separately in this project.

Initial concentrations of radionuclides are also important parameters for RESRAD if dose is to be calculated (computed RSALs do not depend on initial soil concentrations of the corresponding radionuclides; any non-zero value given for a radionuclide will trigger the computation of the RSAL). In the previous assessment, DOE/EPA/CDPHE defined the initial concentrations of each radionuclide of interest as 100 pCi g^{-1}. In contrast, *RAC* used the measured soil concentration data at the site to determine actual soil concentrations, initialized to the year that the soil action level calculations begin. This technique accounted for the appropriate ratios of radionuclides to the initial calculation of action levels. Because soil concentrations for uranium at Rocky Flats are primarily located in hot spots, we calculated separate soil action levels for uranium based on the concentration of uranium in hot spots, as determined from the available literature.

The amounts of the radionuclides considered in the calculation and present in soil were determined relative to ^{239,240}Pu.

Radionuclide	***Relative Concentration***
^{239,240}Pu	***1***
^{241}Am	***0.111***
^{237}Np	***0.000000786***
^{238}Pu	***0.0132***
^{242}Pu	***0.00000762***

Plutonium Solubility and Dose Conversion Factors

An important aspect of the independent calculation involved determining solubility of plutonium in the Rocky Flats environment and determining dose conversion factors for use in our calculations. Ongoing studies of actinide migration at the site have helped to characterize the chemical and physical form of plutonium at the Rocky Flats site (see Attachment D). The plutonium that is found in Rocky Flats soil is thought to be generally highly insoluble and strongly attached to soil particles. Plutonium mobility is another area under investigation by the AME researchers that may play an important role at the site. These solubility studies guided the selection of dose conversion factors for plutonium and other radionuclides. Table 6 shows the most recent values for inhalation and ingestion dose conversion factors in comparison to the values from ICRP 30 for the radionuclides of interest at Rocky Flats.

Insoluble forms of plutonium are classified as slow clearance materials. *RAC* researched the most updated values available for dose conversion factors from ICRP (1999) and used them in our calculations. These newer values account for reduced uptake of plutonium from the lung based on a new respiratory tract model. The newer model accounts for changes in the relative amount of material entering the gastrointestinal-tract from the respiratory tract and also addresses the dose to specific cell populations that are at depth in the airways rather than the smeared dose used in the earlier respiratory model. In addition, dose conversion factors do show some limited age dependence. For very young infants (0-3 months), the ingestion pathway is more important, with a dose conversion factor for ingestion about 16 times higher than in adults. All other ages have ingestion dose coefficients less than a factor of 2 higher than the adult values.

Table 6. Dose Conversion Factors (DCF) for Independent Calculation (mrem pCi^{-1})[a]

Radio-nuclide	ICRP 30[b] Clearance Class	ICRP 30 Inhalation DCF	ICRP 71[c] Clearance Class	ICRP 71 Inhalation DCF	ICRP 30 f_1	ICRP 30 Ingestion DCF	ICRP 67[d] f_1	ICRP 67 Ingestion DCF
^{241}Am	W	0.444	M	0.155	0.001	0.00364	0.0005	0.00074
^{238}Pu	Y	0.288	S	0.059	0.00001	0.0000496	0.0005	0.00085
^{239}Pu	Y	0.308	S	0.059	0.00001	0.0000518	0.0005	0.00093
^{240}Pu	Y	0.308	S	0.059	0.00001	0.0000518	0.0005	0.00093
^{241}Pu	Y	0.00496	S	0.00063	0.00001	0.00000077	0.0005	0.00002
^{234}U	Y	0.132	S	0.035	0.05	0.000283	0.02	0.00018
^{235}U	Y	0.123	S	0.031	0.05	0.000267	0.02	0.00017
^{238}U	Y	0.118	S	0.030	0.05	0.000269	0.02	0.00017

[a] The units of mrem pCi^{-1} are the conventional units used in RESRAD. To convert to standard units of Sv Bq^{-1}, simply divide the value in the table by 3700

[b] ICRP 30 (ICRP 1978) values have been used in RESRAD Versions 5.61 and 5.82. The symbols, W (week) and Y (year) indicate the relative time required for the material to be cleared from the respiratory system.

[c] ICRP 71 listed the latest inhalation dose conversion factors (also given on ICRP CD-ROM [ICRP 1999])

[d] ICRP 67 listed the latest ingestion dose conversion factors (also given on ICRP CD-ROM [ICRP 1999])

Scenarios

RAC evaluated seven scenarios for the project. Three scenarios were developed for the original RSAL calculation (DOE/EPA/CDPHE 1996) and four scenarios were developed by *RAC* after numerous discussions with the RSALOP at the monthly soil action level meetings. Table 7 summarizes the parameter values for these scenarios. In designing the scenarios, we carefully considered offsite exposures so that if the person living onsite full-time is protected, then the person living offsite will be protected.

RAC evaluated seven scenarios designed to ensure that if the person living onsite full-time is protected then a person living offsite also will be protected. We developed four scenarios with input from the Radionuclide Soil Action Level Oversight Panel and included three scenarios from the previous DOE/EPA/CDPHE assessment.

The scenarios are described and defined by numerous parameters, some much more important than others. The scenario parameters include breathing rates for various activity levels and ages, soil ingestion rates for children and adults, fraction of time spent indoors and outdoors, and the potential use of or exposure to contaminated water from the area. We focused our greatest effort on establishing values for breathing rate and soil ingestion, as these are parameters in which the RSALOP expressed primary interest. We based parameter values for breathing rate and soil ingestion on published breathing rate studies. We defined distributions of breathing rates for active and sedentary adults, children, and infants. Using these distributions and the recommended breakdowns of daily activity for each scenario, we created distributions of scenario breathing rates. We then selected the 95th percentile value from that distribution for the annual breathing volume. We used a similar process to establish soil ingestion rates for the hypothetical individuals in the scenarios. While soil ingestion rates based on studies conducted from a few days to a few weeks are valid and important, it is important to consider carefully the implications of translating these short-term soil ingestion rates to an annual soil ingestion rate. For these reasons, we selected the 50th percentile, or median, of the distribution as the daily soil ingestion rate for our scenarios.

Table 7. Key Scenario Parameter Values for DOE and *RAC* Scenarios[a]

Parameter	DOE/EPA/CDPHE scenarios			*RAC* scenarios			
				Nonrestrictive			
	Resident	Open space	Office worker	Resident rancher	Child of rancher (10 y)	Infant of rancher (2 y)	Site industrial worker
	DOE-1	DOE-2	DOE-3	*RAC*-1	*RAC*-2	*RAC*-3	*RAC*-4
Dose limit (mrem y^{-1})	15/85	85	85	15	15	15	85
Time on site (h y^{-1})	8400	125	2000	8760	8760	8760	2100
Time indoors onsite (%)	100	100	100	60	750	90	40
Time outdoors onsite (%)	0	0	0	40	25	10	60
Breathing rate (m^3 y^{-1})	7000	175	1660	10800	8600	1900	3700
Soil ingestion (g y^{-1})	70	2.5	12.5	75	75	75	50
Irrigation water source	Ground-water	na[b]	na	Ground-water	Ground-water	Ground-water	na
Irrigation rate (m y^{-1})	1	na	na	1	1	1	na
Onsite drinking water source	no	no	no	Ground-water	Ground-water	Ground-water	no
Drinking water ingestion (L d^{-1})	na	na	na	2	1.5	1	na
Drinking water ingestion (L y^{-1})	na	na	na	730	550	365	na
Fraction of contaminated homegrown produce	1	0	0	1	1	1	0
Fruits, vegetables and grain consumption (kg y^{-1})	40.1	na	na	190	240	200	na
Meat (kg y^{-1})	na	na	na	95	60	35	na
Milk (L y^{-1}).	na	na	na	110	200	170	na

[a] From Aanenson et al. (1999); see also Attachment B.
[b] This pathway was not applicable to this scenario.

For the remaining parameters, we used the scientific literature to select appropriate values, which in some cases differ from the RESRAD default values or the DOE/EPA/CDPHE scenarios (DOE/EPA/CDPHE 1996). All scenario-related parameters are treated deterministically in this analysis.

TASK 4: METHODOLOGY FOR DETERMINING SOIL ACTION LEVELS

Designing a methodology for calculating soil action levels based on our exposure scenarios was the focus of Task 4. Our approach was presented to the RSALOP orally in November 1998 and documented in the Task 5 report (Killough et al. 2000; see also Attachment B). This methodology included the uncertainties in the input parameters and the resulting soil action levels. Our calculations for the RSALs were required to meet the EPA draft regulation (EPA 1996) that was chosen for the 1996 assessment (DOE/EPA/CDPHE 1996). This regulation stated that a remediation standard of 15 mrem y^{-1} should be used at sites with radioactive material in all environmental media. The radiation dose to be received by an unrestricted release scenario will not exceed 85 mrem y^{-1}. *RAC* developed technically based RSALs using the 15 mrem dose limit because (1) it is more protective of the public and (2) our evaluation of risk associated with this dose better corresponds to the target level of risk associated with federal guidance.

For a single radionuclide, scenario, and dose limit, the soil action level is that concentration of the radionuclide in the soil that would lead to a maximum predicted annual dose equal to the annual dose limit. When considering multiple radionuclides, each radionuclide's soil concentration is divided by its RSAL, and the ratios are added to give a sum-of-ratios. If the sum-of-ratios exceeds 1 for one or more of the exposure scenarios, then some remedial action or special attention is indicated. If the sum-of-ratios is less than or equal to 1, no annual dose limit would be exceeded, and by that criterion the radionuclide levels meet the RSAL standard. This calculation may be applied to observed radionuclide soil concentrations, or it may be used with hypothesized concentrations that represent remediation goals. The sum-of-ratios (SR) is indicated by the following equation:

$$SR = \sum_{i=1}^{n} \frac{C_i}{RSAL_i}$$

where
C_i = the radionuclide soil concentration for radionuclide i (pCi g^{-1})
$RSAL_i$ = soil action level for radionuclide i (pCi g^{-1})

If only one radionuclide is present, the sum-of-ratios reduces to a single ratio, but the interpretation is the same. The sum-of-ratios calculation for uranium was kept separate from that of plutonium. It was not possible to combine the two for a generic site because at Rocky Flats uranium contamination is localized and is not as widespread as plutonium.

The conceptual site model used to calculate plutonium RSALs was based on a heterogeneous distribution of plutonium soil and air concentrations across the RFETS. This conceptual model differs significantly from that used in the 1996 DOE/CDPHE/EPA calculations, which assumed soil and air contamination was homogeneous across the site being modeled.

We used the air dispersion model to incorporate soil and air concentration heterogeneity into the calculation. RESRAD was used only to calculate intakes and doses. Incorporating soil and air concentration heterogeneity into the conceptual model complicates both the calculation and interpretation of RSALs because the RSAL depends not only on the receptor scenario parameters, but also on the location of the receptor relative to sources of contamination. Because our objective was to provide a conservative RSAL that could be applied independent of location across the RFETS, we located each receptor at the point of the maximum air-to-soil concentration ratio. The location where this occurs is at the east edge of the site near Indiana Street. Air concentrations at this location are proportionally higher than the soil concentration because the air concentrations reflect the cumulative flux from all upwind contaminated areas.

Our methodology incorporated environmental dose models that estimate dose from specified concentrations of radionuclides in environmental media. The exposure pathways considered were inhalation, soil and food ingestion, and external irradiation. In addition, groundwater use for both irrigation and drinking water was assumed for some scenarios. We also considered the effect of a prairie fire, which would remove the vegetative cover and result in increased resuspension of soil for a period of time, because such a fire, although not common, is possible. For each scenario, we incorporated the probability of a fire occurring in the area using fire statistics for the Twentieth Century in the Arapaho and Roosevelt National Forests and the Pawnee National Grasslands. For the plutonium assessment, the probability of a fire occurring on the rancher's land at the RFETS was estimated to be about 1×10^{-3}.

We calculated RSALs for uranium differently than those for plutonium because the nature and extent of contamination differs between the nuclides. Our treatment of plutonium considered a 10-km^2 contaminated area. Using spatially variable soil concentrations and measured air concentrations of plutonium around the site, we calibrated a suspension model so that the suspension rates of plutonium-contaminated soil would yield concentrations currently measured at the air samplers. This procedure was not extended to uranium because (a) uranium-specific measurements were not available at the samplers and (b) uranium contamination is not as widespread as plutonium and, therefore, would not be expected to respond in the same manner. Our investigation indicated that uranium contamination was mainly limited to past disposal areas and burn pits. Furthermore, Litaor (1995) notes fundamental differences in solubility characteristics of plutonium and uranium that, in turn, affect their mode of dispersion in the environment.

Furthermore, the prairie fire was not considered for the uranium analysis because the smallest fire area considered in the fire statistics data set was 4.05×10^5 m^2, or 100 acres. Using the area encompassed by uranium contamination (100 m^2), yields a probability of a fire that is 5 orders of magnitude lower than that for the plutonium case. Additionally, only the inhalation pathway was affected by the fire, and inhalation doses made up a small fraction of the total uranium dose. Nevertheless, we ran a trial fire case to verify that, even if there were a fire, the doses from uranium would not be significantly higher. For this trial, we conservatively assumed that any fire occurring on the site encompassed a uranium-contaminated area. Results of this trial showed incorporating the fire made little difference in the calculated dose and RSAL for uranium.

TASK 5: INDEPENDENT CALCULATION OF THE SOIL ACTION LEVELS

RAC presented the results of its independent assessment and calculation of RSALs at Rocky Flats in the Task 5 report (Killough et al. 2000; Attachment B). The Task 5 report contained details of our technical approach for determining isotopic ratios, estimating concentration of plutonium in air, calculating an alternative groundwater dose from measurements in the literature, providing perspective on risk, and describing other computational details of the RSAL calculations. For the calculations, we used the RESRAD Version 5.82, an updated version of the RESRAD program used for the earlier calculations. We developed the methodology for selecting RSALs for the Rocky Flats site and presented the results as probability distributions of possible sum-of-ratio values for each of seven exposure scenarios. The scenarios were selected with consensus by the panel to represent a variety of exposure conditions, some of which were more conservative than others. Each scenario was based on an annual dose limit to the receptor resulting from exposure to Rocky Flats radionuclides.

For each scenario, we presented curves representing the probability of exceeding the radiation dose limit as a function of $^{239+240}$Pu or uranium concentrations in the soil. Figure 2 shows an example of the calculational output. For example, an RSAL at the 5% to 10% probability level means there is a 95% to 90% probability that the dose limit will *not* be exceeded.

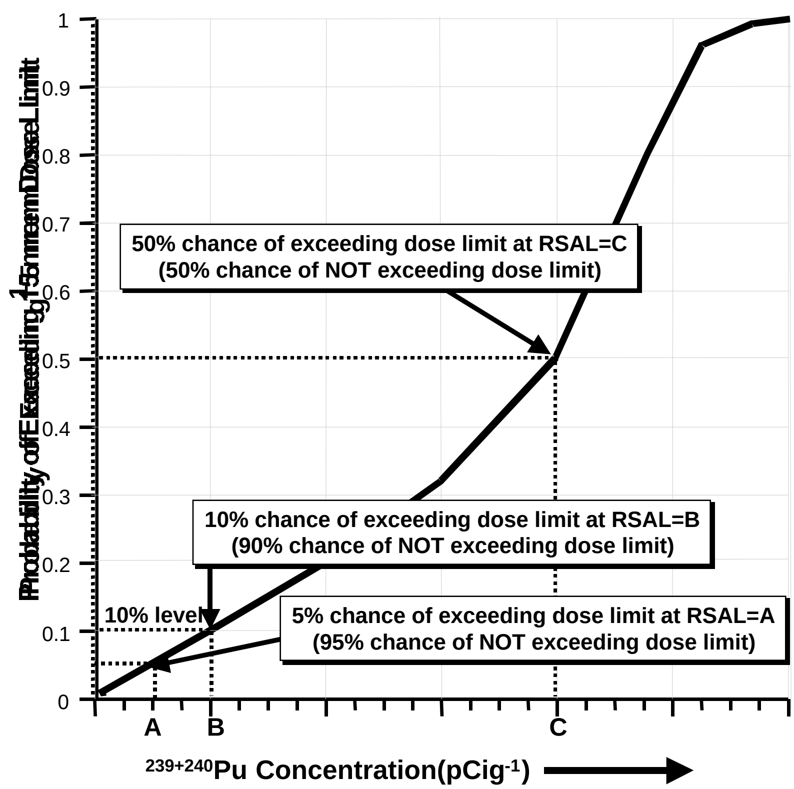

Figure 2. Sample of the results of our calculations. Each probability level corresponds to a distinct concentration of $^{239+240}$Pu in soil. The probability value represents the probability of exceeding the dose limit. For example, at soil concentration A (measured in picocuries per gram), there is a 5% chance that some person identified by the scenario will exceed the annual dose limit. Alternately, there is a 95% chance that the dose limit for the given soil concentration will not be exceeded in any year. When we speak of probability levels throughout the report, we speak in terms of the probability of exceeding the annual dose limit.

A similar probability curve was developed for each scenario and exposure condition (Killough et al. 2000, Attachment B). RSALs are presented for plutonium isotopes for seven scenarios: the three DOE scenarios and the four *RAC* scenarios. RSALs are presented for uranium isotopes (^{234}U, ^{235}U, and ^{238}U) for three scenarios: the DOE resident (DOE-1), the *RAC* rancher (*RAC*-1), and the *RAC* child of the rancher (*RAC*-2). For the plutonium RSAL calculations, each scenario incorporated the impact of a prairie fire, considering both the probability of it occurring and the impact that revegetation might have on the soil conditions after a fire. In the Task 5 report, we also explained the scenarios, important pathways, and radionuclides contributing to dose.

For the DOE scenarios, we calculated RSALs stochastically using our methodology. It is somewhat misleading to compare the results of our calculations with the results of the DOE/EPA/CDPHE calculations (DOE/EPA/CDPHE 1996) because of differences in the methods and parameters used. For the three DOE/EPA/CDPHE scenarios, these differences are attributed to several factors. First, there was a difference in the dose conversion factors because we used the more recent ICRP Publication 72 dose conversion factors, which are higher for ingestion and lower for inhalation than the older dose conversion factors used as defaults in RESRAD (ICRP 1996). Second, the resuspension model used in our calculation results in a lower concentration of plutonium in air for a given soil concentration than the original DOE/EPA/CDPHE calculation. Consequently, the relative importance of the inhalation pathway diminishes in our calculation.

The following section highlights some of our key findings.

Plutonium: Selected Probability Curves and RSAL Values

A sound technical foundation and credible scientific methodology are the most important elements in setting soil action levels for the Rocky Flats site. In the following section we provide RSALs supported by the scientific data, as specified in the scope of work, However, the final decision, which must consider other factors, ultimately lies in the hands of the stakeholders, DOE, and the regulators. In addition to the important calculational aspects of the RSAL, several other criteria influence the decision-making process of selecting an RSAL for the site. Each element of the decision must be carefully considered and its importance weighed accordingly. Our approach has been to develop scientifically defensible soil action levels that both protect the public from receiving an exposure in excess of the dose limit and are reasonable to adopt, given certain social and political implications. The values we presented in the Task 5 report could be used as a starting place for applying such social and political considerations not used in our development of RSAL values. Some of these criteria are social, political, and economic factors that are outside the scope of our scientific work, yet their impact on the final RSAL value could be significant.

In the following sections, we first list selected RSAL values for all of the scenarios in Table 8 and then provide the detailed probability curves for the key scenarios: DOE-1 (resident). *RAC*-2 (rancher), and *RAC*-2 (child of rancher) scenarios. Based on the results of our calculations, Table 8 lists selected plutonium RSAL values at the 10% probability level; this means there is a 90% probability that the dose limit will *not* be exceeded. This probability level is based on a number of things. First, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) guidelines, which apply in this case, indicate that the RSAL is intended to assure protection of the “reasonable maximum exposed” (RME) individual, above the 90th percentile of the distribution. Additionally, 90% confidence intervals are commonly used in statistical parameter estimation. Considerations such as these directed our decision to select the 10% level as the appropriate level for determining a soil concentration to represent an RSAL.

Table 8: Selected RSAL Values For Plutonium (pCi g^{-1}) at the 10% Probability Level[a]

	Dose limit[b]	
Scenario	15 mrem	85 mrem
DOE-1 (resident)	45	260
DOE-2 (open space user)	Not applied	6600
DOE-3 (office worker)	Not applied	1600
RAC-1 (rancher)	35	Not applied
RAC-2 (child of rancher)	35	Not applied
RAC-3 (infant of rancher)	85	Not applied
RAC-4 (industrial worker)	90	530

[a] At the 10% probability level, there is a 90% probability that the dose limit will *not* be exceeded.
[b] Based on draft EPA guidance from 40 CFR 196. These dose limits were used in the previous DOE/EPA/CDPHE calculations.

The relative importance of pathways for plutonium RSALs depends on the value of the RSAL. The lower RSALs are driven by the occurrence of a fire, which would result in enhanced resuspension and therefore higher air concentrations, which lead to higher inhalation doses. As the importance of inhalation decreased with increasing soil concentrations, other pathways, especially soil ingestion, became more important. In the following discussion, we present the RSAL probability curves for *RAC*'s rancher and child of the rancher scenarios and for DOE/EPA/CDPHE resident scenario and we summarize the key findings about the RSAL probability curve and the dominant exposure pathways for the other scenarios.

- **DOE-1 (resident) scenario:** This scenario was part of the original RSAL calculation (DOE/EPA/CDPHE 1996). The RSALs presented here represent this same scenario calculated stochastically using the methodology developed by *RAC*. At the 10% level (90% probability that the dose limit would *not* be exceeded), the *RAC*-calculated RSALs are about 45 pCi g^{-1} for the 15 mrem dose limit and about 260 pCi g^{-1} at the 85 mrem dose limit. Figure 3 presents the RSAL probability curve for the DOE-1 (resident) scenario resulting from *RAC* calculations.

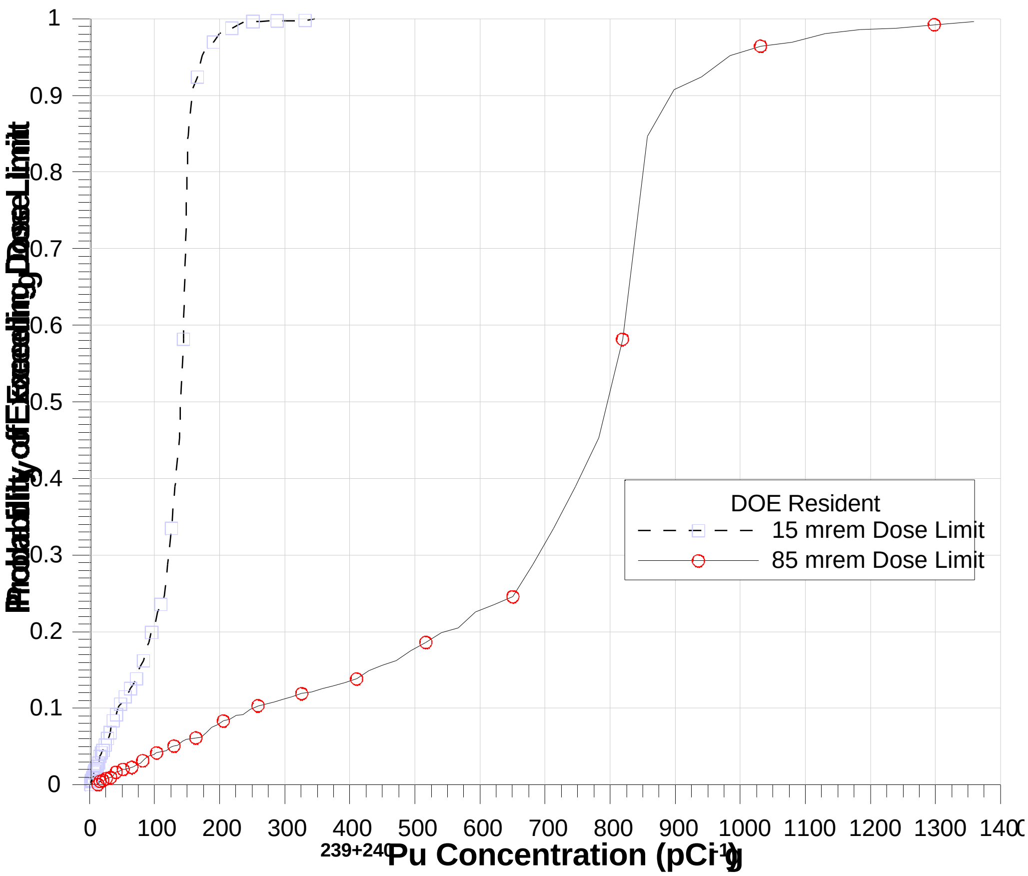

Figure 3. Probability of the total dose exceeding the dose limit for the DOE/EPA/CDPHE resident scenario. Total dose includes the sum-of-ratios calculation for all plutonium isotopes and their daughter products. This distribution includes the impact of a fire considered probabilistically.

- **DOE-2 (open space user) scenario:** This scenario was part of the original RSAL calculation (DOE/EPA/CDPHE 1996) and assumes that the site remains as open space and will not be developed in the future. The RSALs presented here represent this same scenario calculated stochastically using the methodology developed by *RAC*. At the 10% level (90% probability that the dose limit would *not* be exceeded), the *RAC*-calculated RSAL for $^{239+240}Pu$, including the sum-of-ratios calculation, was about 6600 pCi g^{-1} for an 85 mrem dose limit.

- **DOE-3 (office worker) scenario:** This scenario was part of the original RSAL calculation (DOE/EPA/CDPHE 1996) and assumes that the site is developed into an industrial park/office complex. The RSALs presented here represent this same scenario calculated stochastically using the using the methodology developed by *RAC*. At the 10% level (90% probability that the dose limit would *not* be exceeded), the *RAC*-calculated RSAL for $^{239+240}Pu$, including the sum-of-ratios calculation, was about 1600 pCi g^{-1} for an 85 mrem dose limit.

- ***RAC*-1 (rancher) scenario**: This scenario represents a full-time adult rancher who lives and works on what are now RFETS lands. The probability curve shows two distinct slopes (Figure 4). For ^{239}Pu concentrations less than ~80 pCi g^{-1}, the slope of the probability curve is shallow and reflects doses from inhalation of resuspended dust and foliar deposition on plants. For soil concentrations greater than 80 pCi g^{-1}, the probability curve exhibits a steeper slope and is controlled mainly by the soil ingestion and plant ingestion pathways. The steep slope of the probability curve for $^{239+240}$Pu concentrations greater than ~80 pCi g^{-1} results from less variability in the doses from the soil and plant ingestion pathways compared to the inhalation pathway. Inhalation doses were proportional to the estimated air concentration, and air concentrations were considerably more variable than soil concentrations. Therefore, RSALs at the 10% probability level (90% probability that the 15 mrem dose limit will not be exceeded) were controlled mainly by the inhalation of resuspended dust. Note that the characteristic inflection point of this probability curve is also seen in the probability curves for the other exposure scenarios. At the 10% probability level, the $^{239+240}$Pu RSAL, including the sum-of-ratios calculation, results in an RSAL of about 35 pCi g^{-1}. Figure 4 presents the RSAL probability curve for *RAC*-1 (rancher) scenario resulting from *RAC* calculations.

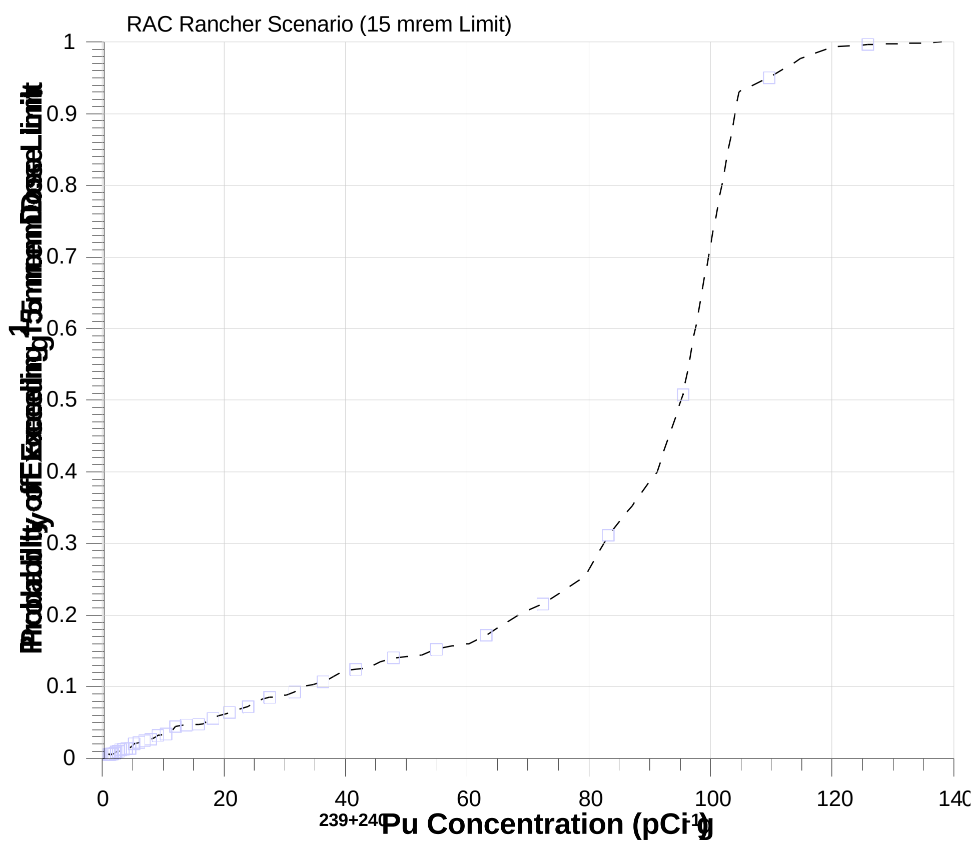

Figure 4. Probability of the total dose exceeding the 15 mrem dose limit for the *RAC* rancher scenario. Total dose includes the sum-of-ratios calculation for all plutonium isotopes and their daughter products. This probability curve includes the impact of a fire considered probabilistically.

· ***RAC*-2 (child of rancher) scenario:** This scenario represents a 10-year old child of a full time resident (rancher) who lives on what are now RFETS lands. The probability curve shows two distinct slopes (Figure 5). For $^{239+240}$Pu concentrations less than ~60 pCi g^{-1}, the slope of the probability curve is shallow and reflects doses from inhalation of resuspended dust and foliar deposition on plants, primarily from fire events. For soil concentrations greater than 60 pCi g^{-1}, the slope of the probability curve exhibits a steeper slope and is controlled mainly by the soil ingestion and plant ingestion pathways. The inflection point of this probability curve occurs at a lower $^{239+240}$Pu soil concentration compared to the adult rancher. Because ingestion rates for the two scenarios were assumed to be the same (75 g y^{-1}), this difference reflects the differences in the ingestion dose conversion factors between the adult and child. At the 10% probability level, the $^{239+240}$Pu RSAL, including the sum-of-ratios calculation, was about 35 pCi g^{-1}. Figure 5 presents the RSAL probability curve for *RAC*-2 (child of rancher) scenario resulting from *RAC* calculations.

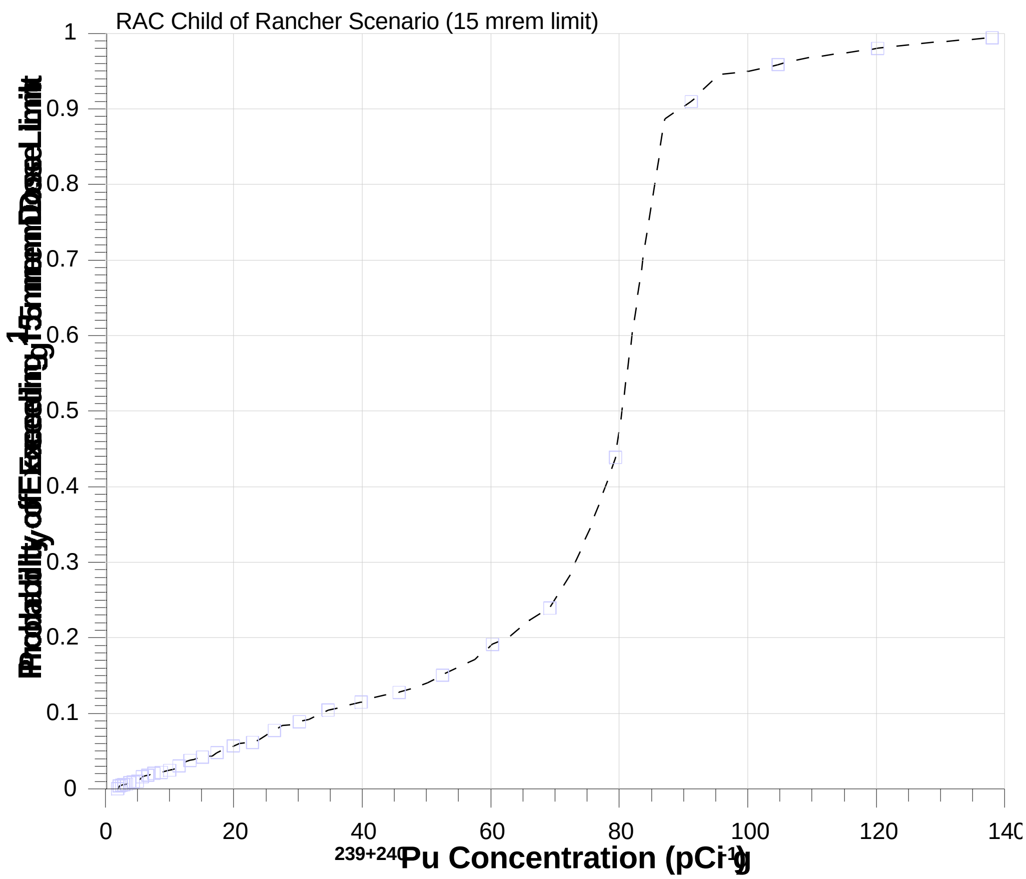

Figure 5. Probability of the total dose exceeding the 15 mrem dose limit for the *RAC* child of the rancher scenario. Total dose includes the sum-of-ratios calculation for all plutonium isotopes and their daughter products. This probability curve includes the impact of a fire considered probabilistically.

- ***RAC*-3 (infant of rancher) scenario:** This scenario represents an infant of a full-time resident (rancher) who lives on RFETS lands. Like the other scenarios, the probability curve shows two distinct slopes. For $^{239+240}$Pu concentrations less than ~90 pCi g^{-1}, the slope of the probability curve is shallow and reflects doses from inhalation of resuspended dust and foliar deposition on plants. For soil concentrations greater than 90 pCi g^{-1}, the slope of the probability curve exhibits a steeper slope and is controlled mainly by the soil ingestion and plant ingestion pathways. The inflection point of this probability curve occurs at a higher $^{239+240}$Pu soil concentration compared to the adult rancher and child scenarios. This difference reflects the differences in the dose conversion factors and intake rates of contaminated media for the adult, child, and infant. While the dose conversion factors are generally higher for infants, their contaminant intake rates (i.e., breathing rate and food ingestion rates) are generally lower. At the 10% probability level, the $^{239+240}$Pu RSAL, including the sum-of-ratios calculation, was about 85 pCi g^{-1}.

- ***RAC*-4 (industrial worker) scenario:** This scenario represents an adult who works at an industrial complex at the RFETS. Like the other scenarios, the probability curve shows two distinct slopes. For $^{239+240}$Pu concentrations less than ~150 pCi g^{-1} (~850 pCi g^{-1} for the 85 mrem dose limit) the slope of the probability curve is shallow and reflects doses from inhalation of resuspended dust (plant ingestion was not considered). For soil concentrations greater than 150 pCi g^{-1} (~850 pCi g^{-1} for the 85 mrem dose limit), the probability curve exhibits a steeper slope and is controlled by soil ingestion. The inflection point of this probability curve occurs at a higher $^{239+240}$Pu soil concentration compared to all other *RAC* scenarios because intake rates of contaminated media are substantially less for this scenario. At the 10% probability level, the $^{239+240}$Pu RSAL, including the sum-of-ratios calculation, was about 90 pCi g^{-1} at the 15 mrem dose limit and about 525 pCi g^{-1} at the 85 mrem dose limit.

Uranium: Selected Probability Curves and RSAL Values

The previous section described the results of the calculations for the major radionuclides in the soil at Rocky Flats, that is, for ^{241}Am and the several isotopes of plutonium (^{238}Pu through ^{242}Pu). Uranium is also present in the soil at a few locations on the Rocky Flats site in concentrations above natural background, but the history of this contamination is different from that of the americium and plutonium from the 903 Area. For uranium, we assumed fixed isotope ratios for the ^{234}U, ^{235}U, and ^{238}U present at the site and expressed the composite uranium level in terms of a single isotope, ^{238}U. The reported calculations incorporated estimates of parameter uncertainty, and results for each scenario are presented in terms of the probability that the dose limit will not be exceeded. The prairie fire was not considered for the uranium analysis because uranium is more of a hazard when ingested and it was, therefore, of interest to leave it in the surface soil available for leaching into groundwater pathways. Table 9 lists the selected uranium RSAL values at the 10% probability level, again indicating that there is a 90% probability that the dose limit will *not* be exceeded.

Table 9: Selected RSAL Values For Uranium (pCi g^{-1}) at the 10% Probability Level[a]

Scenario	Dose Limit[b]		
	Water pathway on	Water pathway off	
	15 mrem	15 mrem	85 mrem
DOE-1 (resident)		35	200
RAC-1 (rancher)	10	80	
RAC-2 (child of rancher)	10	65	

[a] At the 10% probability level, there is a 90% probability that the dose limit will *not* be exceeded.
[b] Based on EPA guidance from 40 CFR 196. These dose limits were used in the previous DOE/EPA/CDPHE (1996) calculations.

RSALs were presented for uranium isotopes (^{234}U, ^{235}U, and ^{238}U) for three scenarios: the DOE-1 (resident), *RAC*-1 (rancher), and *RAC-2* (child of rancher) scenarios (Killough et al. 2000). The rancher and child of rancher scenarios were chosen because these scenarios yielded the most restrictive RSALs for plutonium. A significant difference between the DOE methodology and our methodology was the area of contamination assigned to uranium. The DOE methodology assumed the area of uranium contamination was the same as plutonium (40,000 m^2). Our investigation indicated that uranium contamination is not as widespread as plutonium contamination and it is mainly limited to past disposal areas or burn pits. Therefore, we treated the uranium contamination as a hot spot and restricted its area to 100 m^2.

- **DOE-1(resident) scenario:** The ^{238}U RSALs at the 10% level (90% probability that the dose limit would *not* be exceeded), were about 35 pCi g^{-1} for the 15 mrem dose limit and about 200 pCi g^{-1} at the 85 mrem dose limit. These RSALs incorporated the sum-of-ratios calculation to include the other uranium isotopes. It is important to point out that the groundwater pathway was treated differently in the *RAC* and DOE/EPA/CDPHE interpretations of this scenario. DOE ignored the groundwater pathway and extracted doses for the year 2000. However, they allowed uranium to be leached from the ground surface at a rate proportional to the background infiltration rate (0.38 m y^{-1}) plus the irrigation rate (1 m y^{-1}). In our calculations, we let RESRAD calculate the maximum dose in the 1000-year time of compliance and extracted RSALs for that time. The time of maximum dose varied between year 2000 and year 2500 depending on the contaminant travel times in the unsaturated and saturated zones. Uranium that migrated to the groundwater was then used for irrigation, thereby contaminating edible plants (direct consumption of water was not considered).

- ***RAC*-1 (rancher) scenario**: Soil action levels were calculated for two cases: one that considered a viable groundwater pathway and the other that assumed all water was derived from offsite sources. Differences between the RSALs with the water pathway on and off were substantial. When the water pathways were turned on, a 1 m y^{-1} irrigation rate was used and resulted in a substantial increase in the removal of radionuclides from surface soil via leaching. However, unlike plutonium, unsaturated zone transit times (the time it takes radionuclides to travel from the contaminated zone to the shallow subsurface aquifer) were typically less than 500 years for uranium isotopes. Consequently, the dose as a function of time typically had two peaks: one at year 2000 (the start time of the simulation) and one after uranium reached the water well in the aquifer. At the 10% level (a 90% probability that the 15 mrem dose limit will *not* be exceeded), the RSAL for ^{238}U, including the sum-of-ratios calculation, was about 10 pCi g^{-1} with the water pathway on and about 80 pCi g^{-1} with the water pathway off. Doses were dominated by water dependent pathways for ^{238}U RSALs that were <60 pCi g^{-1} with the water pathway on. With the water pathway off, doses were driven by ground exposure and plant ingestion.

· ***RAC*-2 (child of rancher) scenario**: As with the rancher scenario, soil action levels were calculated for two cases: one that considered a viable groundwater pathway, and the other that assumed all water was derived from offsite sources. Again, differences between the RSALs with the water pathway on and off were substantial. At the 10% level (a 90% probability that the 15 mrem dose limit will *not* be exceeded) the RSAL for ^{238}U, including the sum-of-ratios calculation, with the water pathway on was about 10 pCi g^{-1} and about 65 pCi g^{-1} with the water pathway off. With the water pathway on, doses were dominated by water-dependent pathways for ^{238}U RSALs that were <60 pCi g^{-1}. With the water pathway off, doses were driven by ground exposure and plant ingestion.

TASK 6: SOIL SAMPLING PROTOCOL

An important goal of the project was to develop recommendations for a soil sampling protocol for use at the RFETS to obtain soil concentration data for comparison to the soil action levels. Sampling protocols are written descriptions of the detailed procedures to be followed in collecting, packaging, labeling, preserving, transporting, and documenting the samples. Attachment C contains the soil sampling protocol recommendations, reviews existing procedures and protocols for soil sampling, evaluates the quality assurance procedures for sampling, and describes soil sampling protocols in detail based on statistical methods (Thorne and Rood 1999).

Sampling protocols are generally developed using clearly defined guidelines by the EPA and DOE. These guidelines incorporate the iterative data quality objective process and require DOE and its contractor to evaluate several important considerations. These considerations include evaluating sampling and analytical costs in relation to available resources and accepting potential decision errors that may result in remediating sites that are judged contaminated when they are actually below the soil action levels. Conversely, developing a sampling protocol must also incorporate the concerns of the general public and other stakeholders, which are represented by the RSALOP and the soil action level study. Because of the complexity of developing sampling protocols, with the inherent need to balance the concerns of DOE and the RSALOP, developing a comprehensive sampling protocol was not considered possible. Rather, *RAC* recommended elements of a soil sampling protocol considered essential to ensure that representative soil samples are collected for comparison to the soil action levels. These recommendations were provided to the RSALOP for presentation to DOE and its contractor, Kaiser-Hill Company, for incorporation into the soil sampling protocol and procedures to be used for the soil action level process.

RAC conducted a review of the current sampling program used at the RFETS and found that a specific sampling protocol for the soil action levels study had not been developed. However, during this review, several procedures were identified that are available in the Rocky Flats program for incorporation into a sampling protocol. Task 6 also presented recommendations for a soil sampling protocol to support the final status survey. The final status survey determines the final condition of the site and is performed after decontamination activities are completed. On the other hand, recommendations for a sampling protocol in support of remedial action were not developed for the Task 6 report. Soil sampling in support of remedial action is an important concept; however, a large number of soil samples have already been collected for use in evaluating the nature and extent of contamination in the surface soil at the RFETS (see Attachment C).

RAC provided several recommendations for developing a surface-soil sampling protocol for the final status survey. The following list summarizes some of the recommendations (see Attachment C for the full list). *RAC* recommended the following:

- The data quality objective process should be used to develop the soil sampling protocol for the final status survey.
- DOE should appoint representatives from the RSALOP for inclusion on the data quality objective planning team.
- *RAC*'s technically derived RSAL values from the soil action level probability curves should be used by the RSALOP for comparison to the soil concentration data.
- Profile sampling should be conducted in soil depth increments of 0–3 cm to be consistent with the resuspension model parameters used to develop the soil action levels.
- Soil samples should not be composited; rather, individual soil samples should be analyzed for radionuclide contaminants.
- The arithmetic mean of the soil concentration data and its associated uncertainty at the upper 95% confidence interval should be used for comparison to the soil action levels.
- The non-parametric statistical tests, called MARSSIM, which were developed by the NRC in 1997, should not be used for the soil action level study because these tests compare the median value of the sample distribution to the soil action levels.
- In situ gamma spectroscopy measurement should be performed to identify potential hot spot locations. Hot spots identified by soil samples or in situ gamma spectroscopy measurements should be investigated further to delineate the size of the hot spot and to determine the upper 95% confidence interval of the mean radionuclide concentrations contained in the hot spot.
- DOE should implement an independent verification survey for the RSAL project.

CONCLUSIONS

The primary objective of this project has been to review radionuclide soil action levels (RSALs) adopted by the Department of Energy, the U.S. Environmental Protection Agency, and the Colorado Department of Health and Environment in 1996 for cleanup at the Rocky Flats Environmental Technology Site (DOE/EPA/CDPHE 1996). Another objective has been to recommend a technical approach for independently deriving RSALs for the site. We applied this approach to the Rocky Flats data using the most restrictive exposure scenarios approved by the Oversight Panel and assuming a 10% probability that the 15 mrem per year dose limit will be exceeded (i.e. a 90% probability that the dose limit will not be exceeded). Using this approach, the technically derived RSAL for $^{239+240}$Pu in soil at Rocky Flats would be 35 pCi g^{-1}. This calculation was corroborated by an alternate method calculation that also resulted in an RSAL at the 10% level of about 37 pCi g^{-1}, suggesting 35 pCi g^{-1} as a technically based RSAL for the Rocky Flats site. The results as presented are a reasonable indication of RSAL magnitudes based on purely scientific considerations if the prescribed dose is not to be exceeded.

The calculation of uranium RSALs was done somewhat differently than those for plutonium because of significant differences in the nature and extent of contamination and the mobility of uranium in the subsurface. For each uranium scenario, consideration was given to whether groundwater was a viable pathway. A viable groundwater pathway assumed that the surficial aquifer underlying the site would provide enough water for human consumption and irrigation. The impacts of a probabilistic fire were also evaluated but inclusion of this process in our calculations made little difference in the resulting RSALs. Assuming the groundwater pathway was viable and a 10% probability that the dose limit will be exceeded, the technically derived ^{238}U RSAL for the most restrictive scenario (the rancher child) was 10 pCi g^{-1}.

We believe the general approaches and results presented in this report are sound and we recommend their adoption. Data limitations impose uncertainties on estimates of doses, and we have been careful to indicate these uncertainties in our analysis. The project's time and budget goals precluded a more in-depth investigation of several important areas of research that, if addressed in the future, could strengthen this analysis. We have presented these recommendations for further research and recognize that they could change the current results somewhat and improve them as a basis for decision making.

Our methodology is based on several extensions of an earlier approach proposed by DOE/EPA/CDPHE (1996) that used the RESRAD computer program. The contract required that the work consider maximum annual dose limits of 15 and 85 mrem in any year over the next 1000 years. We adopted the 15 mrem per year limit for a technically based RSAL because it is more protective of the public and because our evaluation of risk associated with this dose better corresponds to the target level of risk associated with federal guidance (e.g. CERCLA). Although we considered several computer codes to use as the basis of our analysis, the RESRAD code was adopted because it was the most practical choice and because we were required to make calculations with RESRAD in addition to any other code that may have been selected. Therefore, we designed extensions to RESRAD to include (1) consideration of the heterogeneity of radionuclide concentrations in soil around the site, (2) quantification of the uncertainty in predictions of dose, (3) consideration of additional exposure scenarios, and (4) treatment of the possible occurrence of a large grass fire.

Other factors beyond the scope of this work should be considered in the selection of cleanup strategies for Rocky Flats. The soil action level that is applied for cleanup should be decided by federal and state authorities and the community working together to arrive at a cleanup level that provides long term protection of the public. Figure 6 shows probability curves for the most restrictive scenarios. This figure broadly summarizes the results of our work. Parties involved in the decision process might find the figure useful in their deliberations, keeping in mind the different exposure scenarios represented by the curves and the uncertainties involved.

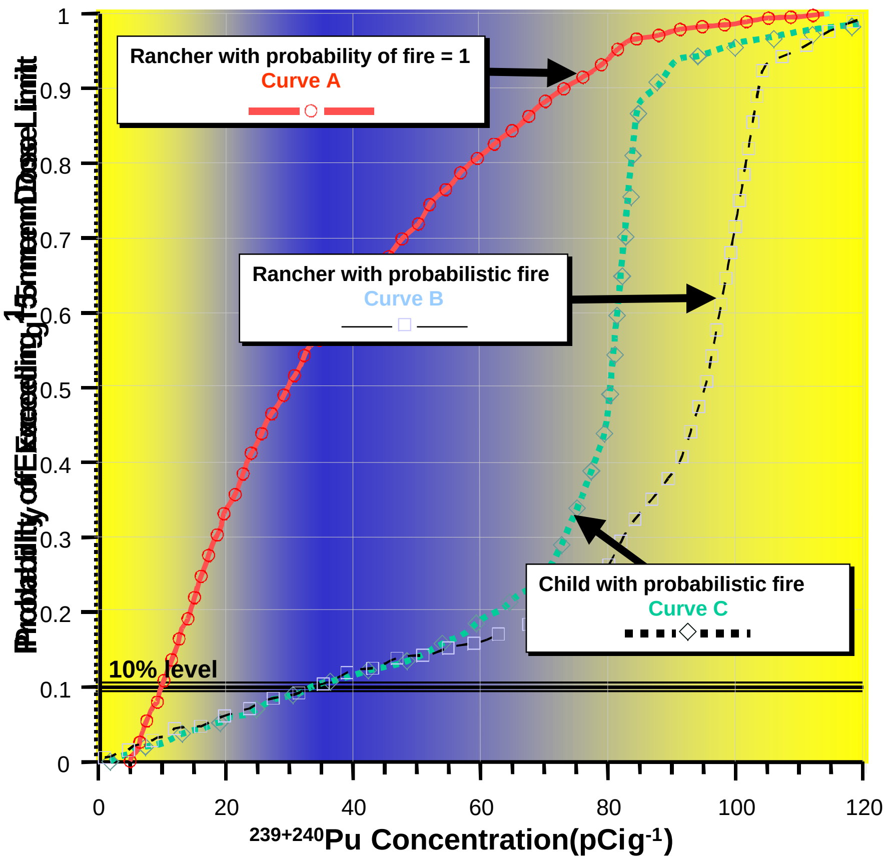

Figure 6. Composite graphic illustrating the most restrictive scenarios and showing a region centered at a soil action level of 35 pCi g^{-1}. Curve A represents the rancher and assumes that a fire occurs with a probability of 1; curve B represents the rancher scenario and takes into account the occurrence of a fire as a probabilistic event; curve C represents the child scenario and, like curve B, incorporates the probability of a fire.

There are several features illustrated in this figure that are important to note. Curve A, defined by the rancher scenario and with the probability of a fire equal to one, likely represents the most conservative set of assumptions and hence the most restrictive radionuclide soil action level. We say “likely” because further research into the impacts of a prairie fire could show that we have underestimated the effects of the fire. Curve B represents the rancher and incorporates a stochastic model of a future fire. With our assumption of a 10% probability of exceeding the dose limit, this curve yields a soil action level of about 35 pCi g^{-1} (the exact value is 33 pCi g^{-1}). Toward the left of the curve, the shape and slope are controlled primarily by inhalation and the probability of occurrence and extent of a fire. However, as the soil concentration of $^{239+240}Pu$ increases, the contribution to dose from ingestion becomes more prominent, and the slope is more influenced by this pathway. Curve C is that of the rancher’s child with the stochastic fire model included. This curve is quite similar to that of the rancher with the stochastic fire model but the curve indicates this scenario is not as protective as the rancher scenarios in the region of lower RSAL concentrations. At higher RSAL concentrations however, this curve becomes more protective than that of the rancher because the ingestion pathway becomes more influential. The steepness of the curve reflects less uncertainty in the calculation. The rancher scenario with the probabilistic fire is our basis for selecting an RSAL at the 10% probability level.

To give a better visualization of our results, we have underlain Figure 6 with a spectrum that expands in both directions around 35 pCi g^{-1} which is about where the rancher and child of the rancher curves intersect the 10% probability level. Colors are darker near the center of the spectrum and lighter farther out. It is important to understand that curves A, B, and C are based on a sum-of-ratios calculation that incorporates the contribution to dose from other radionuclides present in the soil in addition to $^{239+240}$Pu. The graphic suggests a technically based RSAL of about 35 pCi g^{-1} at the 10% probability level and a range of possible RSALs in both directions centered at this value. Although there is no quantitative basis for the boundaries of this range, it is apparent that going too far in either direction from the center of the spectrum can potentially be problematic for a variety of reasons. Radionuclide soil action levels that are significantly lower may correspond to unrealistically conservative scenario descriptions, which could lead to significantly greater cleanup costs than can be justified. On the other hand, RSALs that are significantly larger lead to a high probability of exceeding the prescribed dose limit and could impact human health. It is especially important to understand that the calculation based on the child scenario and influenced primarily by soil ingestion is scientifically well supported. It is unlikely to change greatly unless values for important parameters change, such as the dose conversion factors or the soil ingestion rate. Therefore, curve C effectively represents an upper bound for the RSAL. If the soil action level were too close to this curve, the probability of exceeding the dose limit is greatly increased.

We also developed an alternate method for calculating acceptable levels of radionuclides in soil. This method was based on calculating annual doses to the receptor for different remediation (i.e., cleanup levels) levels. The remediation level that resulted in a 10% probability that the 15 mrem dose limit would be exceeded defined the RSAL. This method more explicitly addresses the heterogeneity of the site and makes it possible to estimate RSALs that correspond more directly to a remediation strategy than does the sum-of-ratios technique used with RESRAD. The approach is more difficult to implement and therefore has not been fully automated in the analysis. However, because it is more explicit, it is a useful check on the sum-of-ratios method, and we include its results in these conclusions. This alternate calculation resulted in an RSAL at the 10% level of about 37 pCi g^{-1} for $^{239+240}$Pu, suggesting the value of 35 pCi g^{-1} should be strongly considered as a technically based RSAL for the Rocky Flats site.

Our analysis is based on the best available data and methods that we could employ. During the course of our work, we have identified important research that should be completed in order to strengthen our methodology. In addition, changes in the design specifications or scenario assumptions on which this methodology is based would change the results accordingly. This flexibility is quite important to keep in mind because a number of issues that could affect these results have been raised during the course of our work.

While our methodology and the resulting RSAL values are scientifically defensible and are based on sound science, *RAC* believes that additional work could reduce some of the uncertainties and refine the RSALs. There were specific areas where more information or more organized research and scientific inquiry would have allowed us to make better estimates of parameters or to develop more well-defined methods in our approach. Foremost among these are data that quantify the impact of a prairie fire on the land now occupied by the Rocky Flats site and the data from the Actinide Migration Evaluation studies. Other important areas include:

- effect of prairie fires on the resuspension of material
- time sequence of revegetation following a natural event like a fire
- more realism in the resuspension model for RESRAD
- developing a methodology to estimate the effects of combined exposure to both the uranium hotspots and the widespread plutonium contamination at Rocky Flats
- construction of a computer-implemented model of the Rocky Flats to permit flexibility in analyzing different radionuclides, sources, and pathways
- groundwater transport properties at Rocky Flats
- new discoveries about site-specific distribution coefficients
- potential for accumulation of actinides on offsite lands and water resources
- protection from violation of the Rocky Flats Cleanup Agreement (RFCA) surface water standards for plutonium

A sound technical foundation and credible scientific methodology are the most important elements in setting soil action levels for Rocky Flats site. However, the final decision on setting the RSALs ultimately lies in the hands of the stakeholders, DOE, and other State and federal authorities. There are other criteria that influence the decision-making process for the Rocky Flats site, such as the cost of cleanup, protection of ecological resources, and community values. The approach to cleanup that is ultimately implemented by the DOE at the RFETS will involve many political, social, economic, and moral decisions. It is imperative that all involved in the decision process recognize these factors and the integration of ideas that must go into making a decision of this type.

RAC's task was to evaluate the RSALs adopted for Rocky Flats in 1996, to develop a methodology for independently determining RSALs, and to calculate RSALs for Rocky Flats by applying this methodology. We conclude that applying our method to the exposure scenarios approved by the Oversight Panel, using 15 mrem y^{-1} as a dose limit, and assuming a probability level of 10%, indicates a technically based RSAL for $^{239+240}Pu$ in soil at Rocky Flats of 35 pCi g^{-1}. For uranium, a technically derived RSAL using our methodology and assumptions would be 10 pCi g^{-1}.

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ATTACHMENTS