Calculating Soil Action Levels and Uncertainties for DECISION-MAKING DURING CLEANUP OF CONTAMINATED SITES

J. E. Till[1], G. G. Killough[2], K. R. Meyer[3], J. W. Aanenson[4], and A.S. Rood[5]

[1]*Risk Assessment Corporation*, Neeses, South Carolina 29107 U.S.A.
[2]Hendecagon Corporation, Oak Ridge, Tennessee 37830 U.S.A.
[3]Keystone Scientific, Inc., Fort Collins, Colorado 80525 U.S.A.
[4]Scientific Consulting, Inc., Freeman, South Dakota 57029 U.S.A.
[5]K-SPAR, Inc., Rigby, Idaho 83442 U.S.A.

Introduction

The Rocky Flats Environmental Technology Site is owned by the U.S. Department of Energy and is part of the nuclear weapons complex. The site is located 8–10 km from the cities of Arvada, Westminster, and Broomfield, Colorado, and 26 km northwest of downtown Denver, Colorado. The Rocky Flats Plant began operations in 1952 as a nuclear weapons research, development, and production complex, and over a period of approximately 40 years, it released various radioactive and nonradioactive materials 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 other actinides from releases during routine operations and from releases to soil that occurred during the storage of contaminated oils and solvents in barrels around the site.

In 1996, the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the Colorado Department of Public Health and Environment proposed interim radionuclide soil action levels to be used in the cleanup of the Rocky Flats site (1). However, because these levels had been developed with little public input and there was considerable concern about their magnitude, local communities formally requested a reanalysis of the radionuclide soil action levels. As a result, in October 1998, the U.S. Department of Energy supported an independent reevaluation of the soil action levels to be overseen by a panel with representatives from the local community, U.S. Department of Energy, U.S. Environmental Protection Agency, and the Colorado Department of Public Health and Environment. Through an open bidding process, the panel selected, *Risk Assessment Corporation* to perform the technical work. This paper summarizes *Risk Assessment Corporation*'s methodology and the project's finding. More details regarding the technical methods of the work can be found in Killough et al. (2).

STUDY DESIGN OBJECTIVES

A number of design objectives for the methodology were dictated by the scope of work. These included

- Use of a dose limit of 0.15 mSv in a year
- Application of exposure scenarios that would protect the public during unrestricted use of the site in the future
- Incorporation of uncertainties in the calculation to the greatest extent possible
- Inclusion of site-specific data into the calculation where they are available
- Use of the RESRAD environmental transport and dose computer code (3) as the basis for calculating radionuclide soil action levels (although modification of the code was permitted).

A radionuclide soil action level is defined as the dose limit divided by the dose-to-source ratio for an individual radionuclide as described below:

$$RSAL = \frac{D_{\lim}}{DSR}$$

where

RSAL	=	radionuclide soil action level
D_{lim}	=	annual dose limit (0.15 mSv) and
DSR	=	dose-to-source ratio (mSv per Bq kg^{-1}).

Realistically though, the soil contains a mix of radionuclides in particular ratios to each other, so a mathematical approach, called sum-of-ratios, is used to account for the ratios of the contaminants in the soil to be cleaned up and assure the 0.15 mSv limit is not exceeded.

Although our methodology and results formed the technical basis for choosing a soil action level, the final decision, which must consider more than just technical aspects, ultimately lies in the hands of the stakeholders, U.S. Department of Energy, and other State and federal authorities. In addition to the technical aspects of the radionuclide soil action level, several other criteria influence the decision-making process that goes into selecting the final radionuclide soil action level for the site. These include a number of important scientific, social, political, and economic factors, not all of which are objective. Each element of the decision must be carefully considered and its importance weighed accordingly. Each criterion may have a different impact on the value recommended—some will raise the value and some will lower it. Our approach should be viewed as a tool and a starting place for selecting a scientifically defensible soil action level that both protects the public and is reasonable to adopt given certain social and political implications. Nevertheless, this methodology forms a sound scientific basis for selecting a soil action level that can be used in the decision-making process.

METHODOLOGY FOR DETERMINING SOIL ACTION LEVELS

A stochastic approach was adopted for this analysis. 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 Monte Carlo 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 curve that plots the soil action level as a function of the probability of exceeding the dose limit of 0.15 mSv y^{-1}.

The sum-of-ratios method is used to assure the 0.15 mSv dose limit is not exceeded when a mixture of radionuclides are present. The sum of ratios is given by

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

where

C_i = the radionuclide soil concentration for radionculide *i* (Bq kg^{-1}) and
$RSAL_i$ = soil action level for radionuclide *i* (Bq kg^{-1}).

When the $SR \leq 1$, then the dose limit is not exceeded, and by that criterion the radionuclide levels are acceptable. The key to the sum-of-ratios calculation is the isotopic ratios that relate the relative concentrations of radionuclides to one another. At Rocky Flats, isotopes of plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu) and their decay products (^{237}Np, ^{241}Am) are present in the soil, although $^{239+240}$Pu makes up the majority of the activity and poses the greatest health risk. Given an empirical distribution of individual radionuclide soil action levels, isotopic ratios, we defined the probability that for a given $^{239+240}$Pu concentration, the 0.15 mSv per year dose limit is exceeded. Using this procedure for a range of possible soil concentrations, we constructed a probability curve that defines the concentration at a given probability level that will not exceed the dose limit.

The conceptual site model used to calculate plutonium radionuclide soil action levels was based on a heterogeneous distribution of plutonium soil and air concentrations across the site. 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 radionuclide soil action levels because the radionuclide soil action level 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 radionuclide soil action level independent of location, we selected a location that corresponded to the location with the highest air-to-soil concentration ratio. Therefore, to provide conservative radionuclide soil action levels that could be applied independent of location across the Rocky Flats Environmental Technology Site, we located each receptor at the point of the maximum air-to-soil concentration ratio.

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. Because the terrain around the site is primarily prairie grass, we had to take into account the effects of a prairie grass fire that burns a large area and, thus, enhances resuspension of radioactive materials during the year the fire occurred. For each scenario, we incorporated the probability of a fire occurring in the area using fire statistics for this 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 Rocky Flats Environmental Technology Site was estimated to be 9×10^{-4}. The impact of a fire was found to be significant in the analysis and the value of soil action level that was estimated.

Inputs and Assumptions to the Model

The RESRAD computer code (3) was used as the basis of the calculations, although a number of extensions to the code were added to accommodate certain site-specific aspects such as resuspension and the occurrence of a prairie fire as described above.

Scenarios were developed to characterize individuals who might be exposed to radioactive contamination at Rocky Flats in the future. The exposure scenarios were created with the assistance of the oversight panel, which provided input regarding their perception of diet, lifestyle, and possible occupational activities on the site after the land became available for public use. The objective was to select scenarios that were realistic but conservative in the sense of identifying individuals who might receive the highest dose at any time in the future. There were two primary pathways of concern: inhalation of resuspended material and ingestion of soil. Therefore, it was important for the panel to agree upon the rate of inhalation and the ingestion rate of soil. Throughout the course of the project, we met frequently with the oversight panel to discuss proposed methods and to seek their support for input parameters to the calculation. This interaction proved to be a vital element of the work. A brief discussion of the most restrictive scenarios follows. Table 1 lists some of the key parameters included in their characterization.

Resident rancher. The resident rancher scenario assumes future loss of institutional control. The rancher is raising a family, maintaining a garden, and leading an active life at the site, spending 24 hours per day, 365 days per year, or 8760 hours at the site. Of that time, approximately 40% of the rancher's time is spent outdoors. The potential pathways of exposure for this person include inhalation, eating produce from a garden irrigated with some water from a stream on the site, direct soil ingestion from outdoor activities, and direct gamma exposure from the soils and airborne radioactivity. The annual breathing rate is 10,800 $m^3\ y^{-1}$ based on a time-weighted average of breathing rates and activity levels.

Child of rancher. The child of the rancher family is assumed to be 10 years of age and onsite 24 hours per day, 365 days per year, or 8760 hours per year. The potential pathways of exposure include inhalation, eating produce from a garden irrigated with water from a stream on the site, direct soil ingestion, and gamma exposure from soils and airborne radioactivity.

Infant of rancher. The infant in the rancher family is 2 years of age and onsite 24 hours per day, 365 days per year, or 8760 hours per year. The infant's potential pathways of exposure include inhalation, some direct soil ingestion from outdoor activities, and direct gamma exposure from soils and airborne radioactivity.

Table 1. Key parameter values used to describe the three most important scenarios

Parameter	**Adult rancher**	**10-year-old child**	**2-year-old child**
Dose limit ($mSv\ y^{-1}$)	0.15	0.15	0.15
Time on the site ($h\ y^{-1}$)	8760	8760	8760
Time indoors onsite (%)	60	750	90
Time outdoors onsite (%)	40	25	10
Breathing rate ($m^3\ y^{-1}$)	10800	8600	1900
Soil ingestion ($g\ y^{-1}$)	75	75	75
Irrigation water source	groundwater	groundwater	groundwater
Irrigation rate ($m\ y^{-1}$)	1	1	1
Onsite drinking water source	groundwater	groundwater	groundwater
Drinking water ingestion ($L\ y^{-1}$)	730	550	365
Fruits, vegetables and grain consumption ($kg\ y^{-1}$)	190	240	200
Meat ($kg\ y^{-1}$)	95	60	35
Milk ($L\ y^{-1}$).	110	200	170

We used the available literature in combination with measured soil concentration data to produce actual concentrations in soil, initialized at the year that the soil action level calculations begin. A number of studies have characterized the ratios of contaminants in the Rocky Flats environment to one another. The relative concentrations of radionuclides derived from these studies are shown in Table 2. The values shown are relative to $^{239+240}Pu$ (given a value of 1) and were used to calculate estimates of concentrations of each radionuclide for the current concentrations of $^{239+240}Pu$. For conversion to dose, the methodology applied dose conversion factors from the International Commission on Radiological Protection (4).

Table 2. Relative Concentrations of Radionuclides in Soil at Rocky Flats in 1999

Radionuclide	Relative concentration (to $^{239+240}Pu$)
^{238}Pu	0.0132
^{239}Pu	0.843
^{240}Pu	0.157
^{241}Pu	0.798
^{242}Pu	7.62×10^{-6}
^{241}Am	0.111
^{237}Np	7.86×10^{-7}

RESULTS

We presented the results as probability distributions of possible values for each of seven exposure scenarios. Each scenario was based on an annual dose limit to the receptor resulting from exposure to Rocky Flats radionuclides. For each scenario, we presented probability curves of the radionuclide concentration as a function of the probability of exceeding the radiation dose limit. An example of the calculational output is shown in Figure 1. For example, if one is seeking a 90% probability that the dose limit will not be exceeded, then the probability level used to select a radionuclide soil action level is 10%. This presentation of results was received very favorably by the panel. Although we used the 10% probability level as the basis for our calculations, we emphasized to the panel that this is a subjective decision-making level and that they could adjust the probability level to reflect not only community concerns about risks but also to take into account costs of cleanup once these are known.

A similar probability curve was developed for each scenario and exposure condition. Radionuclide soil action levels were presented for plutonium isotopes for each scenario. For the plutonium radionuclide soil action level 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.

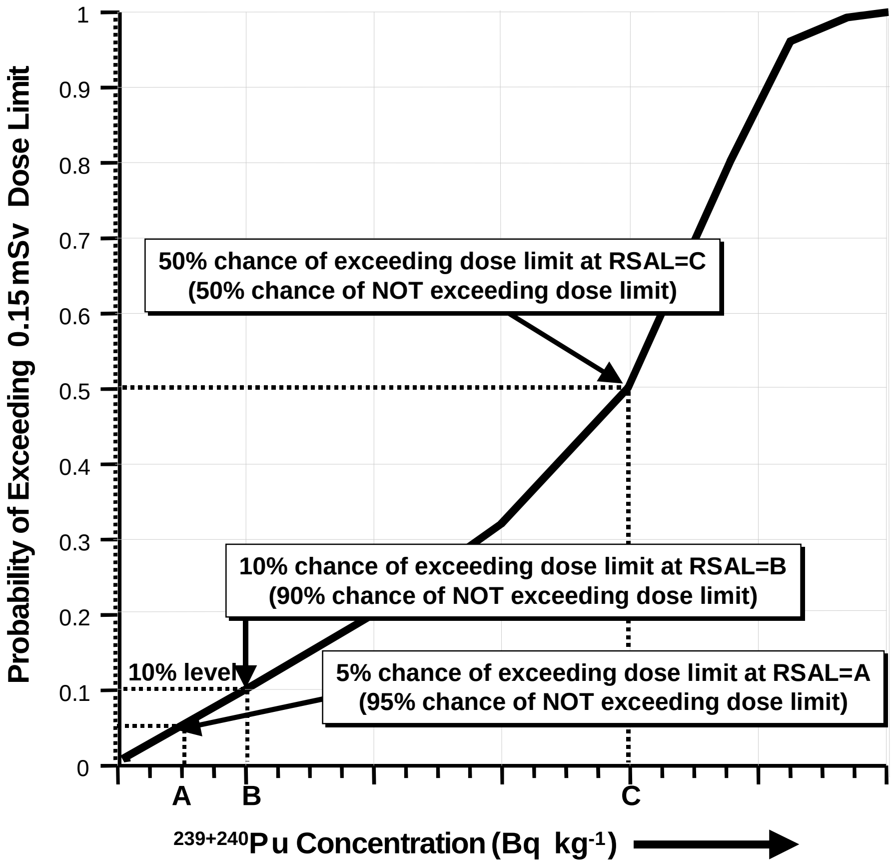

Figure 1. Example of the results of our calculations. Each probability level corresponds to a distinct concentration of $^{239+240}Pu$ in soil. The probability value represents the probability of exceeding the dose limit; that is, at soil concentration A (Bq kg^{-1}), there is a 5% chance that the person 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.

Figure 2 shows probability curves for the three most restrictive scenarios and forms a region of possible soil action levels resulting from our analysis. This figure broadly summarizes the results of our work. Parties involved in the decision process might find the range indicated by the figure useful in their deliberations keeping in mind the different exposure scenarios represented by the curves.

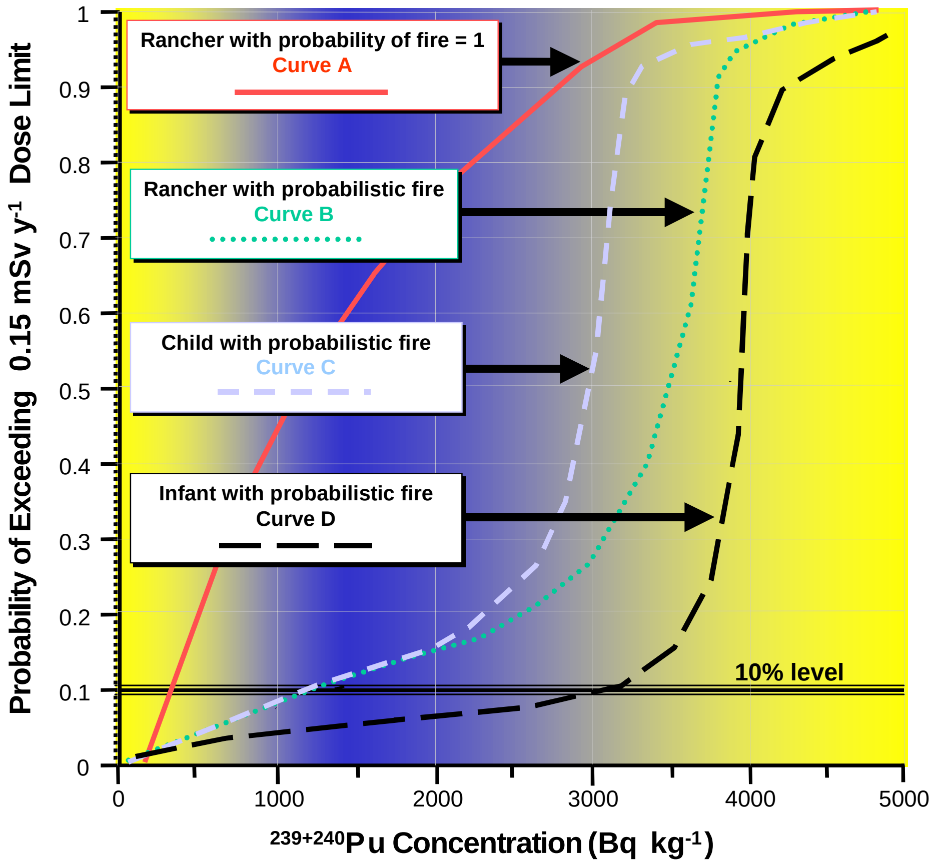

Figure 2. Composite graphic illustrating the bounding scenarios and showing a range of possible soil action levels centered around about 1200 Bq kg^{-1}, which is the 10% probability level for the rancher scenario. Curve A represents the rancher and assumes that a fire occurs with a probability of 1; curve B represents the rancher and takes into account the occurrence of a fire as a probabilistic event; and curves C and D represent the child and infant scenarios, respectively, and incorporate the probability of a fire.

There are a number of 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 1, effectively defines a lower bound for the soil action level. This curve most likely represents the most conservative set of assumptions and, hence, the most restrictive radionuclide soil action level. 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 1200 Bq kg^{-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 shape and slope are 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. However, the ingestion pathway becomes influential at a lower soil concentration of plutonium and within this scope of work forms an upper bound for the soil action level around 3000 Bq kg^{-1}, where the slope of the curve is quite steep. The steepness of the curve reflects less uncertainty in the calculation. Curve D represents the infant and is not a bounding scenario.

To give a better visualization of this range of radionuclide soil action levels, we have underlain Figure 2 with a spectrum that expands in both directions at 1200 Bq kg^{-1}, which is about where the rancher and child of the rancher curves intersect the 10% probability level. The spectrum is darker near the center and lighter farther out. It is important to understand that the curves 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 range of possible radionuclide soil action levels between about 700 and 2000 Bq kg^{-1}. 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 overly conservative scenario descriptions and may incur significantly greater costs than can be justified. On the other hand, radionuclide soil action levels 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 upper bound formed by the child scenario and influenced primarily by soil ingestion is scientifically well supported. It is unlikely to change greatly unless values for key parameters change, such as the dose conversion factors or the soil ingestion rate. It would be prudent to remain significantly to the left of the nearly vertical portion of this curve to ensure that the dose limit will not be exceeded in the future if any of these parameters should change. For this reason, we suggest an upper bound of around 2000 Bq kg^{-1} for the radionuclide soil action level. The probability of exceeding the 0.15 mSv y^{-1} limit at this level is about (16%) and increases rapidly with $^{239+240}Pu$ soil concentrations.

CONCLUSIONS

The primary objective of this project was to develop a methodology that provided the basis for selecting a radionuclide soil action level for cleanup at the Rocky Flats Environmental Technology Site. The project was performed with oversight and input from a panel made up of community and government representatives to improve the acceptability of the results as a decision-making tool for establishing a cleanup level of the site. The results are presented as probability curves of possible values for several of the most restrictive exposure scenarios. Assuming a dose limit of 0.15 mSv y^{-1} and taking uncertainties into account, the results indicate a range of radionuclide soil action levels between about 700 and 2000 Bq kg^{-1}. Assuming a 10% probability level results in a nominal value for a radionuclide soil action level of about 1200 Bq kg^{-1}. Although this result forms the technical basis for a soil action level for cleanup, it must be given further consideration by taking into account economic and socio-political factors that were not addressed this study.

REFERENCES

1. U.S. Department of Energy, U.S. Environmental Protection Agency, and Colorado Department of Public Health and the Environment, "*Action Levels for Radionuclides in Soils for the Rocky Flats Cleanup Agreement*." (1996).
2. G.G. Killough, A.S. Rood, J.M. Weber, K.R. Meyer, H.A. Grogan and W.K. Sinclair, *Task 5: Independent Calculation*. *RAC* Report No. 16-RSAL-1999-FINAL. Prepared for the Radionuclide Soil Action Level Oversight Panel. *Risk Assessment Corporation*, Neeses, South Carolina. February (2000).
3. Yu C., A.J. Zielen, J.-J. Cheng, Y.C. Yuan, L.G. Jones, D.J. LePoire, Y.Y. Wang, C.O. Loureiro, E. Gnanapragasam, E. Faillace, A. Wallo III, W.A. Williams, and H. Peterson, *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0.* Report ANL/EAD/LD-2, Argonne National Laboratory, Argonne, Illinois (1993).
4. International Commission on Radiological Protection, *The ICRP Database of Dose Coefficients: Worker and Members of the Public.* CD-ROM distributed by Elsevier Science Ltd. (1999).